## GSFLOW

Background: Increased demands on our Nation’s water availability have led to a need to manage groundwater and surface water together as a single resource. The USGS has been a leader in the development and application of modeling tools to better understand groundwater and surface-water interactions, to simulate the effects of current and projected future climate conditions and land and water uses on these resources, and to support evaluations of conjunctive management of groundwater/surface-water systems. GSFLOW is a fully coupled groundwater/surface-water model built on the USGS MODFLOW-NWT and Precipitation Runoff Modeling System (PRMS) software. GSFLOW simulates water flow and storage on a daily time step throughout a watershed--from plant canopy, to regional groundwater-flow systems, to surface-water networks—and is applicable to watersheds ranging from 10s to 1,000s of square miles.

GSFLOW has been applied to several types of hydrologic-process and water-management studies in a range of climate and hydrogeologic settings. These applications include the effects of stream-channel incision on montane meadows in the Sierra Nevada (Essaid and Hill, 2014); the introduction of non-native Pinyon Juniper on groundwater levels in a Great Basin watershed (Carroll and others, 2016); groundwater-streamflow-lake interactions in the northern Midwest, including a link between GSFLOW results and one-dimensional stream-temperature modeling for the study area (Hunt and others, 2013); and lake-stage decline and lake salinization in response to agricultural diversions for a terminal lake in a semi-arid desert basin of west-central Nevada (Niswonger and others, 2014). As described previously, one of the benefits of the watershed-simulation capabilities of GSFLOW is the usefulness of the approach for analysis of mountainous terrains for which detailed processes of snow accumulation and depletion (sublimation and melt), soil-zone flow and storage, and runoff are needed to understand (1) the flow of water on the land surface and within the soil and subsurface zones and (2) the timing and sources of groundwater recharge and streamflow (see, for example, Huntington and Niswonger, 2012; Surfleet and others, 2012; Essaid and Hill, 2014; Hassan and others, 2014; and Allander and others, 2014). Water-management issues to which the code has been applied include the evaluation of groundwater and surface-water development for public supplies and for agriculture. Applications to agricultural settings include those in Washington (Ely and Kahle, 2012), California (Woolfenden and Nishikawa, 2014), Nevada (Niswonger and others, 2014), Pennsylvania (Fulton and others, 2015), and northwest China (Wu and others 2014, 2015; Tian and others, 2015a,b).

During fiscal year 2017, the GSFLOW development team made progress on several new enhancements to the software, specifically:

* GSFLOW-MODSIM link: During fiscal year 2016, MODFLOW’s ability to simulate conjunctive management of groundwater and surface-water systems was greatly expanded by the GSFLOW development team by linking MODFLOW with the MODSIM reservoir and river-operations model developed at Colorado State University (Morway and others, 2016). The combined MODFLOW-MODSIM software was applied to hypothetical conjunctive-management problems concerning groundwater overdraft in agricultural systems by Morway and others (2016) and to managed aquifer recharge by Niswonger and others (in review). During FY17, work began on extending the MODSIM link to GSFLOW. The combined GSFLOW-MODSIM tool will allow evaluation of reservoir releases, river diversions, instream-flow requirements, and groundwater-pumping impacts on conjunctively managed systems. Also, a MODSIM training class, including discussion of MODSIM-MODFLOW, was held May 2017, in Sonoma, California, for USGS, water agency, and California state employees.
* Agricultural water demand/irrigation supply package for MODFLOW and GSFLOW: Irrigation supply and demand packages are being developed for GSFLOW to simulate supplemental pumping and demand-based irrigation water application in systems that conjunctively use surface water and groundwater. Development of the agriculture/irrigation package is being done in collaboration with Claudia Faunt and Jon Traum of the California WSC in support of the Russian River Basin GSFLOW model development.
* Continued development and enhancement to GSFLOW pre- and post-processors. Originally developed in collaboration with scientists from the Desert Research Institute, Murphy and Rich are documenting and updating Arc-python scripts that automate the GSFLOW input development process using geospatial datasets and GIS. Rich are collaborating with Josh Larsen, Tracy Nishikawa, and Claudia Faunt on the development of a graphical user interface for GSFLOW that expands upon FloPy and PRMS-Py to create GSFLOW-Py for post-processing model results. Future plans include adding compatibility between GSFLOW-Py and GW-WebFlow in collaboration with Jeremy White for providing web-based graphical display of GSFLOW model results.
* CRT: release of D8 routing; other enhancements. CRT is an important component of the Arc-Python scripts for developing GSFLOW models.

Plans and Products for FY18: The following activities are proposed for FY18: Describe plans and products for each of these activities:

* GSFLOW-MODSIM link: The MODSIM and GSFLOW codes are being coupled together to provide reservoir and river operations/planning capabilities to GSFLOW. This work requires some changes to both codes and the development of an interface module that allows data sharing, consistent time stepping, and nonlinear iteration and convergence checking. This work is leveraging the agricultural water demand/irrigation supply package that Rich is developing for GSFLOW. Similar to the current GSFLOW setup, development of GSFLOW-MODSIM will allow the user to select which mode they would like to run in. For example, if a user only wants to invoke PRMS-MODSIM, or MODFLOW-MODSIM, they will be able to do so, with the longer term vision of facilitating additional model integration (e.g., solute transport). Initial applications of the GSFLOW-MODSIM link are planned for the Deschutes Basin in Oregon with the US Bureau of Reclamation, the Russian River Basin in California with the California…and Sonoma County, and the Carson River Basin in Nevada with the Nevada….Also, a MODSIM training class, including discussion of MODSIM-MODFLOW, was held May 2017, in Sacramento, California, for USGS and California state employees.
* Agricultural water demand/irrigation supply package for MODFLOW and GSFLOW: work being done in collaboration with and support for the USGS California WSC development of an agriculture/irrigation package for GSFLOW, Development of the agriculture/irrigation package will be done in collaboration with Claudia Faunt and Jon Traum of the California WSC in support of the Russian River Basin GSFLOW model development.
* Continued development and enhancement to GSFLOW pre- and post-processors. Murphy and Rich will continue to work on the Arc-python scripts, including finalizing code, continued work on user the documentation/tutorial, and writing a journal article describing the scripts. Rich will continue to coordinate with Josh Larsen on the development GSFLOW-Py (Flopy+PRMS-Py) for GUI support for the Russian River GSFLOW-MODSIIM project.
* Rich will continue to work with Wes Kitlasten Eric Morway on Python-based tools used to convert GSFLOW stream networks into MODSIM network models. These codes are necessary for developing input files for the GSFLOW-MODSIM code.
* CRT: release of D8 routing; improved cut/fill algorithms for DEM conditioning and stream network development.
* Technical Transfer and User Support: (training classes, webinars, direct user support to WSC staff and others, presentations at professional conferences and cooperator/federal partner meetings, etc. See page 9 in FY16 EOY report.

Longer-Term Vision for Software: Integrated hydrologic-economic-water management modeling has been proposed as the way forward to meet present and future resource scarcity issues (Sergeldin, 1995; Cai et al., 2003). However, despite general agreement in the literature that these codes will be highly beneficial to society, they have not been broadly adopted by practitioners. Our philosophy in hydrologic model development has been to leverage proven and effective modeling codes that have been broadly adopted, and to expand their capabilities through integration of multiple codes. For example, the legacy of MODFLOW led us to develop GSFLOW that integrates MODFLOW with the commonly used watershed runoff model PRMS. Our most recent efforts toward integrating process-based hydrologic models with rule-based operations/planning models was a major step forward in simulating supply-demand-consumption feedbacks in develop river basins (Morway and others, 2016). We see our past and present development efforts as providing a basis for integrating other system components in the future, such as climate, optimization, economics, policy, and ecosystems in order to holistically address “supply vulnerability, and long-term sustainability” of our nation’s natural resources (Gorelick and Zheng, 2015). These models will serve as what Fatichi and others (2016) referred to as a “virtual laboratory” for which multidisciplinary teams of scientists can work together to evaluate scenarios pertinent to future social, political, and environmental problems impacting communities in the United States and elsewhere. As our goal is to achieve broad application of these codes by practitioners, and we continue to commit significant efforts toward the development of graphical user interfaces that streamline development of necessary datasets required for model application and analysis of results.

Here are some items we discussed, which we might want to expand:

* Greater communication and collaboration with USGS and external scientists and managers working on ecoflow issues: GSFLOW is the logical tool to use to look at ecoflows, streamflow generation, etc.
* Bring heat- and solute-transport capabilities into PRMS and GSFLOW through linking with MT3D-USGS: An important, national-scale issue to which such a code could be applied is the simulation of stream temperatures to support aquatic ecosystems (discuss preliminary work with MODFLOW-MT3D USGS in the Trout Lake watershed, but no ability to look at watershed temps)
* Further integration with management/optimization models such as MODSIM or the PEST++ groundwater-management capability currently being developed. Perhaps cite the Gorelick and Zheng paper here, as well as the paper by Dai and Labadie on the MODSIMQ integrated water quantity/quality management model.

Relevance and Benefits: This section is very important in building our case for GSFLOW development. Here are some items for consideration; we don’t need to include all of them necessarily:

* Who Benefits from GSFLOW? USGS programs at the national level and state Water Science Center level benefit from GSFLOW. Current GSFLOW applications being undertaken by WSC staff include Upper Colorado River Basin Groundwater Availability study, Russian River Basin, Yucaipa and San Antonio (?) basins in CA (links to SGMA?), Rio San Jose Basin in NM with.list cooperator, Bad River watershed in Wisconsin….
* Customers asking for the software? Did Bureau of Rec ask for the GSFLOW-MODSIM link for the Deschutes basin? California Water Board (?) asking for GSFLOW applications to support SGMA?
* What is the impact of this work? New contributions to the science? Example uses of GSFLOW models, such as ‘The Nevada State Engineer used the results of the Walker Lake GSFLOW model to…’
* What is the unique niche of this work? How does the work differentiate us from our ‘competition’? Why the USGS and not some other entity? A fully coupled model for regional-scale assessments without the run-time and other computational issues associated with Richards-based three-dimensional unsaturated flow? Daily time steps (versus shorter and longer time steps of other codes)?
* Is the work innovative? A fully coupled model for regional-scale assessments without the run-time and other computational issues associated with Richards-based three-dimensional unsaturated flow? Daily time steps (versus shorter and longer time steps of other codes)?
* Are there opportunities for the USGS if this software is produced? Will USGS customer base grow? We might emphasize the ag-irrigation package and GSFLOW-MODSIM link here. Perhaps develop better ties with US Bureau of Reclamation? Dept of Agriculture? State agencies?

Personnel:

* Rich Niswonger, NRP, Menlo Park: All aspects of GSFLOW development, as well as components of MODFLOW 6
* Steve Regan, NRP, Lakewood: Development of PRMS and GSFLOW modules; GSFLOW-MODSIM link
* Steve Markstrom, NRP, Lakewood: Development of PRMS and GSFLOW modules
* Eric Morway, Nevada WSC: Development of GSFLOW-MODSIM link and agriculture/irrigation package for GSFLOW
* Wes Kitlasten, Nevada WSC: Development of Python codes for creating MODSIM linked network models that are consistent with SFR2 stream network models used in GSFLOW-MODSIM models.
* Murphy Gardner, Nevada WSC: Development and release of Arc-Python scripts (version 1) to support development of GSFLOW models
* Wes Henson, California WSC: Modifications to the Cascade Routing Tool to support D-8 “one-to-many routing” and enhanced options for interactions between streams and land HRUs (<http://water.usgs.gov/ogw/CRT/>)
* Stephen Maples, Nevada WSC: Enhancements to the GSFLOW water-budget utility

Budget: Please include all costs (net and gross), including hours to be worked and salary for each team member, travel, equipment, and so forth. (FY17: $259,000)

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