

Using a Coupled Groundwater/Surface-Water Model to Predict Climate-Change Impacts to Lakes in the Trout Lake Watershed, Northern Wisconsin

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Abstract

A major focus of the U.S. Geological Survey's Trout Lake Water, Energy, and Biogeochemical Budgets (WEBB) project is the development of a watershed model to allow predictions of hydrologic response to future conditions including land-use and climate change. The coupled groundwater/surface-water model GSFLOW was chosen for this purpose because it could easily incorporate an existing groundwater flow model and it provides for simulation of surface-water processes.

The Trout Lake watershed in northern Wisconsin is underlain by a highly conductive outwash sand aquifer. In this area, streamflow is dominated by groundwater contributions; however, surface runoff occurs during intense rainfall periods and spring snowmelt. Surface runoff also occurs locally near stream/lake areas where the unsaturated zone is thin. A diverse data set, collected from 1992 to 2007 for the Trout Lake WEBB project and the co-located and NSF-funded North Temperate Lakes LTER project, includes snowpack, solar radiation, potential evapotranspiration, lake levels, groundwater levels, and streamflow. The time-series processing software TSPROC (Doherty 2003) was used to distill the large time series data set to a smaller set of observations and summary statistics that captured the salient hydrologic information. The time-series processing reduced hundreds of thousands of observations to less than 5,000. Model calibration included specific predictions for several lakes in the study area using the PEST parameter estimation suite of software (Doherty 2007). The calibrated model was used to simulate the hydrologic response in the study

lakes to a variety of climate change scenarios culled from the IPCC Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Solomon et al. 2007). Results from the simulations indicate climate change could result in substantial changes to the lake levels and components of the hydrologic budget of a seepage lake in the flow system. For a drainage lake lower in the flow system, the impacts of climate change are diminished.

Introduction

Although groundwater and surface water are generally considered a single resource, simulations involving this single resource commonly do not explicitly couple the two systems. Moreover, models used to evaluate the effects of climate variability often approximate one of the two systems, even though interaction with the other might be important. A more holistic view is to include both the groundwater and surface-water systems. Groundwater and surface-water models can be loosely linked outside of the models (e.g., Hunt and Steuer 2000, Steuer and Hunt 2001), but often only time-averaged/long-term simulations are tractable, which may not include enough interannual characteristics and related system dynamics to be optimal. Coupled hydrologic models, on the other hand, can include various hydrologic feedback pathways and thus more fully encompass the processes and related dynamics that may augment or mitigate the effect of hydrologic stress. These processes include the timing and rates of evapotranspiration, surface runoff, soil-zone flow, and interactions between the surface-water and groundwater systems.

Coupled models can use a fully integrated approach but, because this type of coupling is based on a three-dimensional Richards' equation, they require a much finer spatial grid and smaller time steps than typically are used to simulate saturated hydrologic flows (Markstrom et al. 2008). The high computational requirements limit their applicability for simulating watershed scale flow over societally relevant time periods (years to tens of years). An efficient alternative to a fully integrated coupled model is to simulate unsaturated flow assuming that dominant direction of flow within the unsaturated zone is vertical when averaged over the grid scale typical of a watershed model (Niswonger et al. 2006). Using this type of approximation, equations can be formulated to simulate flow and storage in the various regions/compartments (i.e., soil, unsaturated, and saturated zones) with the goal of attaining some compromise between model efficiency and model accuracy. This "coupled regions" approach was implemented in the recently released code GSFLOW (Groundwater/Surface-water FLOW) model (Markstrom et al. 2008). GSFLOW is an

integration of the USGS Precipitation-Runoff Modeling System (PRMS; Leavesley et al. 1983, Leavesley et al. 2005) with the 2005 version of the USGS Modular Groundwater Flow Model (MODFLOW-2005; Harbaugh 2005).

In GSFLOW, separate equations are coupled to simulate horizontal and vertical flow through the soil zone, gravity-driven vertical flow through the unsaturated zone, and three-dimensional groundwater flow through the saturated zone. GSFLOW was designed to simulate the most important processes using a numerically efficient algorithm, thus allowing coupled simultaneous simulation of flow in and across one or more watersheds. GSFLOW incorporates physically based methods for simulating runoff and infiltration from snow and rain precipitation, as well as groundwater/surface-water interaction. It is intended to be used on watershed-scale problems that can range from a few square kilometers to several thousand square kilometers, and for time periods that range from months to several decades (Markstrom et al. 2008). In

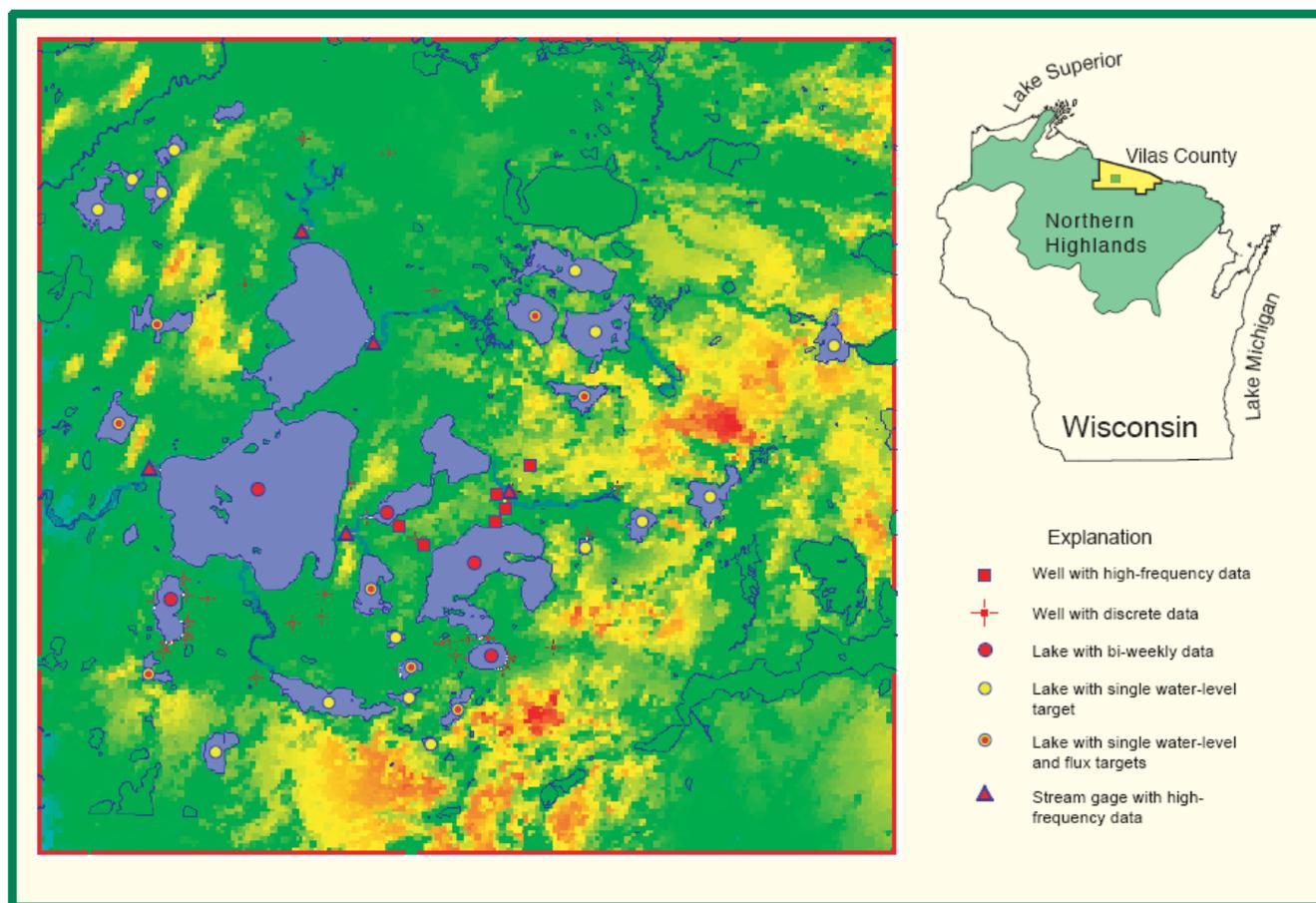


Figure 1. Top elevation, location, and extent of MODFLOW grid with location of calibration data. Warm colors represent higher elevation.

this work, GSFLOW was used to simulate the Trout Lake watershed in northern Wisconsin. The study area is one the densest lake districts in the world with extensive groundwater/surface-water interaction. The focus here is on elements of the model construction and calibration that are general to this type of modeling, and thus transferable to GSFLOW models constructed elsewhere. In addition, the model was run using several climate change scenarios. These are used to highlight the abilities of the coupled approach when applied to a question that has become of more import to decisionmakers.

Site Description and Model Construction

The Trout Lake basin is located in the Northern Highlands district in north central Wisconsin, in an area with many lakes (Figure 1). The aquifer consists of 40–60 m of unconsolidated Pleistocene glacial sediments mostly consisting of glacial outwash sands and gravel. The Trout Lake basin (which includes Trout Lake and all four of the basins that flow into the lake) has been

the focus of previous regional modeling studies including a two-dimensional analytic element screening model and three-dimensional, finite-difference models. See Walker and Bullen (2000) for additional descriptions of the setting and Pint (2002) and Hunt et al. (2005) for more description of previous modeling efforts.

Constructing the GSFLOW model

Many watershed models include only the watershed of interest defined by surface topography; although this assumption may be acceptable in montane settings, most watersheds are not in montane settings but may be in areas where the ground-watershed and surface-watershed do not align (e.g., Hunt et al. 1998). Therefore, the watershed of interest to be simulated in a coupled model is really both the surface-watershed and ground-watershed. The ground-watershed, however, is not well known in most cases; thus, a larger model is commonly used to define physically based perimeter boundaries for a smaller inset model (e.g., Hunt et al.



Figure 2. PRMS hydrologic response units located on the MODFLOW model domain.

1998); the edges of the inset model are usually sufficiently distant that the area of interest is shielded from artifacts from the coarse regional representation of the flow system. Inset approaches result in a domain for the coupled model that is a rectangular grid typical of a MODFLOW model rather than the irregular shape typical of a surface-water model. The rectangular grid includes the entire groundwater and surface watershed for the watershed of interest, as well as areas not included in either (Figures 1 and 2). This larger extent is not problematic as GSFLOW is designed to simulate one or more adjacent watersheds; however, this can confound simple representations of output as GSFLOW currently reports a total mass balance for the entire model domain. Thus, additional post-processing may be required to fully distribute the total model flows between the watershed of interest and the remainder of the simulated area.

Calibration strategy

In many ways the groundwater system can be thought of as a “low pass filter” that removes much of the short-term transient dynamics and leaves the resilient long-term system dynamics. New model construction considerations and potential problem areas arise when the surface-water system is coupled to the groundwater system. Issues with surface-water model calibration are well documented; one such issue is that only a handful of the many parameters that may be employed by a surface-water (or coupled) model are actually estimable on the basis of most calibration datasets (e.g., Beven and Freer 2001; Doherty and Hunt, in press). This suggests that, although more processes can be included in the code, our ability to constrain the parameters needed to employ the additional functionality may not be commensurate. Fully coupled models also require longer run times than either MODFLOW or PRMS models running alone, which can limit the exploration of the parameter solution space (Hill 2006). Thus, a “dual” calibration approach was employed in the Trout Lake modeling whereby the groundwater and surface-water models were calibrated separately using the “MODFLOW-only” and “PRMS-only” options in GSFLOW. The ground-water model was calibrated by polishing results from an earlier calibration (Muffels 2008). The surface-water model was calibrated using the step-wise procedure outlined by Hay et al. (2006). These independently calibrated models were then combined in a subsequent fully coupled GSFLOW run. The idea was to efficiently get both the groundwater and surface-water model

parameters “in the ballpark.” Ongoing work is focusing on approaches for calibrating fully coupled models with derivative methods, as well as assessing different nonderivative calibration strategies for fully coupled GSFLOW models.

Time-series processing

In addition to issues of parameter insensitivity and correlation of observation data for constraining a coupled model, there are also concerns with measurement noise and redundant information as surface-water data sets commonly include many more observations than groundwater data sets—especially with respect to the temporal density of the observations. Because of these issues, we employed a time-series processing approach to reduce the time-series observations into characteristic aspects of the system. The simulated GSFLOW output was then processed in the same way as the raw observations and compared in the parameter estimation process. The processing was performed using the Time-Series Processor (TSPROC; Doherty 2003). TSPROC was modified to read native GSFLOW output generated by both the MODFLOW (e.g., GAGE Package) and PRMS (STATVAR file) portions of the model. TSPROC was used to create the parameter estimation control file for PEST (Doherty 2007), where it automatically translated the observation information to the parameter estimation process and created the necessary files to extract the simulated equivalents from the model output.

Preliminary calibration results

The parameters from the PRMS-only and MODFLOW-only calibrations were used with the fully-coupled GSFLOW model and provided a reasonable fit for lake levels and streamflows. In some cases the general pattern of the system response was simulated well, but there was an offset between the modeled and observed data. To remove the effects of these biases, time-series results for climate change scenarios are presented as a relative difference between the simulated series for current conditions and the simulated series for a given climate change scenario. The coupled model was able to simulate important characteristics of the system not typically explicitly considered by groundwater (MODFLOW) models, such as snowpack depth, lake evaporation, and streamflow duration. The ability to explicitly simulate these important but indirect drivers of the groundwater system using physically based

algorithms is expected to be critical for realistic simulations of the hydrologic system to potential climate change.

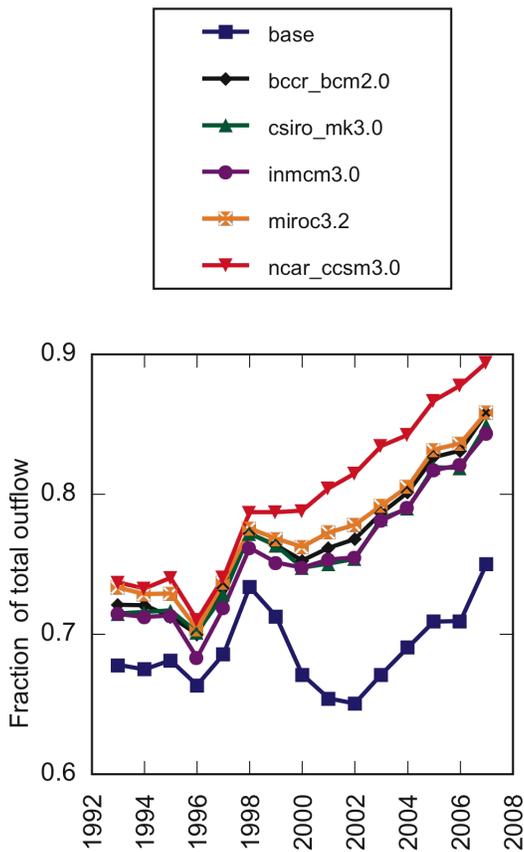


Figure 3. Comparison of annual evaporation from Crystal Lake across the 5 climate models. The base scenario is for the 1993–2007 period.

Climate Change Scenarios

Several climate models and one emission scenario were selected from the Intergovernmental Panel on Climate Change (Solomon et al. 2007) to illustrate the potential effects of climate change on the lake systems. The A2 emissions scenario (A2) was chosen, along with five climate models (bcr_bcm2.0–Bjerknes Centre for Climate Research, Norway; csiro_mk3.0–Commonwealth Scientific and Industrial Research Organization Atmospheric research, Australia; inmcm3.0–Institute for Numerical Mathematics, Russia; miroc3.2–Center for Climate System Research, Japan, medium resolution model; and ncar_ccsm3.0–National Center for Atmospheric Research, United States). There was a fair amount of variability in the results across the climate models; Figure 3 reports

results for annual evaporation from Crystal Lake from the various simulations.

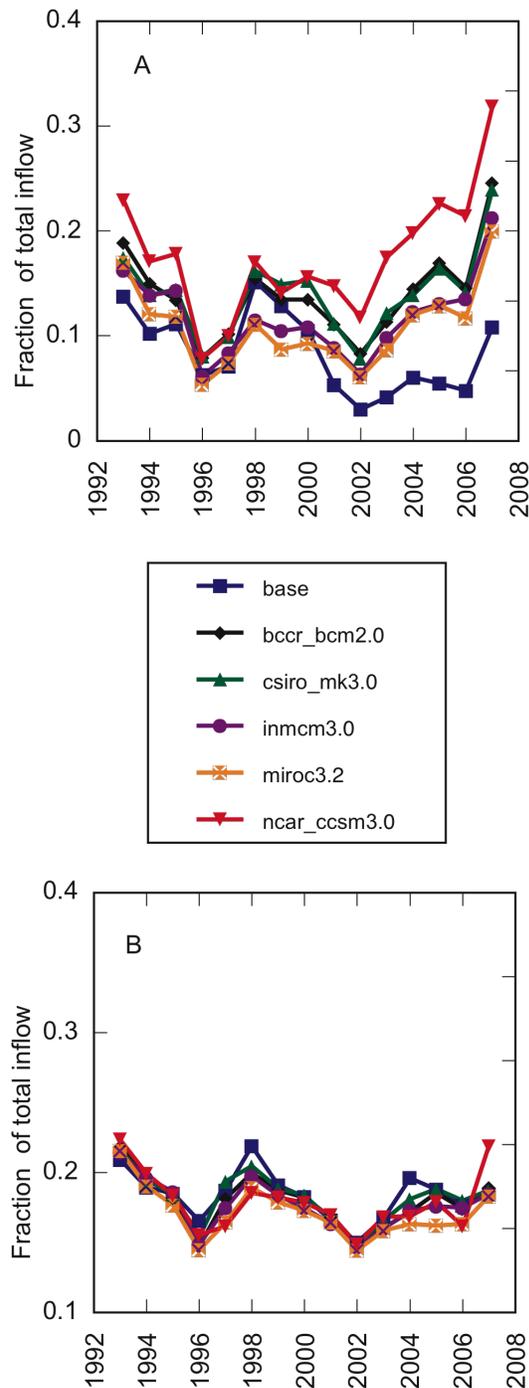


Figure 4. Simulated annual groundwater inflow to Crystal Lake (A) and Allequash Lake (B) for the five climate models. The base scenario is for the 1993–2007 period.

Values for the fraction of groundwater inflow to two lakes in the study area are depicted in Figure 4. Crystal Lake is a seepage lake located near the upper portion of the flow system, and Allequash Lake is a drainage Lake further down in the flow system. Note that the differences between current conditions and projected climate change conditions are more pronounced in the seepage lake than in the drainage lake. In fact, there appears to be little impact of climate change on groundwater inflow to the drainage lake, likely because its hydrologic budget is dominated by streamflow. An example of the potential changes to lake levels in Crystal Lake is depicted in Figure 5. The bulk of the models predict a substantial decrease in lake levels compared to current conditions (2–2.5 meter drop), and one model predicts decreases in excess of 3.5 meters. Note that even after 12 years of model simulation the predicted lake levels have not approached steady-state conditions.

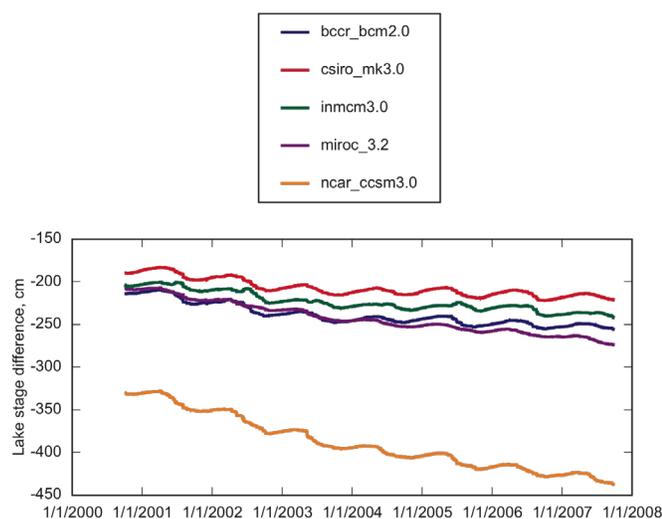


Figure 5. Simulated differences in lake stage between current conditions and simulated conditions from the five climate models.

Discussion and Conclusions

The results for potential lake-level changes as a result of climate change are dramatic and have obvious implications for the individual lakes. The results for groundwater inflow into the seepage lake are more subtle; however, for a soft-water lake such as Crystal, a potential threefold increase in groundwater inflow could have significant impact on the chemistry of the lake. In this paper, GSFLOW provided a simple and transparent way to simulate the effects of climate

change on the coupled hydrologic system. In addition, the ability to use physically based algorithms to extrapolate the system's processes as they move beyond the range of historic conditions is often lacking in other nondeterministic modeling approaches. Finally, its MODFLOW roots provides GSFLOW with a powerful foundation for simulating the groundwater portion of coupled systems, which is critical for realistic simulations of groundwater dependent ecosystems. The results presented here demonstrate the potential utility of GSFLOW modeling for today's resource management decisions.

Acknowledgments

This work was supported by the U.S. Geological Survey's Office of Ground Water and Trout Lake Water, Energy, and Biogeochemical Budgets (WEBB) program, in cooperation with the National Science Foundation's North Temperate Lakes Long-Term Ecological Research program (DEB-9632853). R. Steve Regan, Steve Westenbroek, Dave Prudic, Rich Niswonger, and Roland Viger are thanked for their extensive help during model construction and calibration. Tim Kratz and Mike Fienen are thanked for their thoughtful reviews of the manuscript.

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