HYDROLOGICAL PROCESSES
Hydrol. Process. **30**, 4420–4433 (2016)
Published online 2 August 2016 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.10933

Assessing regional-scale spatio-temporal patterns of groundwater–surface water interactions using a coupled SWAT-MODFLOW model

Ryan T. Bailey,[1] Tyler C. Wible,[1]* Mazdak Arabi,[1] Rosemary M. Records[2] and Jeffrey Ditty[3]

[1] *Department of Civil and Environmental Engineering, Colorado State University, 1372 Campus Delivery, Fort Collins, CO, 80523-1372, USA*
[2] *Department of Geosciences, Colorado State University, 1482 Campus Delivery, Fort Collins, CO, 80523-1482, USA*
[3] *Riverside Technology, Inc., 2950 E Harmony Road, Suite 390, Fort Collins, CO, 80528, USA*

Abstract:

Interaction between groundwater and surface water in watersheds has significant impacts on water management and water rights, nutrient loading from aquifers to streams, and in-stream flow requirements for aquatic species. Of particular importance are the spatial patterns of these interactions. This study explores the spatio-temporal patterns of groundwater discharge to a river system in a semi-arid region, with methods applied to the Sprague River Watershed (4100 km^2) within the Upper Klamath Basin in Oregon, USA. Patterns of groundwater–surface water interaction are explored throughout the watershed during the 1970–2003 time period using a coupled SWAT-MODFLOW model tested against streamflow, groundwater level and field-estimated reach-specific groundwater discharge rates. Daily time steps and coupling are used, with groundwater discharge rates calculated for each model computational point along the stream. Model results also are averaged by month and by year to determine seasonal and decadal trends in groundwater discharge rates. Results show high spatial variability in groundwater discharge, with several locations showing no groundwater/surface water interaction. Average annual groundwater discharge is 20.5 m^3/s, with maximum and minimum rates occurring in September–October and March–April, respectively. Annual average rates increase by approximately 0.02 m^3/s per year over the 34-year period, negligible compared with the average annual rate, although 70% of the stream network experiences an increase in groundwater discharge rate between 1970 and 2003. Results can assist with water management, identifying potential locations of heavy nutrient mass loading from the aquifer to streams and ecological assessment and planning focused on locations of high groundwater discharge.

KEY WORDS groundwater; stream-aquifer interaction; SWAT; MODFLOW; numerical modeling; watershed hydrology

Received 26 May 2015; Accepted 28 May 2016

INTRODUCTION

A thorough understanding of watershed hydrology is essential for sustainable water management in a watershed. Of particular importance are the interactions of groundwater and surface water, especially in semi-arid regions where changes on the management or use of one will impact the availability and use of the other (Fleckenstein *et al*., 2010). Understanding the timing and spatial location of groundwater discharge to streams is required to (1) assess the risk of contamination of surface water by groundwater-borne contaminants, such as nitrate, phosphorus, with "hot spots" of nutrient inputs or contamination plumes posing risks to drinking water quality and ecosystems (Cey *et al*., 1999; Hussein and Schwartz, 2003; Kalbus *et al*., 2009); (2) determine the potential for removal of pollutants in groundwater (e.g. in riparian zones); (3) optimize conjunctive use of groundwater and surface water (Sophocleous, 2002); and (4) evaluate the sensitivity of stream flows and aquatic species to changing climate (Waibel *et al*., 2013), groundwater extraction (Spalding and Khaleel, 1991; Bakker and Anderson, 2003; Falke *et al*., 2011), or land use alterations, and the potential for reaches with higher base-flow to provide refuge to temperature-sensitive species under climate change (Flint and Flint, 2011). For the latter, groundwater contributions under future climate may serve to buffer changes in stream temperatures, an effect that is seasonally dependent.

Many techniques have been used to estimate patterns of groundwater/surface water interaction at variety of spatial and temporal scales. Specific field techniques include performing a water balance on river reaches (Krause *et al*., 2007); the use of permeameter tests and seepage

*Correspondence to: Tyler C. Wible, Department of Civil and Environmental Engineering, Colorado State University, 1372 Campus Delivery, Fort Collins, CO, 80523-1372, USA.
E-mail: Tyler.Wible@colostate.edu

metres (Avery, 1994); electrical resistivity surveys of streambed sediment (Nyquist *et al*., 2008); streambed temperature profiles and accompanied heat transport modelling (Silliman and Booth, 1993; Devito *et al*., 1996; Fryar *et al*., 2000; Becker *et al*., 2004; Conant, 2004; Keery *et al*., 2007), tracer tests (Harvey and Bencala, 1993) (see Conant, 2004 for a complete list of studies). Typically, these studies are performed at small spatial scales (e.g. Conant, 2004) and over a short time period (e.g. Becker *et al*., 2004), although several studies (e.g. Guggenmos *et al*., 2011) have been applied to regional scales.

For assessment at larger spatio-temporal scales, numerical modelling approaches have been employed, for example applying Modular ground-water Flow (MODFLOW)-unsaturated-zone flow (UZF) (Niswonger *et al*., 2006) to a ~500 km^2 region of the Lower Arkansas River Valley in southeastern Colorado (Morway *et al*., 2013) to investigate the change in groundwater return flow patterns under varying irrigation management strategies, and applying Groundwater and surface water flow (GSFLOW) (Markstrom *et al*., 2008) to a 80 km^2 granitic catchment in Spain, and using a coupled GSFLOW-storm water management model model (SWMM) to investigate interactions under various water-use scenarios in the agricultural-intensive Zhangye Basin, China (Tian *et al*., 2015). Integrated hydrologic models such as Parallel groundwater Flow (ParFlow) (Kollet and Maxwell, 2006) also have been applied at small spatial scales, for example along a 5-km reach of the Cosumnes River in California (Frei *et al*., 2009). While many studies focus on spatial patterns of groundwater–surface water interaction, others have focused on salinity changes in floodplains (Lamontagne *et al*., 2005) and wetlands (Jolly *et al*., 2008), changes of these patterns under climate change using global climate model projections (Waibel *et al*., 2013), and the ecological effects and feedbacks of these interactions (Hayashi and Rosenberry, 2001; Ludwig *et al*., 2005; Van der Kamp and Hayashi, 2009).

To enhance understanding of large-scale groundwater–surface water interactions, this study explores the spatial patterns of groundwater discharge to the stream network of a large semi-arid river basin over a multi-decadal time period. The study region is the Sprague River Watershed in the Upper Klamath Basin, Oregon, USA, wherein stream flow is strongly dependent on groundwater discharge along certain reaches (Gannett *et al*., 2010). The assessment is performed using a new model that couples the newest versions of the Soil and Water Assessment Tool (SWAT) (Arnold *et al*., 1998; Gassman *et al*., 2007; Neitsch *et al*., 2011), which simulates water, nutrient, and sediment transport at the watershed scale, and MODFLOW.

The coupled model has several advantages over existing versions (Sophocleous and Perkins, 2000; Galbiati *et al*., 2006; Kim *et al*., 2008; Chung *et al*., 2010; Luo and Sophocleous, 2011), such as geographically located Hydrologic Response Units (HRUs); an efficient HRU-grid cell mapping scheme; the ability to use SWAT and MODFLOW models of different spatial extent; and use of the Newton formulation of MODFLOW-2005 (MODFLOW-NWT: Niswonger *et al*., 2011) for optimal solution of scenarios involving drying and rewetting nonlinearities of the unconfined groundwater-flow equation. Furthermore, the model is publically available. The model is tested against observed stream flow, water table elevation and estimates of groundwater discharge volumetric flow rates, with model output then used to assess and quantify spatio-temporal patterns of groundwater discharge to the watershed's stream network.

METHODOLOGY

This section outlines the methods used to quantify the spatio-temporal patterns of groundwater–surface water interaction in the Sprague River watershed in southern Oregon. Following a description of the study region, the development of the coupled SWAT-MODFLOW model and its application to the watershed will be presented.

Study region: Sprague river watershed, OR

The Sprague River Watershed in southern Oregon, USA (Figure 1) drains an area of about 4,000 km^2 in the Upper Klamath River basin and is comprised mostly of coniferous forest (Rabe and Calonje, 2009), with minor land covers of rangeland, riparian wetlands (5.3% of area), depressional wetlands (0.4% area) and irrigated cattle pasture (Homer *et al*., 2007). The Sprague River and the Williamson River, to which the Sprague is tributary, together contribute about 50% of the annual inflow to Upper Klamath Lake, with the remainder contributed by the Wood River (Records *et al*., 2014), springs, and smaller tributaries. Outflow from Upper Klamath Lake also supplies the US Bureau of Reclamation's Klamath Irrigation Project, which provides water for more than 1000 farms (Thorsteinson *et al*., 2011). Groundwater supplies a large percentage of annual stream flow in the Upper Klamath Basin (Gannett *et al*., 2010; Mayer and Naman, 2011).

There are three large tributaries in the Sprague River: the North Fork and South Fork (Figure 1), and the Sycan River. The watershed is located within the rain shadow of the Cascade Mountains, and average annual precipitation ranges from about 340 to 950 mm/year, with most precipitation occurring October through March. Elevation in the watershed ranges from 1270 to 2600 m above sea level (USGS, 2009). Available data for model testing include stream flow, reach estimates of groundwater discharge to the stream network, and water table elevation.

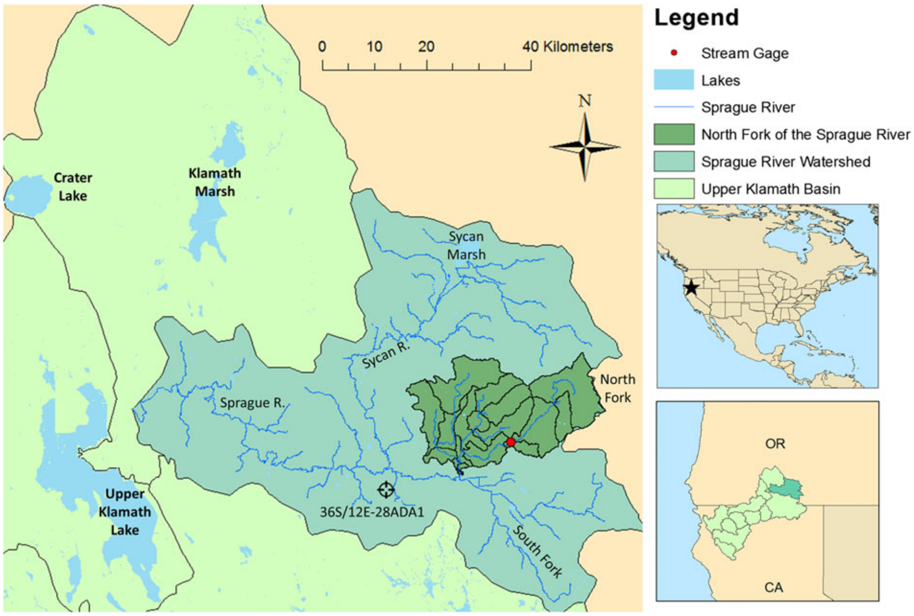

Figure 1. Location of Sprague River watershed, located on the eastern end of the Upper Klamath Basin, Oregon, also showing the North Fork catchment area, the North Fork stream gauge, and an Oregon Water Resources Department observation groundwater well (36S/12E-28ADA1) near the confluence of the Sycan River and Sprague River

Assessment tool: coupled SWAT-MODFLOW model

Because of the strong influence of groundwater on stream flow in the Sprague River watershed, a model capable of simulating surface hydrology and groundwater hydrology and their interaction is required for system analysis. Available published watershed-scale hydrologic models include TOPography-based hydrological model (TOPMODEL) (Beven *et al.*, 1995), MODFLOW-based Hydrologic Modeling System (MODHMS) (Panday and Huyakorn, 2004); the Systeme Hydrologique Europeen model (SHE/MIKE-SHE) (Butts and Graham, 2008), the Integrated Hydrology Model (VanderKwaak, 1999; Loague *et al.*, 2010), the Catchment Hydrology model (Camporese *et al.*, 2010), Parallel groundwater Flow (ParFlow) (Kollet and Maxwell, 2006), GSFLOW (Markstrom *et al.*, 2008), and SWAT (Neitsch *et al.*, 2011). As calibrated SWAT and MODFLOW models are available for the region (Gannett *et al.*, 2012; Records *et al.*, 2014) which simulate surface hydrology and groundwater hydrology, respectively, this study coupled the two models to integrate surface and subsurface hydrological processes. Furthermore, future efforts will employ the coupled model to assess nutrient pollution (Records *et al.*, 2014) in the land surface/subsurface/stream system of the watershed, and from the aforementioned watershed-scale hydrologic models only SWAT simulates nutrient fate and transport.

Previous studies also have linked the SWAT and MODFLOW codes (Perkins and Sophocleous, 1999; Sophocleous and Perkins, 2000; Galbiati *et al.*, 2006; Kim *et al.*, 2008; Guzman *et al.*, 2015), with other studies based on these initial versions or variations (Conan *et al.*, 2003; Chung *et al.*, 2010; Luo and Sophocleous, 2011). Typical model integration includes using SWAT-calculated soil deep percolation as recharge for MODFLOW, and using MODFLOW-simulated groundwater–surface water interaction (i.e. groundwater discharge to streams; stream seepage to aquifer) as input for SWAT. Specific characteristics of these models include internal integration of the two modelling codes and geo-located HRU data (Guzman *et al.*, 2015). Following a brief overview of the SWAT and MODFLOW models, the development of the coupled SWAT-MODFLOW used for this study is detailed.

Overview of the SWAT and MODFLOW modelling codes. SWAT was developed by the US Department of Agriculture's Agricultural Research Service to simulate water flow, nutrient mass transport and sediment mass transport at the watershed scale. It is a continuous, basin-scale, distributed-parameter watershed model emphasizing surface processes, dividing the watershed into sub-basins which are then further divided into multiple unique combinations (HRUs) of land use, soil and slope for which detailed water, nutrient and sediment mass balance calculations are performed. These HRUs may or may not be spatially contiguous within a sub-basin.

Calculations in SWAT are performed for each HRU and then scaled up to the sub-basin outlet by the percent area of the HRU within the sub-basin. This approach results in the HRUs lacking the spatial relations typically seen in a fully distributed model, but yields a computationally efficient calculation scheme allowing for rapid watershed simulation over long time periods. Additionally, water, nutrient and sediment output from each HRU are routed directly to the sub-basin stream for routing through the stream network. For groundwater–surface water interactions, therefore, system response variables such as groundwater discharge to streams or river seepage to the aquifer are available only at the sub-basin level. Furthermore, indicators of groundwater storage such as water table elevation are not geographically located. Because of the simplistic representation of subsurface processes, SWAT often performs poorly when applied to watersheds wherein groundwater discharge contributes significantly to streamfflow (Peterson and Hamlet, 1998; Spruill *et al*., 2000; Chu and Shirmohammadi, 2004; Srivastava *et al*., 2006; Gassman *et al*., 2007).

MODFLOW is a three-dimensional, physically based, distributed finite-difference groundwater model for variably saturated subsurface systems. A recent addition to MODFLOW is a Newtonian-based solver algorithm that better satisfies the complex non-linear drying and rewetting of grid cells in unconfined groundwater systems (Niswonger *et al*., 2011), a problem with previous model versions. Available processes to be simulated in MODFLOW include groundwater recharge, vadose zone percolation (UZF1 package) (Niswonger *et al*., 2006), evapotranspiration, pumping, discharge to subsurface drains and river–aquifer interactions. However, model application is limited to investigating management and climate effects on groundwater and groundwater-surface interactions, as MODFLOW does not simulate surface processes such as land–atmosphere interactions, infiltration and surface runoff, nutrient cycling and transport, plant growth and the impacts of management practices on agricultural systems.

SWAT-MODFLOW model development. The coupled SWAT-MODFLOW framework developed in this study combines the updated SWAT 2012 model (Revision 591) with MODFLOW-NWT. Within the framework, SWAT simulates land surface processes, crop growth, in-stream processes and soil zone processes, whereas MODFLOW-NWT simulates three-dimensional groundwater flow and all associated sources and sinks (e.g. recharge, pumping, discharge to tile drains and interaction with stream network). Both modelling codes are combined into a single FORTRAN code that is compiled and run as a single executable.

The basic process of linking the SWAT and MODFLOW models is to pass HRU-calculated deep percolation (i.e. water that exits the bottom of the soil profile) as recharge to the grid cells of MODFLOW, and then pass MODFLOW-calculated groundwater–surface water interaction fluxes to the stream channels of SWAT. With this approach, SWAT calculates the volume of overland flow and soil lateral flow to streams, MODFLOW calculates the volume of groundwater discharge to streams, and then SWAT routes the water through the stream network of the watershed. Groundwater–surface water interaction is simulated using the River package of MODFLOW, with Darcy's law used to calculate the volumetric flow of water Q_{leak} [L^3/T] through the cross-sectional flow area between the aquifer and the stream channel

$$Q_{leak} = K_{bed}(L_{str}P_{str})\left(\frac{h_{str} - h_{gw}}{z_{bed}}\right) \quad (1)$$

where K_{bed} is river bed hydraulic conductivity [L/T], L_{str} is the length of the stream [L], P_{str} is the wetted perimeter of the stream [L], h_{str} is river stage [L], h_{gw} is the hydraulic head of groundwater [L], and z_{bed} is the thickness of the river bed [L]. Q_{leak} is negative if groundwater flows to the river (i.e. groundwater hydraulic head h_{gw} is above the river stage h_{str}), and positive if river water seeps into the aquifer. These calculations are performed for any grid cell through which a stream passes. The SWAT-MODFLOW model simulation and linking process is summarized in Figure 2. Upon reading input data for both the SWAT and MODFLOW models, the simulation runs through the repeated daily process of SWAT HRU calculations, passing data to MODFLOW, running MODFLOW, passing data to SWAT and routing water through the watershed's stream network.

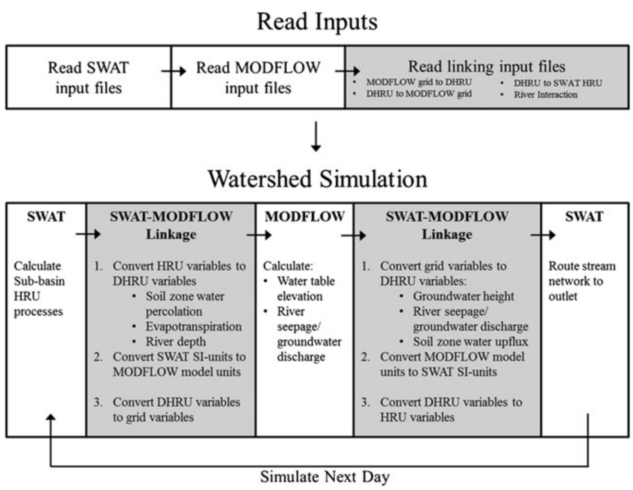

Figure 2. Diagram showing the model code sequence of the coupled SWAT-MODFLOW model. Linking input files are created that contains the information necessary to convert model output from HRUs to geographically located disaggregated Hydrologic Response Units (DHRUs), from DHRs to MODFLOW grid cells, and from SWAT sub-basin rivers to MODFLOW River cells. SI-units: International System of Units.

Data are passed between the models using "mapping" subroutines that relate HRUs to MODFLOW grid cells and MODFLOW River cells to SWAT stream channels (Figure 3). The main elements of this mapping scheme are: HRUs; Disaggregated HRUs (DHRUs), which divide each original HRU into individual, contiguous areas within a sub-basin to allow HRU calculations to be geo-located; MODFLOW grid cells; MODFLOW River cells; and SWAT stream channels. Calculated deep percolation (i.e. recharge) for HRUs are first mapped to each individual DHRU, and then mapped to each MODFLOW grid cell according to the percent area of the DHRU contained within the grid cell for use by the Recharge package. SWAT-calculated channel depth from each sub-basin is mapped to the group of River cells within the sub-basin for use by the River package. MODFLOW then computes groundwater hydraulic head and groundwater–surface water interactions, which are passed to SWAT. Groundwater discharge volumes, computed on a cell-by-cell basis within MODFLOW, are summed and added to in-stream flow for each of SWAT's sub-basins. SWAT then completes the stream routing calculations for the day, with the daily loop continuing until the end of the simulation.

For the possible scenario of a River cell intersecting more than one stream, the length of each stream within the cell is used to calculate a composite weighted value of channel depth for use by MODFLOW and to distribute the cell groundwater discharge volume to the associated sub-basin main channels. Within this scheme, MODFLOW is called as a subroutine within the SWAT framework, providing a single compiled FORTRAN code.

The spatial relationship between HRUs, DHRUs, MODFLOW grid cells and MODFLOW River cells is presented in Figure 3 and Table I for a hypothetical watershed with four original SWAT HRUs overlying a MODFLOW finite difference grid. SWAT HRUs #1–3 each are designated as a single DHRU each, because they are spatially contiguous, whereas SWAT HRU #4 is separated into three separate DHRUs (Table I). For simplicity, DHRU-to-cell mapping is only shown for DHRU #6 Table I, which is the northern-most portion of HRU #4 (Figure 3). As seen in Table I, 12 grid cells intersect DHRU #6 (the eastern-most polygon of HRU #4 in Figure 3), with the portion of the DHRU overlapped by each cell shown in the "Portion of DHRU" column and the portion of the cell within the DHRU shown in the "Portion of Grid Cell" column. These relationships for each HRU, DHRU, and grid cells and also a list of the River cells contained within each sub-basin, are read in at the beginning of a SWAT-MODFLOW simulation and stored in memory for use at each time step (Figure 2).

The linkage procedure allows for SWAT and MODFLOW models of different spatial extents, that is, one of the models can extend beyond the boundaries of the other. This was performed to facilitate linking of existing models, such as regional-scale groundwater models (e.g. Rumman and Payne, 2003; Christenson *et al*., 2011; Paschke, 2011; Gannett *et al*., 2012; Mashburn *et al*., 2013). Beyond the overlap area, the original functionality of each model is retained. Stress period and time stepping information specified in an original MODFLOW model is used to determine calls to read stress data (e.g. pumping) from input files. If the MODFLOW time step is less than 1 day, the code calculates and executes the required number of time steps for the single day. If the time step is greater than 1 day,

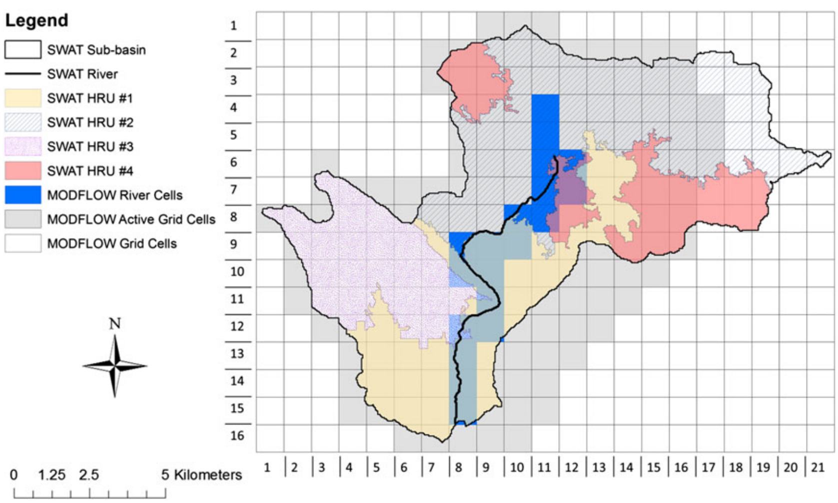

Figure 3. Schematic demonstrating the SWAT-MODFLOW coupling and spatial interaction from SWAT Hydrologic Response Units (HRUs) to MODFLOW grid cells. MODFLOW receives recharge (deep percolation) values from SWAT, simulates groundwater–surface water interaction, and passes groundwater height (water table depth) and groundwater discharge volumes back to SWAT

Table I. Spatial conversion example between SWAT HRUs, geographically-located DHRUs and MODFLOW grid cells for a hypothetical watershed, shown in Figure 2

SWAT HRUs	Intermediate DHRUs		MODFLOW Grid Cells			
			Grid			
HRU ID	DHRU ID	Portion of HRU Area (%)	Row	Column	Portion of DHRU (%)	Portion of Grid Cell (%)
1	1	100	—	—	—	—
2	2	100	—	—	—	—
3	3	100	—	—	—	—
4	4	16	—	—	—	—
	5	62	—	—	—	—
	6	22	2	7	1.31	6.11
			2	8	14.70	68.65
			2	9	9.64	45.06
			3	7	3.68	17.20
			3	8	20.44	95.47
			3	9	19.53	91.47
			3	10	4.11	19.20
			4	8	12.99	60.66
			4	9	10.96	51.21
			4	10	2.24	10.48
			5	8	0.21	0.96
			5	9	0.10	0.47

For simplicity, the spatial area weighting factors (Proportion of DHRU, Proportion of Grid Cell) are shown only for DHRU #6 (which is part of HRU #4). Notice that the area proportions of DHRUs 4-6 sum to 100%.
DHRU, Disaggregated Hydrologic Response Unit; HRU, Hydrologic Response Units; MODFLOW, Modular Ground-Water Flow; SWAT, Soil and Water Assessment Tool.

the code forces MODFLOW to run with a daily time step. The code allows for the MODFLOW subroutine to be called at any specified frequency, for example, every week, every month, etc…depending on the assumed hydraulic connection between the soil zone and the water table. However, this functionality was not used in this study. Also, the code accounts for and converts from time and length units specified in the original MODFLOW model.

Model application to the Sprague river watershed. The SWAT-MODFLOW model developed for the Sprague River Watershed uses the calibrated MODFLOW model of the Upper Klamath Basin (Gannett *et al*., 2012) used to analyse management scenarios on groundwater supply and a calibrated SWAT model (Records *et al*., 2014) developed to study the impacts of combined climate change and wetland extent scenarios on water quality.

The original MODFLOW model (Figure 4A) encompasses the entire Upper Klamath Basin, an area of approximately 20 000 km^2. The region was discretized into finite different grid cells with a lateral dimension of 762 m by 762 m, aligned in a grid consisting of 285 east-west oriented rows and 210 north-south oriented columns with the aquifer discretized vertically into three layers of varying thickness based on the local hydrogeologic units

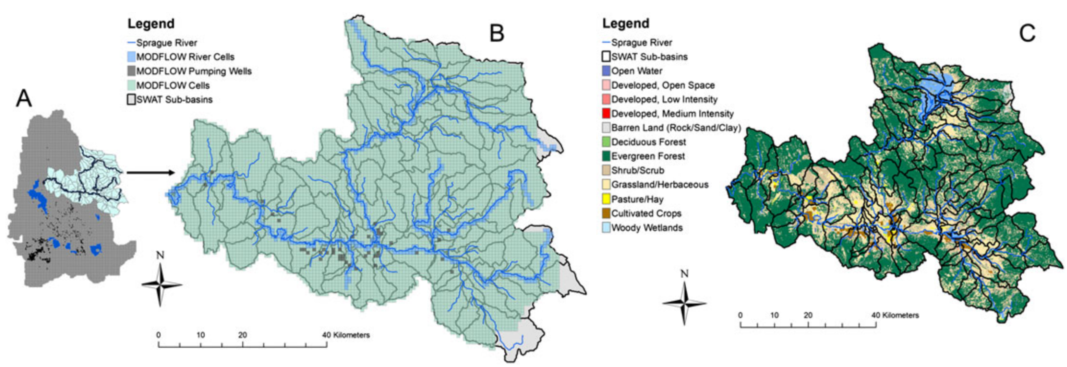

Figure 4. (A) Modular groundwater Flow (MODFLOW) grid, showing the stream network, the river cells and the cells in which pumping wells are located, and (B) Soil and Water Assessment Tool (SWAT) sub-basins and Hydrologic Response Units of the Sprague River watershed

(Gannett *et al.*, 2012). Sources and sinks for the model include tie-dependent and spatially variable recharge calculated using the Precipitation-Runoff Modeling System (PRMS) (Leavesley *et al.*, 1983), evapotranspiration from shallow groundwater, groundwater flow to and from adjacent basins, and groundwater interaction with reservoirs, subsurface drains and the stream network, with the latter employing the Stream package. The original model uses stress periods of 3 months, with each stress period divided into 5 flow time steps. The simulation period of the model is from 1970 to 2004, but was only calibrated for period between 1989 and 2004. Further calibration and results of the original MODFLOW model are available in Gannett *et al.* (2012).

The SWAT model used for the Sprague River watershed (~4100 km^2, see Figure 4C for model domain and land use) included four separate SWAT models (Records *et al.*, 2014), one each for the Sycan, South Fork, North Fork and the Sprague River main stem. Model setup included a 30 m National Elevation Dataset raster for land surface topography, a National Hydrography Dataset stream layer to delineate the stream network, a National Land Cover Dataset 2001 for land use, and the US General Soil Map. Each agricultural field was designed as a separate HRU. The model was calibrated and tested during the 2001–2010 period using monthly stream discharge, with automated calibration performed using dynamically dimensioned search (Tolson and Shoemaker, 2007) algorithms. Model performance was generally acceptable for monthly stream flow with a Nash Sutcliff of greater than 0.7 in the calibration and validation periods for the Sprague River outlet, although monthly stream flow percent bias was outside the range of acceptability (31% overestimation) for the North Fork, a groundwater-driven tributary. In contrast, SWAT model results for the Sycan River, a surface process dominated tributary, were much better. As such, the North Fork model, an area of approximately 500 km^2, was selected for use in the coupled SWAT-MODFLOW model.

The spatial extent of the coupled-MODFLOW model is shown in Figure 4B, with the 142 SWAT sub-basins outlined in grey and the MODFLOW grid cells that SWAT overlaps (a total of 7060) also shown. The land-use map used to create the SWAT HRUs (a total of 1940) is shown in Figure 4C. To provide a single coupled model, one SWAT model was generated for the entire Sprague River watershed in contrast to the four separate, sub-basin models used in Records *et al.* (2014). The single SWAT model is, however, only calibrated for the North Fork catchment, selected for the large contribution of groundwater to stream discharge. The only modification to the original MODFLOW model for the Upper Klamath Basin was replacing the Stream package with the River package for the grid cells along the stream network. The 763 River cells in the Sprague River watershed are shown along the stream network in Figure 4A.

Using the map of HRUs from the original SWAT model, the MODFLOW grid, and the methods outlined in the Section on SWAT-MODFLOW model development, 207,874 DHRUs were created, with spatial relationships between HRUs and DHRUs, between DHRUs and grid cells, and between SWAT sub-basins and MODFLOW River cells created and used in the model simulation for passing data between the two models. The coupled model was run for the period of 1970–2003 using daily time steps.

Simulated stream discharge is compared with both an observed hydrograph (USGS Station 11495800 on the North Fork; see Figure 1) and results from the original SWAT model during the overlapping period of 1995–2003. Groundwater hydraulic head is compared with observed head at an observation well near the confluence of the Sycan and Sprague Rivers (well 36S/12E-28AdA1; see Figure 1). Groundwater discharge to the stream network is compared with field-estimated rates at specific reaches (Gannett *et al.*, 2010). The only modification to original SWAT and MODFLOW model parameters consisted of uniformly decreasing stream bed conductance of MODFLOW River cells to 50% of the original value used in the Stream package, to provide a better match between simulated and observed stream discharge. Using the tested model, the spatio-temporal patterns of groundwater–surface water interaction is assessed for the entire watershed.

Model limitations. The principal limitation of applying SWAT-MODFLOW to the study region is the computational burden imposed by MODFLOW subroutines and the HRU-DHRU-Grid (and vice versa) spatial linkage and conversion subroutines. While model linkage and MODFLOW simulation on daily time steps is essential in most scenarios for accurate representation of water table fluctuation and groundwater–surface water interactions, simulation run-times can be much longer than for the original SWAT and MODFLOW models. For example, the original MODFLOW model for the Upper Klamath Basin uses quarterly (~3 month) stress periods divided into 5 flow time steps, resulting in time steps of approximately ~18 days and a total run-time of approximately 12 min on an Intel Core 2 Duo 2GHz CPU with 4GB of RAM. With the stipulation of daily time steps and the inclusion of SWAT and the HRU-DHRU-Grid mapping subroutines, the linked SWAT-MODFLOW simulation requires approximately 11 h for the 34-year period simulation period. This run-time, however, seems comparable with other regional-scale MODFLOW models that simulate unsaturated-zone flow and stream channel hydraulics, that is, using the UZF1 (Niswonger *et al.*, 2006) and streamflow-routing (SFR) (Prudic *et al.*, 2004) packages. Also, this run-time could be decreased if longer time intervals between MODFLOW calls are specified (Section on SWAT-MODFLOW model development), although this was not tested for this study.

RESULTS AND DISCUSSION

General model results

Annual average recharge (mm), calculated from the daily recharge values pass from SWAT to MODFLOW, is shown in Figure 5A, demonstrating higher recharge rates in the upland forested areas and the watershed outlet area, with low recharge rates along the main corridor of the South Fork and main stem of the Sprague. Simulated cell-wise groundwater hydraulic head (m) at the end of the simulation (2003) is shown in Figure 5B, with the highest water table elevation (~2000 m) occurring in the high-elevation regions of the Sycan and North Fork rivers and low water table elevation (~1270 m) occurring along the Sprague River corridor. Overall, simulated groundwater head in the northwest region of the watershed is higher than for the original MODFLOW model (results not shown), likely because of a larger depth of recharge calculated by the SWAT subroutines as opposed to those determined by PRMS as used in the original MODFLOW model (Gannett *et al*., 2012). The SWAT model uses elevation bands to vary precipitation depth across its sub-basins (Records *et al*., 2014), while the PRMS-calculated recharge values do not use this approach in the original MODFLOW model (Gannett *et al*., 2012). In general, however, water table elevation in the forested upland areas of the basin is not well known, with sparse data available for model calibration (Gannett *et al*., 2012).

Model corroboration

Streamflow. Observed and simulated stream discharge for the gauge site on the North Fork River (see Figure 1 for location) is shown in Figure 6A, demonstrating good similarity of the SWAT-MODFLOW results with the observed hydrograph. Comparison statistics (Nash–Sutcliff NS; coefficient of determination R^2) between the observed and simulated discharge rates are presented in Table II, with values calculated using daily discharge rates, monthly discharge rates and the $\log_{10}$ of both daily and monthly values. The NS values for monthly discharge rates are considered acceptable (≥ 0.5) (Moriasi *et al*., 2007), and in each category the coupled model performed as well or better than the original SWAT model. The NS values for daily

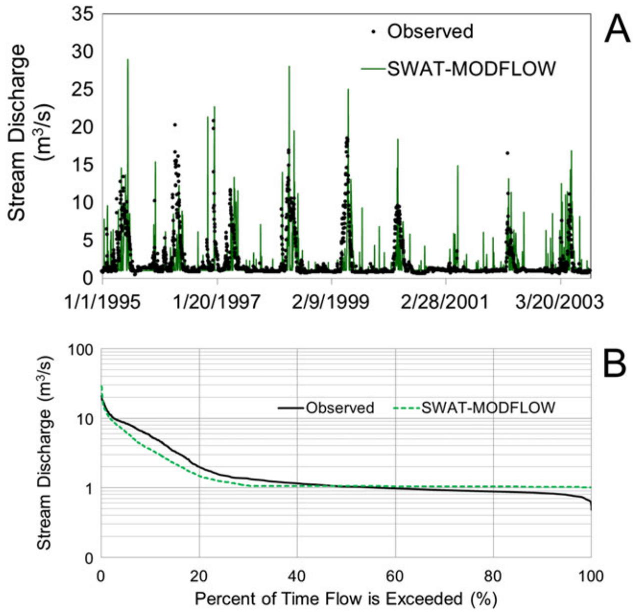

Figure 6. (A) Observed and SWAT-MODFLOW simulated time series of stream discharge (m^3/s) for the North Fork of the Sprague River, with model results available starting 1 January 1995. The location of the stream gauge is shown in Figure 1; (B) Observed and simulated Flow Duration Curve for the North Fork of the Sprague River

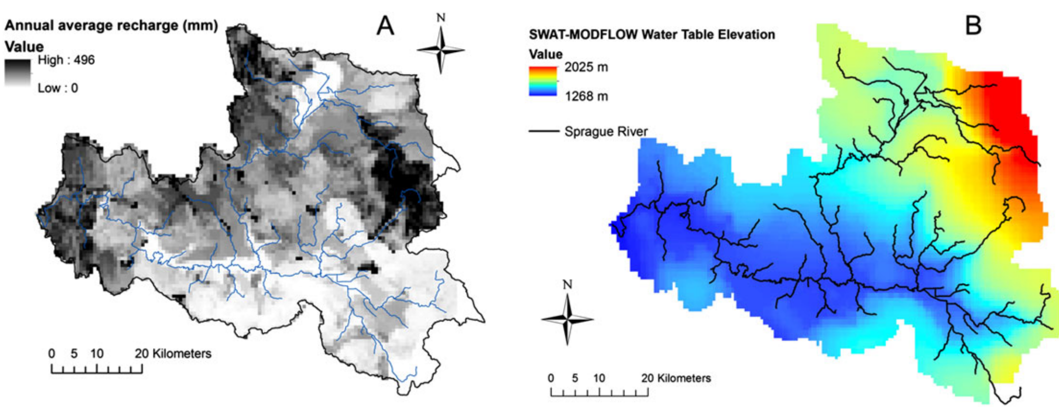

Figure 5. (A) Spatially-varying annual average recharge (mm) in the Sprague River watershed as simulated by the coupled SWAT-MODFLOW model; (B) Cell-wise water table elevation for MODFLOW grid in the Sprague River watershed at the end of the simulation period (12/31/2003)

Table II. Comparison statistics (NS; R^2) between the observed and simulated hydrograph at the stream gauge near the confluence of the Sycan and Sprague Rivers (Figure 3) for the original SWAT model and for the SWAT-MODFLOW model

Statistical Comparison	SWAT-MODFLOW	SWAT
	Daily	
NS	0.39	0.26
R^2	0.36	0.36
	Monthly	
NS	0.59	0.58
R^2	0.66	0.64
	Daily ($\log_{10}$)	
NS	0.38	0.16
R^2	0.40	0.35
	Monthly ($\log_{10}$)	
NS	0.72	0.66
R^2	0.75	0.66

Results are shown for daily flow rates, monthly flow rates and the $\log_{10}$ of these values
MODFLOW, Modular Ground-Water Flow; NS, Nash–Sutcliff; SWAT, Soil and Water Assessment Tool; R^2, Coefficient of determination.

values are still low and may improve with a full calibration of the coupled model. A possible contribution to the low fitting values for the daily data is that the original SWAT model was calibrated on a monthly time step and the original MODFLOW model was calibrated quarterly (3 months).

To better examine differences in base-flow representation by the models, the $\log_{10}$ of both daily and monthly stream flows at the stream gauge near the confluence of the Sycan and Sprague Rivers were compared with the $\log_{10}$ of observed stream flows for 1995–2003, as shown in Table II. For both daily and monthly flow rates, there is a marked improvement in performance statistics for the coupled SWAT-MODFLOW model (daily $R^2=0.40$, NS = 0.38; monthly $R^2=0.75$, NS = 0.72) versus the original SWAT model (daily $R^2=0.35$, NS = 0.16; monthly $R^2=0.66$, NS = 0.66). To further examine the simulation differences to base-flow, the base-flow separation tool BFLOW (Arnold *et al*., 1995; Arnold and Allen, 1999) was used to evaluate the fraction of base-flow from stream flow. A summary of these results is shown in Table III. In all cases, the SWAT-MODFLOW model resulted in a higher base-flow fraction of stream flow than the SWAT model, which more closely matched observed values. For base-flow pass 1, SWAT-MODFLOW and SWAT had a percent difference of 11.3% and 17.5%, respectively, from the observed value. For Passes 2 and 3, SWAT-MODFLOW had a percent difference of 7.4% and 0% from the observed value, whereas SWAT had percent differences of 17.6% and 13.3%.

To provide an additional comparison between observed and simulated daily stream flow at the gauge site, flow duration curves were computed (Figure 6B). As seen in Figure 6B, the shape and magnitude of the flow duration curve produced by the models is similar to the curve from the observed data, with flow rates of approximately 2.0 and 1.0 m^3/s exceeded 20% and 40% of the time, respectively. The SWAT-MODFLOW model underestimates the mid-range to high-range flows (1.0 to 20.0 m^3/s) and overestimates the low-range flows ($< 1.0\,m^3/s$). For example, simulated flow rates are always $\geq 1.0\,m^3/s$, whereas the observed data indicates that flow rates are less than 1.0 m^3/s 50% of the time, with flows exceeding 0.9 and 0.85 m^3/s 80% and 90% of the time, respectively.

Groundwater level and groundwater discharge. For the observation well located near the confluence of the Sycan and Sprague Rivers (Figure 1), the SWAT-MODFLOW simulated average water table elevation of 1328.3 m is 3.9 m lower than the average observed elevation of 1332.2 m (based on 62 observed values between 1989 and 2004) while, the original MODFLOW model simulated an average water table elevation 9 m lower than the observed value.

Field-estimated and simulated groundwater discharge rates were compared for specific stream reaches. This comparison is particularly important as the overall aim of this study is to quantify spatio-temporal patterns of groundwater–surface water interactions in the watershed (Section on Spatio-temporal patterns of groundwater–surface water interaction). Figure 7A shows the average annual groundwater discharge (m^3/day) for each of the 763 River cells. Red bars indicate discharge from the aquifer to the stream, and green bars indicate seepage from the stream to the aquifer. As seen in the figure, the

Table III. Base-flow fraction of stream flow comparison between the observed and simulated hydrograph at the stream gauge near the confluence of the Sycan and Sprague Rivers (Figure 3) for the original SWAT model and for the SWAT-MODFLOW model

Base-flow Pass	Observed	SWAT	Difference (%)	SWAT-MODFLOW	Difference (%)
Base-flow Pass 1	0.80	0.66	17.5	0.71	11.3
Base-flow Pass 2	0.68	0.56	17.6	0.63	7.4
Base-flow Pass 3	0.60	0.52	13.3	0.6	0.0

Base-flow fraction results are provided by the base-flow separator tool BFLOW (Arnold *et al*., 1995; Arnold and Allen, 1999)
MODFLOW, Modular Ground-Water Flow; SWAT, Soil and Water Assessment Tool.

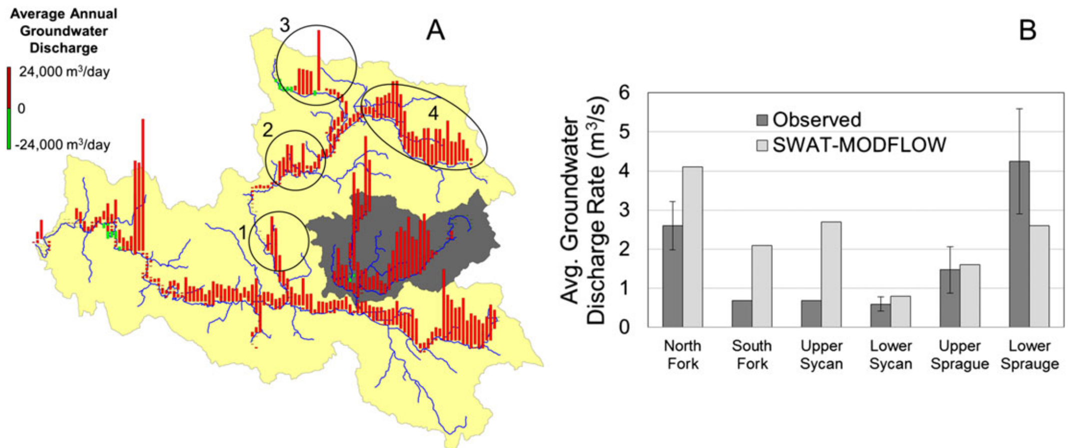

Figure 7. (A) Simulated average annual groundwater discharge (m^3/day) from the aquifer to the stream network. The principal groundwater discharge sites along the Sycan River are circled and numbered 1–4 (Upper Sycan = 3 and 4; Lower Sycan = 1 and 2); (B) Observed and simulated [SWAT-MODFLOW] average groundwater discharge (m^3/s) to streams in the Sprague River watershed

vast majority of groundwater–surface water interaction is discharge from the aquifer to the stream, which matches documented field studies (Gannett *et al*., 2010). The magnitude of groundwater discharge is highly spatially variable, with key locations of discharge including the North and South Fork catchments and the downstream segment of the Sprague River main stem.

Using flow measurements from stream gauges and synoptic measurements, Gannett *et al*. (2010) reported principal areas of groundwater discharge to streams, with volumetric groundwater discharge rates averaged over stream reaches. The average discharge rates for the North and South Forks of the Sprague River, Upper and Lower Sycan River, Upper and Lower Sprague River (Figure 7B) range from 0.7 (Upper Sycan and South Fork) to 4.2 m^3/s (Lower Sprague River). In comparison, the average discharge rates computed by the SWAT-MODFLOW model for the same six reaches (Figure 7B) range from 0.8 to 4.1 m^3/s. The Upper Sycan values are associated with the circled areas 3 and 4 in Figure 7A, whereas the Lower Sycan values are associated with areas 1 and 2.

The largest percent differences between observed and simulated discharge rates occur for the South Fork (0.7 m^3/s vs. 2.1 m^3/s) and Upper Sycan River (0.43 m^3/s vs. 2.7 m^3/s), with the model predicting higher values; however, the observed values for these two streams have at least one reach with insufficient data to assess uncertainty (Gannett *et al*., 2010), and thus there may be more groundwater discharge than was measured. In general, the field-estimated groundwater discharge estimates contain a high degree of uncertainty. The estimates for the North and South Forks of the Sprague River, Upper and Lower Sycan River, Upper and Lower Sprague River have associated confidence levels of 3, 3–5, 1–5, 3, 3–4 and 3, respectively (Gannett *et al*., 2010), with the confidence level representing a subjective assessment of the interval (plus or minus) that has a 95% probability of containing the true value. Confidence level categories are: 1 (10%), 2 (20%), 3 (30%), 4 (50%) and 5 (insufficient data to assess uncertainty), and are assigned to the observed values in Figure 7B. There was insufficient data to assess the uncertainty in the South Fork and Upper Sycan reaches (i.e. confidence level = 5). Overall, we conclude that the SWAT-MODFLOW model provides reasonable spatial estimates of groundwater–surface water interactions in the Sprague River watershed, particularly at the regional scale. However, future small-scale reach studies, e.g. to assess nutrient loading from riparian areas to surface water, may require further model refinement along these segments of the stream network.

Spatio-temporal patterns of groundwater–surface water interaction

As discussed in the previous section, the average annual groundwater discharge rate (m^3/day) (or stream seepage rate) for each MODFLOW River cell is shown in Figure 7A. The highest rates occur in the upper reaches of the Sycan River, the upper reaches of the North Fork, the upper reach of the Sprague River and a section of the Lower Sprague River approximately 10 km from the watershed outlet. The main stem of the Sprague River shows spatially constant discharge rates. As seen in Figure 7B, the discharge rates estimated by the model for the South Fork and the Upper Sycan reaches may over-estimate actual rates; however, field-calculated estimates for these reaches are uncertain. Overall, results show a high degree of spatial variability in groundwater discharge to the stream network. Seepage of stream water to the aquifer occurs in only a few locations (identified in green in Figure 7A).

The average groundwater discharge rates (m^3/s) by month and by year during the 1970–2003 time period for the entire watershed are shown in Figure 8. Monthly rates were calculated using the results of each month for each of the 34 years. A distinct decrease in groundwater discharge occurs in the early spring months (March: 18.4 m^3/s, and April: 18.6 m^3/s), followed by an increase in discharge throughout the summer months with the peak discharge rates occur in the early fall months (September: 22.2 m^3/s). The change in the spatial pattern of groundwater discharge during the year is shown in Figure 9, displayed as a departure from the average annual rates for the months of March (minimum groundwater discharge, Figure 8A), June and September (maximum groundwater discharge). Black bars signify an increase from the average annual rate, whereas hollow white bars indicate a decrease. For the months of March and June, decreases occur mainly in the lower section of the Sprague River, with increases in September occurring along the same reach and also in upper reaches of the Sycan and North Fork rivers.

Overall, annual groundwater discharge rate is estimated to vary from 17.6 (1983) to 22.9 m^3/s (2001), with an average of 20.5 m^3/s and an average increase of approximately 0.02 m^3/s per year, or about one-thousandth of the average groundwater rate. Hence, the amount of

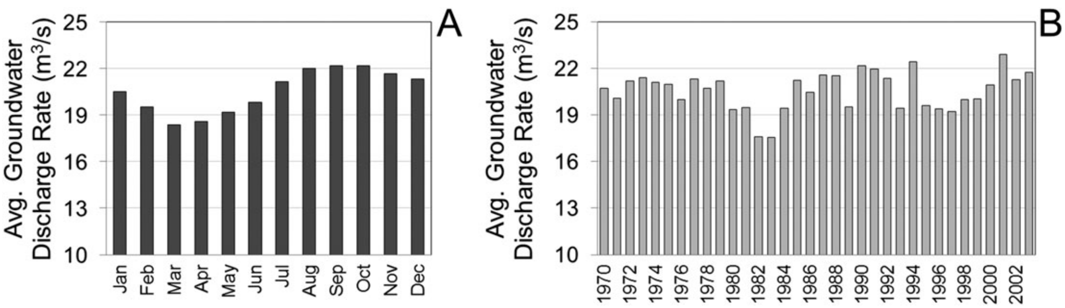

Figure 8. Average groundwater discharge rate (m^3/s) by (A) month and by (B) year for the Sprague River Watershed over the 1970–2003 time period

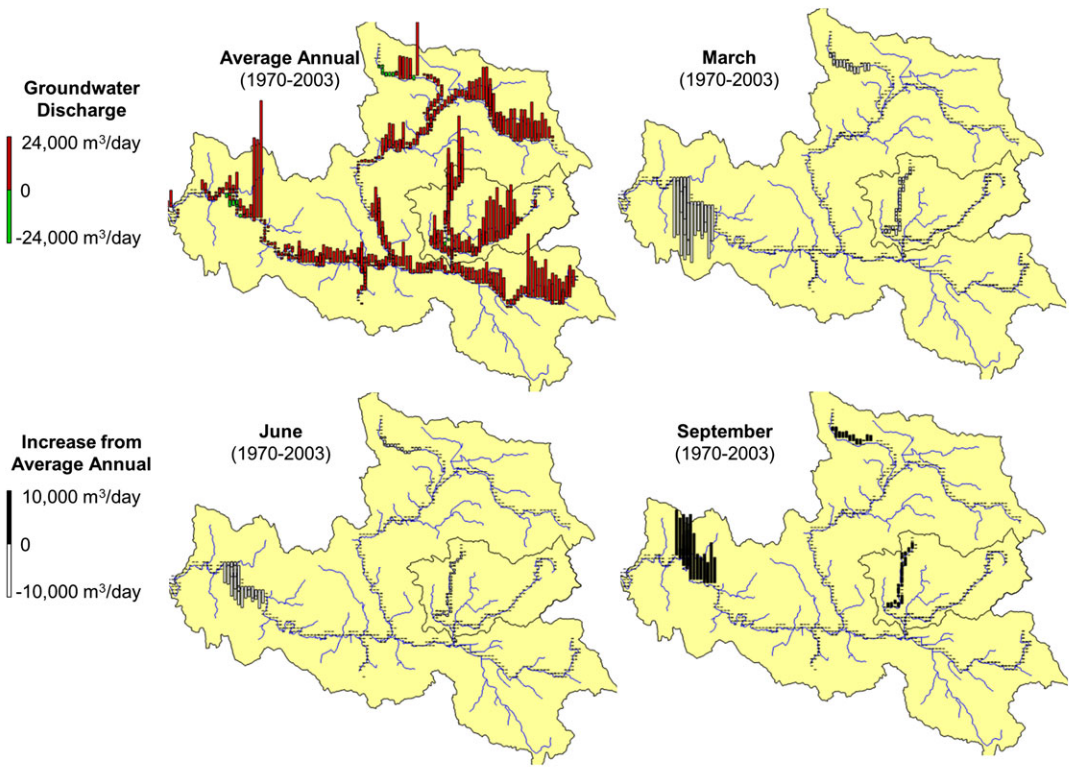

Figure 9. Departure from average annual groundwater discharge rates (m^3/day) for the months of March, June and September over the 1970–2003 time period

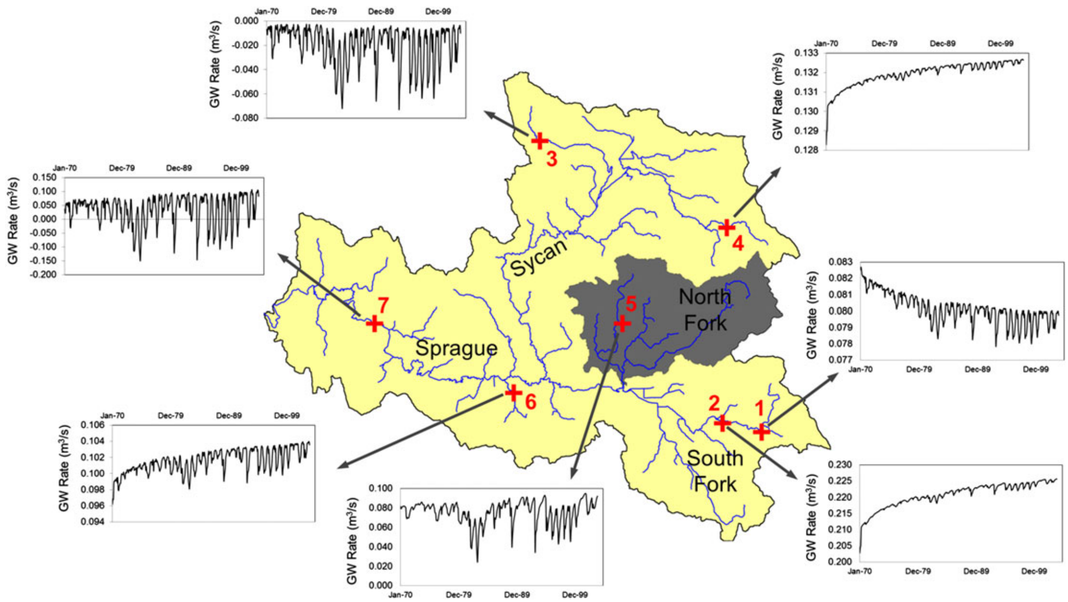

Figure 10. Time series of groundwater discharge rate (m^3/s) for specific locations within the Sprague River watershed, demonstrating the variability in space and time. GW, groundwater

groundwater discharged to the Sprague River stream network, although varying from year to year, is approximately constant over a multi-decadal time period. However, monthly variations of discharge for small-scale reaches along the stream network can be highly dynamic (Figure 10) because of local hydrologic patterns (recharge events, water table and river stage fluctuations). For the 7 locations represented on Figure 10, three (sites 2, 4, 6) have a clear trend in increasing groundwater discharge, with seasonal fluctuations occurring each year. One location (upper South Fork reach, site 1) has a clear decrease in groundwater discharge rate, whereas three other locations (sites 3, 5, 7) have dynamic inter-annual fluctuations but not a clear temporal trend. Overall, 71% of discharge sites have increasing rates during the 1970–2003 time period, 19% have decreasing rates, and 10% of the sites show no change.

Results demonstrate a high spatial variability in discharge rates, which can have a profound impact on water and pollution management in the watershed. Maps of spatially varying groundwater discharge rates can identify potential areas of nutrient loading from the aquifer to the stream network. These areas can be targeted for further field investigation regarding movement of nitrogen and phosphorus in the groundwater-wetland-stream system, with nutrient removal within riparian areas also investigated. These areas could be of particular interest in climate changes studies, to determine how groundwater discharge and associated base-flow are affected by temporal changes in temperature and rainfall, and in turn how these affect aquatic species dependent on in-stream flows. A recent study (Records *et al*., 2014) demonstrated that future climate and land use change scenarios could increase in-stream nutrient and sediment loads, in particular an increase in total phosphorus in the hypothetical event of wetland loss. Results from this study can be used to identify locations of phosphorus loading to the stream network and how loading rates are affected by climate change.

SUMMARY AND CONCLUSIONS

This study investigates the spatio-temporal patterns of groundwater–surface water interaction in the Sprague River watershed (4100 km^2) within the Upper Klamath Basin, Oregon during the 1970–2003 period. A SWAT-MODFLOW model using a newly developed coupled modelling code, tested in the region against streamflow, groundwater level and average groundwater discharge to the stream network for several stream reaches, is used for the assessment. Model output includes spatially varying groundwater discharge (and stream seepage) rates along the stream network, with rates also assessed temporally during the study time period. Average groundwater discharge rate for the entire watershed is 20.5 m^3/s, with minimum rates occurring in March–April and maximum rates occurring in September–October. Local areas can exhibit a high degree of temporal variability from month to month and from year to year. Overall, approximately 70% of the stream network shows increasing groundwater discharge rates over the 34-year period. However, the watershed-wide increase is small, with an average increase of only 0.02 m^3/s per year.

Results enhance understanding regarding the spatial patterns of groundwater influence on streamflow, which can assist in watershed-wide management schemes of groundwater–surface water conjunctive use. Results can also assist with identifying locations of nutrient loading to the stream system, with areas of high groundwater discharge targeted for future field investigations. In regards to the preservation of aquatic species and their sensitivity to in-stream flow, areas of high groundwater discharge rates and associated base-flow can be identified for protection under changing climate patterns.

Documentation and model executable of the SWAT-MODFLOW model can be downloaded from the SWAT model website: http://swat.tamu.edu/software/swat-modflow/. Documentation includes a workshop tutorial, accompanied by an example data set to set up and run a SWAT-MODFLOW model.

ACKNOWLEDGEMENTS

This work was supported by a grant from the Agriculture and Food Research Initiative of the USDA National Institute of Food and Agriculture (NIFA), grant number #2012-67003-19904. This work also was supported by funding from the USDA Natural Resources Conservation Service to the California Cooperative Fish and Wildlife Research Unit, which administered the project. We would also like to thank two anonymous reviewers for comments and suggestions that greatly enhanced the quality of this paper.

REFERENCES

Arnold JG, Allen PM. 1999. Automated methods for estimating base-flow and ground water recharge from streamflow records. *Journal of the American Water Resources Association* **35**(2): 411–424.

Arnold JG, Allen PM, Muttiah R, Bernhardt G. 1995. Automated base flow separation and recession analysis techniques. *Ground Water* **33**(6): 1010-1018.

Arnold JG, Srinivasan R, Muttiah RS, William JR. 1998. Large area hydrologic modeling and assessment part i model development. *JAWRA* **34**(1): 73–89.

Avery C. (1994), Interaction of ground water with the Rock River near Byron, Illinois. U.S. Geological Survey Water-Resources Investigations Report 94-4034.

Bakker M, Anderson EI. 2003. Steady flow to a well near a stream with a leaky bed. *Ground Water* **41**(6): 833–840.

Becker MW, Georgian T, Ambrose H, Sinischalchi J, Fredrick K. 2004. Estimating flow and flux of ground water discharge using water temperature and velocity. *Journal of Hydrology* **296**: 221–233.

Beven K, Lamb R, Quinn P, Romanowicz R, Freer J, Singh VP. 1995. Topmodel. *Computer models of watershed hydrology*. 627–668.

Butts MB, Graham DN. 2008. Evolution of an integrated surface water-groundwater hydrological modelling system. IAHR international groundwater symposium.

Camporese M, Paniconi C, Putti M, Orlandini S. 2010. Surface-subsurface flow modeling with path-based runoff routing, boundary condition-based coupling, and assimilation of multisource observation data. *Water Resources Research* **46**: W02512.

Cey EE, Rudolph DL, Aravena R, Parkin G. 1999. Role of the riparian zone in controlling the distribution and fate of agricultural nitrogen near a small stream in Southern Ontario. *Journal of Contaminant Hydrology* **37**(1–2): 45–67. DOI:10.1016/S0169-7722(98)00162-4

Christenson S, Osborn NI, Neel CR, Faith JR, Blome CD, Puckette J, Pantea MP. 2011. Hydrogeology and Simulation of the Groundwater Flow in the Arbuckle-Simpson Aquifer, South-Central Oklahoma. U.S. Geological Survey Scientific Investigations Report 2011-5029.

Chu TW, Shirmohammadi A. 2004. Evaluation of the SWAT model's hydrology component in the Piedmont physiographic region of Maryland. *Transactions of the ASABE* **47**(4): 1057–1073.

Chung I, Kim N, Lee J, Sophocleous M. 2010. Assessing distributed groundwater recharge rate using integrated surface water-groundwater modelling: application to Mihocheon watershed, South Korea. *Hydrogeology Journal* **18**: 1253–1264.

Conan E, Bouraoui F, Turpin N, de Marsily G, Bidoglio G. 2003. Modeling flow and nitrate fate at catchment scale in Brittany (France). *Journal of Environmental Quality* **32**: 2026–2032.

Conant B Jr. 2004. Delineating and quantifying ground water discharge zones using streambed temperatures. *Ground Water* **42**(2): 243–257.

Devito KJ, Hill AR, Roulet N. 1996. Groundwater-surface water interactions in headwater forested wetlands of the Canadian Shield. *Journal of Hydrology* **181**: 127–147.

Falke JA, Fausch KD, Magelky R, Aldred A, Durnford DS, Riley LK, Oad R. (2011), The role of groundwater pumping and drought in shaping ecological futures for stream fishes in a dryland river basin of the western Great Plains, USA, 697(August 2010), 682–697, doi:10.1002/eco.

Fleckenstein JH, Krause S, Hannah DM, Boano F. 2010. Groundwater-surface water interactions: New methods and models to improve understanding of processes and dynamics. *Advances in Water Resources* **33**: 1291–1295.

Flint LE, Flint AL. (2011), Estimation of Stream Temperature in Support of Fish Production Modeling under Future Climates in the Klamath River Basin. Scientific Investigations Report 2011-5171, U.S. Geological Survey, Reston, VA.

Frei S, Fleckenstein JH, Kollet SJ, Maxwell RM. 2009. Patterns and dynamics of river-aquifer exchange with variably-saturated flow using a fully-coupled model. *Journal of Hydrology* **375**: 383–393.

Fryar AE, Wallin EJ, Brown DL. 2000. Spatial and temporal varaibiltiy in seepage between a contaminated aquifer and tributaries to the Ohio River. *Ground Water Monitoring and Remediation* **20**(3): 129–146.

Galbiati L, Bouraoui F, Elorza FJ, Bidoglio G. 2006. Modeling diffuse pollution loading into a Mediterranean lagoon: development and application of an integrated surface-subsurface model tool. *Ecological Modeling* **193**(1–2): 4–18.

Gannett MW, Lite KE Jr., La Marche JL, Fisher BJ, Polette DJ. 2010. Groundwater hydrology of the Upper Klamath Basin, Oregon and California. U.S. Geological Survey Scientific Investigations Report 2007-5050, Version 1.1.

Gannett MW, Wagner BJ, Lite KE Jr. 2012. Groundwater simulation and management models for the Upper Klamath Basin, Oregon and California. U.S. Geological Survey Scientific Investigations Report 2012-5062.

Gassman PW, Reyes MR, Green CH, Arnold JG. 2007. The soil and water assessment tool: historical development, applications, and future research directions. *Transactions of the ASABE* **50**(4): 1211–1250.

Guggenmos MR, Daughney CJ, Jackson BM, Morgenstern U. 2011. Regional-scale identification of groundwater-surface water interaction using hydrochemistry and multivariate statistical methods, Wairarapa Valley, New Zealand. *Hydrology and Earth System Sciences* **15**: 3383–3398.

Guzman JA, Moriasi DN, Gowda PH, Steiner JL, Starks PJ, Arnold JG, Srinivasan R. 2015. A model integration framework for linking SWAT and MODFLOW. *Environmental Modelling & Software* **73**: 103–116.

Harvey JW, Bencala KE. 1993. The effect of streambed topography on surface-subsurface water exchange in mountain catchments. *Water Resources Research* **29**(1): 89–98.

Hayashi M, Rosenberry DO. 2001. Effects of groundwater exchange on the hydrology and ecology of surface waters. *Japanese Journal of Groundwater Hydrology* **43**: 327–341.

Homer C, Dewitz J, Fry J, Coan M, Hossain N, Larson C, Herold N, McKerrow A, VanDriel JN, Wickham J. 2007. Completion of the 2001

National Land Cover Database for the conterminous United States. *Photogrammetric Engineering and Remote Sensing* **73**: 337–341.

Hussein M, Schwartz FW. 2003. Modeling of flow and contaminant transport in coupled stream-aquifer systems. *Journal of Contaminant Hydrology* **65**(1-2): 41–64. DOI:10.1016/S0169-7722(02)00229-2

Jolly ID, McEwan KL, Holland KL. 2008. A review of groundwater-surface water interactions in arid/semi-arid wetlands and the consequences of salinity for wetland ecology. *Ecohydrology* **1**: 43–58.

Kalbus E, Schmidt C, Molson JW, Reinstorf F, Schirmer M. 2009. Influence of aquifer and streambed heterogeneity on the distribution of groundwater discharge. *Hydrology and Earth System Sciences* **13**(1): 69–77. DOI:10.5194/hess-13-69-2009

Keery J, Binley A, Crook N, Smith JWN. 2007. Temporal and spatial variability of groundwater-surface water fluxes: development and application of an analytical method using temperature time series. *Journal of Hydrology* **336**: 1–16.

Kim NW, Chung IM, Won YS, Arnold JG. 2008. Development and application of the integrated SWAT-MODFLOW model. *Journal of Hydrology* **356**: 1–16.

Kollet SJ, Maxwell RM. 2006. Integrated surface-groundwater flow modeling: a free-surface overland flow boundary condition in a parallel groundwater flow model. *Advances in Water Resources* **29**: 945–985.

Krause S, Bronstert A, Zehe E. 2007. Groundwater-surface water interactions in a North German lowland floodplain – Implications for the river discharge dynamics and riparian water balance. *Journal Hydrology* **347**: 404–417.

Lamontagne S, Leaney FW, Herczeg AL. 2005. Groundwater-surface water interactions in a large semi-arid floodplain: implications for salinity management. *Hydrological Processes* **19**: 3063–3080.

Leavesley GH, Lichty RW, Troutman BM, Saindon LG. 1983. Precipitation-runoff modeling system - User's manual: U.S. Geological Survey Water-Resources Investigations Report 83–4238, 48 p.

Loague K, Heppner CS, Ebel BA, VanderKwaak JE. 2010. The quixotic search for a comprehensive understanding of hydrologic response at the surface: Horton, Dunne, Dunton, and the role of concept-development simulation. *Hydrological Processes* **24**: 2499–2505.

Ludwig JA, Wilcox BP, Breshears DD, Tongway DJ, Imeson AC. 2005. Vegetation patches and runoff-erosion as interacting ecohydrological processes in semiarid landscapes. *Ecology* **86**: 288–297.

Luo Y, Sophocleous M. 2011. Two-way coupling of unsaturated-saturated flow by integrating the SWAT and MODFLOW models with application in an irrigation district in arid region of West China. *Journal of Arid Land* **3**(3): 164–173.

Markstrom SL, Niswonger RG, Regan RS, Prudic DE, Barlow PM. 2008. GSFLOW-Coupled Ground-Water and Surface-Water Flow Model Based on the Integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005). U.S. Geological Survey Techniques and Methods 6-D1: 240p.

Mashburn SL, Ryter DW, Neel CR, Smith SJ, Magers JS. 2013. Hydrogeology and Simulation of Groundwater Flow in the Central Oklahoma (Garber-Wellington) Aquifer, Oklahoma, 10987 to 2009, and Simulation of Available Water in Storage, 2010-2059. U.S. Geological Survey Scientific Investigations Report 2013-5219.

Mayer TD, Naman SW. 2011. Streamflow response to climate as influenced by geology and elevation. *Journal of the American Water Resources Association* **47**(4): 724–738.

Moriasi DN, Arnold JG, Liew MWV, Bingner RL, Harmel RD, Veith TL. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE* **50**(3): 885–900.

Morway ED, Gates TK, Niswonger RG. 2013. Appraising options to enhance shallow groundwater table and flow conditions over regional scales in an irrigated alluvial aquifer system. *Journal Hydrology* **495**: 216–237.

Neitsch SL, Arnold JG, Kiniry JR, Williams JR. 2011. Soil and Water Assessment Tool Theoretical Documentation, Version 2009. Temple, Tex.: Texas Water Resources Institute Technical Report No. 406.

Niswonger RG, Prudic DE, Regan RS. 2006. Documentation of the unsaturated-zone flow (UZF1) package for modeling unsaturated flow between the land surface and the water table with MODFLOW-2005, USGS Techniques and Methods 6-A19.

Niswonger RG, Panday S, Ibaraki M. 2011. MODFLOW-NWT, A Newton formulation for MODFLOW-2005: USGS Survey Techniques and Methods 6–A37.

Nyquist JE, Freyer PA, Toran L. 2008. Stream bottom resistivity tomography to map ground water discharge. *Ground Water* **46**(4): 561–569.

Panday S, Huyakorn PS. 2004. A fully-coupled spatially distributed model for evaluating surface/subsurface flow. *Advances in Water Resources* **27**: 361–382.

Paschke SS. 2011. Groundwater Availability of the Denver Basin Aquifer System, Colorado. U.S. Geological Survey Professional Paper 1770.

Perkins SP, Sophocleous M. 1999. Development of a comprehensive watershed model applied to study stream yield under drought conditions. *Ground Water* **37**(3): 418–426.

Peterson JR, Hamlet JM. 1998. Hydrologic calibration of the SWAT model in a watershed containing fragipan soils. *JAWRA* **34**(3): 531–544.

Prudic DE, Konikow LF, Banta ER. 2004. A new stream-flow routing (SFR1) package to simulate stream-aquifer interaction with MODFLOW-2000: U.S.. Geological Survey Open-File Report 2004-1042, 95 p.

Rabe A, Calonje C. 2009. *Lower Sprague-Lower Williamson watershed assessment*. Prepared for Klamath Watershed Partnership: Klamath Falls, Oregon, USA.

Records RM, Arabi M, Fassnacht SR, Duffy WG, Ahmadi M, Hegewisch KC. 2014. Climate change and wetland loss impacts on a western river's water quality. *Hydrology and Earth System Sciences* **18**: 4509–4527.

Rumman MA, Payne DF. 2003. Model Framework and Preliminary Results of the Regional MODFLOW Ground-Water Flow Model of Costal Georgia, South Carolina, and Florida. 2003. Proceedings of the 2003 Georgia Water Resources Conference held April 23-24, 2003, at the University of Georgia.

Silliman SE, Booth DF. 1993. Analysis of time-series measurements of sediment temperature for identification of gaining vs. losing portions of Juday Creek, Indiana. *Journal Hydrology* **146**: 131–148.

Sophocleous M. 2002. Interactions between groundwater and surface water: the state of the science. *Hydrogeology Journal* **10**: 52–67.

Sophocleous M, Perkins SP. 2000. Methodology and application of combined watershed and ground-water models in Kansas. *Journal of Hydrology* **236**(3–4): 185–201.

Spalding CP, Khaleel R. 1991. An evaluation of analytical solutions to estimate drawdown and stream depletion by wells. *Water Resources Research* **27**(4): 597–609.

Spruill CA, Workman SR, Taraba JL. 2000. Simulation of daily and monthly stream discharge from small watersheds using the SWAT model. *Transactions of ASAE* **43**(6): 1431–1439.

Srivastava P, McNair JN, Johnson TE. 2006. Comparison of process-based and artificial neural network approaches for streamflow modeling in an agricultural watershed. *JAWRA* **42**(2): 545–563.

Thorsteinson L, VanderKooi S, Duffy W. 2011. Proceedings of the Klamath Basin Science Conference, Medford, Oregon, February 1–5, 2010, 312 p, U.S. Geological Survey, Reston, VA.

Tian Y, Zheng Y, Wu B, Wu X, Liu J, Zheng C. 2015. Modeling surface water-groundwater interaction in arid and semi-arid regions with intensive agriculture. *Environmental Modeling and Software* **63**: 170–184.

Tolson BA, Shoemaker CA. 2007. Dynamically dimensioned search algorithm for computationally efficient watershed model calibration. *Water Resources Research* **43**: W01413. DOI:10.1029/2005WR004723

US Geological Survey. 2009. 1-Arc Second National Elevation Dataset SDE raster digital data, available at: http://seamless.usgs.gov (last access: 20 May 2010).

Van der Kamp G, Hayashi M. 2009. Groundwater-wetland ecosystem interaction in the semiarid glaciated plains of North America. *Hydrogeology Journal* **17**: 203–214.

VanderKwaak, JE, 1999. Numerical Simulation of Flow and Chemical Transport in Integrated Surface-Subsurface Hydrologic Systems. PhD Dissertation, University of Waterloo, Waterloo, Ontario, Canada.

Waibel MS, Gannet MW, Chang H, Hulbe CL. 2013. Spatial variability of the response to climate change in regional groundwater systems – Examples from simulations in the Deschutes Basin, Oregon. *Journal of Hydrology* **486**: 187–201.