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 uses pre-existing hydrologic simulation 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 potential evapotranspiration (ET), and 3) demands determined by minimizing the difference between potential and actual ET. The latter two approaches use energy and soil-water balance to determine crop-water demands. Irrigation water is diverted into canals and routed to fields using the MODFLOW SFR Package, or irrigation water is supplemented by groundwater. 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 irrigation practices.

1 Keywords

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

2 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 (AG) 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. The AG Package, including source code, compiles binary files for Windows and Unix, example problems, and Jupyter Notebooks for plotting results are provided with GSFLOW.

3 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 and 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; Morway et al., 2013; 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 regional integrated models is to estimate demands as a pre-processing step. Demands are subsequently specified to a regional integrated model that does not simulate field soil-water balance (Hanson et al., 2010, 2014; Dogrul et al., 2011). Another approach presented herein is to include simulation of field soil-water balance within the regional integrated model to calculate dynamic irrigation demands. The advantage of this approach is that simulated demands and water use are consistent with the soil water conditions and irrigation water supply simulated by the regional integrated model. Furthermore, simulated crop consumption and irrigation diversions can be constrained through validation with independent estimates of crop consumption (e.g., Huntington et al., 2017).

Here we present the Agricultural (AG) water use package for MODFLOW and GSFLOW regional-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 irrigation demand, irrigation efficiency, and crop consumption can be 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 through existing features in GSFLOW and recent enhancements (Regan and LaFontaine, 2017).

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. Evolving supply and demand conditions such as these support simulating demand using energy and soil-water balance within integrated hydrologic models rather than estimating demands as a pre-processing step. 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; Kitlasten et al., 2019).

Two example problems are presented for representing agriculture in MODFLOW and GSFLOW, and these examples are run using different options to demonstrate application of the new package and its capabilities for simulating agricultural water use for different hydrographic settings and irrigation practices. 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).

4 Methods

4.1 Agricultural water use

4.1.1 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 practices that vary with irrigation technique, such as 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.

4.1.1.1 Surface water irrigation

Surface water delivery for irrigation is simulated by the MODFLOW Streamflow-Routing (SFR) Package, including open channel flow in streams and canals, or non-pressurized flow through 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 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 to apply diverted surface water to fields. SFR diversion flow rates are constrained by the amount of water flowing in the upstream segment and 1 of 4 water-use priority options (Prudic et al., 2004).

Surface reservoirs are simulated by the MODFLOW Lake (LAK) Package (Merritt and Konikow, 2000) for MODFLOW simulations and/or open detention storage reservoirs for GSFLOW simulations (Regan and LaFontaine, 2017). SFR routes channel flows into and out of reservoirs represented by LAK and open detention storage reservoirs. 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.

4.1.1.2 Groundwater irrigation

Groundwater irrigation is provided by wells that can pump water from a groundwater cell. 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 automatically be reduced due to drawdown of the water table. Groundwater wells are designated in AG as irrigation wells 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.

4.1.1.3 Mapping point of diversion to place of use

Irrigation provided by diversion segments and groundwater wells is applied to designated cells or HRUs with a user-specified mapping between numerically identified SFR segments, AG wells, and cells/HRUs. The point of diversion is located at the upstream end of a diversion segment or well used for irrigation, and the place of use is the area of fields irrigated by the diversion. MODFLOW cells are identified by their row and column, HRUs are identified by their hru_id, diversion segments are identified by their SFR segment number, and wells are identified by their AG well number. Mapping identifiers are input to the AG input file, and they can change during a simulation. SFR diversion segments can consist of 1 or more reaches, where reaches are the length of stream or canal that spans a single model cell. A segment can span many model cells to represent great distances between a point of diversion and place of use, and diversion segments can divert from other diversion segments. 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.

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4.1.2 Simulating crop consumption

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ET can be simulated using soil-water balance over any time step length for MODFLOW simulations, or ET can be simulated using daily energy and water balance for GSFLOW simulations (Markstrom et al., 2008; Niswonger et al., 2011). Actual crop ET (ET_a) can be calculated by UZF as a function of the depth-dependent soil water contents using a kinematic-wave formulation (Niswonger et al., 2006), or ET_a can be calculated by PRMS as a function of volume-averaged soil saturation using a nonlinear soil-water reservoir approach (Markstrom et al., 2008; Markstrom et al., 2015). Crop-specific ET demand is calculated by multiplying the crop coefficient (K_c) by the reference ET (ET_o; Allen et al., 1998). If using UZF to represent agricultural fields then the product $K_c ET_o$ is input for the UZF variable PET. If using PRMS to represent agricultural fields, ET_o is calculated 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). Example problem 2 below demonstrates how K_c is incorporated into GSFLOW simulations using the PRMS Jensen-Haise formulation.

Sub-irrigation is a process in which plants use shallow groundwater to meet crop water demands. Growers apply less irrigation water where there is shallow groundwater beneath their crops, thus this process is important for estimating irrigation demand. Sub-irrigation is simulated by UZF assuming a linear capillary rise as a function of groundwater head; sub-irrigation 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).

Additional to the previously available approach for simulating ET_a in UZF, a new option was added to simulate crop consumption using a pressure gradient approach. 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). ET_a is calculated using:

$$ET_a = D(t)K(\theta)R(t)[\psi(\theta) - h_{root}]. \quad (1)$$

Where $D(t)$ is the thickness of the root zone or ET extinction depth that can change during the growing season (L); $K(\theta)$ is unsaturated hydraulic conductivity as a function of water content (LT^{-1}), $R(t)$ is the root activity function that can change during the growing season (L^{-2}); $\psi(\theta)$ is capillary pressure head as a function of water content (L), and h_{root} is the negative root pressure head (L). Variables in equation 1 are calculated using Brooks and Corey (1966) unsaturated hydraulic conductivity and capillary pressure functions.

4.1.3 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 return flow because the water becomes available to other growers or for other uses in the system. Return flow can occur anywhere between a point of diversion and a place of use. Gains and losses in the irrigation infrastructure are represented by the integration of surface water and groundwater in SFR and LAK for the channel and surface reservoir domains (canal or pond), and gains and losses are simulated by UZF or PRMS for the overland flow domain (field). Return flow also occurs between the overland flow domain and the channel and reservoir domains. Exchanges between surface water and groundwater are simulated using implicit coupling of the surface water and groundwater equations, or to the kinematic-wave equation for unsaturated flow where streams are separated from groundwater by an unsaturated zone (Niswonger and Prudic, 2005). Pipe networks represented by SFR segments can be made semi-pervious to represent leaky pipes.

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 using 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, for example. 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. Alternatively, irrigation return flow also can be set using irrigation efficiency factors or a combination of explicitly represented infrastructure and efficiency factors.

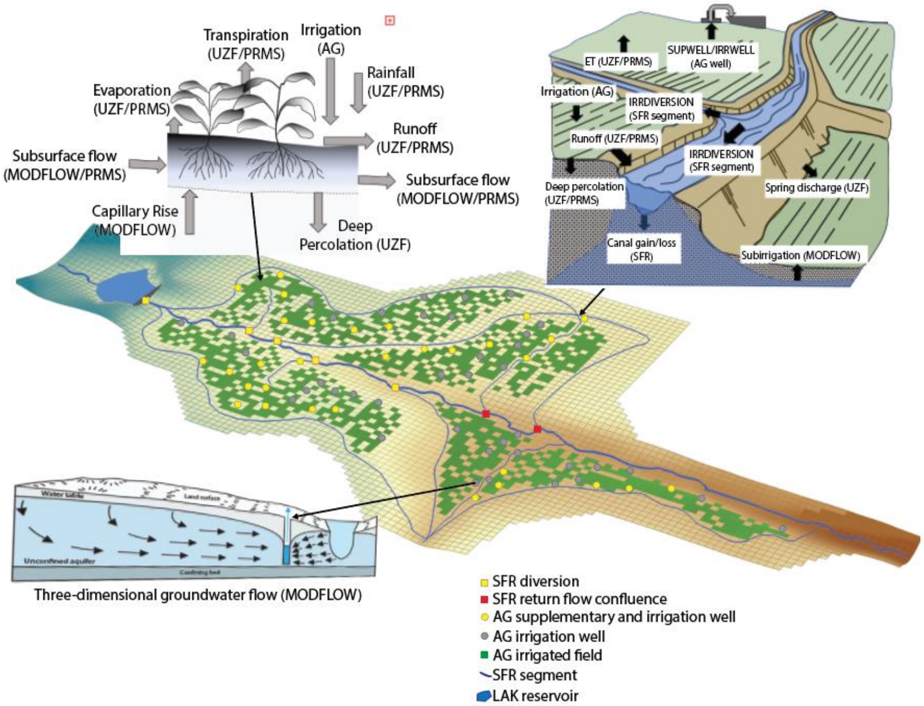

Figure 1. Illustration showing how regional agricultural processes are represented in MODFLOW and GSFLOW. Surface water and groundwater can be used for irrigation by designating diversion segments as irrigation diversions (IRRSEGMENT) and designating wells as irrigation wells (IRRWELLS) and/or supplementary 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.

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4.2 Irrigation demand and scheduling

4.2.1 Option 1: User-specified irrigation demand and schedule using surface water diversions and/or groundwater wells

Option 1 is the default approach (Fig. 2A), and irrigation demand is set using time varying surface water diversions specified in SFR tabfiles, or time varying pumping rates specified in AG. Irrigation water is applied to MODFLOW cells or PRMS HRUs; ET and groundwater and surface water return flow is simulated using explicit representation of irrigation delivery infrastructure. Or, infrastructure can be represented implicitly using efficiency factors, and the difference between irrigation water delivery and crop consumption is applied as groundwater return flow, and surface water return flow is assumed to be zero.

In many agricultural regions, irrigation is provided by surface water, and groundwater is used to supplement surface water during drought or seasonally low flow periods. Irrigation wells can be designated as supplementary wells, and rather than specifying pumping rates, pumping rates are calculated as the difference between the irrigation demand and the actual diverted surface water rate, referred to as the surface water shortfall (SF_{IRR}; L3/T):

$$SF_{IRR} = FAC_{max} Q_{demand} - Q_{diversion}. \qquad (2)$$

Where Q_{demand} is the volumetric demand rate for the irrigation period required for crop growth in 1 or more cells/HRUs supplied by a diversion (L^3T^{-1}), $Q_{diversion}$ is the volumetric diversion rate that can be less than or equal to Q_{demand} if surface water supplies limit the diversion rate (L^3T^{-1}); FAC_{max} is the maximum percentage of Q_{demand} that will be supplemented by groundwater. The volumetric rate of supplementary groundwater irrigation for a diversion that can be supplied by 1 or more wells is calculated as Q_{sup} (L^3T^{-1}):

$$Q_{sup} = FAC_{sup} * SF_{IRR}, \tag{3}$$

where FAC_{sup} is the fraction of SF_{IRR} that will be supplemented by groundwater.

When using efficiency factors to simulate crop consumption, and if water is supplied by surface water and supplemented by groundwater, ET_a for each cell/HRU is calculated as:

$$ET_{a,n} = \sum_{n=1}^{ncell/nHRU} FF_n \left(EF_{GW} Q_{sup+} EF_{sw} Q_{diversion}\right)/A_n. \tag{4}$$

And for groundwater only irrigation, ET_a for each cell/HRU is calculated as:

$$ET_{a,n} = \sum_{n=1}^{ncell/nHRU} FF_n \, EF_{GW} Q_{GW}/A_n. \quad . \tag{5}$$

Where $ET_{a,n}$ is the actual ET for cell/HRU n (LT^{-1}); ncell and nHRU are the total number of MODFLOW cells or PRMS HRUs irrigated by a diversion or groundwater well; FF_n is the fraction of the diverted irrigation water that will be applied to cell n; Q_{GW} is the groundwater irrigation delivered to one or more cells/HRUs (L^3T^{-1}); EF_{GW} is the groundwater irrigation efficiency factor; EF_{sw} is the surface water irrigation efficiency; and A_n is the area for cell/HRU n (L^2). Groundwater return flow for a diversion and/or groundwater well (Q_{return}; L^3/T^{-1}) is calculated as:

$$Q_{return} = (1 - EF_{sw})Q_{SW} + (1 - EF_{GW})Q_{GW}. \tag{6}$$

The amount of groundwater return flow applied to each cell/HRU (RF_n; LT^{-1}) is:

$$RF_n = \sum_{n=1}^{ncell/nHRU} FF_n \, Q_{return}/A_n \tag{7}$$

If efficiency factors are used to represent crop consumption (EF_{sw} and $EF_{sw} > 0$), then ET should be made zero in UZF/PRMS cells/HRUs that contain fields. Note that efficiency factors partition water that is applied to fields into ET_a and RF_n; however, system gains/losses that occur between the point of diversion and the place of use, not including field gains/losses, must be simulated using pervious SFR segments or combined with field gains/losses using efficiency factors.

4.2.2 Option 2: Triggered irrigation events

Option 2 is activated when the character input variable TRIGGER is specified in the AG input file (Fig. 2B). Once the irrigation event is triggered, the user specified diversion or pumped amount is delivered and applied to fields for the user-specified irrigation period. Diversions are specified using SFR tabfiles, and pumping rates are specified in AG. Supplementary groundwater pumping can be used to satisfy a surface water 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.

Irrigation automatically starts when the ET ratio summed over all cells/HRUs supplied by a diversion or AG well decreases below a user-specified threshold. During the growing season, irrigation is turned on when:

$$Q_{ET,actual}/Q_{sum} < FCT_{Trigger}. \tag{8}$$

$$Q_{ET,actual} = \sum_{n=1}^{ncells,nHRUs} A_n ET_{a,n}, \tag{9}$$

and

$$Q_{sum} = \sum_{n=1}^{ncells,nHRUs} A_n K_{c,n} ET_{o,n}. \tag{10}$$

Where $FCT_{Trigger}$ is the user specified ET deficit threshold that triggers an irrigation event; $Q_{ET,actual}$ is the sum of actual ET for all cells/HRUs irrigated by a diversion or well (L^3/T^{-1}); Q_{sum} is the sum of crop ET for well-watered conditions for all cells/HRUs irrigated by a diversion or well (L^3/T^{-1}); $K_{c,n}$ is the crop coefficient for cell/HRU n; and $ET_{o,n}$ is the reference ET for cell/HRU n. An irrigation event for a diversion or well continues until:

$$T_{irr} \geq T_{period}, \tag{11}$$

where is the T_{irr} and T_{period} (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.

4.2.3 Option 3: Optimal net irrigation water requirement

Option 3 is activated when the character input variable ETDEMAND is specified in the AG input file (Fig. 2C). Net irrigation water requirement (NIWR; L) is the total annual quantity of water required for plant growth divided by the irrigated area (Allen et al., 1998). NIWR is calculated by the model according to:

$$NIWR = GIWR - IRR_{L/G}, \tag{12}$$

where $IRR_{L/G}$ (L) is the quantity of irrigation water loss or gain that occurs between the point of diversion and place of use divided by the irrigated area; and $GIWR$ is the annual gross irrigation water requirement defined as the quantity of water required for plant growth divided by the irrigated area, including gains and losses that occur during delivery and on the field (L). Supplementary groundwater pumping can be used to supply the GIWR as described in option 1. Surface water and groundwater return flows can occur during delivery and on farms.

GIWR is calculated by the model as the amount of water that must be diverted and/or pumped such that the difference between the simulated ET_a and K_cET_o is minimized. For MODFLOW simulations, the product K_cET_o under well-watered conditions (ET_{ww}) is specified as variable PET in UZF. For GSFLOW, ET_{ww} is calculated as:

$$ET_{ww} = K_c PET_{HRU} \quad . \tag{13}$$

The volumetric rate of water consumed by a crop for well-water conditions ($Q_{ET,ww}$) is:

$$Q_{ET,ww} = \sum_{n=1}^{ncell,nHRU} ET_{ww,n} A_n, \tag{14}$$

where PET_{HRU} is calculated using the previously described approaches and is multiplied by K_c internally for GSFLOW simulations. The diversion and/or pumped amount is calculated by minimizing (min) the ET deficit (ET_{def}; LT^{-1}) as:

$$min[ET_{def}] = ET_{ww} - ET_a \ , \tag{15}$$

subject to the amount of surface water that can be diverted and/or groundwater that can be pumped. As with option 2, ET_a and ET_{ww} are summed over all fields irrigated by a diversion and/or a well. In addition to simulated water supply constraints, values specified for diversions using SFR tabfiles and pumping rates specified in AG can be used to constrain irrigation timing and maximum amounts.

A solution to equation 15 is accomplished by determining the minimum amount of water required to be diverted or pumped to meet the crop-water demand. The volumetric rate of crop consumption for a time step can be written as a function of the irrigation demand as:

$$Q_{ET,i+1} = Q_{ET,i} + [\partial Q_{ET,i}/\partial Q_{tot,i}]\Delta Q_{tot,i+1} \tag{16}$$

And after substituting $\Delta Q_{tot,i+1} = Q_{tot,i+1} - Q_{tot,i}$ and re-arranging terms, equation 16 becomes:

$$Q_{tot,i+1} = Q_{tot,i} + \frac{Q_{ET,i+1} - Q_{ET,i}}{\partial Q_{ET,i}/\partial Q_{tot,i}} \quad . \tag{17}$$

Where i is an iteration counter for solving nonlinearities between irrigation demand and crop consumption; $Q_{tot,i+1}$ and $Q_{tot,i}$ are total irrigation water diverted and/or pumped for iterations i+1 and i, respectively (L^3T^{-1}); $Q_{ET,i+1}$ and $Q_{ET,i}$ are the crop consumption for iterations i+1 and i, respectively (L^3/T^{-1}). Note that i also is the MODFLOW or GSFLOW outer iteration counter (Markstrom et al., 2008; Niswonger et al., 2011).

The amount of water that is applied to each cell/HRU n (IRR_n; LT^{-1}) that is irrigated by a diversion/well is:

$$IRR_n = \frac{FF_{SW,n}Q_{SW}+FF_{GW,n}Q_{GW}}{A_n}. \quad (18)$$

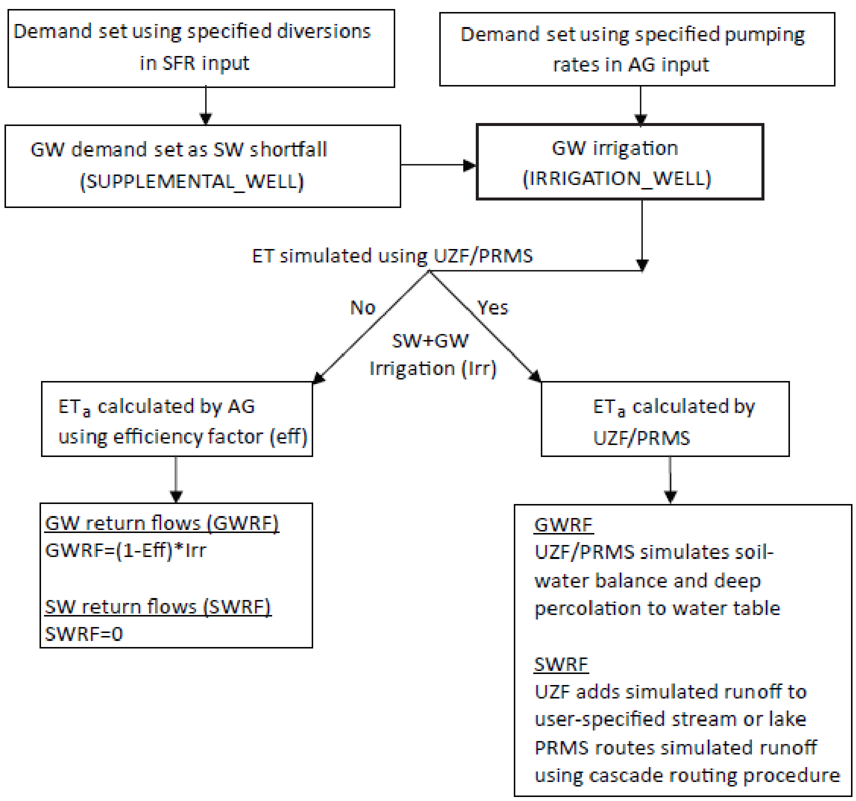
Where $FF_{SW,n}$ and $FF_{GW,n}$ are the fractions of the total irrigation water delivery from surface water and groundwater applied to each cell/HRU n, respectively.

4.2.3.1 Constraining surface water diversions and groundwater pumping rates

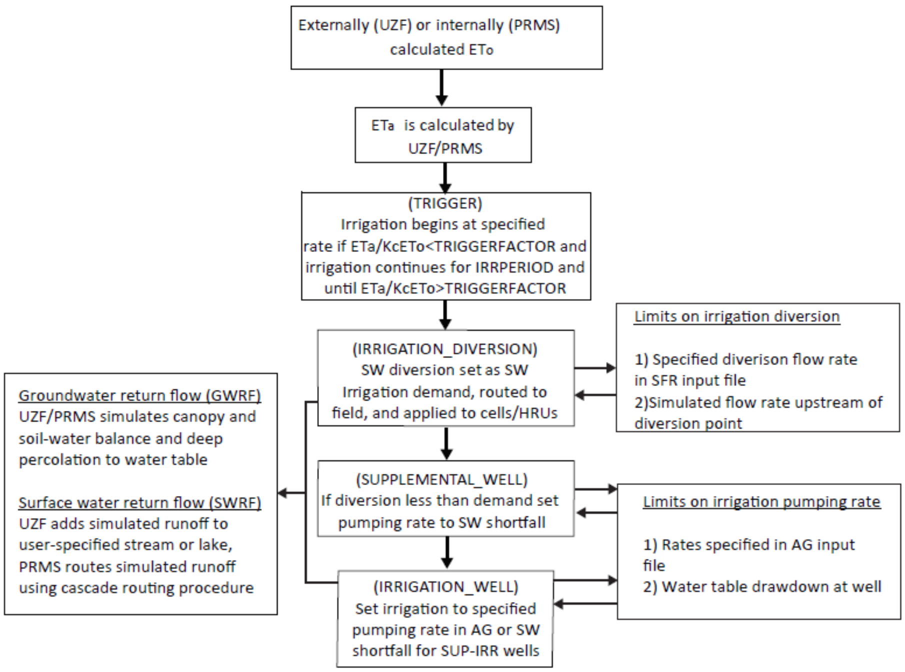
Diversion and pumping rates are automatically constrained by the supply of surface water at the upstream diversion point and by the water table elevation in the cell that contains the well. Pumping rates specified in the AG input file are used to set the groundwater irrigation rate for option 1, or they can be used to set the maximum irrigation pumping rate for options 2 and 3. Additional constraints can be applied to surface water diversions for all 3 options using diversion rates specified in SFR tabfiles and 1 of 4 diversion priority options in SFR (Prudic et al., 2004):

1) demand is greater than the flow available in the upstream segment, and the diversion is reduced to the amount available;
2) demand is greater than flow available in the upstream segment, and no water is diverted from the stream;
3) demand is greater than a specified fraction of the flow in the upstream segment, and the diversion is reduced to the fraction of flow;
4) diversion is set equal to demand only if the remaining streamflow in the upstream segment exceeds the value specified in the SFR tabfile, otherwise no water is diverted.

A) Demands are specified for configuration 1 with Surface water (SW) and groundwater (GW) irrigation simulated using IRRIGATION_DIVERSION and IRRIGATION_WELL features in the AG Package, respectively. The SUPPLEMENTAL_WELL feature is used to supplement an IRRIGATION_DIVERSION when specified demands are greater than SW supply, and the same well can be designated as an IRRIGATION_WELL. ETa is simulated actual evapotranspiration.



B) Irrigation onset and duration are caclulated using configuration 2 (TRIGGER) with Surface water (SW) and groundwater (GW) irrigation simulated using IRRIGATION_DIVERSION and IRRIGATION_WELL features in the AG Package, respectively. The SUPPLEMENTAL_WELL feature is used to supplement an IRRIGATION_DIVERSION when specified demands are greater than SW supply, and the same well can be designated as an IRRIGATION_WELL. ET_a is simulated actual evapotranspiration, and ET_o is reference evapotranspiration.



C) Demands are calculated for configuration 3 (ETDEAMND) with Surface water (SW) and groundwater (GW) irrigation simulated using IRRIGATION_DIVERSION and IRRIGATION_WELL features in the AG Package, respectively. The SUPPLEMENTAL_WELL feature is used to supplement an IRRIGATION_DIVERSION when specified demands are greater than SW supply, and the same well can be designated as an IRRIGATION_WELL. ET_a is simulated actual evapotranspiration, and ET_o is reference evapotranspiration.

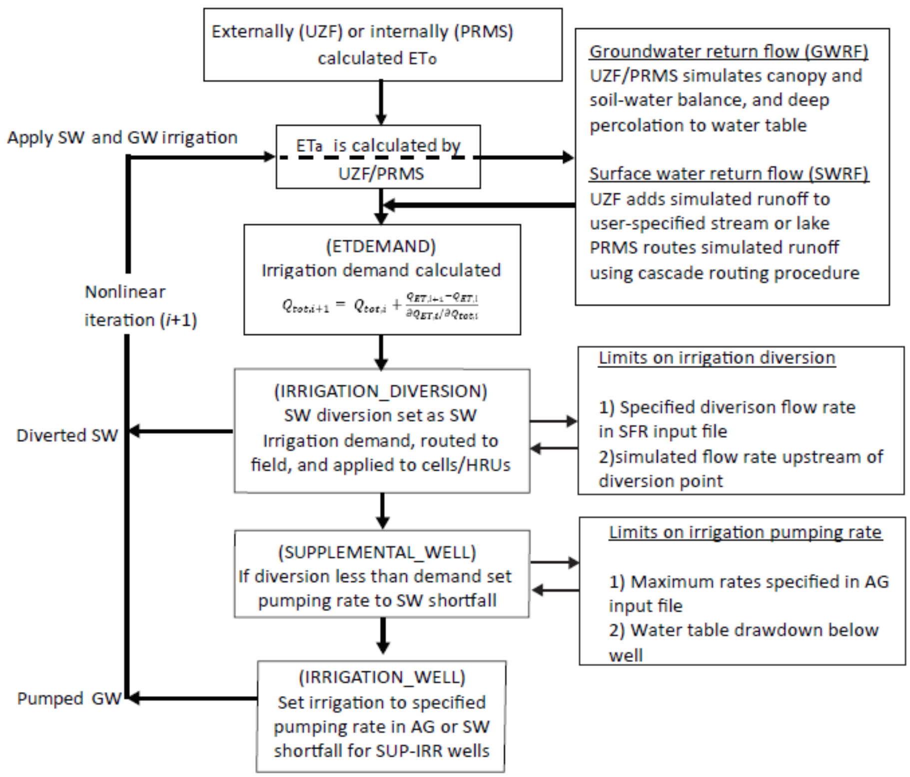


Figure 2. Flow charts showing three different approaches for simulating agricultural water use with the AG Package; A) demands set by user (AG Package default); B) demands calculated by activating irrigation events using an ET trigger (AG Package character input TRIGGER); C) demands calculated using the minimum irrigation water requirement (AG Package character input ETDEMAND).

5 Example Problems

Two example problems are presented to illustrate the capabilities of the AG Package for simulating water use by agriculture. 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.

5.1 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. 3). 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.

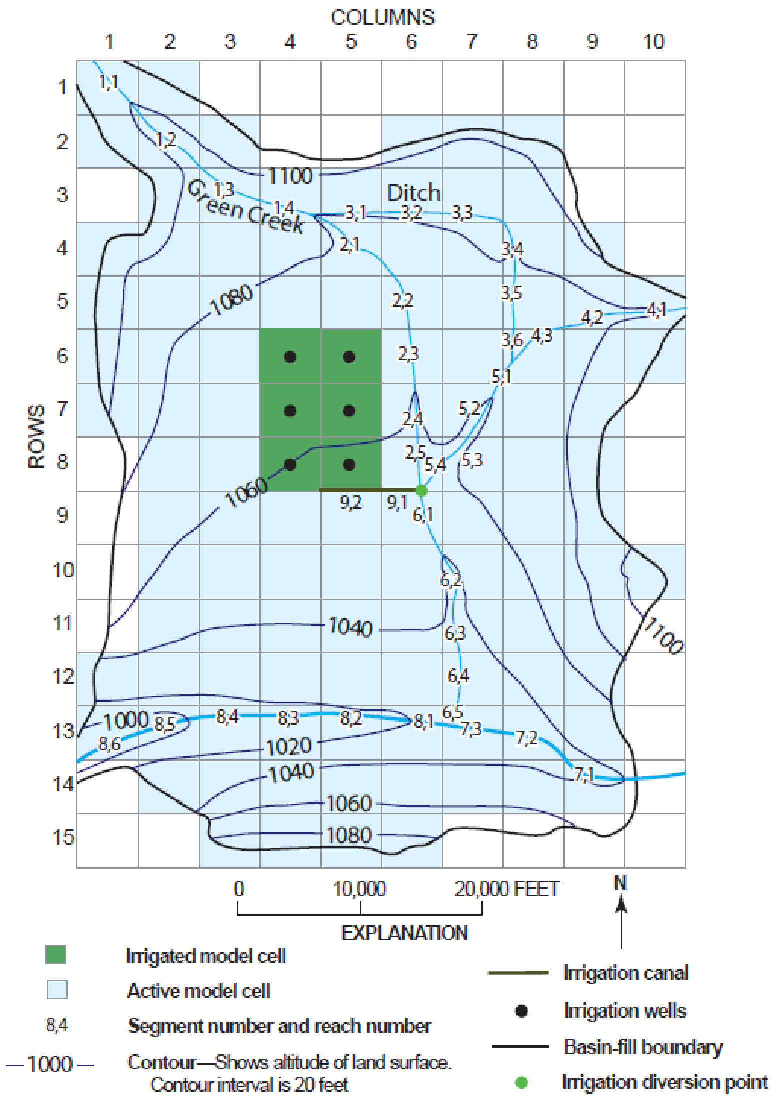


Figure 3. Map showing basin topography, streams and canals, and agricultural region for example problem 1.

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. 3). 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 (Fig. 3) 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. 3). 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 ET_{ww} 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 17. Figure 3 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. 3). NIWR is satisfied solely by groundwater in EP1b.

5.2 Example Problem 2: GSFLOW-Conjunctive use of SW and GW, ETDEMAND versus 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. 4). Sagehen Creek drains a of 27 km^2 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. 4). 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) and example problem 2b (EP2b) simulate demand using the ETDEMAND and TRIGGER options, respectively. Figure 4 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. 4). 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 SFR tabfiles 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.

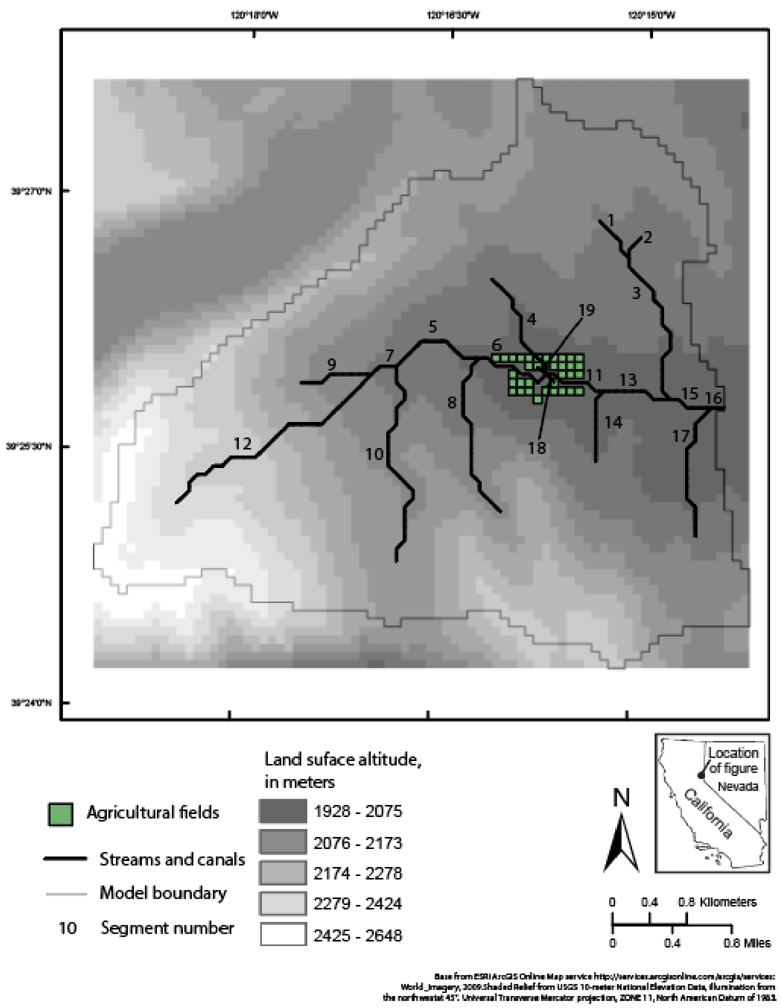


Figure 4. Map of Sagehen Creek watershed with hypothetical irrigated fields used in example problem 2.

6 Results

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

EP1a was run with high and low inflow hydrographs (Fig. 5) representing average and drought years, respectively, to evaluate how differences in surface water supply impact the relative proportions of surface water and supplemental groundwater used for irrigation (Fig. 6). Specified surface water inflow enters the model through segment 1 over the northeast corner of the model boundary (Fig. 3). Maximum surface water diversions rates were set in a SFR tabfile for segment 9 with an irrigation period from April 1 to September 30, and a maximum rate of 100 ft^3/s, which is greater than the maximum irrigation demand, and thus, only the amount of flow in segment upstream of the irrigation segment will constrain irrigation (priority option 1). Soil and crop properties for EP1a are those of the fine-textured soil shown in Table 1.

Figure 6 shows the proportions of surface water and supplementary groundwater used for irrigation for the average and drought conditions. 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. Supplementary pumping rates increase abruptly right as the flow at the diversion point decreases and then re-equilibrate as the crop demand (ETa) decreases; similarly, pumping rates decrease abruptly when the demand decreases abruptly (Fig. 6)

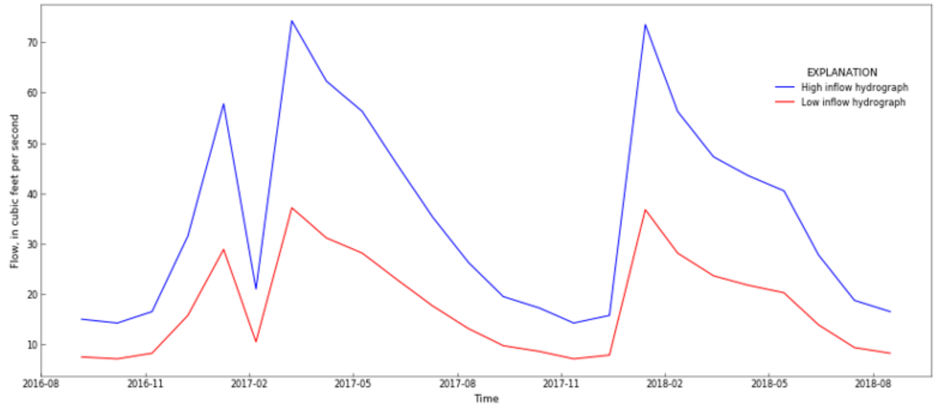


Figure 5. Inflow hydrographs specified in the SFR Package input file for test model 1a, representing years of average (high inflow) and below average (low inflow) precipitation.

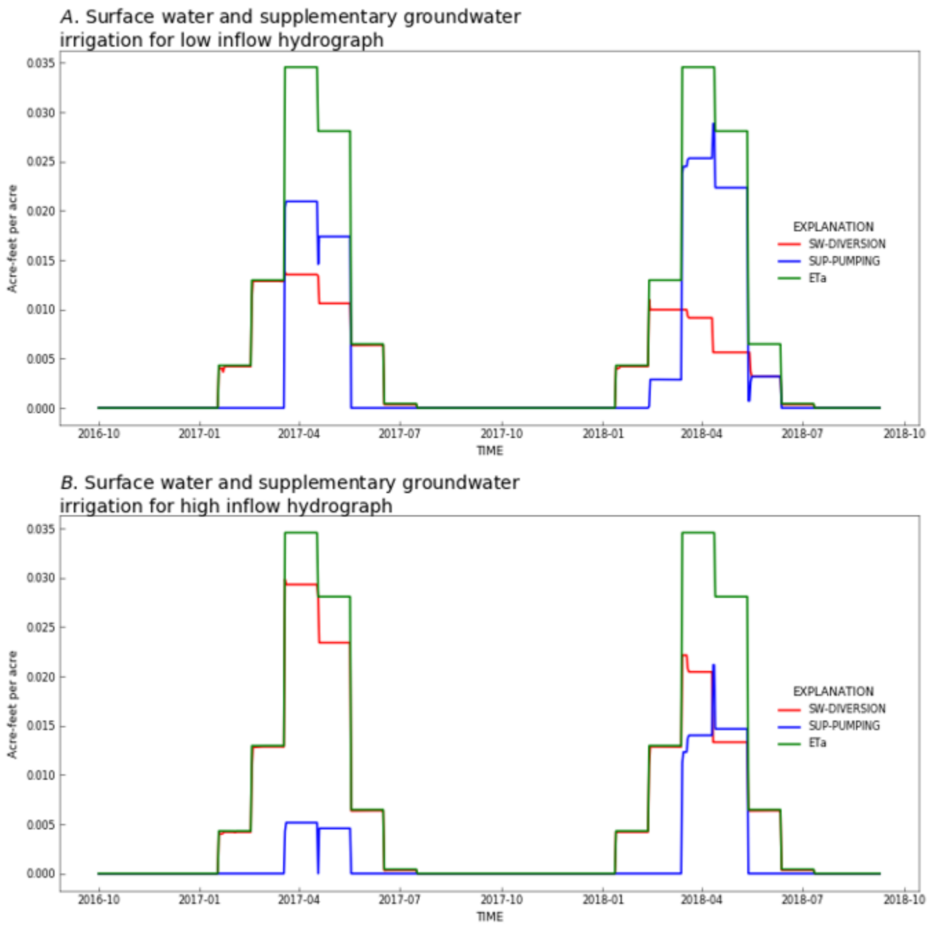


Figure 6. Irrigation provided by surface water diversions and groundwater pumping for A) low, and B) high inflow hydrographs shown in Figure 5.

6.2 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. 7). Faster drainage increases the average annual irrigation demand for the coarse soil (3.1 feet) relative to the fine soil (2.6 feet) due to greater amounts of groundwater return flow. Return flow is greater for coarse soils because water infiltrates faster than it can be used by the roots. As there is no constraint on irrigation supply, average annual ET_a equals the ET_{WW} of 2.7 acre-feet per acre.

Table 1. Soil and crop parameters used in example problem 1a and 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)	4	8.6
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
Root activity function (per feet squared)	1.0	1.0

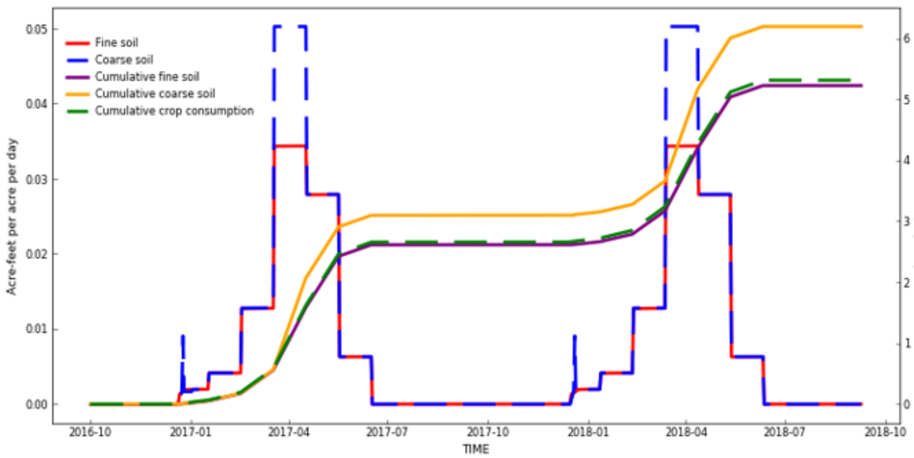


Figure 7. Groundwater pumping rates and cumulative pumping for irrigation in example problem 1b with fine and course agricultural soil properties.

6.3 Example Problem 2a: Effects of crop coefficient on irrigation demands

EP2a illustrates the effects of the crop coefficient (K_c) on irrigation demand and crop consumption using the ETDEMAND option for irrigation (Fig. 8). K_c is incorporated into the ET demand by multiplying the PRMS input parameter JH_COEF by the monthly Kc values. Note that JH_CEOF can be specified for each hydrologic response unit in PRMS and for each of the 12 calendar months (Markstrom et al., 2015). As this option represents optimal irrigation scheduling to minimize the ET deficit, these results reflect optimal water use to meet crop water demand. Annual average GIWR for the period 1991-1993 is 1.1 hectare-meter per hectare for high K_c and 0.70 hectare-meter per hectare for low K_c. Annual average crop consumption is equal to 1.06 hectare-meters per hectare for high K_c and 0.81 hectare-meter per hectare for low K_c. Actual ET equals ET_{ww} in this example because the ETDEMAND option is used, and because constraints on the irrigation amounts set in the SFR tabfile and AG pumping rates did not limit irrigation. Irrigation demand is less than crop consumption for 1992 and 1994 because of water supplied by precipitation and sub-irrigation; however, 1993 was a drought year and demand is greater than consumption.

EP2a also demonstrates the influence that early growing season antecedent soil water conditions have on crop water demand. 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 demand was 79, 158, and 70 percent of the crop water consumption during these years for the case of high K_c, and 66, 129, and 62 percent of the crop water consumption during these years for the case of low K_c (Fig. 9).

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 irrigation demand, and for providing a base model for evaluating factors affecting demand and consumption. Irrigation constraints can be superimposed onto the ETDEMAND option using SFR tabfiles and AG pumping rates to mimic real-world conditions. As will be shown in EP2b, additional flexibility in simulating irrigation practices is provided by the TRIGGER option.

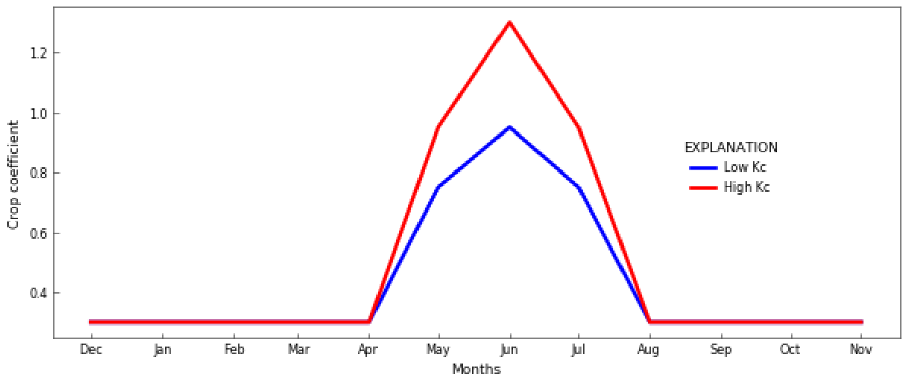


Figure 8. Seasonal crop coefficient (Kc) used for simulating agricultural water use in example problem 2a and 2b. Crop coefficients are incorporated into the evapotranspiration demand by multiplying the PRMS input parameter JH_COEF by the monthly Kc values. Note that JH_CEOF can be specified for each hydrologic response unit in PRMS and for each of the 12 calendar months.

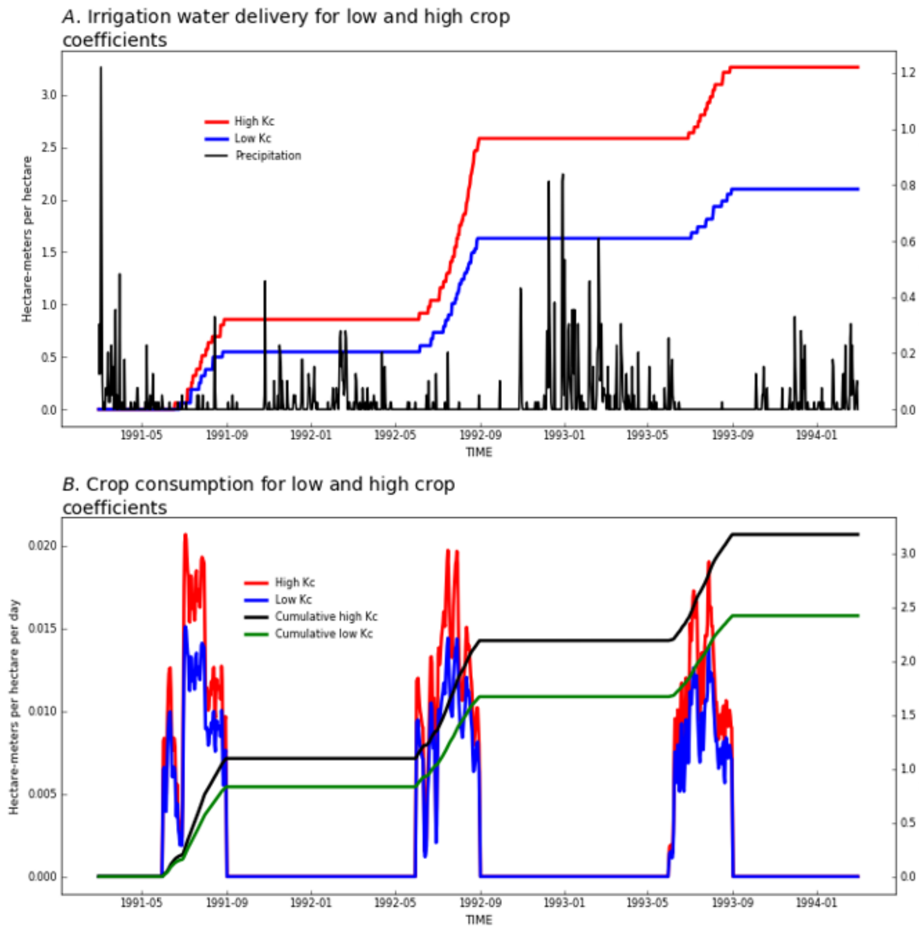


Figure 9. Comparison of agricultural water use for example problem 2a, using low and high crop coefficients (Kc) shown in Figure 8.

6.4 Example Problem 2b: Using irrigation triggers to estimate demand

Example problem 2b is identical to EP2a, except that the TRIGGER option is used, and seasonal K_c were set using the High $K_c$curve (Fig. 8). EP2b illustrates the influence that different irrigation trigger values have on the surface water diversions and groundwater pumping rates. An irrigation event starts when the ET ratio (ET_a/ET_{ww}) becomes less than the specified trigger threshold. Results are shown for a high (0.85) and low (0.35) trigger value, representing well-watered and deficit irrigation conditions, respectively. 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. 10). Irrigation demand for the period 1991-1993 is 1.4 hectare-meters per hectare for a high trigger value and 0.7 hectare-meters per hectare for a low trigger value. Annual average crop consumption is the same as EP2a (1.06 hectare-meter per hectare), except for the low trigger value simulation results in a crop consumption of 0.83 hectare-meter per hectare. 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. 10b). The TRIGGER option with a high trigger value requires significantly more surface water and groundwater to meet crop-water requirements relative to the ETDEMAND option due to the superimposed timing and rates of irrigation.

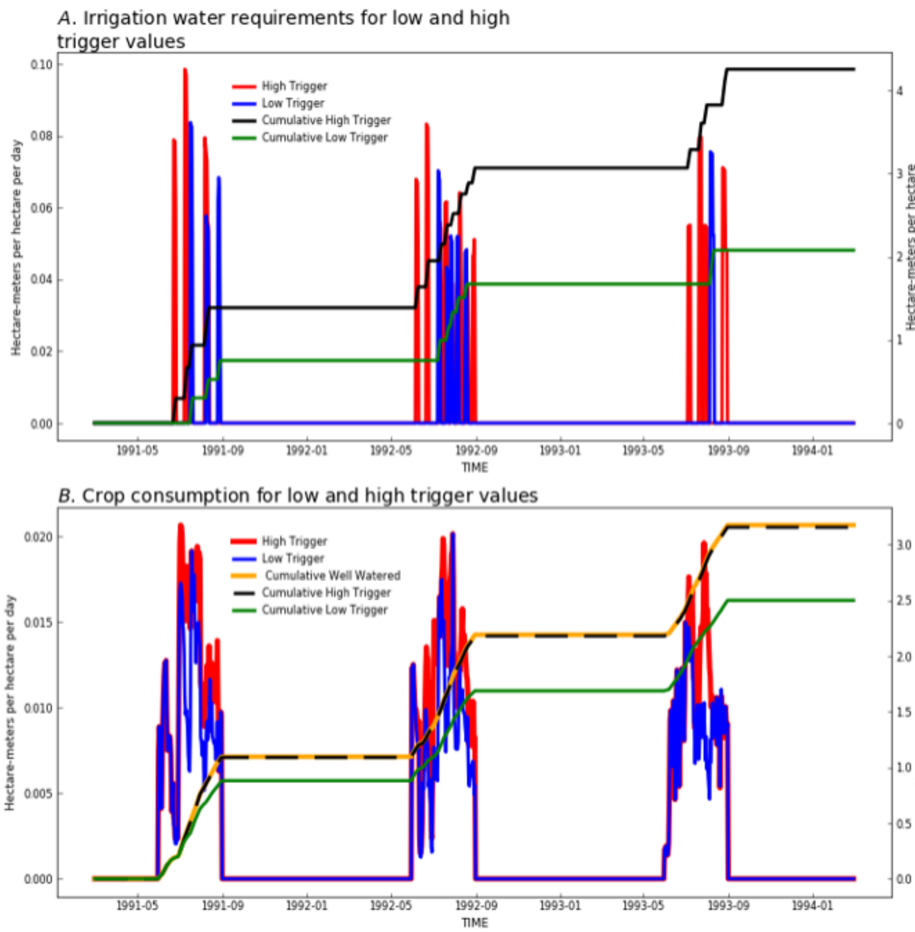


Figure 10. Comparison of agricultural water use for example problem 2a, using low and high irrigation trigger values.

7 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 irrigation supply and demand are not available, or it can be used to simulate the impacts of agricultural water use on water supply. The latter application is important in regions where there are competing needs for water, and 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 irrigation practices, 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 irrigation practices. Complete data sets are rarely 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.

8 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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