

Visualization of Groundwater Withdrawals

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 Irrigation Package (AGI) for MODFLOW-NWT. The program can be downloaded from the USGS for free. The performance of the AGI 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-NWT Web page.

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 Michael N. Fienen and Mathew Conlon. 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

Visualization of Groundwater Withdrawals

By Richard B. Winston and Daniel J. Goode

# Abstract

Generating an informative display of groundwater withdrawals can sometimes be difficult because the symbols for closely spaced wells can overlap. An alternative method for displaying groundwater withdrawals is to generate a “footprint” of the withdrawals (Goode, 2016). WellFootprint implements Goode’s algorithm with two optional variations that can speed up the footprint calculation. ModelMuse (Winston, 2009, 2014) has been modified to be able to generate the input for WellFootprint and to read and graphically display the output from WellFootprint.

# Introduction

When illustrating groundwater withdrawals on a map, it is desirable to convey both the magnitudes and locations of the withdrawals. One method to do this is to plot each withdrawal location as a circle with the area of the circle proportional to the magnitude of withdrawal. Often, however, this results in overlapping symbols which may cause difficulty in understanding the distribution of pumping (figure 1). The problem is described in greater detail by Goode (2016). Goode (2016) also presents an alternative method of displaying the withdrawals that can help overcome this difficulty. In the new method, withdrawals are represented as a composite “footprint” with the area of the footprint proportional to the amount of withdrawal. Where wells are closely spaced, the footprint may encompass multiple wells and the area of the composite footprint is proportional to the combined withdrawals.

1. Illustration of using proportionally sized circles to represent well withdrawal magnitudes. Modified from Kresse and others (2014).

The proportionality between the volumetric withdrawal rates and the footprint areas, that is the overall ‘scale’ of the footprint sizes, is specified by the user through the “depth-rate index” (see Goode, 2016), which has units of length per time. The area of a well’s withdrawal footprint is equal to the withdrawal rate (units of length-cubed per time) divided by the depth-rate index. Thus, the user can make the footprints larger by specifying a smaller depth-rate index, and vice versa. Goode (2016) presents examples of depth-rate indexes related to hydrologic characteristics, and how using such depth-rate indexes can give hydrologic meaning to the sizes of withdrawal footprints. The name “depth-rate index” is used because 1) the volume of a solid (withdrawal volume) is the product of its area (the footprint) and its height, or depth, 2) the rate or ‘per time’ part of the withdrawal needs to be canceled out, and 3) this value is a measure or indicator of the overall scaling used for the footprint map.

To calculate the footprint, Goode (2016) proposed an algorithm, herein the “Footprint” algorithm, in which the mapped area was subdivided into a grid with uniformly sized square cells. Each cell in the grid is assigned a “depth-rate index” with units of length/time. The recharge rate can be used as the depth-rate index but in some cases, other values might be used as the depth-rate index. Some cells may be specified as inactive. The ‘capacity’ of a cell to accommodate withdrawals equals its depth-rate index times its area. That capacity, which may or may not be related to the aquifer’s properties, has the same units, length-cubed/time, as the withdrawals. The withdrawals are mapped to the corresponding cells and then redistributed if the total withdrawals assigned to a cell exceed its capacity. To redistribute the excess withdrawals, the excess for each cell is calculated and divided among the immediately adjacent cells in a process analogous to diffusion. This process is repeated iteratively until the maximum excess in any cell is less than a user-specified stopping criterion. Program WellFootprint, described in this report, performs the Footprint algorithm calculations.

## Limitation

As pointed out by Good (2016), it must be emphasized that the footprint of a well is not equivalent to the source area contributing recharge to that well (fig 2). Instead, it is a method of visualizing the magnitude of withdrawals. The size of the footprint may, however, have a physical meaning if the depth-rate index is assigned based on some physical property of the mapped area. For instance, if the recharge rate is used as the depth-rate index, the footprint would correspond in size to the area needed to supply recharge to the wells in the footprint. Although the depth-rate index is typically the same in all cells, different values can be applied to different cells if that makes the resulting map more informative.

1. 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 Footprint algorithm described by Goode (2016) relies on redistributing excess withdrawals in a manner analogous to diffusion. Although the excess withdrawals will eventually be spread widely enough to reduce the excess to an acceptable level, the process can require many iterations. The algorithm described here modifies the Footprint algorithm in two ways that reduce the number of iterations required to reach an acceptable distribution of the excess withdrawals.

## Initial Redistribution

The first modification occurs before the very first iteration. For each cell that has withdrawals, a group of cells are identified to which the withdrawals will be distributed. This group will be called a “neighborhood”. To be part of the neighborhood, a cell must meet the following criteria.

1. The candidate cell must be active and have a capacity greater than zero.
2. The distance from the cell with withdrawals (W1) to the candidate cell (CC) must be less than half the distance to the closest other cell with withdrawals to W1.
3. The sum of the capacities of all the candidate cells whose distances from W1 is less than or equal to CC must be greater than or equal to the withdrawal from W1.
4. There must be a path from W1 to CC that passes only through candidate cells.

In the neighborhood, those cells that are adjacent to at least one active cell that is not part of the neighborhood with a capacity greater than zero are designated as perimeter cells. The others are designated as interior cells. The distributed withdrawals of the interior cells are set to their capacity with the excess withdrawals distributed evenly among the perimeter cells. An example of how candidate cells are selected is shown in figure 3.

1. 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 second modification is applied during the iterative process when the solution appears stalled. The solution process is considered stalled if distributed withdrawals are only added to cells that already have had at least some distributed withdrawals assigned to them. This can happen when the gradient in excess withdrawals is small. In such cases, neighborhoods are identified but they can be initiated at any cell with withdrawals greater than or equal to the capacity, and the criteria for inclusion in a neighborhood are that the cell is not already part of a neighborhood, and the withdrawals assigned to the cell are greater than or equal to the capacity. The withdrawals from interior cells are set equal to the capacity, and excess withdrawals are distributed among the perimeter cells. The excess is distributed uniformly among all the perimeter cells (fig. 4). The user can specify how many stalled iterations in a row must occur before withdrawals are redistributed to the perimeter cells.

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 starting ModelMuse, the user can choose to start a Footprint project in the Start-Up dialog box. If this option is chosen, the Initial Grid dialog box is displayed. In the Initial Grid dialog box, the user can specify the number of rows and columns, the cell size, the coordinates of the grid origin, and the grid angle. If ModelMuse is open with another project, the user can also select “File|New|New Footprint Project” from the ModelMuse main menu to start a new Footprint project. Another option is to select “Model|Footprint” to convert an existing project of some other type into a Footprint project.

## Editing the Grid

If the grid is not created in the Initial Grid dialog box, or if the user wants to change the grid later, a polygon object can be used to specify a cell size. Once cell size is specified, a grid can be generated by selecting “Grid|Generate Grid…” It also is possible to subdivide all the cells in the grid or to change the grid angle using the ModelMuse tools. However, because WellFootprint requires that the cells be of uniform size, some of the grids editing tools, such as the tools for adding and deleting grid lines, are not active with Footprint Projects.

## Non Spatial Data

The various options that can be specified for WellFootprint are specified in the Footprint Properties dialog box. It is displayed by selecting “Model|Footprint Properties”. Detailed descriptions of the options are included in the help for the dialog box. The options include Closure\_Criterion, Minimum Depth-Rate Index, Max\_Iterations, Initial\_Distribution, Redistribution\_Criterion, Text\_Results\_File, and Binary\_Results\_File.

The location of the WellFootprint program is specified in the Footprint Program Location dialog box. The location of a text editor also is specified in that dialog box. The text editor will be used to open the Footprint Listing file after the results have been calculated if the “Open listing file in text editor” option in the Footprint Properties dialog box has been selected.

## Input Data Sets

There are three input data sets in ModelMuse Footprint projects, DepthRateIndex, Withdrawals, and Active. These correspond to the Footprint input arrays Depth\_Rate\_Index, Withdrawals, and Active respectively. The values of DepthRateIndex and Active data sets are specified with formulas or objects as described in Winston (2009). The values of the Withdrawals data sets are typically specified by defining a withdrawal rate for a “Footprint Well” in the Object Properties dialog box. By convention, Withdrawal values must be positive, and represent the volumetric rate at which water is removed from the aquifer by the well. If two or more such wells are defined in the same cell, their respective withdrawal rates will be added together to define the final withdrawal rate for the cell. Alternatively, if no footprint wells are defined, the Withdrawals data set values can be defined in the normal ways. This option can be useful, if the user wishes to import gridded values of the withdrawal. Footprint wells can imported from point Shapefiles or through the “File|Import |Points” dialog box.

## Running WellFootprint

To generate the input files for WellFootprint, the user selects “File|Export|Footprint Input File. A Save File dialog box will be displayed. If the “Save” button is checked, the WellFootprint input file will be saved. If the “Execute model” checkbox in the Save File dialog box is checked, WellFootprint will be run using the input file that was generated. The extension used for the various input and output files are shown in the table 1.

1. Extensions Used with WellFootprint Files

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

## Displaying Results

To display results from WellFootprint, select “File|Import|Model Results” and select the desired binary results file or text results file. A dialog box will be displayed in which the user can select the Distributed Withdrawals and Footprint Code data sets calculated by WellFootprint. The selected data sets will be imported into ModelMuse. The user can choose to color or contour the grid with one of the imported data sets.

# WellFootprint Input file format

An example input file is included with the software. The input file for WellFootprint is a XML file. The root node of the file must be named **Well\_Footprint\_File**. The values of child nodes directly under the root node specify the model input. For real-number values, the period is used as the decimal separator. The child nodes may be arranged in arbitrary order. The child nodes may have the following names. Required items are in **bold** font. Optional items are in italic font.

* **FileFormatVersion**
* **Number\_Of\_Rows**
* **Number\_Of\_Columns**
* Closure\_Criterion
* Max\_Iterations
* Initial\_Distribution
* Redistribution\_Criterion
* **Cell\_Size**
* **Depth\_Rate\_Index**
* **Withdrawals**
* Active
* Grid\_Angle
* Outline
* Listing\_File
* Text\_Results\_File
* Binary\_Results\_File

**Depth\_Rate\_Index**, **Withdrawals**, or **Active** specify arrays. Arrays can be included directly in the input file or they may be read from a text or binary file. If read from a binary file, real numbers must be signed, double-precision (64-bit) real numbers and integers must be 32-bit signed integers. If read from a text file, a period must be used as the decimal point. Within the nodes for arrays there must be a child node that specifies how the data are to be read. The following child node names are supported: **Uniform**, **Direct**, **Text\_File**, and **Binary\_File**.

With the **Uniform** node, the value of the **Uniform** node is assigned to all members of the array. Values must be real numbers for the **Depth\_Rate\_Index** and **Withdrawals**. They must be either “True” or “False” for **Active**.

With the **Direct** node, the values are included in the input file. The **Depth\_Rate\_Index** and **Withdrawals** arrays are initialized to a default value of zero. The **Active** is initialized to a default value of “True”. Values only need to be specified for cells that have values different from the default values. For each row for which a value will be specified, there is a **Row** child node beneath the **Direct** node whose value is equal to the row number. Row numbers must range from 1 to the number of rows. Beneath each **Row** node, there is a **Column** child node for each column for which a value will be specified whose value is equal to the column number. Column numbers must range from 1 to the number of columns. Beneath each **Column** node is a **Value** child node whose value is the value to be assigned to the corresponding element of the array. Values must be real numbers for the **Depth\_Rate\_Index**, and **Withdrawals**. They must be either “True” or “False” for **Active**. Only one value for the same cell should be specified.

With the **Text\_File** or **Binary\_File** options, the name of a text file or a binary file respectively is specified as the value of the node. Either absolute or relative pathnames are acceptable for the file name. For **Depth\_Rate\_Index**, and **Active**, the contents of the file must be a number of rows times the number of columns values in row-major order. For text files, each line in the file must represent a separate row in the array, and each value in a row must be separated from the next by a comma and, optionally, one or more spaces. This option also can be used for **Withdrawals**. However, another option for **Withdrawals** is to use a text file or binary file containing the distributed withdrawals generated by WellFootprint.

The data required for each major tag is as follows

**FileFormatVersion**: For the current version of WellFootprint, the version number must be 1. The version number may change in future versions of WellFootprint. **FileFormatVersion** must be specified.

**Number\_Of\_Rows**: This is the number of rows in each of the three arrays required by WellFootprint. **Number\_Of\_Rows** must be specified.

**Number\_Of\_Columns**: This is the number of columns in each of the three arrays required by WellFootprint. **Number\_Of\_Columns** must be specified.

**Closure\_Criterion**: The closure criterion is the maximum amount of excess withdrawals assigned to a cell as a fraction of its capacity. When the closure criterion has been met for all the cells, WellFootprint will stop the calculation and print the results. If **Closure\_Criterion** is not specified, a default value of 0.01 will be used.

**Max\_Iterations**: When calculating the distributed withdrawals, Max\_Iterations is the maximum number of iterations that will be allowed before stopping the calculation. If Max\_Iterations is reached before the closure criterion has been reached in all the cells, WellFootprint will print and error message to the screen and the listing file. If **Max\_Iterations** is not specified, a default value of 10,000 will be used.

**Initial\_Distribution**: Initial\_Distribution is a true/false value. If set to true, the first step of the calculation will be to distribute the withdrawals for each well in a circle of cells around the well. The maximum radius of the circle will be half the distance to the nearest other well. If the total capacity of the cells in the circle is greater than the withdrawal, the radius of the circle will be reduced until the withdrawals equal or exceed the sum of the capacities of the cells in the circle. The withdrawals allocated to cells in the interior of the circle will be equal to their capacities. Excess withdrawals will be allocated to the cells on the exterior of the circle. If **Initial\_Distribution** is not specified, a default value of True will be used. A true value may be specified with the text “True” (case insensitive) or a non-zero number. A false value may be specified with the text “False” ” (case insensitive) or zero.

**Redistribution\_Criterion**: During the calculation of the distributed withdrawals, the algorithm may reach a point at which no distributed withdrawals are added to cells that do not already have some distributed withdrawals. At such times, it may be advantageous to redistribute excess withdrawals to the edges of patches of cells that contain excess withdrawals in order to speed up the calculation. The Redistribution\_Criterion determines when this occurs. If Redistribution\_Criterion is set to zero, the excess withdrawals are never redistributed from the edges of the patches with excess withdrawals. If Redistribution\_Criterion is set to a value greater than zero, the program will monitor when withdrawals are redistributed to cells that currently lack any withdrawals. If the number of such iterations in a row exceeds the value of Redistribution\_Criterion redistribution to perimeter cells will be applied. If **Redistribution\_Criterion** is not specified, the default value of 1 will be used.

**Cell\_Size**: Cell\_Size is the area of each cell. (Cells are required to be square in shape with a uniform size.) **Cell\_Size** must be specified.

**Depth\_Rate\_Index**: Depth\_Rate\_Index is a two-dimensional array of values with units of L/T. Each value represents the volume per unit area per unit time of withdrawals that can be applied to a cell. The Depth\_Rate\_Index multiplied by the Cell\_Size is the capacity of the cell. **Depth\_Rate\_Index** must be specified.

**Withdrawals**: Withdrawals is a two-dimensional array of values. Each value represents the volumetric rate of withdrawal from the cell with units of L3/T. **Withdrawals** must be specified.

**Active**: Active is a two-dimensional array of values. Each value must be a 1 or 0. Active cells should be designated as 1 and inactive cells should be designated as 0. Distributed Withdrawals will not be assigned to inactive cells. If **Active** is not specified, every cell will be treated as active.

**Grid\_Angle**: Grid\_Angle is the angle of the grid in degrees measured in the counterclockwise direction. Grid\_Angle is used to help document the position of the grid but is not used in any calculation. If **Grid\_Angle** is not specified, a default value of 0 is used.

**Outline**: Outline contains the coordinates of a polygon surrounding the model area. Typically, this would represent the four corners of the grid but it could be something else such as the coordinates of the outside of the active cells. Outline is used to help document the position of the grid but is not used in any calculation.

**Listing\_File**: Listing\_File is the name of a file that will contain output generated by WellFootprint. The output will list options used in the model. If neither Text\_Results\_File nor Binary\_Results\_File is specified, it will also contain the distributed withdrawals and footprint code. If Listing\_File is not specified, the name of the listing file will be the same as the input file except that the extension will be changed to “.fplst”.

**Text\_Results\_File**: Text\_Results\_File is the name of a text file that will contain the distributed withdrawals and footprint code calculated by WellFootprint. **Text\_Results\_File** is optional.

**Binary\_Results\_File**: Binary\_Results\_File is the name of a binary file that will contain the distributed withdrawals and footprint code calculated by WellFootprint. **Binary\_Results\_File** is optional.

# 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.

The binary result file contains two arrays Distributed\_Withdrawals and Footprint\_Code.

1. A footprint binary file starts with the identifier “Footprint\_Binary\_File” using 2-byte Unicode characters.
2. This is followed by a 32-bit signed integer representing the size of the real numbers (in bytes) saved in the file. Because double-precision is always used, this number is always 8. It is possible that in future versions of WellFootprint, a different precision will be used for real numbers.
3. Next is a 32 bit signed integer that represents the number of characters in the name of the array.
4. The name of the array (in 16-bit Unicode characters) is next. The name will be either “Distributed\_Withdrawals” or “Footprint\_Code”.
5. The number of rows and the number of columns respectively. Both are 32 bit signed integers.
6. This is followed by the numbers in the array in row major order. For Distributed\_Withdrawals, the numbers are double-precision real numbers. For Footprint\_Code, they are 32-bit signed integers.

# 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

Goode, D.J., 2016, Map visualization of groundwater withdrawals at the sub-basin scale: Hydrogeology Journal, v. 24, no. 4, p. 1057-1065.

Kresse, T.M., Hays, P.D., Merriman, K.R., Gillip, J.A., Fugitt, D.T., Spellman, J.L., Nottmeier, A.M., Westerman, D.A., Blackstock, J.M., and Battreal, J.L., 2014, Aquifers of Arkansas—Protection, management, and hydrologic and geochemical characteristics of groundwater resources in Arkansas: U.S. Geological Survey Scientific Investigations Report 2014–5149, 334 p., http://dx.doi.org/10.3133/sir20145149

Winston, R.B., 2009, ModelMuse-A graphical user interface for MODFLOW-2005 and PHAST: U.S. Geological Survey Techniques and Methods 6-A29, 52 p.

Winston, R.B., 2014, Modifications made to ModelMuse to add support for the Saturated-Unsaturated Transport model (SUTRA): U.S. Geological Survey Techniques and Methods, book 6, chap. A49, 6 p., http://dx.doi.org/10.3133/tm6a49.

ISSN (online)  
http://dx.doi.org/x