GIS-Based Groundwater Pollution Hazard Assessment: A Critical Review of the DRASTIC Model

James W. Merchant

Abstract

The protection of groundwater quality is an important issue confronting much of the world's populace. Geographic information systems (GIS) have been shown to be useful tools for assessing groundwater pollution hazard. Efforts to use GIS in implementation of the DRASTIC groundwater vulnerability model and its derivatives are reviewed. Problems related to data quality, model formulation, and model validation are discussed, and suggestions for augmentation and enhancement of the model are offered. It is recommended that additional research be focused upon (1) determination of the relative importance of, and possible interdependencies among, parameters considered in the model; (2) incorporation of other factors (e.g., land use) in the model, and linkage of DRASTIC with complementary models (e.g., capture zone models); (3) investigation of scaling issues; (4) expansion of DRASTIC through GIS-based 3D, finite-element, solute transport, and temporal modeling; (5) use of expert systems; (6) validation and verification of model performance; and (7) means to assist decision-makers in using model results.

Introduction

During the last decade groundwater quality has emerged as one of the most important environmental issues confronting citizens of the United States (Conservation Foundation, 1987). There are good reasons for concern. Groundwater is the principal source of drinking water for about 53 percent of the nation's total population, and for 97 percent of those persons residing in rural areas (Moody, 1990). Nationwide, approximately 40 percent of the public water supply, serving over 74 million people, and at least 34 percent of the water used in agriculture, is withdrawn from groundwater (Nielsen and Lee, 1987). On a regional basis, dependence upon groundwater is especially great in areas such as California, Arizona, Florida, and the Great Plains (Moody, 1990).

Because aquifer recharge rates are typically exceedingly slow, groundwater is considered a finite resource in most locations. Increasing evidence of groundwater contamination in recent years, coupled with uncertainties regarding long-term human health effects, has heightened pressure on public agencies to better manage groundwater resources (Bouwer, 1990; Conservation Foundation, 1987). Management of groundwater quality, however, presents environmental scientists and policy-makers with particularly difficult problems. Detection of contamination and monitoring of water quality, often conducted employing observation wells, are difficult and costly. Clean-up of contamination, if possible at all, is often technically complex, extraordinarily expensive, and only partially effective. Because restoration of groundwater quality is such a formidable and cost-prohibitive task, great emphasis is being placed upon protection of the resource (i.e., prevention of contamination) (O'Neill and Raucher, 1990; Nielsen and Lee, 1987).

Existing data on groundwater contamination clearly show that problems vary spatially. Not all regions are equally vulnerable. Effective protection strategies, therefore, need to be targeted so that limited staff, funds, and technology can be focused upon those areas most threatened so as to provide the greatest benefit for the investment (Great Plains Agricultural Council, 1992; Duda and Johnson, 1987; Nielsen and Lee, 1987). In recent years, many states and the federal government have adopted legislation directed towards management and protection of groundwater resources (Morandi, 1989). In most instances, mapping of aquifer susceptibility to pollution is considered a critical first-step in implementing groundwater management programs.

Geographic information systems (GIS) have been used in many aspects of groundwater management and modeling (see, for example, Maidment (1994); Harlin and Lanfear (1993); Schoolmaster and Marr (1992); Kilborn *et al.* (1992); and Estes *et al.* (1987)). Perhaps, because it is so critical for public agencies to assess and map groundwater pollution hazard, spatial models designed to evaluate groundwater vulnerability to contamination have been more widely implemented in GIS than any other single type of groundwater-related model. One such model, DRASTIC, has been used with exceptional frequency. Developed by the National Water Well Association (NWWA) in collaboration with the U.S. Environmental Protection Agency (EPA), DRASTIC provides a systematic, standardized, nationally-applicable method for assessing and mapping groundwater pollution potential (Aller *et al.*, 1985).

A perusal of the literature on GIS-based groundwater pollution hazard assessment suggests that modeling is often not being conducted with sufficient regard for assumptions, requirements, and limitations of the models themselves; potential impacts of data deficiencies; or possible error introduced

Center for Advanced Land Management Information Technologies, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, Lincoln, NE 68588-0517.

Photogrammetric Engineering & Remote Sensing,
Vol. 60, No. 9, September 1994, pp. 1117–1127.

0099-1112/94/6009-000$3.00/0

through GIS analytic procedures. On the other hand, one observes that the great strengths of GIS are capitalized upon only infrequently to augment and enhance modeling efforts. This paper presents a critical review of extant GIS applications in groundwater pollution hazard assessment, with particular focus on the DRASTIC model. The principal objectives of the paper are to (1) review major contemporary efforts to employ GIS in groundwater pollution hazard assessment, (2) illuminate problems in such work, (3) suggest modifications and alternatives to current approaches, and (4) propose future research directions. In a larger context, this paper addresses issues often encountered in adapting environmental models for use in GIS.

Background

The DRASTIC Model

Although a number of spatial models designed to assess groundwater pollution hazard have been proposed, DRASTIC is arguably the model most widely used for such efforts (Committee on Techniques for Assessing Groundwater Vulnerability, 1993). Aller *et al.* (1985) offer a detailed account of the DRASTIC methodology, its evolution, and guidelines for applications. The model was designed to be a simple, easy-to-use, nationally applicable tool for groundwater pollution hazard assessment.

The acronym, DRASTIC, is derived from the seven factors considered in the model:

Depth to water table,
Recharge (net),
Aquifer media (geologic characteristics),
Soil media (texture),
Topography (slope),
Impact of the vadose zone (unsaturated zone above the water table), and
Conductivity (hydraulic) of the aquifer.

The model is formulated as an equation using a linear combination methodology (Hopkins 1977):

$$\text{Pollution Potential} = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w$$

where r is the rating and w is the weight for each factor.

Ratings, varying from 1 to 10, are intended to reflect the relative significance of classes within each factor. For example, fine textured (e.g., clay) soils are assumed to be less permeable to water than coarse (e.g., sandy) soils. Fine textured soils are, therefore, assigned a lower rating than soils having a coarse texture because, all other things being equal, they are less likely than sandy soils to allow infiltration of a pollutant (Table 1). Likewise, areas where depth-to-water is great are assigned low ratings because it is assumed that, all other things being equal, pollutants are less likely to reach the water table when it is deep (Table 2). Weights, ranging from 1 to 5, are designed to indicate the relative importance of the seven factors with respect to one another. Higher weights indicate greater importance. Note that weights are assigned differently in agricultural and non-agricultural regions to reflect perceived differences in impacts of the factors in cropped areas (Table 3) (for details, see Aller *et al.* (1985)).

TABLE 1. RANGES AND RATINGS FOR SOIL MEDIA

Soil Media	
Range	Rating
Thin or Absent	10
Gravel	10
Sand	9
Shrinking and/or Aggregated Clay	7
Sandy Loam	6
Loam	5
Silty Loam	4
Clay Loam	3
Nonshrinking and Nonaggregated Clay	1
Weight: 2	Agricultural Weight: 5

Source: Aller *et al.*, 1985

TABLE 2. RANGES AND RATINGS FOR DEPTH TO WATER

Depth to Water (feet)	
Range	Rating
0-5	10
5-10	9
15-30	7
30-50	5
50-75	3
75-100	2
100+	1
Weight: 5	Agricultural Weight: 5

Source: Aller *et al.*, 1985

The index value computed by the model is considered a relative indicator of pollution potential. Higher scores indicate greater vulnerability. The index *must*, however, be interpreted within a specific *hydrogeologic setting*, "a composite description of all the major geologic and hydrologic factors which affect and control groundwater movement into, through, and out of an area ... a mappable unit with common hydrogeologic characteristics, and as a consequence, common vulnerability to contamination" (Aller *et al.*, 1985). Use of the index without reference to its hydrogeologic setting may lead to erroneous interpretation of results.

The design and formulation of DRASTIC was predicated on several assumptions: (1) that data required by the model are available; (2) that the variables included in the model are critically related to groundwater vulnerability; and (3) that the ratings, weightings, and mathematical relationships between variables are adequately set forth in the DRASTIC procedure. Furthermore, the model is to be used only for regional (not site-specific) studies.

The Harvey County, Kansas Prototype GIS Study

It is important to note that, although the DRASTIC model was intended to be used in mapping applications, it was not ex-

TABLE 3. ASSIGNED WEIGHTS FOR DRASTIC FACTORS

Feature	Weight	Agricultural Weight
Depth to Water Table	5	5
Net Recharge	4	4
Aquifer Media	3	3
Soil Media	2	5
Topography	1	3
Impact of the Vadose Zone	5	4
Hydraulic Conductivity of the Aquifer	3	2

Source: Aller, *et al.*, 1985

pressly designed for use in a GIS. In fact, initial application employed a manual map overlay and computation procedure (National Water Well Association, 1985). Nonetheless, it obviously lends itself to implementation in GIS, and there are now many examples of such efforts.

Merchant *et al.* (1987) were probably the first to use GIS to implement DRASTIC (see, also, Martinko *et al.* (1987)). Their work focused on an 800 square mile area including Harvey County, Kansas and environs. The region includes a portion of a major aquifer (the Equus Beds) that, in terms of groundwater resources, probably supplies the largest number of people in Kansas for an area of equivalent size. The groundwater supports both irrigation and municipal users. The well field (public water supply) for the City of Wichita (population 400,000) and a major portion of the Equus Beds Groundwater Management District (EBGMD) are within the study site.

The data required by DRASTIC, and ancillary data, were entered into a raster-based GIS. Data were obtained from a multitude of sources, originally having many different formats and scales (Table 4). Some data were in tabular format (i.e., well locations) or had not yet been mapped (land use). The process of transforming these data into digital spatial information required interpretation of aerial photographs. Other data existed as maps, but at differing scales (recharge, soils, geology, oil/gas fields). Some data were available in a digital format (bedrock and water-table elevations, and surface hydrography), but required rectification. Finally, certain databases (e.g., depth to groundwater, saturated thickness of aquifer) were derived using automated techniques. For example, the file for depth-to-groundwater was generated by computer subtraction of water-table elevation from ground-surface elevation at observation wells. The results were then processed using a surfacing program to generate contours of depth-to-groundwater.

A nested multiple-resolution raster data structure was used for database development. At the finest resolution, cells had a dimension of 165 square feet (0.625 acre). Much of the

TABLE 4. HARVEY COUNTY PROTOTYPE GIS–CHARACTERISTICS OF SOURCE DATA

File	Data Source	Format	Scale	Date of Information
Generalized Well Yields	KGS-USGS	Map M-4A	1:500,000	1967 - Revised 1975
Specific Yield for Source	KDHE	Tabular	NA	Variable[1]
Elevation of Water Table	KGS-USGS	Digital	Variable	1980
Depth to Water	KGS-USGS	Digital (Derived[2])	Variable	1980
Annual Recharge	KGS-USGS	Map	1:50,000	1980
Quality (Brine Pollution)	KGS Report	Map	1:70,000	1983
Storage Coefficient (Hydraulic Conductivity)	KGS-USGS	Map	1:50,000	1980
Public Water Supply Wells	KDHE	Tabular	NA	Variable[3]
Publicly Owned Wastewater Treatment Plants	KDHE	Tabular	NA	Variable[3]
Landfills/Dumps	KDHE	Tabular	NA	Variable[3]
Hazardous Waste Generators, Storage, Disposal Sites	KDHE	Tabular	NA	Variable[3]
Industrial Lagoons	KDHE	Tabular	NA	Variable[3]
Agricultural Feedlots	KDHE	Tabular	NA	Variable[3]
Oil/Gas Fields	KGS	Map M-17	1:500,000	1982
Land Use	USGS/ASCS	Aerial Photography	1:58,000	May 1985
Soil Series	SCS – County Soil Survey	Map	1:20,000	Variable[4]
Elevation	USGS	Digital	1:250,000	1955 – Revised 1966 and 1969
Surface Hydrography	KGS	Digital	1:24,000	Variable[5]
Geology	KGS	Map M-1	1:500,000	1964
Transportation Routes (U.S. Highways/Railways)	KGS	Digital	1:24,000	Variable[5]
Public Land Survey (Township-Range-Section)	KGS	Digital	1:24,000	Variable[5]
County Boundaries	KGS	Digital	1:24,000	Variable[5]
Wichita Water Field Boundary	Included on Public Wells Map)			
Slope	(Derived from Soils Data)		1:20,000	Variable[4]

[1] Date based on monitored wells.

[2] Derived from contoured points of elevation of land surface and water table at wells.

[3] Date based on issuance of permit.

[4] Harvey County 1969, Reno County 1969, Sedgwick County 1975.

[5] Date based on last revision of quadrangle.

KDHE - Kansas Department of Health and Environment
KGS – Kansas Geological Survey
USGS – United States Geological Survey
SCS – United States Soil Conservation Service
ASCS – United States Agricultural Stabilization and Conservation Service
NA – Not Applicable

Source: Martinko *et al.*, 1987

source data, however, did not warrant use of such a fine cell size. Subsequent to database development, the DRASTIC model was computed for each of the 15 USGS 7.5-minute quadrangles in the study area (Plate 1).

Subsequent and Related Research

Since 1987 many other investigators have reported on efforts to use GIS for groundwater pollution hazard assessment. These efforts fall generally into three categories: (1) small-area demonstration studies utilizing DRASTIC, (2) large-area operational implementations of DRASTIC, and (3) modifications or derivatives of the DRASTIC concept. A brief overview of such studies is provided below.

A number of projects, focusing on relatively small areas for which data were readily available, have demonstrated that DRASTIC can be used with a variety of GIS software. Griner (1989), for example, employed an Intergraph system to run the DRASTIC model in southwest Florida. Regan (1990) used ARC/INFO on an Arizona study site. Hickey and Wright (1990) discussed DRASTIC applications with the GRASS software. Evans and Myers (1990) used ERDAS and DRASTIC in southeastern Delaware. These studies have largely taken a "cookbook" approach, attempting to carefully follow the model implementation as outlined by Aller *et al.* (1985). They tend to focus on the mechanics of using a GIS to establish digital databases and to run the model. In that respect, they differ little from one another or from the Harvey County project outlined above. It is disconcerting to note that few of these papers make reference to, or explicitly build upon, the efforts of others doing work on GIS-based groundwater vulnerability assessment. Neither do they, in most cases, seek to enhance DRASTIC or capitalize on strengths of GIS beyond those, such as "overlay," required for running the model. The authors frequently cite advantages (e.g., speed, ease, and "increased accuracy") of GIS over manual methods of modeling, but there are few cautions or concerns expressed.

Several researchers have used DRASTIC to develop statewide assessments of groundwater vulnerability. Rundquist *et al.* (1991) employed ERDAS software and DRASTIC to map groundwater pollution hazard in Nebraska at a scale of 1: 250,000. Trent (1993) developed a 1:500,000-scale map of Georgia. Atkinson and Thomlinson (1994) carried out similar work in Texas. These studies differ somewhat from the "demonstration" projects cited above. For example, because the investigations covered large areas, adequate data were sometimes unavailable, and a variety of compromises were made in implementing the DRASTIC model. While an attempt was made to follow guidelines presented by Aller *et al.* (1985), these efforts cannot by any means be characterized as cookbook approaches. The potential implications of this observation are discussed below.

More than a dozen multifactoral spatial models and methods for assessing groundwater vulnerability have been developed over the last decade (see Committee on Techniques for Assessing Ground Water Vulnerability, 1993; Minnesota Department of Natural Resources, Division of Waters, 1991). While not always truly DRASTIC derivatives in the literal sense, most of these clearly owe much to the DRASTIC concept, at the very least sharing common characteristics such as the variables considered and the general approach to groundwater hazard assessment (Christy, 1993; Hamerlinck *et al.*, 1993; Lemme *et al.*, 1990). Attention here is focused primarily on statewide studies which are similar in many respects to those of Trent (1993) and Rundquist *et al.* (1991).

Lusch (1992), for example, reported on the development of a GIS-based methodology for mapping aquifer vulnerability to surface contamination in Michigan at a scale of 1:500,000. His work was based on consideration of data on soils associations, bedrock geology, aquifer characteristics, and glacial drift lithology. Riggle (1988) and Riggle and Schmidt (1991) describe the preparation of a 1:1,000,000-scale map portraying groundwater contamination susceptibility in Wisconsin (Wisconsin Geological and Natural History Survey, 1987). Data on characteristics of soils associations, type of and depth to bedrock, depth to water, and Quaternary geology/surficial deposits were employed in a linear combination model similar to DRASTIC. A modified DRASTIC model, used to construct a similar vulnerability map of Minnesota, was based on consideration of aquifer materials, recharge potential, and soils characteristics (Minnesota Pollution Control Agency, 1989).

Some have attempted to determine average county-level DRASTIC scores, usually for purposes of national investigations of groundwater vulnerability (Mullen; 1991; Nielsen and Lee, 1987). A study of such estimates conducted by the U.S. General Accounting Office (1991) warned that there is as much variability in hydrogeologic vulnerability within counties as between counties. This paper will not deal with county-level DRASTIC approximations.

Discussion

Research such as that cited above has clearly demonstrated the benefits of using GIS in modeling groundwater pollution hazard. Nonetheless, there are some concerns and potential limitations raised by such efforts. The use of GIS has, for example, illuminated a number of issues related to model formulation and performance that have seldom been addressed in the literature. It is also apparent that there are ways in which GIS might be used to enhance and augment models such as DRASTIC in order to foster groundwater quality protection and decision-making.

Model Formulation and Performance

The literature is replete with discussion of error and accuracy issues in GIS (see Veregin (1989) for an excellent overview). Here, we will examine but a few concerns specific to the DRASTIC model. These include potential impacts of variability in database quality, potential interfactor correlation and redundancy matters in model execution, and issues related to model validation.

Database Quality

Among the assumptions made in formulation of the DRASTIC model were (1) that the data required by the model are available and (2) that the data possess sufficient precision, resolution, and accuracy for assignment of ratings following guidelines set forth in Aller *et al.* (1985). Even in many of the small-area demonstration studies cited above, these assumptions have not been upheld. In large-area (e.g., statewide) studies, additional problems are encountered. For example, county-level digital soils data (e.g., USDA/SCS SSURGO data), required by the DRASTIC model, are not currently available for most of the U.S. While generalized soils association data (USDA/SCS STATSGO) are commonly obtainable, and have frequently been used in large-area studies, the methods by which to assign appropriate ratings and weightings to such data are far from clear (for additional discussion of STATSGO data, see Bliss and Reybold (1989) and Committee on Techniques for Assessing Ground Water Vulnerability

(1993)). Moreover, when soils association data are employed in DRASTIC, the effects on model execution are uncertain (see Loague and Green, 1990). It is noteworthy, however, that soils data are some of the *very best* data one normally can obtain for implementing the DRASTIC model.

Some of the issues revolving around variable data quality were apparent in the Harvey County, Kansas project summarized above, and are illustrated in Plate 1 showing the Halstead 7.5-minute quadrangle. The relatively high quality of the county-level soils data is obvious. An area of coarse-textured sand dunes overlying silty clays is present in the northwest portion of the quadrangle (note high DRASTIC index values). In some regions of the map, however rectangular areas are evident. These result from the character of the other data files used to generate the index values (Table 4). For example, the best available source data for recharge and hydraulic conductivity had a spatial resolution of 1 mile^2. The rectangularly shaped areas, therefore, reflect the coarse spatial resolution of the data.

There are also problems with data precision. Often, source data are of insufficient quality to permit assignment of ratings according to guidelines presented by Aller *et al.* (1985). Although the DRASTIC documentation suggests that interpolation and adjustments to reflect local, specialized, or updated information may be warranted, the actual implementation is rather subjective and obviously dependent upon other aspects of data quality. For example, DRASTIC guidelines suggest that net aquifer recharge be expressed in inches of water and be divided into, and rated as, five classes. In Harvey County, however, aquifer recharge characteristics were not well-known, and thus were estimated by hydrogeologists as only high, moderate, or low (Plate 1).

In the Harvey County study, all data required by the DRASTIC model were available, albeit at different levels of precision, resolution, and quality. For large-area (e.g., statewide) projects, data issues become more serious. It may, for instance, be economically infeasible to obtain digital data at high precision and resolution over large areas even when source materials are available. For example, consider computation of the slope factor required by DRASTIC. Aller *et al.* (1985) suggest that slopes be expressed in five percentage classes ranging from 0 to 18+ percent. In a GIS, such estimates might best be made by deriving slope from a high-resolution (e.g., USGS 7.5-minute) digital elevation model (DEM). For many parts of the U.S., however, few adequate DEMs currently exist. As a consequence, it is not uncommon in large-area DRASTIC projects to use available coarse-resolution digital data, such as USGS 1-degree (3-arc-second) DEMs, in spite of their level of generalization. Similarly, as mentioned above, digital STATSGO soils association data may be substituted for county-level soils data, even though the procedures for assignment of DRASTIC ratings are obscure (see, for example, Rundquist *et al.* (1991) and Trent (1993)).

It is interesting to note that the DRASTIC guidelines indicate that the model should not be used on sites smaller than 100 acres (Aller *et al.*, 1985). This might lead to the conclusion that small scale data (e.g., STATSGO or 3-arc-second DEMs) are well-suited for use in the model. Yet, the stated requirements for rather precise intrafactor classification and assignment of ratings are not consonant with that conclusion. In addition, in their discussion of sources of data, Aller *et al.* (1985) make reference to data sets having relatively large scale (high resolution). In short, there are significant ambiguities with regard to scaling issues, and these become especially evident when implementing the model in a GIS (Loague and Green, 1990; van der Heijde, 1988).

Issues such as those discussed here are, of course, commonly encountered in GIS-based spatial modeling. Compromises are frequently required to overcome difficulties with data quality or availability. Some authors writing on groundwater vulnerability assessment (e.g., Baker and Panciera, 1990) warn that source data may be of questionable reliability and effects on models hard to predict. It is, however, disturbing to note how infrequently authors detail the rationale and methods used to resolve problems such as assignment of DRASTIC ratings to STATSGO soils association classes. Moreover, few acknowledge, or express concerns about, the possible impacts of database quality or scaling issues on the outcome of groundwater vulnerability modeling.

Model Formulation and Execution

As noted above, the DRASTIC model is formulated as a linear combination equation. Although widely used, such models have certain limitations that are especially apparent when they are implemented using GIS. Hopkins (1977), for example, cautions that linear combination models are inherently prone to uncertainties about the possible interdependence of factors. Although one cannot be certain about possible interdependencies among factors in DRASTIC, there are some indications that the matter needs to be more thoroughly explored. It is, for instance, not uncommon for soils textural characteristics and terrain slope, two of the seven factors used in DRASTIC, to be closely associated. In fact, when high-resolution DEMs are not available for use in GIS-based slope computation, slope attributes of county-level soils classes are sometimes used as a surrogate (see, for example, Martinko *et al.* (1987)).

It is interesting that states which have used "modified DRASTIC" methodologies (e.g., Michigan, Minnesota, Wisconsin) for groundwater vulnerability mapping have not used both a soils and a slope factor. In fact, as noted above, the hydrogeologists who developed these maps generally employed only four or five factors rather than seven (Lusch, 1992; Riggle, 1988; Riggle and Schmidt, 1991; Minnesota Pollution Control Agency, 1989). There are no direct assertions that such decisions stemmed from concerns about possible redundancy or interdependency among the DRASTIC variables. On the other hand, these maps clearly suggest that DRASTIC-equivalent results can be obtained using fewer than seven factors, and this observation, in itself, has implications for GIS-based modeling (Evans and Myers, 1990).

Newcomer and Szajgin (1984) discuss the potential for error propagation in overlay analysis. They conclude that the accuracy of composite map products, such as DRASTIC, is generally less than the accuracy of the least accurate map layer used in the analysis. Some evidence for this argument can be seen in Plate 1, where the rectilinear artifacts serve to remind map users that some of the DRASTIC factors are rather coarsely estimated. Newcomer and Szajgin (1984) furthermore assert that, as the number of layers increase, the number of possible error combinations increases rapidly. Thus, there are potential advantages in using the fewest number of factors required to produce an acceptable result, particularly when, as in the case of DRASTIC, one is employing data having varying scales, and often unknown, levels of accuracy and precision (Loague and Green, 1990). Moreover, there are potential benefits to be realized in costs for database acquisition and development when the number of variables is restricted.

Composite mapping issues such as those noted above are compounded when weighting schemes are used. The inter-

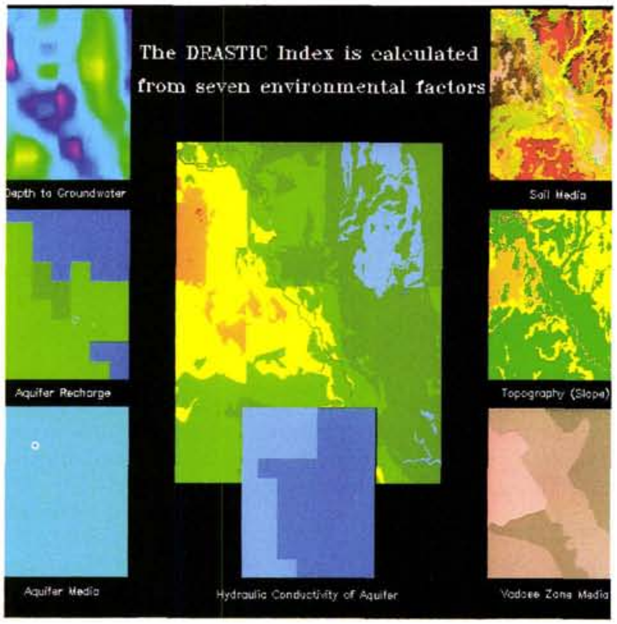

Plate 1. Map of the DRASTIC index for the Halstead 7.5-minute USGS quadrangle, Harvey County, Kansas. Colors indicate values of the index (high to low = red, orange, yellow, light green, dark green, violet). Areas having the highest scores are considered especially vulnerable to groundwater contamination. The seven variables used to compute the index are shown as smaller maps. Notice the great variation in spatial resolution and class number.

factor weighting and intrafactor rating assignments employed in the DRASTIC model were developed through consultation with a broad range of hydrogeologists and other experts (Aller *et al.*, 1985), and probably represent reasonable hypotheses regarding the relative importance of the factors. Nonetheless, it should be recognized that research has demonstrated that even small changes in weightings can result in large differences in the outcome of modeling, and that there are important, though ill-defined, relationships between weighting factors, the spatial distribution of input maps, and model results (Heinen and Lyon, 1989).

Lodwick *et al.* (1990) suggest a means to deal with some of these issues through sensitivity analysis. They specifically discuss error propagation issues in GIS-based groundwater contamination vulnerability modeling. Though DRASTIC is not mentioned in their study, the model they use is virtually identical. In a study of the Denver metropolitan area, the outcome of their modeling effort was a map that portrayed (1) vulnerable areas biased by heavily weighted layers, (2) non-vulnerable areas biased by low weighted layers, and (3) variations in indices that are area and/or population biased. In addition, the methods can be used to identify which layers require more detailed information and precision. Additional research is, however, clearly warranted (Lodwick *et al.*, 1990).

Model Validation

When one considers how widely DRASTIC has been used, it is rather surprising to observe that few attempts have been made to determine how well the model and its kin perform, or to guide users in proper interpretation of the model results. It is common for researchers to emphasize that groundwater vulnerability maps developed through use of DRASTIC and its derivatives are meant to be used as educational or planning tools and should not be employed in site-specific applications (Lusch *et al.*, 1992; Wisconsin Geological and Natural History Survey, 1987; Minnesota Pollution Control Agency, 1989). Nonetheless, there are concerns that such cautions are not being heeded, and that many users neither understand the meaning of the DRASTIC index nor properly interpret the index in the context of a specific hydrogeologic setting (Trent, 1993). Moreover, some suggest that use of GIS may lend unusual, but perhaps unwarranted, credibility to the outcome of spatial modeling (Bailey, 1988).

There are, of course, inherent difficulties in validating a model targeted towards assessment of "hazard" rather than identification of actual groundwater pollution occurrence. The usual evidence for performance has been "visual validation;" that is, a judgement by experts that the maps resulting from groundwater vulnerability modeling look reasonable (Riggle, 1988; Kalinski *et al.*, 1994). This type of assessment should not be discounted. However, additional, more quantitative research needs to be undertaken.

An important new study by Kalinski *et al.* (1994) suggests that, in fact, the DRASTIC model appears to perform well in Nebraska. Using the statewide DRASTIC map prepared by Rundquist *et al.* (1991), they found a positive correlation between groundwater vulnerability as indicated by DRASTIC and the frequency of occurrence of volatile organic chemical (VOC) contamination in groundwater-supplied community water systems. Their results suggest that the link between DRASTIC scores and incidents of VOC contamination is the probable correlation between these scores and vadose zone time-of-travel (Kalinski *et al.*, 1994).

This study has two important implications. First, it seems to indicate that DRASTIC is relatively robust in the sense that, despite likely errors in data and compromises (such as using STATSGO and 3-arc-second DEM data) discussed above, the model still performed well. Second, there is a suggestion in the study results that a hypothesis posed above is supported. Specifically, the postulated relationship between DRASTIC scores and vadose zone time-of-travel appears to lend weight to the observation that just a few of the seven factors (e.g., characteristics of the soils media and depth-to-water) seem to exert an extraordinary influence on index computation in current implementations of DRASTIC (see, also, Evans and Myers (1990)). This may stem from the weightings assigned the factors, quality of the data, or other reasons. The matter, however, deserves further evaluation.

Augmentation and Enhancement of the DRASTIC Model

In spite of legitimate concerns about model formulation and performance, it is evident that DRASTIC and its derivatives have been used to substantial benefit, especially when implemented employing a GIS. It must be recognized that most groundwater models have not been developed specifically for use in GIS. Some investigators have, however, begun to demonstrate that models such as DRASTIC can be made more effective when expanded or augmented by other data or analytic capabilities often available in GIS software.

Point Sources and Wellhead Protection

There is considerable evidence that major groundwater contamination events are often strongly associated with local-

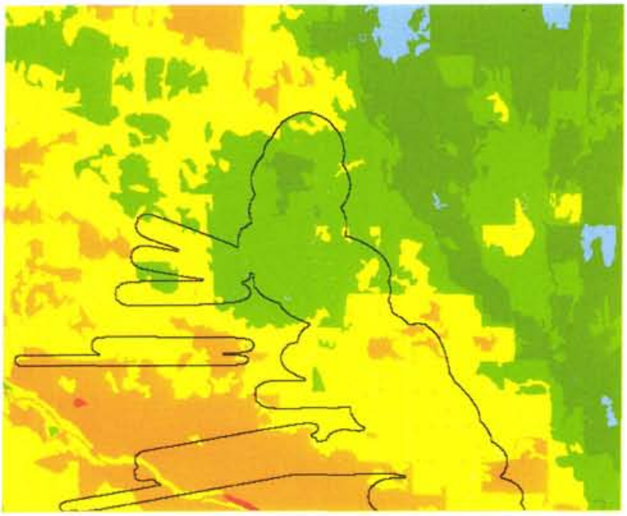

Plate 2. Capture zones plotted on DRASTIC Index. The area shown, in Harvey County, Kansas, consists of six 7.5-minute USGS quadrangles including the well field serving the city of Wichita, Kansas. Individual wells are indicated by light blue crosses. The capture area boundaries (black ellipses) represent the area from which a well would be expected to draw water assuming a 25-year pumping period at an average pumping rate of 1000 gallons/minute. Capture areas overlap and coalesce when wells are closely spaced. The color scheme for the DRASTIC index is described in Plate 1. Areas within the capture zones that have high DRASTIC scores merit special protection.

ized pollution sources (Great Plains Agricultural Council, 1992; Moody, 1990). Not surprisingly, a number of authors have found that the utility of groundwater vulnerability maps can be enhanced by overlaying locations of likely contamination sources (e.g., feedlots, oil field brine pits, underground storage tanks, septic systems, injection wells) and/or water supply wells from which aquifer withdrawals are made (e.g., Merchant *et al.*, 1987; Evans and Myers, 1990; Baker and Panciera, 1990; Evans and Myers, 1990; Hamerlinck *et al.*, 1993). Sometimes buffering is used to define zones around water supply wells that merit special protection. The difficulty and expense involved in cleaning up groundwater contamination has, in fact, provoked substantial interest in wellhead protection programs designed to ensure that municipal well fields and rural water supplies are kept pollution-free.

Wells typically draw water from a "capture zone," conceived, in two dimensions, as an ellipse. McElwee (1991) developed a "time-related capture zone" model used in conjunction with the DRASTIC model in the Harvey County study summarized above (Merchant *et al.*, 1987; Martinko *et al.*, 1987). Previous methods for wellhead zoning have often involved definition of circular capture zones based on a radius defined without consideration of the specific hydrogeologic characteristics of the aquifer. A "time-related capture zone" is defined as the aquifer volume from which groundwater flows to reach a pumping well within a given time, although it is usually delineated on a map as a capture area represented by an ellipse. The capture zone changes from a circle around a well in an aquifer with no regional flow to an elliptical shape with increasing eccentricity the greater the regional flow rate. The well is located near the down-gradient focus of an elliptical approximation of the capture area (Plate 2).

The approach used to determine a capture area involved averaging the hydrogeologic parameters involved in the capture computation over the area of interest, i.e., generalizing the aquifer to a homogeneous, uniform-flow system. An interactive program was developed to allow computation of individual capture zones. The program requires information on (1) the latitude and longitude of the northwest corner of the map area, (2) the average values of the aquifer parameters for the map (hydraulic conductivity, saturated thickness, porosity, flow direction, and hydraulic gradient), (3) the capture zone time, (4) the number and coordinates of the pumping wells, and (5) the average pumping rates of the wells. Some of the required information can be drawn from databases in the GIS. Aquifer parameters for the desired study area can be computed using an averaging routine. As an example, capture-area boundaries generated for the 52 public water supply wells serving the city of Wichita, Kansas were computed. The results were superimposed on a DRASTIC map (Plates 2 and 3). Areas within the capture zones, especially those having high DRASTIC scores, are areas that may demand special observation and protection.

Land Use and Land Management

Land use is clearly related to groundwater pollution hazard and needs to be accounted for in modeling risk of contamination (Harper *et al.*, 1992; Helgesen *et al.*, 1992; Moody, 1990; Hallberg, 1986). Spalding and Exner (1993), for example, document the association of nitrate contamination with irrigated cropland, especially when such cropland is situated on well-drained soils having permeable vadose

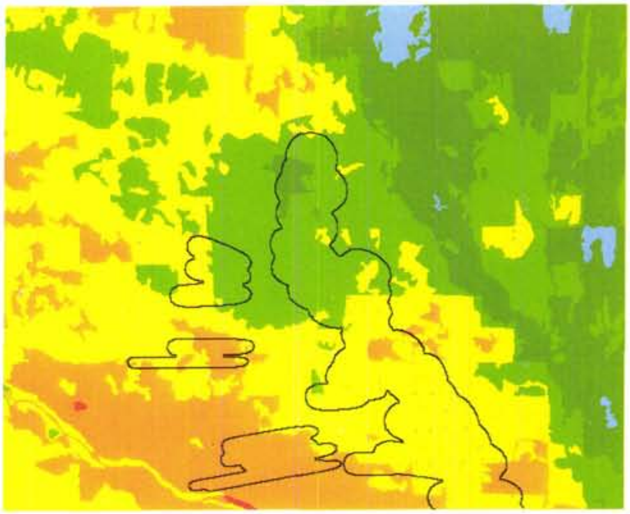

Plate 3. This map is identical to Plate 2 except that the assumed pumping period has been extended to 50 years at an average withdrawal of 1000 gallons/minute. Water flow in the aquifer is generally west to east, so capture zones extend further to the west.

zones (Moody, 1990; Chen and Druliner, 1987). Moody (1990) notes that heavy applications of nitrogen-based fertilizers on corn, wheat, and sorghum in the Midwest deserve special attention. Information on the types of crops grown in a given area may also allow estimation of the kinds and approximate quantities of pesticides used (Perry *et al.*, 1988).

Land management can also influence groundwater quality in important ways (Heinzel *et al.*, 1990). For example, about 25 to 30 percent of the cropped areas in the Great Plains now use some type of conservation tillage ("low till") (Great Plains Agricultural Council, 1992). On such areas it is common to observe greater use of herbicides to compensate for less tillage to control weeds. In addition, these areas tend to have lower surface runoff, providing greater opportunity for farm chemicals to leach into and infiltrate the soil, thus potentially contaminating groundwater (Great Plains Agricultural Council, 1992; Hallberg, 1986).

Terracing, another practice commonly used to reduce surface runoff and soil erosion, may also have detrimental impacts on groundwater quality. One of the seven factors used in the DRASTIC model is slope. Steep slopes are given low ratings in computing DRASTIC scores based on the assumption that surface contaminants deposited on sites having steep slopes will tend to runoff rather than sit long enough to infiltrate (Aller *et al.*, 1985). Yet, large areas of the U.S. are now terraced. In Nebraska, for example, terraces are installed on more than 50 percent of the cropped land in many counties. Terracing, of course, dramatically alters slope, converting a formerly steep slope to a nearly flat area.

In DRASTIC computation, slopes are generally determined from topographic maps (1:24,000 or 1:250,000 scale) or small-scale DEMs. However, these data sources rarely depict terracing. It is arguable that the slope factor used in most DRASTIC efforts to date has, at least in heavily cropped areas, been substantially underrated. Ratings ought to be adjusted upwards to account for terracing.

Issues such as these can be dealt with in several ways. Aerial photography or satellite imagery can, of course, be used to prepare digital map layers portraying certain aspects of land-use, land-cover, and land-management practices. In the Harvey County, Kansas project outlined above, aerial photography was used to improve the positional accuracy of potential pollution sources. Tabular (paper) records on feedlots, industrial waste sites, hazardous waste sites, and landfills were available from the Kansas Department of Health and Environment (Table 4); however, locations were only approximated using Public Land Survey System descriptors. In building the GIS, all such sites were located more precisely on aerial photography and encoded using geographic coordinates (Martinko *et al.*, 1987).

A few investigators have begun to explore modifications of GIS-based groundwater vulnerability models that incorporate land-use information in the modeling process. Erikson (1993) used Landsat Thematic Mapper data to map crop types in eastern Nebraska. Subsequently, the crops were rated to reflect average amounts of nitrogen fertilizer likely applied to each crop. The database was then assigned a weight and incorporated in the DRASTIC model to prepare a map that projected groundwater pollution potential with respect to nitrogen fertilizer applications. The modified DRASTIC map, evaluated by the Nebraska Department of Environmental Quality, was found to be a significant improvement over the original DRASTIC. Evans and Myers (1990), working in Delaware, developed a modified DRASTIC model that incorporated both septic system density and land use and land cover. These factors were assigned ratings and weightings in order to compute the final groundwater contamination hazard index.

In a national study of the economic and social costs of groundwater contamination, Nielsen and Lee (1987) related county-level estimates of the DRASTIC index to population distribution in order to determine human health risks, and also explored relationships between DRASTIC scores and probable farm chemical applications (e.g., pesticides, nitrogen-based fertilizers). Mullen (1991) found that he could improve county-level DRASTIC indices for Nebraska by adjusting the raw DRASTIC score using intensity of Atrazine use and occurrence of leachable soils.

Harper *et al.* (1992) developed a GIS-based empirical methodology to identify the predominant land use contributing specific pollutants in an area. It would be worthwhile to try to link this approach to both the DRASTIC model and the capture-zone model presented above.

Other Enhancements

The DRASTIC approach is only one of many possible approaches to modeling groundwater vulnerability (Committee on Techniques for Assessing Groundwater Vulnerability, 1993). Other modeling strategies, used alone or in combination with DRASTIC, may improve vulnerability assessment, or may suggest ways in which DRASTIC can be improved. GIS technology facilitates testing of new modeling alternatives.

Khan and Liang (1989), for example, developed a GIS-based pesticide-specific model for determining groundwater contamination potential in Hawaii. Their approach involved use of soils and climatic data along with pesticide chemical properties and a computed "attenuation factor," an index of the relative likelihood of groundwater contamination by a specific chemical. Meeks and Dean (1990) proposed to assess groundwater vulnerability using a Leaching Potential Index (LPI) designed to overcome perceived shortcomings of the DRASTIC model, including the subjectivity of ratings and weightings. Their approach attempts to directly model physical processes, especially those that involve interaction between the chemical of concern and the physical environment. Factors considered include soils characteristics, crop types, evapotranspiration, precipitation, and hydrogeologic data. Pickus and Hewitt (1992) have adapted the LPI for use in a GIS environment.

Kellogg *et al.* (1992) developed a Ground Water Vulnerability Index for Pesticides (GWVIP) based on soil leaching potential, pesticide leaching potential, precipitation, and chemical use. The model was implemented in a GIS and used to develop a national assessment of contamination potential. Unlike national studies that have used county-level DRASTIC estimates, the GWVIP draws on but a few existing national databases, especially the USDA/SCS National Resource Inventory consisting of over 360,000 sampling units.

In implementing the DRASTIC model, expert knowledge held by hydrogeologists is typically required to provide ratings for the variables. Decision-making is especially difficult when data quality or availability issues such as those discussed above emerge. Rundquist *et al.* (1989) developed an expert system to facilitate implementation and execution of DRASTIC in Nebraska. The system includes expert knowledge encoded as production rules.

Yet another expert-based methodology has been employed to map groundwater vulnerability regions of Iowa

(Hoyer and Hallberg, 1991; Hoyer, 1991). The procedure is essentially founded on estimation of the travel time of water from the land surface to a well or aquifer. Factors considered included thickness of overlying materials which provide natural protection to groundwater, aquifer type, patterns of well location and construction, and known contamination sources. A GIS was used to aid in data analysis, but the researchers had little confidence in existing mathematical models such as DRASTIC. Consequently, they employed expert judgement and logical rules to develop a map portraying regions having similar combinations of physical characteristics that affect groundwater recharge (Hoyer, personal communication; Committee on Techniques for Assessing Ground Water Vulnerability, 1993). Though more difficult to replicate than a mathematical approach, this strategy has the virtue of being adaptable to specialized local knowledge and relationships difficult to quantify.

It cannot be said with certainty that modeling strategies such as these improve upon DRASTIC. Clearly they suffer from some of the same uncertainties in regard to modeling assumptions, data availability and quality, and validation. On the other hand, they may be better suited for certain types of analyses, they may complement DRASTIC, or they may offer ideas regarding means to enhance DRASTIC.

Modeling in Four Dimensions

Groundwater modeling is especially complex because of its inherent "four dimensional" nature (Mason *et al.*, 1994). Optimally, water movement should be modeled in both the three spatial dimensions and through time. Only recently, however, have GIS and environmental modeling specialists begun to develop means to incorporate 3D and temporal components in spatial models (see Goodchild *et al.* (1993) for a good overview of the state-of-the-art). Only infrequently have such efforts been wed. Nonetheless, the prospects for improving modeling of groundwater processes through such work are promising.

Summary and Conclusions

The protection of groundwater quality is an important issue confronting much of the world's populace. Geographic information systems have been shown to be useful tools for assessing groundwater pollution hazard. This paper has reviewed efforts to use GIS in implementation of the DRASTIC model and its kin. Problems related to data quality, model formulation, and model validation have been identified, and suggestions for augmentation and enhancement of the DRASTIC model have been offered.

Many of the issues discussed above are, of course, not unique to GIS-based models or to DRASTIC. The Great Plains Agricultural Council (1992) reported that water quality models, in general, are currently limited by

- overextension of models or inappropriate applications;
- lack of a sufficient databases;
- insufficient number of scientists properly trained to apply and interpret the models and make management decisions;
- many processes that are poorly understood, improperly or not quantified;
- risk and uncertainty issues beyond the scope of some models;
- scale issues in that most models are developed for laboratory or plot conditions while large-scale (i.e., regional, national, global) problems are of greatest political concern;
- lack of communication between modelers and field researchers; and
- lack of graphics capabilities where models are used as educational and guidance tools.

Many of these ideas have emerged in earlier discussion specific to the DRASTIC model and are supported by findings of the Committee on Techniques for Assessing Ground Water Vulnerability (1993).

The problems and issues brought forth above should, in no way, be considered an indictment of GIS-based groundwater vulnerability assessment. Newcomer and Szajgin (1984) stress that modeling results may be valuable even when data quality and model formulation concerns have not been completely resolved, and this has certainly been true in regard to DRASTIC and its derivatives. Furthermore, there are initial indications (Kalinski *et al.*, 1994) that the DRASTIC model may perform relatively well in spite of problems noted above.

Yet, GIS specialists can contribute to improvement of groundwater vulnerability assessment modeling in a number of ways. First, we need to better document assumptions, compromises, and decisions made in adapting models such as DRASTIC for use in GIS. The lineage of each database used needs to be explicitly presented, and users of model results need to be forewarned about reservations we may have regarding interpretation and application of model results. Of course, we need also, over time, to incrementally improve the quality of data used in modeling, the formulation of models, and our understanding of error propagation.

It is specifically recommended that research be focused upon

- comparative studies to determine if results equivalent to DRASTIC can be obtained using (1) fewer variables and/or (2) a model formulation less prone to reflect possible interdependencies among factors;
- further exploration of the modification of DRASTIC by incorporation of other factors (e.g., land use, land cover, farm chemical applications, well density, irrigation type and intensity, and conservation practices such as terracing), or linkage with complementary models such as capture zone (McElwee, 1991) or risk assessment models (Suter *et al.*, 1987);
- investigation of scaling issues, including research on impacts of compromises in data types, rating, and weightings schemes on modeling outcomes;
- expansion of DRASTIC through utilization of advanced GIS-based tools being developed for three-dimensional, finite-element and solute transport modeling, and temporal modeling (Maidment, 1994; Mason *et al.*, 1994; Harlin and Lanfear, 1993; Harris *et al.*, 1993);
- cooperative work with water scientists (Burkart *et al.*, 1990) to ensure that models reflect our best current knowledge of processes, and that water modelers are using the full potential of GIS;
- use of expert systems to enable incorporation of specialized knowledge held by hydrogeologists through fuzzy logic and logical rules (especially in assignment of ratings/weightings, expression of interfactor relationships, and proper interpretation of the DRASTIC index in the context of a specific hydrogeologic setting);
- investigation of means to use GIS in validation and verification of model performance; and
- means (e.g., multimedia) to assist policy-makers and other decision-makers in understanding and effectively using DRASTIC model results.

Acknowledgments

Financial support for this research was provided by grants from the Kansas Department of Health and Environment, the Nebraska Department of Environmental Quality, and the U.S.

Environmental Protection Agency. The assistance of Jerry Whistler (Kansas Applied Remote Sensing Program, University of Kansas), and Craig Erikson and Fiona Renton (Center for Advanced Land Management Information Technologies, University of Nebraska-Lincoln) in production of graphics, is gratefully acknowledged.

References

Aller, L., T. Bennett, J.H. Lehr, and R.J. Petty, 1985. *DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings*, EPA/600/2-85/018, R.S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, Oklahoma.

Atkinson, S.F., and J.R. Thomlinson, 1994. An Examination of Ground Water Pollution Potential through GIS Modeling, *1994 Technical Papers of the ASPRS/ACSM Annual Meeting*, American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, pp. 71-80.

Bailey, R.G., 1988. Problems with Using Overlay Mapping for Planning and Their Implications for Geographic Information Systems, *Environmental Management*, 12(1):11-17.

Baker, C.H., and C.V. Hansen, 1986. Kansas Ground-Water Quality, *National Water Summary 1986*, USGS Water Supply Paper 2325, U.S. Geological Survey, Washington, D.C., pp. 259-264.

Baker, C.P., and E.C. Panciera, 1990. A Geographic Information System for Groundwater Protection Planning, *Journal of Soil and Water Conservation*, March-April, pp. 246-248.

Bevans, H.E., 1988. *Water Supply and Demand in Sedgwick County, Kansas*, U.S. Geological Survey Open File Report 88-711, U.S. Geological Survey, Washington, D.C.

Bliss, N.B., and W.U. Reybold, 1989. Small-Scale Digital Soil Maps for Interpreting Natural Resources, *Journal of Soil and Water Conservation*, January-February, pp. 30-34.

Bouwer, H., 1990. Agricultural Chemicals and Groundwater Quality, *Journal of Soil and Water Conservation*, March-April, pp. 184-189.

Burkhart, M.R., C.A. Onstad, and G.B. Bubenzer, 1990. Research on Agrichemicals in Water Resources, *Eos*, 71(29):980-981, 988.

Chen, H.H., and A.D. Druliner, 1987. *Nonpoint-Source Agricultural Chemicals in Ground Water in Nebraska - Preliminary Results for Six Areas of the High Plains Aquifer*, USGS Water-Resources Investigations Report 86-4338, USGS Water Resources Division, Lincoln, Nebraska.

Christy, A.D., 1992. Managing Agricultural Chemical Use to Protect Groundwater, *Geo Info Systems*, 2(7):36-39.

Committee on Techniques for Assessing Ground Water Vulnerability, Water Science and Technology Board, Commission on Geosciences, Environment and Resources, National Research Council, 1993. *Groundwater Vulnerability Assessment: Contamination Potential Under Conditions of Uncertainty*, National Academy Press, Washington, D.C.

Conservation Foundation, 1987. *Groundwater Protection - Groundwater: Saving the Unseen Resource, and A Guide to Groundwater Pollution: Problems, Causes, and Government Responses*, The Conservation Foundation, Washington, D.C.

Duda, A.M., and R.J. Johnson, 1987. Targeting to Protect Groundwater Quality, *Journal of Soil and Water Conservation*, September-October, pp. 325-330.

Erikson, C.S., 1993. *Enhancing the DRASTIC Model Using Satellite-Derived Land Cover Data to Reflect Agricultural Practices*, M.A. Thesis, Department of Geography, University of Nebraska-Lincoln, Lincoln, Nebraska.

Estes, J.E., K.C. McGwire, and G.A. Fletcher, 1987. Coordinating Hazardous Waste Management Activities Using Geographical Information Systems, *International Journal of Geographical Information Systems*, 1(4):359-377.

Evans, B.M., and W.L. Myers, 1990. A GIS-Based Approach to Evaluating Regional Groundwater Pollution Potential with DRASTIC, *Journal of Soil and Water Conservation*, March-April, pp. 242-245.

Goodchild, M.F., B.O. Parks, and L.T. Steyaert (editors), 1993. *Environmental Modeling and GIS*, Oxford University Press, New York N.Y.

Great Plains Agricultural Council, 1992. *Agriculture and Water Quality in the Great Plains: Status and Recommendations*, Water Quality Task Force Publication No. 140, Texas Agricultural Experiment Station, College Station, Texas.

Griner, A.J., 1989. The Automation of DRASTIC - A Regional Model for Mapping Susceptibility of Groundwater Contamination, *Proceedings of the GIS/LIS '89 Symposium*, American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, pp. 679-684.

Hallberg, G.R., 1986. From Hoes to Herbicides: Agriculture and Groundwater Quality, *Journal of Soil and Water Conservation*, November-December, pp. 357-364.

Hamerlinck, J.D., D.R. Wrazien, and S. Needham, 1993. Underground Injection Well Database Development for Groundwater Vulnerability Assessment Applications, *GIS/LIS Proceedings*, American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, 1:270-281.

Harlin, J.M., and K.J. Lanfear (editors), 1993. *Proceedings of the Symposium on Geographic Information Systems and Water Resources*, American Water Resources Association, Bethesda, Maryland.

Harper, C.R., W.J. Goetz, and C.E. Willis, 1992. Groundwater Protection in Mixed Land-Use Aquifers, *Environmental Management*, 16(6):777-783.

Harris, J., S. Gupta, G. Woodside, and N. Ziemba, 1993. Integrated Use of a GIS and a Three-Dimensional, Finite-Element Model: San Gabriel Basin Groundwater Flow Analysis, *Environmental Modeling with GIS* (M. Goodchild, B. Parks, and L. Steyaert, editors), Oxford University Press, New York; pp. 168-172.

Heinen, J.T., and J.G. Lyon, 1989. The Effects of Changing Weighting Factors on Wildlife Habitat Index Values: A Sensitivity Analysis, *Photogrammetric Engineering & Remote Sensing*, 55(10): 1445-1447.

Heinzel, W.M., P.G. Thum, S.J. Ventura, B.J. Niemann, Jr., P.J. Nowak, R.B. McCallister, and K. Shelley, 1990. Understanding Relationships Between Farm Management Practices and Groundwater Contamination Using a Geographic Information System, *GIS/LIS '90 Proceedings*, American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, 2:919-927.

Helgesen, J.O., L.E. Stullken, and A.T. Rutledge, 1992. *Assessment of Nonpoint-Source Contamination of the High Plains Aquifer in South-Central Kansas, 1987*, U.S. Geological Survey Open-File Report 91-238, USGS Water Resources Division, Lawrence, Kansas.

Hickey, D.D., and J.R. Wright, 1990. Evaluating Groundwater Pollution Potential Using Geographical Information Systems, *Irrigation and Drainage*, 1990 National Conference, pp. 323-329.

Hopkins, L.D., 1977. Methods for Generating Land Suitability Maps: A Comparative Evaluation, *AIP Journal*, October, pp. 386-400.

Hoyer, B.E., 1991. Groundwater Vulnerability Map of Iowa, *Iowa Geology*, 16:13-15.

Hoyer, B.E., and G.R. Hallberg, 1991. *Groundwater Vulnerability Regions of Iowa*, Special Map Series 11, Iowa Department of Natural Resources, Energy and Geological Resources Division, Iowa City, Iowa.

Kalinski, R.J., W.E. Kelly, I. Bogardi, R.L. Ehrman, and P.D. Yamamoto, 1994. Correlation Between DRASTIC Vulnerabilities and Incidents of VOC Contamination of Municipal Wells in Nebraska, *Ground Water*, 32(1):31-34.

Kellogg, R.L., M.S. Maizel, and D.W. Goss, 1992. *Agricultural Chemical Use and Ground Water Quality: Where Are The Poten-*

tial Problems?, USDA/Soil Conservation Service, Washington, D.C.

Khan, M.A., and T. Liang, 1989. Mapping Pesticide Contamination Potential, *Environmental Management*, 13(2):233-242.

Kilborn, K., H.S. Rifai, and P.B. Bedient, 1992. Connecting Groundwater Models and GIS, *GeoInfo Systems*, February, pp. 9-30.

Lemme, G., C.G. Carlson, R. Dean, and B. Khakural, 1990. Contamination Vulnerability Indexes: A Water Quality Planning Tool, *Journal of Soil and Water Conservation*, March-April, pp. 349-351.

Loague, K., and R.E. Green, 1990. Comments on 'Mapping Pesticide Contamination Potential' by M. Akram Khan and Tung Liang, *Environmental Management*, 14(2):149-150.

Lodwick, W.A., W. Monson, and L. Svoboda, 1990. Attribute Error and Sensitivity Analysis of Map Operations in Geographical Information Systems: Suitability Analysis, *International Journal Geographical Information Systems*, 4(4):413-428.

Lusch, D.P., C.P. Rader, L.R. Barrett, and N.K. Rader, 1992. *Aquifer Vulnerability to Surface Contamination in Michigan, Map and Descriptive Information*, Center for Remote Sensing, Michigan State University, East Lansing, Michigan.

Maidment, D.R., 1993. GIS and Hydrologic Modeling, *Environmental Modeling with GIS* (M. Goodchild, B. Parks, and L. Steyaert, editors), Oxford University Press, New York, pp. 147-167.

Martinko, E.E., J.W. Merchant, D.O. Whittemore, and J.L. Whistler, 1987. *Development of a Prototype Geographic Information System for Groundwater Quality Protection in Kansas*, Kansas Applied Remote Sensing Program, University of Kansas, Lawrence.

Mason, D.C., M.A. O'Conaill, and S.B.M. Bell, 1994. Handling Four-Dimensional Data in Environmental GIS, *International Journal of Geographical Information Systems*, 8(2):191-215.

McElwee, C.D., 1991. Capture Zones for Simple Aquifers, *Ground Water*, 29(4):587-590.

Meeks, Y.J., and J.D. Dean, 1990. Evaluating Ground-Water Vulnerability to Pesticides, *Journal of Water Resources Planning and Management*, 116(5):693-707.

Merchant, J.W., D.O. Whittemore, J.L. Whistler, C.D. McElwee, and J.J. Woods, 1987. Groundwater Pollution Hazard Assessment: A GIS Approach, *Proceedings of the International Geographic Information Systems (IGIS) Symposium*, Association of American Geographers, Washington, D.C., 3:103-115.

Minnesota Pollution Control Agency, 1989. *Ground Water Contamination Susceptibility in Minnesota, map and descriptive information*, Minnesota Pollution Control Agency, St. Paul, Minnesota.

Minnesota Department of Natural Resources, Division of Waters, 1991. *Criteria and Guidelines for Assessing Geologic Sensitivity of Ground Water Resources in Minnesota*, Minnesota Department of Natural Resources, St. Paul, Minnesota.

Moody, D.W., 1990. Groundwater Contamination in the United States, *Journal of Soil and Water Conservation*, March-April, pp. 170-179.

Morandi, L., 1989. *State Groundwater Protection Policies: A Legislator's Guide*, National Conference of State Legislatures, Denver, Colorado.

Mullen, M.P., 1991. A G.I.S. Technology for Ground Water Assessments, *Proceedings of the ASPRS*, American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, 2:243-252.

National Water Well Association, 1985. *Map of Groundwater Pollution Potential of Finney County, KS Generated by the DRASTIC System*, National Water Well Association, Worthington, Ohio.

Newcomer, J.A., and J. Szajgin, 1984. Accumulated Thematic Map Errors in Digital Overlay Analysis, *American Cartographer*, 11: 58-62.

Nielsen, E.G., and L.K. Lee, 1987. *The Magnitude and Costs of Groundwater Contamination from Agricultural Chemicals: A National Perspective*, U.S. Department of Agriculture, Agricultural Economic Report 576, USDA/Economic Research Service, Washington, D.C.

O'Neil, W.B., and R.S. Raucher, 1990. The Costs of Groundwater Contamination, *Journal of Soil and Water Conservation*, March-April, pp. 180-183.

Perry, C.A., F.V. Robbins, and P.L. Barnes, 1988. *Factors Affecting Leaching in Agricultural Areas and An Assessment of Agricultural Chemicals in the Ground Water of Kansas*, USGS Water Resources Investigations Report 88-4104, USGS Water Resources Division, Lawrence, Kansas.

Pickus, J., and M.J. Hewitt, III, 1992. Resource at Risk: Analyzing Sensitivity of Groundwater to Pesticides, *Geo Info Systems*, November-December, pp. 50-55.

Regan, J.J., 1990. "DRASTIC: Ground Water Pollution Potential Mapping in Arizona Counties Using a PC-Based GIS, *Proceedings of the Third Forest Service Remote Sensing Applications Conference*, American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland, pp. 232-240.

Riggle, M., 1988. The Wisconsin Groundwater Contamination Susceptibility Project, *Proceedings of the Urban and Regional Information Systems Association Annual Conference*, Washington, D.C.: Urban and Regional Information Systems Association, 1:139-151.

Riggle, M.A., and R.R. Schmidt, 1991. The Wisconsin Groundwater Contamination Susceptibility Map, *Journal of the Urban and Regional Information Systems Association*, 3(1):85-88.

Rundquist, D.C., R. Li, L. Di, and M. Liu, 1989. *Applying Concepts of GIS and Expert Systems to the DRASTIC Groundwater Vulnerability Model*, Conservation and Survey Division, University of Nebraska-Lincoln, Lincoln, Nebraska.

Rundquist, D.C., D.A. Rodekohr, A.J. Peters, R.L. Ehrman, L. Di, and G. Murray, 1991. Statewide Groundwater-Vulnerability Assessment in Nebraska Using the DRASTIC/GIS Model, *Geocarto International*, (2):51-58.

Schoolmaster, F.A., and P.G. Marr, 1992. Geographic Information Systems as a Tool in Water Use Data Management, *Water Resources Bulletin*, 28(2):331-336.

Spalding, R.F., and M.E. Exner, 1993. Occurrence of Nitrate in Groundwater—A Review, *Journal of Environmental Quality*, 22: 392-402.

Suter, G.W., II, L.W. Barnthouse, and R.V. O'Neill, 1987. Treatment of Risk in Environmental Impact Assessment, *Environmental Management*, 11(3):295-303.

Trent, V.P., 1993. DRASTIC Mapping to Determine the Vulnerability of Ground Water to Pollution, *Proceedings of the Symposium on Geographic Information Systems and Water Resources* (J. Harlin and K. Lanfear, editors), American Water Resources Association, Bethesda, Maryland, pp. 537-545.

U.S. General Accounting Office, 1991. *Groundwater Protection: Measurement of Relative Vulnerability to Pesticide Contamination*, GAO/PEMD-92-8, U.S. General Accounting Office, Washington, D.C.

Van Der Heijde, P.K.M., 1988. Spatial and Temporal Scales in Groundwater Modelling, *Scales and Global Change* (T. Rosswall, R. Woodmansee, and R. Risser, editors), John Wiley & Sons Ltd., New York, pp. 195-223.

Veregin, H., 1989. *A Taxonomy of Error in Spatial Databases*, NCGIA Technical Paper 89-12, National Center for Geographic Information and Analysis, University of California-Santa Barbara, Santa Barbara, California.

Wisconsin Geological and Natural History Survey, 1987. *Groundwater Contamination Susceptibility in Wisconsin, map and descriptive information*, Wisconsin Geological and Natural History Survey, Madison, Wisconsin.