

Agricultural Water Use Package for MODFLOW and GSFLOW

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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.

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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 irrigation demand and do not simulate soil water balance to estimate demand, which is problematic for regions with limited water supply for agriculture. AGWU Package calculates irrigation demands, irrigation amounts, evapotranspiration, and return flows simultaneously during a MODFLOW or GSFLOW simulation. Because AGWU simulates irrigation demands using a ET-demand soil water balance approach, impacts of water supply on irrigation demand 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 irrigation demand and surface water diversion when the surface water diversion is less than the irrigation demand.

# 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. 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 irrigation demand and agricultural consumption are simulated using climate inputs, the model can be used to simulate impacts of climate change on water supply in agricultural basins.

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 irrigation demand using the UZF1/PRMS ET deficit. 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 (evapotranspiration; ET) 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 in order 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.

# Description of the Agricultural Water Use Package

## Surface Water and Groundwater Irrigation

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

1. **Surface water only**

Time varying surface water diversions are specified in the SFR2 Package, and these amounts are used to set the irrigation demand. 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 water consumed by plants can be removed from the model to represent consumption. During flow-limited conditions, irrigation is reduced to the available diversion amount.

1. **Conjunctive use**

Time varying surface water diversions or groundwater pumping rates are specified, and these amounts are used to set the irrigation demand. For conjunctive use systems, surface water diversions are used to set the irrigation demand, and surface water shortfalls are automatically pumped from groundwater and added to the irrigation supply. 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 water consumed by plants can be removed from the model to represent consumption. During flow-limited conditions, irrigation is reduced to the available diversion amount.

1. **Conjunctive use and ET deficit demand**

Irrigation demand () is calculated using the daily ET deficit:

, (1)

where is crop evapotranspiration demand, and is actual crop evapotranspiration; the actual irrigation ( is set equal to the minimum of the irrigation supply ( and ; is calculated using the UZF1 ET option or one of several options in PRMS; interdependencies between , , and are solved during the outer MODFLOW or GSFLOW nonlinear iteration loop; irrigation is supplied by SFR2 diversion segments and/or AGWU groundwater wells.

## Constraints on Irrigation

For options (1) and (2) some fraction of the irrigation demand can be removed from the model to represent as an alternative to explicitly simulating ET within UZF1 or PRMS. For example, a surface water diversion in the SFR2 Package can be used for irrigating a group of cells that contain agricultural fields. For the simplest case, an efficiency factor is used to partition irrigation into crop consumption and return flow as:

. (2)

Where is the irrigation efficiency factor specified in the AGWU input file; is the diversion flow rate specified in the SFR2 input file, L3T-1; and is the area of fields irrigated by the diversion. can be set to values less than one to represent groundwater return flows; to represent surface water and groundwater return flows, it is recommended that ET be simulated explicitly and the full irrigation amount be applied to the cell/HRU to represent the impacts of infiltration capacity on irrigation water partitioning. Thus, the amount of water that will be applied to cells or HRUs to represent return flows from an SFR2 diversion is:

. (3)

The distribution of water applied to each cell or HRU from an SFR2 diversion is:

. (4)

Where is the amount of water per unit area applied to a single cell or HRU to represent return flow, LT-1; is the field factor specified in the AGWU input file to represent how irrigation return flow is distributed among cells or HRUs that are irrigated by an SFR2 diversion, and *i* is the index to the cell or HRU. If an efficiency factor is used to partition into and groundwater return flow, 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; 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 should be set to zero. Because the maximum ET is specified by the user within the UZF1 Package (UZF1 variable PET), the user should specify this value to be equal to the crop ET and not the reference crop ET (Allen et al., 1998).

The third and most complex option for simulating water use by agriculture is to calculate the irrigation amounts using the ET deficit. As with options 1 and 2, options 3 can be used in MODFLOW or GSFLOW simulations. Irrigation will not be specified as the SFR2 diversion amount, rather the irrigation amount is calculated as the amount of irrigation water that must be applied to cells such that the simulated is equal to . For MODFLOW simulations, is specified in the UZF1 Package; however, for GSFLOW the potential ET (PET) is calculated by PRMS and is calculated as:

. (4)

Where is the crop coefficient (Allan et al., 1998) specified in the AGWU input file. The total SFR2 diversion amount for all cells or HRUs irrigated by an SFR2 diversion is:

, (5)

and for MODFLOW simulations:

. (6)

Where is the amount of water diverted for irrigating all associated cells or HRUs; and are the amount of applied irrigation required for minimizing the difference between and for the HRU and cell, respectively; and 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 used for irrigation are limited by the amount of water flowing in the segment that supplies water to the diversion segment. However, in this third case, because the diversion amount is calculated by minimizing the ET deficit ( - ), also must be less than the user specified diversion amount ( specified in the SFR2 input file. This condition is useful for constraining irrigation timing and amounts, for example to represent growers that only can divert water for irrigation during specific time periods. For irrigation solely supplied by groundwater, the specified pumping rate limits , or the pumping capacity of the well limits . For conjunctive-use systems, the specified diversion amount in the SFR2 Package limits , or the combined actual diversion and pumping rate limit .

For option 3, the irrigation amount ( is calculated by minimizing the ET deficit as:

, (7)

and

. (8)

Where

. (9)

and are the area of each HRU and cell, respectively.

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, and 3) Stress Period data for specifying connectivity between segments and irrigation cells, supplemental wells and diversion segments, and irrigation wells and irrigation cells.

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.

## Limitation

As The footprint is NOT the area that contributes recharge to the wells. It is solely a visualization of the magnitude of pumping, centered on the wells (Goode, 2016).

# Description of the Modified Footprint Algorithm

The

## Initial Redistribution

The Steps in selecting cells in the initial redistribution process. Around the two wells, (black, solid cells), a neighborhood is selected in which all the cells are active, sufficiently close to the well, and connected by other candidate cells to the well cell.

## Redistribute to Perimeter Cells when Stalled

The

1. Example redistribution to perimeter cells when stalled. Modified from Goode (2016).

# Using ModelMuse with WellFootprint

ModelMuse (Winston, 2009, 2014) has been modified to generate the input for WellFootprint and to display the output from WellFootprint.

## Starting a New Footprint Project

When

## Editing the Grid

If the

## Non Spatial Data

The various

## Input Data Sets

There

## Running WellFootprint

To

1. Extensions Used with WellFootprint Files

|  |  |
| --- | --- |
| WellFootprint File type | Extension |
| Input | .fpi |
| Listing | .fplst |
| Binary results | .fpb |
| Text results | .fpt |

## Displaying Results

To d

# WellFootprint Input file format

An e

# WellFootprint Output file formats

## Format of text result file

The text result file contains two arrays Distributed\_Withdrawals and Footprint\_Code (table 2).

1. The data for each array starts with a line containing the name of the array.
2. This is followed by two lines containing the number of rows and number of columns in the grid respectively.
3. This is followed by a value for each cell in the grid in row-major order. Commas and white space are used to separate values.
4. Meaning of Footprint Codes

|  |  |
| --- | --- |
| Footprint code | Meaning1 |
| 0 | Inactive |
| 1 | Q = 0 |
| 2 | 0 < Q < D |
| 3 | Q = D |
| 4 | Q > D |

1 Q = Withdrawal rate; D = Cell capacity

## Format of binary results file.

# 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.