Assessing Water Resources Using a New Hydrologic Model

Richard G. Niswonger[1], David Rassam[2], and David E. Prudic[1]
[1] U.S.Geological Survey, Carson City, Nevada, USA
[2] CSIRO, Indooroopilly, Queensland, AUS
Email: david.rassam@csiro.au

Keywords: *Water resources, integrated hydrologic models, surface-water and ground-water interaction*

EXTENDED ABSTRACT

GSFLOW is a new U.S. Geological Survey model for simulating ground-water/surface-water interactions. GSFLOW couples PRMS (the Precipitation Runoff Modeling System) to MODFLOW (the Modular Ground-Water Model) with modules for simulating flow and storage in unsaturated-zones, lakes, and streams. GSFLOW simulates infiltration, runoff generation, and lateral flow in temporarily saturated material (i.e., interflow beneath storm-generated perched water tables) with physically based equations. Unsaturated-zone flow beneath the soil zone is based on a 1-d kinematic-wave approximation to the Richards' equation, implicitly coupled to MODFLOW. GSFLOW simulates spatial- and time-varying ground-water recharge on the basis of daily energy and mass balances among precipitation, solar radiation, heat, evapotranspiration, runoff, infiltration, and storage in the snowpack and soil zone, and percolation and storage through the unsaturated zone as well as changes to recharge caused by ground-water pumping and surface-water diversions. The water resources of multiple basins in the United States and Australia are being evaluated with GSFLOW. The model will be used to relate physical and hydrologic characteristics of the basins such as land use, geography, and climate to water resources issues such as sustainable yield and surface-water/ground-water interaction. Application of GSFLOW in three dissimilar basins will provide a robust means of testing the new model and could provide new insights when assessing water-resources across the world.

1.1. INTRODUCTION

Integrated ground-water and surface-water models are used for making water resource decisions that affect water supply and allocation. Their use has created a need for documented and tested integrated models that are freely available to the public. The need for integrated models led the U.S. Geological Survey to develop the integrated Ground-Water/Surface-Water Flow (GSFLOW) Model. GSFLOW couples PRMS (Precipitation Runoff Modeling System; Leavesley et al., 1983) to MODFLOW (Modular Ground-Water Flow Model; Harbaugh, 2005) with a new family of packages for simulating processes in stream and the unsaturated zone. These packages include the SFR2 Package (Niswonger and Prudic, 2006) that routes flow in channels and streambeds and the UZF Package (Niswonger, et. al., 2006) that routes water through unsaturated zones.

Because the conditions of flow and storage of water both above and below land surface affect water resources, these conditions often need to be simulated together (coupled) to make predictions. Few codes are available for modelling large-scale surface-water/ground-water interactions with capabilities of simulating temporally and spatially variable precipitation, evapotranspiration, overland flow and interflow, soil-zone storage, and unsaturated and saturated flow beneath the soil zone.

GSFLOW includes enhancements to both PRMS and MODFLOW to facilitate their dynamic coupling. GSFLOW uses physically based equations to describe critical processes in the soil zone (the uppermost part of the unsaturated zone), including infiltration, runoff generation, and lateral flow in temporarily saturated material. Flow through the unsaturated zone beneath the soil zone is based on a kinematic-wave approximation to the Richards' equation, implicitly coupled to MODFLOW. Flow in streams is routed while considering interaction with ground water. Recharge varies spatially and temporally in GSFLOW. Precipitation is partitioned between evapotranspiration, runoff, infiltration, and storage by balancing daily energy and mass budgets of the snowpack, soil zone, and unsaturated zone. The model has been applied to several basins in the United States. There also are plans to apply GSFLOW to the Namoi basin in northern New South Wales, Australia.

One of the models developed in the United States is the Sagehen basin in the Sierra Nevada, near Truckee, California, USA, which is geologically similar to the Namoi basin. Results from the Sagehen model could provide useful information for applying GSFLOW to the Namoi basin.

The comprehensive yet efficient simulation of basin hydrology, from the tree canopy to the bottom of aquifers, allows GSFLOW to be calibrated and evaluated using more types of data as compared to ether individual ground-water or watershed models. For example, both storm generated and ground-water generated streamflow can be distinguished in GSFLOW, and thus, can be compared to trends in streamflow measurements. For example, decadal variations in baseflow inferred from stream discharge measurements can be related to ground-water storage and provide a good constraint on aquifer hydraulic conductivity.

Results from the Sagehen basin could provide insights regarding strategies for developing a model for other basins. Important considerations of the results from the Sagehen model include effects of ground-water pumping on soil-moisture storage, ET, and streamflow. We present simulated results for the Saghen basin to demonstrate the utility of GSFLOW and to highlight hydrologic similarities that might exist between the Sagehen and Namoi basins.

1.2. PROBLEM DESCRIPTION—sagehen Basin

Sagehen basin is a U.S. Geological Survey Hydrologic Benchmark Network Basin located on the eastern slope of the northern Sierra Nevada, near Truckee, California (Mast and Clow, 2000). The basin drains an area of 6,672 acres and ranges in altitude from 6,319 to 8,737 ft. The areally averaged annual precipitation is about 38 in. and annual runoff is dominated by snowmelt. There are several small springs in the basin (fig. 1), which consists of volcanic rocks overlain by a veneer of alluvium. The upper 650 ft of the volcanic and granitic rocks and were considered permeable, but much less permbeable than the overlying alluvium. The Namoi and Sagehen basins are geologically similar (McNeilage, 2006). However, mean altitude, relief, and annual precipitation in the Namoi and Sagehen basins differ.

The Sagehen basin was discretized in space differently for the surface and the shallow soil zone as compared to the deep unsaturated and saturated zones. The surface and shallow soil zone was divided into 128 hydrologic response units and 201 stream reaches (fig. 1). Parameters used for simulating hydrologic processes above land surface and in the soil zone were estimated by using available spatial data sets, standard model default values, regional values determined by previous studies in the area (Jeton, 1999), and hydrologic judgment. Additionally, some parameters were adjusted by the Rosenbrock (Rosenbrock, 1960) automated calibration procedure. Climate data used in the model were from the Independence Lake SNOTEL station and Sagehen National Weather Service Cooperative station.

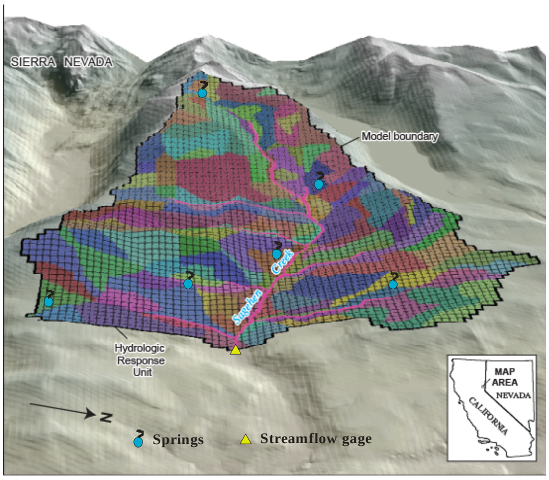

Figure 1. Spatial delineation of the surface (colored polygons) and the subsurface (square grid), Sagehen Basin, near Truckee, California

The subsurface component of the Sagehen basin model (that is beneath the soil zone) consisted of two model layers with 73 rows and 81 columns in which all cells had constant horizontal dimensions equal to 295 ft (Figure 1). The upper layer represented the shallow alluvium and had a maximum thickness of 120 ft whereas the lower layer represented the bedrock material and had a maximum thickness of 650 ft. The portion of the simulation period presented herein began on October 1, 1980, and ended September 30, 1984, and was divided into one-day time steps. Initial conditions for the ground-water model were estimated based on the heads and moisture contents resulting from a steady-state simulation. No-flow conditions were simulated across the bottom and sides of the model except for three cells beneath and adjacent to Sagehen Creek at the basin outlet, which were specified as constant-head cells. The constant-head cells were included to allow a small amount of ground water to flow laterally beneath the stream at the basin outlet.

The distribution of hydraulic conductivity (K) used for MODFLOW was created initially on the basis of the surface geology and was adjusted during calibration. The horizontal K ranged from 0.00045 ft/d on the ridges and beneath the alluvium to 0.79 ft/d in the valleys where the alluvium is thickest. A lower K was specified on the ridges in the top layer because bedrock outcrops at or near land surface, whereas the valleys are covered with alluvium. The K within each cell was assumed isotropic. Specific storage was set to 1 $x10^{-7}$ ft^{-1}, and the specific yield was specified as 0.05 on the ridges and 0.25 in the valleys near streams. The steady-state simulation assumed that the spatially varying ground-water recharge was proportional to the distribution of mean annual precipitation. The range in ground-water recharge for the steady-state simulation was determined by approximating the mean daily discharge at the outlet of Sagehen basin in early December.

The coupled GSFLOW model was calibrated by adjusting variables that control the exchange of water between PRMS and MODFLOW. These variables are the coefficients on the rate equations that control flow between the soil zone and the underlying unsaturated zone or between the soil zone and ground water when the water table is above the altitude of the bottom of the soil zone.

The steady-state simulation resulted in a calculated water table that was as much as 265 ft below land surface along the ridges and at or slightly above land surface in the lowest parts of the valleys next to streams. Although no observation wells have been drilled on the ridges in the basin, the maximum depth to ground water was based on depths measured in wells near ridges elsewhere in the northern Sierra Nevada.

1.3. RESULTS

Preliminary results indicate that the model performs well as indicated by a comparison between the measured and simulated streamflow at the basin outlet (Figure 2), and based on the correspondence between the location of springs in the basin and the simulated ground-water discharge to land surface.

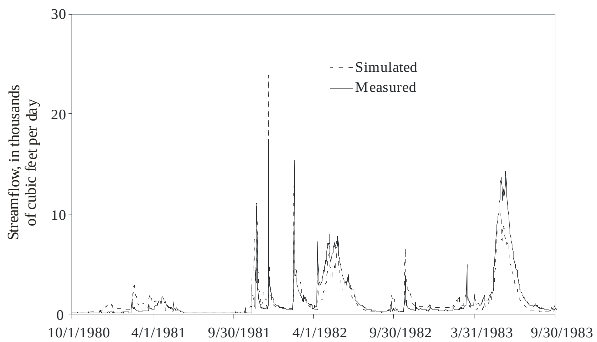

Figure 2. Comparison of simulated and measured streamflow at the outlet of Sagehen basin

Further refinement to the Sagehen model was made by adjusting scaling factors, one that is uniformly multiplied by all of the K values for layer 1 and the other that is multiplied by the K values for layer 2. These K-scaling factors were adjusted to achieve the best fit to the decadal variations in baseflow. Baseflow was estimated from the daily measured stream discharge as the lowest daily-average streamflow for each year (Figure 3).

The good correspondence between the measured and simulated stormflow component of the hydrograph indicated that the surface and soil-zone components of the model were sufficiently calibrated. The subsurface component of the model was considered to be sufficiently calibrated based on the good correspondence between the simulated and measured spring discharge and decadal variations in stream baseflow. These results were very sensitive to adjustments to the K-scaling factors.

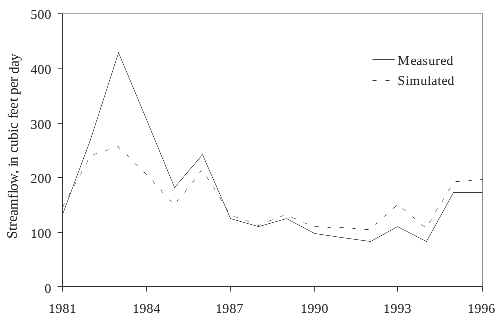

Figure 3. Comparison of simulated baseflow and baseflow estimated from measured stream discharge.

Effects of Pumping on the Hydrologic Budget

Although the Sagehen basin is undeveloped and contains no wells used for water supply, hypothetical wells were added to the model to test the effects of pumping on hydrologic processes. Two well fields were added to the lower part of the basin within the thickest part of the alluvium that is adjacent to the Sagehen Creek (Figure 4).

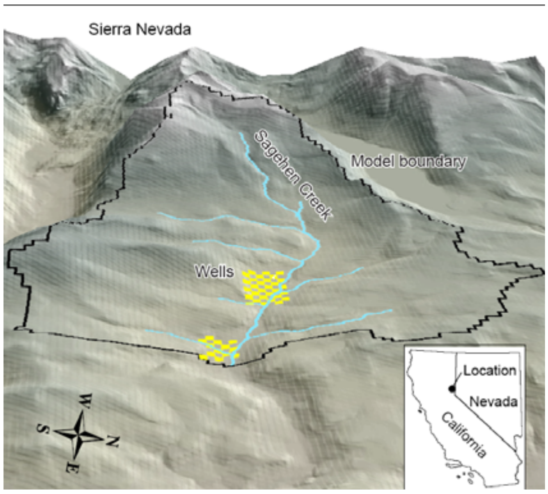

Figure 4. Hypothetical well fields use to evaluate the effects of ground-water pumping on hydrologic processes at Sagehen.

Although well yields were low at the Sagehen basin due to shallow and low permeable bedrock, the pumping did significantly change the simulated hydrologic budget. For example, pumping decreased the baseflow and resulted in as much as 27 percent depletion in the streamflow during the low flow periods (Figure 5).

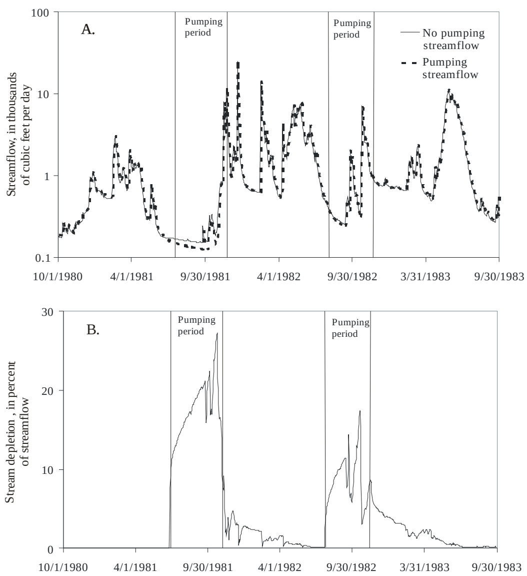

Figure 5. A. Changes in streamflow, and B. percent streamflow depletion caused by ground-water pumping in the Sagehen basin.

Ground-water pumping affected soil moisture storage and ET in addition to streamflow because pumping occurred where ground-water was less than 15 ft below land surface. Pumping decreased the soil moisture storage (Figure 6) and ET (Figure

7).

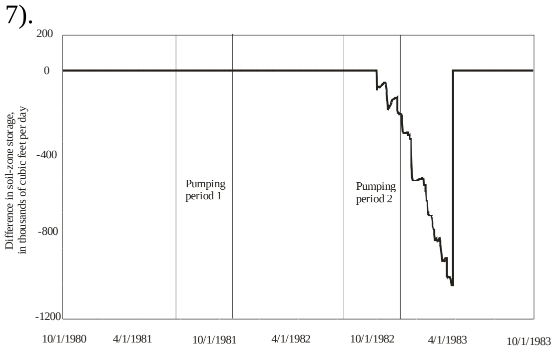

Figure 6. Changes in soil-zone storage caused by ground-water pumping in the Sagehen basin.

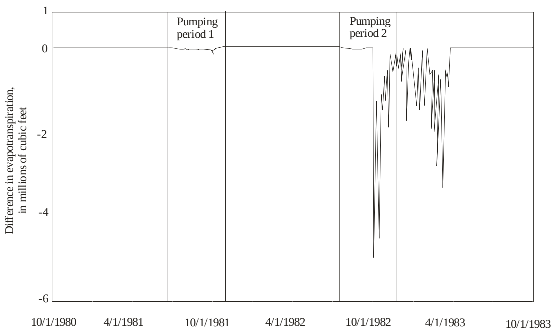

Figure 7. Changes in ET caused by ground-water pumping in the Sagehen basin.

1.4. DISCUSSION

Application of the GSFLOW model to the Sagehen basin demonstrated methods for calibrating an integrated model for a basin in which surface-water and ground-water interactions are important. Although ground-water data were limited, several springs in the basin provided good calibration targets for estimating the average fraction of precipitation that becomes recharge for the steady-state calibration. Because GSFLOW distinguishes storm generated and ground-water generated streamflow, stream discharge measurements were used to calibrate both the surface and soil-zone regions as wells as the deep unsaturated and saturated zones. Decadal variations in baseflow estimated from measured stream discharge allowed for further adjustment of K values during the transient model calibration.

Effects of ground-water pumping on streamflow, soil-zone storage, and ET in the Sagehen basin would generally apply to the effects of pumping in the Namoi basin due to similarities in geology. However, the effects of ground-water pumping might be more extreme in the Namoi basin because the average precipitation is about 20% of that in the Sagehen basin. Based on the results of the Sagehen basin, GSFLOW could be a useful tool for managing water resources in systems with significant surface-water and ground-water interaction, such as in the Namoi basin.

1.5. SUMMARY

GSFLOW is a coupled precipitation-runoff and ground-water flow model that provides mass balances and exchange rates between hydrologic zones, including land surface, soil zone, unsaturated and saturated subsurface zones. GSFLOW is applicable for simulating coupled precipitation, runoff, and ground-water flow over large areas because it relies on an efficient 1-D kinematic wave approximation to Richards' equation for simulating unsaturated flow.

A test simulation demonstrated the ability of the model for simulating coupled watershed and subsurface flow processes. Although there was limited data available for subsurface calibration, the model performed relatively well based on the correspondence between areas of ground-water discharge and mapped springs in the basin. The test simulation showed that the thickness of the unsaturated zone became large in the upland areas when aquifer hydraulic-conductivity values were high, which was unrealistic for Sagehen basin as demonstrated by the presence of several springs in the basin. Thus, the hydraulic properties of the model were constrained to a relatively narrow range by the location of springs and the stream discharge at the basin outlet. The test simulation demonstrated that GSFLOW can simulate coupled ground-water/surface-water interaction efficiently; the model required approximately 2 minutes of computer time on a Xeon 3.2 GHz, 2.6 GB RAM computer to simulate 1 year.

1.6. REFERENCES

Harbaugh, A.W., 2005. MODFLOW-2005. The U.S. Geological Survey modular ground-water model—The ground-water flow process: U.S. Geological Survey Techniques and Methods, 6 A-16, 9 ch., variously paged.

Jeton, A.E., 1999. Precipitation-runoff simulations for the upper part of the Truckee River basin, California and Nevada: U.S. Geological Survey Water-Resources Investigations Report 99-4282, 41 p.

Leavesley, G.H., Lichty, R.W., Troutman, B.M., and Saindon, L.G., 1983. Precipitation-runoff modeling system—User's manual: U.S. Geological Survey Water-Resources Investigations Report 83-4238, 207 p.

Mast, M.A., and Clow, D.W., 2000. Environmental characteristics and water quality of hydrologic benchmark network stations in the Western United States, 1963-95: U.S. Geological Survey Circular 1173-D, 114 p.

McNeilage, Craig, 2006, Upper Namoi ground-water flow model, NSW Department of Natural Resources, ground-water management area 004, zones 2,3,4,5,11, and 12, 175 p.

Niswonger, R.G., and Prudic, D.E., 2006. Documentation of the Streamflow-Routing (SFR2) Package to include unsaturated flow beneath streams—A modification to SFR1: U.S. Geological Survey Techniques and Methods, book 6, chap. A13, 57 p.

Niswonger, R.G., Prudic, D.E., and Regan, R.S., 2006. Documentation of the Unsaturated-Zone Flow (UZF1) Package for modeling percolation between the land surface and the water table with MODFLOW; U.S. Geological Survey Techniques and Methods, book 6, chap. A19, 71 p.

Rosenbrock, H.H., 1960. An automatic method for finding the greatest or least value of a function: The Computer Journal, vol. 3, pp. 175-184.