A Model for the Assessment of Aquifer Contamination Potential Based on Regional Geologic Framework

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ABSTRACT / The texture and three-dimensional framework of geologic materials should be considered in assessments of groundwater's vulnerability to contamination because geology controls the movement of contaminants and groundwater and influences groundwater quality. Contaminants are introduced into, transmitted through, and stored by geologic materials. We present a model that identifies aquifers and ranks sequences of geologic materials by their relative potential for transmitting water and contaminants from land surface. With this basis, the model can be used to assess the potential for contamination of aquifers by surface activities such as landfilling of wastes or application of agricultural chemicals. A regional map of aquifer contamination potential can be generated from the model; it retains the geologic map information intact and available for reinterpretation or other uses.

The model was developed using broad, regional map information and is intended to be a general tool for assessing the regional vulnerability of aquifers to contamination. It is not intended for local, site-specific use, but for prioritizing local areas where contamination potential and/or land-use history warrant more detailed assessment or monitoring. Because it provides a regional view of contamination potential, regional patterns or trends of map units should be evaluated, rather than using the map information literally to assess local areas. Methods of applying this model and contamination potential map to groundwater protection and management are currently being studied; research includes an attempt to statistically validate the model with water-quality data, and to identify natural groupings of the ranked contamination potential map units.

Introduction

The potential that groundwater resources may be contaminated is a critical nation-wide concern, because potential health hazards may arise when chemical or biological agents from the contaminant source enter groundwater and are subsequently extracted by public or private wells and consumed. It has, therefore, become a national priority not only to identify potential contaminant sources and routes of transport, but also to identify and evaluate water-bearing geologic units that are vulnerable to contamination (U.S. EPA 1984).

This paper focuses on one type of water-bearing geologic unit, the aquifer. Aquifers are comprised of mostly porous, coarse-grained sand and gravel deposits in glacial drift, Coastal Plain units, or other surficial deposits, as well as high-permeability bedrock. Aquifer protection is a critical issue for two reasons. First, aquifers can yield economically significant supplies of water (Freeze and Cherry 1979). Second, because aquifers allow water and potential contaminants to travel relatively rapidly, they are particularly vulnerable to contamination.

Groundwater also occurs in aquicludes, or fine-grained confining units (e.g., a surface layer of glacial till). In many areas, wells that tap the water table in a confining unit at land surface are common. However, such wells are generally shallow, large-diameter dug or bored wells for single households that can yield groundwater only at very slow rates. Characterizing the contamination potential of groundwater in fine-grained deposits at land surface requires some different assumptions and types of data from those described in this paper.

The Role of Geology

Groundwater contamination results from surface and nearsurface activities such as the application of agricultural chemicals, leaching from municipal or hazardous waste landfills, septic systems, accidental spills, leakage from underground storage tanks, or surface spreading of wastes. Through these activities, contaminants are introduced into, transmitted through, and stored by geologic materials. Geology not only controls the movement of contaminants and groundwater, but also influences groundwater quality through filtration, sorption, cation-exchange, and other processes. The actual potential for contamination of an aquifer depends in part on the protective properties of geologic materials both above and below that unit. For example, the thicker the sequence of fine-grained, low-permeability geologic materials between a potential contaminant source and an aquifer, the less likely is the aquifer to become contaminated (Berg and others 1984a). Furthermore, low-permeability materials beneath an aquifer can restrict further downward migration of a contaminant into deeper aquifers.

Because of the geologic controls on water movement and quality, data on the texture and three-dimensional framework of geologic materials is essential for a realistic appraisal of groundwater vulnerability. This is especially true for water derived from aquifers beneath the soil horizons. For example, where agricultural chemicals are slowly migrating through a thin confining layer at the surface into a buried aquifer, or entering a confined aquifer in its recharge area, vulnerability assessments that deal only with characteristics of the upper, unconfined part of the hydrologic system cannot adequately characterize the contamination. At the Illinois State Geological Survey (ISGS), contamination potential maps are based on depth to shallow aquifers (50 ft or less) and hydrogeologic properties of materials between aquifers and the surface (Berg and others 1984a). More recently, soil infiltration and presence of deep aquifers [to 300 ft (91 m)] were used as additional factors for contamination potential mapping (Keefer and Berg 1990). Other studies, for example, in Iowa [Kolpin and Burkart 1989; and U.S. Geological Survey (USGS), written communication, 1989] and Michigan (Passero and others 1989), support the use of geologic information as a primary component of a contamination potential assessment model.

Development of a Geologically Based, Regional Contamination Potential Model

The purpose of this paper is to describe a model that identifies aquifers and ranks sequences of geologic materials by their relative potential for transmitting water and contaminants from land surface. With this basis, the model can be used to assess the potential for contamination of aquifers by surface activities such as landfilling of wastes or application of agricultural chemicals. Our model is rules-based, and is an outgrowth of ISGS techniques adapted for a more general, regional approach. It may be especially suited to areas where detailed mapping and subsurface information is poorly distributed or not available.

In practice, the assessment of aquifer vulnerability has proven to be a difficult task. Commonly, it is based on selection of certain factors or variables (e.g., depth to water or texture of surficial deposits) that are known or assumed to have some influence on the rate at which contaminants move from land surface into groundwater. These variables are related according to a model or set of rules to predict the susceptibility of water to contamination. At a local level, for example, at the scale of a farm, deterministic models requiring many variables have been developed [e.g., see models summarized in Ertel (1990)] that can predict rates and patterns of contaminant migration. Although valuable data are provided by these site studies, a more regional perspective is required by planners (e.g., at a county, multicounty, state, or multistate scale). Unfortunately, these quantitative models have not been applied to areas larger than farm-scale with notable success. This is in part because the models require many variables that are not available regionally, and because the three-dimensional variability of the geologic materials is greater and more difficult to characterize regionally than locally.

Models for the regional assessment of aquifer vulnerability (e.g., Aller and others 1987) must rely on a more limited number of generalized, qualitative measures than the localized, deterministic models. Our model is of the regional type; it uses only commonly available, regional three-dimensional geologic information. Limiting the model to basic, readily accessible information saves the user from estimation of data values, which may be required by models using less widely available types of data. In our model, the contamination potential map units retain the source (geologic) information, thereby allowing for reinterpretation of map units, or the basic geologic information, for other purposes.

Development of the Model

A texturally based, regional map of glacial deposits (Soller in press; scale 1:1,000,000), supplemented by regional bedrock lithologic maps, served as the source of information on geologic framework for development of the model. We applied the model to a test area, part of Soller's map (Fig. 1), centered on southern Lake Michigan and encompassing parts of five states. Although the specific geologic information contained on Soller's map was considered in selecting the model components and their classification, comparable types of information are available on other regional surficial and bedrock geologic maps.

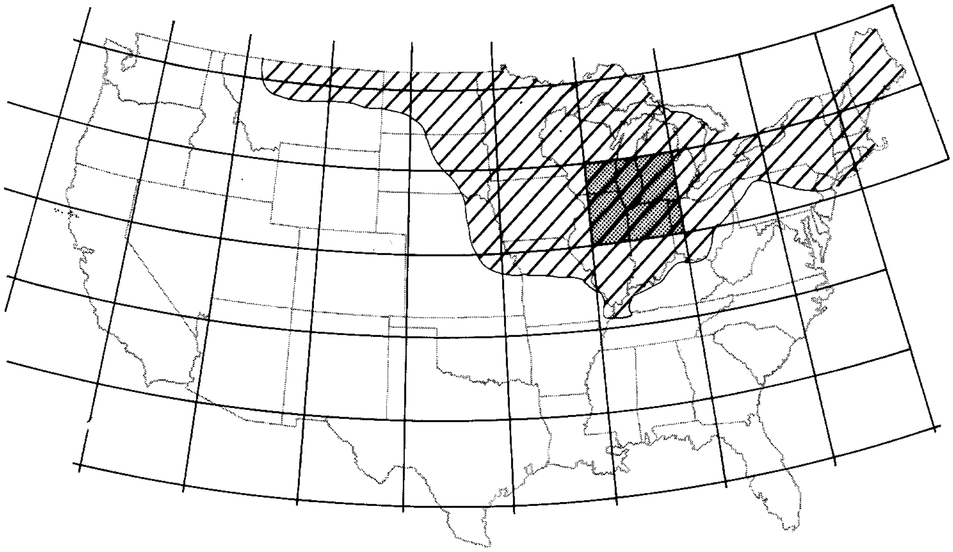

Figure 1. Index map showing the region covered by the Quaternary sediments map of Soller (1992) in ruled pattern, with the test area in stippled pattern.

The model assembles the component information (e.g., glacial drift thickness) into map units according to a set of rules and assumptions. These map units are ranked according to relative contamination potential. These rankings are not quantified or precise, and little significance is implied in small differences in contamination potential rank.

Component Selection

Our model defines four factors or components: (1) texture of surface sediments, (2) presence of aquifers buried within surficial deposits, (3) permeability of bedrock directly beneath surficial deposits, and (4) thickness of surficial deposits. Each component provides important information for evaluating the potential for groundwater contamination on either a regional or site-specific scale. Other types of information (such as organic carbon content of the near surface deposits, presence of fractures or other macropores, climate, and chemical and physical interaction between contaminants and the soil or geologic materials beneath the soil) also have a significant effect on groundwater quality. However, data for these factors can be expensive and time-consuming to obtain, are commonly unavailable, and in some cases cannot be translated easily into map format.

Those aspects of this model concerning surficial deposits were developed with glacial geologic information. Descriptions of components, therefore, commonly refer to glacial sediments, buried glacial drift aquifers, or glacial drift thickness. However, the model can also be applied and evaluated in nonglacial terrain.

Component 1: texture of surface sediments. For this paper, surface sediments are defined as those surficial deposits exposed at land surface. The more general term, surficial deposits, here includes all nonlithified deposits both at land surface and at depth. The distinction between surface and surficial deposits is made because to fully characterize the entire thickness of the surficial deposits, detailed three-dimensional information on sediment texture, lithostratigraphy, and time-stratigraphy is generally required. Such information is commonly not available regionally or locally because surficial deposits: (1) vary greatly in thickness, (2) may be patchy and discontinuous and have complex stratigraphy, (3) may have differing origins (glacial, alluvial, colluvial, eolian, or residual), and (4) may vary widely in age, from Recent to Quaternary or older in some cases. Therefore, a model component describes surface sediments, for which information is more widely available.

In the test area (Fig. 1), surface sediments are largely Pleistocene-age glacial deposits and Holocene-age alluvium and lacustrine deposits, with areas of patchy glacial drift and exposed bedrock. For our model, materials-based map units are derived based on similarities in estimated hydraulic conductivities. Map units are:

- coarse-grained, stratified sediment and organic-rich deposits

Table 1. Typical hydraulic conductivities for selected rocks and sediments

Clean sand and gravel	$>1 \times 10^{-4}$
Fine sand and silty sand	1×10^{-5} to 1×10^{-3}
Silt and clay (lacustrine)	1×10^{-11} to 1×10^{-7}
Till	1×10^{-9} to 1×10^{-5}
Sandstone	$>1 \times 10^{-4}$
Cemented fine sandstone	1×10^{-7} to 1×10^{-4}
Shale	1×10^{-11} to 1×10^{-7}
Dense carbonate rock	1×10^{-11} to 1×10^{-8}
Fractured or porous carbonate rock	1×10^{-6} to 1×10^{-4}

Source: Berg and others (1984a) and Cartwright and Hensel (in press).

- glacial till and fine-grained, stratified sediment
- patchy glacial drift and exposed bedrock.

For the coarse-grained unit (coarse-grained, stratified sediment and organic deposits), hydraulic conductivities are commonly greater than 1×10^{-4} cm/sec. These and other values cited herein are general values (see Table 1). For the fine-grained unit (till and fine grained, stratified sediment), hydraulic conductivities are commonly less than 1×10^{-5} or 1×10^{-6} cm/sec. Conductivities in the third unit depend on the character of the bedrock, as discussed in component 3, below.

Component 2: presence of aquifers buried within the surficial deposits. Buried aquifers may occur anywhere within surficial deposits. Within the glaciated United States, such aquifers are common and can supply significant amounts of groundwater. On a regional basis, however, the geometry of buried glacial drift aquifers is poorly documented because of difficulties in mapping glacial deposits in three dimensions. Our model uses Soller's (in press) information on buried aquifers. Because of the scarcity of regional subsurface information, Soller's map shows only the few buried aquifers that are well-documented in the literature. His map does not show the thickness of, or depth to, those aquifers or their stratigraphy and subsurface geometry.

Component 3: hydraulic conductivity of the uppermost bedrock unit. Bedrock varies widely in composition and ability to transmit fluids (see Table 1). For our model, we reinterpreted bedrock geologic maps to derive lithologic information, and classified bedrock lithologies by relative permeabilities. In the test area, sandstones and fractured and/or jointed carbonate rocks generally have high hydraulic conductivities (greater than 1×10^{-5} cm/sec) (Table 1), whereas shales, siltstones, and unfractured and cemented carbonate rocks generally have low hydraulic conductivities (less than 1×10^{-7} cm/sec). However, it is recognized that these conductivities are estimates based on regionally mapped rock characteristics. The actual conductivity of bedrock in any given location may vary significantly due to differences in depositional, diagenetic, or structural history.

Component 4: thickness of surficial deposits. Aquifers at the land surface have the highest potential to be contaminated. In confined aquifer settings, the deeper the aquifer, the lower the probability for contamination (Berg and others 1984a; Keefer and Berg 1990). Kolpin and Burkart (1989; and USGS, written communication, 1989) conducted a preliminary statistical analysis of geologic, hydrologic, water-chemistry, soil, and well construction factors, to determine the most significant element affecting pesticide migration into shallow aquifers, which they defined as occurring within 61 m (200 ft) of the surface. Their model indicated that overlying sediment thickness was the most significant factor affecting contamination potential of aquifers; the thinner the sediment overlying an aquifer, the higher the likelihood of contaminated groundwater.

This model uses thickness categories, whose intervals are dictated by available data. This is acceptable if the available data permits adequate resolution of the upper hundred feet or so (e.g., into more than one thickness class). The upper hundred feet of surficial deposits are particularly important to contamination potential mapping because waste repositories and other potential sources of groundwater contamination commonly occur in that interval. For our test area, Soller's (in press) data and drift thickness intervals of 0–50 ft (0–15 m), 50–100 ft (15–30 m), 100–200 ft (30–61 m), and >200 ft (>61 m) were used.

Assumptions of the Model

The rules used in our model focus on the *documented* occurrence or absence of aquifers and the *probable* occurrence or absence of aquifers. For example, because the locations and stratigraphic settings of buried glacial drift aquifers are not well-documented regionally, there is some likelihood or probability that an unmapped, buried glacial drift aquifer *may* exist: the thicker the surficial deposits, the greater is the probability for aquifer materials to be buried within those surficial deposits.

Assumptions are listed in the order in which they are invoked in the model. Because the model builds the map units starting with the component judged most significant to aquifer contamination potential, it may be said that assumptions are listed roughly in decreasing order of importance. Our assumptions are:

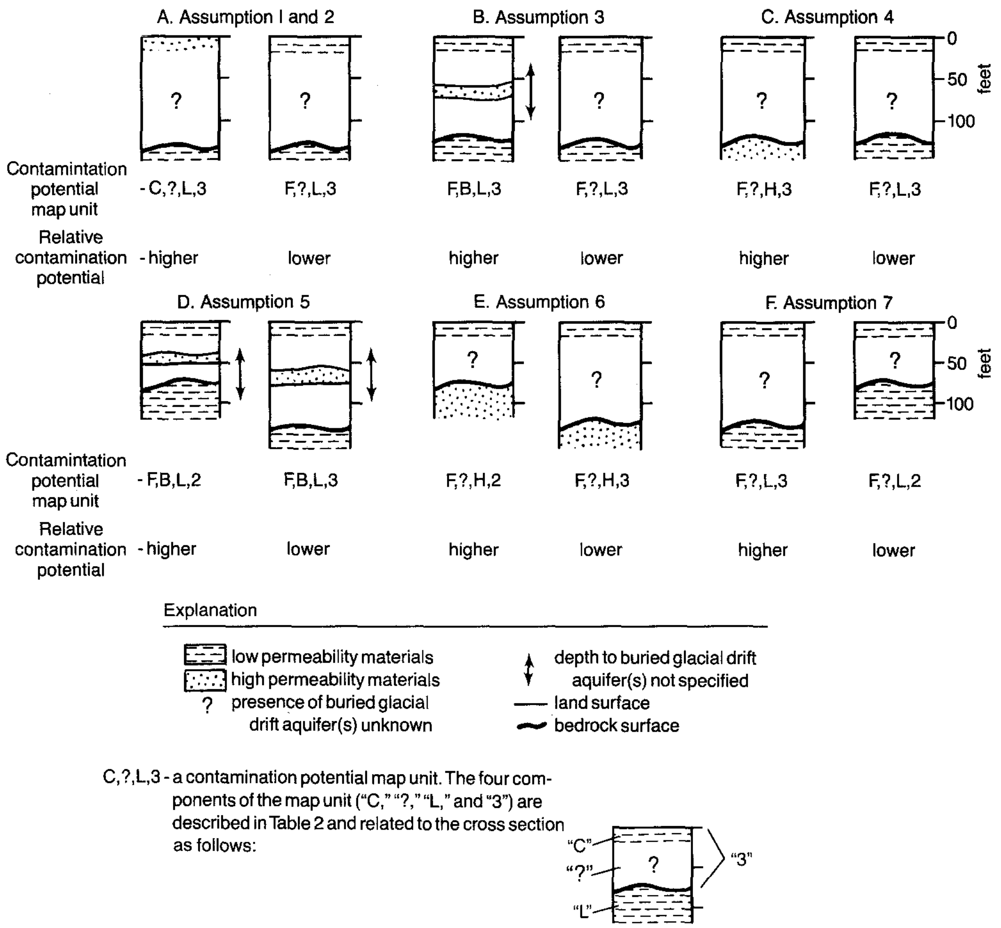

Figure 2. Cross-sections illustrating the model's assumptions.

1. Coarse-grained surface sediments (sand and/or gravel) are considered to be aquifers. Areas with these surface sediments are, therefore, assigned a higher relative contamination potential rating (Fig. 2A).
2. Till and fine-grained, stratified deposits are not considered to be aquifers (Fig. 2A).
3. Areas with buried glacial drift aquifers have a relatively higher potential for aquifer contamination than areas where such aquifers are unknown (Fig. 2B). Absence of such aquifers may, however, be merely an artifact of the database; given more detailed subsurface information, buried glacial drift aquifers may be found, thereby increasing the contamination potential.
4. Bedrock of relatively high permeability is considered to be an aquifer, but bedrock of relatively low permeability is not (see Fig. 2C).
5. If a buried glacial drift aquifer is present but its precise depth is unknown, the overall thickness of surficial deposits can be used to constrain the potential aquifer depth and, therefore, the contamination potential (Fig. 2D). For example, an aquifer buried in thin drift is more likely to be nearer the surface than an aquifer buried in thick drift.
6. The deeper an aquifer (e.g., in the bedrock) is buried beneath low-permeability material, the lower is the potential for contamination (Fig. 2E). Aquifers with the maximum potential for becoming contaminated lie at land surface.
7. As the thickness of surficial deposits increases, so does the probability of encountering a buried glacial drift aquifer. This assumption is counter to assumption 6, and is invoked when neither bedrock nor buried glacial drift aquifers are known (Fig. 2F). In such a geologic setting, assumption 6 should not be used because of the lack of information about buried aquifers. Assumption 7 serves as the more conservative approach to evaluating contamination potential because it does not as-

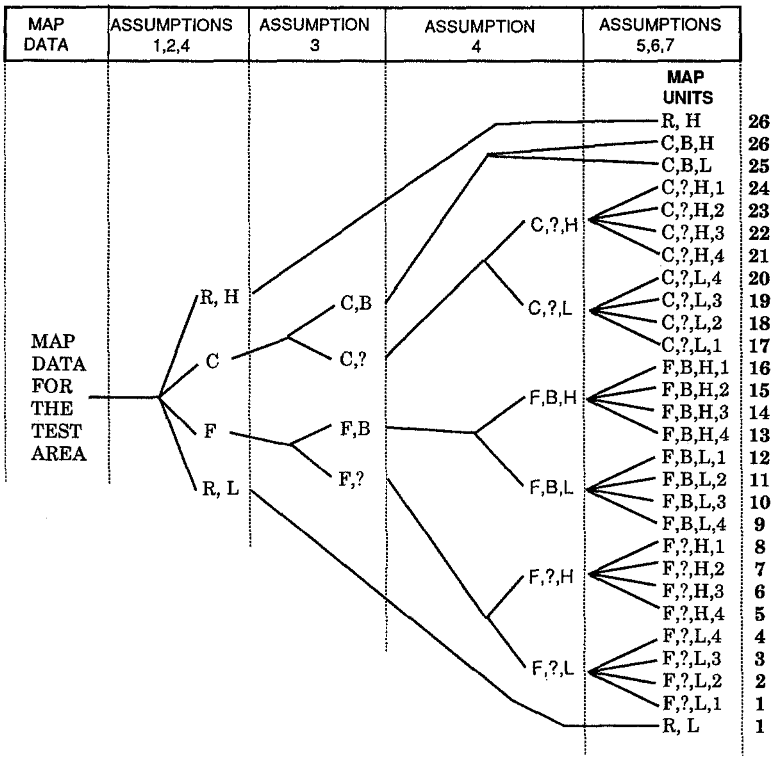

Figure 3. Flow chart showing how the contamination potential map units are assembled. Map units are described by four components of geologic information. These components are systematically combined in four steps. At each step, preliminary map units are defined by subdividing a component (e.g., "C," or "F") based on the assumptions listed. Components are explained in Table 2. The final step derives 26 contamination potential map units. To the right of each map unit code is a corresponding number referred to in the text and in Table 3, where the units are ranked for contamination potential.

sume the presence of unknown aquifers, as assumption 6 would, but rather relies on sediment thickness to indicate the likelihood of encountering a buried aquifer.

Assembling the Contamination Potential Map Units

Using the assumptions, the model component information is assembled into preliminary contamination potential map units. This procedure is summarized in Fig. 3, using the model components and codes listed in Table 2. The model assumes that of the four components, primary importance for contamination potential can be attributed to the surface sediments, with lesser importance attributed to buried aquifers, the bedrock, or sediment thickness. Map units are, therefore, assembled from components in that order.

The surface sediment component is subdivided first. Based on assumptions 1 and 2, all areas with coarse-grained surface sediment ("C") (Table 2 and Fig. 3) are, as a group, assigned a higher preliminary contamination potential than areas with fine-grained surface sediment ("F"). For areas with patchy drift or exposed bedrock, contamination potential is governed by bedrock permeability (assumption 4); areas of relatively high-permeability bedrock ("R,H") are considered to have the highest contamination potential, and areas of relatively low-permeability bedrock ("R,L") the lowest. The groupings of coarse- and fine-grained surface sediment are then subdivided according to the presence or absence of mapped buried glacial drift aquifers (assumption 3). Within both the coarse- and fine-grained surface sediment groups, areas of known, buried glacial drift aquifers ("C,B"; "F,B") are assigned a higher preliminary contamina-

Table 2. Description of model components and associated symbols used in this paper

Model component	Symbol
1. Surface sediments	
Coarse-grained, stratified sediment or organic-rich deposits	C
Glacial till or fine-grained, stratified sediment	F
Patchy glacial drift or exposed bedrock	R
2. Aquifers buried within the surficial deposits	
Known buried aquifer, depth unspecified	B
Presence of buried aquifer unknown	?
3. Relative permeability of bedrock	
Low	L
High	H
4. Thickness of surficial deposits	
50 ft	1
50–100 ft	2
100–200 ft	3
>200 ft	4

tion potential than areas where buried aquifers were not mapped ("C,?"; "F,?"). The four subgroupings of surficial deposits are further subdivided into eight categories, according to high ("H") or low ("L") bedrock permeability as stated in assumption 4 (for example, "F,B,H"). Using assumptions 5, 6, and 7, the eight surficial deposit subgroupings are subdivided into 26 map units.

Areas with mapped buried glacial drift aquifers are subdivided (e.g., "F,B,H,1") according to assumption 5 (the thinner the drift, the greater the likelihood that the known buried aquifer is closer to the surface). For areas with coarse-grained surface sediment and a buried glacial drift aquifer (units 25 and 26 on Fig. 3), contamination potential is innately high, and we decided that a further subdivision based on drift thickness would not be meaningful.

For areas without mapped buried glacial drift aquifers, the potential that such aquifers *may* exist is addressed by assumptions 6 and 7. For those areas where the bedrock is relatively permeable, a higher preliminary contamination potential was assigned to areas with thin surficial deposits than to those with thick surficial deposits (assumption 6). For those areas where the bedrock is of relatively low permeability, a lower preliminary contamination potential was assigned to thin surficial deposits than to thick surficial deposits (assumption 7) because the likelihood of an unknown buried glacial drift aquifer is greater in thick drift areas than in thin drift areas (see Fig. 2F).

Ranking the Contamination Potential Map Units

Our ranking of contamination potential map units is shown in Table 3, and is based on the preliminary order of map units in Fig. 3, with certain modifications. For example, unit 8 is assigned a significantly higher ranking than its position in Fig. 3 would indicate because of the vulnerability of the unit's geologic setting: permeable bedrock occurs within 50 ft of the surface. The other modification concerns map units with buried glacial drift aquifers, which were assigned relatively higher ranks than map units without known aquifers of this type (e.g., see units 2, 7, 11, and 15).

Table 3 shows a range of colors and patterns that could be used to convey rankings of contamination potential on a map. As has become conventional for maps of this theme [Berg and Kempton 1984; Berg and others 1984a,b; Schmidt and Kessler 1987; Keefer and Berg 1990; and maps made according to the DRASTIC model (see Aller and others, 1987, p. 101)], red colors indicate higher contamination potential than shades of yellow, brown, green, or blue. In our model, a green-colored map unit does not necessarily imply that vulnerable aquifers are not present or that groundwater in the deposits cannot be contaminated. Rather, it may indicate a lack of subsurface information, which dictates a lower rank than areas where aquifers are known from more detailed subsurface information.

This model is executed readily with digital map information, using geographic information system (GIS) techniques. If all source map information is in digital format, as it was for the test area, a contamination potential map can be generated efficiently as a derivative map. For the test area, the digital maps for the four model components were combined into a single map that shows relative contamination potential while retaining all information from the original maps (see Table 3 for notation of map color unique to each map unit and geologic sequence).

Table 3. Ranking of map units for relative contamination potential

Map unit no.	Map color	Overprint pattern
26	dark purple	—
25	purple	—
24	light purple	—
23	purple-red	—
16	red	1
12	red	2
8	red	—
22	pale red	—
21	dark orange	—
20	orange	—
19	orange-yellow	—
18	yellow	—
17	pale yellow	—
15	tan	1
11	tan	2
7	tan	—
14	light brown	1
10	light brown	2
6	light brown	—
13	brown	1
9	brown	2
5	brown	—
4	pale green	—
3	light green	—
2	green	—
1	dark green	—

These rankings are not quantified or precise, and little significance is implied in small differences in contamination potential rank. The suggested range of map colors follows conventional usage for this map theme. Patterns can be used to differentiate certain related units; here, two different patterns are used (arbitrarily labeled "1" and "2").

Map Interpretation

This model is intended to be a general tool for assessing the regional vulnerability of aquifers to contamination. The resulting map is not intended for local, site-specific use, but rather for indicating broader areas of greater and lesser contamination potential. As such, it is useful for prioritizing local areas where contamination potential and/or land-use history warrant more detailed assessment or monitoring. In addition, because our map provides a regional view of contamination potential, regional patterns and trends of map units should be evaluated, rather than using the map information literally to assess local areas.

Commonly, regional patterns and trends on maps can be more clearly understood and used if map units are organized into provinces, or settings, of similar characteristics. To aid in comprehension, our contamination potential map was organized into provinces, which will be shown with the map when published. These provinces are delineated mostly by the relative level of contamination potential and its variability, and by the geologic materials. Also, some provinces are delineated by geologic history. For example, certain provinces correspond to areas once covered by a particular ice lobe or lobes during a glacial stage, or to areas between ice lobes, or to areas of older drainage now filled with glacial deposits. The geologic processes that formed these areas imparted a particular geologic signature that influences the contamination potential map patterns and rankings.

For our test area, certain provinces are characterized by uniform geology and contamination potential, and show logical and predictable patterns among contamination potential map units. Other provinces have complex, widely varying geology and contamination potential. Some provinces can be defined as regions of great uncertainty, where there is little three-dimensional control. For example, map units 4, 5, 20, and 21 have drift thicknesses exceeding 200 ft, with no mapped buried glacial drift aquifers. On the southern peninsula of Michigan, these map units occur in a region underlain by drift exceeding 800 ft across broad areas (Soller in press). There, the surface sediments are primarily till, with coarse-grained, stratified surface sediments confined to lowlands. The map pattern is mostly defined by the surface sediments because surficial deposits exceed 200 ft and, therefore, fall within a single thickness category. If more information on texture of subsurface glacial deposits were available for such an area or province, the map might appear substantially different.

Although the province concept can be a useful tool for organizing map data, the subjective boundaries and definitions of provinces do not lend themselves to statistical analysis, which may be required to support environmental management or economic choices. For such applications, gridded data may be more appropriate. Gridded map data may provide a tool for area prioritization and analysis of contamination potential trends that can complement the information contained on conventional contamination potential maps. We are researching the use of geologic information and our model in a statistically based approach to assessing contamination potential.

Concluding Remarks

Our model uses commonly available, basic geologic information on texture and three-dimensional framework, and produces a derivative geologic map with all original information intact but with map units defined to rank sequences of geologic materials by their relative potential for contamination. Information for a variety of purposes can be derived from a contamination potential map generated by this model. For example, all areas of coarse-grained, surface sediment, or areas of exposed, permeable bedrock can be derived from the contamination potential map, for use in the management of groundwater recharge areas.

This model and map are intended to support decisions on management of groundwater resources. To do so, the map can be supplemented by analysis according to map province and gridding techniques. Spatial variability and uncertainty of data must also be an integral part of map interpretation and decision-making. Of necessity, these analyses and decisions are subjective. Ideally, contamination potential maps should be statistically validated to show the correlation between contamination potential rankings and water quality and to determine the statistical probability of contamination for different map units so that area prioritization for groundwater management and protection can be statistically defensible. However, this goal has not yet been attained, in part because of difficulties in obtaining a statistically acceptable population of water-quality data for mapped areas, and in translating map data into statistically valid sample points or areas. In our continuing research, we intend to statistically test the predictive ability of our model and its components. The economic benefits of using contamination potential mapping in economic/regulatory choices could be more realistically addressed with a validated, statistically based model.

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