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TECHNICAL NOTE

Map visualization of groundwater withdrawals at the sub-basin scale

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Abstract A simple method is proposed to visualize the magnitude of groundwater withdrawals from wells relative to user-defined water-resource metrics. The map is solely an illustration of the withdrawal magnitudes, spatially centered on wells—it is *not* capture zones or source areas contributing recharge to wells. Common practice is to scale the size (area) of withdrawal well symbols proportional to pumping rate. Symbols are drawn large enough to be visible, but not so large that they overlap excessively. In contrast to such graphics-based symbol sizes, the proposed method uses a depth-rate index (length per time) to visualize the well withdrawal rates by volumetrically consistent areas, called "footprints". The area of each individual well's footprint is the withdrawal rate divided by the depth-rate index. For example, the groundwater recharge rate could be used as a depth-rate index to show how large withdrawals are relative to that recharge. To account for the interference of nearby wells, composite footprints are computed by iterative nearest-neighbor distribution of excess withdrawals on a computational and display grid having uniform square cells. The map shows circular footprints at individual isolated wells and merged footprint areas where wells' individual footprints overlap. Examples are presented for depth-rate indexes corresponding to recharge, to spatially variable stream baseflow (normalized by basin area), and to the average rate of water-table decline (scaled by specific yield). These depth-rate indexes are water-resource metrics, and the footprints visualize the magnitude of withdrawals relative to these metrics.

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Introduction: map visualization of withdrawal magnitude

Information about the magnitude of groundwater withdrawals is useful in understanding, managing, and simulating groundwater systems. Because withdrawal wells remove water from an aquifer, groundwater flow in the vicinity of the well is affected by the rate of withdrawal. The licensing and allocation of groundwater withdrawals is often done with consideration of overall withdrawals within management areas. In particular, managers may wish to limit new withdrawals from areas where withdrawals are already 'large', based on some water-resource metric. In addition, groundwater-flow models that are used to simulate the impact of withdrawals on groundwater flow, streamflow, and water budgets, require withdrawal locations and magnitudes as model inputs.

The standard map symbol for wells in US Geological Survey (USGS) publications is an open or filled circle (Miller and Balthrop 1995). A common method to indicate withdrawal magnitude is to color the well symbols using distinct colors corresponding to withdrawal rate classes, or using a gradational color mapping between withdrawal magnitude and color—for example, from green (low) to red (high). However, this method does not take advantage of the intuitive visual perspective that large symbols imply large withdrawals.

Circular well symbols on a map can be scaled proportional to withdrawal magnitude, with larger symbols corresponding to larger withdrawals, in order to graphically display the 'size' of those withdrawals. For example, Baldwin and McGuinness (1963) mapped state-by-state withdrawals in the US with circles whose areas were proportional to total withdrawals. In practice, the sizes used may not correspond linearly to withdrawal, or discrete symbol sizes may be used, corresponding to categories of withdrawal magnitude (e.g. Goode et al. 2013; Senior and Goode 2013). Furthermore, the sizes used are chosen based on graphical-design considerations, so that the symbols are neither too small to be easily seen, nor so large that they overlap excessively and obscure adjacent symbols. When well symbols do overlap, the overall visual impression of a group of overlapping symbols does not visually convey the cumulative magnitude of those withdrawals equitably compared to non-overlapping symbols for isolated wells.

Any visualization in which well symbol areas are proportional to withdrawal rate is implicitly using a scale, here-in called the "depth-rate index", for the symbol areas. The value of the uniform depth-rate index used for a particular map can be determined by dividing a well's withdrawal rate by its symbol area on the map (in the map's spatial units, not the physical dimensions on the paper or screen). The depth-rate index has units of length per time.

The method proposed uses the depth-rate index to compute a "footprint" area for each well's withdrawal. The product of the footprint area and the depth-rate index is the withdrawal rate magnitude. The resulting footprints are displayed as circles for individual isolated wells. For closely spaced wells, merged footprints are shown for the combined withdrawals. This method is thus similar to the common use of scaled symbols, but uses a volumetrically explicit and consistent scaling, and accounts for the combined withdrawals of nearby wells with a combined 'symbol' or area. As the produced map is a graphical display of well withdrawal magnitudes alone, and not a capture zone or recharge source area, it is called a groundwater withdrawal "footprint". The footprint illustrates the magnitude of withdrawal, but not its physical source, nor its impact on groundwater levels (i.e. storage), discharges, and other hydrologic features.

Groundwater footprints at the basin scale have previously been mapped by Gleeson et al. (2012), using areas on a map to display magnitudes. Basin-scale withdrawal magnitudes are commonly shown by using color gradation or classes to indicate either total withdrawal within a basin (as also used by Gleeson et al. 2012), or to indicate withdrawal per unit area. The Gleeson et al. (2012) footprint is a scaled image of a basin or watershed outline, the size of which is proportional to the ratio of the total withdrawal to the available groundwater resource for the basin, as they define it. Thus, if the total withdrawal magnitude in the basin is one-half of the available water resource (per unit time), the footprint on the map is shaped the same as the basin, but is only one-half as large; it is displayed within the actual basin outline on the map. If the withdrawals within a basin exceed the available groundwater resource for the basin, then the footprint is larger than the basin. For their case the basin recharge rate, less ecological flow requirements (per unit basin area), corresponds to the depth-rate index used here. While the Gleeson et al. (2012) footprint is a compelling graphical comparison of withdrawals to available groundwater resources, their method may be less useful at the scale of the watershed of interest, or for sub-basin scales. These scales are often relevant for stakeholders and decision makers concerned with, for example, water-resource management in a specific locale, or for visualization of withdrawals for a groundwater flow model.

The proposed method builds on the visual perspective employed by the Gleeson et al. (2012) footprint, but focuses on the locations of individual wells and well fields, at the sub-basin or well-field scale. Available recharge (recharge minus ecosystem flow requirements) as a depth-rate index, as used by Gleeson et al. (2012), is but one example of a depth-rate index that may be useful as a scaling parameter. Use of a water-resource metric for a depth-rate index, such as the Gleeson et al. (2012) available recharge, allows display of groundwater withdrawal magnitudes relative to that water-resource metric. However, the user can select different depth-rate indexes for other purposes such as using a total allocation limit, divided by the area to which it applies, to visualize how much of the allocation limit is withdrawn, and how the corresponding withdrawal wells are spatially distributed within the management area.

Method: distribution of withdrawals on a grid

Inputs: grid geometry, depth-rate index, and withdrawals mapped to the grid

A computational and display grid of uniform square cells is used to determine the footprint area covered for each well, and for groups of wells. The method and inputs (Table 1) are described for a single map, corresponding to a single set of withdrawals and depth-rate index. Separate time periods can be mapped independently by using the corresponding data for that time period only.

A rectilinear grid with uniform square cells in rows and columns is specified covering the area of interest for the groundwater withdrawal footprint map. Optionally, an area of the grid may be indicated as 'active' by using a boundary that could indicate the groundwater basin, or a groundwater-flow model domain, as examples. No calculations are performed on the 'inactive' cells in the grid. Using grid spatial indexes i,j, the footprint code $I_{i,j}$ of each cell is set as 0 for 'inactive' cells and 1 for 'active' cells. (The grid spatial indexes i,j are implicit for the current computational cell.) The number of active neighbors (sharing a cell side), N for each cell, ranging from 1 to 4, is computed and stored. (If $N=0$ then the cell has no active neighbors and no further computations are possible for the cell.)

Table 1 Groundwater withdrawal footprint algorithm input requirements, internal variables, and computed outputs

Term	Definition and properties	Notes
Input		
Grid	i,j indexes; A[L^2]: uniform area of each cell	Square grid cells covering the area of interest
Domain boundary (optional)	I: initial footprint code for each cell, 0 is 'inactive', 1 is 'active'	Indicates 'active' part of grid where the withdrawal footprint will be computed; Examples: groundwater-model domain, watershed, groundwater basin
Well withdrawal	W [L^3/T]: total withdrawal rate for all wells within the cell	Can represent observations for a specific time period, or allowable allocations, as examples
Depth-rate index	d [L/T]: depth-rate index for each cell, a user-defined non-negative volumetric rate per unit area	The area of a well's (or group of wells') footprint is equal to the withdrawal rate divided by the depth-rate index. Examples: recharge; stream baseflow divided by basin area; rate of water-table decline scaled by specific yield
Number of iterations	MAXIT	Algorithm stops after MAXIT iterations, or at convergence
Tolerance	TOL [−]: convergence criterion	Algorithm converges if the grid maximum of $E/D - 1$ is less than TOL. Default value TOL = 0.01, or 1 %
Internal		
Maximum distributed withdrawal	$D = d\,A$. [L^3/T]: for each cell	Computed from input
Number of active adjacent cells	N: for each cell, $1 \leq N \leq 4$.	Computed from input, counts the number of active cells that share a cell side with the current cell
Distributed withdrawal	Q [L^3/T]: for each cell	Initial value set by input W. The algorithm re-computes Q each iteration
Excess distributed withdrawal	$E = Q - D$. [L^3/T]: excess distributed withdrawal	For each iteration, $E\,/\,(N+1)$ is distributed to each adjacent active cell. For example: $Q_{i,j+1} = Q_{i,j+1} + E_{i,j}/(N_{i,j}+1)$
Output		
Distributed withdrawal	Q [L^3/T]	The total of all distributed withdrawals on the grid equals the sum of input withdrawals W
Groundwater withdrawal footprint code	Footprint code I, updated: 0: inactive 1: $Q = 0$ 2: $0 < Q < D$ 3: $Q = D$	The footprint is comprised of cells with codes 2 and 3. Displaying code 2 shows the boundary of the footprint, at the resolution of the grid. Code 3 is determined based on the user-defined tolerance

A user-defined non-negative depth-rate index is specified for each cell in the active part of the grid. Different depth-rate indexes can be used in different areas, corresponding to, for example, hydrogeologic conditions, or allocation limits for different areas. A cell's maximum distributed withdrawal, D [L^3/T], is the product of the depth-rate index d [L/T] and the uniform cell area, A [L^2]: $D \equiv d\,A$.

Withdrawal wells of interest are mapped onto the grid and the total initial withdrawal for each cell, W [L^3/T] is the sum of the withdrawals for all wells within that cell. If an active cell has no withdrawals within it, its initial footprint code remains I =1. If some withdrawal occurs within the cell, but the total magnitude W is less than D, then the code is set to I =2. If W is greater or equal to D, then the code is set to I =3.

Computations: iterative cascading of excess withdrawals to adjacent cells

An algorithm distributes the excess withdrawal for each cell equally to adjacent cells (sharing a side) in the grid, and this process is repeated iteratively until no cells have excess withdrawals above a specified tolerance. The algorithm is explicit and the distribution from each cell is independent of the other cells for each iteration. The initial input withdrawals W provide the initial value for the distributed withdrawals Q. The excess withdrawal E [L^3/T] is then computed for all cells as $E = Q - D$, and the footprint code for all cells updated based on the updated distributed withdrawal Q. If the maximum value of $E/D - 1$ for all cells is below the input tolerance, the distribution is final and output is prepared.

For one iteration, the distribution amount ΔQ [L^3/T], defined as $\Delta Q = E\,/\,(1+N)$, is added to the distributed withdrawal Q for each adjacent active cell, yielding updated values of Q for those adjacent cells. Note that a cell may receive distribution from more than one of the up to four adjacent cells. The withdrawal in the cell from which the distribution occurs is reduced by the total distribution to adjacent cells, or $N\,\Delta Q$, also yielding an updated $Q_{i,j}$. As an example, if there is only 1 active adjacent cell, $N = 1$, then half of the excess withdrawal is distributed from the current cell to that adjacent cell, and the withdrawal in the current cell is reduced by half the excess, for one iteration.

After an iteration over the grid is completed, distributed withdrawal amounts will have decreased in cells with excess withdrawals, and increased in adjacent cells. During one iteration over the grid, cells may have both increases and decreases from different adjacent cells, but the cumulative result is a gradual distribution of the excess withdrawals to a set of nearest neighbor cells until no cell has excess withdrawal, compared to *D,* within the specified tolerance. Figure 1 shows a small example grid with only 2 cells that have input withdrawals, and those withdrawals exceed *D*. Several iterations of calculations are shown. The algorithm presented is applicable only for a grid composed of uniform square cells.

The distribution process stops when the maximum excess withdrawal for any cell is small compared to the cell maximum, within the user-defined tolerance, or when the user-defined number of iterations is reached. If neither criterion is met, the iterative computation is repeated, starting with updating *E*.

Limited experience with the examples shown below indicates that the computations converge quickly when the individual input withdrawals are on the order of 100 times larger than the cell maximum *D*. Reducing the computational-grid cell size, which improves the smoothness of the footprint outline, reduces *D*, and can lead to long computation times and many iterations for convergence, using the algorithm presented here. A recommendation can be made to compute footprints using relatively coarse grids initially, and only compute a fine-grid footprint after confirming the domain specification and appropriateness of inputs.

Output: distributed withdrawals and the footprint code

The distribution of withdrawals ensures that the distributed withdrawal in each cell does not exceed the maximum *D* computed from the depth-rate index *d*, within the user-defined tolerance. The algorithm also ensures that the total distributed withdrawal is equal to the total input withdrawal. If the depth-rate index is spatially variable, the maximum distributed withdrawal allowed in each cell will not be uniform.

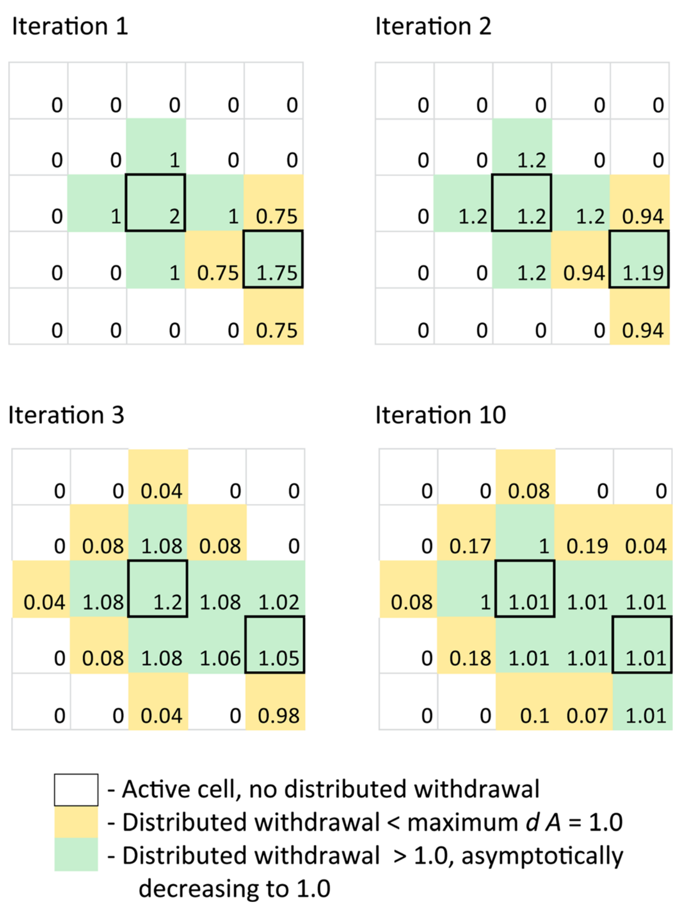


Fig. 1 Distributed withdrawals for iterations *1*, *2*, *3*, and *10* on an example footprint grid. The product of the depth-rate index and the cell area, $d\,A = 1$. The input (iteration 0, not shown) withdrawals are zero in all cells except for the outlined cell (*3rd column from left*, *3rd row from top*) which has withdrawal $W = 6$, and the outlined cell (*5,4*) which has $W = 4$. By iteration *10*, the footprint codes are the final values, but the distributed withdrawal is about 1 % above the cell maximum in some cells

The groundwater withdrawal footprint code is a classification of the cells based on comparison of the distributed withdrawal Q to the maximum D for the cell. The codes are defined in Table 1. Code 3 represents cells where the distributed withdrawal Q equals, within the input tolerance, D, the maximum computed from d. Code 2 represents cells where the distributed withdrawal is greater than zero, but less than D. An area of cells with code 3 is bordered by cells with code 2, unless adjacent to inactive cells or on the grid boundary. Distinct colors assigned to code values 2 and 3 display the groundwater withdrawal footprint map. Showing only code 2 (setting other cells to transparent) yields a map of the boundary of the groundwater withdrawal footprint, useful for visualization on a map with other information.

Gleeson et al. (2012) showed examples of many groundwater basins where the groundwater footprint of the basin is larger than the entire basin, corresponding to basins where total withdrawals exceed the depth-rate index times the basin area. For such cases, the proposed algorithm does not yield a useful visualization because no cells can accept excess withdrawals. The recursive iterations will distribute withdrawals throughout the grid, but the final rates will exceed the cell limits and the footprint will cover the entire active grid. In such cases, the method of Gleeson et al. (2012) can be used to show the basin-scale footprint of the magnitude of total withdrawals for the entire basin. Alternatively, a larger depth-rate index, for example a multiple of the recharge rate, could be used with the proposed algorithm to reduce the well-withdrawal-footprint size such that it is smaller than the entire domain.

Example applications with alternative depth-rate indexes

Maps of well withdrawals commonly show which wells are pumping large amounts and which are pumping small amounts, along with the spatial location of withdrawals. Similar to the footprint of Gleeson et al. (2012), the well footprint map proposed here additionally illustrates withdrawals relative to a depth-rate index. The depth-rate index can represent a measure related to the renewable groundwater resource such as long-term average recharge, similar to Gleeson et al. (2012). Use of a depth-rate index computed from low-flow stream baseflow statistics is similar to the use of recharge, but visualizes withdrawals relative to different risk levels, based on streamflow records. The depth-rate index can also represent a measure of groundwater-storage depletion such as the average rate of water-table decline. Three examples are presented using such depth-rate indexes. Additional depth-rate indexes are envisioned for different purposes such as a regulatory withdrawal limit or target, expressed as an overall volumetric withdrawal rate divided by the area within which the limit is applicable. It is hoped that different depth-rate indexes will be identified by others to relate groundwater withdrawal magnitudes to different measures of groundwater resources, or for other purposes, using the proposed footprint visualization method.

Recharge

Groundwater-flow models are powerful tools for evaluating the impact of withdrawals on groundwater levels and fluxes, stream baseflow, water budgets, and other features of a hydrologic system. Recharge rates and groundwater withdrawals are necessary input for such models. The model recharge rate can be used as a depth-rate index for visualization of the magnitude of the input groundwater withdrawals on the model grid. Such a withdrawal footprint map can augment the standard approach of showing wells symbols scaled by withdrawal rates as part of model documentation.

Senior and Goode (2013) simulated steady-state groundwater flow in an area of southeastern Pennsylvania (USA) to evaluate the impact of changing groundwater withdrawals on flow directions, and to identify areas contributing recharge to withdrawal wells and streams. The outline of the groundwater withdrawal footprint, computed using the recharge value for a particular simulation, is a display of the magnitude of withdrawals relative to that recharge, as *input* to the model (Fig. 2). This display augments the use of scaled circular symbols to indicate withdrawal magnitudes. Note that the configuration of the area of the model domain contributing recharge to wells (blue shading) is *not* the same as the groundwater withdrawal footprint (black outline), which is solely a visualization of withdrawal magnitudes, centered on the wells.

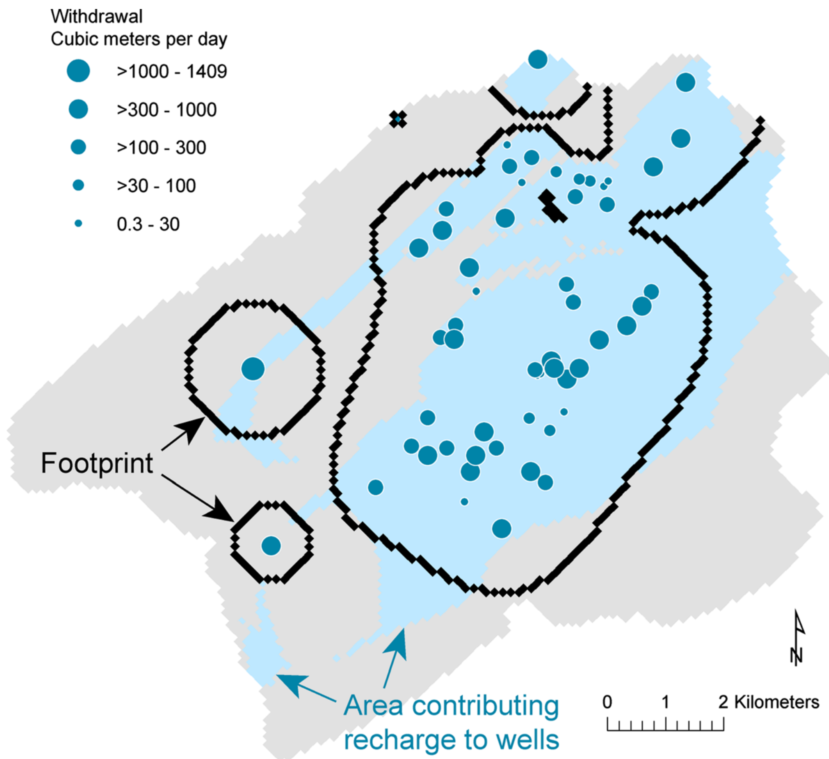
The withdrawal scaling used by Senior and Goode (2013) for the well symbols, which often overlapped, did not change for different simulation periods, although the recharge rates were not the same for those periods. The display here could use a different scaling of the footprints for simulations with different recharge rates, to show the withdrawal magnitudes, as model *input*, relative to those different recharge rates. This use would conceptually correspond to the changes in the impact of the wells on the steady-state flow simulations using different recharge rates. The footprint area for the same well withdrawal will be larger for a simulation period with a lower recharge rate used as the depth-rate index.

Rather than overlap nearby symbols, the groundwater footprint shows the withdrawal magnitudes as composite areas around closely spaced wells. Whether wells are 'closely spaced' or not is a function of the depth-rate index magnitude.

Stream baseflow

A common concern among stakeholders and water managers is the magnitude of groundwater withdrawals relative to

Fig. 2 The groundwater withdrawal footprint for withdrawal wells for a groundwater-flow model in the area of the North Penn 7 Superfund site in southeastern Pennsylvania, USA using the model recharge rate (0.13 m/year) as the depth-rate index. Also shown are well symbols with size classifications based on withdrawals, and simulated areas contributing recharge to wells (*blue*) and streams (*gray*) (after Senior and Goode 2013)



stream baseflow, especially where that baseflow is composed primarily of groundwater discharge. A common regulatory metric is the low streamflow for a specified recurrence interval (or return period), based on streamflow records.

For example, Schreffler and Bird (1996) prepared maps comparing groundwater withdrawals to annual baseflow statistics for Neshaminy Creek, a tributary to the Delaware River, in southeastern Pennsylvania (USA). The maps indicated areas where pumping was large, relative to those baseflow rates, within sub-basins of the Neshaminy Creek basin. The stream baseflow statistic, for example the 50-year recurrence low flow, was determined for each sub-basin from streamflow records and regression with surface geology (Schreffler 1996). The resulting statistic was divided by the corresponding sub-basin area, yielding the area-normalized baseflow on a 750 × 750-m grid. This area-normalized baseflow had units of length per time. For comparison, the total withdrawal within a 1,500 × 1,500-m area surrounding each grid point was divided by (1,500 m)^2, yielding the area-normalized withdrawal. The resulting difference between the area-normalized baseflow and the area-normalized withdrawal was contoured, showing positive contours where withdrawals were less than baseflow, the zero contour where withdrawals equaled baseflow, and negative contours where withdrawals exceeded baseflow.

The Schreffler and Bird (1996) maps of the difference between baseflow and withdrawals are similar to the groundwater withdrawal footprint map, but the latter has flat display areas where pumping is high, due to the distribution of excess withdrawals on the grid (Fig. 3). The computation of the footprint uses the same input data as the map of Schreffler and Bird (1996), but the proposed footprint method does not require contouring and is easier to explain and understand. Additionally, rather than deeper depressions in the contours (Fig. 3a), the large withdrawals are shown as large areas on the footprint map (Fig. 3b), and the larger areas are more directly interpreted visually as larger withdrawals.

This example illustrates use of the withdrawal footprint method with a spatially variable depth-rate index. The baseflow statistics were computed by sub-basin in the map of Schreffler and Bird (1996; also see Schreffler 1996), and thus the depth-rate index used for the footprint is also spatially variable. The value for each cell in the grid corresponds to that for the sub-basin within which the cell is located.

Water-level decline

Groundwater withdrawal in many areas of Jordan, an arid to semi-arid country, exceeds net inflow to groundwater basins, and water levels are declining. The average rate of groundwater-level decline is about 1 m/year in major groundwater basins used for water supply (Goode et al. 2013). This rate of decline can be used in a depth-rate index as a basis for visualization of withdrawal magnitudes at individual wells and well fields.

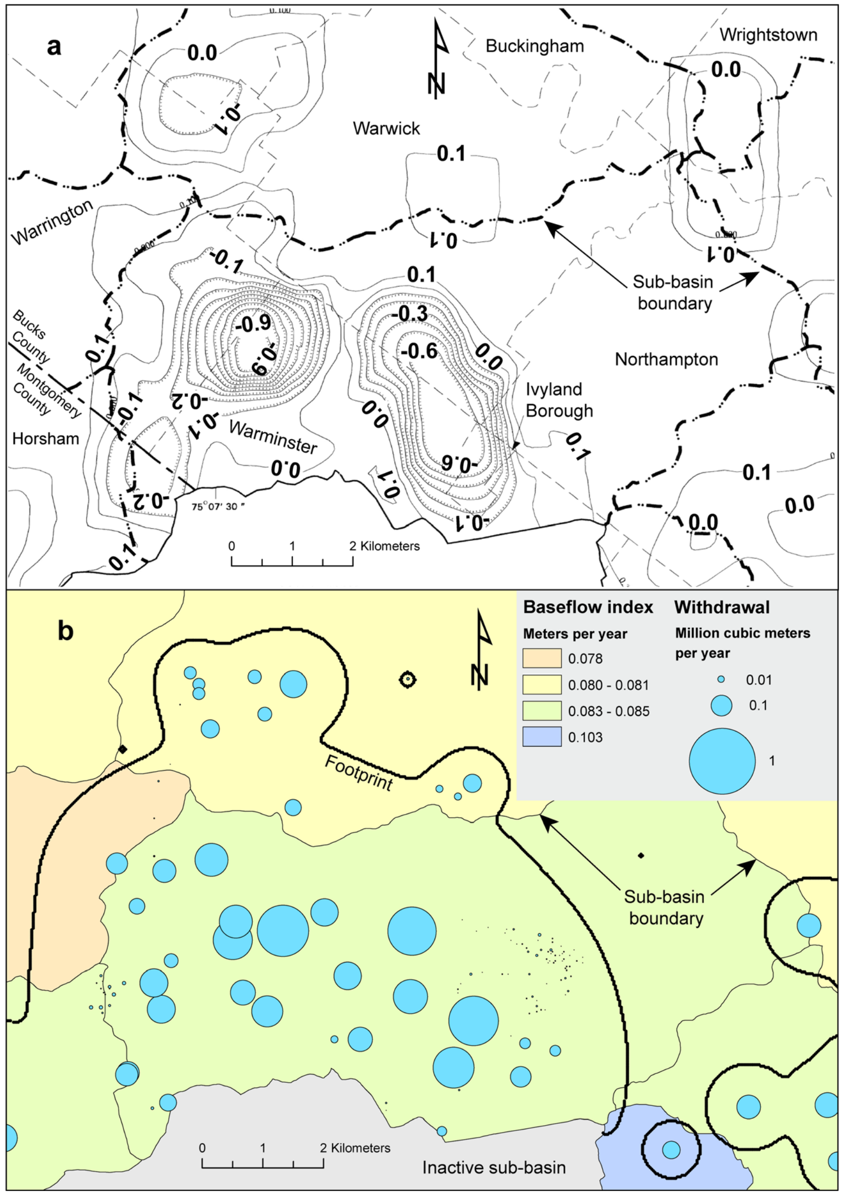


Fig. 3 Maps of part of the Neshaminy Creek watershed in southeastern Pennsylvania, USA showing **a** the difference between groundwater withdrawals and 50-year recurrence interval low stream baseflow (Schreffler and Bird 1996), and **b** the groundwater withdrawal footprint using depth-rate indexes of each sub-basin's baseflow statistic divided by the sub-basin's area. While for **b**, only a portion of the area of the computational grid is shown, the contour units for **a** are in million gallons per day, per square mile (Schreffler and Bird 1996), a length per time unit, and only a portion of the original map is shown

Groundwater storage in an unconfined aquifer is primarily due to volumetric water content in the available, drainable, porosity at the water table. Specific yield is defined as the volume of water released from storage for a unit decline of the water table, per unit area of the aquifer. Thus, an example depth-rate index could be the product of a water-level decline-rate index and the aquifer's specific yield. Conceptually, in an otherwise closed basin with no inflow, if withdrawals (divided by basin area) are less than this depth-rate index, then average water-level declines will be less than the water-level decline rate index. This conceptualization is a gross simplification of the hydrologic processes by which water is actually supplied to wells from both storage and changes in boundary fluxes, but it may, nonetheless, be a useful scale for visualization of withdrawal magnitudes from different wells and well fields within a given aquifer relative to the average water-level decline rate.

Literature values of specific yield in aquifers in Jordan are highly variable, ranging from less than 0.01 to 0.4 and higher; a value of 0.1 is assumed for this illustrative example. Multiplying this representative specific yield by a water-level decline-rate index of 1 m/year yields a depth-rate index of 0.1 m/year. The corresponding groundwater withdrawal footprints can be shown on a map with, for example, observed water-level trends (Fig. 4). This map visually displays the spatial correlation, or lack thereof, between the magnitude of withdrawal rates from production wells, relative to a depth-rate index of 0.1 m/year, and observed water-level trends. This example also illustrates the benefit of the footprint method for equitably

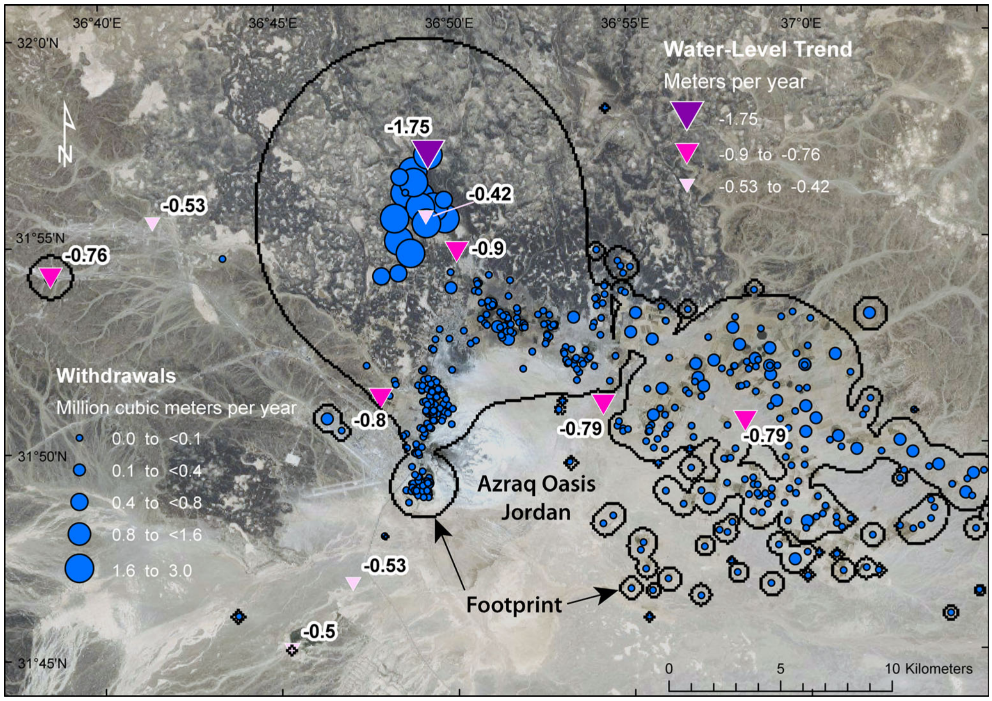


Fig. 4 Groundwater withdrawal footprint and observed water-level trends (*labeled triangular symbols*, from Goode et al. 2013) in a portion of the Azraq groundwater basin, Jordan. The depth-rate index is 0.1 m/year, corresponding to a water-level decline rate of 1 m/year, scaled by a specific yield of 0.1. The trends shown at individual wells indicate declining water levels in m/year as negative rates, by convention. Only a portion of the area of the computational grid is shown. (All hydrologic data provided by Jordan Ministry of Water and Irrigation; imagery ESRI 2015)

displaying cumulative withdrawal magnitudes for a group of wells whose standard scaled symbols overlap on the map.

Conclusions and limitations

The groundwater withdrawal footprint is a simple method to visualize the magnitudes of withdrawals from wells at the sub-basin scale, relative to a user-specified depth-rate index. Different applications of the method may use different depth-rate indexes, depending on the purpose of the map, and the hydrologic characteristics of the groundwater system. The method is similar to the scaling of well symbols to indicate withdrawal magnitudes, but ascribes a physical significance to the area of the 'symbol', through the depth-rate index. The method merges the footprints for individual wells for which scaled symbols would overlap, so that the combined magnitude is equitably displayed relative to the footprint areas for isolated wells. The method is also similar to the Gleeson et al. (2012) footprint of scaled basin areas using recharge or baseflow-based depth-rate indexes, but displays the footprints associated with individual wells and well groups at the sub-basin scale.

The proposed algorithm can be applied in areas where hydrogeologic information is limited. In addition to well locations and withdrawal rates, the only additional input required is a depth-rate index, which can be based on hydrogeologic information, regulatory limits, or can be a user-defined consistent, and reported, graphical scale. The output on a display and computational grid includes distributed withdrawals and cell codes that can be visualized as the groundwater withdrawal footprint. Optionally, part of the grid can be inactive, which can be useful for displaying footprints limited to basin, management area, or model boundaries. The depth-rate index can also vary in space and time. The algorithm to compute the footprint is compact and can be incorporated in interfaces for flow or water-budget models, or interactive mapping applications.

The groundwater withdrawal footprint is useful for visualizing the magnitudes of groundwater withdrawals at the sub-basin scale relative to water-resource metrics. However, it should not be misinterpreted as illustrating the *impact* of groundwater withdrawals on groundwater levels, fluxes, or other characteristics of the aquifer. As shown by the first example here, the area that contributes recharge to a well is *not* coincident with its withdrawal footprint. More advanced methods of analysis, including the use of groundwater-flow models, are required to display contributing areas, flow directions, changes in water levels and aquifer storage, or other hydrologic processes, caused by withdrawals. The footprint map may nonetheless be a useful preliminary analysis tool that suggests areas where groundwater-flow modeling or other hydrologic methods could be used to evaluate the impacts of large withdrawals on groundwater and surface-water resources.

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