GSFLOW—A BASIN-SCALE MODEL FOR COUPLED SIMULATION OF GROUND-WATER AND SURFACE-WATER FLOW—PART A. CONCEPTS FOR MODELING SURFACE-WATER FLOW WITH THE U.S. GEOLOGICAL SURVEY PRECIPITATION-RUNOFF MODELING SYSTEM

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Abstract: The Precipitation-Runoff Modeling System (PRMS) is a semi-distributed hydrologic model that can be used to assess surface-water resources. Such assessments often are made with a simplistic representation of ground-water interaction with surface water. While the awareness of ground-water and surface-water interactions has increased through field observations and modeling studies, the ability to simulate these interactions has been limited by a lack of coupled models applicable at a range of spatial and temporal resolutions. To address this limitation, PRMS was coupled with the U.S. Geological Survey (USGS) ground-water flow model (MODFLOW). The coupled model (GSFLOW) consists of the integration of three parts: (1) partitioning of precipitation, snow melt, and soil moisture into overland flow, infiltration, evapotranspiration, interflow, and recharge; (2) routing of surface flow in channels; and (3) computing unsaturated flow and ground-water discharge. This paper discusses the modifications necessary for coupling PRMS to MODFLOW and an example of its application.
The modifications to couple PRMS and MODFLOW include: (1) development of algorithms relating the spatial discretization of MODFLOW to PRMS; (2) development of a new algorithm for routing overland- and inter-flow to the streams; (3) development of a feedback scheme where ground-water and surface-water interact in the soil zone; (4) combining the PRMS soil-moisture and subsurface-reservoirs into a single soil-zone reservoir; and (5) distributing runoff and interflow to associated stream reaches.

Energy and water states at and above the land surface (precipitation, radiation, interception, snowmelt, sublimation, and potential evapotranspiration) are computed by PRMS at the beginning of each time step. The interaction between the soil zone, stream beds, and unsaturated and saturated ground-water zones require that common states and fluxes be solved simultaneously. Consequently, GSFLOW incorporates the PRMS surface-runoff, infiltration, and soil-zone calculations within the MODFLOW iteration scheme.

GSFLOW was applied to Sagehen Creek, a USGS Hydrologic Benchmark Network Basin located on the eastern slope of the northern Sierra Nevada. The basin drains an area of 27 square kilometers and ranges in elevation from 1,926 to 2,663 meters above sea level. Mean annual precipitation for the basin is about 970 millimeters. GSFLOW is being used to assess ground-water contribution to stream discharge and the accuracy of low-flow simulations.

INTRODUCTION

The need for assessing ground-water and surface-water interactions has increased as a result of competing demands for water. Watershed models, such as the U.S. Geological Survey (USGS) Precipitation-Runoff Modeling System (PRMS) (Leavesley, et al., 1983), have been used to assess surface-water resources and to make management decisions regarding natural- and engineered- watershed systems. Such assessments and decisions are often made with a simplistic representation of the ground-water hydrology and its interaction with surface and atmospheric hydrology. Similarly, ground-water flow models, such as the USGS MODFLOW model (McDonald and Harbaugh, 1988), have been used to assess ground-water resource problems and to manage and develop ground-water supplies. These models often make simplistic representations of surface water and energy budgets for spatial and temporal partitioning of precipitation and snowmelt into evapotranspiration, runoff, interflow, and recharge. These processes are important for assessing the effects of ground-water development on basin-scale water resources.

While knowledge of ground-water and surface-water interactions has increased through field observations and modeling studies, the ability to simulate these interactions has been limited by a lack of integrated models. The issues of different spatial and temporal resolutions, incompatible software, and dynamic feedback between the models have hindered development of integrated models. To address these limitations, the Ground-water/Surface-water FLOW model, GSFLOW, was developed by integrating PRMS and MODFLOW-2005 (Harbaugh, 2005). Specifically, GSFLOW can be used to address the following questions:

What are the effects of fine spatial and temporal resolution on evaporation, soil moisture, and infiltration information on ground-water simulations?

What are the effects of a rising or falling water table on surface-water processes?

What are the dynamics of surface-water and ground-water interaction in springs, wetlands, and riparian areas?

What are the sources of streamflow?

What are the effects of different climate scenarios (e.g., floods and droughts) on a surface-water and ground-water system?

What are the effects of different management scenarios (e.g., conjunctive use, urbanization, and irrigation) on the surface- and ground-water system?

GSFLOW consists of the integration of five model components (Figure 1): one component spatially distributes precipitation, temperature, and solar radiation and computes potential evapotranspiration, interception, snowmelt, and surface evaporation (PRMS); a second component partitions precipitation into surface infiltration, overland flow, evapotranspiration, interflow, and shallow seepage (PRMS Soil Zone); a third component routes flow in channels and streambeds (SFR2); a fourth component computes vertical unsaturated flow below the soil zone (UZF); and a fifth component computes ground-water flow (MODFLOW-2005). See

Niswonger and others (2005, 2006, in press) for a more detailed description of components three and four.

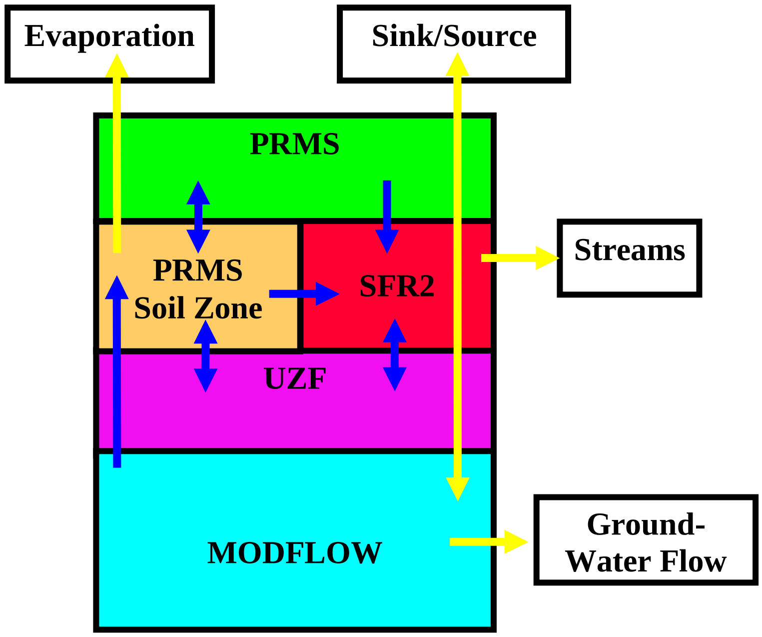

Figure 1. A schematic diagram showing the integration of the five PRMS and MODFLOW components in GSFLOW.

These five components are tightly integrated using the existing MODFLOW-2005 and the Modular Modeling System (MMS) (Leavesley, et al., 1996). These programs are both modular programming frameworks that allow modelers to add their own software to easily extend or replace existing functionality. Each component, which comprises a MODFLOW package(s) or MMS module(s), represent processes within the hydrologic cycle. Additional components can be developed that provide new or alternative analytical and numerical solutions for hydrologic processes, and integrated within GSFLOW. New components must be compatible with the spatial and temporal resolution of existing components, that is, the MODFLOW finite-difference grid and solution matrix, PRMS hydrologic response unit (HRU) delineation, and daily time step. Internally, components can use different time steps or spatial domains as long as their states and fluxes are available on a daily time step and integrated to the existing spatial units, for example, to a MODFLOW cell or a PRMS HRU. In addition, development of GSFLOW is according to the following principles:

Modular design to allow new and existing simulation techniques to be added.

Standard PRMS and MODFLOW source code and data files are used without modification.

Spatial discretization is according to the requirements of each component.

Isolate integration algorithms from components.

Use geographical information system (GIS) tools to relate spatial features between components.

Common states and fluxes between components are well defined.

ENHANCEMENTS TO PRMS FOR GSFLOW

The GIS Weasel (Viger et al., 1998), a software tool for the development of spatial information used in physical-process modeling, has been enhanced to generate the spatial data necessary to run GSFLOW. Figure 2 shows the discretization of model features (HRUs, stream reaches, and grid cells) used by the GSFLOW model. The delineation procedure consists of developing geographically referenced feature maps using the following steps: (1) determination of the spatial domain of the model; (2) development of a MODFLOW grid-cell map; (3) development of a stream segment network map based on flow accumulation analysis; (4) determination of flow planes for each stream segment; (5) development of an HRU map by intersecting the flow plane map with specified elevation band(s) and depth to ground-water contour(s); (6) development of the stream reach map by intersecting the stream segment network map with the MODFLOW grid-cell map.

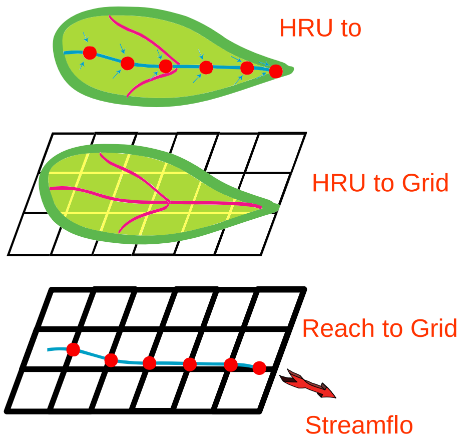

Figure 2. A schematic diagram showing the spatial features for the integration of PRMS and MODFLOW components in GSFLOW.

Data defining these spatial features and the relations between them are input to GSFLOW as model parameters derived by the enhanced GIS Weasel. These parameters are of two basic types: attribute and topology. Attributes are physical properties of the features such as slope and length of the stream reaches, aspect and soil type of the HRUs, and land surface elevation of a grid cell. Topologies describe connectivity between features such as connectivity of the stream reaches, degree of intersection of the HRUs and grid cells, and identification of the down-slope HRU or stream reach.

A new PRMS module (soilzone) was developed that combines and extends the soil-moisture balance module (smbal) with the subsurface reservoir flow module (ssflow). The soil zone and subsurface reservoirs were merged into a single-partitioned reservoir at the HRU spatial resolution. Extensions include the addition of soil moisture flow paths to account for macropore flow, slow and fast interflow, ground-water discharge, and excess soil moisture to surface runoff.

The soilzone module partitions infiltration and antecedent soil moisture by subdividing the PRMS soil zone into three reservoirs: field capacity, macropore, and gravity flow (Figure 3).

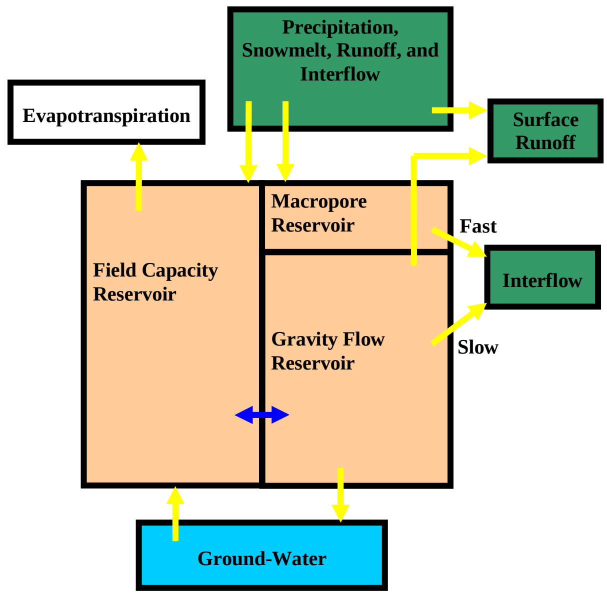

Figure 3. A schematic diagram showing the conceptual model of the GSFLOW soil zone module for a single HRU.

The field capacity reservoir contains soil moisture below the specified field capacity and above the wilting point. This moisture is partitioned between evapotranspiration (ET), percolation to ground-water storage, and storage. The macropore reservoir contains a specified percentage of infiltration which is partitioned into fast interflow and storage. The gravity flow reservoir contains water when soil moisture is above field capacity. Fast interflow is computed when soil moisture is greater than or equal to a specified threshold, whereas, slow interflow and ground-water percolation are computed when soil moisture conditions are less than the threshold. Soil moisture exceeding fully saturated conditions is exfiltrated as surface runoff.

Based on this system of soil moisture reservoirs, interflow occurs after precipitation and/or snowmelt, and for a period that depends on specified flow-routing parameters, whenever water exists in the macropore and gravity flow reservoirs. Ground-water percolation occurs only when total soil moisture exceeds field capacity and is dependent on the available water in the gravity flow reservoir.

A cascading flow-routing procedure was added to the soil moisture modules (srunoff_smidx and soilzone) that routes surface runoff and interflow from HRU to HRU and/or to stream reaches. Cascading surface runoff is treated as infiltration to down slope HRUs for partitioning into soil zone reservoirs. Cascading interflow is applied only to the field capacity reservoir.

SAGEHEN CREEK APPLICATION

Sagehen Creek is a USGS Hydrologic Benchmark Network Basin located on the east slope of the northern Sierra Nevada (Figure 4). The basin drains an area of 27 square kilometers and ranges in elevation from 1926 to 2663 meters above mean sea level. The annual hydrograph is controlled by snowmelt, and peak flows occur in late spring and minimum flows in the fall (Rademacher et al., 2005). Daily discharge records are available beginning October 1953.

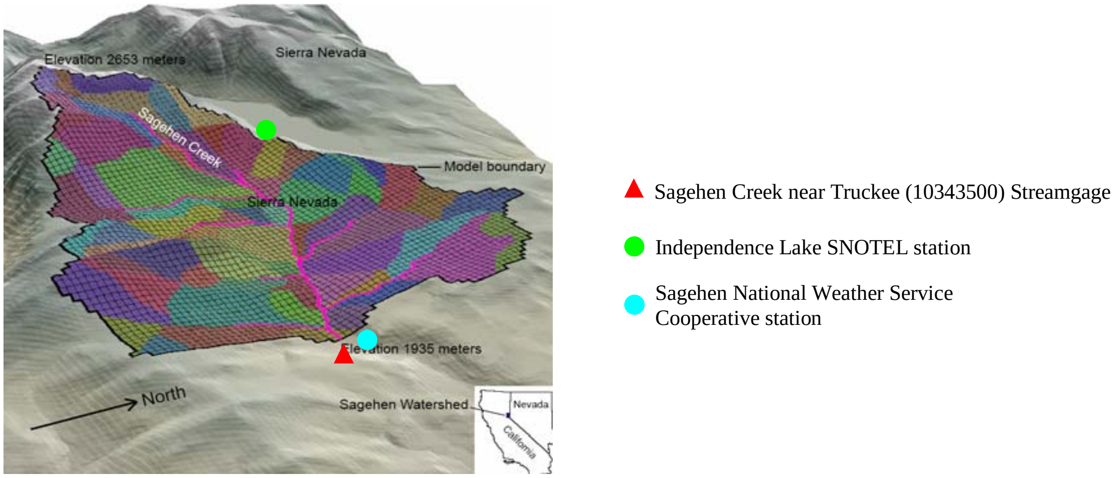

Figure 4. Location map and discretization of the Sagehen Creek basin showing grid cells, HRUs, stream network, and location of stream gage and climate stations.

A data file was assembled for the Sagehen Creek basin model for the time period from October 1, 1980 to April 25, 2004. This data file included both streamflow and climate data. Mean-daily, stream-flow measurements were recorded at the Sagehen Creek near Truckee, California, USGS stream gage. This record was used to calibrate and evaluate the GSFLOW model. The climate data included in this file were from the Independence Lake SNOTEL station and Sagehen National Weather Service Cooperative station. Both of these climate stations are located in the basin; however, the Sagehen station was selected to provide input to the model because of a longer and more complete temperature record.

The Saghen Creek basin was delineated into 128 HRUs, 5913 grid cells, and 201 stream reaches (figure 4) using the GIS Weasel as described above. Parameters were estimated using available spatial data sets, standard model default values, regional values determined by previous studies in the area (Jeton, 1999), and best hydrologic principles. Additionally, some parameters were adjusted by the Rosenbrock automated calibration procedure (Rosenbrock, 1960). While a detailed analysis of model performance is beyond the scope of this report, preliminary results indicate that the model performs well. Figure 5 shows a 2-year calibration period of mean-daily measured and simulated streamflow for the Sagehen Creek stream gage.

Figure 6 shows the partitioning of the simulated hydrograph, shown in figure 5, into surface runoff, interflow, and base flow. The surface runoff and interflow traces represent the basin total response at the outlet. The base flow trace is the response of the ground-water system interacting with the flow in the stream reaches. GSFLOW computes many more states and fluxes which also are available as model output. Niswonger and others (2006) present more examples of GSFLOW output from the ground-water perspective.

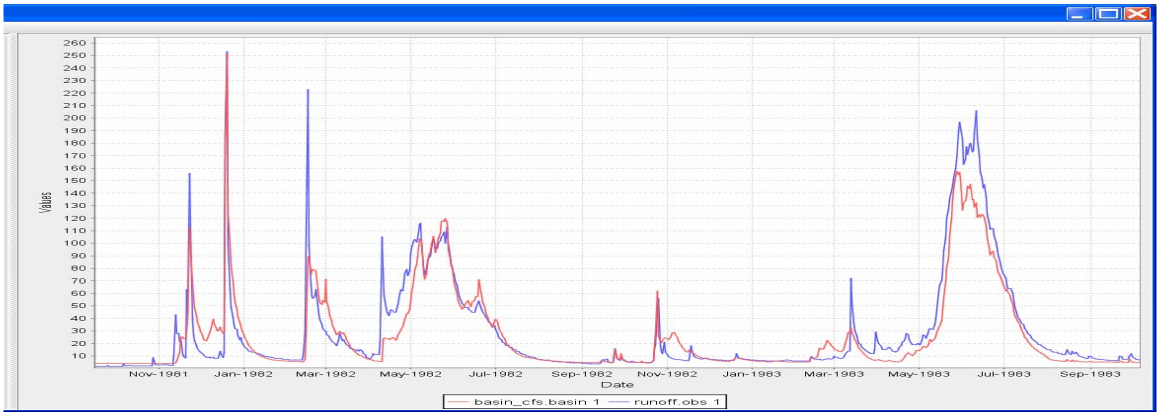

Figure 5. Measured (blue) and simulated (red) mean daily stream flow for Sagehen Creek.

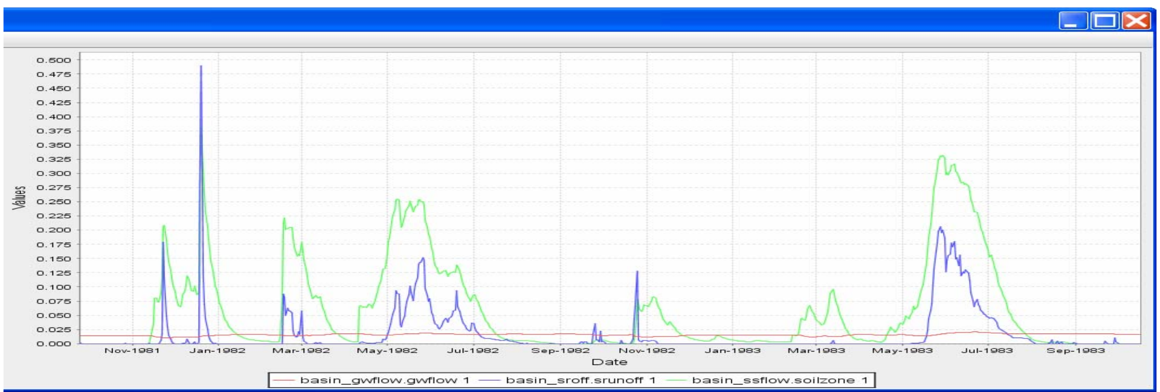

Figure 6. Simulated components of total stream flow from the GSFLOW model for Sagehen Creek. Direct surface runoff (blue), interflow (green), and base flow (red) are shown.

CONCLUSION

As sciences mature, their integration becomes increasing possible and powerful. Dr. Ven Te Chow made the following statement in the preface of his classic book, *Open-Channel Hydraulics*: "In a science that has reached so advanced a state of development, a large portion of the work is necessarily one of coordination of existing contributions." (Chow, 1959). While the context for Dr. Chow's statement was open-channel hydraulics, it holds true for interdisciplinary integration of hydrologic modeling that considers the hydrosphere, atmosphere, and biosphere as coupled and interactive systems.

Addressing the ever increasing range and complexity of environmental resource management and policy development requires interdisciplinary and adaptive approaches that build on existing science and technology. Also, these approaches must provide mechanisms for modeling over different spatial and temporal scales, and provide for the integration of science and management objectives. These are the objectives of the GSFLOW model.

While the main reason for developing GSFLOW was to build a tool to quantify and predict spatial and temporal variability of inter-dependent atmospheric, surface and subsurface hydrologic fluxes of precipitation, solar radiation, evaporation, transpiration, runoff, infiltration, interflow, percolation, recharge, storage, and discharge, its modular structure allows for integration with other scientific disciplines and environmental processes. Work is underway to expand GSFLOW to include geochemical, water quality, conjunctive use and river system management, full-hydrodynamic streamflow with fate and transport of constituents, and ecosystem and habitat modeling.

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