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Comparing modelled responses of two high-permeability, unconfined aquifers to predicted climate change

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Abstract

The responses of two small, regional-scale aquifers to predicted climate change are compared. The aquifers are unconfined, heterogeneous, highly permeable, and representative of glaciofluvial environments in southern British Columbia, Canada and Washington State, USA. In one case, river–aquifer interactions dominate the hydraulic response. The climate change data set is that predicted by Canadian Global Climate Model 1 (CGCM1), for consecutive 30-yr intervals from present to 2069. Downscaling of GCM predictions and stochastic weather generation were done for each geographic location separately. Both studies employed identical methodologies and software for downscaling global climate model data, modelling weather for input to recharge models, determining the spatio-temporal distribution of recharge, and modelling groundwater flow using MODFLOW. Results suggest observable, but small, changes in groundwater levels, forced by changes in recharge. At the site in which river–aquifer interactions occur, water levels within the floodplain respond significantly and more directly to shifts in the river hydrograph under scenarios of climate change.

Keywords: climate change; groundwater; aquifer; recharge; groundwater–surface water interaction; numerical modelling

1. Introduction

With increasing concerns surrounding global climate change, there has been growing interest in the potential impacts to aquifers; however, relatively little research has been undertaken to determine the sensitivity of groundwater systems to changes in critical climate change parameters. It is expected that changes in temperature and precipitation will alter groundwater recharge to aquifers, causing shifts in water table levels in unconfined aquifers as a first response to climate trends (Changnon et al., 1988; Zektser and Loaiciga, 1993). Where an aquifer is hydraulically connected to surface water, shifts in the hydrologic regime can also be anticipated to impact water levels, although the nature of this interaction may be more difficult to quantify.

Undertaking a climate change impacts assessment on a groundwater system is complicated because, ultimately, atmospheric change drives hydrologic change, which, in turn, drives hydrogeologic change. The latter requires detailed information about the subsurface; information that is traditionally difficult to obtain. Each aquifer is unique in its physical properties (geology), its geometry (controls the hydraulic gradient), and the nature its connection with surface water bodies. Thus,

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each aquifer requires detailed characterization and, eventually, quantification (e.g., numerical modelling) in order to determine what the potential impacts of climate change might be.

In our study, we developed and tested methods for linking climate change predictions to regional scale aquifers. To accomplish realistic links between regional climate, station-specific climate, and the groundwater system at an appropriate scale, we selected two small regional unconfined aquifers (less than 150 km^2 in area) to test high-resolution groundwater flow models, climatic inputs through recharge, and climate-driven surface water links, where appropriate.

The general methodology consisted of constructing a three-dimensional groundwater flow model for each aquifer (using Visual MODFLOW version 3.1.0, Waterloo Hydrogeologic Inc., 2003), modelling spatially distributed and temporally varying recharge (annual variation) based on the historic climate scenario, applying that recharge to the groundwater model, and then calibrating it to historic water levels. For the climate scenarios, recharge values for future climate change scenarios were modelled and input into the calibrated model, and the response of water levels in the aquifer quantified.

2. 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+A) transient simulation. Daily data sets for CGCM1 were downloaded from Canadian Institute for Climate Studies (CICS) website. These include absolute and relative changes in precipitation, including indirect measures of precipitation intensity, dry and wet spell lengths, temperature, and solar radiation. Climate data were downscaled using Statistical Downscaling Model (SDSM) software (Wilby et al., 2002; Yates et al., 2003), and downscaled data were calibrated to observed historic climate data. Note that a second downscaling method based on principal component analysis was also used (PCA K-nn), but SDSM gave superior results. Details concerning downscaling and the comparison of methods are provided in Allen et al. (2004). Three-year-long climate scenarios were generated using the calibrated downscaled model, each representing one typical year in the present and future (2020s and 2050s): current climate (1961–1999), 2020's climate (2010–2039), and 2050's climate (2040–2069). For recharge modelling, daily weather was generated using the LARS–WG stochastic weather generator (Semenov et al., 1998).

3. The study sites

The Abbotsford–Sumas (AB–SUM) aquifer is located in southwest British Columbia (BC) and northern Washington State (WA) (Fig. 1). It covers an area of approximately 150 km^2 within the Fraser and Nooksack River lowlands in the central and eastern Fraser Valley. The aquifer is highly productive, is bisected by the international boundary, and provides water supply for nearly 10,000 people in the US, and 100,000 in Canada, mostly in the City of Abbotsford. The coastal climate is humid and temperate, with normal precipitation (mostly as rainfall) of 1564 mm/yr.

The valley fill consists of complex sequences of till and stratified drift, in various associations with marine and deltaic sediments, showing complex structure and chronology of deposition (Armstrong, 1981). The valley sediments are underlain at depth by the Tertiary bedrock surface, which outcrops to the north and south of the aquifer study area, and by the older Cascade Mountains to the west. The bedrock surface is considered relatively impermeable and serves as an effective lower boundary to groundwater flow. Above the bedrock, and immediately underlying the aquifer in most areas is an extensive glaciomarine deposit. This unit outcrops to the north and northwest, forming a thick low-permeability confining layer in that area (dark grey-brown area near Langley in Fig. 1). The Abbotsford–Sumas aquifer itself is mostly unconfined and is composed of un-compacted sands and gravels of the Sumas Drift, a glacial outwash deposit of late Pleistocene age (Fraser Glaciation). There is significant heterogeneity of the hydrostratigraphic units, and units are laterally discontinuous making the identification of layers difficult if not impossible. This heterogeneity likely results in complex groundwater paths, particularly at a local scale, as suggested by previous groundwater investigations (e.g., Cox and Kahle, 1999), the analysis of over 2500 borehole lithology logs, and numerical modelling results (Scibek and Allen, 2005a). The thickness of the surficial aquifers (drift deposits) ranges from about 20 m to 100 m, whereas the total thickness of Pleistocene deposits is up to 500 m in the central parts of the study area (although much of this thickness is comprised of the glaciomarine sediments).

The Grand Forks aquifer (GF) is located within a small valley in the mountainous and relatively dry climate of the south-central BC interior (Fig. 2). Here,

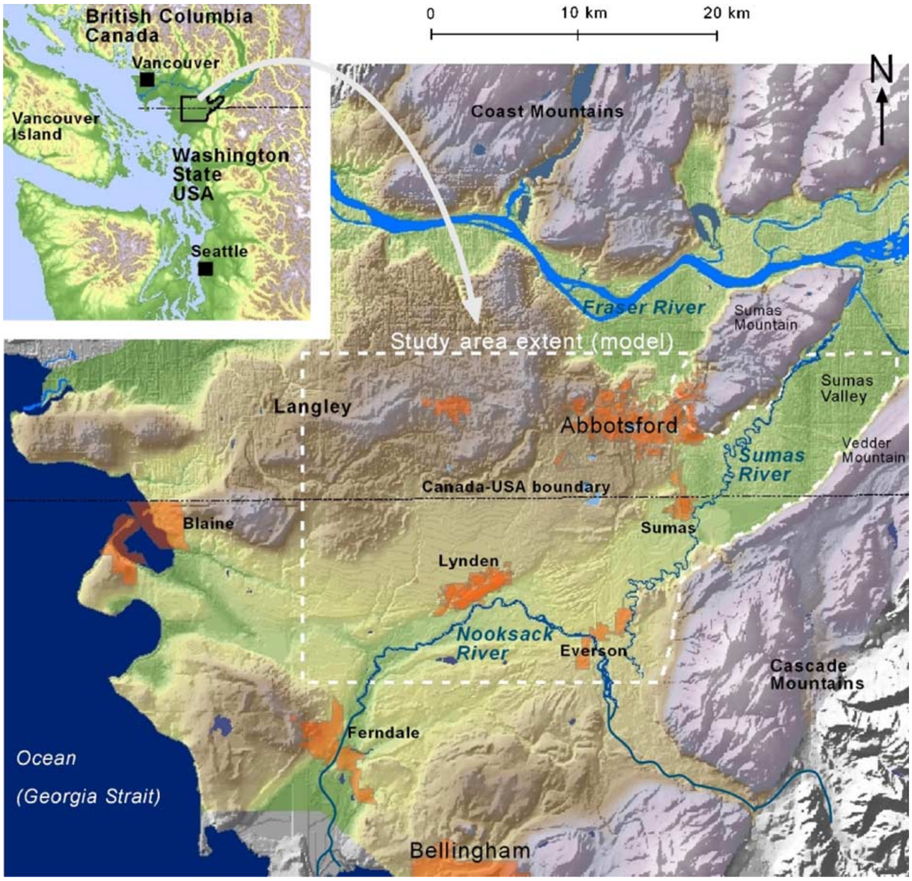

Fig. 1. Abbotsford–Sumas (AB–SUM) aquifer location in British Columbia, Canada and Washington State, USA. Inset map at top left shows location of the study area in a more regional context. The white dashed line shows the extent of the model domain.

approximately 353 mm of precipitation falls as rain and 118 mm falls as snow, with a total yearly average precipitation of 471 mm. This unconfined aquifer covers an area of 34 km^2 along the border between BC and WA, and is surrounded by low mountains comprised of metamorphic rock. The Kettle River meanders through the valley, and is incised within the alluvial gravels which form the upper horizon of the unconfined aquifer.

Approximately 150 shallow groundwater well lithology logs were used to constrain the stratigraphy of the aquifer. The upper stratigraphic unit of the aquifer consists of fluvial gravel, which overlies a sand and gravel unit. The stratigraphic sequences at depth are poorly understood, but well records suggest that these deeper units are glaciolacustrine silts and, most likely, tills. Sediment thickness in the valley does not exceed 100 m in most places. Groundwater flow occurs mostly in a surficial gravel unit, which is strongly hydraulically connected to the river, as evidenced by the aquifer water balance, and the synchronous relation of water levels between an observation well in the aquifer and the Kettle River.

4. Groundwater model construction

To construct each groundwater flow model, first, the valley shape was modeled using profile extrapolation, constrained by well lithology logs, and geostatistical interpolation. 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. For the GF aquifer, solid models (layers) were constructed using GMS software (v. 4.0) (Brigham Young University, 2002) and imported into Visual MODFLOW (WHI, 2003), as is typically done with complex multi-layer aquifer systems (Herzog et al., 2003). Details of the GF model construction are described in Allen et al. (2004).

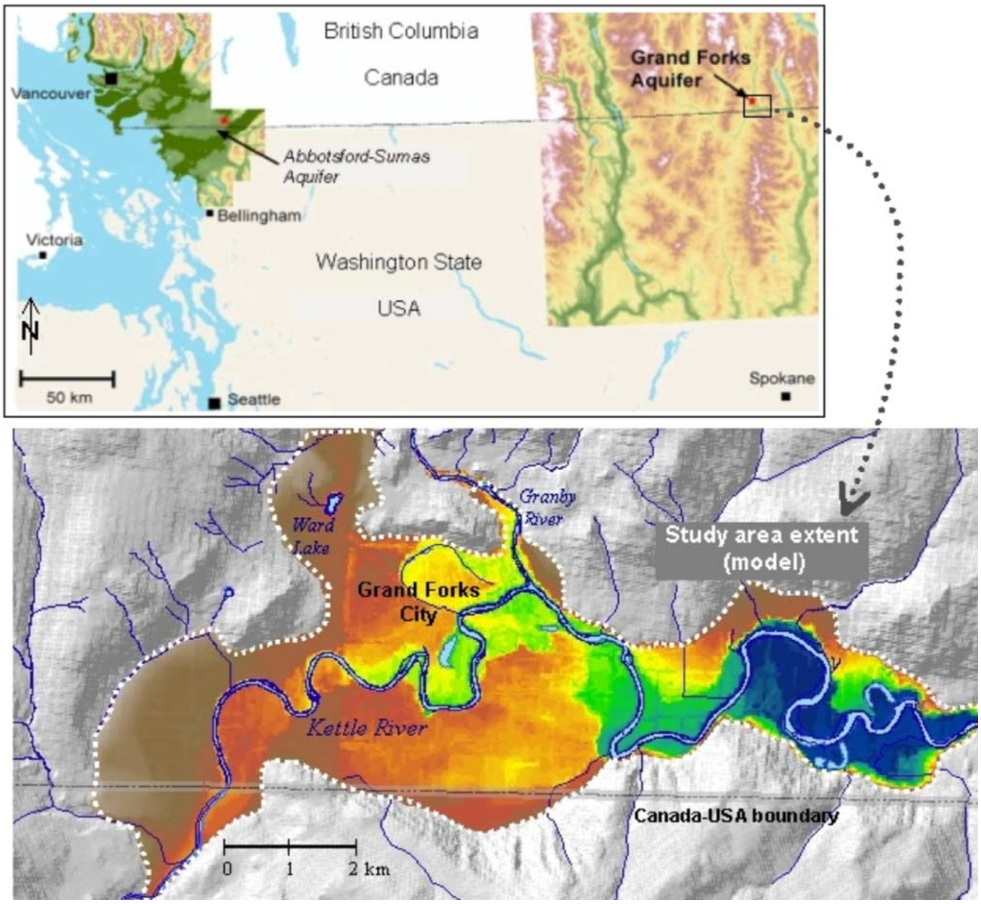

Fig. 2. Grand Forks (GF) aquifer location in British Columbia, Canada. Top figure shows the relative location of the AB–SUM aquifer. Colour shading for GF aquifer indicates topography, with drainage from west (red) to (blue).

For the AB–SUM aquifer, due to the significant heterogeneity of the sediments, the traditional approach of constructing cross-sections (by interpolating lithologies between boreholes to create a solid model) was not possible. This approach invariably led to a "smoothed and homogenized" representation of the stratigraphy. An alternative approach involved examining clusters of boreholes on a layer by layer basis and mapping the lithologies as hydrostratigraphic unit zones (K-zones) directly into Visual MODFLOW. These zones were then assigned unique hydraulic properties (K and S_s). Geographical Information System (GIS) data visualization allowed conjunctive viewing of borehole lithologs, surficial geology maps, ground and bedrock surfaces, and MODFLOW grid layers (mostly planar surfaces). Details of model construction for the AB–SUM aquifer are provided in Scibek and Allen (2005a).

For both models, representative isotropic hydraulic properties (K and S_s) were initially assigned to each hydrostratigraphic unit, based on values determined from pump test data, the magnitudes of which were later slightly adjusted during model calibration. The models were calibrated to replicate the observed static groundwater levels as well as the temporal variation in water levels, where such data were available (discussed later).

5. Hydrology

In the AB–SUM aquifer, runoff is roughly one third of estimated precipitation over the catchment area (Connely et al., 2002). The large rivers draining the valleys around the AB–SUM aquifer receive a significant baseflow component from the aquifer. The largest valley in the region is the Sumas Valley, which runs north-east to south-west and contains the lower drainage of the Sumas River (Fig. 1). Sumas River flows to the north-east and picks up significant baseflow component from aquifer discharge on its eastern side. To the south is the Nooksack River, flowing to the west and then south. Many of the small streams (e.g., Bertrand Creek, Pepin Creek and Fishtrap Creek, which flow from the uplands southward) and groundwater flow from the Abbotsford–Sumas aquifer ends up in the Nooksack River. Thus, the Nooksack River has significant baseflow contributions from the Abbotsford–Sumas aquifer, as well as from the aquifers to the south. To the north, the model area includes a portion of the Fraser River floodplain.

Previous investigations in WA on streams draining the Abbotsford uplands (e.g., Fishtrap Creek) established that the baseflow component is very high, between 70% and 95% of stream flow (Sinclair and Pitz, 1999). In the upper reaches of these streams, the stream bed is often perched above the regional water table during the dry season. In the lower reaches, the stream receives large inflow from groundwater. Away from the streams, groundwater elevations change by 2 to 4 m seasonally according to observation well hydrographs. Stream stage varies by much less, although streamflow does change seasonally (Hii and Liebscher, 1999).

Within the groundwater flow model, small lakes, swamps, ephemeral streams, and the upper reaches of the streams, are represented with drain boundary conditions. Drains only affect the flow model when water table rises to or above the drain elevation. The drain then takes groundwater out of the aquifer to simulate seepage and baseflow. In effect, the model can be calibrated to simulate filling of drains during high water table levels (high recharge months) and dry drains during low water table levels (low recharge months). Drain modes were used only in areas where the flow model calculated heads were too high above ground (or lake) surface, and thus, act to modulate groundwater levels. The drains are not assumed to be in contact all year with saturated zone of the aquifer, and many are probably perched above mean annual water table elevation. There is simply a lack of data to verify which of these drains are linked to the aquifer, and to what extent.

Flowing streams are represented in the groundwater flow model by specified head boundary conditions, with the stream channel profiles represented as accurately as possible. With this type of boundary condition, the river can leak and receive water to and from the aquifer, but the river stage will not change as a result of such interaction. In other words, the river will act as an inexhaustible supply of water and will influence the aquifer water levels, but the aquifer will not have any effect on river discharge and stage. It is a simplification in the model to represent the larger valley rivers as constant head boundary conditions, but because the groundwater flow model covers mostly aquifer area above the valley floodplains that contain the larger rivers, the assumption of specified head in the larger rivers will not affect model results in those upland areas, even in a transient model. Nonetheless, where there is suspicion of potential changes in streamflow caused by stream–aquifer interactions and feedbacks from climate change, these boundary conditions could be modified to perhaps drain boundary conditions, bearing in mind that model convergence in the absence of more rigorous boundary condition constraints (e.g., specified heads) could be problematic.

In the GF valley, Kettle River discharge is significantly greater than the inflow of tributaries in the valley watershed (Allen et al., 2004). 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 minimum discharge of 0.0137 m^3/s from the creeks and baseflow from the aquifer. Thus, the combined aquifer and tributary contribution to the rivers have very small effect on Kettle and Granby River water levels. In contrast, the river water levels have a strong effect on groundwater levels in the aquifer, and the bottom sediments of the Kettle and Granby Rivers above the GF aquifer consist of mostly gravels, with very little fine sediments. Therefore, the rivers are represented as specified head boundaries, such that the head schedules will represent the modelled river stage in transient groundwater flow model.

In both study areas, surface bodies such as streams are represented with model grid cells of 5 to 10 m width where possible and, using GIS, tens of kilometres of streams and ditches were included in the groundwater flow models.

6. Recharge

Aquifer recharge was generated as spatially distributed and temporally varying recharge zonation (Allen et al., 2004) using GIS linked to the one-dimensional HELP model (Hydrologic Evaluation of Landfill Performance) (Schroeder et al., 1994). Recharge estimates were based on soil type and depth, vadose zone conductivity, and water table depth. The approach used for recharge modelling is similar to that of Jyrkama et al. (2002), in which a methodology was developed for estimating temporally varying and physically based recharge for any MODFLOW grid cell. Our method differs from previous distributed–recharge methods in that we also estimate the distribution of vertical saturated hydraulic conductivity in the vadose zone, and the thickness of the vadose zone, both at high spatial resolution. A total of 64 unique recharge zones were defined based on classed soil column properties, and recharge was estimated for each. All map processing was done on 20-m raster grid cells. The temporal inputs for HELP are derived from the LARS-WG stochastic weather generator at daily time steps. Then recharge is calculated daily and, later, averaged monthly for use in transient groundwater flow models.

Soil permeability maps were first modified by land use to account for less permeable (i.e., paved) areas. Four representative permeability classes were created for very high, high, medium, and low permeability based on published soil descriptions. Soil thickness was interpolated from well lithology logs and soil pit information. With the exception of a few anomalous locations, the soil thickness is similar for both aquifers. Therefore, the soil thickness was assumed to be simply 1.0 m in all percolation columns for recharge modeling. Depth to water table was estimated via raster computations between ground surface and a numerically derived static groundwater table. Representative soil columns were assigned representative mid-class depths (4 classes) based on the results of each aquifer. Finally, saturated hydraulic conductivity was estimated for geologic units encountered above the water table; a slightly different method was used for each aquifer.

In the AB–SUM aquifer, values of K were assigned to each hydrostratigraphic unit in each layer above the water table based on values obtained from pumping tests and values from the literature. A representative vertical hydraulic conductivity, K_z (weighted according to layer thickness) ,was computed for each raster cell 50×50 m over the aquifer area. K_z values over a million pixels ranged from 0.1 to 105 m/day, median of 50.91 m/day, mean of 46.3 m/day, and quartile values of 0.51 and 89.84 m/day. Five K_z classes were chosen as 1×10^{-6} to 20 m/day, 21 to 40 m/day, 41 to 60 m/day, 61 to 80 m/day, and 81 to 120 m/day, with the mid-value in each class used in HELP.

In GF, a representative K value was assigned for each material type noted on the well lithology log for a particular depth range, and geometric means of the K values were calculated for each layer in each well where more than one material type was recorded. An equivalent K_z was computed for each well point location. K_z values in 285 wells ranged from a maximum of 1000 m/day to a minimum of 1×10^{-6} m/day, median value of 13 m/day, and quartile values of 100 and 0.14 m/day. The K_z values in the vadose zone were interpolated using Inverse Distance Weighed interpolator, and computed on representative vertically averaged log K_z values at all available point locations where lithologs exist. After interpolation, the inverse logarithm (i.e., 10^[Log K_z]) of the interpolated raster was computed, and converted to units of m/day. Four classes were chosen as 1×10^{-6} to 0.14, 0.14 to 13 m/day, 13 to 100 m/day, and 100 to 1000 m/day, with the mid-value in each class used in HELP.

Recharge zones were defined for a 50-m raster grid through cross-classification of maps of all important variable distributions. In this study, the limiting variable is soil type (originally soil polygons), and the most uncertain is K_z, whereas depth to water table can be represented at 20-m grid or smaller with reasonable accuracy. The uncertainty in K lies in the absolute values used to represent each unit; however, the relative differences in K as they affect recharge will be captured in the model.

In the Fraser Valley, the site of AB–SUM aquifer, the mean annual rainfall was represented as a precipitation gradient (1000 to 1600 mm/yr) interpolated from high-quality climate normals (Fig. 3a). To link the precipitation gradient over the valley to daily precipitation records at the Abbotsford Airport weather station, which was used as an index station for climate downscaling, the percent difference in mean annual precipitation to that recorded at the Abbotsford Airport was calculated. Thus, all recharge estimates were adjusted proportionally by the same percent difference, assuming that recharge is directly proportional to precipitation for any given recharge zone. The overriding assumption is that the precipitation gradient is similar in all months throughout a "typical" year. The modelled recharge for the AB–SUM aquifer is between 650 and 1150 mm/yr, and is controlled mostly by the local precipitation gradient.

In the GF model, a uniform rainfall distribution was assumed. The modelled recharge at GF was between 30 and 120 mm/yr, depending on location (Fig. 3b). In this semi-arid climatic region, the model suggests that there is insufficient precipitation to recharge the aquifer where there are thick sand and gravel terraces—most of the precipitation changes moisture content in these areas, but little of it recharges the groundwater aquifer. The depth of the unsaturated zone is less important in the AB–SUM aquifer where large amounts of rainfall infiltrate and where moisture content remains high.

As discussed later, the AB–SUM groundwater system is mostly controlled by aerial recharge, and the maximum groundwater elevations are constrained by topography and local surface drainage. The AB–SUM aquifer system is much more complex than the GF

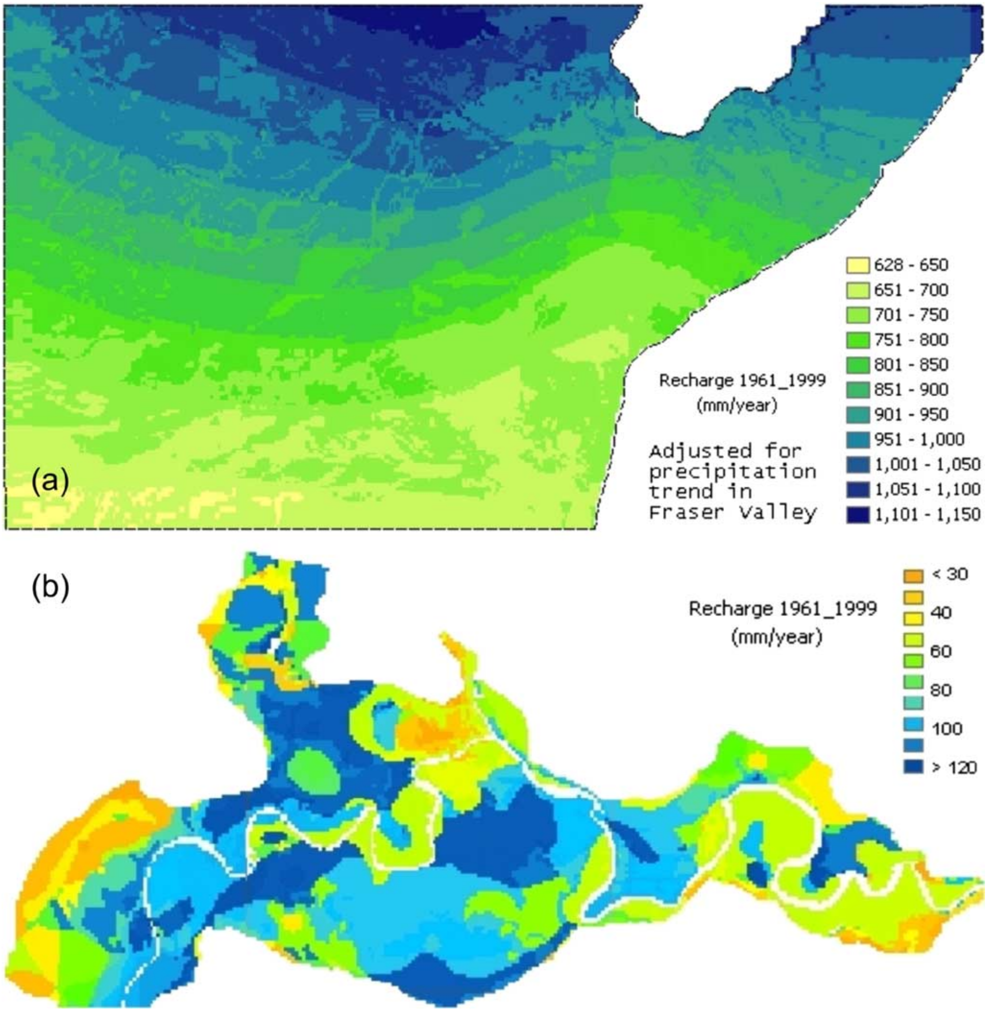

Fig. 3. (a) Map of mean annual recharge to the AB–SUM aquifer. (b) Map of mean annual recharge to the GF aquifer.

aquifer, as it includes many perched water table areas and strongly heterogeneous porous media (note the differences in magnitude of recharge between the two sites in Fig. 3a and b). At both study sites, the soil and other properties of the subsurface control the recharge spatial variation (up to 100 mm/yr), but the two locations are very different in recharge rates. The question is whether at much larger precipitation the subsurface heterogeneity has larger effect or not, on infiltrating recharge.

7. Predicted climatic change

At both the coastal and interior mountainous locations, the air temperatures are predicted to increase in all months from present to future. After downscaling of CGCM1 climate predictions, we noted that the summer temperatures will increase at a relatively constant rate of 1 °C per 30 yrs, up 3 °C by end of century compared to present. In other seasons, the increase can reach up to 4 to 6 °C by 2080s, at a relatively constant rate of increase from present (Allen et al., 2004).

Summer precipitation was much more difficult to model from downscaled GCM runs than winter precipitation. For the interior of BC, at the location of the GF aquifer, there is a serious limitation of using CGMC1 predictions. CGCM1 is unable to adequately model precipitation in the summer months (convective activity, high-intensity rainfall, rain-shadow effects), giving an underestimate of rainfall of up to 40% compared to observed, even after downscaling with a well-calibrated model. This is referred to as the “model bias”, where model is the global climate model. At the coastal location, containing the AB–SUM aquifer, there is a much smaller model bias for summer

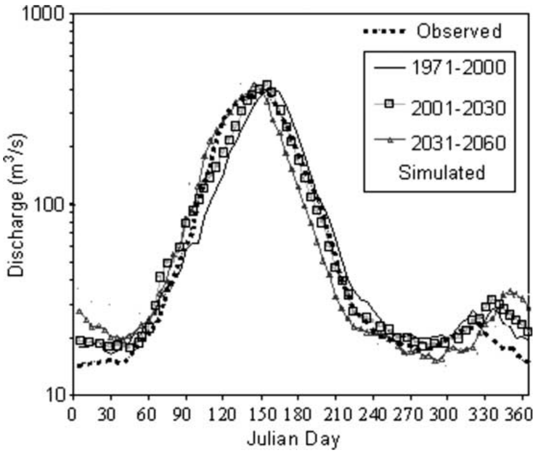

Fig. 4. Predicted discharge in Kettle River at Laurier (WA) modeled using statistical downscaling model and comparing to observed discharge in last 30 yrs.

months, and the CGCM1 downscaled climate data matches observed historic data reasonably well. Winter precipitation has relatively small model bias for both locations, but it is still better at the coastal location than in the interior.

In the GF aquifer model, we also obtained predictions for basin-scale runoff and discharge in the Kettle River, which interacts with the aquifer at the study site. The runoff model was derived from a statistical downscaling method (PCA K-nn), which links river discharge to GCM-predicted climate. River stage and water elevation were calculated from stage–discharge curves along 67 channel cross-sections, interpolated along river length, and then input to the groundwater flow model as boundary conditions. The predictions for future conditions indicate that the hydrograph peak will shift slightly to an earlier date, although the peak flow

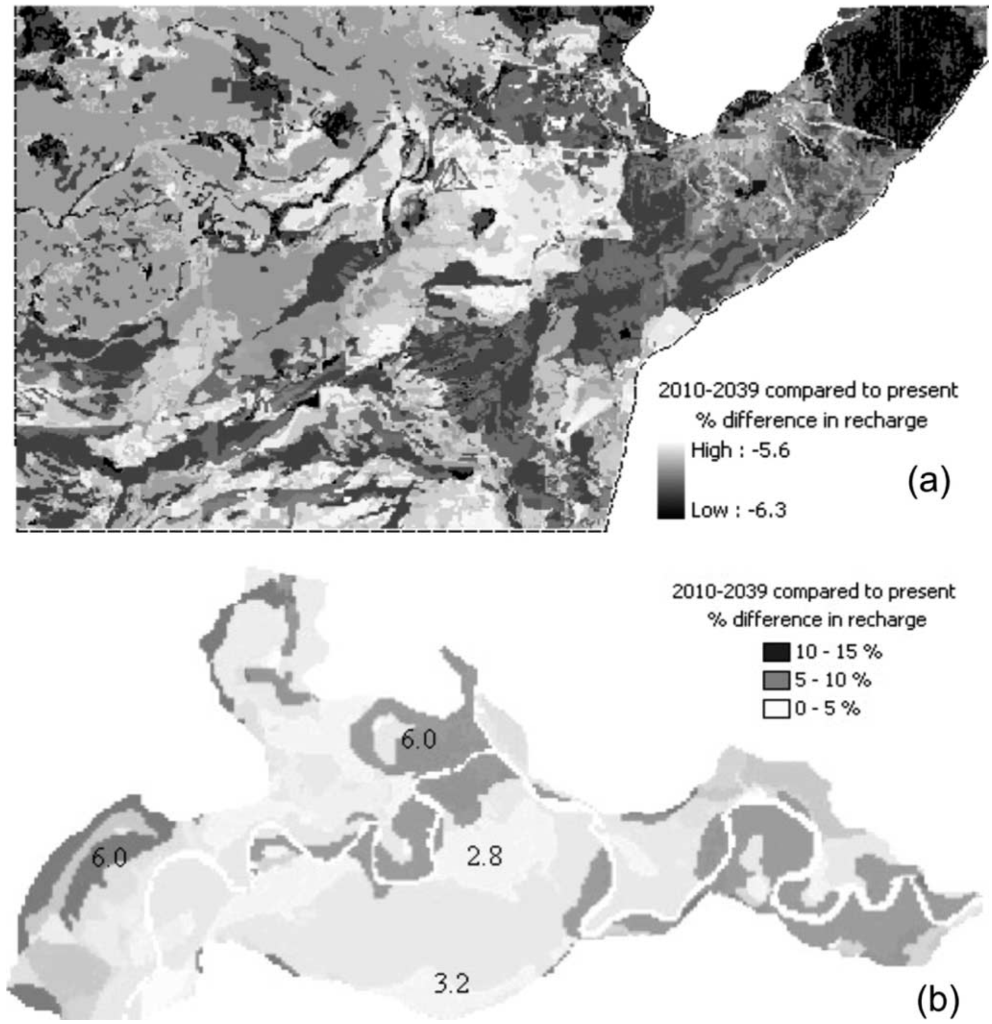

Fig. 5. (a) Predicted changes in recharge to the AB–SUM aquifer as percent difference maps from 2010–2039 climate scenario to present. (b) Predicted changes in recharge to the GF aquifer as percent difference maps from 2010–2039 climate scenario to present.

will remain the same as at present (Fig. 4). This shift is consistent with type of shift in response measured over the past two decades (Whitfield and Taylor, 1998). Changes to the river hydrograph are predicted to be much larger by 2040–2069 than by 2010–2039 yrs, compared to the historical 1961–1999 time period. The AB–SUM aquifer differs from the GF aquifer in that a significant portion of the aquifer lies in the uplands, above the floodplains of larger rivers, which may also experience hydrograph shifts as a result of climate change. However, groundwater levels will be affected only in small areas of the aquifer adjacent to the rivers.

The predicted changes in recharge to the aquifers are presented in Fig. 5. The changes are depicted as percent change in recharge from present to the 2010–2039 climate scenario. At the AB–SUM aquifer, recharge is predicted to decrease between 5.6% and 6.3% compared to present, with variation on the order of 1% attributed to heterogeneity of soils and aquifer media (Fig. 5a). However, for the GF aquifer (Fig. 5b), recharge is predicted to increase by between 2% and 6%, depending on location in the valley. At GF, most of the recharge occurs in the spring during snowmelt and also in the summer during convective rain events, which are predicted to increase in intensity. In contrast, at the Abbotsford–Sumas aquifer, most of the recharge occurs as rainfall during the winter months.

8. Model calibration

Model calibration for the AB–SUM aquifer was difficult, despite high data density (over 2500 water level observations), because of the presence of perched water tables, spatial clustering of data, conflicting data, strong heterogeneity of the sediments, and an uncertain hydraulic conductivity distribution in some areas. The normalized RMS was 7.15% using roughly 1700 static water levels from drilled wells. The transient model roughly predicted the observed 2 to 3 m seasonal variation in groundwater levels, but it was not exceptionally well calibrated for all locations for transient conditions, due to poorly defined three-dimensional distribution of the hydrostratigraphic units. In the river valleys and floodplains (lowlands), however, model calibration was excellent.

In the GF aquifer, there were many fewer static water levels (roughly 300), with a less than an ideal spatial distribution, but the inclusion of detailed river water levels helped to constrain the model to observed groundwater levels through well-defined boundary conditions. The normalized RMS was 8.29%.

9. Impacts on groundwater levels

At both study sites, the effects of climate change are difficult to observe on head distribution maps because the highly variable and localized hydraulic gradients in the aquifers dominate all other trends. Impacts of climate change on water levels were represented by head difference maps for different model time steps. The differences were calculated between the output from each future climate scenario model and the output from the present climate scenario model.

9.1. AB–SUM aquifer

In the Abbotsford uplands, the main recharge area of the surficial AB–SUM aquifer, the groundwater levels were predicted to decrease by between −0.05 m and more than −0.25 m due to climate change by the 2010–2039 period (Scibek and Allen, 2005b) as shown in Fig. 6. The decrease in groundwater levels was even greater in the next climate scenario 2040–2069, such that in the Abbotsford uplands, groundwater level decreases were between −0.10 and −0.25 m in most areas. In places with suspected perched water tables, which tended to be areas of poor model calibration, the changes were between −0.5 and −3.0 m.

As a consequence of reduced groundwater levels, streams in upland areas, which were treated as drains, are expected to have lower seasonal flows. In lowland areas containing creeks that drain the AB–SUM aquifer, changes in climate and recharge did not produce any significant changes in water table elevation (Fig. 6). This result is not surprising, given that both the valley floor and the water table surface are generally flat, and are constrained in the model by constant head boundary conditions. What we expect to see, under a regime of lower recharge, and resulting lower groundwater levels, is a shift in the nature of the groundwater–surface water dynamics for entire streams or stream reaches. Streams at lower elevation could become perched above the water table at certain times of the year, particularly during intense rainfall events, thereby loosing more water along their channels and contributing to indirect groundwater recharge (i.e., becoming effluent streams rather than influent streams). A more likely consequence of reduced groundwater levels across the aquifer would be a lowering of the hydraulic gradients, and a consequent reduction in baseflow, particularly during the summer months as less groundwater is released from storage. To investigate the complex nature of the interactions between groundwater and surface water in this aquifer, a coupled groundwater–surface water model

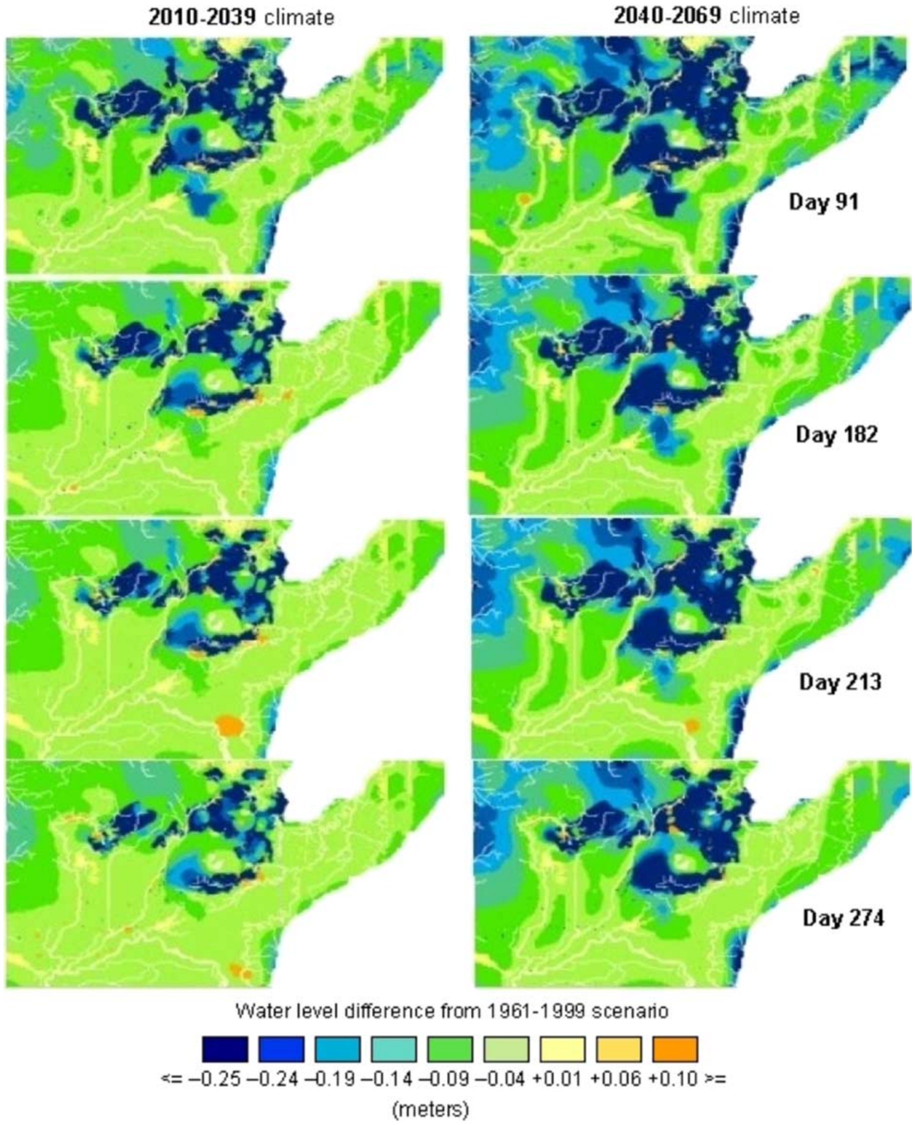

Fig. 6. Water level differences of the modeled water table at days 91, 182, 213, and 274 between future and present climate (a) scenario 2010–2039 and (b) scenario 2040–2069. Values were reclassified to range from 0 to −0.25 m. Values of −0.25 in discrete areas have changes between −0.25 and −3.0 m.

should be used, and consideration should be given to shifts in the hydrologic regime of all streams, as was done for Kettle River in the GF aquifer as discussed below.

9.2. GF aquifer

In this aquifer, the effects of changing recharge on groundwater levels are very small compared to changes in the timing of basin-scale snowmelt events in the Kettle River and the subsequent shift in the hydrograph (Allen et al., 2004). During spring freshet in the Kettle River under current conditions, the rise in river stage causes an inflow of water to the aquifer, where it is stored for 30 to 60 days. As river stage drops, the hydraulic gradient is reversed, and water is released back to the river as baseflow. The river–aquifer interaction has a maximum flow rate equivalent to 11–20% of Kettle River flow during spring freshet, suggesting that stage shifts will be negligible.

In the 2010–2039 scenario, groundwater levels rise and fall with the river hydrograph at different times relative to historic conditions, because of the shift in peak flow to an earlier date. When comparing groundwater levels at the same Julian Day (the difference in water level from the climate change scenario compared to present as shown in Fig. 7), elevated water levels, up to 0.30 to 0.40 m, persist along the channel into the early summer months. From late summer to the end of the year, water levels near the river are generally lower than present as a result of both the timing of the flow and a small reduction in streamflow during late summer (see Fig. 4). Away from the floodplain, groundwater levels are similar to present conditions, with small increases observed due to the increase in recharge.

In the 2040–2069 climate scenario, groundwater levels are higher by up to 0.50 m near the river and up to 0.20 m away from the river, as a result of the even greater shift in peak flow compared to the 2010–2039 scenario. Changes in recharge from precipitation are similarly minor in importance.

10. Conclusions

The climate-to-groundwater model link and associated methodology was successfully applied to two separate small regional aquifers. The downscaled CGCM1 climate predictions were linked through local weather stations to recharge models for the aquifers. Summer precipitation was much more difficult to model from downscaled CGCM1 runs than winter precipitation, especially at the GF location, due to the inability of

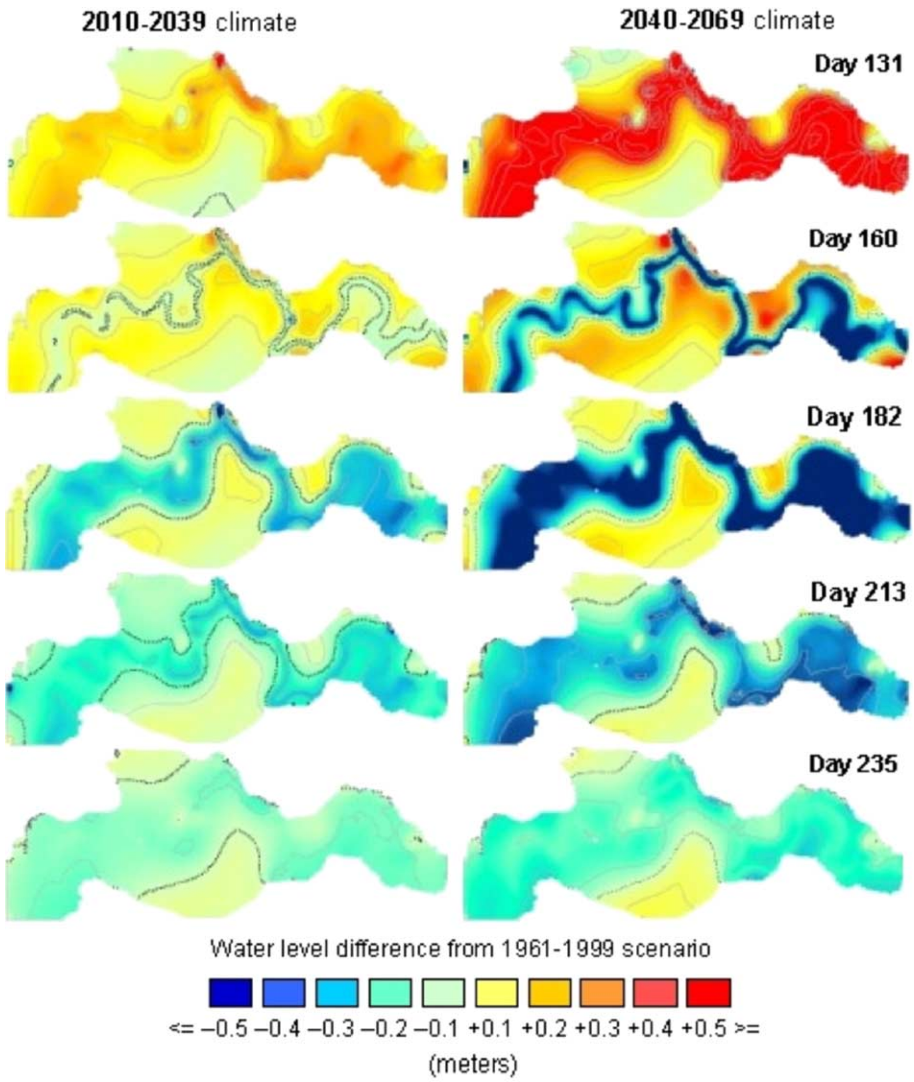

Fig. 7. Water level differences of the modeled water table at days 131, 160, 180, 205, 235 and 305 between future and present climate (a) scenario 2010–2039 and (b) scenario 2040–2069. Positive contours shown at 0.1 m interval. Zero contour is dashed line. Negative contours not shown. Darkest blue colours indicate values < − 0.5 m (along rivers only). At day 101, difference map (not shown) has values within 0.1 m of zero.

the GCM to resolve summer convective activity and precipitation events. At the coastal location (AB–SUM aquifer), there is much smaller model bias for summer months and the CGCM1 downscaled climate matched observed reasonably well. Winter precipitation had relatively small model bias for both locations, but it was still better at the coastal location than in the interior.

Overall, the groundwater flow models showed relatively small impacts of changes in climate on the groundwater systems studied. The absolute magnitudes of these changes lie within the realm of model uncertainty. However, the overall influence of aquifer geometry and the distribution of material properties, the climate region, and the nature of surface water–groundwater interaction clearly influence the impact on water levels. In the recharge-dominated AB–SUM aquifer, groundwater levels are predicted to decrease from 0.05 m to more than 0.25 m due to climate change by the 2010–2039 period. Impacts on water levels are generally restricted to the upland areas because the lower elevation portions of the model, where the major streams are located, are constrained by specified head boundary conditions; however, reductions in baseflow are anticipated due to the lowering of the groundwater gradient across the aquifer. In the GF aquifer, climate impacts are mainly driven by Kettle River stage. In particular, peak flow in the river is expected to shift to an earlier date, and there will be a slightly prolonged and lower baseflow period. Parts of valley aquifer that are strongly connected to the river have the largest climate-driven changes. As the river peak flow shifts to an earlier date in the year, groundwater levels shift by the same interval. When comparing the difference in groundwater levels at the same Julian Day between 2040–2069 and current conditions, groundwater levels increase by up to 0.50 m near the river and up to 0.20 m away from the river. Increases in recharge under future climate scenarios are of minor importance at this site.

The ability of a groundwater flow model to predict changes to groundwater levels, as forced by climate change, depends on the locations and types of model boundary conditions, the success of model calibration, and model scale. There are limitations in using codes such as MODFLOW for modelling very complex aquifers, especially where there are perched water tables or where changes in the groundwater regime might be anticipated to cause changes to the surface water regime. The results from these two study sites demonstrate that different site-specific linkages exist for climatic impacts on groundwater resources, and that these can be evaluated using standardized and consistent methodologies that allow for comparison of results and quantification of changes to groundwater levels, as well as for accounting for causes to such changes.

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