Enhancement of aquifer vulnerability indexing using the analytic-element method

K. C. Fredrick · M. W. Becker · D. M. Flewelling · W. Silavisesrith · E. R. Hart

Abstract Indexing methods are used for the evaluation of aquifer vulnerability and establishing guidelines for the protection of ground-water resources. The principle of the indexing method is to rank influences on groundwater to determine overall vulnerability of an aquifer to contamination. The analytic element method (AEM) of ground-water flow modeling is used to enhance indexing methods by rapidly calculating a potentiometric surface based primarily on surface-water features. This potentiometric map is combined with a digital-elevation model to produce a map of water-table depth. This is an improvement over simple water-table interpolation methods. It is physically based, properly representing surface-water features, hydraulic boundaries, and changes in hydraulic conductivity. The AEM software, SPLIT, is used to improve an aquifer vulnerability assessment for a valley-fill aquifer in western New York State. A GIS-based graphical user interface allows automated conversion of hydrography vector data into analytic elements.

Keywords Groundwater · Analytic-element modeling · Indexing methods · DRASTIC · GIS · New York

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Introduction

The protection of shallow ground-water resources requires the integration of many disparate forms of information. Geologic, hydrologic, and environmental data are compared with possible sources of contamination to evaluate the vulnerability of aquifers to pollution. Often these studies are carried out by planning commissions or other local agencies with limited resources. Sophisticated risk assessment and contaminant-transport models are not a viable option for such entities and, therefore, they must rely upon data at hand to make the best decision. So-called "indexing" methods have been of use in such instances, as they rely upon existing data and do not require sophisticated predictive methodologies. The essence of an indexing method is to overlay relevant maps and assign weights to information that gauge their importance to aquifer protection. Through a linear combination of these weighted indicators, an index is generated that corresponds to the perceived probability that an aquifer might become polluted. With the advent of Geographic Information Systems (GIS), such calculations can be made rapidly, often with software already available in local agencies.

In this article, the authors focus on an indexing method that considers only natural (i.e. hydrogeologic) information in the assessment of aquifer vulnerability. With this approach, the natural propensity for the environment to shield ground-water resources from the surface is evaluated through a weighted combination of geologic factors. As with any indexing method, this method is only as useful as the information that goes into it. Errors within individual maps, especially heavily weighted maps, propagate throughout the indexing process. One factor that is heavily weighted in the indexing scheme applied here is depth to the water table. It is intuitive that shallow water tables are more difficult to protect than deeper water tables. As a result, aquifer vulnerability maps tend to reflect the water table elevations in many applications. Depth to water table is not a simple factor to obtain from a map, however. If one simply interpolates water levels in wells, the water table can be erroneously deep in uplands or high in lowlands. If one assumes a constant depth to water table, the water table will not intersect topography at open water surfaces.

In addition, the water table is not normally at a constant depth in regions of topographic relief. It tends to be a subdued reflection of the topography; deeper in the uplands and shallower in the lowlands. A more meaningful approach to predicting water table depth is to take advantage of the physics of flow through porous media. As the water table represents ground-water flow potential in the subsurface, numerical ground-water flow models preserve hydraulic continuity at surface water features and should correctly predict topographically driven water-table elevation. The Analytic Element (AE) approach to numerical ground-water flow modeling is particularly well suited to indexing applications. AE models represent hydrologic features with analytic equations, such that the water table can be predicted through the superposition of multiple analytic equations. One series of equations may represent a lake, for example, and another a stream. A tremendous advantage to this approach is that it is vector (rather than raster) based, as are most map elements. As a result, AE models have been generated directly from GIS databases by assuming a nearly one-to-one correspondence between map features (e.g. streams) and analytic elements (e.g. line element). The Minnesota Department of Health used this approach to evaluate capture zones for water supply wells, for example (Seaberg 2000).

In this article, the authors discuss the use of a GIS based AE interface to predict water table depth for use in an aquifer-vulnerability indexing method. Both the water table prediction and the indexing are accomplished within the same GIS framework, to produce a seamless approach to aquifer vulnerability mapping. The specific tools used are a GIS interface written for ArcGIS(c) (Environmental Systems Research Institute, 2001, Redlands, California) based upon the ArcFlow interface developed by the Minnesota Department of Health. The DRASTIC indexing methodology is adopted, which was developed by the U.S. Environmental Protection Agency and has been widely used (Aller and others 1987). The indexing method, including the AE-predicted water table, is applied to the Ischua Creek Watershed, Cattaraugus County, New York State.

DRASTIC method

Developed in 1987 by the United States Environmental Protection Agency (EPA) along with the National Water Well Association (NWWA), the DRASTIC method is a widely used index-modeling tool. DRASTIC is an acronym for the hydrogeological parameters included within the model structure, including Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone media, and hydraulic Conductivity (Aller and others 1987). It uses the superposition of relative weights and ratings of hydrogeological characteristics to determine a "score" that indicates aquifer susceptibility to contamination.

DRASTIC is intended as a screening tool to determine relatively vulnerable areas where further research and resources should be focused. It is well suited for integration with a GIS because of its reliance on spatial data (Aller and others 1987).

The DRASTIC method is flexible, allowing the modeler the discretion to adjust the model, based on the data available and the regional characteristics (Evans and Myers 1990). While the weights for each DRASTIC factor are fixed, there is flexibility in the ratings within each category. For this reason, there is an element of subjectivity involved in the selection of parameters and their impact on the model. However, if subjectivity and redundancy is minimized through prior knowledge and data management, a DRASTIC model can provide an adequate preliminary evaluation of an aquifer's pollution potential.

A previous DRASTIC model of the Ischua Creek watershed (Hart 2001) incorporated the parameters related to soil properties (R, I) and surficial geology (S, C, T) and neglected depth to water (D) and aquifer media (A). For the purposes of incorporating the AEM method, depth to water table is added into the DRASTIC calculation. The potentiometric surface map used to determine depth to water incorporates geology, surface water features, and recharge from precipitation.

Aller and others (1987) describe depth to water data based upon water table maps or well logs. Subsequent DRASTIC models have used interpolative contouring procedures, such as kriging, to establish depth to water from well logs (Zhang and others 1996). Simple interpolation has limited efficacy when a region has a paucity of well or head data, as is the case in the Ischua Creek Watershed.

Analytic element modeling

The ground-water table, or potentiometric surface, used in determining depth to water for the indexing model was calculated using an analytic-element model. This method is based on a set of governing equations for an analytic solution to ground-water flow problems (Haitjema 1995). Aquifer properties, such as streams, lakes, and geological heterogeneities, are represented as "elements" within the domain. Each element is represented by a mathematical function. The solution is calculated by the superposition of these functions within the domain. The University of Minnesota developed the method in 1978 for a project for the U.S. Army Corps of Engineers (Haitjema 1995). It has been developed further and several software packages have been made available (Strack 1999).

For this particular application, the software application SPLIT was used. SPLIT is a freeware package, made available by the University at Buffalo (Janković 2001). It is different from the other analytic-element modeling packages because it uses high order elements to represent hydrologic characteristics. High order elements allow the characteristics (such as head) along the element to vary. This permits the user more flexibility in element specification within the domain, as well as higher precision of the solution to the governing equations.

The graphical user interface for this project is named ArcAEM and is a modified version of ArcFlow (Seaberg 2000) by Warit Silavisesrith (2003) of the Department of Geography at the University at Buffalo. ArcAEM is an extension to the ArcGIS(c) platform (ESRI 2001). ArcFlow was originally developed by the Minnesota Department of Health (Seaberg 2000) as an extension to the ArcView(c) software of the Environmental Systems Research Institute (ESRI 2000). ArcAEM allows the user to create element layers from map parameters. For example, a stream layer based upon a digital-line graph can be simplified as a stream element. A SPLIT input file is written by the ArcAEM extension based on the distribution and properties of all of the elements in the domain. The AEM model is then executed through the SPLIT iterative solver. The solution is written as output files of the stream function, head, leakage, extraction, and error. The output files can then be displayed with the GIS display as map layers.

Ischua Creek, Cattaraugus County, New York

Ischua Creek flows from north to south along the eastern border of Cattaraugus County in southwestern New York State. The watershed also includes the western edge of Allegheny County. The stream flows from the headwaters west of the town of Machias, to Hinsdale where it meets Olean Creek, eventually flowing into the Allegheny River and ultimately the Ohio River.

The region is dominated by glacial-geomorphic features, including deep valleys (on the scale of hundreds of meters) and deposits of till and outwash. The bedrock consists of limestone and shale and is overlain by till of varying thickness, generally thickening down slope. The valley floors are broad, relatively flat deposits of outwash of varying sediment types, ranging from clay till to sand and gravel (Frimpter 1974). These valleys were carved by glaciers and filled with glacial drift as the glaciers receded to the north. Fig. 1 shows the relative location of the Ischua Creek valley, represented by the red rectangle in the lower left of the image.

The upper aquifer of the Ischua Creek watershed is generally unconfined. Many of the wells are completed in the glacial sediments of the valley floor or the fractured top of bedrock. Clay lenses in the valley sediments create isolated confined and perched conditions; however, poor connectivity of these units allow the model to be based solely on a solution for unconfined conditions.

Methods

The initial DRASTIC index of pollution potential for Ischua Creek was calculated using five parameter maps. Figures 2a through 2e show each of the maps in vector format. To calculate an index including the AEM model, these vector maps are classified according to the DRASTIC rating (parameter weight X impact rating). These classified maps are then converted to raster format using ArcMap (ESRI 2001). The five parameter maps are summed using the raster calculator function, based on their DRASTIC score.

The two-dimensional, steady-state analytic-element model was constructed with spatial data of aquifer properties for the Ischua Creek watershed and surrounding areas. These data, including hydrography, soil media, surface geology, and recharge were organized in ArcMap(c). Model elements were then created by selecting features and transforming them based on their characteristics. Fig. 3 shows the arrangement of the elements used in the AE model. Specifically, the GIS stream features, from digital-line graph shapefiles, were used as the basis for AEM streams. The number of segments used to represent the streams in the GIS layer was reduced through the Douglas and Peucker (1973) simplification algorithm created for ArcAEM(c). The use of the Douglas-Peucker algorithm

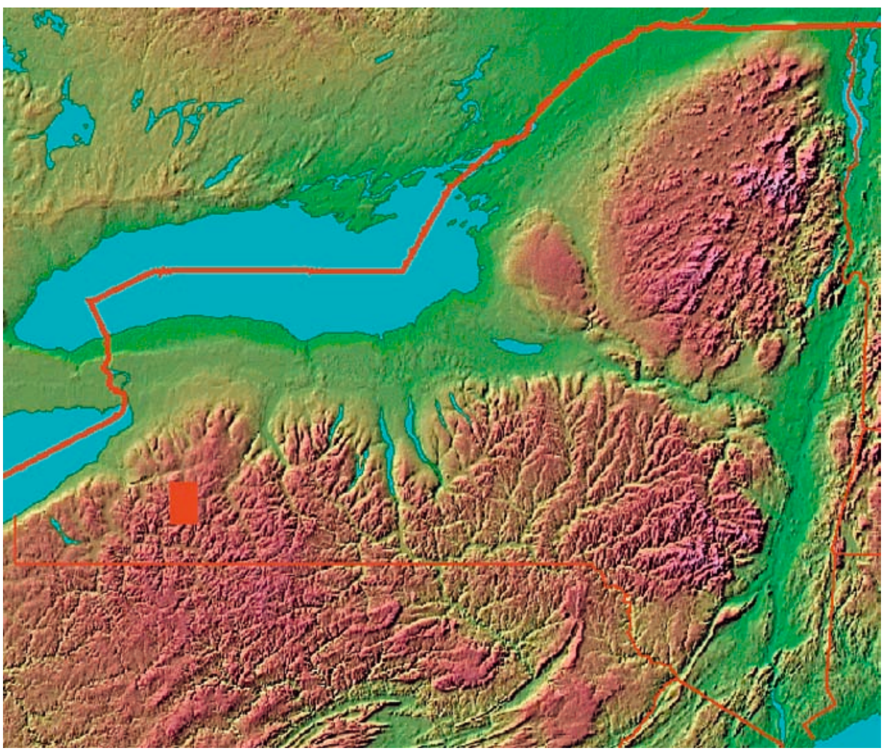

Fig. 1
New York State landform map. Red rectangle indicates study area. From Sterner, Johns Hopkins Univ., 1995, Applied Physics Lab

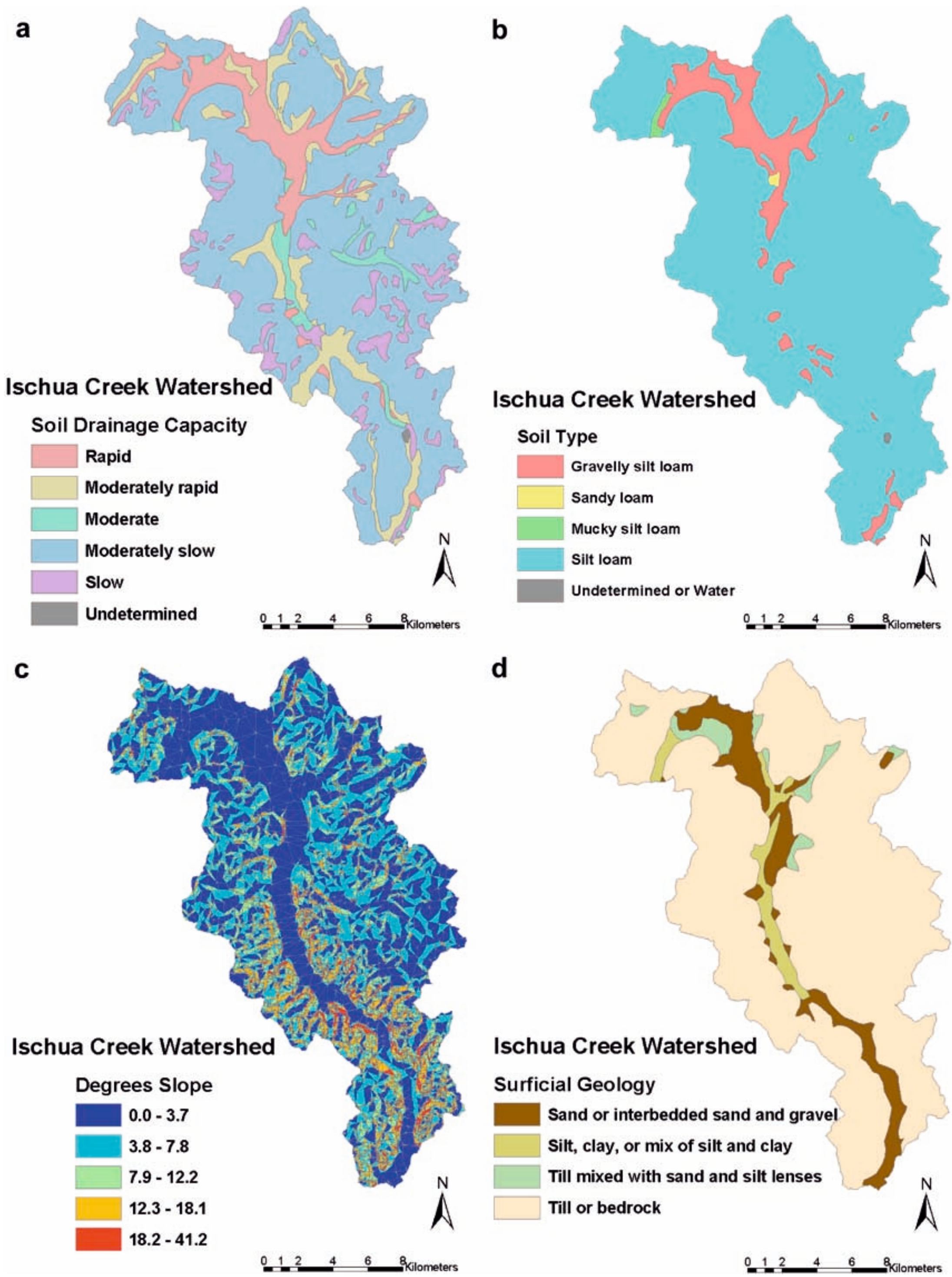

Fig. 2a–e
Map layers used in initial DRASTIC model.**a** Soil permeability map. **b** Soil type map. **c** Slope map. **d** Surficial geology map. **e** Well yield map

ensured reproducibility of the simplification and reduced computational processing time. The degree of simplification was variable, chosen for individual stream elements. Stream detail was retained to more accurately represent Ischua Creek and its active tributaries, and decreased with distance from the surface watershed boundary.

Aquifer recharge was initially calculated as one third of precipitation (Frimpter 1974), as a polygon encompassing the model area (not shown in Fig. 3). This represents an annual average of the fraction of precipitation that reaches the aquifer, disregarding surface runoff and evapotranspiration. The value of 0.75 mm per day was used for recharge for the steady-state model.
Hydraulic conductivity polygons, or heterogeneities, were delineated based on the surface-geology map. The polygons representing geologic material were simplified

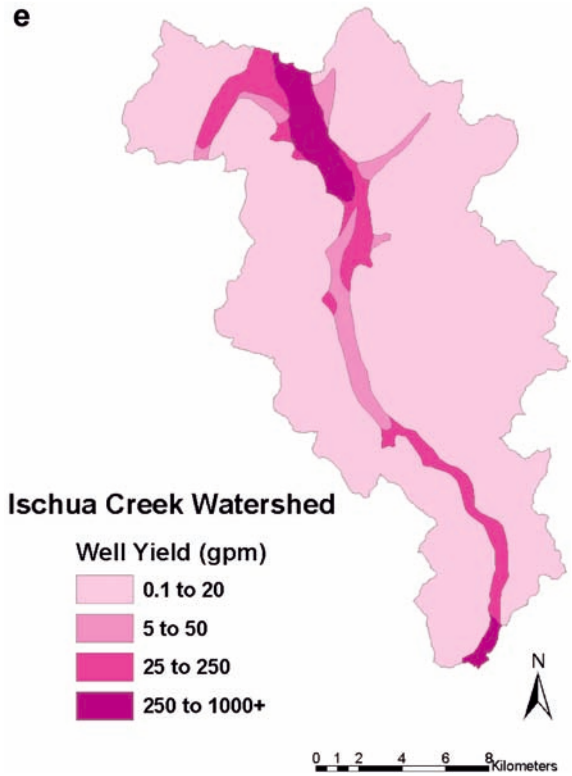

Fig. 2a–e
(Contd.)

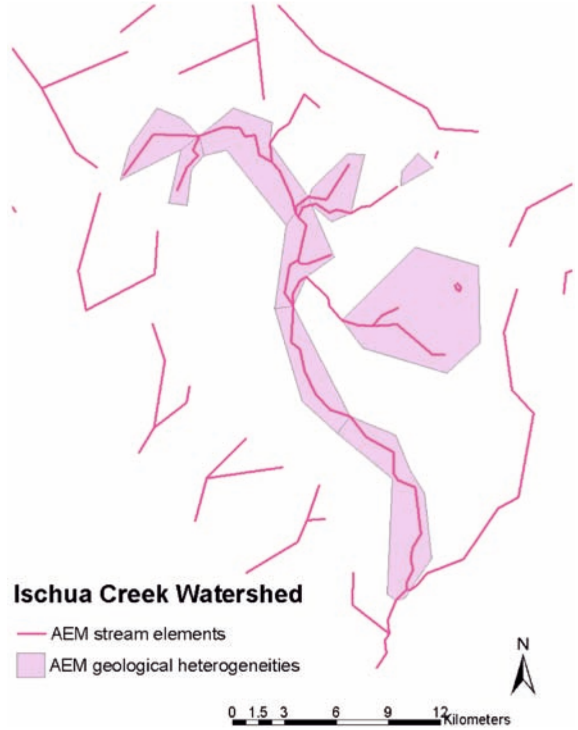

Fig. 3
Analytic elements used in the AEM model. An estimate of the portion of precipitation that recharges the aquifer is include as a recharge element but is not shown

manually from the original digitized form to map objects with no more than ten sides to maintain acceptable computation time. To represent the general distribution of geologic units, the heterogeneities are primarily constrained to the valleys, separated into five different sections of varying conductivity. Early model results exposed an unreasonably high water table in the upland regions, especially the tributary valleys. This could be accounted for by adding stream elements to represent the tributaries; however, since this is a steady-state model and many of the streams are ephemeral, this is not a reasonable solution. To account for the ground-water mounding, additional heterogeneities were added in the uplands. These heterogeneity polygons are distributed in an attempt to represent the varying facies seen in and around the larger tributary valleys. Fig. 3 shows the AEM model with pink polygons as hydraulic-conductivity elements.

Ground-water model calibration is the process of evaluation whereby the model outputs are compared to known values. It is a measure of the error distribution of the model. Model input parameters are manipulated and the model is re-solved. The resultant model outputs or calibration parameters are compared to the known values until the errors are minimized to some subjective level. Calibration of this analytic-element model is based on trial and error matching of heads. Observation heads from wells are constrained mainly to the valley floor, while head values from the uplands are taken from small lakes and ephemeral-stream channels. Conductivity values were the primary focus of calibration due to the high uncertainty and distribution of sediments and fractured bedrock making up the unconfined aquifer. Initial values of the hydraulic conductivities were obtained from the regional environmental report by Frimpter (1974). Final conductivity values were determined through calibration of the model. It should be noted that all of the model construction and calibration procedures were accomplished within the GIS framework and ArcAEM discussed above.

The most conductive of the heterogeneities is a sand and gravel deposit (approximately 13 m/day) in the northern section of the valley. The lowest conductivity value within the valley fill is sandy clay till of 2 m/day. The conductivity (0.3 m/day) of the majority of the watershed is representative of bedrock with a thin (3 to 10 m) fractured top of rock, overlain by till of varying thickness and composition. As mentioned earlier, additional heterogeneities were added in upland areas to assist in calibration due to unrealistically high values of head.

The potentiometric surface (a standard output of SPLIT) was displayed as a raster layer of head elevation in the GIS. This surface was subtracted from the digital-elevation model (30-m resolution) using the raster Calculator function in ArcGIS[(c)], with the syntax [dem_30.dem] - [head.grd]. A new raster map of depth to water was produced and displayed in the view window. This raster was classified into five categories. The new classified raster was then assigned a rating scheme of 1 to 9 (odd numbers) to establish the relative susceptibility to pollution for each classification of water depth. Classification 1 corresponds to the areas where the water table is over 100 m below the

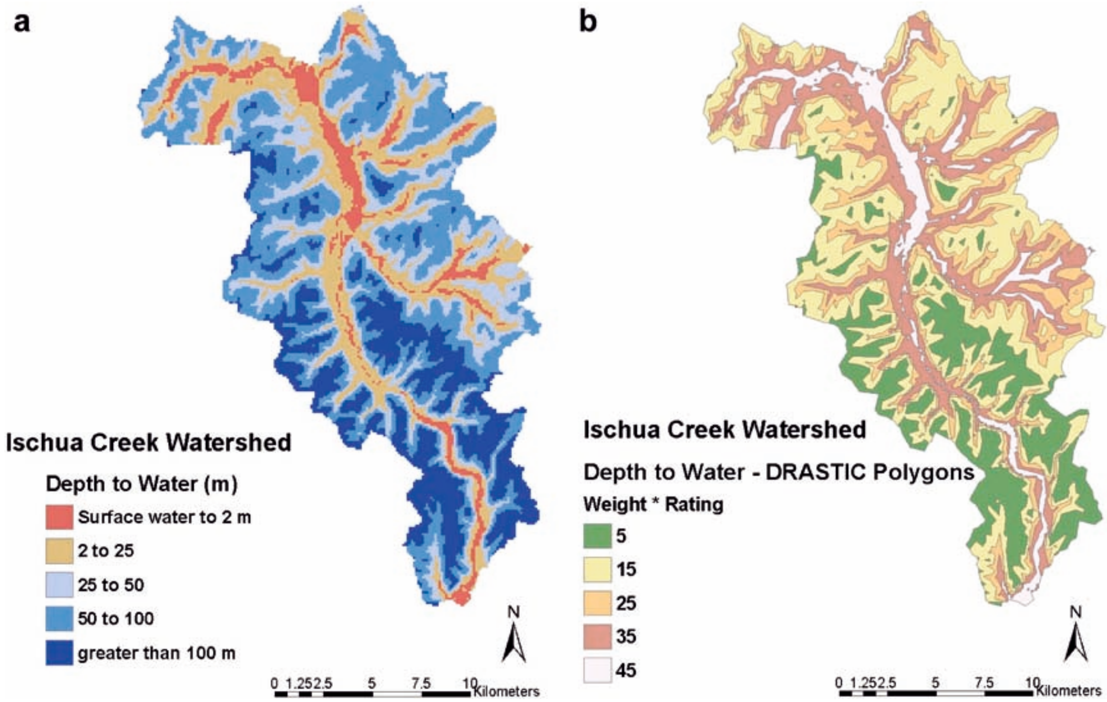

Fig. 4a,b
Depth to water maps determined from AEM model. **a** Raster representation of depth to water.**b** Polygon representation of depth to water map converted from raster map

topographic surface, while 9 represents surface water and groundwater within 2 m of topography. Figures 4a and 4b are the final depth to water maps that were used in the aquifer susceptibility calculation. Fig. 4a is the raster layer classified into the five depth categories. Fig. 4b is this raster map, converted into vector format, with the DRASTIC score for each classification.

In DRASTIC, depth to water is assumed to have a high impact on aquifer susceptibility relative to the other parameters. The methods described by Aller and others (1987), recommend a weight of five for depth to water. To complete the AEM/DRASTIC model, the classified depth to water map is reclassified with the ratings multiplied by five. All of the maps were then added together based on their DRASTIC scores (weight X impact) to produce the final susceptibility map.

The final aquifer susceptibility map is in raster format, with several hundred classes based on scores for each raster cell. To display the susceptibility map in a more appealing and comprehensive manner, it has been reclassified into five categories ranging from low to high susceptibility. The classifications are based on the ranges from the initial DRASTIC susceptibility map (Fig. 5a), with depth to water included. For example, the low susceptibility category had a range of 0 to 49 and the depth to water layer's lowest impact category is five. Consequently, the AEM/DRASTIC model (Fig. 5b) has a low susceptibility category with a range of 0 to 54. Figures 5a and 5b show the two aquifer susceptibility maps in their final, vector format.

Results and discussion

The inclusion of the depth to water layer in the aquifer vulnerability model shows significant differences from the previous DRASTIC model, particularly in higher elevations. The previous model displayed variability in aquifer vulnerability only in the valley floor due to the heterogeneous geology there. Depth to water table is variable within the uplands while geology is not. Consequently, the relative pollution potential of the aquifer calculated by the combination of these maps is concentrated in the valley. This is not necessarily an incorrect or undesired outcome; however, it may not be an adequate solution because of the paucity of data in the uplands.

The addition of the depth to water map from the AEM model into the DRASTIC model incorporates the effects of the water table in an unconfined aquifer as a function of topography. This is especially apparent when comparing the upland regions of the two models. The AEM/DRASTIC model is inclined toward a higher overall aquifer sensitivity, but the differences are most obvious in the uplands. The modified DRASTIC model shows the pollution potential to be slightly greater in local topographic lows, including ditches, ephemeral-stream channels, and local depressions. However, it also accounts for the overall water table elevation variability from the valley bottom to the uplands.

Interpretation of the differences from the initial DRASTIC model can be focused on the AEM/DRASTIC model's increased area of aquifer sensitivity (particularly noticeable are the green regions in Fig. 5). The reason for this increase is due to the relative difference of the classifications of the depth to water layer versus those of each of the other layers. With the exception of the slope map, each of the initial indexing model layers has a distinct

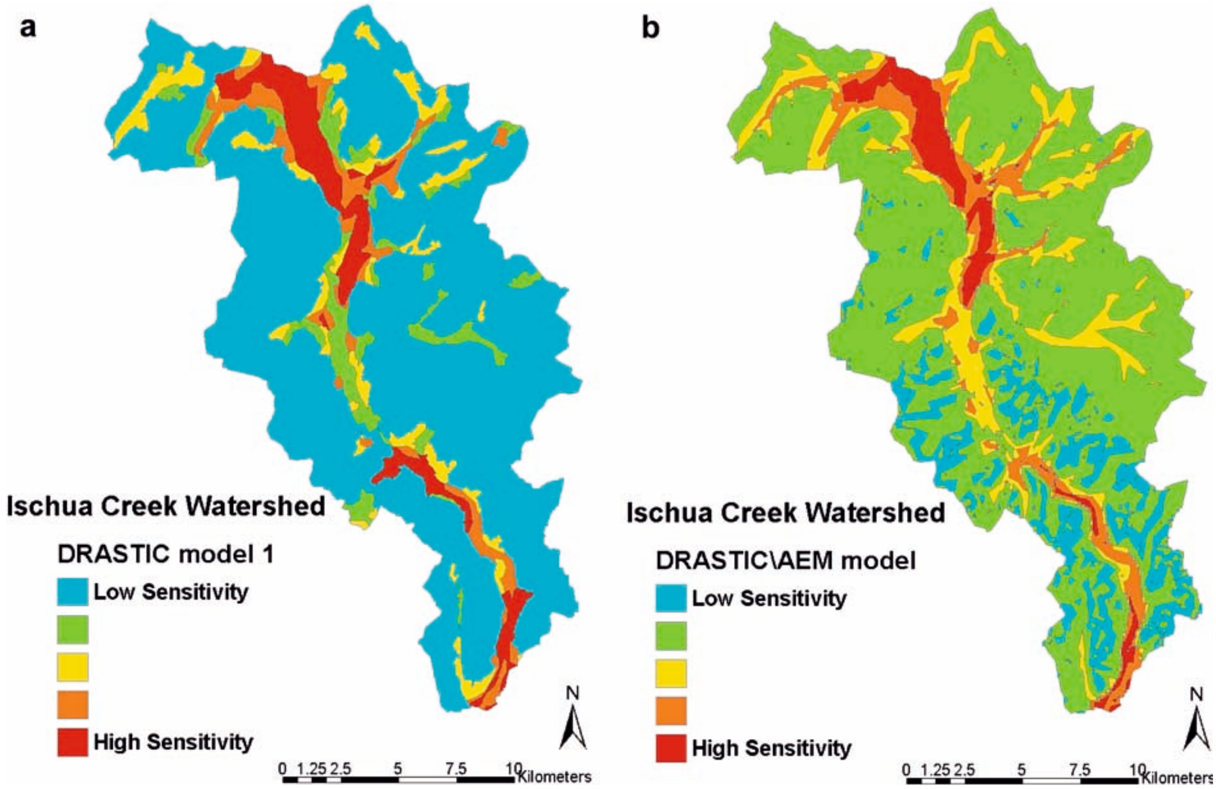

Fig. 5a,b
Final aquifer vulnerability maps.**a** DRASTIC model without depth to water layer included.**b** DRASTIC model including the AEM-derived depth to water map

variation in classification and, consequently, in rating. This is particularly obvious with respect to the different properties of the valley floor from the uplands. The depth to water map, however, has a "smoother" distribution of classes, muting the distinction from class to class. Therefore, in the areas where the soil-related and geology-related classes have relatively low impact on the aquifer (uplands), the depth to water has a more dramatic impact on the solution. Where the other classes have a relatively high impact (valley), the depth to water is masked. The water table is not directly correlated to geology like the other parameters. Consequently, the inclusion of water table depth may help to remove bias toward geologically susceptible regions.

The validity of an indexing model is difficult to quantify. Intuitively, one assumes that the more refined the layers used to produce an indexing model, the more valid, or "correct" the model output. This research is accomplished with the understanding that the initial DRASTIC model is a reasonable representation of the pollution potential for the Ischua Creek Watershed, given the available data resources and the intended results. With this in mind, the addition of the depth to water map based on the analytic-element model improves the indexing model. The addition of the depth to water layer is an improvement over the DRASTIC model without it. Using AEM to calculate the potentiometric surface incorporates important physical parameters that may be otherwise disregarded with simpler procedures.

The ease of use of AEM in this way is ideal for integration with a database of aquifer impacts and spatial distribution of aquifer characteristics. Map layers and their accompanying attributes provide an efficient method of data management. This allows the ground-water model (and consequently the indexing model) to communicate with the database for dynamic updating and model improvement. ArcAEM provides a useful platform for the integration of all of these methods.

Conclusions

The Ischua Creek DRASTIC model exemplifies the importance of the inclusion of the depth to water table as a parameter in indexing models. The initial DRASTIC model of the Ischua Creek watershed in western New York State incorporated five parameter maps, but did not include depth to water. The aquifer susceptibility model exhibited a bias toward the valley floor, due to the uneven distribution of data. Inclusion of the depth to water into the DRASTIC scheme improved the model by removing this bias, incorporating physical properties of the system that were lacking. The analytic-element method, SPLIT, was used in a GIS environment with the ArcAEM interface. This AEM model was used to produce a potentiometric surface for the watershed. The potentiometric surface was subtracted from the topography to provide a physically-based parameter map of depth to the water table. The Ischua Creek AEM/DRASTIC model shows that through the integration of GIS, AEM, and indexing models, aquifer susceptibility assessments can be improved. These maps are an important preliminary step in determining regions for focused studies in the future, as well as possible regions of concern in terms of protection of ground-water resources.

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