Integrated Hydrologic Modeling of Lake Tahoe and Martis Valley Mountain Block and Alluvial Systems, Nevada and California

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ABSTRACT

The U.S. Department of Interior has identified the Truckee River basin as highly likely for potential water supply conflict in the future. A critical water supply to the Truckee River is outflow from Lake Tahoe, and surface and groundwater contributions from the Martis Valley hydrographic area. This paper highlights the development of an integrated surface water and groundwater model, GSFLOW, in the Lake Tahoe and Martis Valley hydrographic areas to ultimately assess the effects of changing climate on surface and groundwater resources, and to identify the hydrologic mechanisms responsible for observed and simulated effects. Maintaining a balance between accurate representation of spatial features (e.g., geology, streams, and topography) and computational efficiency is a key objective for developing a realistic and computationally efficient model that can adequately simulate important hydrologic processes, including groundwater, stream, lake, and wetland flows and storages. Computational efficiency is required in order to calibrate to a diverse set of observation data, including surface water flows, lake levels, and groundwater head observations. Our work highlights how maintaining continuity between mountain block, stream zones, and basin fill units through data driven and conceptual layering is efficient, and results in accurate calibration to both surface water and groundwater observations. Additionally, we treat spring and wetland areas as groundwater head observations equal to land surface elevation, which provides constraints on groundwater heads over a much broader part of the model domain relative to well head observations alone.

INTRODUCTION

The U.S. Department of Interior (DOI) is currently initiating a historical and future water supply and demands investigation in the Truckee River basin as part of the WaterSMART (Sustain and Manage America's Resource for Tomorrow) program. Snowmelt runoff from the Sierra Nevada is a multibillion dollar resource that is critical to the region's economy, forest health, aquatic ecosystems, and agriculture. Snow melt runoff and storage water from Lake Tahoe and Martis Valley hydrographic areas is the primary water supply to the Truckee River, Reno, NV, and surrounding agricultural areas. Significant shifts in the timing of snowmelt and streamflow, and reductions in summer streamflow have recently been observed in the Lake Tahoe basin and larger Sierra Nevada region (Coats, 2010; Kim and Jain, 2010). Groundwater in the Martis Valley watershed has recently been identified as vulnerable to changing climate (Singleton and Moran, 2010).

Groundwater will be pivotal for future water supplies and the health of groundwater dependent ecosystems (GDEs), yet our understanding of climate change impacts on surface water and groundwater (SW/GW) supply and exchange is very limited. The majority of water in the Truckee River basin emanates from high-altitude mountain catchments, thus a better understanding of how climate change affects hydrology in mountain catchments is essential for long-term water and biological resources planning in the region. Hydrologic modeling capabilities of mountain catchments are not very well developed. Most climate change hydrologic modeling studies of mountain catchments have relied on simple bucket and linear reservoir representation of groundwater, while either ignoring or over simplifying the effects of the unsaturated zone. These models calculate recharge independently of dynamic groundwater levels and SW/GW interactions. Furthermore, the important interplay between snowmelt-derived streamflow and SW/GW interactions are not simulated in a coupled manner, which is essential for evaluating climate-change impacts on summertime flow (baseflow) and GDEs in snow-dominated regions (Huntington and Niswonger, 2012).

Recent developments of integrated hydrologic models provide a means of simulating coupled hydrologic processes in mountain catchments. Integrated hydrologic models can provide greater insight into climate change effects on watershed hydrologic processes due to their ability to more realistically simulate feedback between hydrologic processes that occur above and below land surface (Maxwell and Kollet, 2008; Ferguson and Maxwell, 2010; Sulis et al., 2011; Huntington and Niswonger, 2012). In this paper, we present an application of the integrated hydrologic model, GSFLOW (Markstrom et al., 2008) to simulate climate change effects on the hydrology in all the mountain catchments tributary to Lake Tahoe, and Martis Valley hydrographic areas. The regional scale and hydrologic complexity of these catchments pose difficult challenges for hydrologic modeling; however, we have constructed useful models through innovative methods and automated calibration procedures. Century-long simulations of surface water and ground water flow provide unique insights into the feedbacks between climate and hydrologic fluxes that drain from the Sierra-Nevada to the Truckee River. For this paper, we focus on conceptual model development and calibration of GSFLOW and present some preliminary results that demonstrate the unique hydrologic conditions of these mountain catchments.

CONCEPTUAL AND NUMERICAL MODEL DEVELOPMENT

Maintaining a balance between adequate horizontal and vertical grid discretization, while honoring known stream, wetland, and lake locations and elevations (i.e., heads), is particularly difficult in mountain catchments due to complex topography and geology. Generally, the geology in the Sierra Nevada is characterized by low-permeable mountain block overlain by thin, high-permeable alluvium and glacial deposits near stream channels that gradually thicken in the down-valley direction. We developed grid-block representations of the alluvium and mountain block subsurface geology using deductive reasoning and a combination of data-driven automated and manual interpolation to observed lithologies, cross sectional and surficial geologic maps, and geophysical surveys, while explicitly considering known stream and wetland locations. Key to the development of the model grid is the conditioning of the model grid-scale digital elevation model to ensure proper location of streams and wetlands, and their sub-grid scale geometries. This conceptual model, which merges data-driven hydrostratigraphic interpolation with conceptual understanding of the surface water and groundwater systems, is useful for constructing integrated models in data limited mountain block regions.

Lake Tahoe and Martis Valley basins are largely representative of typical topography, geology, climate, and hydrology of the greater Sierra Nevada region. Important characteristics that are shared among the upland watersheds of the region are the large topographic relief, high precipitation gradients with significant winter snowfall, and relatively impermeable shallow bedrock that accentuates the dominance of shallow groundwater-flow paths in the regional system. Because the alluvial aquifers are typically small and have limited storage, they are likely to be more sensitive to climate fluctuations as compared to thick valley aquifers. Mean annual precipitation over the model domains ranges from 380 to 1,650 mm, with 90 percent of the precipitation occurring between November and March. Monthly average extreme temperatures range from 30^{o}C in August to -10^{o}C in January. Vegetation consists of subalpine and conifer forest, with some deciduous riparian and meadows association. Mountain block geology is primarily composed of granitic and volcanic rocks, overlain with glacial moraines and stream deposits in low-elevation areas that primarily make up the alluvial aquifers, while soils are generally shallow and derived from parent rock consisting of mostly sand and silts. Gridded datasets of elevation, geology, vegetation, soils, and land use were used to discretize and parameterize GSFLOW. Precipitation and temperature was distributed spatially across model domains (1,900–3,000 m above Mean Sea Level, AMSL) using the Parameter-elevation Regression on Independent Slopes Model (PRISM) monthly precipitation spatial distributions (Daly et al., 1994), and daily temperature and precipitation recorded at the Mt. Rose, Squaw Valley, Tahoe City Cross, and Truckee #2 SNOTEL stations, and Tahoe City cooperative-observer weather station.

Spatial hydrogeologic and stratigraphic data, primarily reported by Brown and Caldwell (2012) and Plume et al. (2009), were used to develop the conceptual hydrogeologic framework model (HFM) and vertical

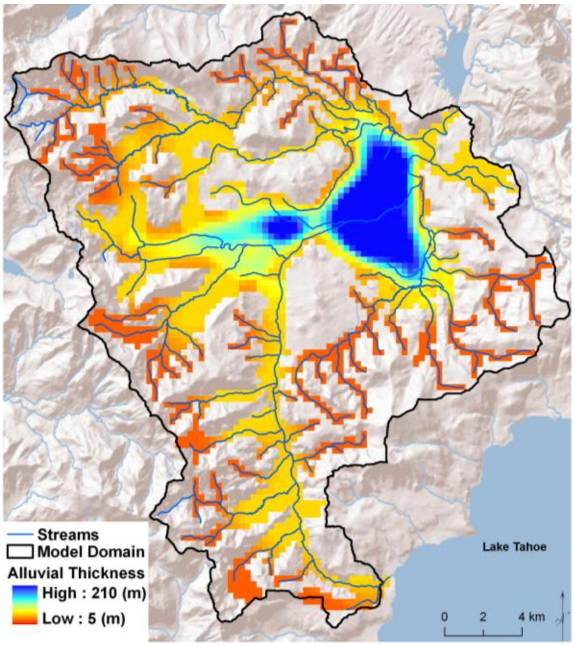


Figure 1. Total alluvial thickness (layers 2 plus 3) for Lake Tahoe and Martis Valley models. Mountain block layers were assigned zero alluvial thickness shown as no data.

and horizontal model discretization for both study areas. Well logs and geophysical data were used to develop the HFM and define the layer thicknesses that represent alluvium, and these data were interpolated and mapped to the model grid using the geologic modeling software, Leapfrog. HFM results from Leapfrog were modified in GIS to simulate thin alluvial stream deposits along streams in the mountain block, as well as simulating gradual transitions of alluvial layer thicknesses from the mountain front to the valley floor while maintaining layer continuity (Figure 1). Model cells were set to a 300×300 m spatial resolution over the 1,310 km^2 and 500 km^2 model domains for Lake Tahoe and Martis Valley, respectively. The HFM was discretized vertically into five layers, and horizontally into approximately 15,000 and 5,600 active grid cells per layer, for a total of 73,100 and 28,000 active cells for Lake Tahoe and Martis Valley, respectively. The HFM was divided into four basic geologic units, including top soil, alluvium, weathered bedrock, and less-weathered bedrock. Layer 1 (soil), 2 and 3 (alluvium), and 4 and 5 (mountain block) ranged in thickness from 0-4m, 0-210m, and 60-120m, respectively. Based on the steep topography near the watershed divides, no-flow boundary conditions were assigned along the edges of the model domain that coincide with watershed divides.

MODEL CALIBRATION AND RESULTS

GSFLOW is typically calibrated using a 3-step process, where PRMS is calibrated independent of MODFLOW-NWT, and MODFLOW-NWT is calibrated for a steady state stress period, and lastly, PRMS and MODFLOW-NWT are calibrated jointly for transient daily stress periods in GSFLOW. In this work, we calibrated PRMS for a 29-year period by matching observed streamflows. PRMS was calibrated in a stepwise automated framework utilizing the Differential Evolution Adaptive Metropolis (DREAM) algorithm (Vrugt et al., 2008), where solar radiation, precipitation, evapotranspiration, and parameters controlling the shape of the hydrograph are calibrated independently, in that order. Goodness of fit between the simulated and observed streamflow was assessed using the Nash-Sutcliffe statistic (N-S = 0.75) at the monthly timestep (Figure 3).

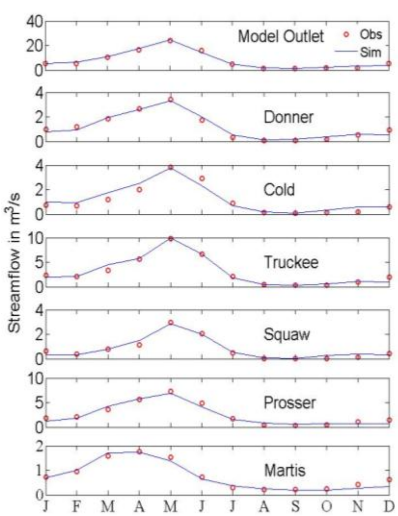


Figure 2. Observed and simulated mean monthly streamflow for Martis Valley basin outlet and subwatersheds.

For the second step, MODFLOW-NWT (Niswonger et al., 2011) was calibrated independent of PRMS using a steady-state stress period, including representation of stream flow (SFR2), Lakes (LAK7), and unsaturated-zone flow (UZF1). Mean annual PRISM precipitation was scaled to represent the mean annual streamflow (i.e., sum of recharge, interflow, and overland runoff), and utilized as net infiltration for UZF1 and MODFLOW-NWT. Calibration of UZF1 and MODFLOW-NWT was performed by adjusting the precipitation scaling factor and layer specific homogeneous aquifer hydraulic conductivity values until there was a good correspondence between the simulated steady-state flows in streams, lake levels and lake outflows, groundwater heads, and the locations of major discharge and wetland areas. Wetland areas were also used to calibrate the model by comparing surface elevations to simulated head. Goodness of fit between

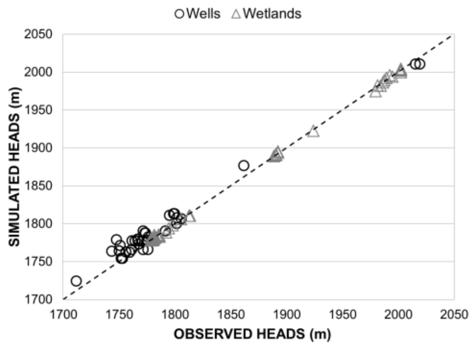


Figure 3. Observed and simulated steady state heads at wells and wetland areas for Martis Valley.

observed and simulated heads was assessed using the RMSE (Figure 3). Results of the calibration generally show excellent agreement between simulated and observed heads for Martis Valley, where the RMSE is 8.6m, and normalized RMSE, NRMSE (RMSE/total head loss), is 2.8%. A small NRMSE indicates that model errors are only a small part of the overall model response (Anderson and Woessner, 1992). The calibrated spatial distribution of depth to water (DTW) is very intuitive, where there is shallow DTW near streams, valleys, and meadows, with DTW increasing in mountain block and high elevation areas (Figure 4). Groundwater heads are shown for layer 4 and are above land surface in some valley floor mountain transition zones, while heads in layer 2 in these areas are only slightly above land surface and discharging as groundwater ET and stream seepage. Preliminary steady state simulations for Lake Tahoe also reveal very interesting but intuitive results. Figure 5 illustrates the spatial distribution of steady state net flux (recharge – discharge) for Lake Tahoe and tributary watersheds, where significant groundwater discharge is occurring along stream valleys and around the lake rim at major transition areas of changing topography and hydraulic head gradients. Analyses of model results indicate that the preliminary calibration and model results of PRMS and MODFLOW-NWT for both Martis Valley and Lake Tahoe are fairly robust and accurate. In addition, our preliminary calibrated water budget compares well to precipitation, ET, and recharge percentages derived from recent watershed modeling, chloride mass balance, and Darcian flux estimates of recharge in adjacent watersheds with similar geology, vegetation, and precipitation magnitudes (Maurer and Berger, 1997; Jeton and Maurer, 2007).

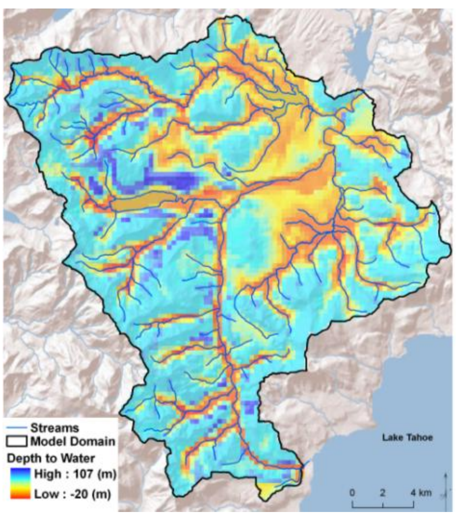
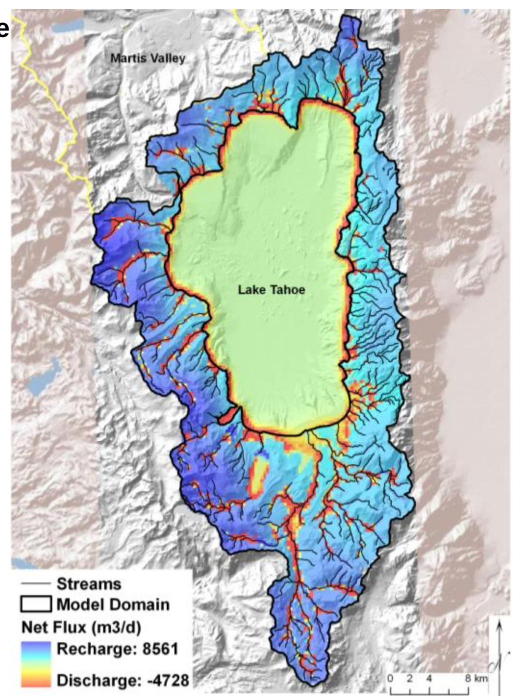


Figure 4. Martis Valley simulated depth to groundwater using layer 4 (mountain block) heads.

Figure 5. Lake Tahoe simulated steady state groundwater net recharge and discharge provided by lakes, streams, evapotranspiration, and diffuse recharge for each model cell. Positive values indicate recharge and negative values indicate discharge.



CONCLUSIONS

Here we present preliminary results from two integrated hydrologic models of complex mountain basins. Upland catchments represented in these models are very important because the majority of available water in the Truckee River basin emanates from these catchments as snowmelt runoff. Because these models can simulate the interactions among all the major co-varying hydrologic processes, including snowmelt, runoff, evapotranspiration, and SW-GW interactions, they are a big step forward in terms of simulation capabilities for assessing the effects of climate on water resources. As described in this paper, efficient and accurate representation of hydrogeologic features within the model is paramount for developing a robust model that can be calibrated using automated procedures that ensure objective model performance relative to diverse sets of observation data.

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