UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Applying the DRASTIC model -- a review of county-scale maps

by

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Open-file Report 92-297

1992

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Introduction

The potential for contamination of ground water has become an issue of great concern to citizens and government alike, especially in the last decade. Numerous methods for assessing ground water vulnerability to contamination have been proposed and used. These methods include field-scale deterministic models that predict the rate of migration and fate of specific chemicals, and regional models that attempt to show general trends of ground-water vulnerability to contamination. To address regional ground-water vulnerability, a model may focus on characteristics of the soil, the geologic materials at and above the unconfined water table, or on the larger part of the geologic framework containing aquifers. A model's focus significantly affects the characteristics and, therefore, the utility of maps produced by the model. For example, a model focusing on the soil or vadose zone cannot adequately characterize the contamination potential of confined aquifers.

The most commonly-used method for regional assessment of ground-water vulnerability is called "DRASTIC," an acronym for the seven factors that comprise the model. The U.S. Environmental Protection Agency (EPA) funded the development of the DRASTIC model, and used it as an assessment tool in their National Pesticide Survey (USEPA, 1992). In that Survey and in other assessments of contamination potential from application of agricultural chemicals, the pesticide version of DRASTIC is used; it differs from the standard DRASTIC model only in the degree of weighting applied to the seven factors. The DRASTIC model was developed by a committee of technical advisors who used the consensus approach to specify the relative significance of each factor. DRASTIC was designed primarily as a regional tool for prioritization, or screening, to indicate those areas (of at least 100 acres in size) which are generally more sensitive to contamination and, therefore, in need of more detailed mapping and evaluation or monitoring. The committee also intended DRASTIC to support decisions on allocation of scarce monitoring or remediation resources, and to serve as an educational tool.

A detailed user's manual for the DRASTIC model (Aller and others, 1987) provides descriptions of common hydrogeologic settings across the United States and expected values for the seven factors; with this information and a specified "weight" or multiplier applied to each factor, DRASTIC scores can be calculated for each setting, and a map of these DRASTIC scores generated. The authors of this model intended it to be sufficiently objective and straightforward that it could be effectively used by persons with but a rudimentary knowledge of hydrogeologic principles. By adjusting the factor values for actual or interpreted local conditions a more knowledgeable person should be able to produce a somewhat more realistic and, therefore, reliable map of ground water vulnerability than by using the expected values for a given hydrogeologic setting.

Other models for evaluating regional ground-water vulnerability have been developed; of importance to this report are models developed by the Illinois State Geological Survey (ISGS), the Wisconsin Department of Natural Resources (WDNR), and a joint effort between the U.S. Geological Survey (USGS) and the ISGS. All of these models, as well as DRASTIC, can only estimate the *relative* potential for contamination, either with a numerical scheme or a hierarchy of contamination potential map units.

The model developed by WDNR (Schmidt, 1987) is based on a numerical scheme. It was used to generate a statewide contamination susceptibility map of Wisconsin (Schmidt and Kessler, 1987); Schmidt (1987) defines ground water contamination susceptibility as the "ease with which water (and, presumably, accompanying contaminants) at the surface can reach the water table." The model is not limited to aquifers, but rather considers all unconfined ground water whether in sandy surface aquifers or low-permeability glacial till. Ground water in confined aquifers is not addressed. Contamination susceptibility is estimated by a factor-weighting scheme similar in concept to DRASTIC. The factors (soil texture, surficial deposits, depth to the water table, bedrock type, and glacial drift thickness) are assigned an arbitrary value based on perceived importance. These numbers are then weighted and summed to produce the contamination susceptibility score. This model is compared and contrasted with other models elsewhere in this report.

In contrast, the ISGS method avoids the use of a numerical system to rate the relative potential for contamination, and instead orders the map units in a hierarchy from relatively low to relatively high contamination potential. Also in contrast to the two models described above, the ISGS model relies solely on the textural character of the geologic framework to a specified depth. For example, a statewide map (Berg and others, 1984, scale 1:500,000) addresses land burial of wastes, and shows the contamination potential of aquifers within geologic units in the upper 50 feet. Another ISGS map (Keefer and Berg, 1990) addresses the contamination of major, economically important aquifers, and therefore evaluates contamination potential to greater depths (to greater than 300 feet). In general, the ISGS contamination potential maps evaluate aquifers, and do not evaluate potential for contamination of ground water at the unconfined water table in geologic units that are not aquifers (for example, in glacial till or fine-grained lake sediments).

With the cooperation of the ISGS, I have developed a model (Soller and Berg, in press) for the regional assessment of aquifer contamination potential that is based on ISGS techniques, adapted to a broader map area where detailed information may be unavailable. This model was used to generate a map of aquifer contamination potential for an area encompassing parts of five states near southern Lake Michigan and Lake Erie; the model and map are currently being refined and evaluated.

Purpose of this report

The DRASTIC model has become perhaps the most commonly-used approach for Federal and State agencies to produce a regional overview of ground water vulnerability. In the mid to late 1980's, the Monsanto Agricultural Company conducted their National Alachlor Well Water Survey. It was designed to statistically estimate the proportion of private, rural drinking water wells in the United States in which the pesticide alachlor could be detected. For that Survey, 90 counties in hydrogeologically diverse areas were evaluated using the pesticide version of the DRASTIC model; these reports have been made publicly available by Monsanto, as guides for local planning (Research Triangle Institute, 1989). At the request of EPA, this report evaluates several reports published by the Monsanto Company for counties in the U.S. agricultural midcontinent (fig. 1).

Since its introduction, various research and regulatory entities have begun evaluating the DRASTIC model, mostly to assess its ability to predict where contamination is actually occurring. At this time, results are preliminary and few published conclusions are available on the subject. Based on oral communications with other researchers and preliminary published results, it is evident that DRASTIC cannot, by itself, adequately predict contamination. Curry (1987) found essentially no statistical correlation between DRASTIC scores at specific sites and water-quality data for a drainage basin in karstic terrain. Baker and others (1989) compared composite DRASTIC scores calculated for each county in Ohio with county average nitrate concentrations from private wells. At that broad scale, a weak positive correlation was measured ($r^2 = .3$). It is likely that future studies will more clearly define the predictive abilities of DRASTIC in different hydrogeologic settings and at different map scales. Then, DRASTIC's role in vulnerability assessments can be better defined, and new regional approaches to assessing vulnerability can be devised.

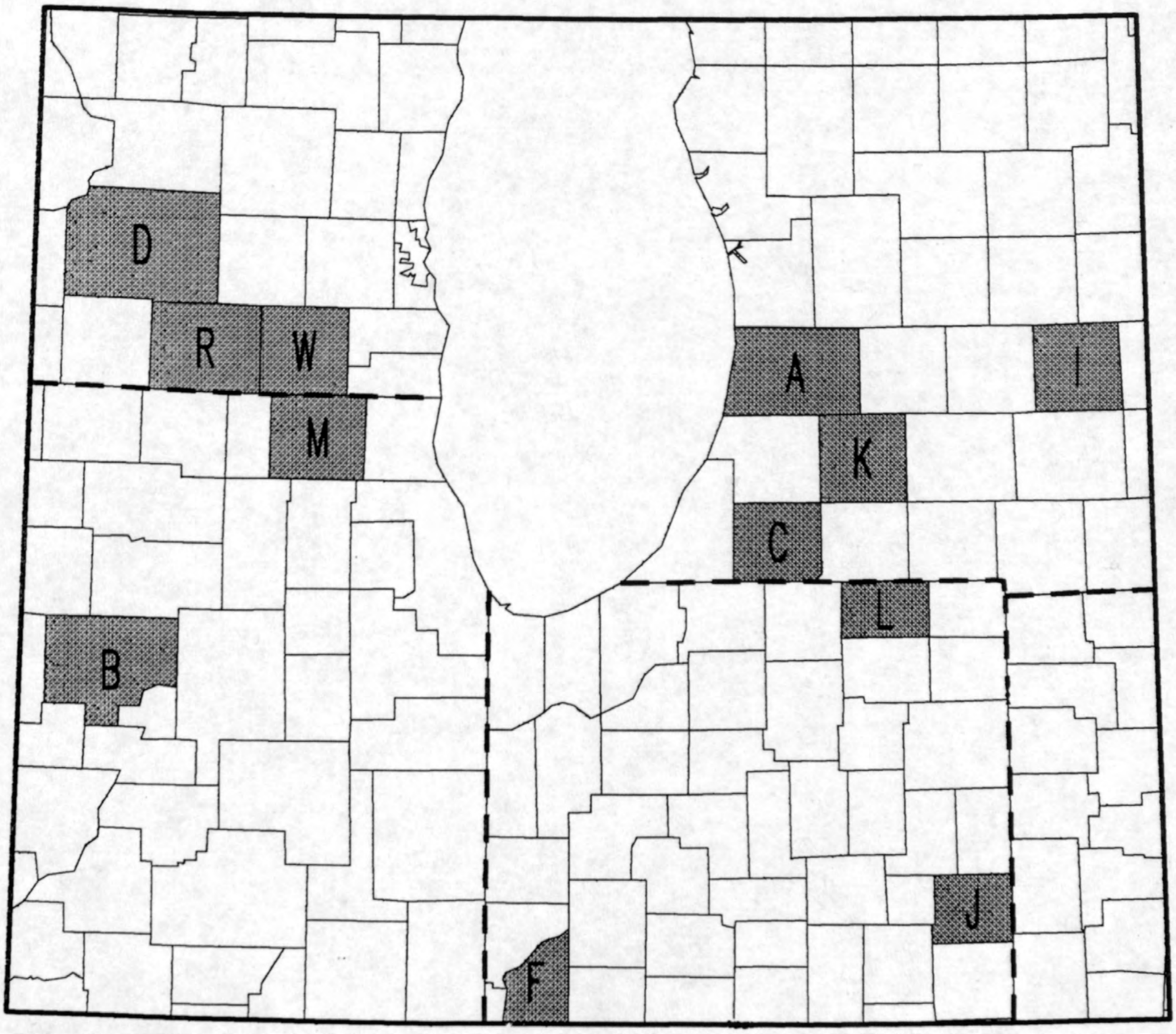


Figure 1. Map showing location of counties discussed in this report. The map area is centered on southern Lake Michigan, surrounded by (clockwise from upper right) Michigan, Ohio, Indiana, Illinois, and Wisconsin. In Michigan, "A" = Allegan County, "C" = Cass County, "I" = Ingham County, and "K" = Kalamazoo County. In Indiana, "F" = Fountain County, "J" = Jay County, and "L" = Lagrange County. In Illinois, "B" = Bureau County and "M" = McHenry County. In Wisconsin, "D" = Dane County, "R" = Rock County, and "W" = Walworth County.

This report focuses on an aspect of DRASTIC even more fundamental than its predictive abilities; that is, what problems arise when the model is applied to real settings with imperfect data sets? Given the well-documented "cookbook" approach of the DRASTIC model (in Aller and others, 1987), how difficult is it to implement, and how do results vary depending on available data and the level of expertise or judgement of the modeler? These issues have not been thoroughly addressed for the DRASTIC model, but as will be supported in this report, a number of problems may arise when the model is applied.

To address these issues, several Monsanto reports were evaluated and compared and contrasted with vulnerability maps made by other models discussed in the Introduction. Those Monsanto reports were for counties lying within the area covered by the aquifer contamination potential map generated by the USGS-ISGS model (see Introduction). This author is, therefore, reasonably familiar with the hydrogeologic setting and framework of the region, and with the quality and utility of the available literature on hydrogeologic data.

Acknowledgments

This work was mostly supported by the U.S. Environmental Protection Agency's Office of Pesticide Programs, with additional support provided by the USGS Toxic Substances Hydrology Program and National Geologic Mapping Program. Thanks to Elizabeth Behl (EPA) and Dennis McKenna and Richard Berg (both ISGS) for their constructive suggestions.

Evaluating the reports

Background

The DRASTIC model consists of seven factors that influence the movement of water from land surface to the water table or to a confined aquifer. Single-letter abbreviations for these factors form the acronym "DRASTIC." The factors and their abbreviations are:

- "D" - depth to water
- "R" - net recharge
- "A" - aquifer media
- "S" - soil media
- "T" - topography
- "I" - impact of the vadose zone media
- "C" - hydraulic conductivity of the aquifer

To apply DRASTIC to a study area, hydrogeologic settings in that area must first be defined and mapped. Commonly, each setting has hydrogeologic characteristics somewhat different from those of adjacent settings. A map of surficial materials and geologic framework is commonly used to delineate the hydrogeologic settings. For each setting, measurements or descriptive data for each DRASTIC factor are gathered. For each factor, a rating is determined on the basis of standard values (see Aller and others, 1987) or interpretation of the available data. These factor ratings are multiplied by weighting factors, and the products are added to obtain a composite DRASTIC index or score for the setting.

Computation of DRASTIC scores from the factor values presents certain restrictions for the user. The values, which represent physical measurements in some unit of measure or classification system, are classified into dimensionless numbers (the factor "rating"). This simplifies the DRASTIC computations, allowing both physical measurements and physical descriptions to be factored into a composite index. The user of a DRASTIC map must either accept the composite DRASTIC score at face value or, based on certain assumptions, estimate the raw data from the score.

To properly evaluate the DRASTIC scores in the Monsanto reports, it was essential to examine the source data and the interpretations and assumptions made by the report authors. This information was available, more or less, on the DRASTIC computation worksheets supplied with each DRASTIC report. On these worksheets, data and source references are cited for each DRASTIC factor and used as evidence to determine the best data value and rating for each factor. Although it may be considered impractical in some instances, I nevertheless suggest that before basing decisions on DRASTIC maps (or other maps of this type), users should acquire a sense of the map's accuracy by examining the source data and interpretations, as done in this report.

Each Monsanto county DRASTIC report follows a standard format that includes a DRASTIC map (single-page or fold-out) of scale roughly 1:250,000, a short summary of the map's hydrogeologic settings, cited and general references, general information on the DRASTIC factors, and the worksheets for each setting. Reports are commonly about 20 pages in length. Reports were done by a contractor to Monsanto, who allotted two to three days for the literature search and map and report preparation.

Evaluating the hydrogeologic settings

For each county report, one of my primary objectives was to evaluate the hydrogeologic settings shown on the DRASTIC map. The definition of each setting and its distribution on the map are vital to an effective vulnerability assessment. The source map(s) from which the hydrogeologic setting boundaries were defined was not cited in any of these reports, but in most cases the source map(s) could be identified. Such citations are essential to properly identify and credit the source of the map information. Citations also allow the user to evaluate whether the degree of complexity of map units is realistic for that map scale, or if the lack of detailed geologic map information has dictated a highly generalized DRASTIC map. In several cases, this lack of documentation severely limits evaluation of the DRASTIC maps.

In most cases, the DRASTIC maps show hydrogeologic setting boundaries that are clearly derived from geologic contacts on published maps, and this is entirely appropriate. However, an example illustrates that these boundaries may be drawn incorrectly if physical relationships among settings are not properly considered. For Jay County, Indiana, four settings appear on the DRASTIC map: "outwash", "glacial till over bedded sedimentary rocks", "moraine", and "buried valley." The buried valley unit is emphasized on that map, shown as a continuous feature that takes precedence over other units (for example, where the buried valley trends beneath a moraine, the moraine is bisected by the buried valley unit). Moraines are surficial features with sand and gravel aquifers that are relatively shallow compared to aquifers assumed to occur in the buried valleys. Primarily for this reason, the moraine setting has the relatively higher DRASTIC score. It seems, therefore, that the moraine should bisect the buried valley map unit. To extend this argument, perhaps the buried valley setting should not be shown anywhere in this county, because it represents a feature deeply buried beneath the aquifers evaluated in the settings it displaces, and has the lowest DRASTIC score on the map. In certain areas, however, buried valleys contain the most productive aquifers, whose protection is vital despite the low DRASTIC scores. On ground water vulnerability maps, buried valleys should be shown in some manner in order to illustrate the three-dimensional nature of vulnerable ground water. In this example, the DRASTIC map combines surficial and deeply buried deposits in a simple, two-dimensional representation. Perhaps these buried features could be better represented by an overlay pattern that would show their location beneath other settings.

In certain reports, a given hydrogeologic setting includes deposits with different ground water vulnerabilities. In general this occurs with all maps, because complex geologic materials must be classified and grouped in order to portray them at a usable map scale. However, in the McHenry County (Illinois) report, for example, areas of outwash covered by a thin layer of till are grouped in a hydrogeologic setting with deposits of thicker till because the stratigraphic distinction was not noted by the report authors.

Evaluating the worksheets and source data

After reviewing the DRASTIC map, I examined the worksheets to identify the source information offered as evidence to support selection of values for each factor. The evidence given on the worksheets, as well as the cited references, served as the basis for the majority of my comments. These worksheets emphasize some difficulties with implementing DRASTIC, including: the general lack of uniform data coverage of sufficient quality; the ambiguity of data and inherent subjectivity of interpretations; the use of standard factor values to supplement real data; and difficulties in treating confined and unconfined aquifers in a single hydrogeologic setting.

The most significant problem may be the lack of adequate data. Where the model is applied to sparse, ambiguous data, they must be supplemented by standard factor values. The process of selecting factor values can be highly subjective, and is especially noticeable when DRASTIC maps made by different people are compared. For example, for "C", the value 1-100 gpd/ft^2 is used for settings in McHenry County, Illinois, where "I" = glacial till and "A" = sand and gravel lenses in the till. For Bureau County, Illinois, "C" values of at least 700 gpd/ft^2 are used for settings with apparently the same geologic materials as in McHenry County. These are significant differences in hydraulic conductivities for presumably the same type of aquifer material in similar settings. There may be real differences in materials, but because values for "C" are generally standard values for specific materials, it is more likely that the different persons who calculated the DRASTIC scores did so with slightly different assumptions or criteria. Despite the model's essentially straightforward, "cookbook" approach, it is apparent that subjective, informed decisions are required to a certain extent.

Based on what can be deduced from regional geologic framework, the use of standard values in lieu of real data can result in significant errors for a setting. For example, certain reports delineate a buried valley hydrogeologic setting and cite a value for "D" of 30-50 ft, derived from standard references (for example, see the Bureau County, Illinois summary). However, in that part of the U.S. midcontinent, sand and gravel aquifers in the buried valleys commonly occur beneath more than 100 ft of glacial deposits dominated by till. If a value of >100 ft were used for "D", the DRASTIC score would be reduced by 20. For certain reports, cited references supply this information, yet it is not applied.

The DRASTIC manual (Aller and others, 1987) cites the common availability of data as a primary consideration in the selection of the seven factors. However, these reports and this author's experience indicate that information is not widely available for certain factors. Lack of real data is most common for factors "D", "R", and "C." Although these three factors have some relation to water movement and hence to the vulnerability of water to contamination, it does not seem worthwhile for a model to include a data category if data are not generally available. In extreme cases (Cass County, Wisconsin, for example) almost no real data were available for any factor, and the DRASTIC scores were derived from standard values and data extrapolated from other areas. Given the interrelationships and redundancy among factors (Aller and others, 1987, p. 62-65), it would seem preferable to reduce the model to as few commonly available, independent variables (factors) as possible. Additional factors may refine a vulnerability assessment where such data are commonly available and of high quality, but for most areas will not be useful.

DRASTIC permits evaluation of either the unconfined aquifer or a single confined aquifer. For a confined aquifer, "D" indicates depth to the top of the aquifer. For settings where wells tap aquifers in both the bedrock and the surficial deposits, several county reports compute a composite value for each factor based on the proportion of wells in each aquifer (for example, see summaries of Ingham (Michigan), Walworth (Wisconsin), and Jay (Indiana) counties). The source data for these composite scores is not readily determined in all cases.

More importantly, the logic behind these composite scores is flawed. Glacial and bedrock aquifers can have very different characteristics, and will occur at different depths in a given area. For example, a glacial sand and gravel aquifer may occur at depths of 30-50 ft below till, whereas bedrock aquifers will occur beneath the glacial deposits, at greater depth. The vulnerabilities of the two aquifers cannot be the same and, therefore, a composite score is not appropriate because it does not adequately characterize the vulnerability of the uppermost aquifer.

In the Jay County, Indiana, report, composite factor values are computed for a hydrogeologic setting that includes distinct areas of thin drift where water is drawn from bedrock and areas of thicker drift where glacial aquifers are used. The factor values were calculated by assuming that an equal proportion of wells tap the two aquifers. It would seem preferable to divide the setting in two on the basis of drift thickness: one setting for areas where bedrock is at shallow depth and is the predominant aquifer, and another setting for areas where drift is sufficiently thick that sand and gravel aquifers are the predominant source of water.

Comparison with other vulnerability models and maps

Contamination potential maps generated by the WDNR, ISGS, and USGS-ISGS models (see Introduction) were compared to the DRASTIC maps. Ideally, such a comparison might include a quantitative evaluation of each DRASTIC score and contamination potential map unit. However, to obtain an absolute ranking of the map units, in essence a numeric probability of contamination, would require correlation of the map units with actual contamination incidents. This has yet to be accomplished. Therefore, regional evaluation of contamination potential is based on a very general, qualitative comparison of the *relative* contamination potential on each map. This involves comparing the hierarchical position of a DRASTIC map unit to the correlative map unit in the contamination potential ranking scheme of another model.

Despite the problems with scoring the individual DRASTIC factors, as described in the county reports, comparison with maps made by the other models generally suggests that the relative hierarchy of DRASTIC map units seems reasonable. Apparently, the influence of an inappropriate factor value on the overall DRASTIC score is so small that it does not commonly effect a reordering of map units in the scoring hierarchy; the number of factors is large enough and the scoring system is sufficiently intricate that inconsistencies in factor data interpretation are minimized by the model. Although this could be viewed as a positive attribute, I feel it indicates an unwarranted level of intricacy and detail in the scoring technique and the model in general.

Although the information represented by the dimensionless, numeric DRASTIC score has little intrinsic value, the distribution of map units can be informative. The map distribution of relatively high- and low-vulnerability areas, for example, can provide significant input for ground-water management decisions. My comparison focused on similarity in map patterns and general correlation of areas of relatively high (and low) contamination potential among the maps. For each map, the accuracy and detail of contacts between map units were evaluated based on correlation with the best available source map information of appropriate scale.

The USGS-ISGS contamination potential map includes the counties for which DRASTIC maps were reviewed; it serves as a common basis for comparison, supplemented in certain counties by comparison with the WDNR and ISGS maps. The DRASTIC and USGS-ISGS maps are generally similar because they are based on the nature of the surficial geologic materials. In some cases, the DRASTIC maps were more detailed than the USGS-ISGS map, and in some cases they were more generalized despite their larger map scale (approximately

1:250,000 for the DRASTIC maps and 1:1,000,000 for the USGS-ISGS map). Areas of low and high DRASTIC scores generally correspond to areas of low and high contamination potential on the USGS-ISGS map; exceptions are caused by an inconsistent approach to mapping from county to county, especially for confined aquifers in buried valleys. In general, the most common shortcomings of the DRASTIC maps included a low level of map detail for the map scale, inaccurate mapping based on improper assumptions, and failure to address the significance of aquifers in buried valleys. These problems are discussed in the county summaries below.

To evaluate relative contamination potential among several counties, mapping techniques must be consistent; for example, this is important if the contamination potential of several counties must be ranked and compared, or if a single area of highest or lowest contamination potential must be identified among several counties. The USGS-ISGS map, which covers parts of five states, contains a large, consistent base of information for assessing relative contamination potential in different counties. In contrast, each county DRASTIC report and map is prepared as an isolated study, without a proper regional context for either the geologic framework or appropriate DRASTIC factor values. This regional context is essential for constructing DRASTIC maps, especially if several maps across a broad area are to be compared and evaluated to determine the area with the highest (or lowest) contamination potential. Compounding the problem of regional context is the preparation of reports by different authors, which naturally leads to different interpretations and differing content and styles of maps.

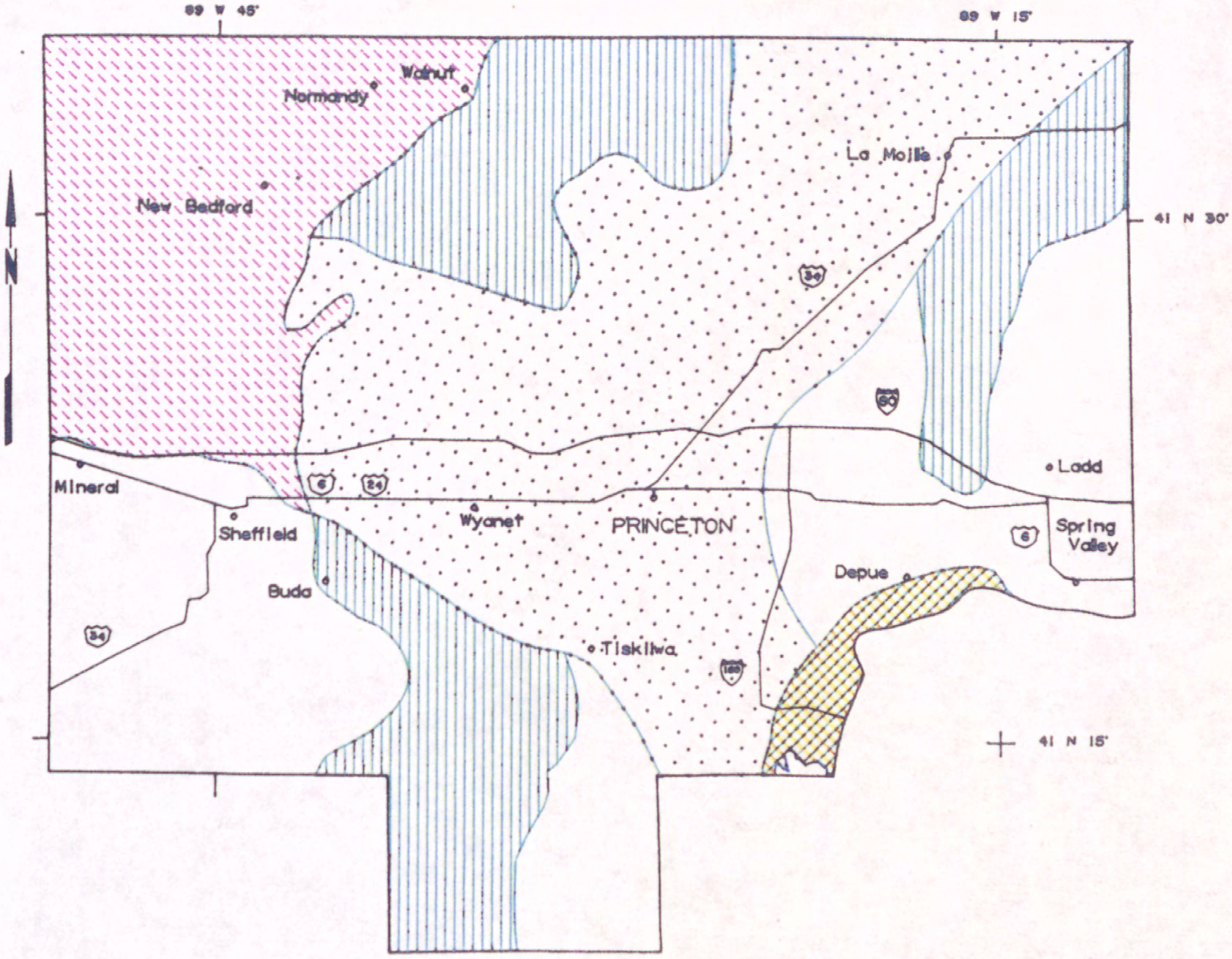
Procedurally, the DRASTIC and WDNR models have much in common, as discussed in the Introduction. However, little similarity was noted in map pattern, probably because of the manner in which map units are determined. In contrast to the DRASTIC model, the WDNR model intersects the map patterns for each of the five factors. This results in a complex pattern of hundreds of map units, each reflecting a unique combination of values for the five factors. Although map patterns are quite different, areas of low and high vulnerability generally correspond. More similarity exists between the USGS-ISGS and the WDNR maps, reflecting the higher number of factors in common (drift thickness and bedrock lithology are considered by both models but not by DRASTIC).

County report summaries

Bureau County, Illinois

Bureau County is predominantly till-covered, with extensive coarse-grained sediment (outwash) in the northwest quadrant. The county is traversed by a large buried valley system from north to south. In that valley, glacial sediment exceeds 400 ft in thickness. Sediment thins away from the valley, to less than 50 ft in the southeastern and southwestern corners of the county.

Five hydrogeologic settings are delineated on the DRASTIC map: 7Ba - outwash; 7I - swamp/marsh; 7C - moraine; 7D - buried valley; and 7Aa - glacial till over bedded sedimentary rocks (fig. 2). The DRASTIC map pattern is relatively simple, and might be generalized from a 1:500,000-scale statewide map of Quaternary deposits (Lineback, 1979) and a figure in Hackett and Bergstrom (1956, scale approx. 1:1,000,000) which delineates the buried valleys. However, the map's origins are not clear, as the moraines are not faithfully reproduced from Lineback's map. The number of communities located over the buried valley aquifer suggest its importance as a municipal water supply, yet its relatively deep position and low score indicate that it is not considered by DRASTIC to be a vulnerable aquifer. Nevertheless, the buried



Legend	Hydrogeologic Setting	Pesticide DRASTIC Score
	7Ba - Outwash	206
	7I - Swamp/Marsh	149
	7C - Moraine	134
	7D - Buried Valley	126
	7Aa - Glacial Till Over Bedded Sedimentary Rocks	108

Scale 1:393,023

Figure 2. DRASTIC map of Bureau County, Illinois. Reproduced with permission of Monsanto Company.

valley setting is shown instead of the moraine setting in places on the DRASTIC map, indicating its higher priority for ground water protection. This is a compromise necessitated by DRASTIC's emphasis on nearsurface factors: if the report authors had based the delineation of hydrogeologic setting boundaries solely on DRASTIC scores, the buried valley would not be shown in places.

DRASTIC scores range from 206 for setting 7Ba (outwash) to 108 for setting 7Aa (glacial till over bedded sedimentary rocks). For most factors, values were obtained from an unpublished personal communication or from regional or statewide maps and reports. Values for "D" are standard values from Aller and others (1987). Evidence in support of values for "A" and "I" is rather tenuous; source data are generally so incomplete or sparse that several different yet valid interpretations could be reached, resulting in different factor values and small differences in DRASTIC scores. This is a recurring issue with DRASTIC, because real data (not regional generalizations) for some of the factors (notably "D", "R", and "C") are commonly not available.

For setting 7D (buried valley), "D" is reported as 35-50 ft (should actually be 30-50 ft as listed in the reference cited for this value (Aller and others, 1987)). Because in this setting a confined aquifer is being evaluated, the value indicates the depth to the top of the buried valley aquifer. It seems unlikely that the buried aquifer lies within 50 ft of land surface, based on the commonly-known regional geologic framework. Hackett and Bergstrom (1956) note that in Lee and LaSalle counties, which border Bureau County, the sand and gravel aquifer in the buried valleys occurs below 100 ft, and down to about 300 ft in depth. Although this DRASTIC report seems to have used Hackett and Bergstrom's buried valley outline as the hydrogeologic setting boundary, the report assumes the presence of much shallower aquifers (at 30-50 ft). Based on my cursory examination, I find no evidence to support this. If a corrected "D" value of +100 ft were substituted, the recalculated DRASTIC score would be 106, or 20 less than the value in the report.

Comparison with other vulnerability maps - The areas with highest contamination potential roughly correspond on the DRASTIC map, the ISGS map, and the USGS-ISGS map. Less map detail is shown on the DRASTIC map than on the other maps, despite its more detailed map scale. The ISGS and USGS-ISGS maps show similar patterns, as might be expected given the similarity of the models and source data. However, the USGS-ISGS map evaluates contamination potential to greater depths, so buried valley deposits are shown; these deposits are not delineated as a separate map unit but merely constitute additional information that modifies the contamination potential ranking of the unit.

McHenry County, Illinois

McHenry County is mantled by glacial deposits ranging from 50 ft on the uplands to nearly 400 ft in thickness in the buried valleys. Till is somewhat more common at land surface than coarse-grained, stratified sediment (outwash).

Five hydrogeologic settings are delineated on the DRASTIC map: 7Ba - outwash; 7I - swamp/marsh; 7Aa - till over bedded sedimentary rock; 7Aa1 - till over bedded sedimentary rock; and 7C - moraine (fig. 3). The DRASTIC map pattern is relatively complex; hydrogeologic settings appear to be copied directly from the surficial geologic map of Hackett and McComas (1969), scale 1:130,000, with moraines from Hackett and McComas and from Nicholas and Krohelski (1984).

DRASTIC scores range from 182 for setting 7Ba (outwash) to 121 for setting 7C (moraine). For most factors, values were obtained from reports dealing specifically with McHenry County, rather than standard values or values extrapolated from other studies in a comparable setting. The factors that most contributed to variability in scores are "C" and "D." Values for "C" were mostly standard values for different types of aquifer media (factor "A"). Therefore, they essentially provide information on the same physical attribute as "A." There is

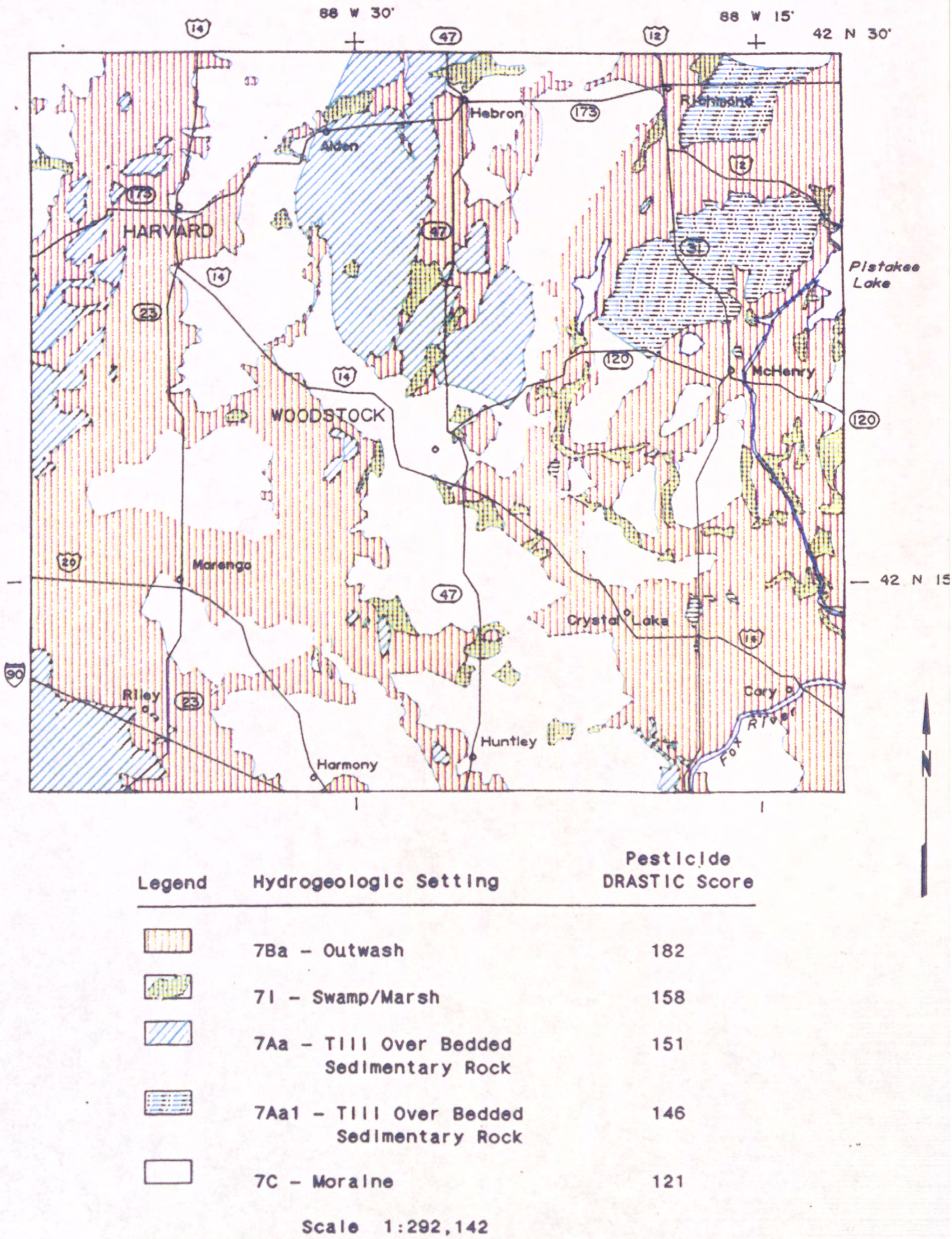


Figure 3. DRASTIC map of McHenry County, Illinois. Reproduced with permission of Monsanto Company.

also some apparent discrepancy among reports in the assignment of values for "C" (see discussion in "Evaluating the worksheets and source data," above).

Values for "D" vary widely, from 0-5 ft to 75-100 ft. For most settings, the values seem reasonable. However, for setting 7C (moraine), the depth to water is listed as 75-100 ft. This appears to be excessive in places, because the report has lumped moraines of different internal character into a single unit. The moraines in the eastern part of the county are not composed solely of till, but rather consist of 0-10 ft of till overlying sand and gravel (Hackett and McComas, 1969, p.26). These morainal deposits should have been defined as a distinct setting. Nicholas and Krohelski (1984) indicate depths to water of 50 ft or less for these areas. If a value for "D" of 30-50 ft were used instead of the selected value, the DRASTIC score would increase from 121 to 136. If the top of the buried sand and gravel aquifer (assumed here to be about 10 ft) were used as the value for "D", the DRASTIC score would increase by 35 to 156. If values for "A", "I", and "C" were also changed to reflect the different conditions, as they should be, the DRASTIC score could become as high as 176. This is a significant increase resulting from more precise definition of the local geologic conditions.

Comparison with other vulnerability maps - Because some areas (especially in the eastern half of the county) mapped as moraine are actually underlain by sand and gravel within perhaps 20 ft of the surface, some DRASTIC scores are incorrect. Therefore, the map does not agree with the ISGS and USGS-ISGS maps as well as it would if the moraine setting were properly defined. In general, however, these three maps portray the geologic materials and their vulnerability to contamination in similar patterns. The ISGS and USGS-ISGS maps are highly similar, because of their shared model assumptions and similar data bases.

Fountain County, Indiana

The county is mantled by a till plain, with coarse grained stratified drift mostly confined to the Wabash River valley and tributary valleys. The county is underlain by a buried valley network, with drift thicknesses up to 100 to 200 ft. Thinner drift occurs in the northern half of the county and in places to the west, on uplands between the Wabash River tributaries where drift is commonly less than 50 ft thick.

Three hydrogeologic settings are delineated on the DRASTIC map: 7Ba - outwash; 7D - buried valleys; and 7Aa - glacial till over bedded sedimentary rocks (fig. 4). DRASTIC scores range from 172 for setting 7Ba to 113 for setting 7Aa. The boundaries of the buried valley setting appear to be drawn from Watkins and Jordan (1965). The source of map data for the outwash setting is not documented and is unknown. In other reports at least one of the sources of information cited for "I" is also the source used to delineate the setting boundaries. However, in Fountain County, only Watkins and Jordan (1965) and the county soil survey are cited for "I" and are not the source. A map (Wayne and others, 1966) from the 1:250,000-scale regional geologic map series for the State, although cited as a reference for this report and used for DRASTIC maps in other reports, was not used here. Wayne and others (1966) show significant areas of outwash not shown on this DRASTIC map, especially in the northern part of the county. Outwash on the DRASTIC map is much more limited in distribution, and in places cuts across drainage rather than following it. Because it bears little resemblance to existing surficial geologic maps, the DRASTIC map is difficult to evaluate or accept as valid.

For the buried valley setting, a standard value for "D" of 30-50 ft was selected from Aller and others (1987). However, based on the well depths, sand and gravel is buried by 30 to 190 ft of till, with an average depth of about 90 ft (Watkins and Jordan, 1965, p.7). The appropriate value for "D" is, therefore, 75-100 ft. For "R", the report cites the same standard source and value as for outwash despite the report's acknowledgment of a substantial thickness of till overlying the aquifer. A value of 2-4 in/yr, cited for the bedrock aquifer in the "glacial till over bedded sedimentary rock" setting, is more appropriate. With these revised values for "D" and "R", the DRASTIC score for the buried valley setting drops by 35, to 110.

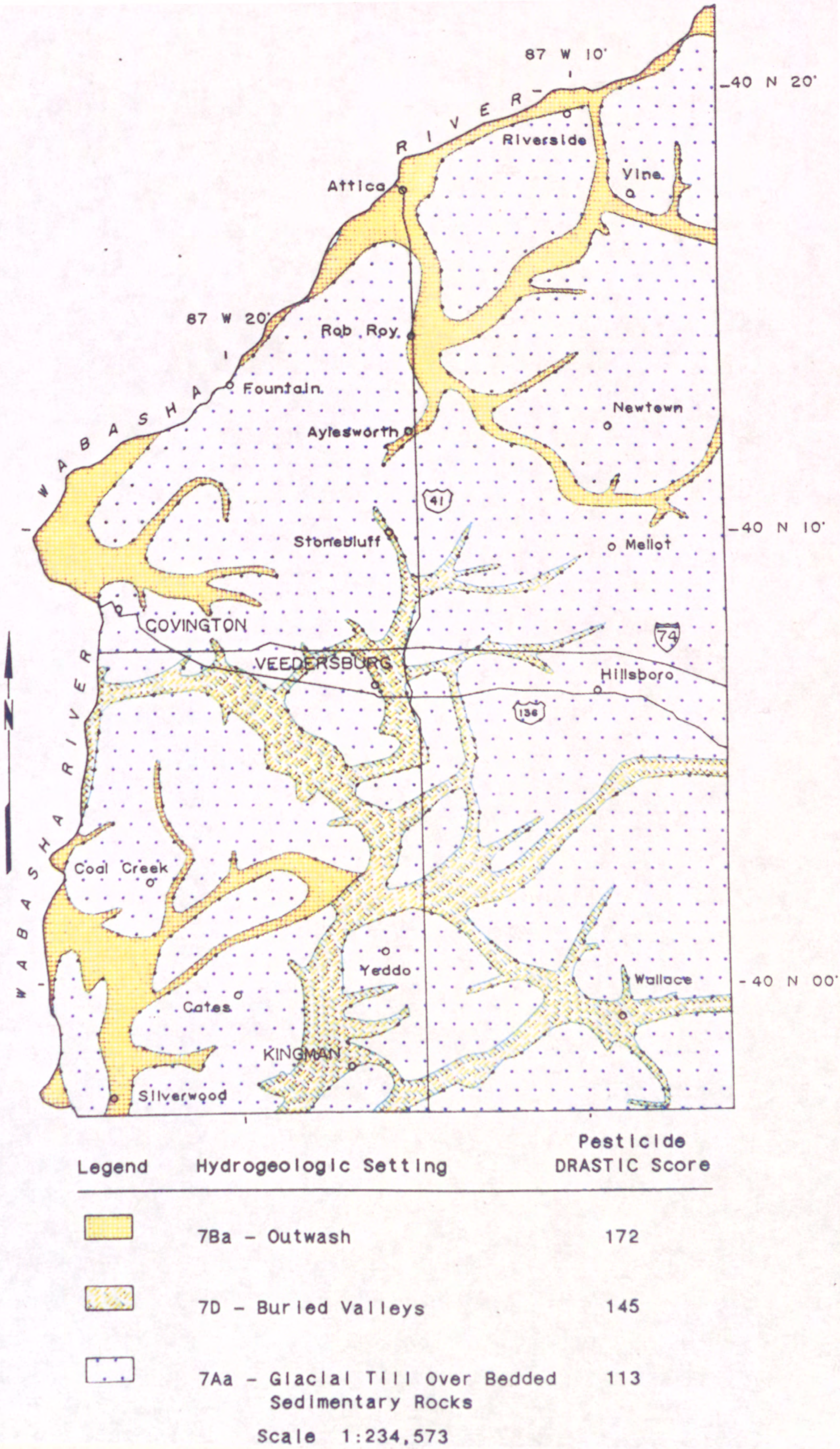


Figure 4. DRASTIC map of Fountain County, Indiana. Reproduced with permission of Monsanto Company.

For the glacial till over bedded sedimentary rock setting, the value for "A" is based on the bedrock, not the glacial till. Therefore, the value for "D" should be at least as great as the depth to rock. The report uses a value of 30-50 ft, from Aller and others (1987). However, the depth to rock varies widely in the county and exceeds 100 ft in many areas. This setting should be subdivided into two settings on the basis of depth to rock, or a greater depth to water should be used. Using a value of >100 ft for "D", the DRASTIC score would be reduced by 20, to 93. For "C", the report uses a value of <100 gpd/ft^2 from a standard reference (Freeze and Cherry, 1979), and the rating reflects this value. However, the worksheet also states "Assume 700-2000 gpd/ft^2," which contradicts the other evidence.

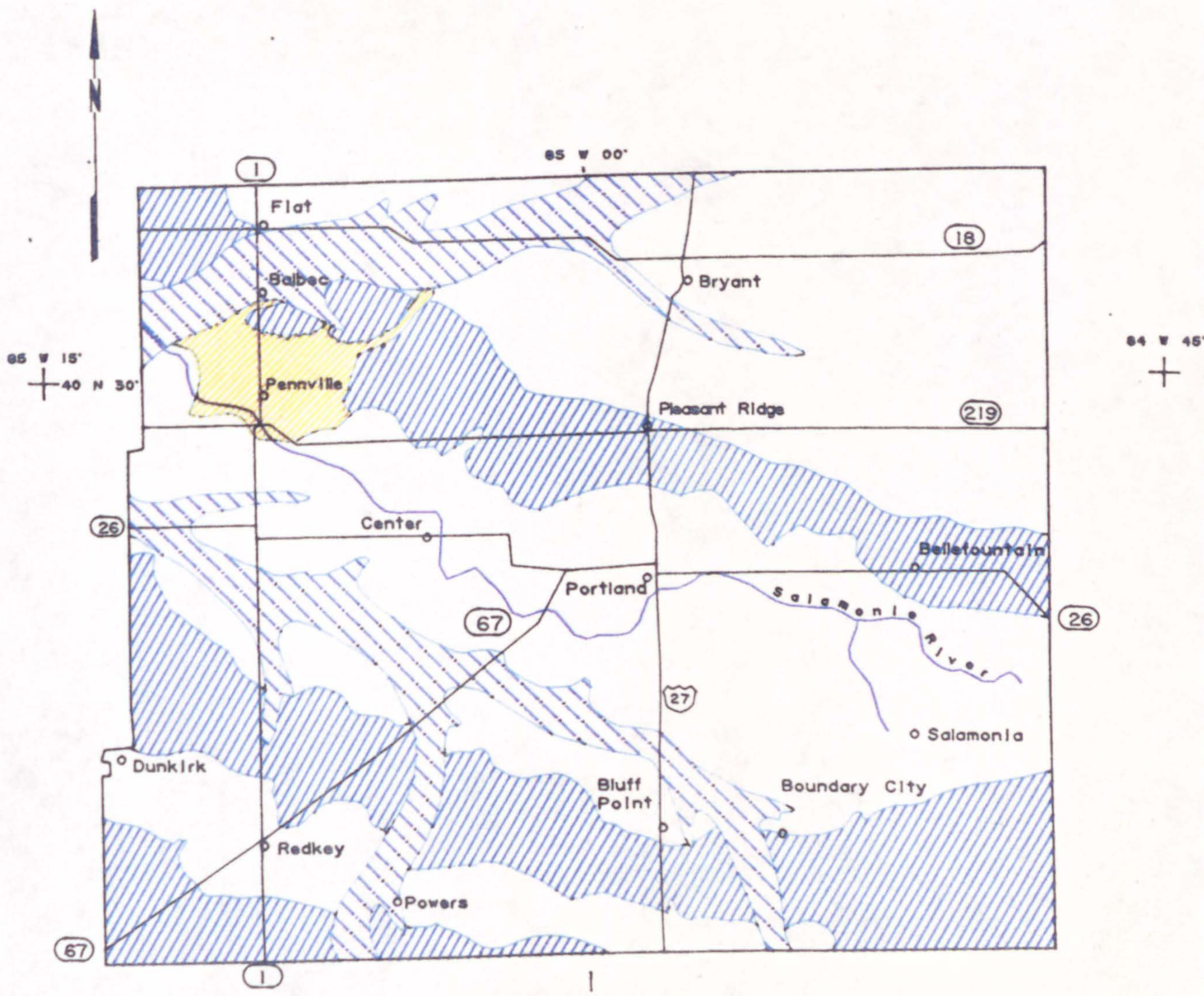
Comparison with other vulnerability maps - The DRASTIC map has little in common with the USGS-ISGS map. Given the more modern information and more realistic mapping on the USGS-ISGS map, it is preferred. Although the outwash settings have high contamination potential rankings on both maps, their boundaries are different in form; the DRASTIC map is more diagrammatic despite its more detailed map scale. The buried valley setting boundary bears no resemblance to the bedrock valleys as delineated on modern maps and as shown on the USGS-ISGS map. The "glacial till over bedded sedimentary rocks" setting has a low DRASTIC score. It should be subdivided based on glacial drift thickness and bedrock lithology information as shown on the USGS-ISGS map. For example, in the northeastern part of the county, the relatively high-permeability bedrock occurring at varying depths should dictate higher DRASTIC scores.

Jay County, Indiana

The county is mantled by a till plain consisting of ground moraines and end moraines covering buried valleys mostly in the northwestern and southwestern parts of the County. The depth to bedrock is less than 50 ft in the valley of the Salamonie River, increasing to more than 400 ft in the buried valleys. For most of the county, bedrock lies more than 50 ft below land surface. Patches of outwash and narrow alluvial valleys occur in places.

Four hydrogeologic settings are delineated on the DRASTIC map: 7Ba - outwash; 7Aa - glacial till over bedded sedimentary rocks; 7C - moraine; and 7D - buried valley (fig. 5). The predominant features on the DRASTIC map are the end moraines and the buried valley network. Setting boundaries appear to be drawn from Burger and others (1971) with only minor omission of patches of outwash (west of Portland, Indiana). As noted in the "Evaluating the hydrogeologic settings" section above, the buried valley setting is given priority over the moraine setting on the DRASTIC map, despite its lower DRASTIC score; this priority is manifested where the buried valley unit cuts across the moraine areas on the map. The moraine setting receives a higher DRASTIC score mostly because it is a surficial feature with relatively shallow sand and gravel aquifers compared to aquifers assumed to occur in the buried valleys. If the report authors had based the delineation of hydrogeologic settings solely on DRASTIC scores, the buried valley would not be shown in areas also underlain by the moraine setting. By extension, perhaps the buried valley setting should not be shown anywhere, because it represents a feature deeply buried beneath the aquifers evaluated in the settings it displaces, and has the lowest DRASTIC score on the map. Clearly, this report and others (Bureau County, Illinois, for example) do not base their DRASTIC map solely on the DRASTIC index, but also prioritize the settings according to other criteria.

DRASTIC scores range from 167 for setting 7Ba (outwash) to 123 for setting 7D (buried valley). Values were obtained from a variety of sources, including the geologic map of Burger and others (1971), the county soil survey, a personal communication, and standard references. For the outwash and moraine settings, values appear reasonable. However, for the buried valley setting certain assumptions are not supported by evidence and may not be appropriate. For example, the report assumes that the buried valley, which is part of the regional valley network known as the Teays valley, has sand and gravel aquifers buried at 30-



Legend	Hydrogeologic Setting	Pesticide DRASTIC Score
(yellow)	7Ba - Outwash	167
(blank)	7Aa - Glacial Till Over Bedded Sedimentary Rocks	126
(hatched)	7C - Moraine	125
(dashed hatch)	7D - Buried Valley	123

Scale 1:254,113

Figure 5. DRASTIC map of Jay County, Indiana. Reproduced with permission of Monsanto Company.

50 ft depth. These aquifers are described as high-yielding deposits ("C" = 1000-2000 gpd/ft^2) in contrast to the sand and gravel lenses in the moraines, which yield water at lower rates. For both "D" and "C", standard values from Aller and others (1987) were used. The report's characterization of the buried valley setting may be flawed, for two reasons. First, aquifers in the buried valley are likely much deeper than 30-50 ft, based on knowledge of buried valleys elsewhere in the region. Second, the western Ohio-eastern Indiana segment of the Teays is not known for extensive buried sand and gravel; lake clays and till are more common at depth.

For setting 7Aa (glacial till over bedded sedimentary rock), the following evidence is cited for "D", "A", and "C": "...bedrock aquifers used where till was thin. Sand and gravel aquifers used where till thick enough, highly variable. ...could not map distinct areas. 50% Bed Sed Rx 50% Sand and gravel." Because the report authors did not map areas of thin and thick drift, they assumed that an equal proportion of wells tap the glacial and bedrock aquifers. However, they could have used the State drift thickness map (Gray, 1983) to differentiate thin from thick drift on, for example, the 50 ft isopach interval. If they had done so, the maps would have more accurately portrayed the aquifer vulnerability, by showing two different settings rather than a single one with values based on estimated contributions from two aquifers.

Comparison with other vulnerability maps - Overall, similarities exist between the DRASTIC and the USGS-ISGS maps, probably in part because the surficial materials are uniform (glacial till) except for one patch of outwash in the northwestern part of the county. However, in the till-covered areas, differences between the maps are notable; because the USGS-ISGS map includes drift thickness information, moderate variations in contamination potential are shown, whereas there is almost no distinction on the DRASTIC map (only 3 DRASTIC points distinguish the 3 settings). For those settings, drift thickness implicitly plays a role. For example, the report assumes that thick till underlies the moraine setting and thin till underlies the "glacial till over bedded sedimentary rocks" setting; for the thin till setting, factor values are a composite of drift and bedrock data. However, drift thickness (from the USGS-ISGS map) and areas underlain by these two settings do not appear to correlate. In general, the USGS-ISGS map shows a more realistic appraisal of contamination potential for this county.

Lagrange County, Indiana

The county is mantled by glacial deposits mostly between 200 and 400 ft thick. At land surface, coarse grained, stratified sediment predominates, with till confined to patches mostly in the southern half of the county.

Five hydrogeologic settings are delineated on the DRASTIC map: 7Ba-1 - outwash; 7H - sand dunes; 7Ba-2 - outwash; 7F - glacial lake deposits; and 7C - moraine (fig. 6). The DRASTIC map pattern is moderately complex, and appears to be copied from Johnson and Keller (1972); although Bailey and others (1985) is cited as a source of information on the worksheets, that map was in turn derived from Johnson and Keller's map. The DRASTIC map is generally accurate but, based on Johnson and Keller (1972), a few incorrectly drawn and mislabeled areas were noted in the eastern half of the county.

One setting on the map seems to be improperly defined. On the DRASTIC map it is labeled 7F (glacial lake deposits) whereas on Johnson and Keller's map these deposits are labeled "Muck, peat, and marl (Recent age)." If redefined as a "swamp/marsh" setting to more closely agree with Johnson and Keller (1972) and other DRASTIC reports (nearby Kalamazoo County, Michigan, for example), the value for "D" could be changed from 15-30 ft to 0-5 ft, increasing the DRASTIC score by 15, to 166.

DRASTIC scores range from 210 for setting 7Ba-1 (outwash) to 146 for setting 7C (moraine). Values were obtained from a variety of sources, including Johnson and Keller (1972), Bailey and others (1985), the county soil survey, personal communications, and

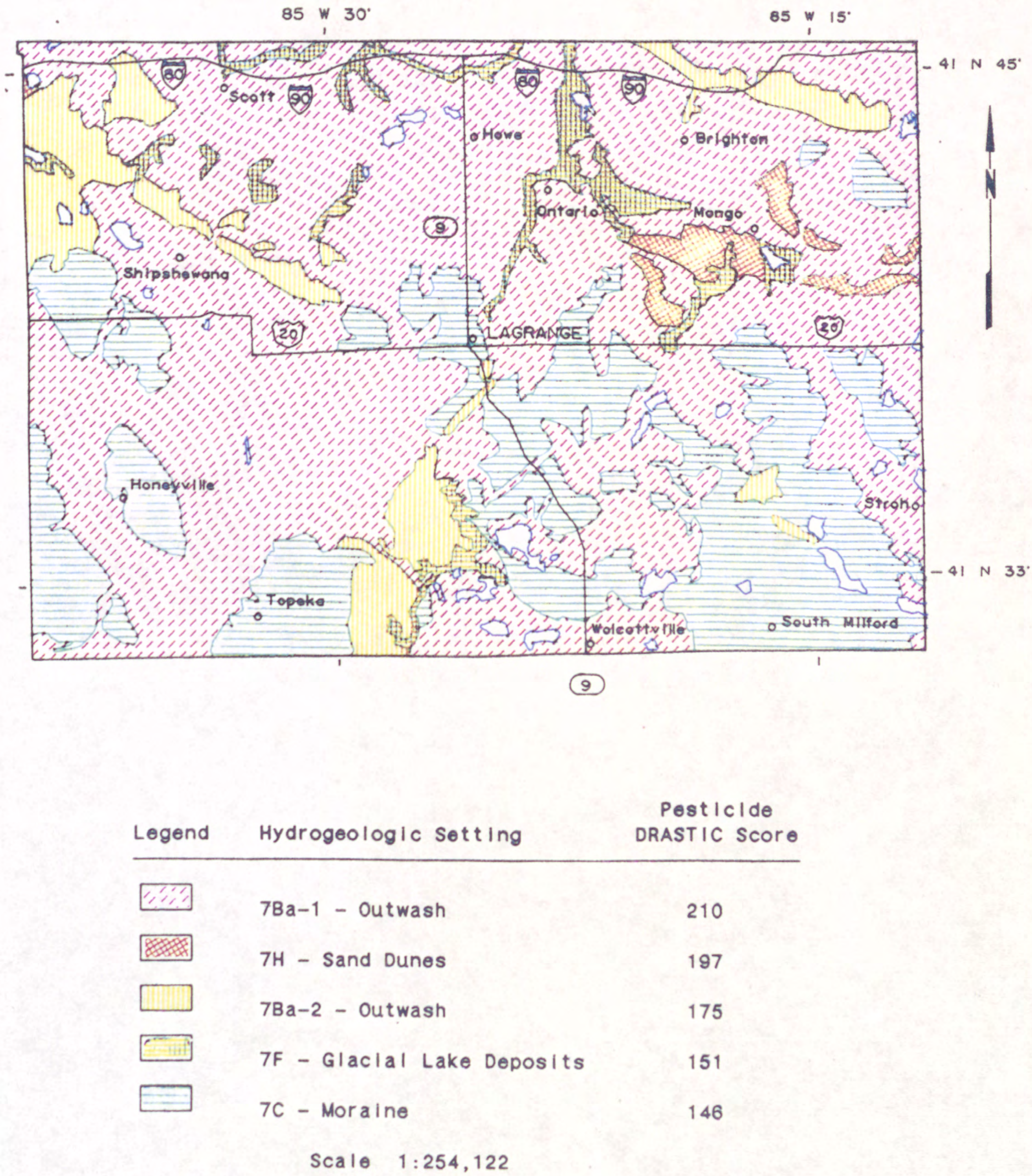


Figure 6. DRASTIC map of Lagrange County, Indiana. Reproduced with permission of Monsanto Company.

standard references. For most of the factors, values seem reasonable. However, factor "R" requires some comment. Bailey and others (1985) is cited as the source for values for "R," and Bailey's report cited Pettijohn (1968) as the source for the recharge data. I could not locate that data in Pettijohn. In fact, it was difficult to find actual data for net recharge in other reports as well, indicating that, if the model is to rely on actual data, the "R" factor is of limited value.

Comparison with other vulnerability maps - The DRASTIC map is similar in nature to the USGS-ISGS map; areas of high and low contamination potential and surficial materials correspond on the two maps.

Allegan County, Michigan

This county borders Lake Michigan, and is mantled by glacial sediment ranging in thickness from more than 50 ft on the uplands to more than 400 ft in a buried valley near the Lake. Glacial till is common on topographically higher areas, surrounded by outwash and glacial lake sands.

Ten hydrogeologic settings are delineated on the DRASTIC map: 7H - beaches, beach ridges, and sand dune; 7F - glacial lake deposits; 7Bb - outwash over bedded sedimentary rock; 7Ba - outwash; 7I - swamp/marsh; 7Ea - river alluvium with overbank; 7Ad - glacial till over sandstone; 7Ab - till over outwash; 7C1 - moraine 1; and 7C2 - moraine 2 (fig. 7). The DRASTIC map pattern is relatively complex, and appears to be copied from Puzio and others (1983a) with minor alterations in the northeast quadrant.

The settings "outwash" and "outwash over bedded sedimentary rocks" are assigned the same values for each factor, thereby yielding identical DRASTIC scores. The only difference between the settings appears to be that the "outwash over bedded sedimentary rocks" setting is underlain by relatively high-permeability bedrock (a sandstone) whereas no bedrock is noted for the "outwash" setting. The bedrock is buried by more than 200 ft of drift in places, and has no impact on the factor values; therefore, a single setting would be more appropriate.

DRASTIC scores range from 218 for setting 7H (beaches, beach ridges, and sand dune) to 130 for setting 7C2 (moraine 2). For factor "A", values are the same for all settings; despite widely varying lithologic descriptions on the worksheets, the standard value for sand and gravel was selected. For "I", values seem generally correct although the value for "moraine 1" seems somewhat too high; this unit is a sandy till, yet it has the same factor value as the outwash setting, which is texturally different. For "R" and for "D," evidence cited on the worksheets doesn't seem to support the selected values, so it is not clear how the values were derived. In one setting, for example, two sources of data are cited as evidence to support the "R" value: ".... irrigation 6.7 in/yr; .... about 33 in/yr precipitation." However, the selected value is 7 to 10 in/yr.

For "D," the values generally seem appropriate, but certain details may cause the reader to question the interpretations in general. For example, setting 7H (beaches, beach ridges, and sand dune) consists of eolian sand overlying outwash, according to the report. As shown on the map, this setting is mostly surrounded by glacial lake sediments and till; it is, therefore, more likely that it overlies these deposits. For setting 7H, "D" = 0-5 ft; in contrast, "D" = 5-15 ft for the glacial lake sediment, which is comprised mostly of sand. It is not clear why the sandy, and topographically high, setting 7H would have a water table higher than the mostly sandy, and topographically lower, setting that surrounds it. This incongruity casts doubt on the accuracy of the worksheets, and cannot be resolved based on the evidence supplied in the report. Furthermore, glacial drift thickness is offered as evidence for "D" values, even though the great thicknesses of drift encountered in this county are irrelevant where water tables lie in the upper part of the glacial section.

Comparison with other vulnerability maps - The DRASTIC map pattern is more detailed than the USGS-ISGS map pattern, because of the more detailed source map. Areas of relatively high and low contamination potential generally correspond on the two maps, so

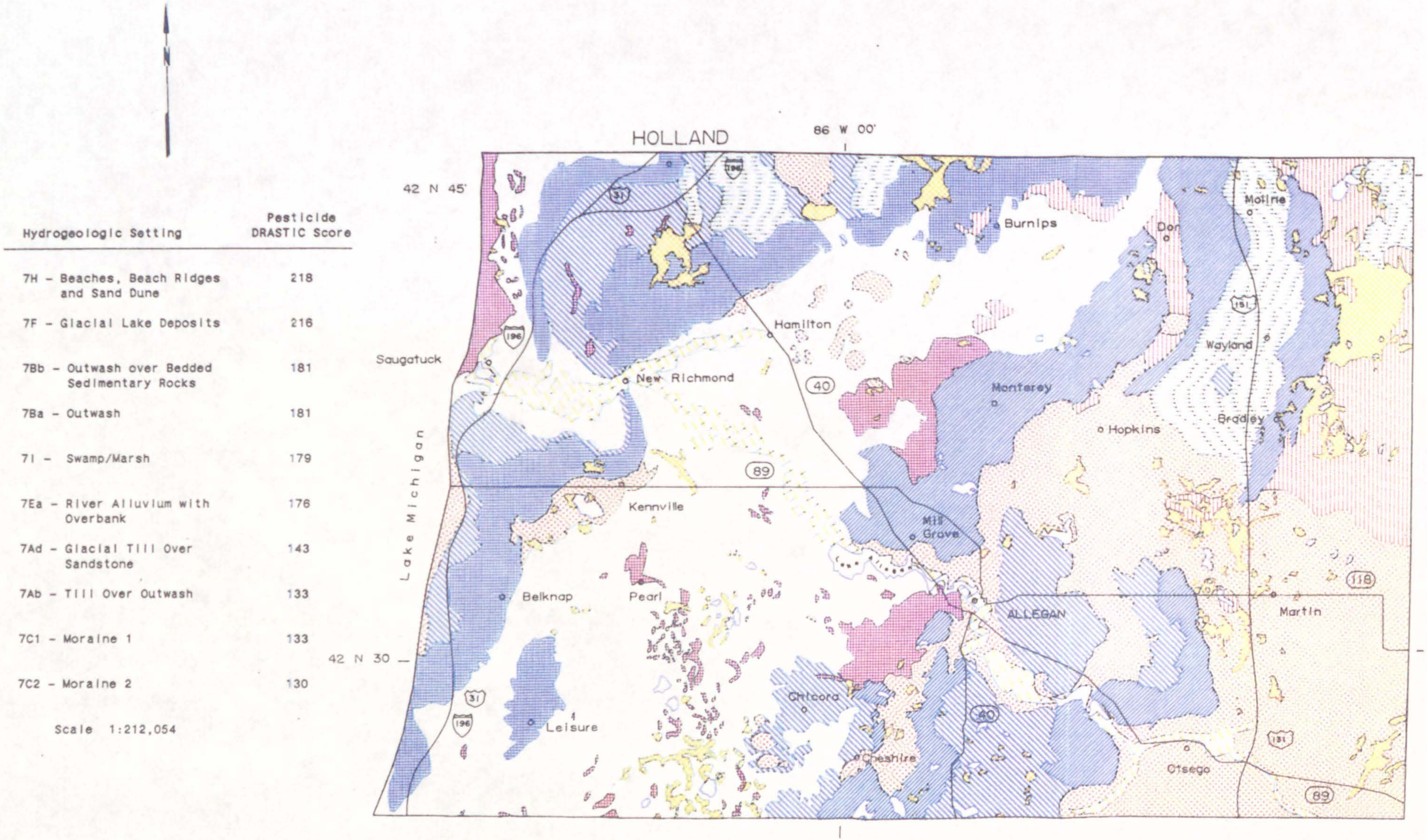


Figure 7. DRASTIC map of Allegan County, Michigan (reduced to approx. 1:326,740 scale). Reproduced with permission of Monsanto Company.

despite some reservations about values shown on the worksheets, the content of the map seems reasonable. The county is underlain by a southeast-northwest trending buried valley that abuts Lake Michigan; the DRASTIC map did not portray this feature, but it is likely an important feature in the regional hydrogeology.

Cass County, Michigan

This county lies in a region where coarse-grained stratified deposits (outwash, for example) are widespread at land surface. Exposures of till are mostly confined to moraines that trend southwest-northeast. Glacial deposits are commonly more than 200 ft thick.

Four hydrogeologic settings are delineated on the DRASTIC map: 7F - glacial lake deposits; 7Ba - outwash; 7Ab - glacial till over outwash; and 7C - moraine (fig. 8). DRASTIC scores range from 196 for setting 7F (glacial lake deposit) to 136 for setting 7C (moraine); against convention, settings are listed in the explanation in ascending order of DRASTIC score. The DRASTIC map pattern is relatively simple, and appears to be a generalization of the Statewide map shown in a hydrogeological atlas (Western Michigan University, 1981). That map was adopted from a 1955 state map. A more current state map (Farrand and Bell, 1982) was not used in this report.

This report is difficult to evaluate because there is little, if any, real data for the DRASTIC factors; values are derived from studies of Kalamazoo County, from standard values in Aller and others (1987), and from a Statewide atlas. Evidence for selection of factor values, cited on the worksheets, is in places cryptic, and does not provide enough information to permit evaluation. This task is further complicated by misspellings and the citation of data sources on the worksheets that are not listed in the References section.

Comparison with other vulnerability maps - A comparison with other maps, specifically the USGS-ISGS map, is not productive because the source map for the DRASTIC setting boundaries is unknown. The DRASTIC map appears to be in error, over-mapping the surficial till deposits especially in the eastern half of the county. In general, however, the map is somewhat similar to the USGS-ISGS map, with broad areas of vulnerable deposits (sands) and more isolated areas of lower-vulnerability deposits (glacial till).

Ingham County, Michigan

This county is mantled by glacial sediment ranging in thickness from less than 50 ft to more than 100 ft in areas underlain by buried valleys. Glacial till predominates, with coarse grained, stratified sediment (outwash, for example) confined to relatively small and narrow valleys.

Five hydrogeologic settings are delineated on the DRASTIC map: 7Bb - outwash over bedded sedimentary rock; 7I - swamp/marsh; 7Ea - river alluvium with overbank deposits; 7C - moraine; and 7Ad - glacial till over sandstone (fig. 9). The DRASTIC map pattern is relatively complex; hydrogeologic settings appear to be copied directly from the surficial geologic map of Puzio and others (1983b).

DRASTIC scores range from 205 for setting 7Bb (outwash over bedded sedimentary rock) to 146 for setting 7Ad (glacial till over sandstone). Factor values were obtained from detailed reports on the county, standard values, and a Statewide atlas. Certain values for "D" seem questionable, although it is admittedly difficult to assess the values based on evidence supplied and references cited on the worksheets. For example, for setting 7Bb (outwash over bedded sedimentary rock), the value for "D" (0-5 ft) seems too shallow, given the high permeability of such material and the values used in other reports. Also, the value for "C" in river alluvium seems too low (1-100 gpd/ft^2) by comparison with values for swamp/marsh (700-1000) and moraine (300-700); however, because these values were derived from standard references, it is not clear which values are appropriate.

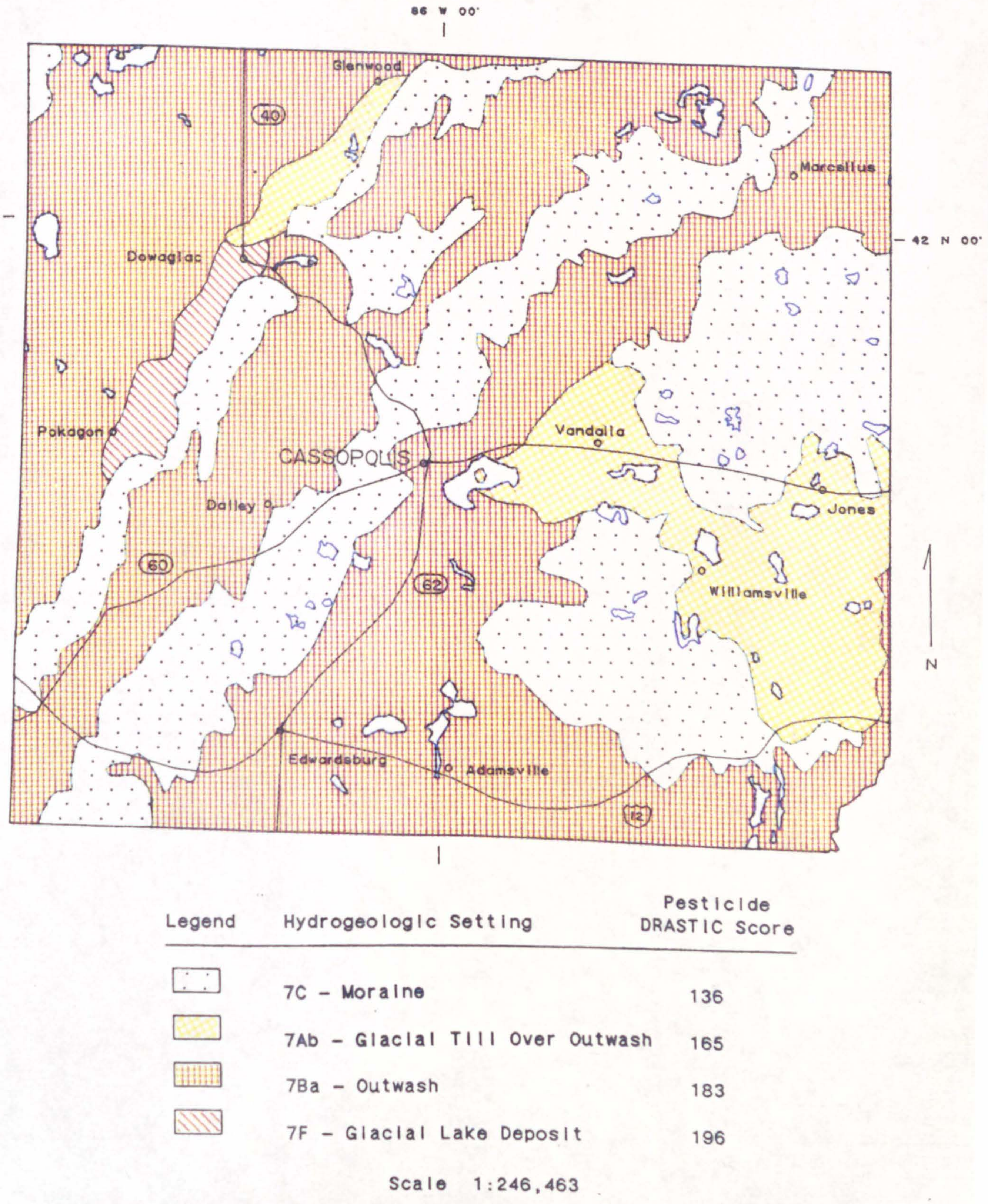


Figure 8. DRASTIC map of Cass County, Michigan. Reproduced with permission of Monsanto Company.

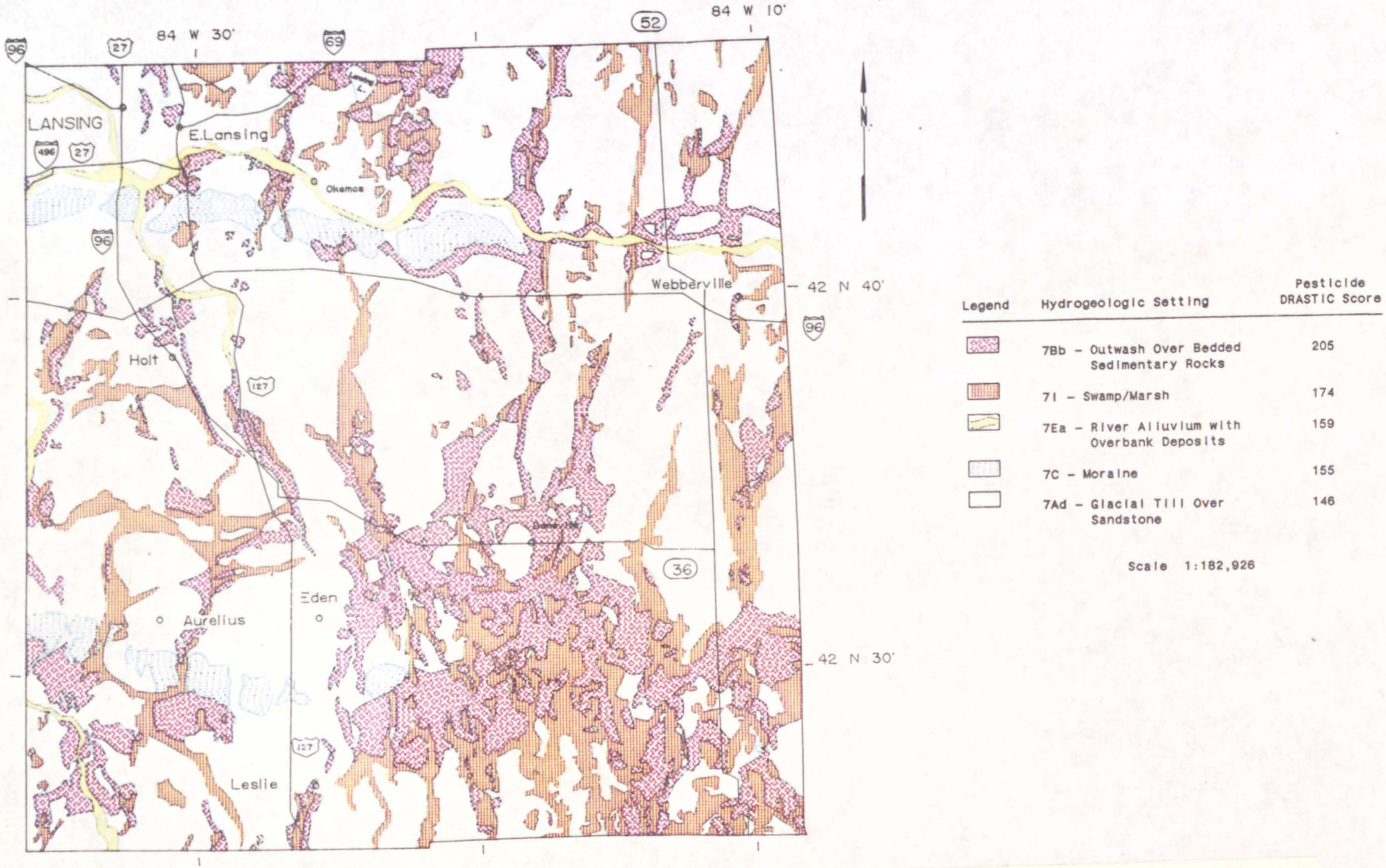


Figure 9. DRASTIC map of Ingham County, Michigan (reduced to approx. 1:282,730 scale). Reproduced with permission of Monsanto Company.

For the setting "outwash over bedded sedimentary rock," wells tap both the outwash and bedrock, which lies more than 50 ft below land surface. Values for "A" and "C" reflect both glacial and rock aquifers, thereby effectively treating them as a single aquifer. Such an approach cannot fully address the vulnerability of the unconfined glacial aquifer.

Comparison with other vulnerability maps - Despite the inconsistencies and problems noted with the worksheets, the DRASTIC map seems reasonable and generally correlates with the USGS-ISGS map. The DRASTIC map is more detailed, as it was drawn from a more detailed source map. The county is underlain by a network of buried valleys, where thicknesses vary up to nearly 200 ft; the DRASTIC map did not portray these features, but they are likely an important feature in the regional hydrogeology.

Kalamazoo County, Michigan

The county is mantled mostly by coarse grained, stratified deposits, with till confined to moraines that form narrow upland areas trending southwest-northeast. Glacial drift thickness ranges from at least 50 ft on the uplands to more than 600 ft in areas underlain by buried valleys.

Eight hydrogeologic settings are delineated on the DRASTIC map: 7H - beaches, beach ridges, and sand dune; 7Bb - outwash over bedded sedimentary rock; 7Ba - outwash; 7Ab - till over outwash; 7Ea - river alluvium with overbank; 7I - swamp/marsh; 7F - glacial lake deposits over outwash; and 7C1 - moraine (fig. 10). The DRASTIC map pattern is relatively complex; hydrogeologic settings appear to be copied directly from Monahan and others (1983).

DRASTIC scores range from 214 for setting 7H (beaches, beach ridges, and sand dune) to 138 for setting 7C1 (moraine 1). For most factors, values were obtained from detailed reports on Kalamazoo County (for example, Deutsch and others, 1960; Monahan and others, 1983) and from standard values. The DRASTIC worksheets cite evidence for selection of factor values that is in places confusing and seemingly irrelevant. For example, for one setting, evidence for "R" is ".... 6 in/yr irrigation", ".... about 35 in/yr", and "7 - 10 in/yr." The selected value, 7-10 in/yr, is a standard value from Aller and others (1987). With no access to real data on net recharge, the authors must resort to a general value for "R" for a given type of deposit. For "D", evidence does not in every case support the selected value, especially for settings where the only evidence cited is the thickness of the glacial drift. For setting 7H (beaches, beach ridges, and sand dune), the 0-5 ft depth to water seems too shallow, given the high permeability and topographic position of these deposits.

The setting "till over outwash" evaluates the contamination potential of a confined aquifer composed of glacial outwash. However, the evidence for "D" is quoted as "Supplies adequate for Domestic use are pumped from shallow-driven wells in this area.", which better describes isolated lenses of sand and gravel in till than a buried outwash unit. Evidence for "A" is "Coarse sand and cobble gravel boulder common on surface, clay rick(?) to SE" and "Where drift is <100 to 200 about 10% of wells are in bedrock." Again, this evidence does not support presence of a buried outwash unit. Nonetheless, the standard value for sand and gravel is assigned to "C." A more realistic value for "C" is the lower value used for setting 7C1 (moraine 1); it is also a standard value, but is better suited to the evidence presented for the geologic conditions. The "till over outwash" setting seems to be poorly characterized, and perhaps should be redefined or more closely linked with the moraine setting.

To this author, the setting "outwash over bedded sedimentary rocks" implies that bedrock is shallow enough to be vulnerable according to DRASTIC criteria. However, the report lumps the unconfined surficial aquifer and the confined bedrock aquifer into a composite number although the bedrock aquifer lies 100 to 200 ft deep. Granted, the bedrock is only apportioned an influence of 10 percent of the factor value, but such a composite setting does not seem appropriate because it adds little if any relevant information to the map.

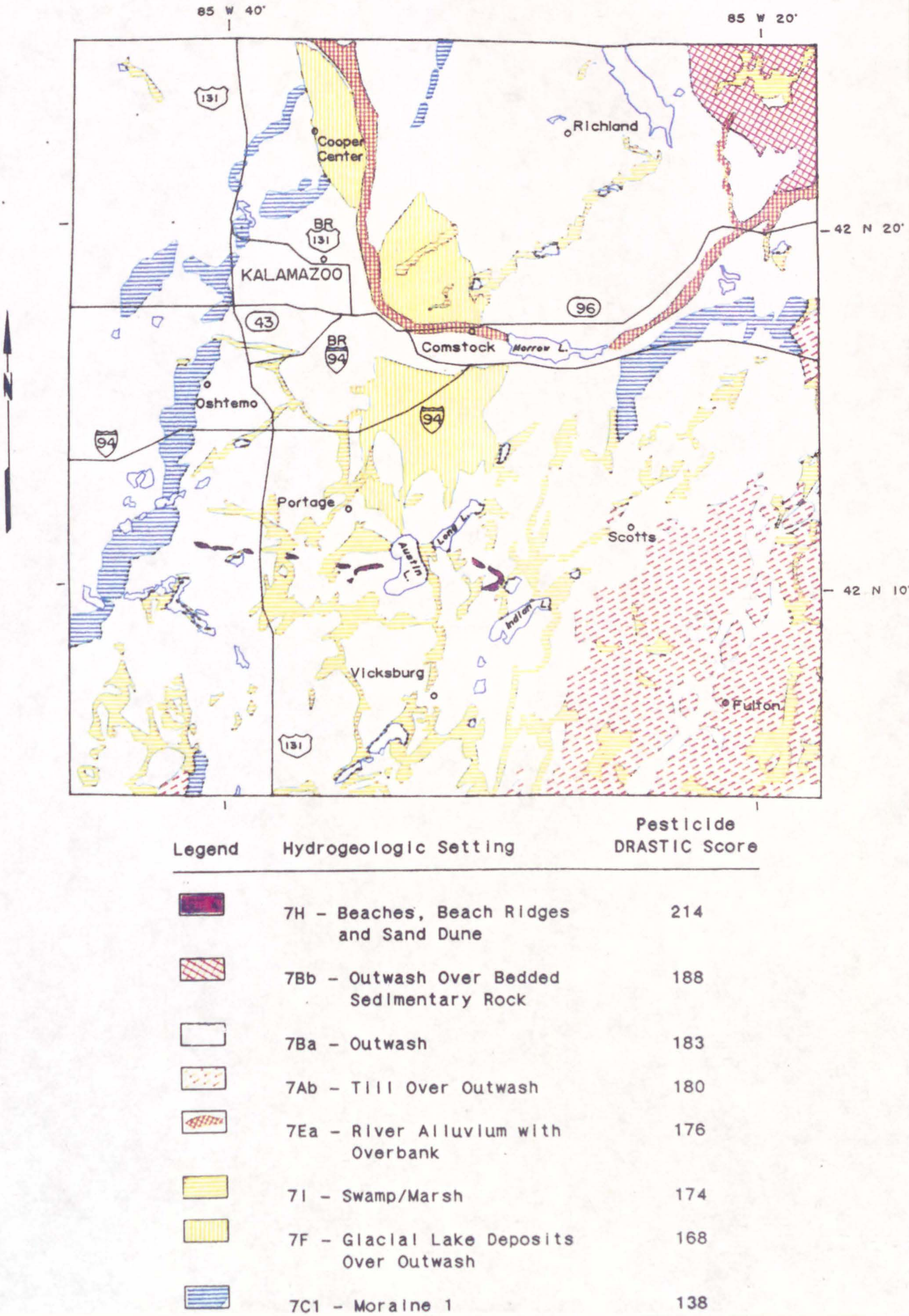


Figure 10. DRASTIC map of Kalamazoo County, Michigan. Scale 1:267,914.
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Comparison with other vulnerability maps - The DRASTIC and USGS-ISGS maps generally correspond, but the DRASTIC map is considerably more detailed owing to its more detailed source map. However, such detail may not be overly significant for assessing regional contamination potential. For example, there are many small areas of "glacial lake deposits over outwash" mapped. These fine-grained lake deposits are discontinuous and less than 1 m thick. This setting's significance for contamination potential is questionable. Also, the county is underlain by a network of buried valleys containing glacial sediment more than 400 ft thick in places, as shown on the USGS-ISGS map but not on the DRASTIC map. This valley underlies the county's largest city, Kalamazoo, and should be considered in a contamination potential assessment.

Dane County, Wisconsin

Glacial ice covered all but the western part of Dane County, where sedimentary rocks are exposed. The glaciated terrain is mantled mostly by till, with patchy outwash and swamp deposits. A terminal moraine crosses the western part of the county, trending northwest-southeast. Glacial sediment is generally less than 50 ft thick, except in the extensive network of buried valleys where drift thickness commonly exceeds 100 ft.

Five hydrogeologic settings are delineated on the DRASTIC map: 7Ba - outwash; 7I - swamp/marsh; 7Aa - till over bedded sedimentary rock; 6Da - alternating sandstone, limestone, and shale (thin soil); and 7C - moraine (fig. 11). The DRASTIC map pattern is relatively complex; hydrogeologic settings appear to be copied directly from the surficial geologic map of Cline (1965), which in turn was modified from the regional map of Alden (1918).

DRASTIC scores range from 182 for setting 7Ba (outwash) to 120 for setting 7C (moraine). For most factors, values were obtained from a Dane County report by Cline (1965). Standard values were used for certain factors, in particular for "C" and "S." Values for "I" were the same for all settings. Values for most other factors varied little among the settings. For "R", a single value for recharge was used for the entire county, with that value adjusted slightly for one setting because of its relatively great depth to water. It seems inappropriate to essentially use a single net recharge value for an area underlain by such varied geologic units; it is an inherent problem with the model that factor values are required even where real data does not exist. For "I", descriptions and values are essentially the same for the outwash, swamp, till over rock, and moraine settings, even though the vadose zone media are clearly different. Again, lack of adequate data may be the cause.

Buried valleys occur in Dane County along the Wisconsin River, to the north and southeast of Madison, and on the eastern edge of the county. These valleys contain outwash at depth, and have saturated thicknesses of hundreds of feet (Cline, 1965). The DRASTIC map, however, does not show these valleys, which should have somewhat different vulnerabilities than adjacent land.

Comparison with other vulnerability maps - The DRASTIC map shows a reasonable level of detail for the map scale, with overemphasis of the swamp setting and omission of buried valleys being two possible shortcomings. The WDNR map is very complex, and the map pattern in Dane County seems related to the directions of glacial ice flow, although it is difficult to determine the source of the map unit patterns because the map is a composite of 5 data layers. In the western part of the county, the WDNR contamination susceptibility is mostly high, with susceptibilities slightly less than "moderate" in the valleys; the low scores in the valley appear to be contrary to logic and to a hand-computed score derived from the 5 data layers. The USGS-ISGS map shows some similarity to the WDNR map; most of the county has relatively high contamination potential, with the lesser rankings in thicker-drift areas where the high-permeability bedrock is deeply buried. However, the USGS-ISGS map is more akin to the DRASTIC map in its portrayal of map units. If a choice were to be made, the USGS-ISGS map would be the preferred map; the WDNR map pattern is too complex and does not

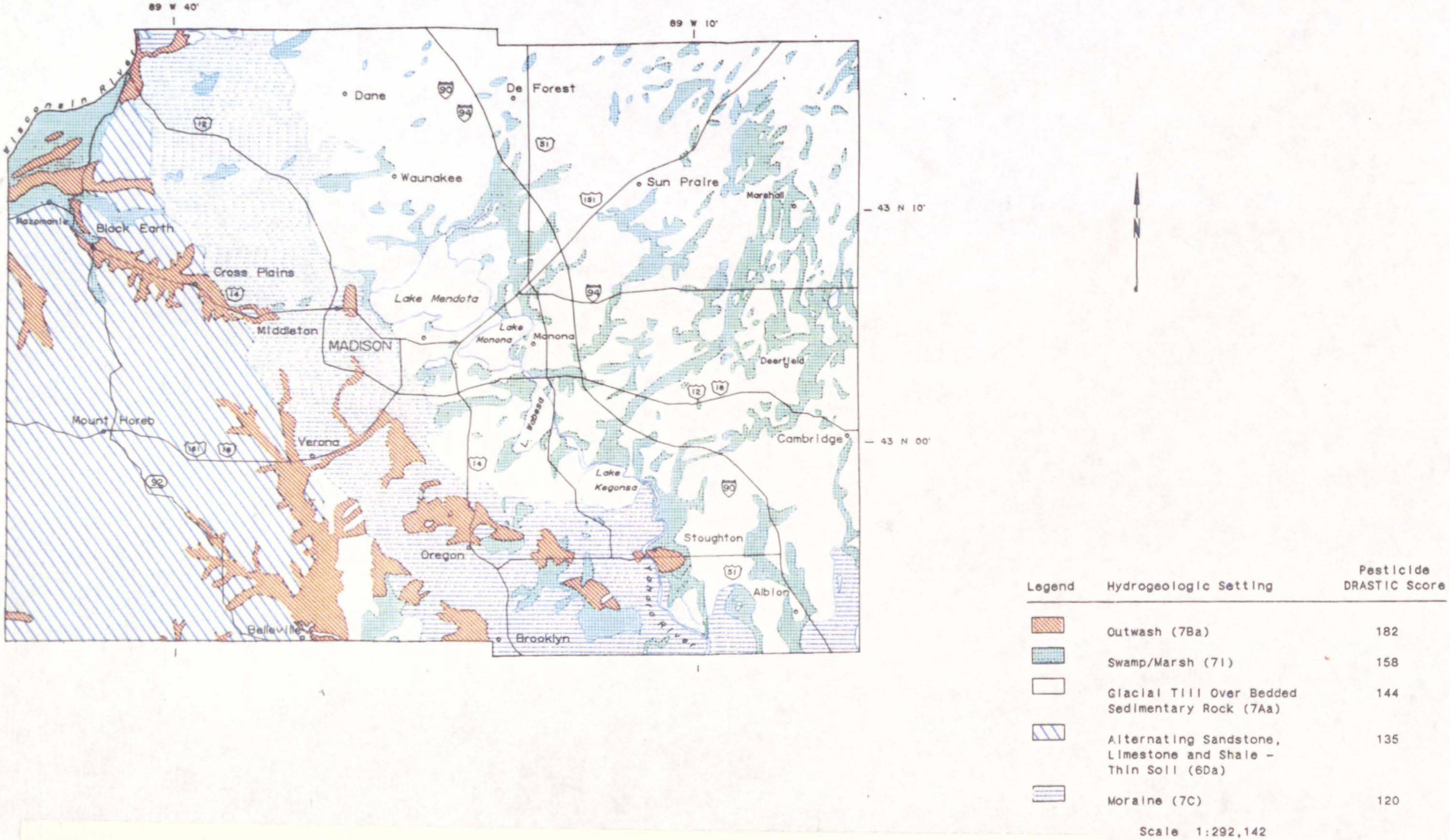


Figure 11. DRASTIC map of Dane County, Wisconsin (reduced to approx. 1:454,340 scale). Reproduced with permission of Monsanto Company.

clearly discriminate among geologic units with different hydrogeologic characteristics, whereas the DRASTIC map has the shortcomings discussed above and does not address the contamination potential of the buried valley network.

Rock County, Wisconsin

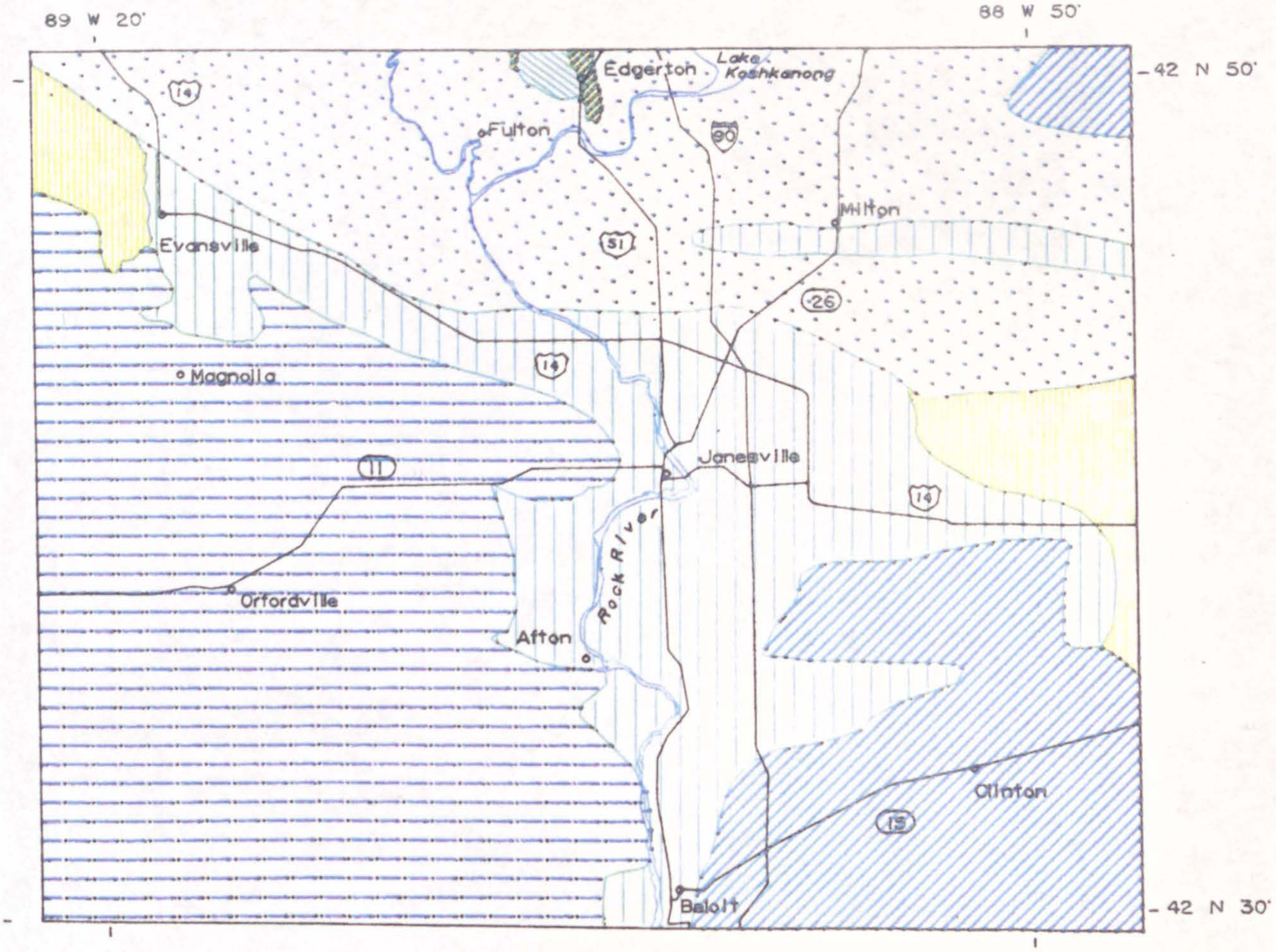
This county is covered by glacial deposits ranging in thickness from less than 50 ft on the uplands to more than 200 ft in areas (commonly in the lowlands) underlain by buried valleys. On the uplands, glacial till is common, whereas coarse-grained, stratified sediment occurs in the extensive lowland in the central part of the County, which is partly occupied by the Rock River.

Seven hydrogeologic settings are delineated on the DRASTIC map: 7Ba - outwash; 7I - swamp/marsh; 7Ba1 - outwash; 7Aa2 - till over bedded sedimentary rock; 7Aa1 - till over bedded sedimentary rock; 7G - thin till over bedded sedimentary rock; and 7C - moraine (fig. 12). The DRASTIC map pattern is quite simplistic; hydrogeologic settings appear to be adapted from a figure in LeRoux (1963) and sources unknown.

DRASTIC scores range from 172 for setting 7Ba (outwash) to 120 for setting 7C (moraine). Many of the factor values were obtained from LeRoux's (1963) report on Rock County and a study of Dane County by Cline (1965). For "R", the report used a single value taken from Cline (1965) for all settings, even though variations in net recharge almost certainly occur among the various settings; LeRoux (p.26-27) discussed such variations, although no actual values are given. Only "D" and "C" vary greatly, accounting for most of the differences in DRASTIC scores. Values for these two factors are a broad mix of real data, assumed or standard values, and values extrapolated from Dane County. Although real data on depth to water is not readily available for most areas, and the ambiguities of the available information are well known, the DRASTIC report uses "D" to differentiate the outwash into two settings. For one of the settings, the value for "D" was extrapolated from Dane County, whereas for the other setting, the value was apparently derived from LeRoux (1963).

Rock County is traversed by a north-south trending buried valley with two large tributaries on the west side. As was also the case for the report on adjoining Dane County, this valley was disregarded even though it contains buried outwash and more than 100 ft of saturated thickness. The valley's buried aquifer must certainly have a different level of vulnerability than the thinner glacial deposits on the uplands. The reason for omitting this hydrogeologic setting is not clear, especially since the DRASTIC model is capable of addressing confined aquifers. One of the western tributaries, filled with up to 200 ft of glacial sediment, traverses the "thin till over bedded sedimentary rock" setting.

Comparison with other vulnerability maps - The DRASTIC map is highly generalized; much more so than the 1:1,000,000-scale USGS-ISGS and WDNR maps. The DRASTIC map shows highest scores in the outwash, and low values in the till-covered areas to the south and north. The WDNR map is very complex, and shows the entire county as moderately to highly susceptible; susceptibilities are slightly higher in the thin drift areas around the north-south trending outwash-filled valley. Because this map is a composite of 5 data layers, it is difficult to relate the many small map units to identifiable physical features such as outwash plains or buried valleys; this may hinder the interpretation and application of this map. The USGS-ISGS map also shows moderate to high contamination potential for the entire county. It shares elements with both the DRASTIC and the WDNR maps: it has geologically-recognizable map units like the DRASTIC map, but with more detail and definition, yet its rankings seem more in line with the WDNR map, albeit with more variation in contamination potential.



Legend	Hydrogeologic Setting	Pesticide DRASTIC Score
	7Ba - Outwash	172
	7I - Swamp/Marsh	158
	7Ba1 - Outwash	157
	7Aa2 - Glacial Till Over Bedded Sedimentary Rocks	143
	7Aa1 - Glacial Till Over Bedded Sedimentary Rocks	138
	7G - Thin Till Over Bedded Sedimentary Rock	132
	7C - Moraine	120

Scale 1:330,333

Figure 12. DRASTIC map of Rock County, Wisconsin. Reproduced with permission of Monsanto Company.

Walworth County, Wisconsin

This county is underlain by glacial drift mostly 100 to 400 ft thick. A broad buried valley crosses the western half of the county from northeast to south. Both till and coarse grained, stratified sediment are common at land surface.

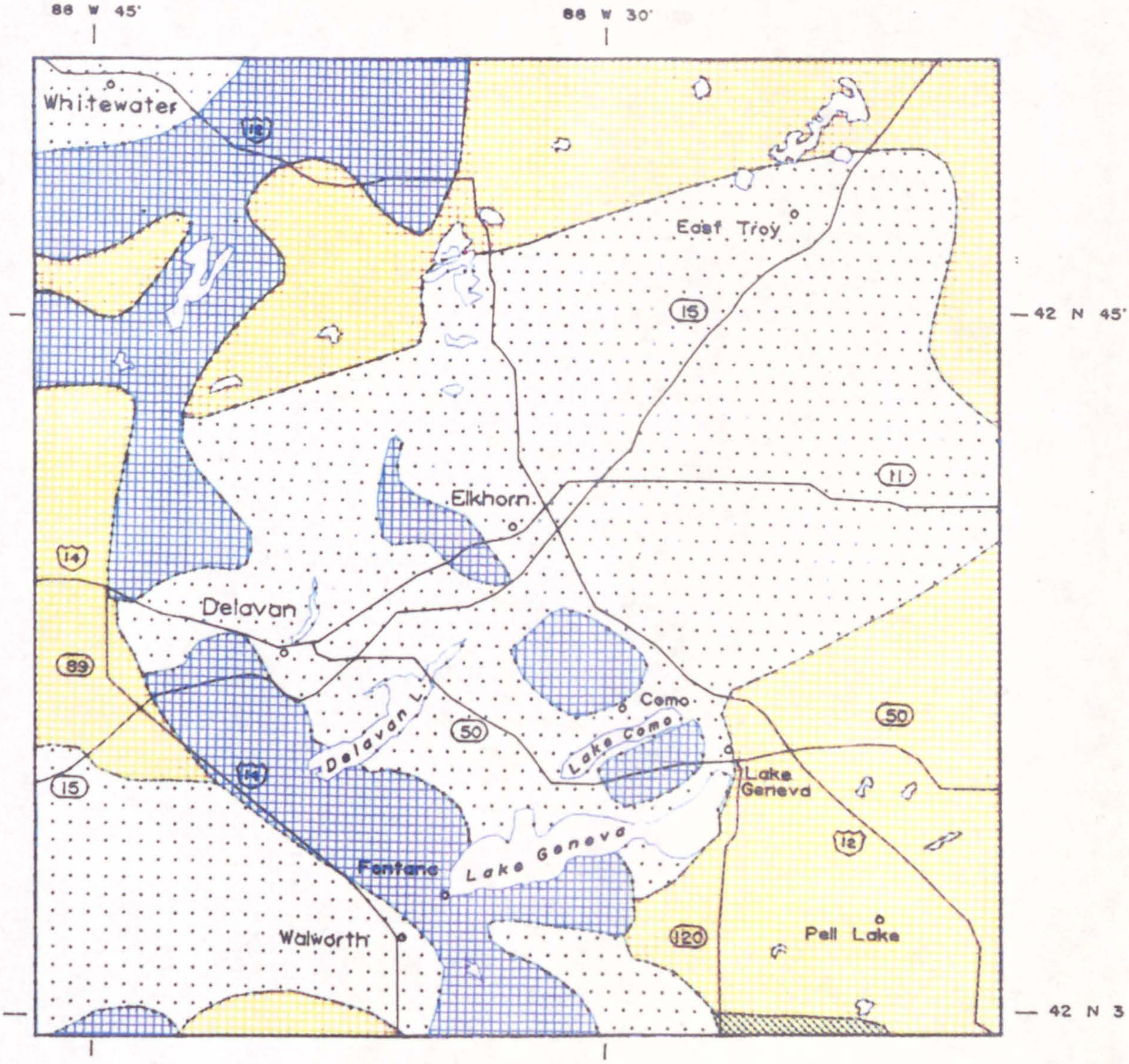
Four hydrogeologic settings are delineated on the DRASTIC map: 7Ba - outwash; 7Aa2 - till over bedded sedimentary rock; 7Aa1 - till over bedded sedimentary rock; and 7C - moraine (fig. 13). The DRASTIC map pattern is simplistic, and the source of the map information is not clear. A report by the Southeastern Wisconsin Regional Planning Commission (1969) is cited as the source of information for factors "I" and "A", and could conceivably, therefore, be the source of the hydrogeologic settings boundaries, but it does not appear to be so. The map also does not bear resemblance to existing regional geologic maps (for example, Lineback and others, 1983).

DRASTIC scores range from 172 for setting 7Ba (outwash) to 116 for setting 7C (moraine). Factor values were obtained from reports on neighboring Rock County, Wisconsin (LeRoux,1963) and McHenry County, Illinois (Nicholas and Krohelski, 1984), from a regional planning document (Southeastern Wisconsin Regional Planning Commission, 1969), and from standard values. Values for several factors varied little among the four settings. As was the case for other county reports, lithologic descriptions and values for "I" are uniform for the settings even though their textures and mode of deposition are different.

One of the primary distinctions between the three settings underlain by glacial till is factor "S." Values are extrapolated from soil survey reports of nearby counties. However, Lineback and others (1983), not cited in this report although available at the time, does not indicate a difference in till texture among these three settings in Walworth County. Values for "D" are also extrapolated, and must be considered uncertain. If available data had been used, DRASTIC scores might have been significantly different.

The deep buried valley network in the County was not considered a factor in defining the settings. For example, the valley traverses one of the "glacial till over bedded sedimentary rock" settings, where the value for "A" was determined by deriving 90% of the value from bedrock aquifer media, and 10% from glacial aquifer media. However, the bedrock aquifer is in places buried by hundreds of feet of glacial drift, and, therefore, should not be evaluated in the same setting as a shallower, glacial aquifer.

Comparison with other vulnerability maps - The DRASTIC map is highly generalized; much more so than the 1:1,000,000-scale USGS-ISGS and WDNR maps. Scores range from moderately low (for "moraine") to moderately high (for "outwash"). On the WDNR map, all areas are of moderate to high susceptibility except for the southwest corner of the county. The WDNR map pattern is complex and appears to have little in common with the DRASTIC map pattern. Map patterns on the USGS-ISGS map are complex, and appear to share some elements with both the DRASTIC and WDNR maps. The USGS-ISGS map is probably the most reasonable of the three maps, because it has elements in common with the other maps, is more readable than the WDNR map, more complex and precisely drawn than the DRASTIC map, and considers the buried valley deposits not shown on the DRASTIC map.



Legend	Hydrogeologic Setting	Pesticide DRASTIC Score
(yellow)	7Ba - Outwash	172
(hatched)	7Aa-2 - Till Over Bedded Sedimentary Rock	147
(dotted)	7Aa-1 - Glacial Till Over Bedded Sedimentary Rock	144
(blue grid)	7C - Moraine	116

Scale 1:278,389

Figure 13. DRASTIC map of Walworth County, Wisconsin. Reproduced with permission of Monsanto Company.

Summary

1. General comments on the DRASTIC model and its implementation:

A. The DRASTIC model is designed to be usable even by persons with a rudimentary knowledge of hydrogeologic principles. According to the manual (Aller and others, 1987), such individuals should be able to produce a DRASTIC map. Such a map, however, can be of only limited reliability and utility if its author delineated hydrogeologic settings and selected factor values without adequate training or information. In this model, opportunities for the modeler to err are numerous, and include the selection of hydrogeologic settings, the delineation of those settings on the DRASTIC map, and the computation of the DRASTIC score. This computation is a complex process that involves the gathering and subjective interpretation of sparse data. As stated in Aller and others (1987), vulnerability assessments improve with the modeler's knowledge and experience. Unfortunately, the map user cannot readily discern a skillfully-prepared map from one prepared by a novice.

B. The source information upon which factor values are based is not readily available. This can be a significant problem. Map users might need access to the source information for a variety of reasons, including verification of DRASTIC scores, reinterpretation of the data for related purposes (development of a depth-to-water table or recharge-area map, for example), or to increase the map user's understanding of regional hydrogeologic framework. In these reports, documentation on source data and maps is sparse and uneven in quality.

C. Perhaps the greatest shortcoming of the DRASTIC model is the scarcity of adequate source data to characterize the factors. For certain factors, notably "R," real data are rarely found for a study area. Because data are sparse for most factors and may also be ambiguous, and because ratings must be selected for each factor, factor values are all too commonly based on standard values from Aller and others (1987) or on extrapolated values from nearby areas. Interpretation of the evidence offered on DRASTIC computation worksheets can, therefore, be highly subjective. As a result, a range of values for a factor is possible.

D. For most of the county reports, the level of DRASTIC map detail was appropriate to the map scale. However, in several cases, the maps were far too simplistic; there, the DRASTIC map showed less detail than the USGS-ISGS map, which is a map of broad, regional extent (scale 1:1,000,000). The most current source map data of appropriate scale was not used in every DRASTIC report, which may partially account for the lack of detail.

E. Each county report seems to have been prepared as an isolated product, with little consideration for regional context or consistency with the other reports. Regional context can be considered to be the distribution of map units in and around the study area. The importance of understanding and using the regional context cannot be overemphasized because it forms the framework upon which interpretations of data, and selection of appropriate factor values, should be based. Regional context can also help to standardize local vulnerability assessments conducted for a large area such as the agricultural belt in the U.S. midcontinent. If the DRASTIC model is to provide a consistent format for depicting vulnerability, it must be implemented in a consistent manner based on regional context and a common level of expertise among the modelers. This consistency will be difficult to achieve because the model is designed for use by virtually anyone who needs to create a vulnerability map.

F. DRASTIC is designed to address either the unconfined aquifer or a confined aquifer; the county reports are inconsistent in their treatment of confined aquifers. For areas with confined aquifers in buried glacial valleys, some county reports depict them whereas others do not. These buried valley hydrogeologic settings commonly have low DRASTIC scores, and displace more vulnerable settings (that describe unconfined aquifers) on the DRASTIC map. For areas where wells tap both unconfined glacial aquifers and the confined bedrock aquifers beneath, some county reports use a composite score based on estimates of the proportion of ground water withdrawals from the two aquifer types. This approach can cause the vulnerability of the unconfined aquifer to be misrepresented, especially where the bedrock aquifer lies at depths too great to be vulnerable to contamination from the land surface.

G. In certain respects, the county DRASTIC reports are somewhat deficient. In part, the data requirements of the model are at fault, causing a map to be produced without adequate data to support it. However, problems with report preparation are also noted, including instances of weak assumptions for factor ratings, lack of internal consistency, and failure to use the latest and most detailed information available at the time. These problems may be attributed to unfamiliarity with regional geologic setting, poor source data, or inadequate time allowed for report preparation.

2. *Correlation with other maps and actual contamination:*

A. Ground-water resources can be defined to include shallow, unconfined water in low-permeability deposits, or can be restricted to ground water in aquifers. Likewise, a depth limit for consideration can be imposed, or confined aquifers can be excluded from consideration. From these different perspectives, distinctly different ground-water vulnerability maps can be produced to address different ground-water protection goals. For example, the WDNR map emphasizes unconfined ground water both in aquifers and aquicludes, whereas the ISGS map emphasizes economically significant ground water in both unconfined and confined aquifers.

B. Regional evaluation of contamination potential is based on very general, qualitative comparisons of the *relative* contamination potential on each map. This involves comparing the hierarchical position of a DRASTIC map unit to the correlative map unit in the contamination potential ranking scheme of another model. The need for more precise measures of vulnerability is discussed in point G, below.

C. Despite problems with scoring the individual DRASTIC factors (as described in the county reports), comparison with maps made by the other models generally suggests that the relative hierarchy of DRASTIC map units seems reasonable. Apparently, the influence of an inappropriate factor value on the overall DRASTIC score is so small that it does not commonly effect a reördering of map units in the scoring hierarchy; the number of factors is large enough and the scoring system is sufficiently intricate that inconsistencies in factor data interpretation are minimized by the model.

D. In general, areas of relatively high and low DRASTIC score correspond to areas of high and low contamination potential on the ISGS and the USGS-ISGS maps. However, as noted above in this summary, differences in source data and interpretations (especially for portrayal of aquifers in buried valleys) lead to significant differences in the details shown on these maps.

E. Procedurally, the DRASTIC and WDNR models have much in common. However, little similarity was noted in map pattern between these maps, probably because of the manner in which map units are determined. In contrast to the DRASTIC model, the WDNR model intersects the map patterns for each of its five factors. This results in a complex pattern of hundreds of map units, each reflecting a unique combination of values for the five factors. Although map patterns are quite different, areas of low and high vulnerability generally correspond.

F. The models discussed in this report need not be viewed as competing approaches, and no model should be seen as clearly superior to another. Each addresses a slightly different facet of the ground-water vulnerability issue; the map information produced by one model may, therefore, serve to complement and support information produced by the other models. Also, different applications may be more suited to one model than another. For example, a regional assessment of the vulnerability of both confined and unconfined aquifers can be provided by the USGS-ISGS model, which uses map units defined and delineated by the geologic framework. In some instances, map units in a vulnerability assessment *must* be defined by political/cultural boundaries, whether for jurisdictional reasons or for expediency. The USGS-ISGS model would be difficult to implement in this manner because geologic and political boundaries rarely coincide. The DRASTIC model translates physical information to a factor rating, and is well-suited to this task; composite factor ratings for all hydrogeologic settings within a political subdivision can be computed, as done in EPA's National Pesticide Survey.

G. Contamination potential as predicted by regional models has yet to be correlated with actual contamination incidents in a rigorous, statistical manner. Therefore, current models can only provide intuitive, "common-sense" assessments of regional contamination potential. These assessments can be highly informative and useful, but cannot be as effective in predicting contamination as a comprehensive, quantitative model for predicting an absolute *probability* of contamination. Such a model might use data on geologic framework, hydrology, land use, and climate. Currently, research indicates little correlation between DRASTIC scores and contaminated sites (for example, Curry, 1987, and Baker and others, 1989). However, the literature on this subject is quite limited. It is likely that future studies will more clearly define the predictive abilities of DRASTIC in different hydrogeologic settings and at different map scales. Then, DRASTIC's role in vulnerability assessments can be better defined, and new regional approaches to assessing vulnerability can be devised. Assessment of contamination *probability*, not relative contamination *potential*, should be a primary goal for research and testing to support sound land-use management and ground-water protection strategies.

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