Agricultural Water Use Package for MODFLOW and GSFLOW

in these cases the net irrigation water requirements (NIWR)

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# Abstract

The agricultural Water Use (AG) Package was developed for simulating demand-driven and supply-constrained agricultural water use in MODFLOW and GSFLOW models. The AG Package makes use of pre-existing hydrologic simulation capabilities provided by MODFLOW and GSFLOW. Distribution of water for irrigation is automatically represented using daily potential evapotranspiration and the antecedent soil-water conditions. Irrigation diversions and pumping rates are determined using the concept of net irrigation water requirement (NIWR). NIWR is diverted into canals and routed to fields using the MODFLOW SFR Package, or NIWR can be supplied/supplemented by groundwater wells. The AG Package can estimate NIWR by calculating the required diversion/pumping that minimizes the difference between the well-watered crop evapotranspiration (ET) and the simulated actual ET. Alternatively, the irrigation schedule can be specified directly or can be determined by the model using field conditions as a trigger, such that when the ET deficit reaches a minimum threshold, irrigation automatically occurs for some specified irrigation time and rate. Combined with MODFLOW or GSFLOW, the AG Package can simulate dynamic water use by agriculture in developed basins while providing flexibility to represent a range of grower behaviors and irrigation infrastructure.

# Software and/or data availability section

Software and data used for this work, including software, model input files for each problem, and ancillary data are available through the USGS model archive website: name of software or dataset, developer and contact information, year first available, hardware required, software required, availability and cost. Also for software: program language, program size; for data: form of repository (database, files, spreadsheet), size of archive, access form. Note that "Contact the author" is not acceptable for software or data access

# Introduction

Agriculture is a major water consumer in many basins around the world, and representation of this water-use sector in hydrologic models is important for water resources planning and management (Wang and others, 1996; Jones and others, 2017). Decision support software is paramount in many river basins in the western United States and other parts of the world for adapting to water use, climate change, and for evaluating new water management strategies (Tian and others, 2015). Hydrologic models that incorporate surface water and groundwater can provide valuable information about water resources sustainability. This is especially true for agricultural regions susceptible to climate change and population growth that stress water supply systems (Faunt, 2009; Elliott and others, 2014).

MODFLOW and GSFLOW have been widely used for simulating regional scale agricultural systems due to its robust hydrologic simulation capabilities (Hu and others 2010; Bailey and others, 2016; Wu and others, 2016; Guzman and others, 2015; Woolfenden and Nishikawa, 2014). Representing agricultural water use was done previously using the Farm Process for MODFLOW (Schmid and others, 2006; Hanson and others, 2010; Hanson and others, 2014), and energy and water budget approaches in GSFLOW that combines MODFLOW with the precipitation runoff modeling system (PRMS; Woolfenden and Nishikawa, 2014); however, in these cases the NIWRs were estimated external to the model and water supply constraints were neglected. Another approach is to use dynamic energy and soil-water balance calculations within an integrated hydrologic model to calculate NIWR, and explicitly simulate irrigation systems. This latter approach must simulate irrigation scheduling and requires irrigation by applied automatically in the model as a function of energy demands, antecedent soil water conditions, and irrigation water supply. The advantage of this approach is that simulated NIWR is consistent with the applied irrigation schedule and soil-water conditions in the model.

GSFLOW can simulate all the major hydrologic processes in watersheds, including partitioning of precipitation into snowpack, runoff, ET, and groundwater flow using energy and water balance approaches (Markstrom and others, 2008). However, GSFLOW does not have capabilities to automatically calculate NIWR, divert surface water, pump groundwater and apply irrigation to agricultural fields. Accordingly, a new package was developed for MODFLOW and GSFLOW to provide these capabilities called the Agricultural (AG) Water Use Package.

The AG Package is integrated into MODFLOW and GSFLOW solutions and can incorporate land-use change and daily climate variability for the estimation of agricultural water use at a regional scale. The AG Package also can simulate conjunctive use of surface water and groundwater by automatically pumping groundwater when surface water availability is less than demand (Schmid and others, 2006). Because the NIWR, irrigation efficiency, and crop consumption are simulated using daily climatic conditions, the model can be used to simulate impacts of climate change on water supply. The AG Package can represent changes in land use, including changes in crop type, expansion or contraction of farmlands, or changes in irrigation technology.

Climate variability can cause regional shifts in agricultural demand due to systematic changes in soil moisture and irrigated areas, and indirectly as reductions in return flows (Fischer and others, 2007). Interactions such as these occur over time periods that span irrigation events or irrigation seasons, or they can span much longer time periods due to multi-year shifts in climate and groundwater supply. The AG Package for MODFLOW and GSFLOW provides a wholistic approach for representing dynamic water use by agriculture and can be used for planning and assessing impacts of agriculture on other water-use sectors and for evaluating long-term sustainability. The AG Package also provides necessary capabilities for integration of GSFLOW with the river operations models such as MODSIM for simulating impacts of water use priorities on agricultural systems (Labadie, 2010; Morway and others, 2016; Niswonger and others, 2017)

This report describes the AG Package developed for MODFLOW and GSFLOW (Niswonger and others, 2011; Markstrom and others, 2008; Markstrom and others, 2015). The AG Package works with the Streamflow-Routing (SFR) and the Unsaturated Flow (UZF1) Packages, and the PRMS soilzone module, and includes capabilities for simulating pumping wells, like the WELL Package for MODFLOW-NWT. The AG Package has several capabilities, including application of water flowing in SFR diversion segments as irrigation to UZF1/PRMS cells/HRUs; application of groundwater pumped by wells in the AG Package as irrigation to UZF1/PRMS cells/HRUs; automatic pumping of groundwater to supplement SFR diversions when the available flow in a diversion segment is less than demand; and calculation of using the UZF1/PRMS crop evapotranspiration (ET) deficit and simulated irrigation efficiency. Sub-irrigation also is represented where the ET demand can be supplemented by direct uptake of groundwater by plants, and irrigation scheduling can be fully automated or triggered by threshold ET deficits. Irrigation water is explicitly applied to cells/HRUs, and ET is simulated using a daily energy and soil-water balance (Markstrom and others, 2008). Surface water and groundwater return flow is routed to receiving water bodies or aquifers.

All exchanges of irrigation water between different packages (SFR, UZF, LAK, and AG) and with aquifers are calculated within the AG Package; however, the SFR, UZF, and LAK Packages must be active in MODFLOW and GSFLOW to divert surface water from streams and lakes and apply irrigation water to cells/HRUs. Diversion segments must be specified within the SFR Package to deliver stream or lake water to fields. All data for supplementary and irrigation wells is specified within the AG Package input file; the AG Package calculates and applies its own boundary conditions for representing groundwater pumped by wells.

Two example problems are presented for representing agriculture in MODFLOW and GSFLOW, and these examples are run for several configurations to demonstrate application of the new package and its capabilities for simulating agricultural water use for a range of hydrographic settings. Example problem 1 demonstrates the new package in a MODFLOW simulation and represents an agricultural basin in northwest Nevada (Prudic and others, 2004). The second example demonstrates the package in a GSFLOW simulation and represents an undeveloped basin in northeast California. There are many publications documenting theory and application of MODFLOW and GSFLOW, and only new theoretical and implementation details for the AG Package are provided herein. Readers can refer to previous publications for simulations capabilities related to MODFLOW and GSFLOW, including energy and water balance calculations for hydrologic simulations that are used by the AG Package (Harbaugh, 2005; Markstrom and others, 2008; Niswonger and others, 2011).

# Methods

## Description of the Agricultural Water Use Package

The AG Package can be used to simulate irrigation with 4 different configurations (Fig. 1):

1. **Specified NIWR supplied by surface water or groundwater**

NIWR set using time varying surface water diversions specified in the SFR Package, or time varying pumping rates specified in the AG Package. Irrigation water is applied to UZF1 cells or PRMS HRUs, and ET can be simulated by UZF1 or PRMS, including groundwater and surface water return flows. Alternatively, crop consumption can be specified and automatically removed from the model, and the difference between irrigation water delivery and specified consumption is applied as groundwater return flow.

1. **Specified NIWR supplied by surface water and supplemented by groundwater**

This option is identical to (1) except that groundwater pumping rates for irrigation are not specified directly. Rather these rates are calculated as the difference between the NIWR and diverted surface water rate, referred to as the surface water shortfall ():

(1)

Where (L3/T) is the surface water diversion rate that can be less than NIWR if surface water supplies limit the diversion rate; is the maximum percentage of NIWR that will be supplemented by groundwater. The amount of supplementary pumping is calculated as (:

. (2)

Where is the fraction of that will be supplemented by groundwater pumping.

1. **Simulated NIWR**

NIWR is calculated by the model according to:

, (3)

Where is the total irrigation water loss or gain that occurs between the diversion or well and the agricultural field(s). NIWR is calculated by minimizing the ratio of crop reference ET () for well-watered conditions () and the simulated actual crop ET (). Supplementary groundwater pumping can be used to supply the NIWR as described in option 2.

1. **Triggered irrigation events**

For this option, the onset of an irrigation event is triggered when the ET ratio falls below a user specified threshold. Once the irrigation event is triggered it continues for the user-specified irrigation period at the user specified time varying application rate. Supplementary groundwater pumping can be used to supply the NIWR after an irrigation event is triggered as described in option 2.

All 4 configurations rely on irrigation water that is supplied by SFR diversion segments and/or AG Package groundwater wells (Niswonger and Prudic, 2005). During flow-limited or draw-down limited conditions, irrigation is reduced to the actual diverted and/or pumped amount. Surface water and groundwater return flows caused by irrigation are simulated as runoff produced on the cell/HRU and water reaching the water table beneath a cell/HRU, respectively. Runoff is simulated by UZF/PRMS using the cascade routing approach (Markstrom and others, 2008; Henson and others, 2013), or the UZF1 input option IRUNBND for MODFLOW simulations (Niswonger and others, 2006).

is specified in the UZF1 input file for MODFLOW simulations, or for GSFLOW simulations it is calculated using daily energy balance and one of six options available in PRMS, including Jensen-Haise, Hargraeves-Semani, Penman-Monteith, Priestly-Taylor, Hamon, and pan potential ET modules (Markstrom and others, 2015). HRU-based ET coefficients must be multiplied by the crop coefficient () in the calculation of (Allen and others, 1998). Example problem 2 below demonstrates how is incorporated into GSFLOW simulations for the Jensen-Haise formulation. is calculated using the UZF1 Package or by the PRMS Soilzone Module using a kinematic wave formulation or nonlinear soil-water reservoir approach, respectively (Markstrom and others, 2008).

## Irrigation Systems

The AG Package supports several configurations for representing irrigation systems, including using simple factors that represent the average system gains/losses and crop water consumption to using detailed representations of agricultural infrastructure and model state dependent crop water consumption (Fig. 1A and 1B). For the simpler case, some fraction of the can be removed from the model to represent crop consumption, as an alternative to explicitly simulating ET. For example, a surface water diversion in the SFR Package and a well in the Ag Package can be used to irrigate a group of cells that contain agricultural fields. Assuming irrigation water supply (i.e., annual water yield) is greater than or equal to the for illustrative purposes, an efficiency factor can be used to partition into crop consumption and .

is calculated as:

, (4)

and

. (5)

Where is the irrigation efficiency factor specified in the AG Package input file; is the total irrigation demand, supplied by the surface water diversion and/or groundwater pumping rate, L3T-1; and is the irrigated area (L2) that is represented by the total area of HRUs/cells that receive irrigation water, and is the gross irrigation water requirement that is the amount of water that must be applied to a field such that (LT-1). As described above, is specified in MODFLOW or calculated daily by GSFLOW using energy balance calculations (Markstrom and others, 2015). can be set to values less than one to represent surface water and groundwater return flows on fields, or it can be set to a value of 1 to represent perfect irrigation efficiency, and all water that reaches fields will be removed from the model. However, it is recommended that ET be simulated explicitly when interested in representing the impacts of infiltration capacity on irrigation water partitioning, such that will be applied to a cell/HRU. When simulating ET explicitly, should be set to zero. If not simulating ET explicitly then return flows are calculated using separate efficiency factors for surface water and groundwater as:

. (6)

Where is the total return flow that will percolate to the water table or runoff laterally to receiving streams or HRUs; and are the surface water and groundwater irrigation delivery rates (L3T-1), which can be less than the diversion rate and/or pumped amount due to system gains and losses from leaky canals or pipes between the point of diversion and the fields. These system losses can be simulated explicitly using pervious pipes/canals using the SFR Package, or they can be included implicitly using efficiency factors. The amount of water applied to each cell/HRU () is:

. (7)

Where is the field factor specified in the AG Package input file to represent how the is distributed among cells/HRUs that are irrigated by an SFR diversion and/or AG Package well, and *i* is the index to the cell/HRU. for all cells/HRUs irrigated by a diversion should sum to one. If efficiency factors are used (eq. 6) to represent crop consumption ( and > 0), then ET should not be simulated on cells/HRUs (Fig. 1A and 1B). If explicitly is simulated using the specified or calculated and the UZF1 Package or PRMS Soilzone Module then irrigation is partitioned into , surface water return flow, and groundwater return flow using the hydraulic properties of the cell/HRU and the runoff and unsaturated flow simulation capabilities in UZF1 or PRMS. Note that equations 4-7 are used to simulate crop consumption and return flow due to irrigation from a single surface water diversion and/or well; however, a cell can be irrigated by multiple diversions or a combination of surface water diversions and groundwater wells.

The third approach for simulating water use by agriculture is to have the model calculate using the dynamic ET deficit (Fig. 1C). As with options 1 and 2, option 3 can be used in MODFLOW or GSFLOW simulations. is not determined by the specified SFR diversion or the specified pumping rate, rather the NIWR is calculated as the amount of water that must be diverted and/or pumped such that the difference between the simulated and is minimized. For GSFLOW, is calculated as:

. (8)

The volumetric rate of water consumed by a crop under well-water conditions () is:

, (9)

and for MODFLOW simulations:

. (10)

and are the total number of HRUs or cells irrigated by a diversion, respectively. is calculated using the previously described approaches by GSFLOW. The diversion amount is calculated by minimizing (min) the ET deficit ( as:

, (11)

Subject to the amount of surface water available for the diversion and/or well pumping capacity/aquifer production. In addition to simulated water supply constraints, values specified for diversions in the SFR Package input file and pumping rates specified in the AG Package can be used to constrain irrigation timing and maximum amounts. For example, specified diversions and pumping rates can be used to represent growers that only can divert water or pump groundwater for irrigation during specific time periods, or to represent water rights, surface water conveyance, or pump capacity.

Assuming for simplicity that one well supplements one diversion, is calculated to minimize as:

, (12)

Where

, (13)

and is a nonlinear acceleration parameter that controls the convergence of during nonlinear iterations, and is the nonlinear iteration counter. The diversion amount is calculated from during each nonlinear iteration according to:

, (14)

and the supplemental groundwater pumping rate ( is calculated using equations 1 and 2; is the surface water diversion amount required to meet the for nonlinear iteration (L3/T-1). The amount of water that is applied to each cell/HRU that is irrigated by a diversion/well is:

. (15)

Where and are the fractions of the total irrigation water delivery from surface water and groundwater, respectively. If irrigation water solely is supplied by a well then the pumping rate is calculated using equations 12-14.

The fourth approach for simulating agricultural water use automatically starts irrigation events when the ET deficit decreases below a user-specified threshold for each agricultural system in the model (Fig. 1D). During the growing season, irrigation is turned on when:

, (16)

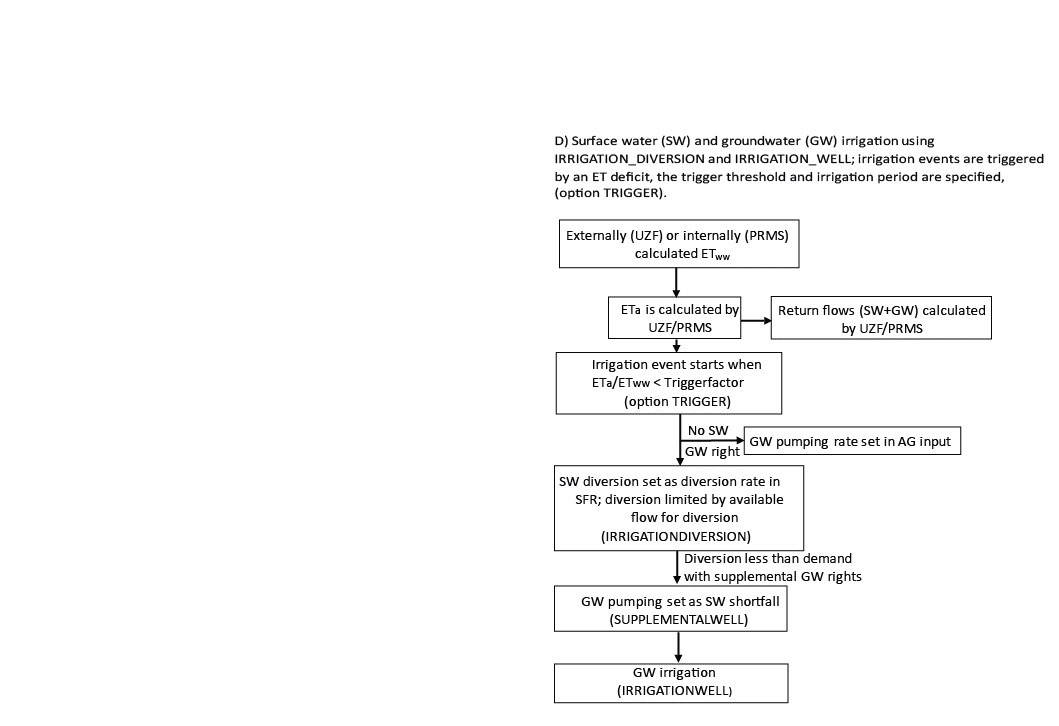
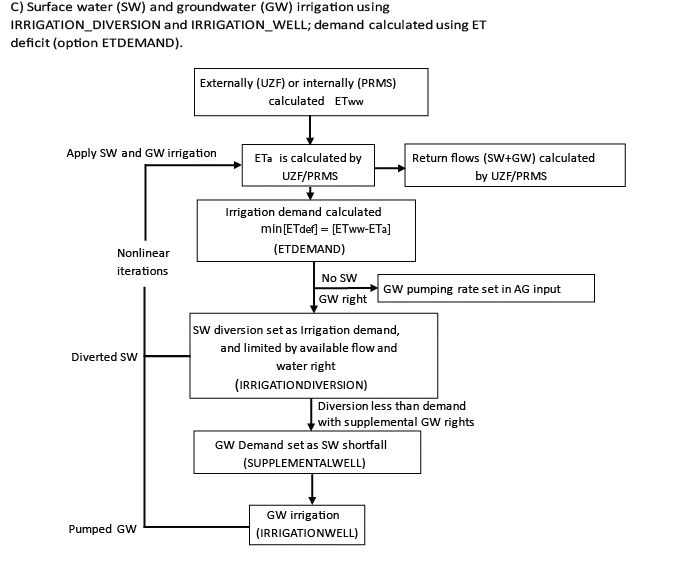
And the irrigation event continues until:

. (17)

Where is the user specified ET deficit threshold that triggers an irrigation event, and and are the elapsed and specified irrigation time, respectively. The surface water irrigation or groundwater pumping rates for this option are set as the user-specified SFR diversion rate and AG well pumping rate, respectively, subject to water supply constraints.

As with the third approach, ET is simulated using energy and water balance formulations, and water is explicitly diverted and/or pumped and applied to fields.





1. Flow charts showing four different configurations for using the agricultural Water Use Package; A) Surface water irrigation using IRRIGATION\_DIVERSION Option; B) Surface water (SW) and groundwater (GW) irrigation using IRRIGATION\_DIVERSION and IRRIGATION\_WELL; C) Surface water and groundwater irrigation using IRRIGATION\_ DIVERSION and IRRIGATION\_WELL, demand calculated as ET deficit using ETDEMAND;.D) Surface water and groundwater irrigation using IRRIGATION\_ DIVERSION and IRRIGATION\_WELL, irrigation events are started when is below Triggerfact using option TRIGGER.

# Example Problems

Two test problems are presented to illustrate the capabilities of the AG Package for simulating water use by agriculture in MODFLOW-NWT and GSFLOW. Test problem 1 was modified from Test 1 presented previously by Prudic and others (2004). Test problem 2 was modified from the Sagehen Creek Watershed GSFLOW example problem. Although there is no agriculture in the Sagehen Creek Watershed, the AG Package was added for this example to simulate irrigation from surface water and supplementary wells to several HRUs in the lower part of the watershed that represent hypothetical agricultural fields.

## Example Problem 1

This test model represents an alluvial river basin in a semi-arid region. Agriculture in central part of the basin relies on water diverted from the Green River and pumped from the shallow aquifer. The basin receives most of its precipitation in the surrounding mountains, and intermittent streams drain the mountains and flow into a perennial river that crosses the southern portion of the valley (Fig. 2). The valley aquifer consists of alluvium dominated by sand and gravel, and the mountains consist of bedrock that has much lower hydraulic conductivity than the valley alluvium. Recharge in the basin primarily occurs as seepage loss from the intermittent stream channels and to a lesser extend as groundwater flowing to the valley from the mountain block.



1. Map showing basin topography, streams and canals, and agricultural region for example problem 1.

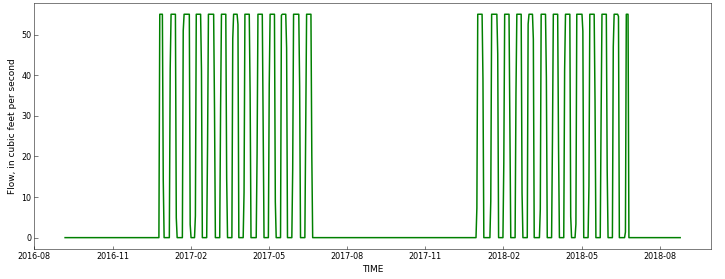
The model domain extends to a maximum of 520 feet below land surface in the valley bottom; and extends laterally 75 km in the north-south direction, and 50 km in the east-west direction (Fig. 2). The model is discretized into 1 layer, 15 rows, and 10 columns, and only model cells coincident with the basin fill are active; consolidated rocks are not included. Layer 1 ranges in thickness between 130 feet and 520 feet. Model cells have a constant dimension of 5000 feet in the row and column directions. Two tributary streams that enter the model from the northwest and northeast join the mainstem in the southern part of the model (Fig. 2). Twenty-four transient stress periods are simulated, proceeded by an initial steady state stress period. Each stress period represents a calendar month and are divided into daily time steps. The simulation begins on January 1.

Hydraulic conductivity and specific yield of the water table aquifer increase in the valley bottoms that comprise of floodplains or new alluvium of the tributary streams and river (Table 1). Prudic and others (2004) present additional details describing this test problem, including representation of the stream network, and distribution of recharge and ET parameters used within the model. Niswonger and others (2006) describe modifications made to this example to replace the ET and Recharge Packages with the UZF1 Package; excess applied infiltration and rejected infiltration/spring discharge is routed to streams. is specified in UZF1 Package and varies on a monthly basis. Other UZF1 Package input values were modified from previous values to better represent agricultural water use.

Two versions of Example Problem 1 are presented. Example Problem 1a (EP1a) simulates irrigation water provided by surface water and supplementary groundwater, and Example Problem 1b (EP1b) that simulates irrigation water provided solely by groundwater. Both models simulate irrigation demands using the ETDEMAND approach that minimizes the ET deficit using equation 11. Figure 2 shows the cells designated as agricultural fields that receive irrigation. SFR diversion segment number 9 was used to divert water from the Green River and route it to the fields (Fig. 2). The irrigation schedule or maximum surface water diversion for irrigation for EP1a and EP1b is 7 days of irrigation followed by 7 days without irrigation during the April to September period, and a maximum rate of 55 ft3/s can be diverted from the stream for irrigation (Fig. 3). These constraints on the surface water diversions for irrigation were specified using a time series inflow file for SFR segment 9 (Fig. 2). EP1b is identical to EP1a, except that NIWR is satisfied by groundwater instead of surface water. An important difference between EP1a an EP1b is that control on the timing of irrigation events set in EP1a (Fig. 3), limits irrigation, representative of deficit irrigation practices. For EP1b maximum pumping rates are set to large values (10,000 ft3/s) in the AG Package input file to avoid any constraints on irrigation. Thus, equals throughout the EP1b simulation.

## Example Problem 1a Results

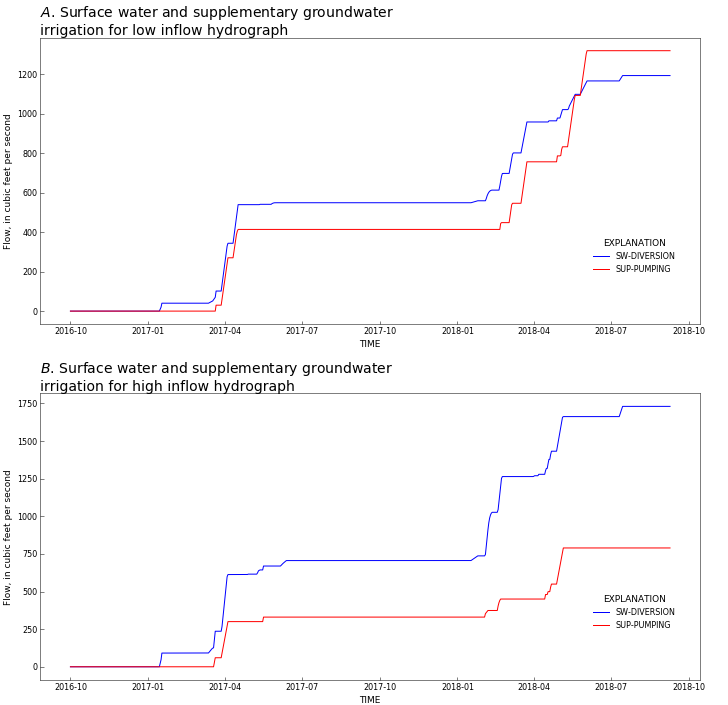
EP1a was run with 2 different inflow hydrographs to evaluate how differences in surface water supply impact the relative proportions of surface water and supplemental groundwater used for irrigation (Fig. 5). In many agricultural regions irrigation is provided by surface water and groundwater to supplement surface water during drought or seasonally low flow periods. This example also illustrates how irrigation can be turned on or off during specific time periods, such as when a water master staggers delivery of surface water among different growers to reduce the instantaneous diversion rate from a stream. Figure 6 shows the proportions of surface water and supplementary groundwater used for irrigation for the cases with a high and a low inflow hydrograph. Supplementary groundwater makes up a greater proportion of the for the simulation with a low inflow hydrograph due to surface water supply constraints (Fig. 6). Because surface water and groundwater irrigation are not applied when diversion flows are set to zero (Fig. 4), an irrigation deficit causes to be less than intermittently for both the low and high inflow hydrographs (Fig. 6). Note that irrigation scheduling defined using time series input files for the SFR Package also controls the schedule for supplemental groundwater pumping. Thus, when diversion flows are set to zero, supplemental groundwater pumping also is set to zero (Fig. 4).



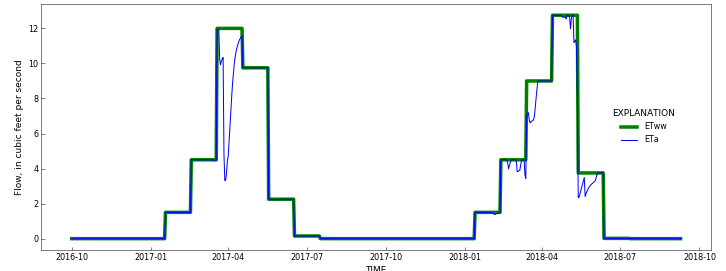
1. Maximum irrigation diversions during growing season. Diversions and supplementary pumping for irrigation are limited to periods when flows are nonzero.



1. Inflow hydrographs for test model 1a, representing years of average and below average precipitation.



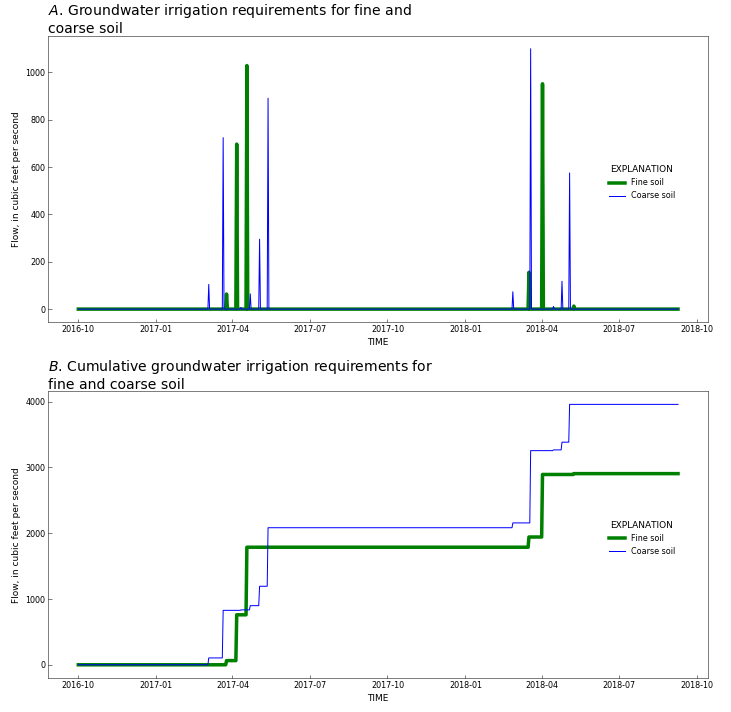
1. Irrigation provided by surface water diversions and groundwater pumping for A) low, and B) high inflow hydrographs shown in Figure 4.



1. Well-watered and actual evapotranspiration for simulated agricultural fields in example problem 1a.

## Example Problem 1b Results

This example problem is run for 2 different agricultural field soil types, including fine and coarse soil textures. Note that unlike example problem 1a, there is no defined irrigation schedule, and that irrigation events are determined by the ET deficit (Fig. 8). The coarse soil requires irrigation earlier during the growing season relative to the fine soil due lower antecedent soil moisture at the onset of the growing season (Fig. 8). Faster drainage increases the NIWR for coarse soils due to greater amounts of groundwater return flows. A single irrigation event requires a maximum of 7 inches applied to an area of 3,440 acres of fields, and 2-3 large irrigation events are required per season to satisfy crop-water demands.

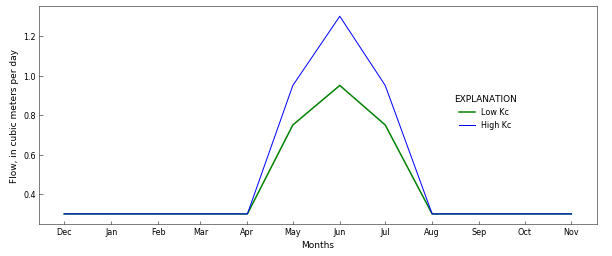


1. Groundwater pumping for irrigation in example problem 1b with fine and course agricultural soil properties.

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## Example Problem 2

Sagehen Creek drains a of 27 km2 watershed on the east slope of the northern Sierra Nevada (Fig. 8). Geology of the Sagehen Creek watershed consists of granodiorite bedrock overlain by andesitic, tertiary volcanics, which are overlain by till and alluvium composed of granodiorite and andesite clasts and some quaternary gravels (Burnett and Jennings, 1965).Very little is known regarding the depths and thickness of these different geologic formations. However, the volcanics were assumed to make up the principal component of the watershed aquifer and the volcanics were assumed to range in thickness between 50 and 300 m. Alluvium is thin or nonexistent in the upper parts of the watershed and thickens in the lower parts and near stream channels (Burnett and Jennings, 1965). Alluvium was assumed to range in thickness between 0 and 10 m.



1. Seasonal crop coefficient (Kc) used for simulating agricultural water use in example problem 2a.

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1. Surface water diversions for irrigation in example problem 2a, using low and high crop coefficients (Kc) shown in Figure 8.

# Discussion

While

# Conclusions

# Acknowledgements

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