

agricultural Water Use Package for MODFLOW and GSFLOW

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Open–File Report 2017–#

Version X.X, Month 201X [if needed]  
Supersedes USGS Series Report XXXX–XXXX [if needed]

U.S. Department of the Interior

RYAN ZINKE, Secretary

U.S. Geological Survey

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U.S. Geological Survey, Reston, Virginia: 2017

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Suggested citation:  
Niswonger, R.G., 2017, agricultural Irrigation Package for MODFLOW-NWT, U.S. Geological Survey Open File Report 2017-xxx, 13 p,   
<http://dx.doi.org/x>.

ISSN XXXX-XXXX (print) [if applicable]  
ISSN XXXX-XXXX (CD/DVD) [if applicable]  
ISSN XXXX-XXXX (online)  
ISBN XXX-X-XXXX-XXXX-X [if applicable]

Preface

This report describes the agricultural Water Use (AG) Package for MODFLOW and GSFLOW. The program can be downloaded from the USGS for free. The performance of the AG Package has been tested in a variety of applications. Future applications, however, might reveal errors that were not detected in the test simulations. Users are requested to send notification of any errors found in this model documentation report or in the model program to the contact listed on the Web page (https://doi.org/10.5066/F70C4TQ8). Updates might be made to both the report and to the model program. Users can check for updates on the MODFLOW and GSFLOW Web pages.

Acknowledgments

This research was supported by the U.S. Geological Survey Water Availability and Use Science Program. We appreciate the technical reviews provided by the USGS scientists. Their suggestions resulted in a distinctly better manuscript.

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agricultural Water Use Package for MODFLOW and GSFLOW

By Richard G Niswonger

# 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. Daily potential evapotranspiration calculated by GSFLOW is used to determine the net irrigation water requirement (NIWR) using the daily climate and simulated agricultural field conditions. NIWR is diverted into canals and routed to fields using the MODFLOW SFR Package, or NIWR can be supplied/supplemented by groundwater wells. The Ag Package solves for NIWR by calculating the required irrigation amount that minimizes the difference between potential crop evapotranspiration (ET) and the actual simulated ET. The minimization procedure iteratively increases a surface water diversion and routes the water through the irrigation delivery system to fields where it is applied as irrigation. Variably saturated flow, storage and ET in agricultural fields is simulated using the UZF Package for MODFLOW-only simulations and the PRMS soilzone module for integrated GSFLOW simulations. Combined with MODFLOW and GSFLOW, the Ag Package can simulate dynamic water use by agriculture in developed basins.

# 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. Existing MODFLOW-based codes can simulate water use by agriculture; however, these approaches have not been combined with GSFLOW, or they do not simulate dynamic soil-water conditions to estimate net irrigation water requirements (NIWR). NIWR can be estimated using inverse methods that minimize the ET deficit throughout the growing periods. As ET is directly dependent on the soil saturation, minimizing the ET deficit will result in optimal soil saturation for a crop. A new package developed for MODFLOW and GSFLOW called the Agricultural (Ag) Water Use Package can simulate demand driven and supply limited agricultural water use.

The Ag Package is integrated into the MODFLOW and GSFLOW solutions and can simulate land use change and daily climate variability in the estimation potential ET and water use at a regional scale. The new Package also can simulate conjunctive use of surface water and groundwater by automatically pumping groundwater when surface water availability is less than demand. Because NIWR, irrigation efficiency, and crop consumption are simulated using daily climate inputs, the model can be used to simulate impacts of climate change on water supply in agricultural basins. Dynamic land use can be simulated, including changes in crop type, expansion or contraction of farmlands, or changes in irrigation technology.

agricultural demand is dependent on regional hydrologic states that are not measured but can be simulated using a hydrologic model, including dynamic surface water, soil, vadose zone, and groundwater storages. In water limited environments, decisions must be made regarding whether to fallow land or modify irrigation practices. 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. 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. MODFLOW and GSFLOW can represent both natural hydrologic processes and water use by humans, which makes them useful tools for water resources planning and management. The agricultural (Ag) Water Use Package for MODFLOW and GSFLOW provides a wholistic approach for representing agriculture in MODFLOW or GSFLOW and can be used for planning and assessing impacts of agriculture on other water-use sectors and for evaluating long-term sustainability.

# Purpose and Scope

This report describes the Agricultural Water-Use Package developed for MODFLOW and GSFLOW (Niswonger and others, 2011; Markstrom and others, 2008; Regan and others, 2015). The Ag Package works with the Streamflow-Routing (SFR2) and the Unsaturated Flow (UZF1) Packages, and the PRMS soilzone module, and includes capabilities for simulating pumping wells, like the WELL Package for MODFLOW-NWT. The Ag Package has 4 major capabilities, including 1) application of water flowing in SFR2 diversion segments as irrigation to UZF1/PRMS cells/HRUs; 2) application of water pumped by wells in the Ag Package as irrigation to UZF1/PRMS cells/HRUs; 3) automatic pumping of groundwater to supplement SFR2 diversions when the available flow in a diversion segment is less than demand; and 4) calculate NIWR using the UZF1/PRMS crop evapotranspiration (ET) deficit and simulated irrigation efficiency. Option 4 includes sub-irrigation where the ET demand can be supplemented by direct uptake of groundwater by plants. Irrigation water is explicitly applied to cells/HRUs, and ET is simulated using a daily soil-water balance. Surface water and groundwater return flow is routed to receiving water bodies or aquifers.

All exchanges of irrigation water between different packages (SFR2, UZF1, LAK7, and ag) and with aquifers are calculated within the Ag Package; however, the SFR2, UZF1, and LAK7 Packages must be active in MODFLOW and GSFLOW to divert surface water from streams and lakes and apply irrigation water to cells/HRUs. Diversion segments must be specified within the SFR2 Package to deliver stream or lake water to fields. All data for supplementary and irrigation wells is specified within the Ag Package input file; the Ag Package calculates and applies its own boundary conditions to the groundwater flow equation for representing groundwater pumped by wells.

# Description of the agricultural Water Use Package

## Surface Water and Groundwater Irrigation

The Ag Package can be used to simulate surface or groundwater water use by agriculture with 3 different options (Figure 1):

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

Time varying surface water diversions are specified in the SFR2 Package, or time varying pumping rates are specified in the AWU Package, and these amounts are used to set the NIWR. All, or a portion of irrigation water is applied to UZF1 cells or PRMS HRUs, and ET is simulated by UZF1 or PRMS, including groundwater and surface water return flows. Alternatively, a portion of diverted or pumped water can be removed from the model to represent the gross irrigation water requirement (GIWR), such that ET is not simulated explicitly. The remaining portion of water is applied as groundwater return flows. During flow-limited or draw-down limited conditions, irrigation is reduced to the actual diverted or pumped amount.

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

Time varying surface water diversions are specified in the SFR2 Package input file, and these amounts are used to set the NIWR. For conjunctive use systems, specified surface water diversions are used to set the NIWR, and the difference between the NIWR and diverted surface water rate, referred to as the surface water shortfall, is automatically pumped from groundwater wells. All, or a portion of the irrigation supply is applied to UZF1 cells or PRMS HRUs, and ET and groundwater and surface water return flows are simulated by UZF1 or PRMS. Alternatively, a portion of diverted water assumed to be consumed by plants can be removed from the model to represent the GIWR, and crop consumption is not simulated explicitly. During flow-limited or draw-down limited conditions, irrigation is reduced to the actual diverted or pumped amount.

1. **Simulated NIWR**

NIWR is calculated by the model according to:

, (1)

Where is the total irrigation water loss or gain that occurs between the diversion or well and the agricultural field(s). NIWR is calculated by minimizing the difference between the crop reference ET () for well-watered conditions () and the simulated actual crop ET (). If the irrigation water supply is less than NIWR then will be less than . is specified in the UZF1 input file as the product for MODFLOW simulations, or it is calculated using daily climate data and one of six options available in PRMS, including Jensen-Haise, Hargraeves-Semani, Penman-Monteith, Priestly-Taylor, Hamon, and pan potential ET modules (Markstrom and others, 2015). For the latter case, HRU-based ET coefficients must be multiplied by the crop coeficient () in the calculation of (Allen and others, 1998). Example problem 2 below demonstrates how is incorporated into GSFLOW simulations for the Jensen-Haise formulation. is calculated using the UZF1 Package or by the PRMS Soilzone Module using a kinematic wave formulation or nonlinear soil-water reservoir approach, respectively (Markstrom and others, 2008). Irrigation is supplied by SFR2 diversion segments and/or Ag Package groundwater wells. During flow-limited or draw-down limited conditions, irrigation is reduced to the actual diverted and/or pumped amount.

## Constraints on Irrigation

For options (1) and (2), some fraction of the NIWR can be removed from the model to simulate GIWR, as an alternative to explicitly simulating ET. For example, a surface water diversion in the SFR2 Package and a well in the Ag Package can be used to irrigate a group of cells that contain agricultural fields. For the simplest case, and assuming irrigation water supply is greater than or equal to the , an efficiency factor can be used to partition into and as:

, (2)

and

Where is the irrigation efficiency factor specified in the Ag Package input file; is the sum of surface water and groundwater diverted or pumped for irrigation, L3T-1; and is the irrigated area (L2) that is represented by the total area of HRUs or cells that receive irrigation water. can be set to values less than one to represent surface water and groundwater return flows or it can be set to a value of 1 to represent perfect irrigation efficiency. It is recommended that ET be simulated explicitly, and the irrigation amount after system delivery losses be applied to a cell/HRU if the user wants to represent the impacts of infiltration capacity on irrigation water partitioning. GIWR is calculated using separate efficiency factors for surface water and groundwater as:

. (3)

and are the surface water and groundwater irrigation delivery rates (L3T-1), which can be less than the diversion rate or pumped amount due to system’s gains and losses if they are represented in the model using a leaky canal or pipe; and is the area of the fields irrigated by a diversion and/or well. The amount of water applied to each cell or HRU () is:

. (4)

Where is the field factor specified in the Ag Package input file to represent how the GIWR is distributed among cells or HRUs that are irrigated by an SFR2 diversion and/or Ag Package well, and *i* is the index to the cell or HRU. for all cells and HRUs irrigated by a diversion should sum to one. If an efficiency factor is used (eq. 3) to represent all system losses, then ET should not be simulated on the cell or HRU and surface water return flow is set to zero. For the case where explicitly is simulated using the UZF1 Package or PRMS Soilzone Module, irrigation is partitioned into , surface water return flows, and groundwater return flow using the hydraulic properties of the cell/HRU and the runoff and unsaturated flow simulation capabilities in UZF1 or PRMS.

Note that equations 2-4 are used to simulate crop consumption and return flow due to irrigation from a single surface water diversion and/or well; however, a cell can be irrigated by multiple diversions or a combination of surface water diversions and groundwater wells. If ET is explicitly simulated by UZF1 or PRMS, then can be set to zero as return flows and other system losses are simulated.

The third option for simulating water use by agriculture is to calculate the irrigation amounts using the ET deficit. As with options 1 and 2, option 3 can be used in MODFLOW or GSFLOW simulations. NIWR is not determined by the specified SFR2 diversion or the specified pumping rate, rather the NIWR is calculated as the amount of water that must be diverted and/or pumped such that the difference between the simulated and is minimized. For GSFLOW, is calculated as:

. (5)

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

, (6)

and for MODFLOW simulations:

. (7)

and are the total number of HRUs or cells irrigated by a diversion, respectively. Like the first two approaches for simulating agricultural water use, surface water diversions and groundwater pumping rates used for irrigation are limited by the amount of water flowing in the segment that supplies water to the diversion segment and the pumping capacity of the wells. However, in this third case, if the diversion is not limited by the flow at the diversion point and/or specified pumping capacity, the diversion amount is calculated by minimizing (min) the ET deficit ( as:

, (8)

Values specified for diversions in the SFR2 Package input file and pumping rates specified in the Ag Package are useful for constraining irrigation timing and maximum amounts, for example, to represent growers that only can divert water or pump groundwater for irrigation during specific time periods, or to represent maximum surface water conveyance or well pump capacity.

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

, (9)

Where

, (10)

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

, (11)

and

. (12)

Where is the percentage of the surface water shortfall that will be pumped and is specified in the Ag Package input file; is the surface water diversion amount required to meet the NIWR for nonlinear iteration (L3/T-1), is the actual surface water diversion amount (L3/T-1), and is the supplemental groundwater pumping rate (L3/T-1). The amount of water that is applied to each cell or HRU that is irrigated by the diversion is:

. (13)

1. Flow charts showing three different configurations for using the agricultural Water Use Package; A) Surface water irrigation using IRRIGATION\_SFR Option; B) Surface water (SW) and groundwater (GW) irrigation using IRRIGATION\_SFR and IRRIGATION\_WELL; and C) Surface water and groundwater irrigation using IRRIGATION\_SFR and IRRIGATION\_WELL, demand calculated as ET deficit using ETDEMAND.

# Ag Package Input File

The Ag Package is activated, and the input file is read when the file type “AG” is specified within the MODFLOW Name file. The Ag Package input file consists of character variables that define 1) model options, 2) time series output, 3) well list, and 4) stress period data. The options block must begin with the character “options” and end with the character “end” and is not case sensitive. At least one option is required for the Ag Package to be used. The time series data only are required if one or more of the time series character variables are specified within the options block. The time series block must begin with the character “time series” and end with the character “end.”

The optional well list data input includes all wells that will be used during a simulation and is included only if the variable “MAXWELLS” is specified in the options block followed by a nonzero value specified for nummaxwell. The well list block must begin with the character “well list” and end with the character “end.” Any well can be made inactive or active during a simulation within the stress period block. Specified pumping rates can be used to limit the pumping capacity for supplementary wells (character option “SUPPLEMENTAL\_WELL”) or for wells with simulated pumping rates using the NIWR (character option “ETDEMAND”). Pumping rates can be specified in the well list and these rates will remain constant during a simulation. For cases where pumping rates vary in time, tabular input files (character option “TABFILES”) can be used to specify pumping rates. Only negative pumping rates can be specified for the Ag Package. Details regarding these inputs are provided in a separate input instructions document.

# Output Options

Three output options are available for the Ag Package, including 1) standard cell by cell pumping rates output to an unformatted file; 2) lists of flows for each SFR2 surface water diversion and well, irrigated amount for each cell/HRU for a diversion, and irrigated amount for each cell/HRU for a well; and 3) time series of diversion flows or groundwater pumping rates for wells, and time series of volumetric rates of well-watered (potential) consumption and actual crop consumption for cells/HRUs supplied by a diversion/well. The time series file generated for “TIMESERIES\_SFR” includes all supplemental pumping for the SFR diversion if there are supplemental wells. The last column of values for all other time series files will be labeled “NULL” and should be ignored. Additional to these output options, a water budget table that lists all inflows and outflows for the Ag Package can be output to the MODFLOW List File or separate formatted output file using Output Control options. All flows are output as volumetric flow rates in units determined from the unit specifications in the MODFLOW Discretization Package.

# Example Problems

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

## Example Problem 1

A hypothetical model was developed for MODFLOW-NWT that 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 (Figure 1). The valley aquifer consists of alluvium dominated by sand and gravel, and the mountains consist of bedrock that has much lower hydraulic conductivity than the valley alluvium. Recharge in the basin primarily occurs as seepage loss from the intermittent stream channels and to a lesser extend as groundwater flowing to the valley from the mountain block.

Figures 2 and 3 illustrate the model parameterization for this example. The model domain extends to a maximum of 520 feet below land surface in the valley bottom; and extends laterally 75 km in the north-south direction, and 50 km in the east-west direction. The model is discretized into 1 layer, 15 rows, and 10 columns, and only model cells coincident with the basin fill are active; consolidated rocks are not included. Layer 1 ranges in thickness between 130 feet and 520 feet. Model cells have a constant dimension of 5000 feet in the row and column directions. Two tributary streams that enter the model from the northwest and northeast join the mainstem in the southern part of the model (fig. 2). Twenty-four transient stress periods are simulated, proceeded by an initial steady state stress period. Each stress period represents a calendar month and are divided into daily time steps. The simulation begins on January 1.

Aquifer hydraulic conductivity and specific yield increase in the valley bottoms that comprise of floodplains or new alluvium of the tributary streams and river (fig. 3). Prudic and others (2004) present additional details describing this test problem, including representation of the stream network, and distribution of recharge and ET parameters used within the model. Niswonger and others (2006) describe modifications made to this example to replace the ET and Recharge Packages with the UZF1 Package; excess applied infiltration and rejected infiltration/spring discharge is routed to streams. PET specified in UZF1 Package represents . Other UZF1 Package input values were modified from previous values to better represent agricultural water use (Table 1).

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 8. Figure 1 shows the cells designated as agricultural fields that receive irrigation. The irrigation schedule or maximum surface water diversion for irrigation for EP1a and EP1b is 7 days of irrigation followed by 7 days without irrigation during the April to September period (Fig. 3a). A maximum of 20 ft3/s can be diverted from the stream for irrigation. SFR2 diversion segment number 9 was used to divert water from deliver surface water to the fields. The maximum NIWR that is diverted from the stream was specified in the model using a SFR2 tabular inflow file for diversion segment 9.

### Example Problem 1 Results

## Example Problem 2

# Discussion

While

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