

Agricultural Water Use Package for MODFLOW and GSFLOW

By Richard G. Niswonger

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

William Werkheiser, Acting Director

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

For more information on the USGS—the Federal source for science about the Earth,  
its natural and living resources, natural hazards, and the environment—visit  
<http://www.usgs.gov>/ or call 1–888–ASK–USGS (1–888–275–8747).

For an overview of USGS information products, including maps, imagery, and publications,  
visit <http://www.usgs.gov/pubprod>/.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply  
endorsement by the U.S. Government.

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 (AGWU) Package for MODFLOW and GSFLOW. The program can be downloaded from the USGS for free. The performance of the AGWU 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.

Contents

Abstract 1

Introduction 1

Description of the Modified Footprint Algorithm 3

Initial Redistribution 3

Redistribute to Perimeter Cells when Stalled 4

Using ModelMuse with WellFootprint 4

Starting a New Footprint Project 5

Editing the Grid 5

Non Spatial Data 5

Input Data Sets 6

Running WellFootprint 6

Displaying Results 7

Input file format 7

Output file formats 12

Format of text result file 12

Format of binary results file. 13

Acknowledgments 13

References Cited [or Selected References] 14

Figures

**Figure 1.** Illustration of using proportionally sized circles to represent well withdrawal magnitudes. 2

**Figure 2.** The Footprint is NOT a capture zone, or the area that contributes recharge to the wells. It is solely a visualization of the magnitude of pumping, centered on the wells (Senior and Goode, 2013). 2

**Figure 3.** Steps in the initial redistribution process. *A.* Colored cells are all less than half the distance to the nearest from a withdrawal point to the nearest neighboring withdrawal point are candidate cells. *B.* Cells from A have been eliminated as candidate cells to reduce the sum of the capacities of the candidate cells to less than the associated withdrawal from the withdrawal point. *C.* Candidate cells that lack a path from the withdrawal point through other candidate cells have been eliminated. 4

Agricultural Water Use Package for MODFLOW and GSFLOW

By Richard G Niswonger

# Abstract

The Agricultural Water Use (AGWU) Package was developed for simulating water use by agriculture in MODFLOW and GSFLOW models. Conventional approaches for simulating agricultural water use are not integrated within the broader hydrologic system, making it difficult to simulate supply-limited water use. Currently available approaches used in MODFLOW rely on external calculations for calculating the net irrigation water requirement (NIWR) and do not simulate soil water balance to estimate demand, which is problematic for regions with limited water supply for agriculture. The AGWU Package calculates the NIWR, irrigation water supply, evapotranspiration, and return flows simultaneously during a MODFLOW or GSFLOW simulation. Because AGWU can simulate the NIWR using an ET-demand soil water balance approach, constraints on NIWR due to limited irrigation water supply are represented. Irrigation is explicitly simulated by applying diverted surface water and pumped groundwater to fields. The AGWU Package is integrated with the UZF1 and SFR2 Packages for MODFLOW simulations, and it is integrated with the PRMS Soilzone Module and the SFR2 Package for GSFLOW simulations. Surface water diversions simulated by the SFR2 Package can be automatically applied as irrigation to UZF1 cells or PRMS HRUs. Irrigation supplied by groundwater is calculated by the AGWU Package, using the same approach of the MODFLOW-NWT WELL Package, and pumped groundwater can be automatically applied to UZF1 cells or PRMS HRUs as irrigation. Groundwater irrigation can be the sole source of irrigation water, or it can be calculated as the difference between the NIWR and surface water irrigation supply when the surface water diversion is less than the NIWR.

# Introduction

Agriculture is a major water-use component 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 rely on preprocessed water demands and consumption. Capabilities were added to MODFLOW and GSFLOW by creating a new MODFLOW package that can simulate dynamic soil water balance on farmlands and the feedbacks between supply and demand. Because this new package is integrated into the MODFLOW and GSFLOW solutions, it can simulate water supply-limited conditions that leaves a portion of water demands unsatisfied, or generate demands that change due to deficits in irrigation. The new package also can simulate agricultural water use in systems that conjunctively use surface water and groundwater. Because NIWR, irrigation efficiency, and crop consumption are simulated using climate inputs, the model can be used to simulate impacts of climate change on water supply in agricultural basins. Finally, dynamic land use can be simulated by changing irrigation processes during a simulation.

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. 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 Water-Use (AGWU; pronounced as the Spanish word agua) Package for MODFLOW and GSFLOW provides a wholistic approach for representing agricultural water use in MODFLOW or GSFLOW that 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-NWT and GSFLOW (Niswonger and others, 2011; Markstrom and others, 2008). The AGWU Package works with the Streamflow-Routing (SFR2) and the Unsaturated Flow (UZF1) Packages, and includes capabilities for simulating pumping wells, like the WELL Package for MODFLOW-NWT. The AGWU Package has 4 major capabilities, including 1) apply water flowing in SFR2 diversion segments as infiltration to UZF1/PRMS cells/HRUs; 2) apply water pumped by wells in the AGWU Package as infiltration to UZF1/PRMS cells/HRUs; 3) automatically pump water in wells 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. As irrigation water can be explicitly applied to cells/HRUs, and water consumption by plants is simulated using soil-water balance, both surface water and groundwater return flows also can be simulated.

Use of the AGWU Package does not require changes to the input files for any other MODFLOW Package or GSFLOW Module. All exchanges between different packages (SFR2, UZF1, and AGWU) are calculated within the AGWU Package; however, the SFR2 and UZF1 Packages must be active in MODFLOW and GSFLOW to divert surface water and apply irrigation water to cells/HRUs. Diversion segments must be specified within the SFR2 Package to apply diverted surface water as irrigation. All data for supplementary and irrigation wells is specified within the AGWU Package input file; the AGWU Package calculates and applies its own boundary conditions to the groundwater flow equation for representing groundwater pumped by wells. Terminology used in this report follows as much as possible those used by Allen et al. (1998).

# Description of the Agricultural Water Use Package

## Surface Water and Groundwater Irrigation

The AGWU 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 available diversion 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 surface water supply, 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. During flow-limited conditions, diversions for irrigation are set equal to the available water supply. Excessive drawdown or a limited well pumping capacity also can reduce irrigation below well water conditions.

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 () and the actual crop ET (). If the irrigation water supply is less than NIWR then will be less than ; is calculated using the UZF1 Package or one of the PRMS ET modules. Irrigation is supplied by SFR2 diversion segments and/or AGWU groundwater wells. The product is specified by the user in the UZF1 Package input file for MODFLOW simulations; is calculated using one of several potential ET modules in PRMS, for example the Penman-Monteith equation, and is specified within the AGWU Package input file (Allen et al., 1998).

## 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 within UZF1 or PRMS. For example, a surface water diversion in the SFR2 Package and a well in the AGWU 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 AGWU input file; is the sum of surface water and groundwater diverted or pumped for irrigation, L3T-1; and is the irrigated area (L2). 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 includes a portion of the 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 AGWU input file to represent how the GIWR is distributed among cells or HRUs that are irrigated by an SFR2 diversion and/or AGWU well, and *i* is the index to the cell or HRU. The sum of for all cells and HRUs irrigated by a diversion or well should be 1. If an efficiency factor is used to represent all system losses then ET should not be simulated on the cell or HRU and surface water return flow is assumed to be zero. For the case where is simulated, irrigation is partitioned into and surface water and groundwater return flows using the hydraulic properties of the cell/HRU and the runoff and unsaturated flow simulation capabilities in UZF1 and 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 crop ET deficit. As with options 1 and 2, option 3 can be used in MODFLOW or GSFLOW simulations. The net NIWR is not determined by the specified SFR2 diversion or the specified pumping rate, rather the net 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, the potential ET (PET) is calculated by PRMS, and the crop ET for well water conditions ()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, the diversion amount is calculated by minimizing (min) the ET deficit ( as:

, (8)

For this approach, values specified for diversions in the SFR2 Package input file and pumping rates specified in the AGWU Package are useful for constraining irrigation timing and 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:

, (7)

Where

, (8)

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:

, (9)

and

. (10)

Where is the percentage of the surface water shortfall that will be pumped and is specified in the AWU 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:

where

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.

# AGWU Package Input File

The AGWU Package is activated by specifying a file type of “AGWU” within the MODFLOW-NWT Name file.

The AGWU input file contains 3 types of data, including 1) Options, 2) Well List, 3) Time series output, and 4) Stress Period data for specifying connectivity between segments and irrigation cells, supplemental wells and diversion segments, and irrigation wells and irrigation cells. For these options, canals can be constructed using the SFR segments to represent conveyance gains/losses due to surface water and groundwater interactions. Leaky pipes also can be represented explicitly using SFR segments or implicitly using efficiency factors input to the AGWU Package.

The AGWU 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 AGWU 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 well list data input includes all wells that will be used during a simulation. Any well can be made inactive or active during a simulation. 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 AGWU Package.

Details regarding these inputs are provided in a separate input instructions document.

# Output Options

Three output options are available for the AGWU 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. Additional to these output options, a water budget table that lists all inflows and outflows for the AGWU 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 AGWU 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 example problem. Although there is no agriculture in the Sagehen Creek Watershed, the AGWU Package was added this example to simulate irrigation from surface water and supplementary wells to a small number of HRUs in the lower part of the watershed.

## 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. Overland routing of excess applied infiltration and groundwater discharge to streams was made active. PET specified in UZF1 Package represents and thus the specified value for in the AGWU Package is not used. Other UZF1 Package input values were modified from previous values to better represent agricultural water use.

Two versions of Example Problem 1 are presented. Example Problem 1a (EP1a) simulates irrigation water provided solely by groundwater, and Example Problem 1b (EP1b) that simulates irrigation water provided by surface water and supplementary 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 for EP1a and EP1b is 7 days of irrigation followed by 7 days without irrigation during the April to September period for each of the two years of simulation. 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

# Discussion

While the use of WellFootprint to display well withdrawals has been emphasized here, there are other sorts of data that could be displayed using WellFootprint. For instance, disease frequency could be displayed to create maps that are easier to understand. In general, the footprint method might be useful when plotting any type of closely spaced point data of varying intensity.

# References Cited

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome, 300(9), D05109.