An Agricultural Water Use Package for MODFLOW and GSFLOW

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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. Three options are available for simulating water use for agriculture: 1) user-specified demands, 2) demands determined by a user specified irrigation trigger value that is compared to the ratio of the simulated actual to reference evapotranspiration (ET), and 3) demands determined by the optimal amount of irrigation required to minimize the difference between reference and actual ET. The latter two approach use energy and soil-water balance to determine demands and to simulate crop consumption and return flows. Irrigation water is diverted into canals and routed to fields using the MODFLOW SFR Package, or irrigation water can be supplied/supplemented by groundwater wells. Combined with MODFLOW or GSFLOW, the AG grossPackage can simulate dynamic water use by agriculture in developed basins while providing flexibility to represent a range of grower behaviors and irrigation infrastructure.

# Keywords

Integrated hydrologic modeling, agricultural water use, GSFLOW, MODFLOW, drought, water resources, conjunctive use, surface water and groundwater interactions

# Software and/or data availability section

Software and data used for this work, model input files for each example problem, and ancillary data are available through the GitHub repository [address]. The Agricultural Water Use Package was developed by Richard Niswonger (rniswon@usgs.gov), year first available, hardware required, software required, availability and cost. GSFLOW and its components are written in Fortran, and the program files are less than 10 Mbytes ; for data: form of repository (database, files, spreadsheet), size of archive, access form.

# 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 et al., 1996; Jones et al., 2017). Water management decision support software is paramount in many river basins in the western United States and other parts of the world for adapting to climate change, population growth, and for evaluating new water management strategies (Tian et al., 2015). Hydrologic models that incorporate surface water and groundwater can provide valuable information about water resources sustainability in conjunctive-use systems. This is especially true for agricultural regions susceptible to climate change and population growth that stress water supplies (Faunt, 2009; Elliott et al., 2014; Gorelick and Zheng, 2015).

Hydrologic software such as MODFLOW simulates 3-dimensional groundwater flow and includes many add-on capabilities, such as representation of surface-water features and other hydrologic processes (Harbaugh, 2005; Langevin et al., 2017). GSFLOW is the integration of MODFLOW and PRMS and can simulate all major hydrologic processes in watersheds, including distributed energy and water consumption by plants (Markstrom et al., 2008; Markstrom et al., 2015). GSFLOW can simulate partitioning of precipitation into snowpack, runoff, evapotranspiration (ET), and groundwater flow using energy and water balance approaches (Markstrom et al., 2008).

MODFLOW and GSFLOW have been used for simulating regional-scale agricultural systems (Hu et al., 2010; Bailey et al., 2016; Wu et al., 2016; Guzman et al., 2015; Woolfenden and Nishikawa, 2014; Essaid and Caldwell, 2017). An add on to MODFLOW called the Farm Process was developed to represent agricultural systems supplied by surface water and groundwater (Schmid et al., 2006; Hanson et al., 2010; Hanson et al., 2014). A common approach for simulating agricultural systems in groundwater and surface water models is to estimate demands as a pre-processing step, and to subsequently apply these demands to hydrology simulations to avoid simulating field-scale soil water balance (Hanson et al., 2010, Woolfenden and Nishikawa, 2014; Dogrul et al., 2011). In these cases, irrigation demands are estimated externally and independent of evolving conditions in the hydrology model.

As presented herein, another approach is to dynamically calculate demands within an integrated surface water and groundwater hydrology model using energy and field-water balance. The advantage of this approach is that simulated demands and water use are consistent with dynamic conditions in the model. Furthermore, simulated crop consumption can be validated using independent estimates to constrain simulated irrigation water diversions and groundwater pumping during model calibration (e.g., Huntington et al., 2017).

Here we present the Agricultural (AG) Water Use Package for MODFLOW and GSFLOW for basin-scale simulations. 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 et al., 2006). Because the irrigation demand, 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 et al., 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 river/reservoir-operations models such as MODSIM for simulating impacts of water use priorities on agricultural systems (Labadie, 2010; Morway et al., 2016; Niswonger et al., 2017).

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 and irrigation techniques. Example problem 1 demonstrates the new package in a MODFLOW simulation and represents an agricultural basin in northwest Nevada (Prudic et al., 2004). The second example demonstrates the package in a GSFLOW simulation and represents an undeveloped basin in northeast California, including hypothetical irrigated regions. Previously published work provides 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 these published works for simulation 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 et al., 2008; Niswonger et al., 2011).

# Methods

## Simulating agricultural water use in MODFLOW and GSFLOW

### Irrigation water delivery

In practice, irrigation water is diverted or pumped from one location, and it is routed through reservoirs, streams, canals, pipes, and furrows to its place of use (Fig. 1). A place of use is an agricultural field where plant roots uptake water from shallow soils. As water is delivered to its place of use, part of it is lost along the way due to ET, leaky pipes and canals, misdirected surface flows, and seepage. Irrigation water also can increase during delivery if the irrigation system gains from other sources. Not all the water applied to a field is used by the crop, and instead there are field losses due to surface runoff, seepage below the plant roots, and evaporation. Field losses depend on field conditions and the irrigation scheduling and rates that vary with the irrigation approach that is used to apply water to the field, including flood, sprinkler, and drip irrigation. Gains and losses cause the amount of irrigation water at the point of diversion to be different than the amount of water at the place of use. This difference is referred to as the system efficiency (Allen et al., 1998). The AG Package was developed to represent these processes explicitly using hydrologic simulation capabilities in MODFLOW and GSFLOW or implicitly by specifying efficiency factors to represent all or a portion of the system gains and losses.

Surface water delivery for irrigation is simulated by the MODFLOW Streamflow-Routing (SFR) Package, including open channel flow in streams, canals, and pipes (Prudic et al., 2004; Niswonger and Prudic, 2005). Surface water demands for diverting irrigation water can be set by user-specified values, or they can be calculated by the model using field-based crop-water demands. SFR routes steady or kinematic flow by coupling continuity and Mannings’s equation and user-defined relationships between flow, area, and depth to represent a variety of flow geometries. SFR assumes atmospheric pressures and neglects diffusion and other acceleration terms in the shallow water and pipe flow equations; however, as times steps are typically 1 day or longer, this simplification is generally applicable for regional agricultural systems. Diversion segments are used to deliver irrigation water and are initialized in the SFR input file. Diversion segments can be designated as irrigation segments in the AG input file using the character variable IRRSEGMENT to apply diverted surface water to fields.

Surface reservoirs are simulated by the MODFLOW Lake (LAK) Package for MODFLOW simulations and/or open detention storage reservoirs for GSFLOW simulations (Merritt and Konikow, 2000; Regan and LaFontaine, 2017). SFR routes channel flows into and out of reservoirs represented by LAK and open detention storage reservoirs in PRMS. Diversion segments and reservoirs represented by SFR and LAK are integrated with the groundwater flow equation to simulate surface water and groundwater interactions; however, open detention reservoirs do not interact with groundwater.

Groundwater irrigation is provided by wells that pump water from a model layer. Wells are defined, and pumping rates are specified within the AG Package input file, and wells function like the WELL Package for MODFLOW-NWT (Niswonger et al., 2011). AG wells must have negative pumping rates (out of aquifer), and pumping rates can be reduced due to drawdown of the water table. Groundwater wells are designated in AG as irrigation wells using the character input variable IRRWELL to apply pumped groundwater to fields. Pumping rates for irrigation wells can be set by user-specified values, or they can be calculated by the model using groundwater irrigation demands. Pumping rates also can be calculated by the model to supplement surface water demands using the character input variable SUPWELL.

Irrigation from diversion segments and groundwater wells is applied to designated cells or HRUs according to user-defined mapping that links segments and wells to cell/HRU identifiers. Irrigation is applied over the entire area of cells/HRUs, and thus, irrigation cannot be applied to a partial area of a cell/HRU. A diversion and/or well can provide water for multiple cells/HRUs or multiple diversions and/or wells can provide water for a single cell/HRU. Additionally, a well can supplement several diversions or several wells can supplement one or more diversions.

### Simulating crop consumption

ET can be simulated using a daily energy and field-water balance for GSFLOW simulations, or ET can be simulated for any time step length with the user-specified reference evapotranspiration () and soil-water balance in the UZF Package for MODFLOW simulations (Markstrom et al., 2008; Niswonger et al., 2011). Sub-irrigation can occur where the water table is near the crop root zone. Sub-irrigation is simulated by UZF for MODFLOW simulations using a linear function of the depth to the water table; groundwater ET is simulated in GSFLOW by groundwater discharge to the PRMS soil zone due to linear capillary rise or saturated discharge conditions (Niswonger et al., 2006; Markstrom et al., 2008).

The product of the crop coefficient and reference ET () is specified in the UZF input file using the input variable PET for MODFLOW simulations. GSFLOW simulations calculate using one of six options available in PRMS, including Jensen-Haise, Hargraeves-Semani, Penman-Monteith, Priestly-Taylor, Hamon, and pan potential ET modules (Markstrom et al., 2015). HRU-based ET coefficients must be multiplied by the crop coefficient () for the calculation of (Allen et al., 1998). Example problem 2 below demonstrates how is incorporated into GSFLOW simulations for the Jensen-Haise formulation. is calculated using the UZF Package or by the PRMS Soilzone Module using a kinematic-wave formulation or nonlinear soil-water reservoir approach, respectively (Niswonger et al., 2006; Markstrom et al., 2008; Markstrom et al., 2015). Root uptake by crops is simulated in the PRMS soil zone using a conceptual function of soil saturation (Markstom et al., 2008).

Rather than using the conventional approach for simulating in UZF, a new option was added to support the AG Package that uses a pressure gradient approach. This is the same approach documented in the newest version of MODFLOW called MODFLOW6 (Langevin et al., 2017). For this case, the capillary pressures are calculated in the crop root zone using the Brooks-Corey retention function and 3 new UZF input variables, including the root activity function, air entry pressure and root pressure (Lappala et al., 1987). is calculated using:

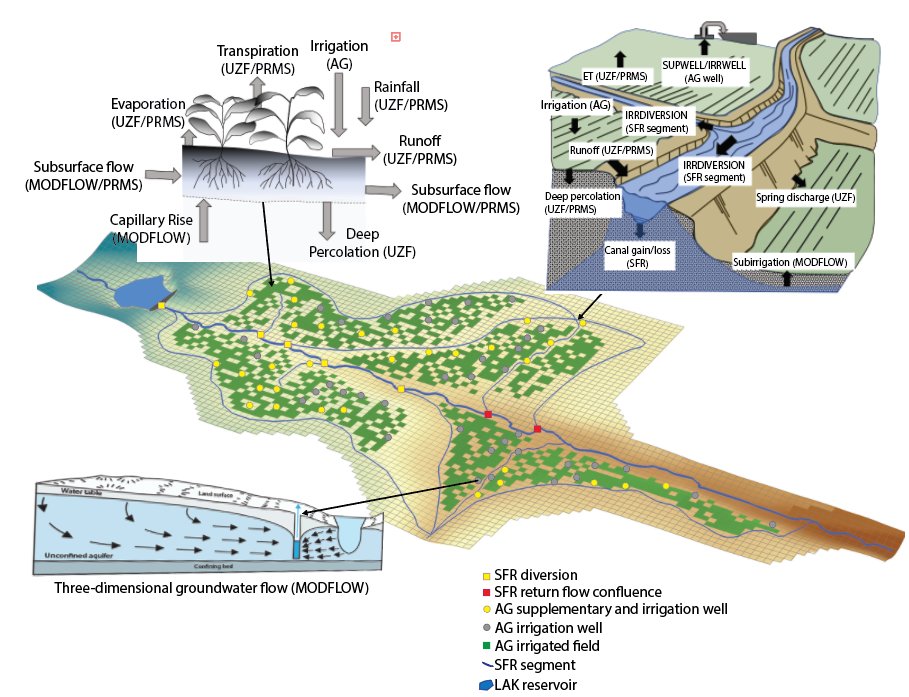
(4)

Where is the thickness of the root zone that can change during the growing season (L); is unsaturated hydraulic conductivity as a function of water content (LT-1), is the root activity function that can change during the growing (L-2); is capillary pressure as a function of water content (L), and is the negative root pressure (L). Variables in equation 4 are calculated using Brooks and Corey (1966) unsaturated hydraulic conductivity and capillary pressure functions.

### Simulating irrigation return flows

Irrigation return flow is water that returns to a surface water body or seeps to groundwater rather than entering the atmosphere due to ET. It is considered returned because the water becomes available to other growers or for other uses in the system. Return flow can occur at any point along the path between the point of diversion and the place of use. Water that is diverted from a stream or pumped from the ground is delivered to its place of use by irrigation infrastructure. Irrigation infrastructure is represented in the model using SFR segments, LAK and PRMS open detention reservoirs, and groundwater pumping wells. Gains and losses in surface networks are simulated through the coupling of SFR to the unsaturated zone beneath streams or groundwater flow equation in MODFLOW (Prudic et al., 2004; Niswonger and Prudic, 2005). Similarly, reservoirs interact with groundwater and spill water that flows to other locations in the system. Pipe networks represented by SFR segments can be made semi-pervious to represent leaky pipes.

Return flow also can occur while water is applied to a field. There is no explicit representation of irrigation technology in the AG Package, such as sprinkler and drip equipment; however, differences in how irrigation is applied can be emulated by irrigation scheduling and application rates. Accordingly, water can be applied to fields at a greater rate to represent flood irrigation, and at a lower rate to represent sprinkler irrigation. Depending on the application rate and duration, a portion of this water will runoff and flow laterally toward another surface water body. Runoff is routed in UZF using the IRUNBND procedure for MODFLOW simulations and by the PRMS cascade routing procedure for GSFLOW simulations (Niswonger et al., 2006; Markstrom et al., 2008; Henson et al., 2013). Additionally, applied irrigation water can pass through the root zone beneath a field and deep percolate to the water table. The amount of deep percolation also is dependent on irrigation technology, scheduling, and field hydraulic properties that can vary for each cell/HRU representing fields in the model. Irrigation return flow also can be set using irrigation efficiency factors instead, or additional to, the previously described physical representation.



1. Illustration showing how regional agricultural processes are represented in MODFLOW and GSFLOW. Surface water and groundwater can be used for irrigation by designating diversion segments as irrigation diversions (IRRSEGMENT) and designating wells as irrigation wells (IRRWELLS) and/or supplementary wells (SUPWELLS) in the AG Package. Diversion segments are included as part of the regional stream network within the Streamflow Routing (SFR) Package and are designated as irrigation segments in the AG Package.

## Irrigation demand and scheduling

### Options for setting demand and schedule

The irrigation demand and schedule can be simulated with 3 different approaches (Fig. 2):

1. **User-specified irrigation demand and schedule using surface water diversions and/or groundwater wells (Fig. 2a)**

Irrigation demand is 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 MODFLOW cells or PRMS HRUs, and ET, groundwater return flow, and surface water return flow can be simulated by UZF for MODFLOW simulations or PRMS for GSFLOW simulations. Alternative to using UZF or PRMS to simulate ET, crop consumption can be specified using efficiency factors, and the difference between irrigation water delivery and specified consumption is applied as groundwater return flow. If crop consumption is simulated using efficiency factors, then applied water is equal to the groundwater return flow and surface water return flow is assumed to be zero.

Irrigation wells can be designated as supplementary wells, and rather than specifying pumping rates, they are calculated as the difference between the irrigation demand and the actual diverted surface water rate, referred to as the surface water shortfall (; L3/T):

(1)

Where (L3/T) is the volumetric flow rate for the irrigation period required for crop growth, (L3/T) is the surface water diversion rate that can be less than or equal to if surface water supplies limit the diversion rate; is the maximum percentage of that will be supplemented by groundwater. The amount of supplementary pumping is calculated as (; L3/T):

, (2)

where is the fraction of that will be supplemented by groundwater.

1. **Triggered irrigation events**

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 application rate. Supplementary groundwater pumping can be used to satisfy demand after an irrigation event is triggered as described in option 1. Irrigation events can be triggered consecutively if the ET ratio remains below the specified threshold. Surface water and groundwater return flows can occur during delivery and on farms.

1. **Optimal net irrigation water requirement**

Net irrigation water requirement (NIWR; LT-1) is the quantity of water required for plant growth expressed as the volume of irrigation water divided by irrigation time and irrigated area (Allen et al., 1998). NIWR is calculated by the model according to:

, (3)

where (LT-1) is the quantity of irrigation water loss or gain that occurs during irrigation delivery divided by the irrigated area, not including return flows that occur on the field, and is the gross irrigation water requirement defined as the quantity of water required for plant growth minus all gains and losses that occur during irrigation delivery (LT-1). NIWR is calculated by minimizing the difference between (LT-1) and the simulated actual crop ET (; L). Supplementary groundwater pumping can be used to supply the NIWR as described in option 1. Surface water and groundwater return flows can occur during delivery and on farms.

### Calculation of the irrigation demand, schedule, and return flow

The AG Package supports three approaches for setting irrigation schedules and demands, including a simple approach of using efficiency factors that represent the average system gains/losses and crop water consumption, to the more complicated approach using detailed representations of agricultural infrastructure and model state dependent crop-water demand and consumption (Fig. 2). Irrigation demand is user-defined or calculated by the model for each irrigation diversion segment or irrigation well. Demand for supplemental wells is set using the demand for the associated diversion segment(s). Field properties, including crop type are assumed constant for each cell/RHU. Irrigation demands, crop consumption, and return flows are calculated as rates over the model time step.

The default approach is the simplest approach and relies on user-specified demands. This approach can include explicit simulation of ET using UZF/PRMS, or ET can be specified through efficiency factors that are used to partition into consumption and return flow (Fig. 2A). Efficiency factors also can represent gains and losses during irrigation delivery if they are not simulated explicitly using SFR and LAK. Assuming irrigation water supply is greater than or equal to the crop-water demand for illustrative purposes, an efficiency factor can be used to partition irrigation water into crop consumption and return flows on the field (Fig. 2a).

is calculated as:

, (4)

and

. (5)

Where is the irrigation efficiency factor that is specified in the AG Package input file; is the user-specified irrigation demand associated with an irrigation diversion and/or groundwater well (L3T-1); and is the irrigated area (L2) that is represented by the total area of HRUs/cells that receive water from an irrigation diversion. As described above for explicit simulation of ET, is specified in UZF for MODFLOW simulations, or is calculated by GSFLOW using energy balance calculations.

When simulating ET explicitly, should be set to zero. If not simulating ET explicitly then field return flows are calculated using separate efficiency factors for surface water and groundwater as:

. (6)

Where is the return flow generated on the fields (L3/T-1); is the surface water irrigation delivered to the field, and is the groundwater irrigation, respectively (L3T-1).

The amount of water applied to each cell/HRU per unit area (; LT-1) 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 a diversion and/or well. 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 be made zero in UZF/PRMS cells/HRUs that contain fields.

The second approach for simulating irrigation demand and scheduling is activated when the character input variable TRIGGER is specified in the AG input file (Fig. 2B). Irrigation automatically starts when the ET ratio () averaged over all fields supplied by a diversion decreases below a user-specified threshold. During the growing season, irrigation is turned on when:

, (8)

And the irrigation event continues until:

. (9)

Where is the user specified ET deficit threshold that triggers an irrigation event, and and (T) are the elapsed and specified irrigation time, respectively. Conditions for starting a new irrigation period are evaluated at the end of each period, and irrigation can occur for consecutive periods. Irrigation demands are specified in the SFR input file for surface water and supplementary groundwater wells, and demands are set in the AG input file for irrigation supplied solely by groundwater. Actual irrigation amounts are constrained by the amount of surface water available for the diversion and/or well pumping capacity/aquifer production.

The third approach for simulating irrigation demand and scheduling is activated when the character input variable ETDEMAND is specified in the AG input file (Fig. 2C). 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 MODFLOW simulations, the ET under well-watered conditions () is specified as variable PET in UZF. For GSFLOW, is calculated as:

. (10)

For MODFLOW simulations, the volumetric rate of water consumed by a crop under well-water conditions () is:

, (11)

and for GSFLOW simulations it is:

, (12)

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

, (13)

subject to the amount of surface water available for the diversion and/or well pumping capacity/aquifer production. and are summed over all fields irrigated by a diversion. In addition to simulated water supply constraints, values specified for diversions in the SFR input file and pumping rates specified in the AG input file can be used to constrain irrigation timing and maximum amounts. For example, specified diversions and pumping rates can be used to represent irrigation restrictions during specific time periods, or to represent water rights, surface water conveyance, or pump capacity.

A solution to equation 13 is accomplished by determining the minimum amount of water required to be diverted or pumped to meet the crop-water demand. Crop consumption can be written as a function of the irrigation demand as:

(14)

And after substituting and re-arranging terms, equation 14 becomes:

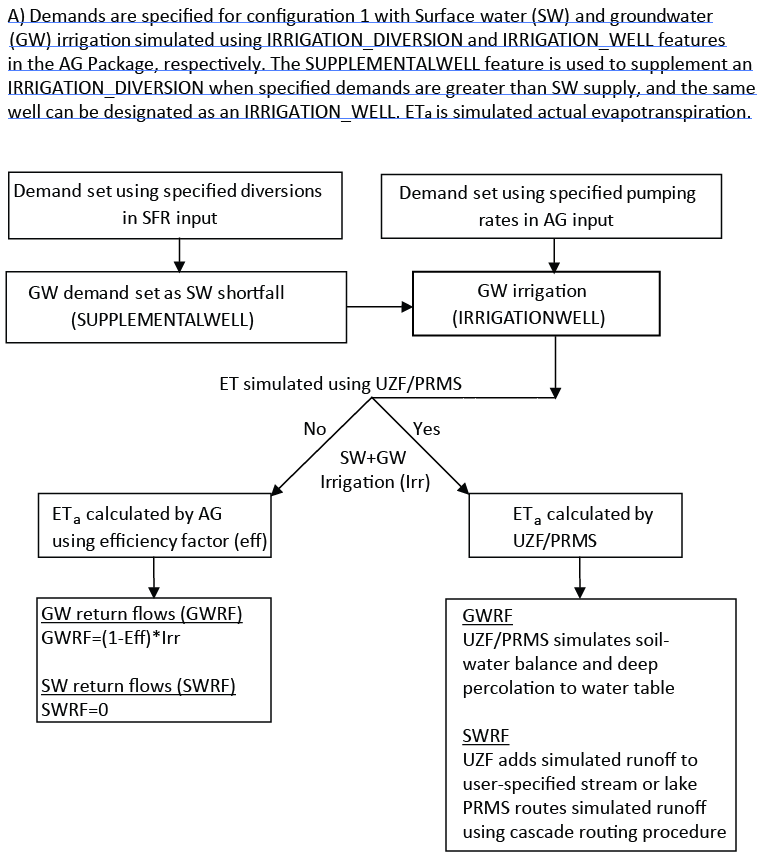
. (15)

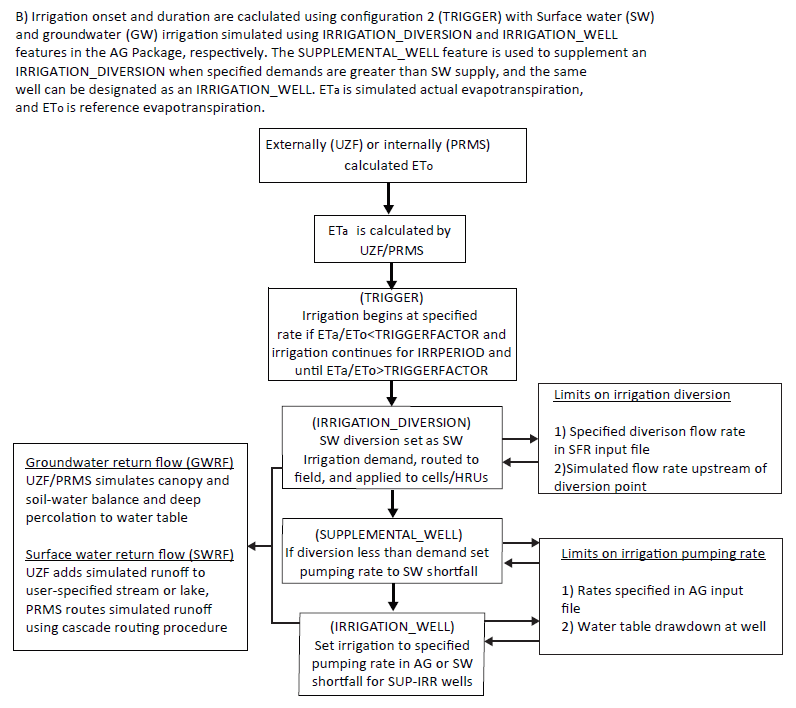
Where is an iteration counter for solving nonlinearities between irrigation demand and crop consumption; and are total irrigation water diverted and/or pumped for iterations i+1 and i, respectively (L3T-1); and are the crop consumption for iterations i+1 and i, respectively (L3/T-1). Note that is also the MODFLOW or GSFLOW outer iteration counter (Niswonger et al., 2011; Markstrom et al., 2008).

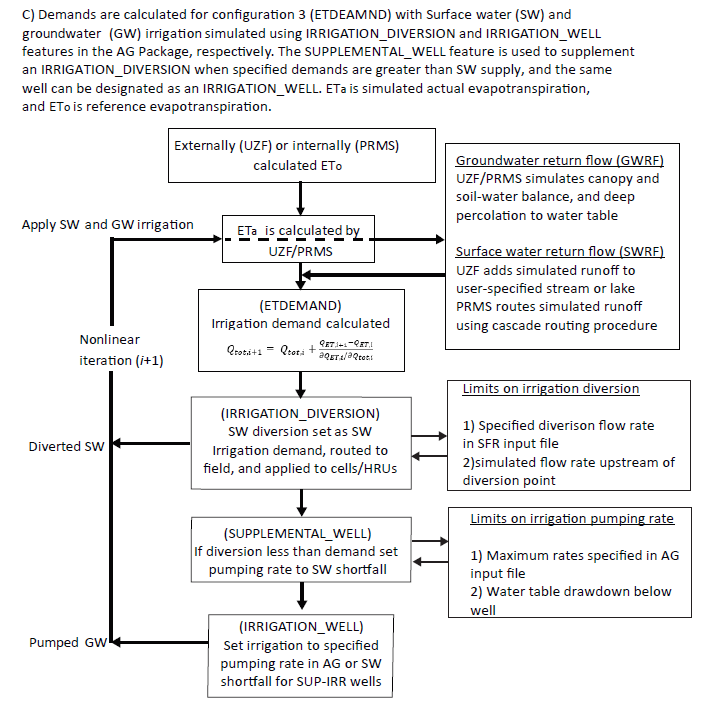
The amount of water that is applied to each cell/HRU that is irrigated by a diversion/well is:

. (16)

Where and are the fractions of the total irrigation water delivery from surface water and groundwater applied to the cell/HRU, respectively.







1. Flow charts showing three different approaches for simulating agricultural water use with the AG Package; A) demands set by user (AG Package default); B) demands calculated by activating irrigation events using an ET trigger (AG Package character input TRIGGER); C) demands calculated using the minimum irrigation water requirement (AG Package character input ETDEMAND) .

# Example Problems

Two example problems are presented to illustrate the capabilities of the AG Package for simulating water use by agriculture in MODFLOW and GSFLOW. Example problem 1 is a MODFLOW simulation that was modified from Test 1 presented previously by Prudic and others (2004). Test problem 2 is a GSFLOW simulation that was modified from the Sagehen Creek Watershed GSFLOW example problem (Markstrom et al., 2008). 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. Both example problems retain the units used in their original presentations, and thus example problem 1 uses English units and example problem 2 uses metric units.

## Example Problem 1: MODFLOW with conjunctive use of surface water (SW) and groundwater (GW), ETDEMAND option

This model represents an alluvial river basin in a semi-arid region. 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 extent as groundwater flowing to the valley from the mountain block and diffuse recharge through valley sediment. 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 UZF Package; excess applied infiltration and rejected infiltration/spring discharge is routed to streams.



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 14 miles in the north-south direction, and 9.5 miles 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. A total of 3,440 acres (6 model cells) are irrigated for agriculture in the central part of the basin; irrigation water is diverted from the Green River and pumped from the shallow aquifer beneath the fields. Two tributary streams that enter the model from the northwest and northeast join the mainstem in the southern part of the model (Fig. 2). Simulations included an initial steady state stress period followed by forty-eight transient stress periods. Each stress period represents a calendar month and are divided into daily time steps. The simulation begins on January 1. Results are presented for the final 2 years of the simulation, as the steady state stress period and first 2 years of the simulations are used to establish initial conditions.

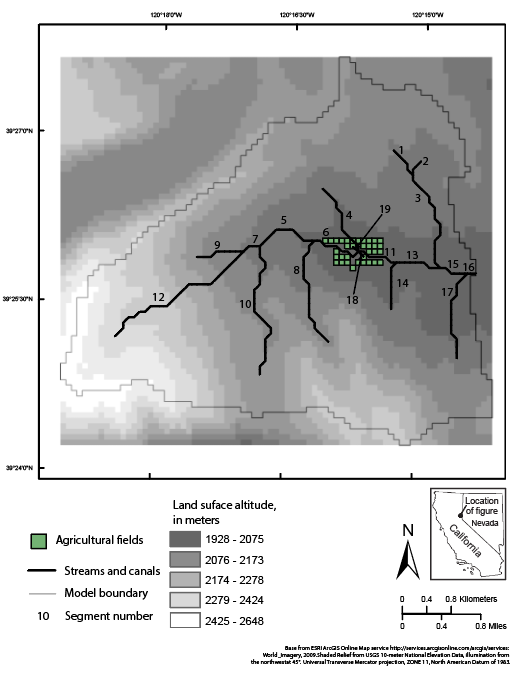
Hydraulic conductivity and specific yield of the water table aquifer increase in the valley bottoms that comprise of floodplains or new alluvium of the tributary streams and river. Monthly was specified in the UZF input file using annual estimates disaggregated into monthly values using average monthly temperatures (Prudic and Herman**,** 1996). Users are referred to the input files for this problem that accompany this work for additional details.

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 15. 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). NIWR is satisfied solely by groundwater in EP1b.

## Example Problem 2: GSFLOW-Conjunctive use of SW and GW, ETDEMAND verses TRIGGER options

Example problem 2 was developed by modifying the GSFLOW Sagehen example problem (Markstrom et al., 2008) to include agricultural fields in the lower part of the basin (Fig. 3). Sagehen Creek drains a of 27 km2 watershed on the east slope of the northern Sierra Nevada. Geology of the Sagehen Creek watershed consists of granodiorite bedrock overlain by andesitic, tertiary volcanic material, which are overlain by till and alluvium composed of granodiorite and andesite clasts and some quaternary gravels (Burnett and Jennings, 1965). The principal aquifer (model layer 2) was assumed to consist of volcanic material with thickness ranging between 50 and 300 m. A veneer of alluvium covers the volcanic material that is thicker along channels in the lower section of the watershed (Burnett and Jennings, 1965). Alluvium (model layer 1) was assumed to range in thickness between 0 and 10 m. The model domain extends laterally 6.4 km in the north-south direction, and 7.1 km in the east-west direction (Fig. 3). The model is discretized into 90x90 m cells using 2 layers, 71 rows, and 79 columns. Eighteen years are simulated, each year is divided into 12 stress periods, each period represents a calendar month and is divided into daily time steps. The transient simulation begins on October 1.

Two versions of example problem 2 are presented. Example problem 2a (EP2a) simulates NIWR by minimizing the ET deficit (ETDEMAND option), and example problem 2b (EP2b) uses the ET deficit trigger (TRIGGER option) to simulate irrigation. Figure 3 shows the cells designated as agricultural fields that receive irrigation, including 34 cells irrigated by 2 segments that divert water from Sagehen Creek. Segment 18 supplies water for 14 cells, and segment 19 supplies water for 20 cells (Fig. 2). All 34 irrigated cells sum to an area to 27.5 hectares. Irrigation can be nonzero during the growing season (June 1-August 30) and zero outside the growing season. These constraints on the surface water diversions for irrigation were specified using time series inflow files in SFR that define maximum diversion amounts for segment numbers 18 and 19. Wells were placed in each agricultural cell for supplementary pumping to meet irrigation requirements.



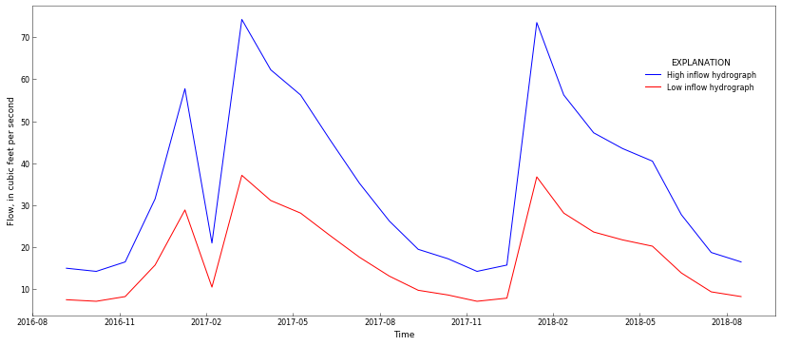
1. Map of Sagehen Creek watershed with hypothetical irrigated fields used in example problem 2.

# Results

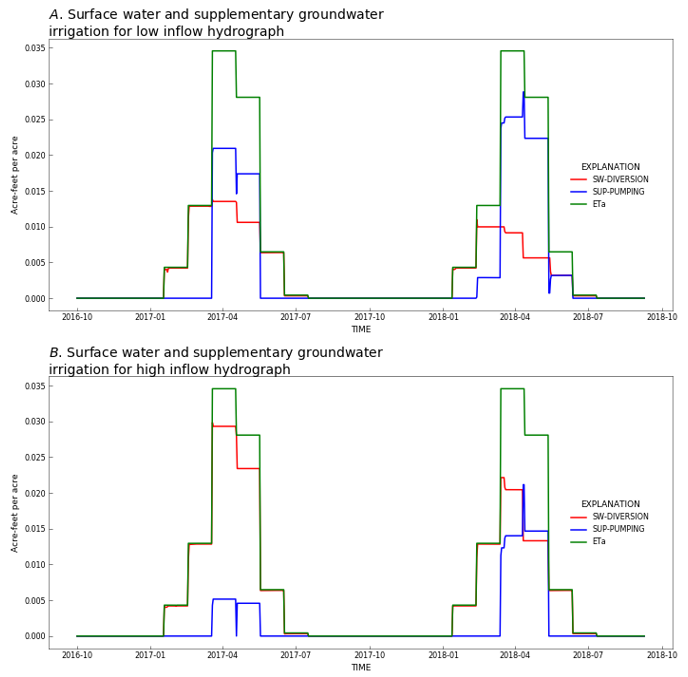
## Example Problem 1a: Impacts of SW supply on supplementary GW pumping

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. 4). In many agricultural regions, irrigation is provided by surface water and groundwater to supplement surface water during drought or seasonally low flow periods. Maximum surface water diversions rates were set within the SFR Package time series input files for an irrigation period from April 1 to September 30, and a maximum rate of 100 ft3/s is specified to allow the amount of water flowing in the stream from which water is diverted to control diversion amounts during the irrigation season. Soil and crop properties for EP1a are like the fine-textured soil shown in Table 1.

Figure 5 shows the proportions of surface water and supplementary groundwater used for irrigation for the cases with a high and a low inflow hydrograph, representing average and drought conditions, respectively. Supplementary groundwater makes up a greater proportion of the irrigation water supply during the low flow hydrograph (53%) relative to the high flow hydrograph (42%) due to surface water supply constraints (Fig. 5). Average annual irrigation water requirements were the same for both simulations (2.58 feet) and slightly less than the annual average crop consumption (2.6 feet) due to small amounts of precipitation in the valley. Note that although the inflow hydrographs were difference for the simulations, the valley precipitation was assumed equal.



1. Inflow hydrographs specified in the SFR Package input file for test model 1a, representing years of average and below average precipitation.



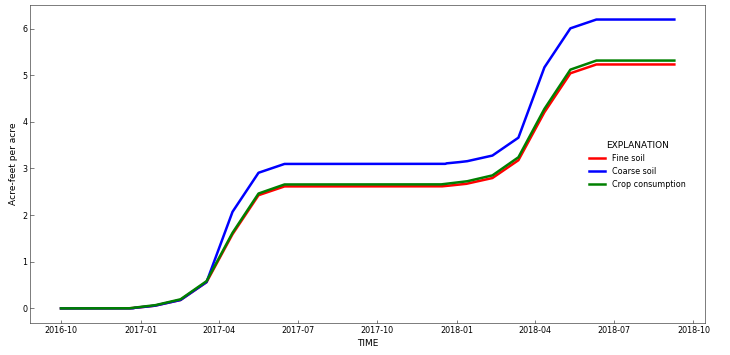
1. Irrigation provided by surface water diversions and groundwater pumping for A) low, and B) high inflow hydrographs shown in Figure 4.

## Example Problem 1b: Impacts of soil properties on GW irrigation demand

This example problem is run for 2 different agricultural field soil types, including fine and coarse soil textures (Table 1). The coarse soil requires greater amounts of irrigation earlier during the growing season relative to the fine soil because of lower antecedent soil moisture at the onset of the growing season (Fig. 6). Faster drainage increases the average annual NIWR for the coarse soil (3.1 feet) relative to the fine soil (2.6) due to greater amounts of groundwater return flows. Because there is no constraint on irrigation supply, average annual equals the of 2.7 acre-feet per acre.

1. Soil and crop parameters used in example problem 1b.

|  |  |  |
| --- | --- | --- |
|  | **Fine soil** | **Course soil** |
| Saturated water content of unsaturated zone (cubic foot of water per cubic foot of bulk volume) | 0.38 | 0.30 |
| Brooks-Corey exponent  (unitless) | 7.5 | 4.5 |
| Vertical hydraulic conductivity of the unsaturated zone (feet per day) | 8.6 | 4 |
| Evapotranspiration extinction depth  (feet) | 0.50 | 0.50 |
| Residual water content  (cubic foot of water per cubic foot of bulk volume) | 0.20 | 0.10 |
| Air entry pressure (feet of water) | -1.10 | -0.1 |
| Root pressure (feet of water) | -30.0 | -30.0 |



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

## Example Problem 2a

EP2a illustrates the effects of the crop coefficient () on NIWR and ET using the ET demand approach for irrigation (Fig. 7). As the ET demand option represents optimal irrigation scheduling to minimize the ET deficit, these results reflect optimal water use to meet crop water demand. Annual average NIWR for the period 1991-1993 is 0.97 hectare-meter per square meter for high and 0.70 hectare-meter per square meter for low . Annual average crop consumption is equal to 1.06 hectare-meters per square meter for high and 0.81 hectare-meter per square meter for low . Actual ET equals well-watered ET in this example because the ET demand approach is used and there are no constraints on irrigation amounts. NIWR is less than crop consumption in this example because of water supplied by precipitation and groundwater.

Real world irrigation practices likely cannot exactly mimic this optimal irrigation schedule for practical and logistical reasons. Nonetheless, these model results are useful for providing guidance on irrigation schedules, setting lower bounds on NIWR, and for providing a base model for evaluating factors affecting NIWR. As will be shown in EP2b, additional flexibility in simulating irrigation practices is provided by the TRIGGER option. Additionally, irrigation constraints can be superimposed onto ETDEMAND option to more closely mimic real-world conditions using SFR diversions and AG well time series input files. Accordingly, constraints on the timing and rates of irrigation can constrain irrigations using the ETDEMAND approach.

EP2a also demonstrates the influence that antecedent soil water conditions have on NIWR. Total annual precipitation amounts measured at the Independence Lake climate station for water years 1991, 1992, and 1993 was 83 cm, 71 cm, and 149 cm, respectively, while NIWR with low was 78, 100, and 77 percent of the crop water demand during these years (Fig. 8). Although antecedent conditions impact NIWR for the case of high , the effects are lower relative to low because greater consumption depletes soil moisture more rapidly.



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

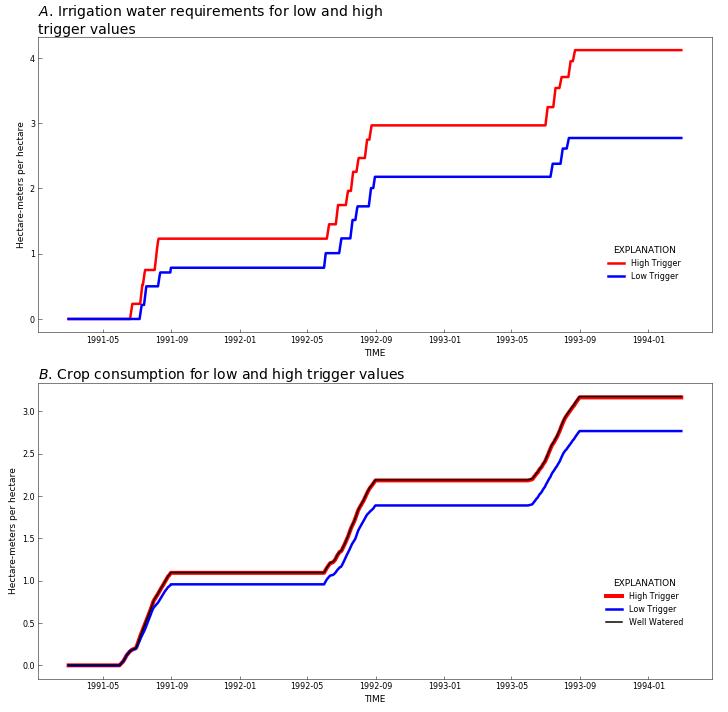
# 

1. Comparison of agricultural water use for example problem 2a, using low and high crop coefficients (Kc) shown in Figure 7.

## Example Problem 2b

Example problem 2b is identical to EP2a, except that the TRIGGER option is used, and the seasonal crop coefficients were set as shown in Figure 7 as the High curve. EP2b illustrates the influence that different irrigation trigger values have on the surface water diversions and groundwater pumping rates. In this case an irrigation event starts when the ET ratio () becomes less than the specified trigger threshold. Results are shown for a high (0.85) and low (0.35) trigger value. Note that the length of an irrigation period is specified as 3 days for both high and low trigger values; however, if the ET ratio is below the trigger value at the end of a period then a new irrigation period will begin immediately.

Irrigation delivery is directly proportional to the trigger threshold, where higher trigger values result in greater surface water diversions, pumping, and crop water consumption (Fig. 9). Annual average NIWR for the period 1991-1993 is 1.4 hectare-meters per square meter for a high trigger value and 0.92 hectare-meters per square meter for a low trigger value. Annual average crop consumption is the same as EP2a (1.06 hectare-meter per square meter), except for the low trigger value simulation results in a crop consumption of 0.92 hectare-meter per square meter. Because setting a low trigger value allows the soils to drain longer between irrigation events, lower trigger values result in less actual ET as compared to higher trigger values (Fig. 9b). The TRIGGER option requires significantly more surface water and groundwater to meet crop-water requirements due to the imposed timing and rates of irrigation.



1. Comparison of agricultural water use for example problem 2a, using low and high irrigation trigger values.

# Discussion

A new package for MODFLOW and GSFLOW is presented that provides capabilities for simulating agricultural water use in regional scale hydrologic models. The AG Package can be used to estimate agricultural water use for systems where information about NIWR, surface water and groundwater use is not available, or it can be used to simulate the impacts of agricultural water use on water supply. The latter use is important in regions where there are competing needs for water, and system changes such as climate change, population growth, and land use change are causing unknown impacts. Design of the AG Package includes flexibility for representing systems with varying amounts of data, different grower behavior, and feedbacks between water supply and water use by agriculture. Water demands rely on energy and soil-water balance calculations and regionally specific conditions can be represented, such as spatial variations in temperature, solar radiation, and plant type. Specific attributes of a region can be considered, including soil hydraulic properties, depth to groundwater, canal or pipe properties, and antecedent soil moisture and precipitation. Water consumption relies on explicit simulation of irrigation infrastructure, soil-water budgets, and surface water and groundwater availability. These design features provide flexibility for evaluating water use in a wide variety of agricultural systems, and for developing optimal irrigation schedules unique to a region.

A variety of options are provided for mimicking different irrigation approaches, specifically with regards to the timing and amounts of irrigation. Examples are presented that illustrate impacts of surface water supply on groundwater pumping (EP1a), irrigation supplied solely by groundwater (EP1b), irrigation estimated for optimal water-use conditions that minimizes the ET deficit (EP2a), and irrigation that is triggered when the ET deficit drops below a specified threshold. All these approaches are provided as options to best represent regionally specific conditions. Because irrigation water is explicitly routed and applied to individual fields, the model can be used to evaluate irrigation return flows and changes in land use.

Practical applications of integrated hydrologic models that represent agricultural water use must rely on data that characterize a broad range climactic and hydrogeologic conditions. Additionally, representation of agriculture requires characterization of water governance and grower behavior. Complete data sets are never available, and integrated models provide a means of maximizing information with partial data sets by combining data with physical process equations and generalized frameworks for representing human impacts on water distribution and consumption. The AG Package for MODFLOW and GSFLOW provides a powerful decision support tool that can maximize understanding of water resources in agricultural basins and provide hindcast information about historical water budgets and system response as well as future projections of sustainability and management change.

# Conclusions

Hydrologic simulation of developed basins is difficult or impossible without representing agricultural water use. Integrated hydrologic models are useful decision support tools for developing regional water budgets and evaluating water management strategies and sustainability for human populations and ecosystem services. Despite significant data gaps in water use at regional scales, hydrologic models can complement incomplete datasets and provide a more complete picture of water resources. Process understanding, and theoretical representation of agricultural water use are well established; however, limited software is available that explicitly represents agricultural water use in regional-scale integrated hydrologic models. The AG Package for MODFLOW and GSFLOW provides a wholistic representation of agricultural water use in the context of the natural hydrologic system and other water use sectors. Through a series of simple but realistic example problems, this paper demonstrates the software’s applicability for a variety of approaches for simulating irrigation practices and associated effects on water distribution and supply in regional-scale systems.

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