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Groundwater—surface water interaction under scenarios of climate change using a high-resolution transient groundwater model

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Summary A three-dimensional transient groundwater flow model is used to simulate three climate time periods (1960—1999, 2010—2039, 2040—2069) for estimating future impacts of climate change on groundwater—surface water interactions and groundwater levels within the unconfined Grand Forks aquifer in south-central British Columbia, Canada. One-year long climate scenarios were run, each representing a typical year in the present and future (2020 s and 2050 s), by perturbing the historical weather according to the downscaled Canadian Coupled Global Model 1 (CGCM1) general circulation model results. CGCM1 downscaling was used to predict basin-scale runoff for the Kettle River upstream of Grand Forks. These results were converted to river discharge along the Kettle and Granby River reaches. Future climate scenarios indicate a shift in river peak flow to an earlier date in a year; the shift for the 2040—2069 climate is larger than for the 2010—2039, although the overall hydrograph shape remains the same. Aquifer water levels shift by the same interval, when compared on the same day of the year. Distal from the river, modeled water level differences are less than 0.5 m, but were found to be greater than 0.5 m near the river. The maximum groundwater 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.

Introduction

With increasing concerns surrounding global climate change, there has been growing interest in the potential impacts to aquifers. It is expected that predicted global changes in temperature and precipitation will alter regional

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climates and hydrologic systems. One of the expected consequences will be changes in recharge to regional groundwater aquifers, causing shifts in groundwater levels (Changnon et al., 1988; Zektser and Loaiciga, 1993). Most research to-date has been directed at forecasting the potential impacts to surface water hydrology, while for groundwater hydrology, large regional and coarse-resolution models have been used to determine the sensitivity of groundwater systems to changes in critical input parameters, such as precipitation and runoff (York et al., 2002; Yusoff et al., 2002), with few exceptions of very small aquifers and detailed investigations (e.g., Malcolm and Soulsby, 2000). Of particular interest are coupled hydrologic systems, where changes in surface flow regime and changes in recharge to groundwater interact to affect both groundwater and surface water levels.

The purpose of this study is to investigate the impacts of climate change on groundwater levels in a small regional unconfined aquifer (34 km^2) by modeling groundwater flow in a transient three-dimensional numerical model, which is linked to river flow and has spatially- and temporally-distributed aquifer recharge. This paper describes the methodology and results of the groundwater and surface water interaction component of this work. Scibek and Allen (in press) describe in detail the recharge modeling methodology and impacts of climate change on recharge and groundwater levels.

Aquifer model development

The unconfined Grand Forks aquifer, located in south-central British Columbia (BC), Canada (Fig. 1), is contained within the mountainous valley of the Kettle River in BC along the Washington State (WA), United States border. At Grand Forks, the climate is semi-arid and most precipitation occurs in the summer months during convective activity. In the winter, much of the precipitation at high elevation is as snow, although the observing sites at valley bottoms record less snowfall. 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., 2003) demonstrated that the aquifer water levels are highly sensitive to water levels in the Kettle River. Fig. 2 shows a conceptual model of the interaction between the Kettle River and the aquifer. At peak flow, river water recharges the aquifer and moves laterally away from the channel, causing groundwater levels to rise over a broad area. Within a relatively short period following the peak discharge, when river levels begin to fall, the groundwater direction is reversed and contributes to baseflow. Direct recharge to the aquifer from precipitation also results in a rise in water levels; however, the overall effects of direct recharge are very small in comparison to the indirect recharge from the rivers, except in areas removed from the influence of the rivers (i.e., the benches along the valley sides) (Scibek and Allen, in press).

Because climate change is anticipated to impact both the timing and amplitude of flow in the Kettle River, as discussed in a later section, consideration of impacts of climate change must necessarily consider both surface water and groundwater. Thus, a high-resolution transient groundwater flow model is constructed. The high-resolution (spatial and temporal) model is intended to capture not only the transient responses to river discharge and direct groundwater recharge from precipitation under the various climate change scenarios, but also the complex geometry of the aquifer and rivers. In addition, in order to assess the impact of future climate change on groundwater resources, it was necessary to include pumping wells and irrigation return flow during the peak demand period in the summer months (Scibek and Allen, in press).

To construct the groundwater flow model, first, the valley shape was modeled using profile extrapolation, constrained by well lithology logs, and geostatistical interpolation. The valley was found to attain a maximum depth of approximately 250 m below ground surface, but typical sediment thickness is about 100 m. The stratigraphic sequences in the Grand Forks valley are poorly understood, particularly at depth. Approximately 150 well lithology logs

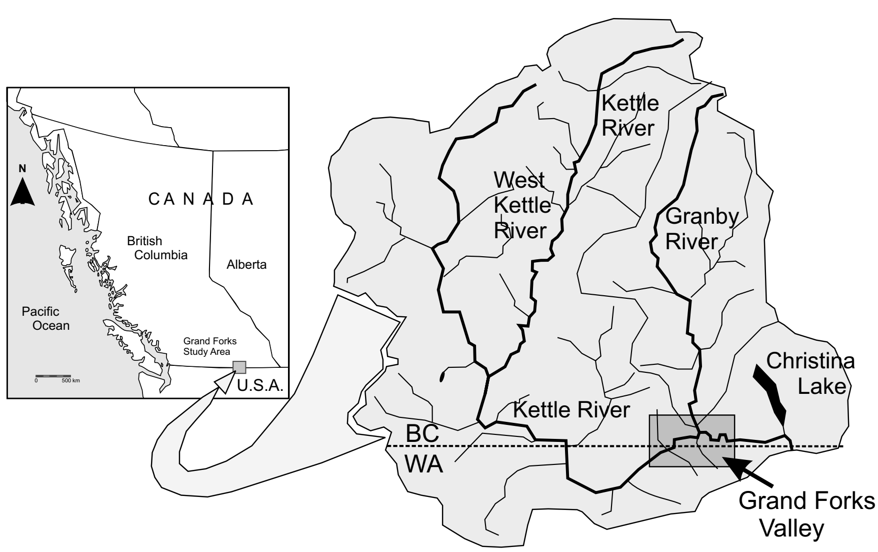

Figure 1 Map of the Kettle and Granby River drainage areas with inset maps show the study area in British Columbia, Canada.

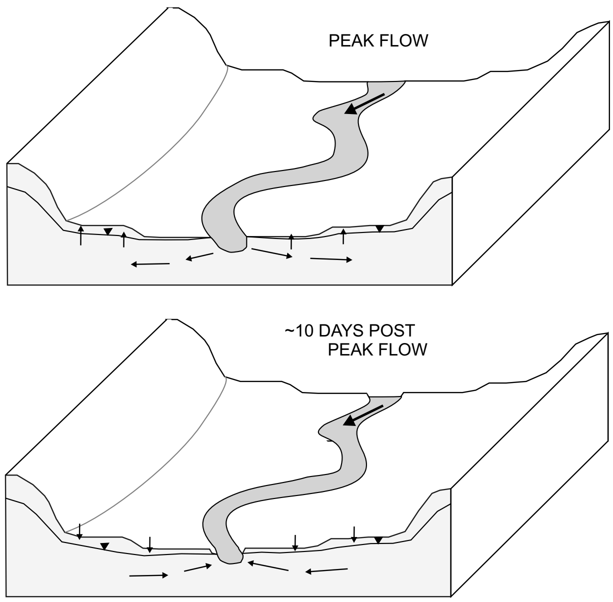

Figure 2 Schematic drawing showing the conceptual model for interaction between the Kettle River and the aquifer. At peak flow, river water recharges the aquifer and moves laterally away from the channel, causing groundwater levels to rise over a broad area. Within a relatively short period of time following the peak discharge (~10 days), when river levels begin to fall, the groundwater direction is reversed and contributes to baseflow.

are available for mostly shallow groundwater wells, and have been previously interpreted within the uniformly layered paradigm of hydrostratigraphy (Wei et al., 1994). In other valleys in southern BC, the basal units are commonly silt, clay and gravel, overlain by thick glaciolacustrine silts (Fulton and Smith, 1978; Clague, 1981; Ryder et al., 1991), and capped by Holocene sandy and gravelly outwash and floodplain deposits and paraglacial alluvial fans.

The hydrostratigraphy 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 MODFLOW, as is typically done with complex multi-layer aquifer systems (Herzog et al., 2003). Representative homogeneous and isotropic hydraulic properties were initially assigned to each layer, based on values determined from pumping test data, but were later adjusted slightly during model calibration. Details of model construction are described in Scibek (2005).

Direct recharge was applied to the top active layer of the model using the results of spatially-distributed recharge modeling (Scibek and Allen, in press). Fig. 3a shows the distributed mean annual recharge. Although not represented on this figure, 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 has moderate recharge, less than in early summer. The predicted changes in mean annual recharge (expressed as percentage differences: (future − historical)/historical) are shown for two future climate periods: 2010–2039 and 2040–2069. The seasonality of recharge has very similar pattern as historical recharge, but there are small differences in recharge values. The 2010–2039 climate scenario has a predicted 2–7% increase from historical mean annual recharge (Fig. 3b). The 2040–2069 climate scenario has a predicted 11–25% increase from historical mean annual recharge (Fig. 3c). Monthly recharge results (not shown) have the lowest recharge occurring in January through May, the highest recharge occurring in June to September, and October through December receiving moderate recharge.

Ultimately, the groundwater flow model was calibrated to replicate the historic groundwater levels in the aquifer (steady-state simulation) as well as the observed variation in groundwater levels in the floodplain (transient simulation) as described in a later section.

Hydrology of Kettle and Granby Rivers

The Kettle River system drains approximately 9800 km^2 within BC, where effectively most of this study area is located (Fig. 1). The river crosses the US border at Ferry, WA and loops back to the Canadian side at Carson, BC (Fig. 4). The valley widens near the City of Grand Forks, where the Granby River flows into the Kettle River. The Kettle River flows east through a narrow valley for about 10 km, turns south near Christina Lake, and crosses the US border at Laurier, and drains another large area before it flows into the Columbia River. The Granby River has a drainage area of 2050 km^2 at its confluence with the Kettle River at Grand Forks, BC.

In the Kettle River drainage area, the snowpack increases over the winter until early April, and melts between April and the end of June, with the end date of the snowmelt season varying from mid-May to mid-July. The hydrological response is extremely sensitive to seasonal variations in climate. During years with unusually warm winters, the system shifts from a snowmelt-dominated regime to a regime where there is an increasing number of days of higher flows due to rain, but with a decreasing number of days of high flow due to snowmelt. The predicted warming trends in global, and also regional, climate, may impact the snowfall amounts and the duration of winter season, and may shift the hydrologic regime, potentially affecting hydrologically linked regional aquifers. In this study, we investigate these linkages of the Kettle River and the Grand Forks aquifer.

Whitfield and Cannon (2000) analyzed data from hydrometric stations in southern BC over two decades (1976–1985 and 1986–1995). The study determined these streams are currently snowmelt-dominated. Observed changes in Kettle River discharge between these two decades, is indicated on the polar plot shown in Fig. 5, which shows a shift in peak flow to an earlier date, although the peak flow magnitude remains the same. Similar responses were observed in other streams in south-central BC (e.g., Similkameen River) (Whitfield and Cannon, 2000). The low flow period now begins earlier in the summer and baseflow levels are lower in fall. In addition, flow is higher in the late fall due to rainfall during this period. Streams in this region are expected to become increasingly bi-modal as a result of

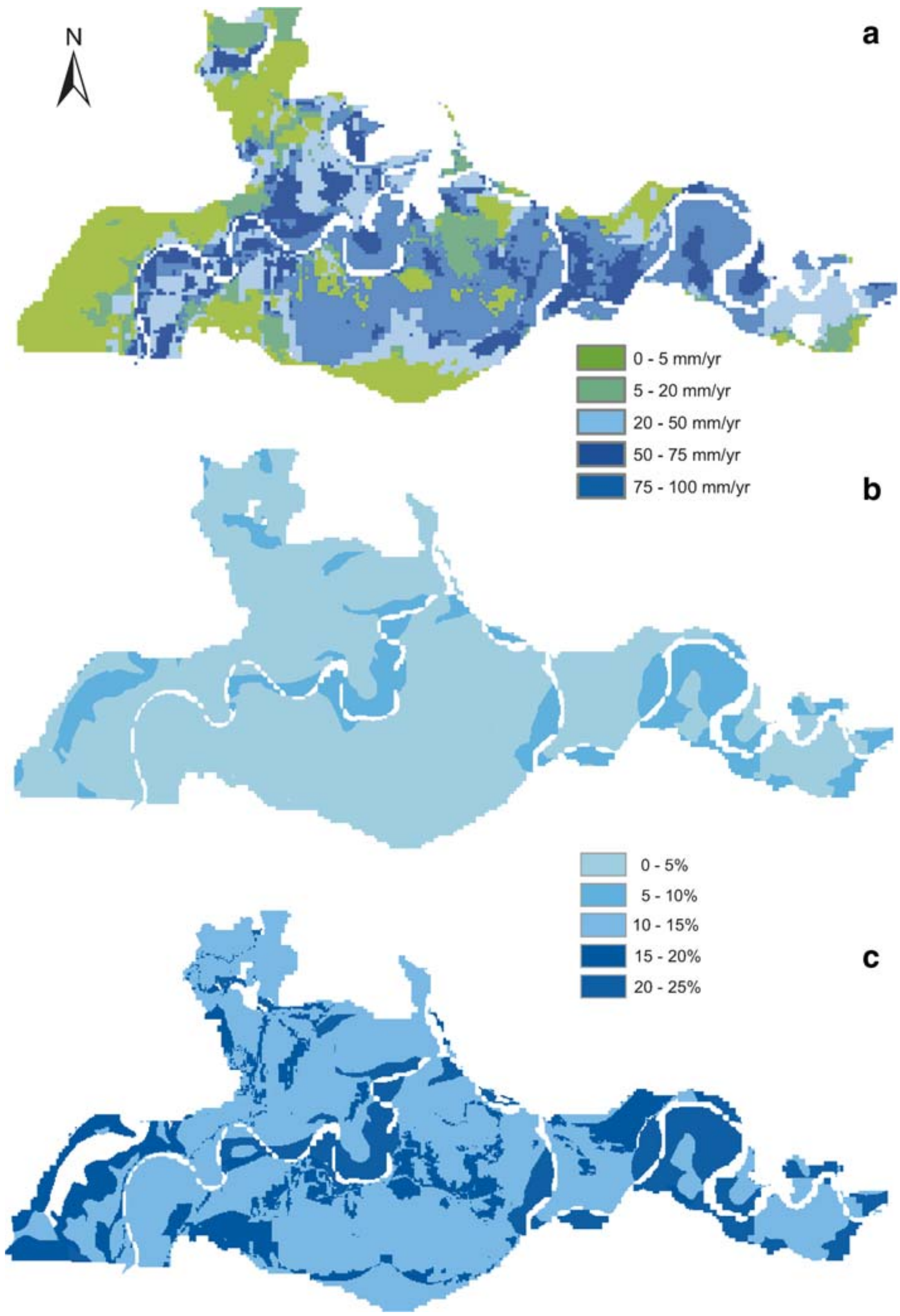

Figure 3 (a) Historical mean annual recharge to the Grand Forks aquifer for the historical climate scenario (1961—1999), (b) percent change in mean annual recharge between 2010—2039 and historical, (c) percent change in mean annual recharge between 2040—2069 and historical.

predicted winter warming associated with climate change (Whitfield and Taylor, 1998; Whitfield and Cannon, 2000).

River discharge rates in Grand Forks valley

In order to model the interaction between groundwater and surface water in the valley, stage elevations are required as a function of time for each river node in the groundwater flow model for each climate scenario. The challenges in constructing the model were firstly, balancing the discharge volume in the valley, given that hydrometric stations are located outside the valley and have different periods of record; secondly, modeling basin scale discharge from downscaled Global Climate Model (GCM) outputs; and thirdly, accurately modeling stage variation in river branches, such that stage could be linked to the groundwater flow model and used to predict impacts on groundwater levels.

Daily discharge records were supplied by Environment Canada (Whitfield and Cannon, 2000) and from the United States Geological Survey (USGS) website. As most river gauges record only water elevation, the discharge records are calculated from stage—discharge rating curves. Repre-

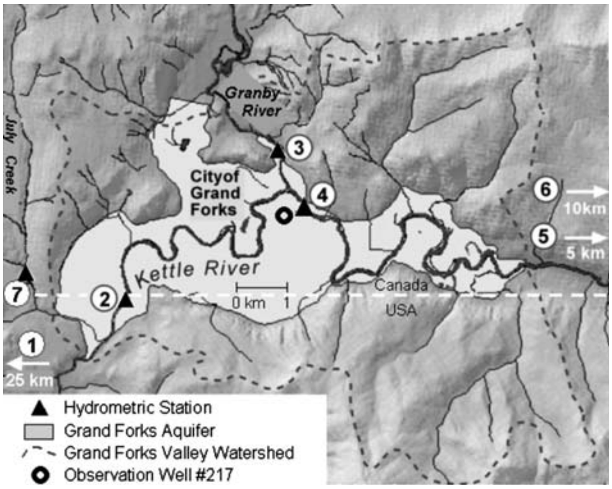

Figure 4 Grand Forks valley watershed and hydrometric stations near the Grand Forks aquifer. (1) Kettle River at Ferry, (2) Kettle River at Carson, (3) Granby River at Grand Forks, (4) Kettle River at Grand Forks, (5) Kettle River at Cascade, (6) Kettle River at Laurier, (7) Kettle River at Laurier.

sentative annual hydrographs, averaged for the period of record, were plotted for each hydrometric station. An example of the hydrograph at Ferry, WA is shown in Fig. 6. The available hydrometric stations in the valley have non-overlapping periods of record; the longest records are at Ferry (WA) and Laurier (WA) gauges on the Kettle River. Therefore, it is necessary to scale these discharge records to represent flow at points between these two gauges in the Grand Forks valley.

Using runoff as a hydrologic response allows for adjustments for differences in drainage areas. Runoff (R) is the volumetric streamflow discharge (Q) [m^3/s] over a period of time (t) divided by the drainage area (A_B) of the basin:

$$R = \frac{Q \cdot t}{A_B} \tag{1}$$

Discharge records from gauges along the Kettle and Granby Rivers were converted to 30-day runoff values. The Granby River basin has much larger runoff values than the Kettle River basin, suggesting greater precipitation in that region.

To determine the runoff at a location downstream of a gauge, the observed daily flows at the upstream station were adjusted by the drainage area ratio of downstream/upstream stations, following methodology of Leith and Whitfield (2000). The scaling factor was computed from the product of the ratio of basin areas at upstream station (A_1) and downstream station (A_2) locations along the river. Then, discharge at the downstream station (Q_2) was computed from discharge at the upstream station (Q_1) using the equation:

$$Q_2 = \frac{A_2}{A_1} Q_1 \tag{2}$$

The streamflow records at Laurier were scaled to represent the streamflow hydrographs in the Grand Forks valley downstream of the confluence of the Kettle and Granby Rivers. The upper section of Kettle River in the valley was then modeled using scaled discharge values from the gauge at Ferry (Table 1).

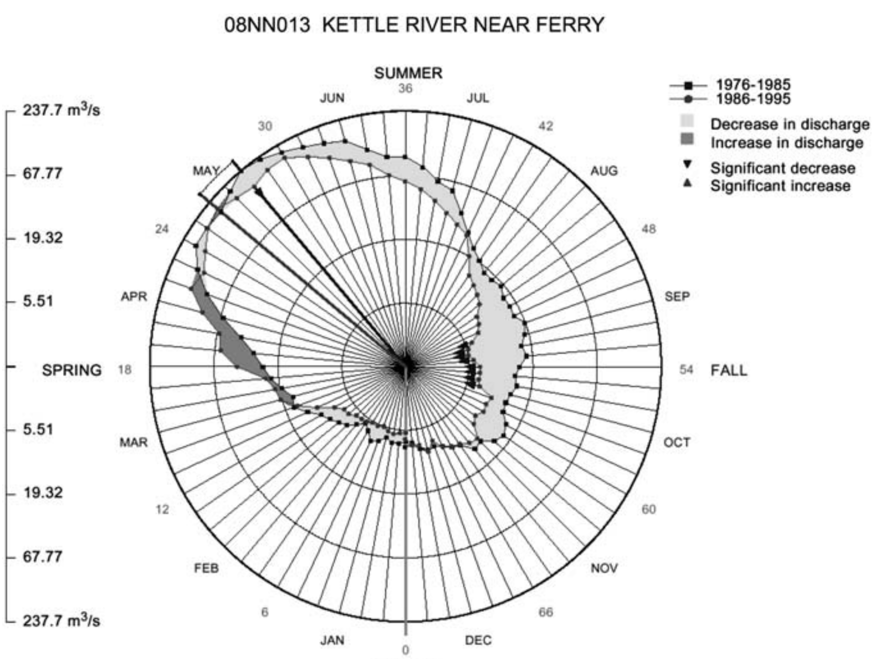

Figure 5 Observed changes in streamflow for the Kettle River near Ferry, WA between 1976—1985 and 1986—1995. The shading between the two curves is dark when increased, and light when decreased. Up and Down arrowheads indicate statistically significant changes (0.05) as determined by Mann—Whitney (Leith and Whitfield, 1998). The two radial lines extending beyond the circle indicate the highest flow in the first period (dark) and the second period (light).

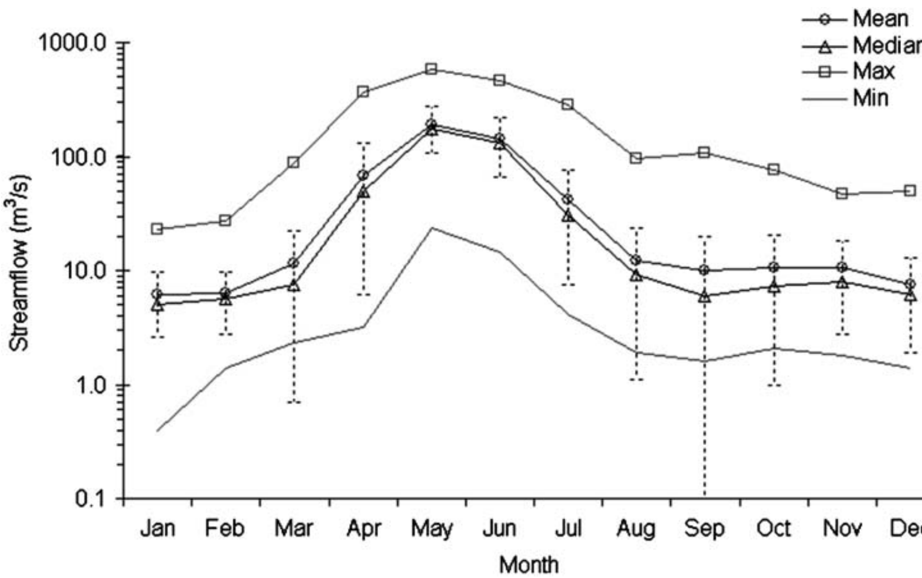

Figure 6 Monthly discharge statistics calculated from mean daily discharges for the complete period of record (1928–1996) for the hydrometric station on the Kettle River at Ferry, WA. Plotted are the mean, median, maximum, and minimum values. Also shown are standard deviations of monthly means (vertical bars).

The inflow from small creeks in the Grand Forks valley watershed (95 km^2) to the rivers was estimated using a scaling approach. Here, the mean annual discharge in the July Creek (see Fig. 4) catchment (45 km^2) is known from records, and is representative of local climate and hydrology. Thus, its discharge is increased by a factor of 2.09 (ratio of 95/45) to arrive at estimates of minimum, maximum and mean discharge in the Grand Forks watershed as shown in Table 2.

The mean annual discharge of the Granby River is 30.5 m^3/s, and for the Kettle River, upstream of Grand Forks, it is 44.3 m^3/s, both adding to 70.8 m^3/s. Downstream from this confluence, mean annual discharge is 72.8 m^3/s as measured at Cascade hydrometric station. The discrepancy comes from different periods of record available at those three locations. Therefore, at the confluence of these rivers, the Granby contributes approximately 40% of the flow, and the Kettle contributes 60% of the flow to the Kettle River. The ratio of discharge of 0.69 from the Granby to the Kettle River varies from year to year. During the mean flow or high flow conditions, the small tributaries contribute only 0.64 to 4.12 m^3/s daily discharge to the larger Kettle River, within the extent of the Grand Forks aquifer, or approximately 1% of the combined Kettle and Granby River discharge. In most years, at low flow in August, the Kettle River maintains a discharge of between 10 and 14 m^3/s, compared to a combined minimum discharge of 0.0137 m^3/s from all creeks in Grand Forks watershed.

Simulating river flows of the Kettle and Granby Rivers

The BRANCH model is a one-dimensional flow model developed and validated by the USGS (Schaffranek et al., 1981). The model is intended for broad operational use to compute unsteady flow and water-surface elevation (stage) of either singular or interconnected channels. The time-dependent variables are the flow rate and the water-surface elevation. Water-surface elevations and discharges are computed at segment nodes and branch junctions.

A new user interface was developed for the BRANCH code, where all inputs and outputs are included in a single spreadsheet file. Model parameters and inputs were read either directly from spreadsheets, or optionally from old BRANCH format text files. A new module was written to al-

Table 1 Selected Kettle River and Granby River hydrometric stations

Station	Reference number	Basin area (km^2)	Conversion	Scaling ratio
Kettle River at Ferry	USGS 08NN013	5750		
Kettle River at Carson	WSC 08NN005	6730	Ferry → Carson	1.1704
Granby River at Grand Forks	WSC 08NN002	2050		
Kettle River at Grand Forks, below confluence with Granby	Est.	6825 + 2050 = 8875	Kettle R. + Granby R.	
Kettle River at Cascade	WSC 08NN006	8960		
Kettle River at Laurier	USGS 08NN012	9840		

Hydrograph for Kettle River at Ferry is shown in Fig. 6.

Table 2 Estimated contribution of discharge from drainages within the Grand Forks valley watershed, scaling up from the July Creek catchment

Annual discharge (m/s)	July Creek (m^3/s)	Grand Forks watershed (m^3/s)
Minimum	0.00686×2	0.0137
Maximum	2.06×2	4.12
Mean	0.32×2	0.64

low for hydrograph generation to create boundary value data series in any time increments to simulate the hydrograph wave form based on monthly values. Mapping of the channel network into a raster grid as defined by groundwater flow model implemented in Visual MODFLOW v 3.1 (Waterloo Hydrogeologic Inc., 2004). This divides the channel into segments, and uses BRANCH output to update the MODFLOW boundary value file for specified-head boundary schedules for any number of cells. The new version of BRANCH was verified with USGS sample data.

The model was applied to 26 km length of the Kettle River channel, including a small section of the Granby River (about 1 km). The channel sections of the Kettle and Granby Rivers with BRANCH schematization are presented in Fig. 7a. Boundary conditions were specified at three external nodes, and river stage was computed at 67 channel cross-sections (British Columbia Environment, 1992) as shown in Fig. 7b. It is important to note that although the cross-section spacing along the Kettle River is dense (150 to 600 m with an average of approximately 400 m), the river channel geometry varies greatly with location. There is also a lack of consistency in high-water mark surveying along the cross-sections. Thus, due to lack of more information, it was assumed during calibration that not all the high-water level scour or debris on channel banks were caused by the same high flow at all points along the channel. Limitations of the model also include a lack of accounting for channel storage, variations of channel roughness with stage, or backing up of water along un-surveyed sections of the channel, which could impact the surveyed locations. Therefore, neither the surveyed high-water marks nor the modeled stages are without error. At low flow, there are small rapids in various places along the river channel (in both the Kettle and Granby Rivers), creating unsteady flow in some sections, and violating the assumption of steady flow in the flow equations.

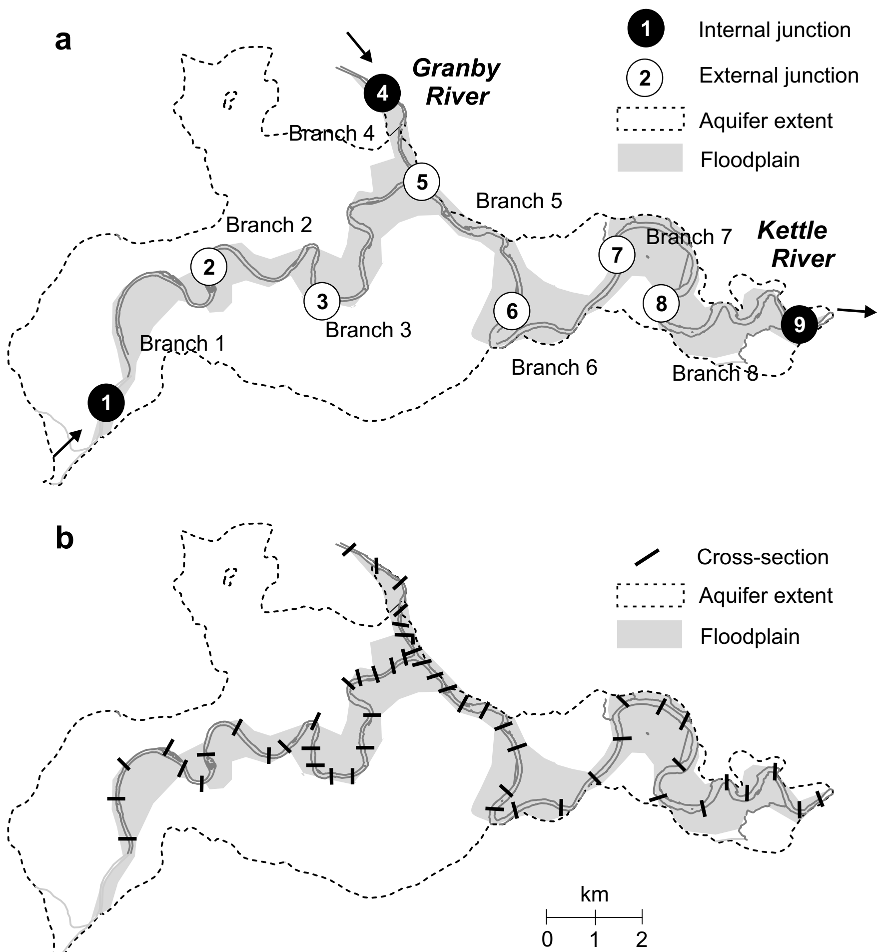

Figure 7 (a) River branches in the BRANCH model, (b) location of Kettle River cross-sections 1—67. In the upper panel, the numbers in the dark circles indicate external junctions and the numbers in the light circles indicate internal junctions. The dark shading shows the extent of the river floodplain, and the dashed line the extent of the aquifer.

Stage—discharge curves

Notwithstanding the limitations of BRANCH, stage and discharge (rating curves) were calculated for all river cross-sections at 1-min time intervals over the specified number of 10,000 time steps. The input consisted of a rising river discharge hydrograph from baseflow to near peak flow, similar to that observed in early freshet, for a typical range of discharge values. Tabular and graphical output was specified at coarser time steps of 60—120 min, but finer output steps were used for calibrating initial stages at early time steps of model runs. Stage—discharge plots were created from scatterplots of computed stage and discharge for each cross-section. Rating curves were fitted with a simple power law function ($y = ax^b + c$). The shapes of these curves are compared to historical rating curves from hydrometric stations in the Grand Forks valley (Fig. 8a).

High water marks were added to stage—discharge plots as horizontal lines and the fitted curves were extrapolated to intersect the high-water mark lines at typical flood level discharges (Fig. 8b). If the modeled rating curves deviated greatly from the high-water mark and the cross-section geometry indicated that modeled stages were not reasonable when compared to other nearby cross-sections with similar geometries, the rating curve equation was adjusted and the curve fitted to intersect the high-water mark. As described in the following sections, river stage hydrographs at all cross-sections were imported to the groundwater model as nodal boundary conditions by linearly interpolating between cross-sections.

Type of river boundary condition in MODFLOW

Transient simulations are needed to analyze time-dependent problems, such as the impact of climate-change induced shift in river hydrographs on the water levels in the Grand Forks aquifer. Boundary conditions influence transient solutions when the effects of the transient stress reach the boundary, and the boundaries must be selected to produce a realistic simulated effect (Anderson and Woessner, 1992). The MODFLOW model contains two packages that account for leakage to and from rivers. The River package allows rivers to be represented with a stage fixed during a stress period, with leakage to and from the aquifer (McDonald and Harbaugh, 1988). It requires an input value for streambed conductance to account for the length and width of river channel, the thickness of riverbed sediments, and their vertical hydraulic conductivity. New versions of Visual MODFLOW include a Streamflow-Routing Package, which allows leakage to and from the stream, but assumes a very simplified uniform rectangular geometry for the river channel, which unfortunately simplifies greatly the non-linear stage—discharge relation.

A comprehensive water balance in the valley demonstrated that the river discharge in both the Granby and Kettle Rivers is not measurably affected by inflows from small catchments in the Grand Forks valley (discussed previously). Nor is river discharge affected from groundwater discharge. Using a steady-state groundwater flow model (calibrated to baseflow levels in August), Allen et al. (2003) calculated that the magnitude of flows between the aquifer and the rivers is on the order of 0.5 m^3/s in both directions. Under low flow conditions, the Kettle River maintains a discharge of roughly 12 m^3/s. Therefore, groundwater exchange with the river is on the order of 4%. At peak flow the exchange is considerably lower; on the order of 0.1% (mean annual river discharge is 450 m^3/s). Therefore, the rivers can reasonably be represented as specified head boundaries, allowing exchange of water with the aquifer, but with no significant consequential increase or decrease in river stage.

The bottom sediments of the Kettle and Granby Rivers above the Grand Forks aquifer consist of mostly gravels, with very few fine sediments. In effect, the aquifer is in direct contact with the river channel and there is no impediment to flow. The constant head nodes do not require any conductance coefficients and, thus, assume perfect hydraulic connection between the river and the aquifer. The river

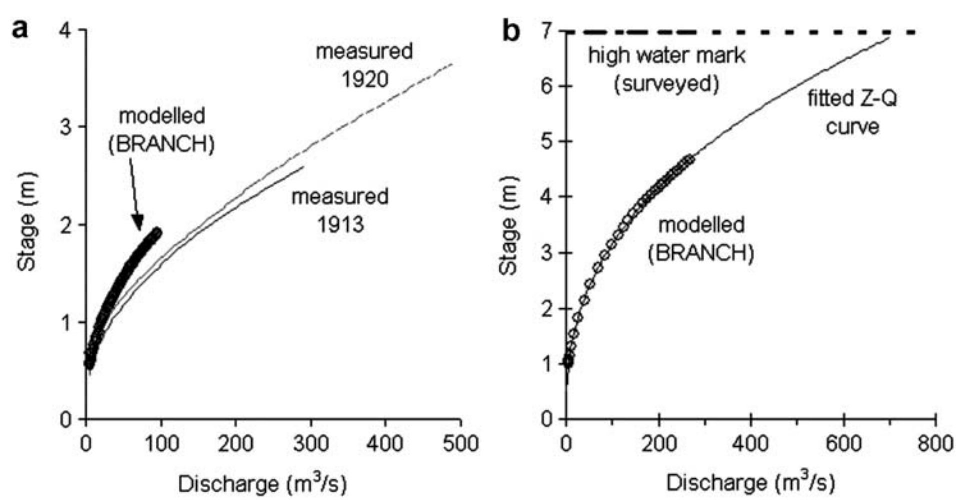

Figure 8 (a) Stage—discharge curves derived from historical records (1913, 1920) and modeled by BRANCH for gauges on the Kettle River in Grand Forks valley near US—Canada border, (b) BRANCH output, surveyed high water mark, and fitted rating curve for Kettle River channel in Grand Forks near confluence with Granby River.

can leak and receive water to and from the aquifer, but the river stage will not change significantly as a result of such interaction. Head schedules are used to represent the modeled river stage in transient Grand Forks aquifer model. The head is held at a constant value for the duration of a time step, but changes to a different value with successive times.

Using BRANCH output as boundary conditions in MODFLOW

The calculated rating curves, together with automated mapping of river water elevations to the groundwater flow model, allows for modeling seasonal variation of groundwater levels and their sensitivity to changed river hydrographs. Modeled discharge hydrographs were converted to river stage hydrographs at each of the 123 river segments, each roughly 200—250 m in length, and interpolated between known river channel cross-sections that have stage—discharge curves. River channels were represented in three-dimensions using a high grid density (14—25 m) in MODFLOW. River segments were mapped onto MODFLOW cells in a GIS system (to mid points of cells), providing a database link between river water levels and appropriate river boundary cells. For each segment, the program located the nearest upstream and downstream cross-section location, and the stage—discharge rating curve for that cross-section was used to calculate water elevation from discharge. River water elevation was interpolated between cross-sections with fitted channel profile. The program then updated the appropriate boundary file of Visual MODFLOW. River stage schedules along the 26 km long meandering channel were imported at varying, temporal resolution (1 to 5 days) for every cell location independently. The channel width of Kettle River was 2—4 cell lengths at most locations. The actual thalweg, or water-filled and flowing channel width, may be less than two cell widths during low-flow months, but this schematization does not adversely affect the groundwater flow model.

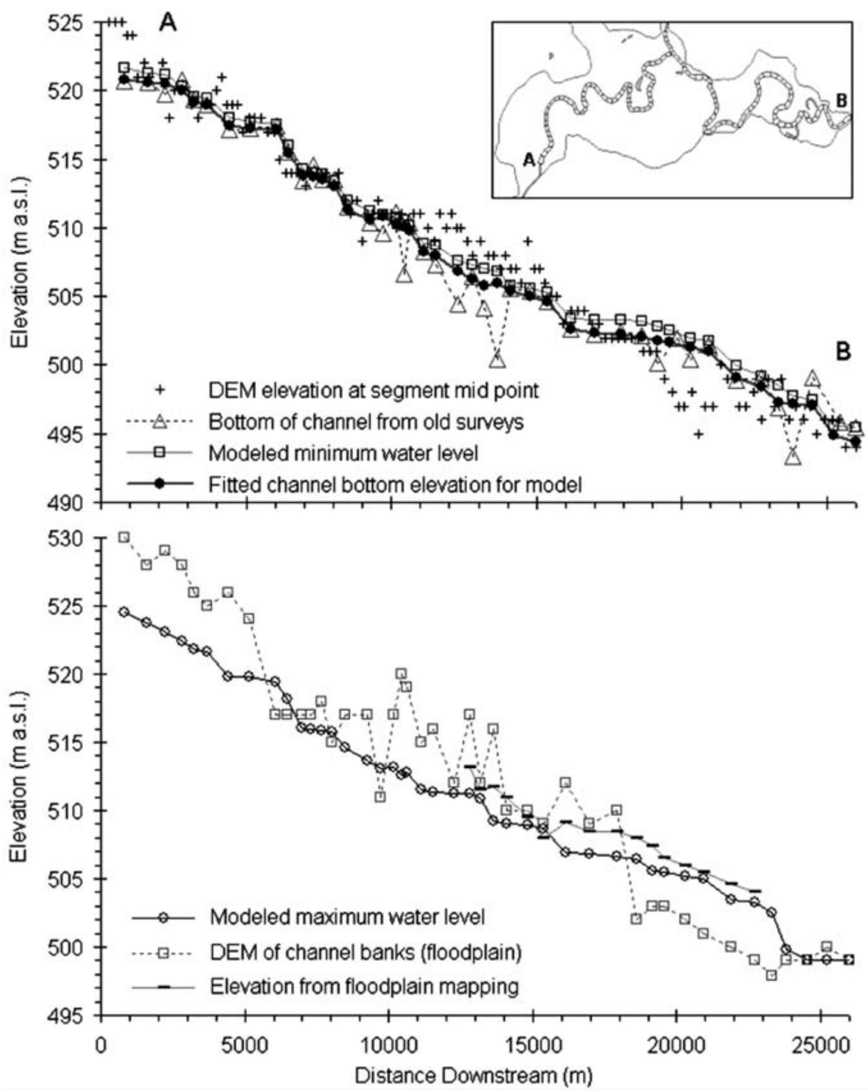

Figure 9 Elevation profile of the Kettle River. Top graph shows digital elevation model (DEM) at segment mid point, surveyed channel bottom elevations, modeled minimum water level flood, and fitted channel bottom. Bottom graph shows DEM of channel banks, modeled maximum water level and elevation from floodplain mapping.

Adjusting the river elevation profile

The DEM (20 m grid) was rather inaccurate in the valley; river floodplain elevations were too low in many places and the river channels poorly defined. The channel bottom elevation profile, representing the minimum elevation at each cross-section along the length of the river (Fig. 9), has jagged appearance because there are local depressions in the river channel, or perhaps surveying errors. It would be expected that channel bottom would decrease or remain level in a downstream direction. This inconsistency of minimum channel bottom elevation profile caused problems in MODFLOW because the ground surface digital elevation model (DEM) and the river channels did not correspond to the surveyed channel bottom elevations. Thus, these had to be modified along river channels. River water elevation was calculated by adding river stage, computed from stage–discharge curve, to the channel bottom elevation. Consequently, the river channel bottom profile was smoothed out to ensure that calculated minimum and maximum stage were always decreasing downstream, as required by BRANCH. Locally, pools and riffles were not modeled, but at the scale of the model, these minor bed topographic variations were small compared to the overall slope.

River stage should also be below local floodplain elevation, where ''floodplain'' is the area mapped along the river channel (on floodplain maps of the Kettle River) that would be flooded in a 20 year flood (or similar measure). But, we did not attempt to model such extreme events in our model. MODFLOW layers were edited along all river channels to put all constant head boundary cells in first layer (gravel) of the model. The channels were also deeper than on the original DEM surface of the valley, but were similar to the surveyed channel profiles.

Downscaling of river discharge (historical and future predictions)

Models for streamflow generation from watersheds can be calibrated to present conditions, and extrapolated to predict future conditions. These include physically-based watershed models, empirical or statistical models relating hydroclimatic variables to streamflow, and empirical downscaling models, where local or regional-scale variables (e.g., streamflow), which are poorly described by coarse-resolution GCMs, are related to synoptic- or global-scale atmospheric fields (Landman et al., 2001). Beersma et al. (2000) showed climate scenarios to be useful for hydrologic impacts assessment studies. Climate downscaling techniques are treated in more detail by Hewitson and Crane (1996). A review of applications of downscaling from GCM to hydrologic modeling can be found in Xu (1999).

Climate data from the Canadian Global Coupled Model (CGCM1) (Flato et al., 2000) for the IPCC IS92a greenhouse gas plus aerosol (GHG + A) transient simulation were used in this study. The three climate periods were: current climate (1960–1999), 2020s climate (2010–2039), and 2050s climate (2040–2069). The current climate statistics are based on 40 years of record, while the future climate scenarios represent two steps, each step representing an average of a 30 year period.

The dimension of the large-scale climate dataset (from the GCM) was reduced (downscaled) using principal component analysis (PCA). Here, 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 National Center for Environmental Prediction (NCEP) database (Kalnay et al., 1996). This dataset provided large-scale climate variables that are used as historical analogs. 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 daily discharge data at the three sites for the simulated 1962–2100 period: Kettle River at Ferry (WA), Granby River at Grand Forks (BC), and Kettle River at Laurier (WA). The discharge data set for present climate scenario was truncated to 1971–2000 period (30 years) to make it the same length as the modeled river discharge for future climate scenarios. In the groundwater flow model, the base case (present climate) river hydrograph is the mean hydrograph for the 1971–2000 period (the original dataset 1962–2000 was also downscaled from 1962–2000 climate model runs from the GCM), 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.

The GCM gives one possible realization of simulated climate given historic forcings. The poor fit between the downscaled and observed hydrograph for 1971–2000 (Fig. 10) can mostly be attributed to biases existing between the GCM simulated climate fields and the observed climate fields from the NCEP dataset. The downscaled CGCM1 data underestimate temperature in the late winter and early spring periods and overestimate temperature in the late fall and early winter periods. Consequently, the onset of freshet is delayed. Wilby and Wigley (1997) demonstrated that downscaled climate scenarios are sensitive to many factors, including the choice of predictor variables, downscaling domains, season definitions, mathematical transfer functions, calibration periods, elevation biases and others. Although the output may be adjusted, there is a tradeoff between discharge time series ''smoothness'' and accuracy of modeled peak flows. This was expected, and may be inevitable given the state of GCMs at present. The model bias is similar for all three hydrometric stations, but the model bias is greater for median discharges than for mean discharges. Therefore, only mean hydrographs were considered in future analyses.

Where the model bias is unacceptable, the downscaled results could be used as a basis for adjusting the observed historical hydrograph to match the simulated changes. However, such an approach might be hard to justify, especially for the future scenarios, and the GCM bias should be explicitly shown, along with the resulting impact on the subsequent hydrologic simulations (Whitfield et al., 2002) – see Fig. 10. The comparisons of impacts of future climates is then always between the unadjusted GCM-driven hydrologic simulations for future time periods and those for the baseline period.

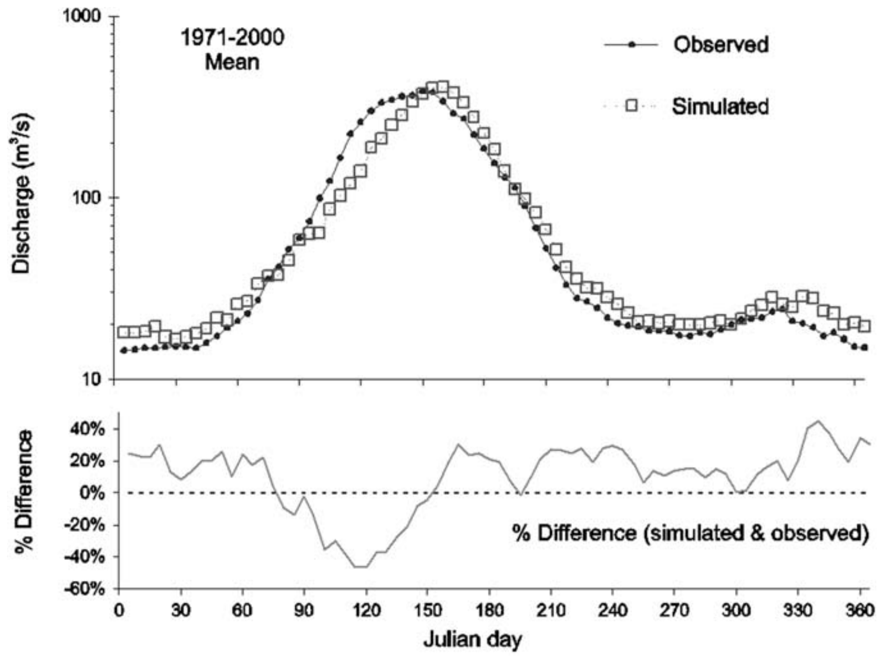

Figure 10 Observed and simulated discharge at Ferry (WA) on Kettle River, downscaled from CGCM1 (Environment Canada, 2002) showing model bias.

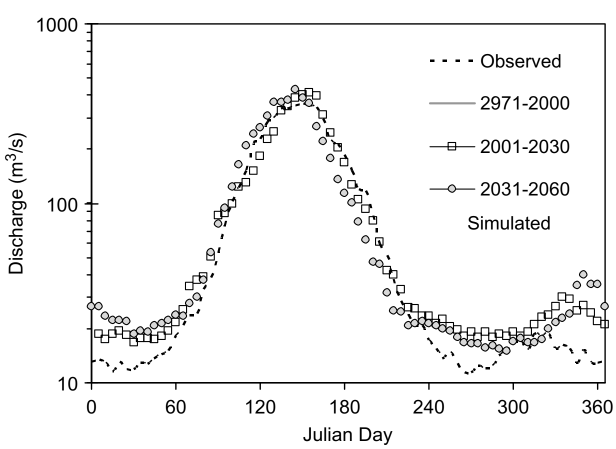

Figure 11 Predicted discharge in the Kettle River at Laurier, WA, modeled using statistical downscaling model and comparing to observed discharge in last 30 years (Environment Canada, 2002).

In the future climate scenarios (Fig. 11) the hydrograph peak is shifted to an earlier date, although the peak flow remains the same. There is also a measurable 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 period than for the 2010—2039 period, compared to the modeled 1971—1999 period. The Kettle River and the Granby River had very similar responses to climate change. It is worthwhile noting that the climate change predictions for streamflow do not consider potential changes to the river morphology. However, over this relatively short time frame it is anticipated that there will not be significant changes in the river morphology (e.g., river sinuosity, pattern of width to depth ratios, channel location, and sediment size), particularly as peak flows tend to remain the same; only the timing changes.

Groundwater model calibration results

The base case transient model simulated groundwater flow under present climatic conditions (1960—1999 period). Two models were created, one with pumping wells turned on and one without pumping of groundwater. Only large production wells within the aquifer were considered, and average mean daily pumping rates were assigned and activated during the summer months when groundwater wells supply irrigation demand in the valley. The calibration process was carried out on the non-pumping model, which is more representative of static groundwater levels. Model calibration was undertaken manually, although very few adjustments were made to the model parameters during calibration. The recharge was not varied at all, as recharge had been modeled external to the groundwater flow model (Scibek and Allen, in press). Only the hydraulic properties for the aquifer media were adjusted slightly from those obtained directly from pumping tests. The hydraulic conductivity and storage coefficient for the upper aquifer layers were adjusted to reproduce the timing of the observation well shift in response to river level changes.

The calibration graph for Observation Well 217, one of the BC provincial monitoring wells in Grand Forks (Fig. 12), displays the observed long term monthly mean water elevation and modeled groundwater elevation after model calibration (present climate scenario). The groundwater levels in the observation well were taken on the last day of each month, then averaged for the period of record

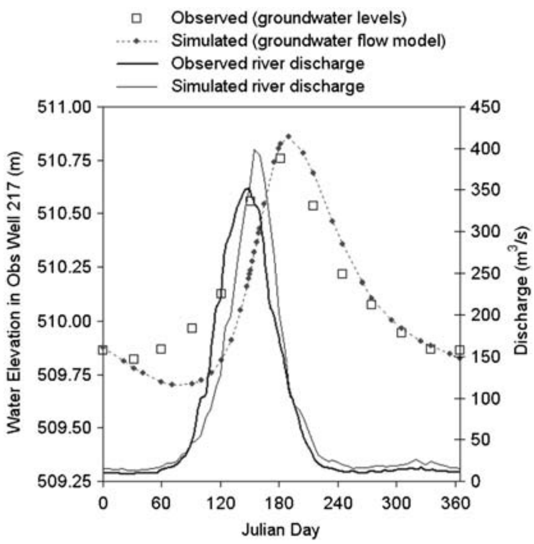

Figure 12 Mean hydrograph of water table elevation (total head) in Observation Well 217 in the Grand Forks aquifer for period of record 1974—1996, and estimated water surface elevation of Kettle River at Grand Forks (1971—2000) approximately 400 m from well 217.

(1974—1996), and graphed on last day of each month. Also shown are observed and simulated discharge hydrographs for the nearby Kettle River at Carson for the corresponding time period. There is a regular seasonal pattern to groundwater levels, similar to the stage hydrograph of the Kettle River. The groundwater level in the well varied between 1 and 1.8 m over the period of record, whereas the river experienced stage fluctuation of 3 m (Fig. 12). The mean monthly water table elevation varied only by about 1.0 ± 0.2 m. The shape of the well hydrograph is similar to the Kettle River hydrograph, but the amplitudes of seasonal fluctuations are damped, which would be expected at wells some distance away from the river channel.

The vertical offset of the hydrograph was calibrated by adjusting bottom elevation of river channels (see Fig. 9) around the observation well location, and by allowing for 0.2 m error in the absolute elevation of the observation well (top of casing). The water levels are measured with 0.01 m accuracy by a water level recorder and datalogger. The amplitude of the hydrograph (peak) was calibrated by changing specific yield (Sy) and horizontal hydraulic conductivity (Kxy) values in layers 1 and 2 (surficial gravel and sand aquifer) of the model. As Sy was varied from 0.04 to 0.20, the amplitude of the hydrograph decreased and the slope of the decreasing hydrograph also flattened, ending with higher groundwater levels at the end of the year. The same effect was obtained by lowering Kxy and keeping Sy constant. A phase shift of the hydrograph occurs due to the delay of groundwater flow across the distance from the Kettle River (in 3 directions). It was calibrated by allowing for river model bias (from downscaled CGCM1 linked to river discharge), and by changing slightly Kxy and Sy. Nevertheless both parameters remain within the range of values obtained from pumping tests.

The transient model consistently predicted lower than observed groundwater elevations at Observation well 217 in the early spring season. It is important to recognize that the river discharge hydrographs do not show the stage of the river. The BRANCH model, which was used to compute stage—discharge elevations, assumes ice-free conditions in the river, and only ice-free river stages were used in stage—discharge curves in the past for this river. It is well known that in Canadian rivers that partially freeze in the winter; the ice breakup on the river causes an increase in river stage due to icing of the channel, resulting in higher actual river stage than would be predicted by a given discharge. The modeled water levels do not account for this effect because the groundwater model uses modeled river stage, which is computed from river discharge, without accounting for ice effects. Therefore, it is expected that modeled groundwater levels would decline from day 1 to day 60 when river discharge begins to increase due to snowmelt. In reality, the observed river stage is probably higher in spring due to ice damming and icing within the channel, but still conveys the same discharge.

The groundwater model is calibrated to the modeled (not observed) discharge and stage in the Kettle River. If there was no bias in the river model (observed to modeled present), the modeled well hydrograph would match the observed hydrograph. The modeled peak of groundwater was maintained at a level slightly higher than observed to account for this positive bias in modeled versus observed river discharge (and thus stage). Similarly, the modeled hydrograph is shifted to a later date. The calibrated model is also shifted by the same number of days to account for this bias. The groundwater model is very well calibrated at the location of observation well 217. However, this does not mean that it is well calibrated for other regions of the aquifer. Calibration residuals for static water levels had an acceptable error distribution, but residuals tended to be high near the model boundaries, which might be anticipated due to lack of physical data in these areas with which to constrain the conceptual model. Observation wells where residuals were very large (>5 m) were examined in detail, and compared to other observation wells near to them, the possible range of river water levels if the well was adjacent to the river, ground surface elevation, and the expected water table surface in that area. The RMS error for model was 8%.

Surface water—groundwater interaction

In order to quantify the linkages between the surface water and groundwater regime, a water balance analysis was conducted. The model domain was divided into several water budget zones, and Zone Budget (ZBUD) in Visual MODFLOW was run. In the upper two layers, these zones correspond to the floodplain (extending along the rivers), the various individual irrigation areas, areas not included with the irrigated land (background zone), and the deeper silt and clay layers.

During spring freshet on the Kettle River, the rise in river stage causes inflow of water to various ZBUD zones (after passing through the floodplain area). This excess water is stored in the aquifer. Mass balance calculations indicate that storage rates are less than 50% of inter-zonal groundwater flux, and 15—20% of river-aquifer flux. As river stage drops, the hydraulic gradient is reversed; water is released

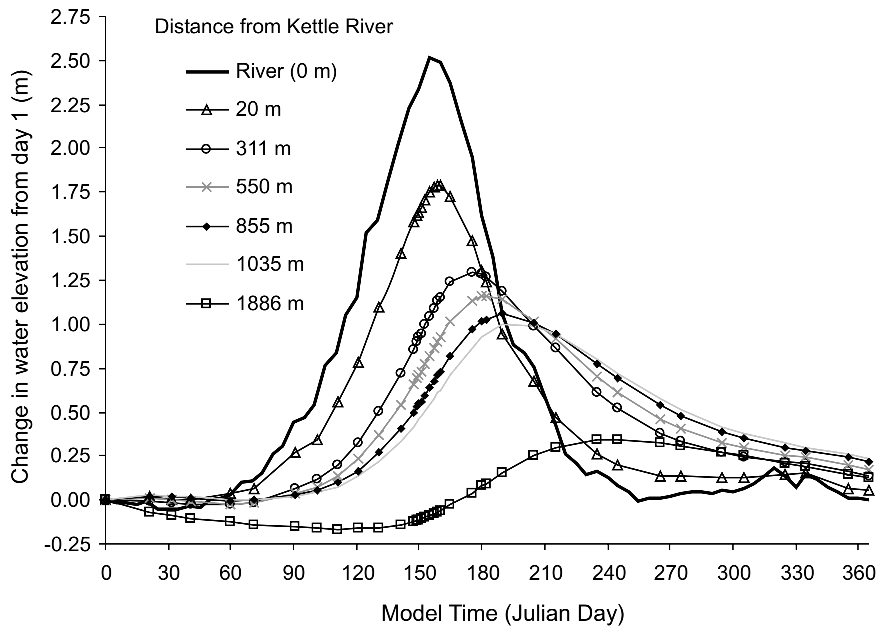

Figure 13 Change in water elevation over 1 year of transient model run, relative to day 1 water elevation. Modeled variation of groundwater levels with distance away from the Kettle River. Non-pumping model and historical climate scenario.

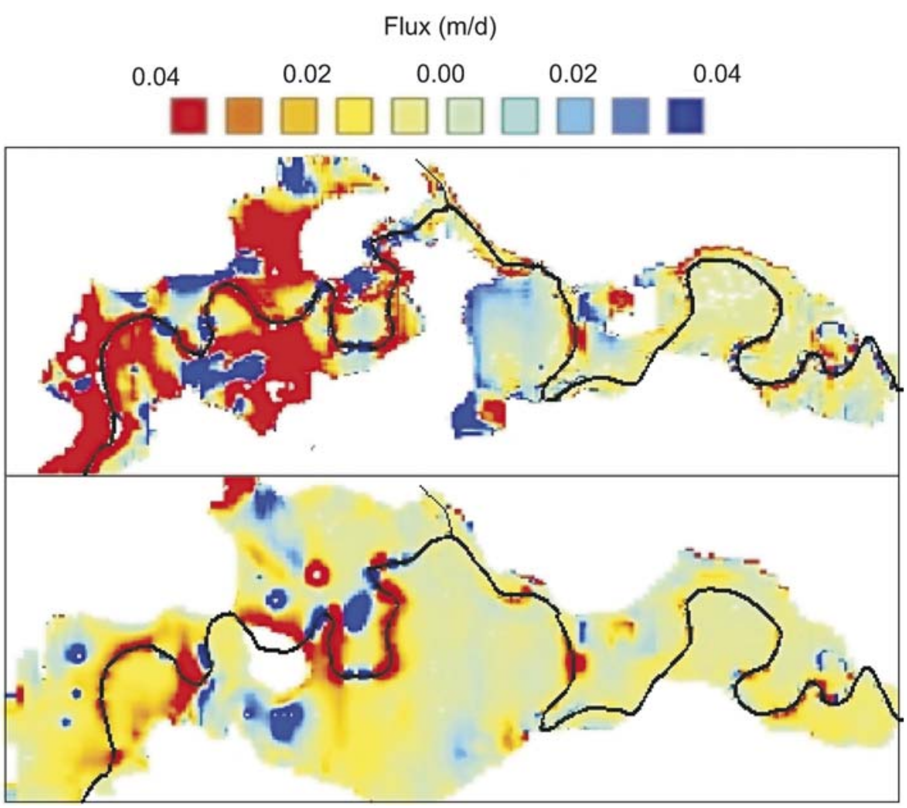

Figure 14 Groundwater flux between layers shown for top two layers of the groundwater flow model (layer 1: gravel; layer 2: sand), as simulated in the model.

from storage and enters the floodplain zone where it eventually returns to river as baseflow. The rate of inflow to groundwater from the river along the floodplain zone follows very closely the river hydrograph during the rise in river stage. As the river stage levels off and begins to decrease, the flow direction is reversed, generally within 10 days. At this time, the rate of inflow from aquifer to the river begins to rise, and then dominates for the rest of the year, as water previously stored in aquifer drains back to river as baseflow seepage. As most of the pumping water is lost to evapotranspiration on irrigated fields, there is a small reduction in the baseflow component to the Kettle River during the pumping period.

The river-aquifer interaction has maximum flow rate of 41 m^3/s, which translates to approximately 15% of river flow during spring freshet (regional snowmelt). Thus, the river puts about 15% of its spring freshet flow into storage in Grand Forks valley aquifer, and within 30–60 days most of that water is released back to the river as baseflow. Over the year, the net exchange is roughly zero when pumping is not included in the model.

The temporal variation in water table elevation, expressed as difference from Day 1 (for each point along the profile), is shown for different distances away from Kettle River (Fig. 13). Non-pumping model output was used for the historical climate scenario. Kettle River stage hydrograph was computed for nearest river cross-section and graphed as ''River'' on the graph at 0 distance. The next nearest point is 20 m away, just outside the river channel. The modeled water level has almost an immediate response to the river, although peak amplitude is lower than that of river, showing effects of groundwater storage. Further away from the river, the amplitude of the hydrograph decreases and also shifts to a later day. The furthest observation point (1886 m) is only slightly influenced by river stage variation.

Groundwater flow directions (not shown) are generally downslope in the valley from west to east, and also away from valley slopes and toward the floodplain areas. The flow vectors deviate between river channels, and locally toward pumping wells. Patterns also change seasonally. Vertical groundwater flux (Fig. 14) has a complex pattern in the aquifer layers. The positive flux areas (shown in red) along Kettle River in layers 1 and 2 represent outflow of water from the river into the aquifer (influent river reaches). The negative flux areas (shown in blue) are mostly located along the river, and suggest effluent river reaches where aquifer supplies baseflow to river as seepage. River reaches that have inflow or outflow can be identified from these maps.

Aquifer responses to climate change

The aquifer responses to climate change are difficult to observe on head distribution maps because the high hydraulic gradient in the Grand Forks valley dominates flow patterns.

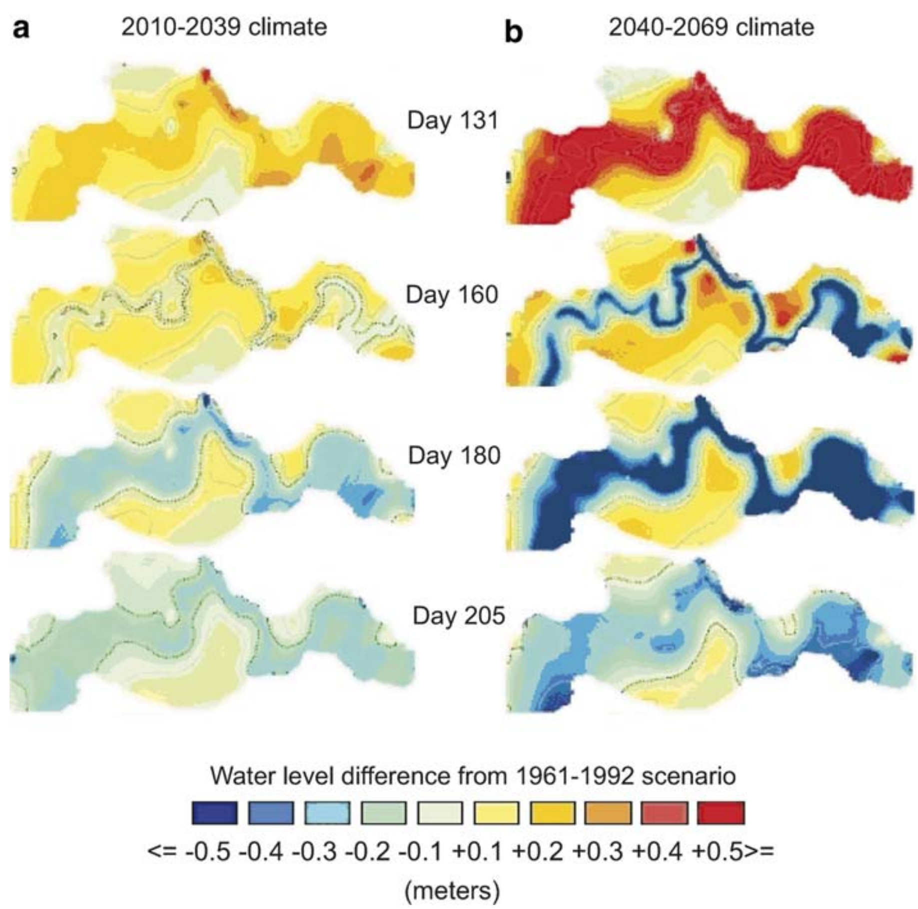

Figure 15 Water level differences (measured as head in layer 2 of the unconfined aquifer) between (a) future (2010–2039) and present climate, and (b) future (2040–2069) and present climate under pumping conditions. Maps by time step in days 131–180. Positive contours are shown at 0.1 m interval. The zero contour is a dashed line. Negative contours are not shown. Darkest blue colours indicate values <−0.5 m (along rivers only). At day 101 (not shown), difference map has values within 0.1 m of zero.

Climate-induced changes in water elevations are on the order of 0.5 m, while the gradient in the valley spans about 30 m in elevation. Thus, it was necessary to develop a different strategy for displaying any changes induced by climate, which would remove the hydraulic gradient of the valley (and valley topography) and allow direct comparison to present conditions. Accordingly, head difference maps (Fig. 15) show only differences due to climate change between future climate scenario model outputs and present climate scenario model outputs (pumping wells activated during summer). Note that because drawdown was identical in all climate scenarios (pumping rates were held constant in all models), ultimately, the pumping effects were subtracted out in these maps.

At day 131, the main cause for the observed changes is the shift in river hydrograph peak flow to an earlier date, which creates a positive difference in water levels between the 2010–2039 and 1960–1999 models. In other words, in the future the peak river stage would be earlier and water levels would be higher in the aquifer at an earlier date. The zone of storage is roughly along the river floodplain and also in areas where there are higher river terraces. Within one month, the peak flow passes and river water levels begin to drop rapidly.

By day 160, the river water levels are similar in both the 2010–2039 and modeled present, but only along the river channel. Away from the river channel water levels are elevated by 0.30–0.40 m (stored water), which are still draining until day 180. Water levels in the floodplain in the 2010–2039 period are lower by 0.10–0.40 m at day 180 than at present climate at that day, but the temporal shifts in river hydrographs cause changes in aquifer water levels compared to present, when compared to the same day of year. The overall hydrograph shape remains the same, simply shifted earlier in the season. At day 205 the increased recharge in the 2010–2039 period over historical climate causes up to 0.10 m higher water levels away from the river.

The hydrograph shift for the 2040–2069 period is larger than in the 2010–2039 period, so the computed differences to historical climate are similarly larger (Fig. 15).

Overall, the climate change effects for the 2010–2039 and 2040–2069 climate scenarios relative to present are limited to the floodplain, as well as to the early part of the year when the river hydrograph shifts and is at peak flow levels. As the river peak flow shifts to an earlier date in a year, the aquifer levels (hydrographs) also shift by the same interval, confirming our expectations, but showing a surprisingly strong hydraulic connection between the river and the aquifer.

Impacts of climate change are smallest in zones least connected to the river (distant from the river and at higher elevations). A small increase of water levels due to an increase in recharge is forecast for future climate scenarios (Scibek and Allen, in press), but these increases tend to occur only in areas that are not strongly influenced by the river (i.e., benches at higher elevation around the periphery of the valley).

From the perspective of groundwater resource sustainability, groundwater levels are expected to decline over the summer months (up to 0.5 m), as a direct consequence of a reduction in summer baseflow in the Kettle River. Therefore, shallow wells may have to be deepened as a first response. Although not shown in paper, several of the irrigation well capture zones extend back to the Kettle River, and water is derived from river discharge. In the summer months, when the contribution of groundwater to river flow is on the order of 5% of the discharge, there may, in fact, be a measurable reduction in Kettle River stage. This reduction in stage could have significant impacts on aquatic habitat. To investigate this effect, a coupled groundwater–surface water model would be required; however, the development of such comprehensive codes remains limited. We did not explicitly model the impact of increased groundwater demand under future climate

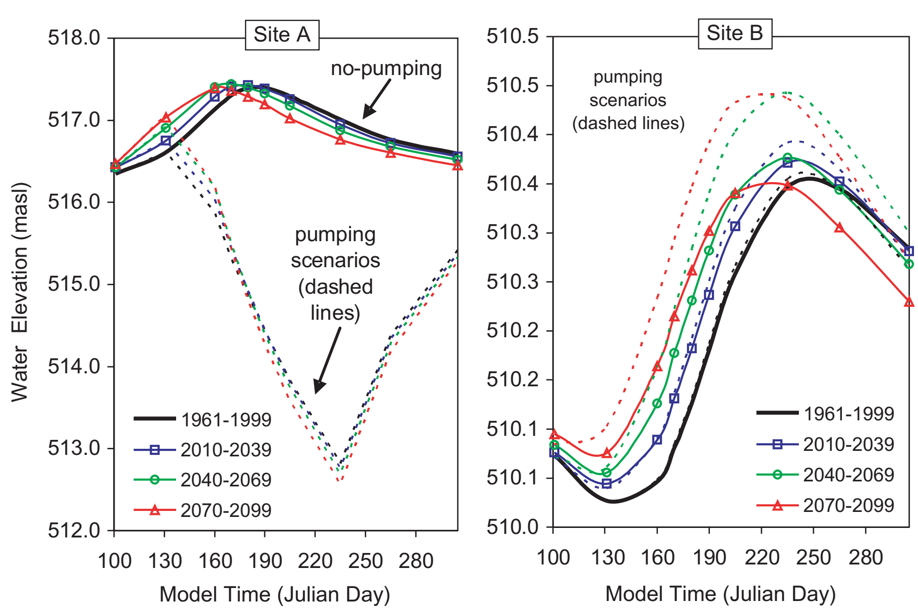

Figure 16 Effect of climate change under pumping and non-pumping conditions on groundwater elevations: Site A (close to pumping wells), Site B (away from pumping wells).

conditions, but likely the demand will increase, not only because temperatures will be higher, but also because of population growth and more intensive agricultural activities. Finally, irrigation return flow was included in our model (which adds to the direct recharge); however, with increased temperatures, it is likely that more of this water will be lost through evapotranspiration.

Generally, the natural groundwater level variation and pumping drawdown are much larger than climate change effects. For example, Fig. 16 shows the same profile as was used for Fig. 13. In this case, however, the effects of pumping and non-pumping are compared; the profile intersects the largest irrigation district in the valley. Site A is situated close to the pumping wells, whereas, 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 is different because of the different distances to the river of each site. As the river hydrograph shifts to earlier peak day in future climates, the groundwater levels follow. There is also a small effect of changing recharge in future climate.

One limitation of our approach is that long-term changes in climate were not explicitly modeled, and so our model does not capture the long-term changes in groundwater storage, which would result in changes in average static groundwater levels in the valley. Models at this time cannot adequately resolve long-term storage trends (computing constraints) nor manage the uncertainties involved.

Conclusions

The water balance analysis and the relation between water levels in the observation well and the Kettle River have established that the unconfined Grand Forks valley aquifer is hydraulically linked to the river. Kettle River discharge is much greater than the inflow of tributaries in the valley watershed. The river-aquifer interaction has a maximum flow rate between 11% and 20% of river flow during spring freshet — on average, the river contributes about 15% of its spring freshet flow into aquifer storage, and within 30 to 60 days most of that water is released back to the river as baseflow. Storage rates are less than 50% of inter-zonal groundwater flux, and 15—20% of river-aquifer flux. Most of the connection between aquifer and river occurs within the floodplain, but under pumping conditions, there is a reduction in the return of water from the aquifer to the river as baseflow compared to non-pumping conditions.

Future climate scenarios indicate temporal shifts in river hydrographs. 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. However, the overall hydrograph shape remains the same. 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.

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