Incorporating Stream Features into Groundwater Contouring Tools Within GIS

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Abstract

Hydrogeologists often are called upon to estimate surfaces from discrete, sparse data points. This estimation is often accomplished by manually drawing contours on maps using interpolation methods between points of known value while accounting for features known to influence the water table's surface. By contrast, geographic information systems (GIS) are good at creating smooth continuous surfaces from limited data points and allowing the user to represent the resulting surface resulting with contours, but these automated methods often fail to meet the expectations of many hydrogeologists because they do not include knowledge of other influences on the water table. In this study, we seek to fill this gap in the GIS-based methodology for hydrogeologists through an interactive tool that shapes an interpolated surface based on additional knowledge of the water table inferred from gaining or losing streams. The modified surface is reflected in water table contours that, for example, "V" upstream for gaining streams, and can be interactively adjusted to fit the user's expectations. By modifying not only the contours but also the associated interpolated surface, additional contours will follow the same trend, and the modified surface can be used for other analyses like calculating average gradients and flow paths. The tool leverages Esri's ArcGIS Desktop software, building upon a robust suite of mapping tools. We see this as a prototype for other tools that could be developed for hydrogeologists to account for variations in the water table inferred from local topographic trends, pumping or injection wells, and other hydrogeologic features.

Introduction

Subsurface investigations pose a variety of challenges for hydrogeologists, not the least of which is having limited direct access to the phenomena of interest. Samples collected at discrete locations form the basis for interpreting continuous surfaces such as the water table. Sample sizes tend to be limited both spatially and temporally due to the expense associated with drilling, developing, and sampling monitoring wells. Robinson et al. (1995) consider small numbers of samples to have large potential impact on the accurate location of contours. Spacing between wells varies widely from tens of feet for small sites to thousands of feet for regional studies, leaving the hydrogeologist with much uncertainty in-between. Additionally, access constraints and cost, amongst other factors, usually prevent sample locations from being regularly spaced and remedial investigations often have clusters of sample locations near contamination hot spots. Hydrogeologists supplement this sparse and clustered well data with observations of features such as local topography, surface water bodies, and springs to better define the water table.

Conceptualizing the water table is an inherently three-dimensional (3D) process that is commonly represented in a two-dimensional (2D) map view with contour lines. An experienced hydrogeologist manually drafting contours honors the water level measurement points, but also calls upon a mental picture of the subsurface. This is a nontrivial challenge not typically faced in mapping contours of exposed surfaces such as topography. Contours of subsurface features are iteratively refined as the interpretation of the subsurface evolves. The quality of contours is judged subjectively, with emphasis generally placed on attributes such as smoothness (e.g., Slocum et al. 2009) and spacing (e.g., Robinson et al. 1995; DeMers 2003), and overall logical consistency. Additionally contours of the water table must adhere to hydrogeologic principles understood by the scientist but not captured in current contouring algorithms (Siegel 2008).

The combination of small sample sizes, widely and irregularly spaced samples, variable supplemental information requiring expert knowledge to utilize, and artistic license make it difficult to completely replicate this process with a computer algorithm. Several general purpose deterministic algorithms are available in contemporary
geographic information systems (GIS) software. The simplest methods accept point measurements as input and solve for locations on a regularly spaced grid (raster model) by applying a weighting scheme based on proximity. The resulting gridded surface often misses important nuances that may appear obvious to the hydrogeologist. A common strategy used to improve results involves adding control points with ancillary or human estimated values along features such as streams or in poorly sampled areas in which the grid is ill-defined (DeMers 2003, 356). However, this strategy is iterative, tedious, and often counter-intuitive for hydrogeologists with little experience with GIS.

In this study, we developed an interactive ArcGIS-based tool to augment water well data points with hydrogeologic knowledge about gaining and losing streams in creating the interpolated water table surface. A stream’s interaction with the water table conceptually creates valleys (gaining streams) and ridges (losing streams) in the water table surface manifested in contours with characteristic "V"-shaped patterns (Heath 1983; Fetter 2001). We parameterize the streams to allow intuitive changes to interactively and predictably update an interpolated surface and associated contours.

**Background**

The topic of interpolation by drawing contour lines appears in several hydrogeology text books, but most devote very little time to the topic (Kresic 1997; Fetter 2001; Hiscock 2005). Linear interpolation is generally the only method presented in older hydrogeology textbooks, but newer textbooks such as Kresic and Mikszewski (2013) address additional interpolation methods commonly available in software used in applied hydrogeology. The linear interpolation method (e.g., Fetter 2001; Slocum et al. 2009) begins by dividing the sample network into nonoverlapping triangles by connecting sets of three points. The hydrogeologist assumes a linear trend along the edges of each triangle, interpolating between measured values at the vertices and drawing contour lines connecting equal measured or interpreted values. Typically this method provides an initial pass at the contours and the hydrogeologist will adjust the contours based on professional judgment. This may include incorporating knowledge of local topography, surface water bodies, changes in geology, and other factors that affect the water table.

Computer algorithms that implement linear interpolation provide rapid solutions through rigidly mechanical means. Most algorithms employ Delaunay triangulation (Weibel & Heller 1991) to divide the sample network into triangles such that a circle circumscribed around each triangle contains no other sample points. With very limited exceptions this method provides a single solution for any given set of points and ensures repeatability. The output of computerized linear interpolation, characterized by angular or blocky contours due to contours changing direction rapidly at triangular edges, lacks the artistry of the smooth organic curves typical of hand-drawn contours (Slocum et al. 2009).

An alternative to linear interpolation is the natural neighbors algorithm which also is based on Delaunay triangulation (Sibson 1981). Natural-neighbor contours are smoother, and the associated surface is generally smooth as well. They also, however may contain tight, closed contours indicating small, isolated highs or lows in the surface surrounding input data points. Subjectively, the smoothness of these contours may be more appealing than the angular linear interpolated contours; however, the algorithm still lacks any professional hydrogeologic judgment. Other common interpolation algorithms such as inverse distance-weighted (IDW), spline, and various forms of kriging are implemented in mapping software.

IDW applies a weight matrix that is inversely proportional to the distance between the interpolated point and the data points and create characteristic bulls-eye contour patterns (Philip & Watson 1982). Spline fits a surface that passes exactly through the data points while minimizing the overall curvature of the surface (Franke 1982). Spline results in both a surface and contours that are smooth, and at the same time honor all input data points. Kriging uses geostatistical methods to estimate the surface based on variography (Oliver 1990). While commonly applied in geology, kriging requires expert knowledge and relatively large datasets to generate surfaces with statistical validity.

Which sort of algorithm should be used to create the smooth surface is a moot point for many hydrogeologists; however, as none inherently account for professional judgment of the nature of the surface between known data points. During manual contouring, the hydrogeologist implicitly considers the entire surface but only explicitly defines values at the contour lines. However, computer algorithms explicitly define values for the entire surface as either a regularly spaced grid (raster) or a triangulated irregular network (TIN) model. TIN models represent a surface with a set of irregularly spaced points connected to form nonoverlapping triangles (Kumler 1994). Areas of critical change likely won’t be well defined in the interpolated surface if there are too few data points sampling these areas. Additionally many geologically important features are better represented with lines than points, such as streams, and express lateral trends on the surface.

Tools obeying rules based on expert knowledge of geologic phenomena should improve the interpolated surface and the resulting contours. For example, some spline algorithms specifically adapted for geologists incorporate fault lines as discontinuities in geologic surfaces (Zoraster 2003). In the same manner, the tool presented here is designed to replicate the effect of a gaining or losing stream on a water table surface.

**Methods and Results**

We programmed our tool as an add-in for ArcGIS for Desktop 10 using the ArcObjects VB.Net libraries (Esri,.),
with the source code available from the authors upon request. The ArcGIS Software Development Kit (SDK) offers a wide array of functionality allowing programmers to create highly customized and interactive tools. The tool described here is designed to work with the water table of an unconfined surficial aquifer as modified by a gaining or losing stream. We believe such tools would be most useful to hydrogeologists with basic ArcGIS skills but limited experience with complex or multistep geoprocessing workflows. We also note that this project is designed to improve the interpolated, static water table surface and not represent dynamic flow within the aquifer.

Incorporating stream features requires defining rules for the algorithm that replicate or mimic (1) the thought process during interpretation of sample points, (2) the physical features and interactions taking place, or (3) both. For instance, a nearby stream will influence the water table in various ways defined by hydrogeologic principles, and the hydrogeologist uses this knowledge to influence his/her drawing of the contours. If groundwater discharges into the stream (known as a gaining stream), a cross section perpendicular to the stream will show the water table sloping down toward the stream (Heath 1983). As an analogy, the stream’s trace in the water table looks like a topographic valley. Similar to the rule of V’s in topographic contours (Kimerling et al. 2011), the hydrogeologist then bends the contours upstream. However, if the stream is discharging water to the water table (known as a losing stream) then the water table in cross section will slope up to the stream, and the stream will look like a ridge line in the water table’s surface (Heath 1983). The hydrogeologist then bends the contours downstream. Figure 1 shows an example of hand-drawn contours at a site with a gaining stream. Figure 2 shows the same points fed through a linear interpolation algorithm. The contours cross the stream awkwardly and form closed loops because no data points exist at the stream. Adding data points along the stream helps to define the surface in an important area.

Our tool is based on the natural neighbors algorithm because it can incorporate lines where the surface is allowed to change abruptly, known as breaklines (e.g., Chang 2009), and it generally creates smooth surfaces with contours that honor data points. Figure 3 shows the same dataset from previous figures using natural neighbors, estimated elevations on the stream, and the stream as a breakline. The Natural Neighbors tool in the ArcGIS 3D Analyst Toolbox does not itself accept breaklines as input. A TIN with breaklines, however, can be converted to a raster with a natural neighbors option. Breaklines force TIN edges to be drawn along breaklines that otherwise may not meet the Delaunay triangulation criteria. This allows the slope of the interpolated surface to either change abruptly (hard breaklines) or gradually (soft breaklines) along the breakline (Esri 2013). The slope of the water table changes abruptly at streams as surrounding groundwater flows toward (gaining) or away from (losing) streams so they are modeled as hard breaklines. Additionally, parallel sets of breaklines help “burn in” ridges or valleys in the water table along streams by demarcating a zone in which the slope of the water table changes due to variations caused by the stream’s inflow or outflow.

A detailed methodology is outlined in Figure 4. Although tools cited are specific to ArcGIS, the same methodology should be applicable to any GIS that is designed for 3D vector, raster, and TIN formats, permits the use of breaklines, and allows the direction of stream
flow to be captured in the line’s topology (Chang 2009), with the left and right sides of the line based on the perspective of the observer facing downstream. The user provides two data inputs: well gauging point data and stream lines with elevation values. The tool creates a temporary breakline dataset and then constructs 3D lines to the topological left and right of the stream. These lines are independently offset in horizontal and vertical directions according to user-defined values stored in the stream’s attribute table. For simplicity, offsets are constant along the entire length of the stream’s line. 3D data from the streams, gauging points, and breaklines are then converted into a temporary TIN model using the Create TIN geoprocessing tool, which is then converted to raster format using a natural neighbors algorithm with the TIN to Raster tool. Contours are finally created from this raster surface and the intermediate outputs are discarded.

Figure 5 shows two sample sites, each with five monitoring wells and a nearby gaining (Figure 5a) or losing (Figure 5b) stream with contours processed by our tool. The dashed lines indicate the dynamically constructed soft breaklines parallel to the stream. The surface gradually steepens in the vicinity of the soft breaklines until it reaches the hard breakline at the stream and abruptly changes direction. The user provides estimates of the start and end elevation of the stream along with the width of the stream’s influence and drawdown (vertical offset of the water table due to the gaining stream) to the topologic left and right of the stream. For simplicity, the offset of the water table is constant along the length of the stream but lateral offsets may differ as shown in the topologic left and right offsets in Figure 5a.

Occasionally data points contain errors (e.g., transcription blunders), which create unusual patterns in the contours. The user is able to interactively toggle individual points to be included or excluded from contouring and automatically regenerate the surface and contours allowing the user to quick explore possible problems with their data. Additionally, the user is able to interactively change the contour interval to visually determine the best interval for the dataset.

Figure 3. Example using natural neighbors in ArcGIS using the same data points as Figure 1 with estimated values on the stream, and using the stream as a breakline (from Kresic 1997). Note that the contours are smoother than in linear interpolation and create a pattern more consistent with a gaining stream.

Figure 4. Flowchart for incorporating stream features into groundwater contouring.
Figure 5. Two examples of contours generated for sites that each have five monitoring wells and a gaining stream (a) or a losing stream (b) on site. Dynamic soft breaklines are automatically added using the contouring tool, and may be adjusted via input parameters of the tool.

Conclusions

Tailoring GIS interpolation tools to account for stream features helps address common contouring challenges for hydrogeologists. The tool developed during this study yielded a gridded surface that is represented by more realistic contour lines with test datasets demonstrating the potential of customized tools to provide better results than general purpose tools and lower the level of GIS experience required for specific hydrogeology workflows. Additional tools could be developed to address other hydrogeologically important features such as lateral changes in hydraulic conductivity, dikes/impermeable barriers such as slurry walls, or extraction/injection wells. A similar approach to encoding domain knowledge into GIS contouring tools could have applications beyond hydrogeology (e.g., modifying isohyets with respect to topography in climatology or modifying the behavior of isobars across fronts in meteorology).

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References