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Visualization of Groundwater Withdrawals

Open-File Report 2017–1137

U.S. Department of the Interior
U.S. Geological Survey

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By Richard B. Winston and Daniel J. Goode

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U.S. Department of the Interior
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Preface

The program WellFootprint can be downloaded from the U.S. Geological Survey for free. The performance of the WellFootprint 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 the report and to the model program. Users can check for updates on the WellFootprint web page.

Contents

Figures

Tables

Conversion Factors

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
kilometer (km)	0.6214	mile (mi)
	Flow rate	
cubic meter per day (m^3/d)	35.31	cubic foot per day (ft^3/d)

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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. WellFootprint version 1.0 implements the Footprint algorithm with two optional variations that can speed up the footprint calculation. ModelMuse has been modified in order 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 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 (fig. 1). The problem is described in greater detail by Goode (2016). Goode (2016) presents an alternative method of displaying the withdrawals that can help to 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.

The proportionality of the volumetric withdrawal rates to 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 is in units of length per time (L/T). The area of a well’s withdrawal footprint is equal to the withdrawal rate (units of length cubed per time [L^3/T]) 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 the manner in which 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, referred to as the “Footprint algorithm,” in which the mapped area is subdivided into a grid with uniformly sized square cells. Each cell in the grid is assigned a depth-rate index with units of L/T. 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

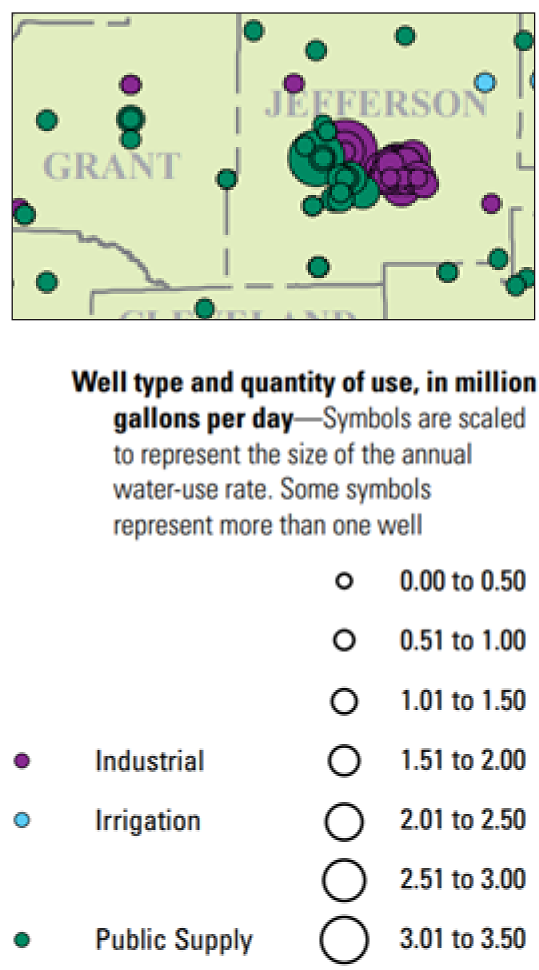

Figure 1. Illustration using proportionally sized circles to represent well withdrawal magnitudes. Modified from Kresse and others (2014).

inactive. The capacity of a cell to accommodate withdrawals equals its depth-rate index times the cell's area. That capacity, which may or may not be related to the aquifer's properties, has the same units, L^3/T, 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.

Purpose and Scope

This report describes the modified Footprint program, WellFootprint version 1.0. The use of, input to, and output from the program are also described. The report describes changes to ModelMuse (Winston 2009, 2014) to allow it to generate the input for WellFootprint, run WellFootprint, and import and display the results of WellFootprint,

Limitation of the Program WellFootprint

As pointed out by Goode (2016), it must be emphasized that the program does not produce a footprint that is equivalent to the source area contributing recharge to a well (fig. 2). Instead, it is a method for visualizing the magnitude of withdrawals. The size of the footprint may, however, have a physical meaning if the depth-rate index is assigned on the basis of 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.

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 and redistribution to perimeter cells when stalled.

Initial Redistribution

The first modification of the algorithm occurs before the very first iteration. For each cell that has withdrawals, a group of cells to which the withdrawals will be distributed are identified. This group will be referred to as a "neighborhood." To be part of the neighborhood, a cell must meet four 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 of W1 to the closest other cell with withdrawals.

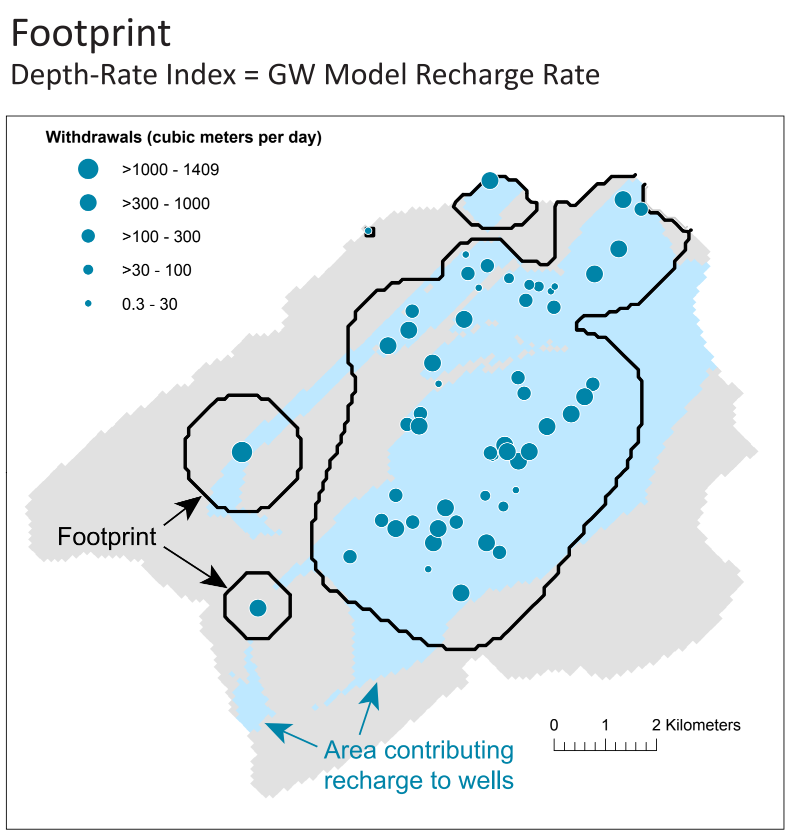

Figure 2. Footprint area versus contributing area. Modified from Goode (2016). The footprint is not the same as the area that contributes recharge to the wells. It is solely a visualization of the magnitude of pumping centered on the wells.

3. The sum of the capacities of all the cells in the neighborhood must be greater than or equal to the withdrawal from W1. If that criterion is not met initially, the radius of the neighborhood will be reduced until it is met.

4. There must be a path from W1 to CC that passes only through candidate cells.

In the neighborhood, some cells are designated perimeter cells. Perimeter cells must be adjacent to at least one active cell that is not part of the neighborhood, and that adjacent cell must have a capacity greater than zero. The other cells in the neighborhood are designated interior cells. The distributed withdrawals of the interior cells are set to the cell capacity with the excess withdrawals distributed evenly among the perimeter cells. An example of CCs that meet criteria 2, 3, and 4 is shown in figure 3.

Redistribution to Perimeter Cells When Stalled

The second modification is applied during the iterative process when the program appears to be stalled. The iterative process is considered stalled if distributed withdrawals are added only to cells that already have at least some distributed withdrawals assigned to them. This can happen when the gradient of 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. In addition, 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.

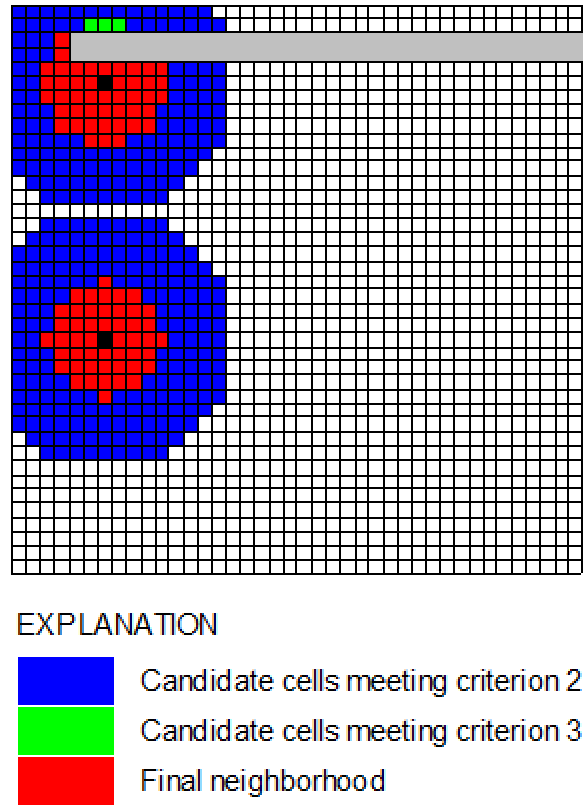

Figure 3. Cells in the initial redistribution process. Around the two well cells, (black, solid cells), a neighborhood is selected in which all the cells are active, sufficiently close to the well, and connected by other candidate cells to the well cell. (Inactive cells are gray.)

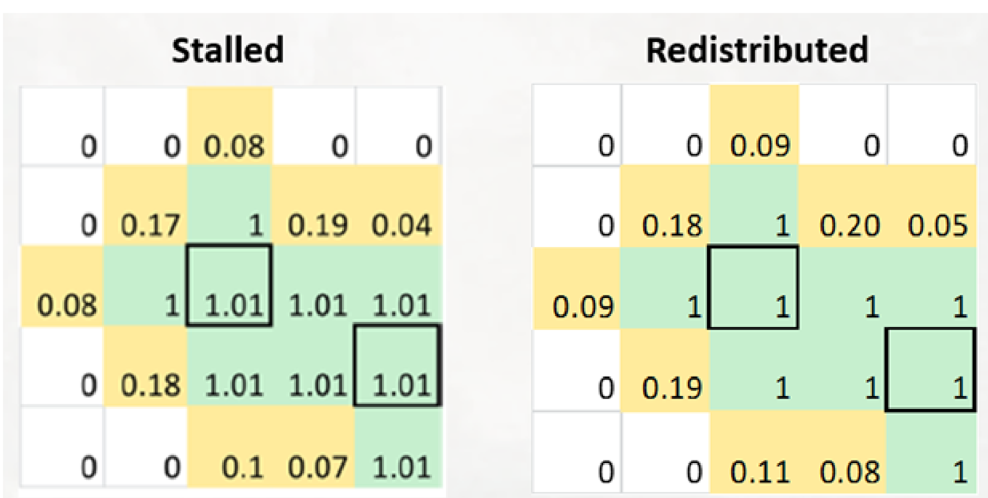

Figure 4. Example redistribution of withdrawals to perimeter cells when the modified Footprint program is stalled. Modified from Goode (2016).

Use of ModelMuse With WellFootprint

ModelMuse (Winston, 2009, 2014) has been modified to generate the input for WellFootprint (Winston and Goode, 2017) and to display the output from WellFootprint.

Starting a New Footprint Project

When starting ModelMuse, the user can choose to start a new 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 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 grid editing tools, such as those for adding and deleting grid lines, are not active for Footprint projects.

Non-Spatial Data

The various options that can be specified for WellFootprint are specified in the Footprint Properties dialog box. The dialog box is displayed by selecting Model|Footprint Properties. Detailed descriptions of the options are included in the help for the dialog box. The options are 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 Datasets

There are three input datasets in ModelMuse Footprint projects—DepthRateIndex, Withdrawals, and Active. These correspond to the Footprint input arrays Depth_Rate_Index, Withdrawals, and Active, respectively. The values in the DepthRateIndex and Active datasets are specified with formulas or objects, as described in Winston (2009). The values in the Withdrawals dataset are typically specified by defining a withdrawal rate for a Footprint Well in the Object Properties dialog box. By convention, Withdrawal dataset 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 withdrawal rates will be summed to define the final withdrawal rate for the cell. Alternatively, if no Footprint wells are defined, the Withdrawals dataset values can be defined in the usual ways. This option can be useful if the user wishes to import gridded values of the withdrawal. Footprint wells can be imported from point Shapefiles or through the File|Import|Points dialog box.

Running WellFootprint

To run WellFootprint from ModelMuse, the user first must specify the location of WellFootprint on the computer by selecting Model|WellFootprint Program Location to display a dialog box in which the location can be entered. 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 clicked, 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 extensions used for the various input and output files are shown in the table 1.

Table 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, then 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 datasets calculated by WellFootprint. The selected datasets will be imported into ModelMuse. The user can choose to color or contour the grid with one of the imported datasets.

WellFootprint Input File Format

An example input file is included with the software. The input file for WellFootprint is an XML file. More information about XML files can be found at https://en.wikipedia.org/wiki/XML. 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**, and **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 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 array is initialized to a default value of True. Values need to be specified only 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 that 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 arrays. They must be either True or False for Active array. Only one value per 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 path names are acceptable for the file name. For Depth_Rate_Index and Active arrays, the contents of the file must be values of the array in row-major order. In row-major order, all the elements of the first row are listed sequentially followed by the elements of the following rows in order until all the elements in the array have been listed. 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 requirements for each major tag are described below.

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 an 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 one-half the distance to the nearest 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 of cells 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 L^3/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 1, and inactive cells should be designated 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 document the orientation 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 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 Results File

The text results file contains two arrays—Distributed_Withdrawals and Footprint_Code (table 2).

1. The data for each array start 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 spaces are used to separate values.

Table 2. Meaning of Footprint Codes.

Footprint Code	Meaning[1]
0	Inactive
1	Q = 0
2	0 < Q < D
3	Q = D
4	Q > D

[1] Q = Distributed withdrawal rate; D = Cell capacity.

Format of Binary Results File

The binary results file contains two arrays—Distributed_Withdrawals and Footprint_Code.

1. A footprint binary file starts with the identifier Footprint_Binary_File and uses two-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. Next comes the number of rows and the number of columns. 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

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

Summary

The WellFootprint program (version 1.0) in conjunction with ModelMuse can be used to generate a map that can provide a more intuitive display of the magnitude of well withdrawals than can traditional methods of displaying withdrawals. WellFootprint calculates the data needed for the plot, whereas ModelMuse generates the input for WellFootprint and creates the map using the results of WellFootprint. Optional initialization and redistribution methods substantially reduce the computation time for WellFootprint.

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