Mapping Groundwater Withdrawals from Wells Relative to Water-Resource Metrics or Management Targets

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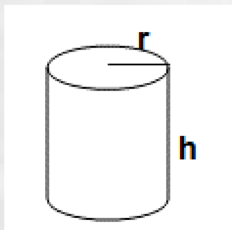
Abstract Maps of groundwater withdrawals are useful for informing stakeholders about groundwater use and its spatial character. Common methods for illustrating groundwater withdrawal magnitudes at individual wells on a map include using color gradation for the well symbols (usually circles), using discrete symbol sizes for categories of pumping rate, or scaling symbol sizes proportional to pumping rate. The latter method directly utilizes our intuition that visually larger symbols correspond to larger quantities, in this case withdrawal. Building on this approach, we developed a method that ascribes a physical significance to the proportionality between withdrawals (i.e. long-term average pumping rate, in units of volume per time) and symbol areas (units of length squared) on the map. For example, the user-defined proportionality, called the depth-rate index (units of length per time), can be based on the groundwater recharge rate, and the resulting map displays withdrawal magnitudes relative to that recharge. For a constant withdrawal, the symbol area increases as the depth-rate index decreases. Further, the method illustrates composite ‘symbols’, or ‘footprints’ for closely spaced wells, so that the combined withdrawal from a group of wells is equitably displayed relative to other, isolated, wells.

We implemented this method in a graphical user interface that facilitates input, algorithm execution, and map display of computed withdrawal footprints. The minimum data required are well locations and withdrawal rates, and the depth-rate index defined over a rectangular computational and display grid of uniform square cells. We demonstrate application of this new tool for several examples that visualize on maps the magnitudes of well withdrawals relative to depth-rate indexes corresponding to recharge, stream baseflow, water-table decline rates, and areal allocation limits.

In addition to illustrating withdrawal rates used as input to groundwater-flow or water-budget models, the footprint map may help increase stakeholder awareness about withdrawal rates in relation to water-resource metrics or to management limits. The footprints only visualize the magnitudes of withdrawal as areas spatially distributed around wells, and do NOT represent capture zones or recharge source areas for those withdrawals. Used as a screening tool, the footprint map may help identify areas where withdrawals are large, relative to the depth-rate index, and where groundwater modeling and other advanced methods of analysis may be warranted to characterize the impact of withdrawals on groundwater levels (storage), flow directions, and inflows to and discharge from the aquifer system.

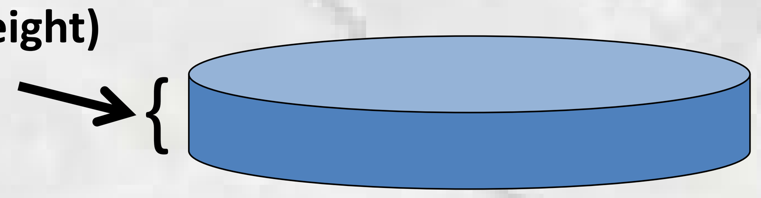
Withdrawal Map Symbol Scale: Depth-Rate Index



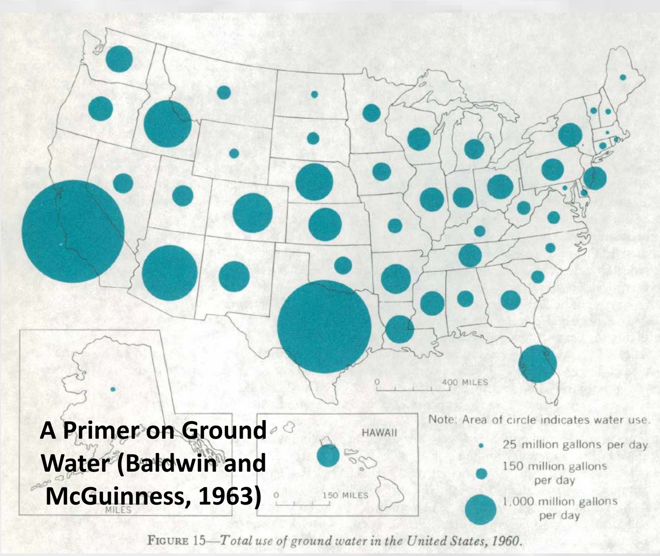
Volume = area of base • height
Volume = $\pi r^2 h$
** The base is a circle, so the area of a circle is πr^2

$$\text{Area of Symbol} = \frac{\text{Volume per Time}}{\text{Depth per Time}}$$

Depth (height) of Water per Time



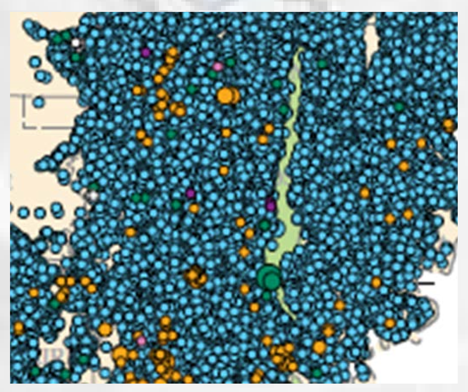
Existing Formats for Withdrawal Magnitude Mapping



Proportional Circles

No physical significance to size of circle on map. Only size (area) relative to other circles.

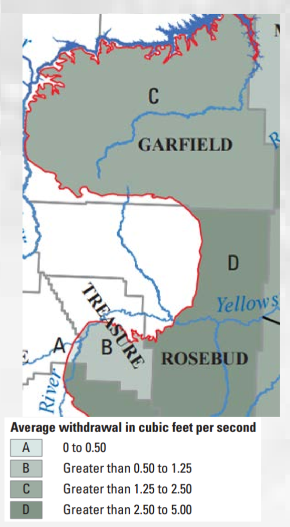
Overlapping symbols for ‘closely’ spaced wells obscure (visually misrepresent comparative) magnitudes.

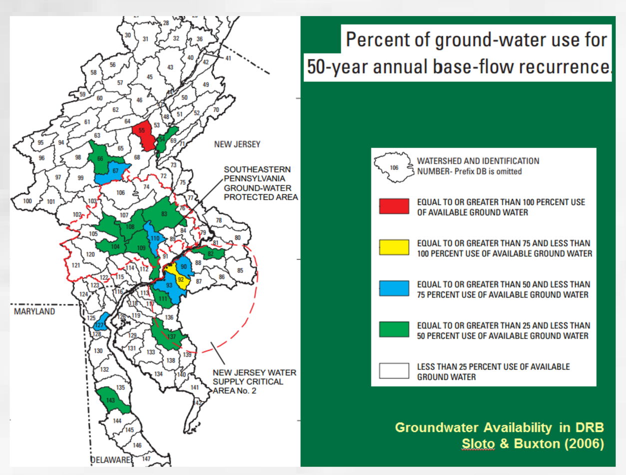


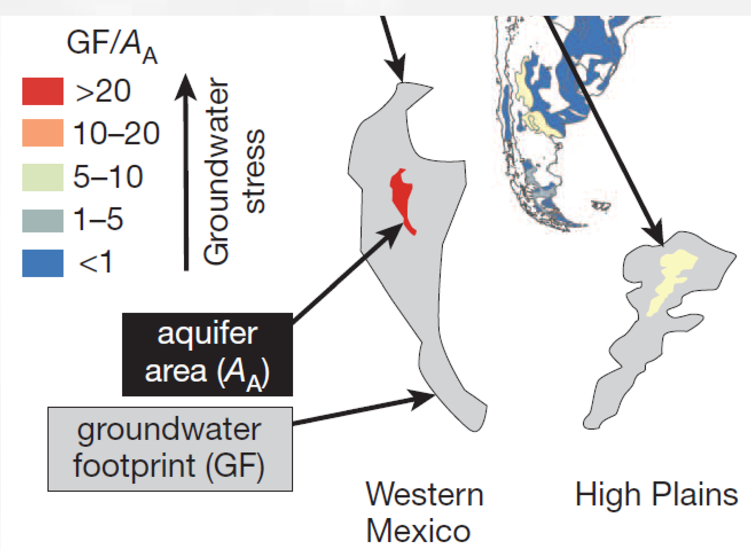
Shading / Coloring of Basins

Variable shown can be total $\sum Q$ (L^3/T) for all wells (or basin average Q), or Ratio of Q to a volumetric flow such as Baseflow for the basin, or a regulatory level.

Shading by volume on different size (area) basins misleads as to withdrawal intensity (pumping per unit area).







Scaled Basin Area

Showing ‘footprint’ as *area relative to actual basin area* imparts physical significance to its size on the map. The ratio of areas is set equal to ratio of total withdrawal to ‘available’ recharge.

GroundwaterFootprint.org (Gleeson & others, 2012, Nature)

Iterative Nearest-Neighbor Cascade of ‘Excess’ Withdrawal to Adjacent Cells

The new method developed combines circles for well symbols with a physically meaningful symbol size via a “depth-rate index”, area A = Q / d, where d [L/T] is the depth-rate index. For example, using recharge as the depth-rate index, the symbol area on the map is the area for which the volumetric recharge equals the well’s withdrawal rate. However, there is no physical significance to the location or shape of the well symbol. Composite ‘symbols’ or merged areas are computed on a grid of square cells. The grid resolution is user selected.

This simple example has withdrawals in 2 cells that exceed the product of the depth-rate index and the cell’s area (dA=1), the cell’s ‘capacity’. In cell (col=3,row=3), Q=6, and in cell (5,4), Q=4.

Iteration 1

0	0	0	0	0
0	0	1	0	0
0	1	2	1	0.75
0	0	1	0.75	1.75
0	0	0	0	0.75

Iteration 2

0	0	0	0	0
0	0	1.2	0	0
0	1.2	1.2	1.2	0.94
0	0	1.2	0.94	1.19
0	0	0	0	0.94

Iteration 3

0	0	0.04	0	0
0	0.08	1.08	0.08	0
0.04	1.08	1.2	1.08	1.02
0	0.08	1.08	1.06	1.05
0	0	0.04	0	0.98

Iteration 10

0	0	0.08	0	0
0	0.17	1	0.19	0.04
0.08	1	1.01	1.01	1.01
0	0.18	1.01	1.01	1.01
0	0	0.1	0.07	1.01

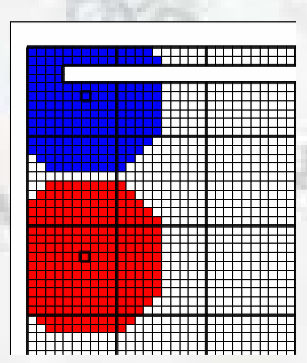
- Active cell, no distributed withdrawal
- Distributed withdrawal < maximum $d\,A$ = 1.0
- Distributed withdrawal > 1.0, asymptotically decreasing to 1.0

ModelMuse User Interface & Faster Algorithms

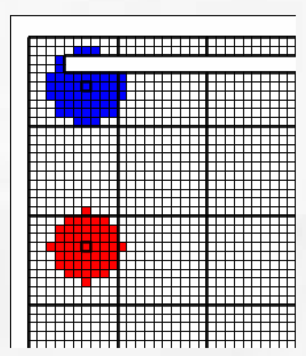
We developed a simple PC program, WellFootprint, to calculate the Footprint on a rectangular grid of square cells. ModelMuse (Winston, 2009, 2014), a groundwater-model pre-processor, has been modified to generate or import the input for WellFootprint, to run it, and to display and export the output. Two new modifications to the algorithm of Goode (2016) were implemented in WellFootprint for cases in which individual grid cells have Q that is much larger than a cell’s capacity. These modifications yield results that are very similar to those using the algorithm of Goode (2016), in much less execution time.

Mod 1 – Initial Distribution to Nearby Cells

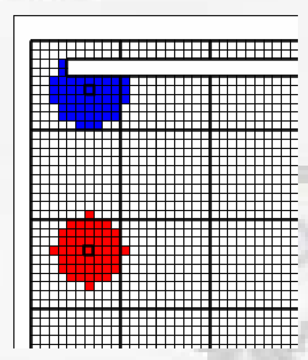
Cell candidate neighbors identified that are closer to each pumping well cell than ½ the distance to the closest other cell with Q>0.



Add capacities in order of distance from pumping well cell until sum exceeds Q, then remove all cells at that distance or further away.



Remove cells that are not connected through other active cells to the pumping well cell.



Mod 2 – Redistribute Interior Withdrawals to Footprint Perimeter when ‘Stalled’

Iterative process is considered ‘stalled’ if no cells with zero distributed withdrawals are turned ‘on’. When this occurs, the distributed withdrawal in interior cells is set to each cell’s capacity, and the total excess is distributed equally among the perimeter cells.

Stalled

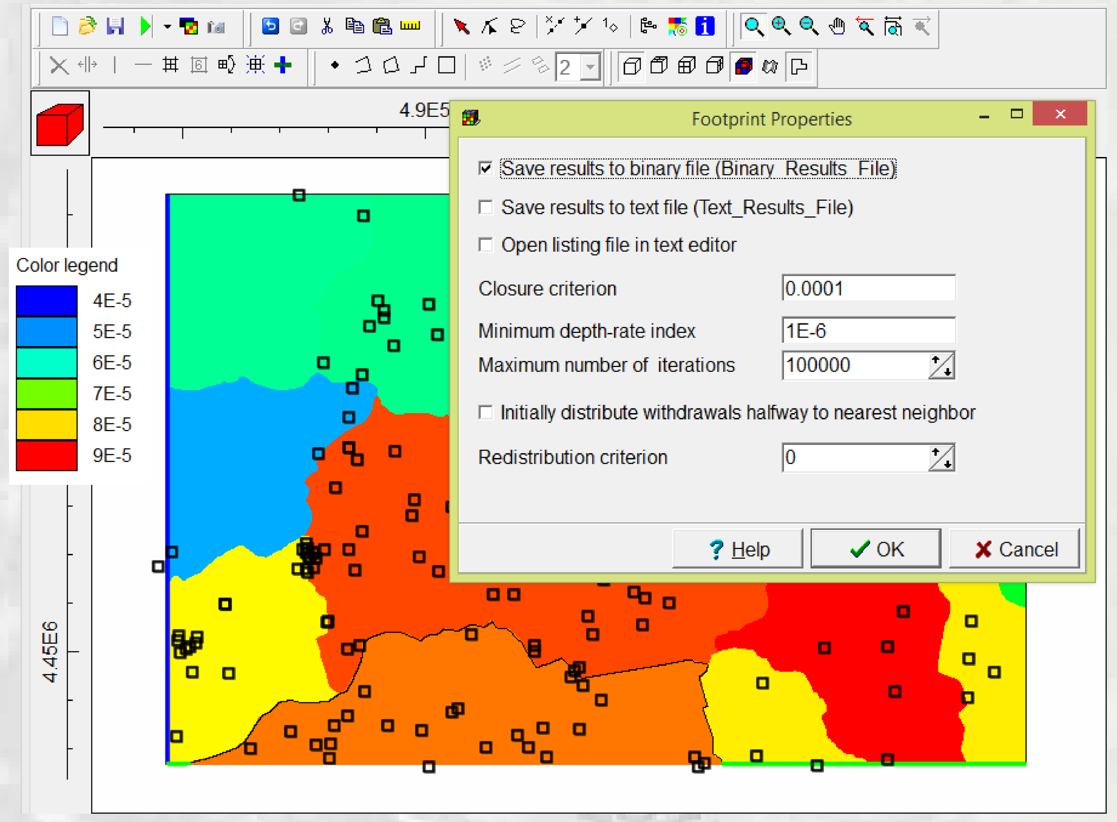
0	0	0.08	0	0
0	0.17	1	0.19	0.04
0.08	1	1.01	1.01	1.01
0	0.18	1.01	1.01	1.01
0	0	0.1	0.07	1.01

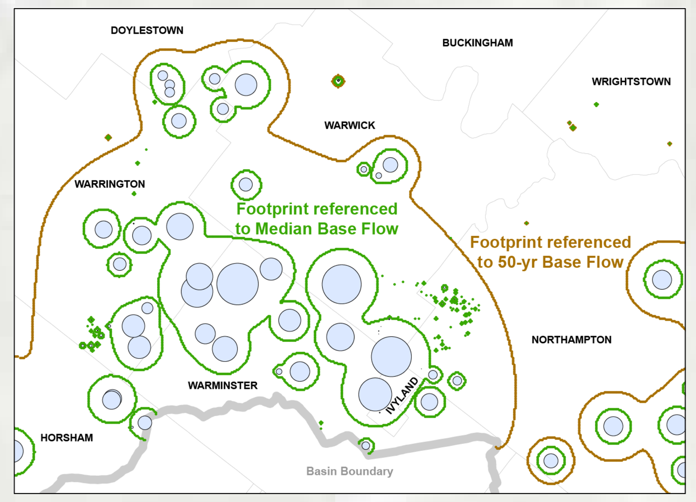
Redistributed

0	0	0.09	0	0
0	0.18	1	0.20	0.05
0.09	1	1	1	1
0	0.19	1	1	1
0	0	0.11	0.08	1

Baseflow Index by Return Periods

ModelMuse screenshot showing WellFootprint control variables. Options for importing wells include shapefile and XLS. For this case, depth-rate index values input by shapefile using sub-basin baseflow (L^3/T; colors) for different return periods, normalized by sub-basin area (L^2).

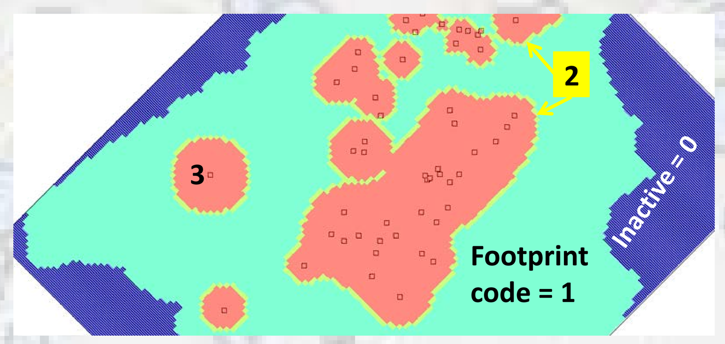


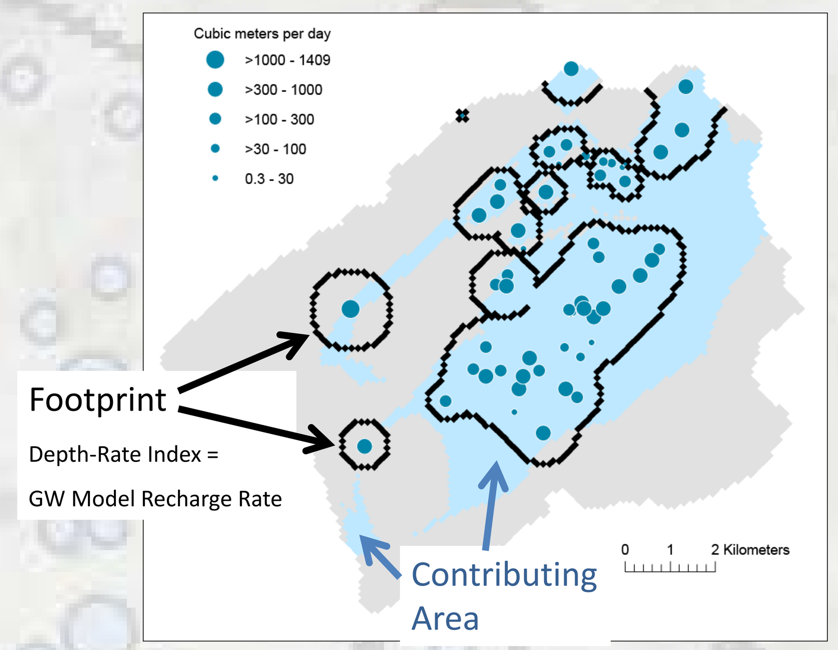


ModelMuse exports Footprint code and other input/output to shapefile. ArcGIS map above displays Footprint perimeter (code=2) for two different return periods, 2-yr (median), and 50-yr low baseflow. This map displays well withdrawals relative to (spatially variable) stream baseflow, and shows composite footprints around closely spaced wells.

Groundwater Model Recharge Rate

ModelMuse screenshot (cropped) of computed Footprint code for a steady-state groundwater flow model (Senior & Goode, 2013) using the recharge rate as a depth-rate index. Grid is same resolution as MODFLOW model. Well locations also shown.



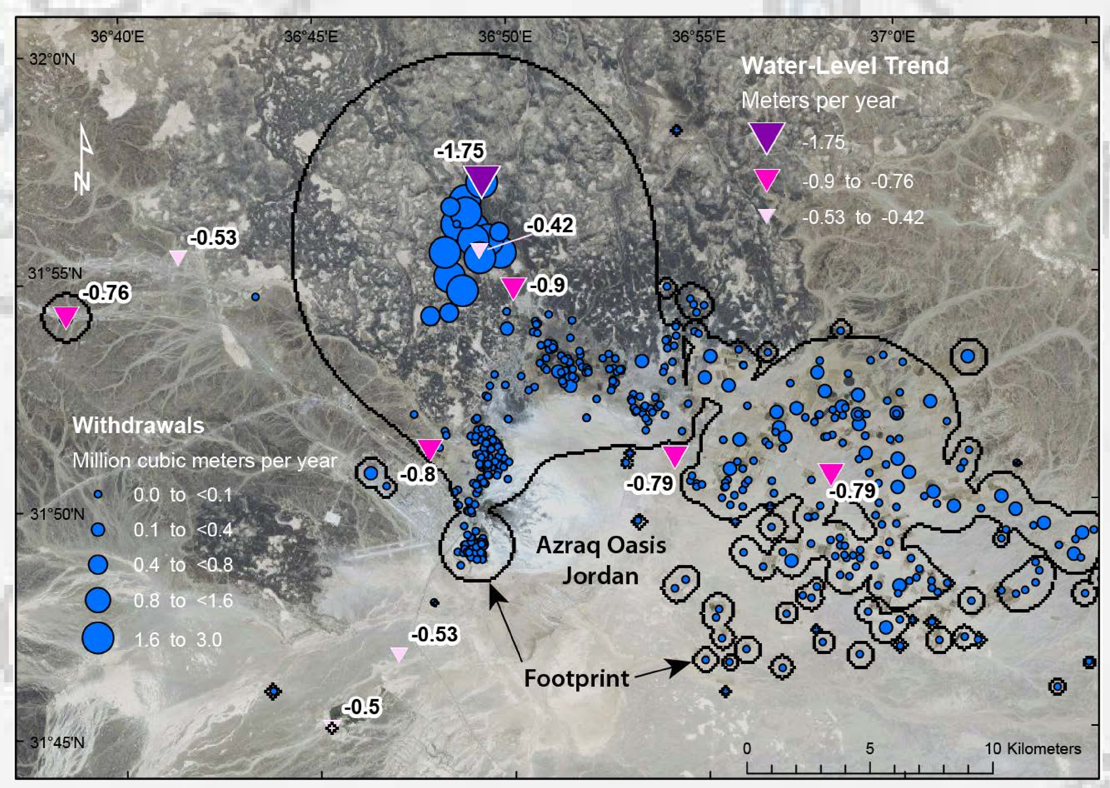


N.B.: The Footprint is NOT a capture zone, or the area that contributes recharge to the wells. It is solely a visualization of the magnitude of pumping, centered on the wells.

Water-Level Decline Rate

Footprint for wells in the Azraq Oasis area, Jordan. The depth-rate index is the average rate of water-level decline, about 1 m/yr (Goode et al. 2013), scaled by an illustrative specific yield of 0.1, d = 0.1 m/yr. The individual wells are plotted using rate classes (non-proportional), a common option for displaying well Q. Highest rates of water-level decline occur in center of the largest footprint area.

The Footprint map displays a physically meaningful ‘size’ of withdrawals, relative to user-defined water-resource metrics, and may be useful to convey withdrawal magnitude to stakeholders. The combined pumping of closely spaced wells is equitably visualized relative to isolated wells.



Documentation and Examples

Conlon, M.D., D.J. Goode, R.B. Winston, and D.W. Risser, 2016, Visualizing the “footprint” of Groundwater withdrawals in parts of Centre and Adams Counties, Pennsylvania: (abs.) Pennsylvania State University, Pennsylvania Groundwater Symposium, May, 2016.

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

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): USGS Techniques & Methods, book 6, chap. A49, 6 p.

Winston, R.B., and Goode, D.J., *in preparation*, Use of ModelMuse for map visualization of groundwater withdrawals from wells.