GEOLOGIC FACTORS AFFECTING THE SENSITIVITY OF THE PRAIRIE DU CHIEN–JORDAN AQUIFER

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INTRODUCTION

The Groundwater Sensitivity Project is a multi-agency cooperative effort to develop methods of delineating sensitive ground-water areas. A sensitive area, as defined by the Groundwater Protection Act of 1989, is "a geographic area defined by natural features where there is a significant risk of groundwater degradation from activities conducted at or near the land surface." The Minnesota Geological Survey's primary contribution to the project, and the subject of this report, is an investigation of geologic factors that affect the sensitivity of the Prairie du Chien–Jordan aquifer to degradation. In a related activity, MGS staff members helped develop preliminary criteria and application guidelines to discriminate more sensitive areas from less sensitive areas on the basis of geologic conditions.

In a practical sense, all aquifers are hydrologically connected to the land surface, and it is the effectiveness of this connection that determines their relative sensitivity to contamination. Those aquifers that quickly receive water (and contaminants) from the land surface are considered more sensitive than those aquifers that receive water more slowly from the land surface. The differences in flow velocity are difficult to measure precisely over time, but they can be related to the rate of water flow in the the earth materials that lie between the land surface and the aquifer, and to the thickness of those earth materials. Lower flow rates and thicker overburden reduce sensitivity; higher flow rates and thin overburden increase sensitivity. For many contaminants, there are no natural processes that will remove them once they enter the ground, particularly once they move below the zone of biologic activity (the soil). Given enough time, any aquifer, even one of low relative sensitivity, can become contaminated.

We have made certain assumptions to constrain the size of this study. We have assumed that potential contaminants behave like water; that is, the contaminants are not subject to processes of adsorption, ion exchange, or redox reactions that can diminish their concentration. We have assumed that these contaminants move from the land surface to the aquifer through natural flow paths rather than through poorly constructed wells or other man-made pathways. And, last, for an aquifer that is buried by a significant thickness of younger geologic materials, we have assumed that it is the material directly above any point in the aquifer that most strongly affects sensitivity at that location; vertical flow paths are more important than lateral flow paths for assessing ground-water sensitivity. The validity of this assumption, and its effect on our interpretations, will be discussed in more detail in another section of this report.

Most scientific investigations are conducted by (1) observing a particular behavior or phenomenon; (2) hypothesizing possible factors that affect the behavior or phenomenon, (3) gathering data on these factors; (4) creating a model of the behavior or phenomenon, and (5) testing the model against the observed behavior or phenomenon. In this study, we have observed that nitrate contamination is unevenly distributed within the Prairie du Chien–Jordan aquifer (Plate 1). We have hypothesized that the thickness and hydrologic properties of the earth materials that overlie the aquifer control the introduction of contaminants to the aquifer (sensitivity), and that the hydrologic properties of the rocks that form the aquifer control the distribution of the contaminants within the aquifer (intra-aquifer sensitivity). To test these hypotheses, we must first determine if the presence of nitrate is a reliable indicator of sensitivity to contamination and, if it is reliable indicator, if our hypothesized geologic factors control the distribution of nitrate in the aquifer.

The study area comprises those places where strata of the Prairie du Chien Group or Jordan Sandstone are the first bedrock units encountered beneath the glacial drift. Most of the possible flow paths from the land surface to the aquifer are thereby limited to the glacial drift, and any effects on ground-water sensitivity of any overlying bedrock formations are eliminated. The rocks of the Prairie du Chien–Jordan aquifer are in places overlain by other bedrock formations, the hydrology and associated sensitivity of which are relatively uniform regionally and better understood than those of the glacial drift. Numerous studies have been made of these overlying formations, the results of which can be used in conjunction with the geologic factors identified in this report to assess the sensitivity of the aquifer where it is overlain by glacial drift and bedrock formations.

The intent of this work is to identify and map geologic factors that affect sensitivity rather than to map aquifer sensitivity directly. The geologic maps accompanying this report (Plates 1–12) are part of this experimental mapping procedure that was created for this investigation and should not be used as direct indicators of sensitive areas. Before evaluating the sensitivity of a specific site, the user of these maps must first understand the amount and type of data used to compile them, the scales used for mapping, how the various geologic factors interrelate, and the reliability of the contaminant data as an indicator of sensitivity.

EFFECTS OF GLACIAL DRIFT ON THE SENSITIVITY OF THE PRAIRIE DU CHIEN–JORDAN AQUIFER

In a time-based assessment of aquifer sensitivity, the hydraulic conductivity of earth materials that overlie the aquifer is of fundamental importance. The effects of conductivity begin at the surface and are cumulative with depth. If the surficial material is of low conductivity, more uncontrolled contaminants will be incorporated in surface runoff and enter surface-water systems; if the surficial material is of high conductivity, infiltration will be maximized. It is the earth materials between the soil and the aquifer that determine how quickly contaminants reach the aquifer.

Glacial drift is a complex mix of diverse materials of various depositional modes (till, outwash, etc.). To map the hydrologic character of the drift, one must recognize and map units within it that are regionally comparable in hydrologic properties and can be distinguished in the available data. The uppermost portion of the glacial drift can be mapped with some detail, owing to the availability of soil and surficial geologic maps. In previous Minnesota Geological Survey (MGS) sensitivity mapping efforts as part of the County Atlas Program, the hydrologic characteristics of glacial drift were inferred from published maps, from known glacial history, and from mapped drift thickness. Site-specific subsurface information has generally not been utilized in these sensitivity assessments. A sensitivity map, which was compiled using the traditional sources of surficial geologic data, has been prepared for the study area (Plate 2) so that this mapping method can be compared with a new technique of mapping.

The new mapping technique requires less inference and knowledge of glacial history than the traditional mapping method. It emphasizes data that describe the entire thickness of the glacial-drift section. The descriptions of the materials encountered in the drilling of water wells are the most abundant and widely available data for the mapping of glacial drift at depth. These descriptions are written by well drillers, who generally do not have training in geology. However, the success of these drillers in constructing wells depends on their ability to differentiate aquifer materials from nonaquifer materials. The two most abundant genetic units in glacial drift are till and outwash. In well records, till is commonly described as clay or some mixture of clay and other components; outwash is commonly described as sand, gravel, or a mixture of these materials. Other drift units, such as lacustrine deposits or fluvial deposits, are also commonly described as clay or clay mixtures, or sand and gravel mixtures. Differentiating glacial materials with a significant clay component from glacial materials without clay was the basis for the creation of the map units that were used in this study to assess the effects of glacial drift on the sensitivity of the underlying Prairie du Chien–Jordan aquifer.

Mapping Glacial Drift

To accommodate the three-dimensional variability of the glacial drift, it was mapped in a series of maps that represent the character of the glacial drift at different depth intervals (Plate 3). Depth-based layers were used rather than elevation-based layers because the greatest drift thickness was less than the range in elevation of the highest and lowest glacial drift in this area. Therefore, fewer maps were needed to represent the complete drift section. A three-unit map was constructed for each 25-foot depth interval (0-25 ft, 26-50 ft, . . .). The first of the three glacial map units is sand and gravel; the second, a transitional unit containing subequal thicknesses of clayey and sandy materials; and the third, till and other clayey material. An interval containing greater than 18 feet of sand was designated a sand-and gravel unit; an interval containing less than 18 feet of both sand and gravel and clay was designated a transitional (or mixed) unit; and an interval containing greater than 18 feet of clay was designated a clay unit. Figure 1 traces the steps that were taken to create these maps from well-record data.

To characterize the hydrologic properties of the entire glacial section at a single point, each of the three map units was assigned an index value that reflects its relative hydraulic conductivity. The index value is the absolute value of the exponent of hydraulic conductivities (in cm/sec. units) proposed for glacial materials (Fetter, 1988; Freeze and Cherry, 1979; Todd, 1970). The clay map unit has an index value of 7; the sand unit, an index value of 2; and the mixed unit, a value of 5. The sum of the index values for the entire glacial sequence is the **confinement index** for that point. A map of these confinement-index values is a two-dimensional representation of the three-dimensional hydrologic character of the glacial sequence. The confinement-index values were compared with nitrate distribution in the study area to determine the effects of the character and thickness of glacial drift on sensitivity. Because this index reflects *vertical* conductivity, and most ground-water flow is lateral, the confinement index may not be applicable to assessing ground-water sensitivity. However, the transfer of contaminants from the land surface to a buried aquifer obviously involves some vertical flow. The intervals of low vertical conductivity may lessen the sensitivity of buried aquifers by limiting the depth of local flow systems and separating contaminated waters at shallow depths from waters of deeper, regional flow systems.

Manual method

Confinement-index and depth-interval maps can be created separately if the work is done manually (Fig. 1). The confinement-index map is compiled by calculating the index value for each well log that describes the entire sequence from the land surface to the aquifer, and then plotting and contouring these values. The work of compiling the layer maps is made easier by punch-registering the mylar sheets for each layer and the covering data sheet. Each well location and the sequence of map units is plotted on the data sheet. The map unit designators are then transferred to their respective layers. The contact for each individual layer is drawn separately between areas of different rock types as indicated by the designators for each well location. This step involves considerable geologic inference, but, because of the simplicity of the map units, it is usually not difficult.

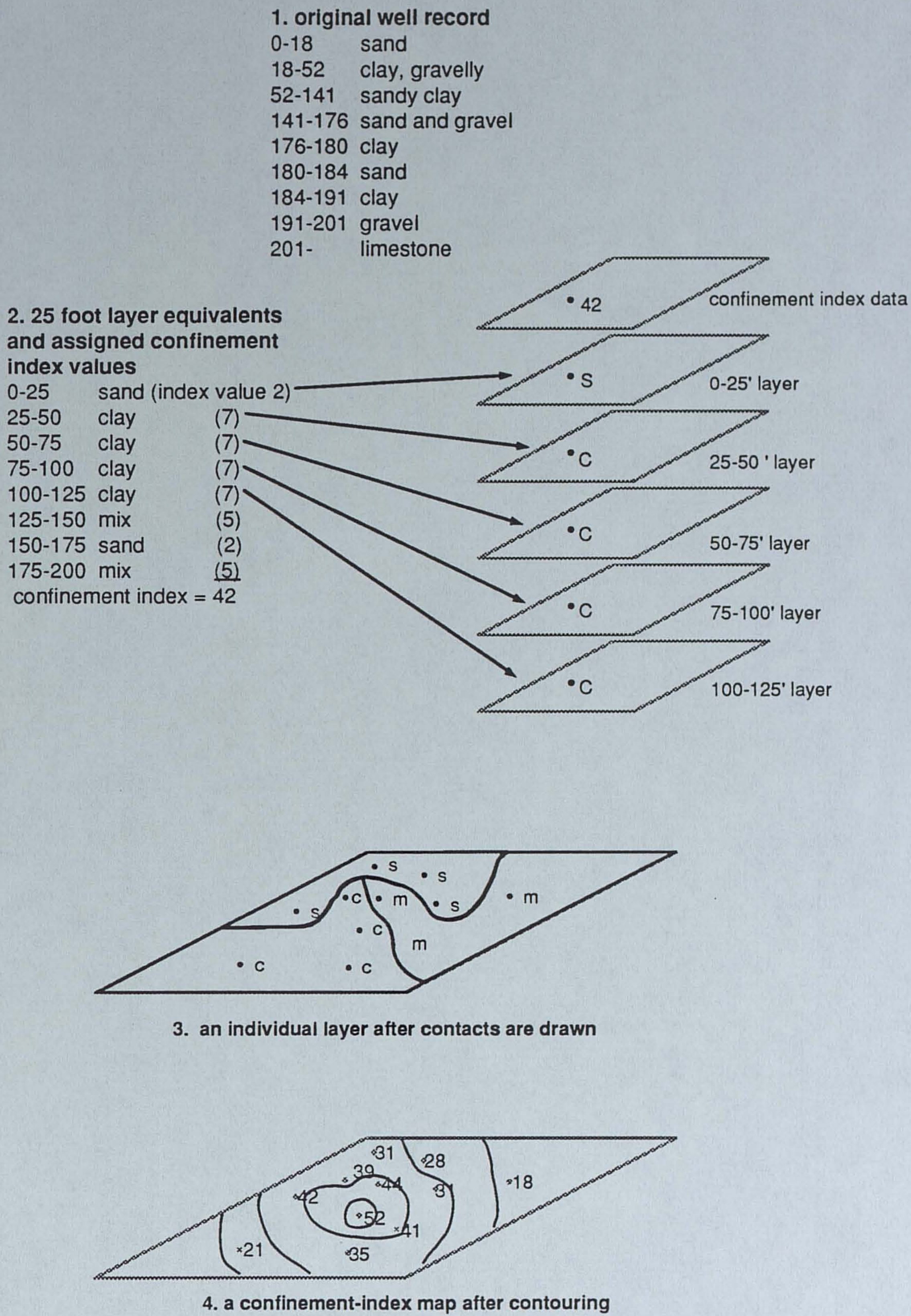


Figure 1. Steps in creating layer maps of glacial drift and the confinement-index map by manual methods.

Because only a small part of the study area has glacial drift greater than 200 feet thick, a single layer map was constructed to represent the entire drift section in that area. That layer has confinement-index values assigned to its units that represent the total drift sequence below 200 feet. Manually created versions of both the confinement-index map and the series of layered maps are available for inspection at the MGS.

Computer-driven method

Computers can be used at one or more stages in the process of making a confinement-index map or a series of layer maps. The maps produced for this project utilized manual and digital mapping techniques. The series of layer maps (Plate 3) was created manually. However, these maps were then digitized, and the geographic information system (ARC/INFO; Environmental Systems Research Institute, Redlands, Calif.) was used to intersect them and create a confinement-index map (Plate 11). There are several advantages to this procedure. In the manual method, the confinement-index map is generated by contouring the summed index values from each well log. In the computer method, the mapped areas are assigned the confinement values and these values are summed by digitally intersecting the maps. Because the computer intersects the *areas* designated by the map units and creates a new map using these intersections, no additional contouring is necessary and an interpretive step is eliminated. The confinement-index map and the layer maps can be easily compared and intersected with any other digital mapping. This facilitates the introduction of cultural or other, nongeologic factors into sensitivity assessments.

EFFECTS ON SENSITIVITY OF GEOLOGIC CONDITIONS WITHIN THE PRAIRIE DU CHIEN–JORDAN AQUIFER

The travel time for water and contaminants within a bedrock formation (and thus its relative sensitivity) is controlled by the type and number of flow paths in the rock and the driving force (head). The flow may be intergranular, and therefore affected by grain size, cementation, and the related properties of porosity and permeability, or flow may be through fractures and solution cavities and affected by fracture sizes and patterns. The lithologic character of an aquifer will affect the sensitivity of the water within it, as well as the sensitivity of any additional aquifers that receive flow from it. The Prairie du Chien Group and Jordan Sandstone have long been regarded as a single aquifer because they have similar potentiometric values and no intervening confining units have been recognized. However, as two parts of an aquifer they have distinct lithologic characteristics and, therefore, distinct hydrologic properties. Nitrate is unequally distributed in their waters, which suggests parts of the aquifer probably also have different sensitivity to contamination. To address these known and hypothesized differences, the subcrop area of the Prairie du Chien Group and Jordan Sandstone (those areas where these rocks are the first bedrock encountered beneath the glacial drift) was used to define the study area and was mapped using water-well records on file at the MGS and information obtained from MGS county atlases for Washington (Swanson and Meyer, 1990), Hennepin (Balaban, 1989), Dakota (Balaban and Hobbs, 1990), Scott (Balaban and McSwiggen, 1982) Ramsey (work in progress), Winona (Balaban and Olsen, 1984), and Olmsted (Balaban, 1988) counties. This mapping effort also utilized other regional MGS mapping (Mossler, 1983). The structure and isopach maps of the aquifer (Plates 4–8, 10) are also largely based on water-well records, with the addition of borehole geophysical logs. The contour interval was 50 or 100 feet, depending on the data available and cartographic constraints.

The lithologic properties of the Prairie du Chien Group and Jordan Sandstone were investigated through outcrop descriptions, approximately 350 borehole geophysical logs, and samples from about 60 drillholes. By combining these sources of information, it was possible to map lithostratigraphic units that were either previously unrecognized, or recognized in outcrop but not mapped, owing to a lack of high-resolution subsurface data.

Stratigraphic Nomenclature

The Jordan Sandstone is mostly quartzose sandstone. It is divided into two members (Fig. 2). The Norwalk Member is the lowermost part of the Jordan Sandstone and consists largely of fine-grained sandstone and siltstone. The Van Oser Member is the upper part of the Jordan and consists mostly of fine- to coarse-grained sandstone. Lenses of very fine-grained sandstone and siltstone interbedded with the Van Oser Member are probably analogous to the Sunset Point Member of Wisconsin and the Waukon Member of Iowa (Odom and Ostrom, 1978).

The Prairie du Chien Group is composed of sandstone and dolostone. It is divided into two formations: the lower Oneota Dolomite and the upper Shakopee Formation. The Oneota Dolomite is mostly fine-grained dolostone except for the lowermost part of the formation, where clastic parts of the section have been designated as members. The Blue Earth siltstone in the western limb of the study area and the Coon Valley Member in the eastern limb of the study area are composed of interbedded siltstone, sandstone, sandy dolostone, and shale. They lie between the medium- to coarse-grained sandstone of the upper part of the Jordan Sandstone below and the relatively pure dolostone of the Oneota Dolomite above. The Blue Earth siltstone and Coon Valley Member are regarded as a single lithofacies in this discussion and treated as a part of the Oneota Dolomite. Previous workers have assigned these transitional beds to the upper part of the Jordan Sandstone (Thomas, 1991; Mossler, 1987; Odom and Ostrom, 1978) or to the basal part of the Oneota Dolomite (Adams, 1978; Davis, 1970). It is easier when examining drill cuttings, outcrops,

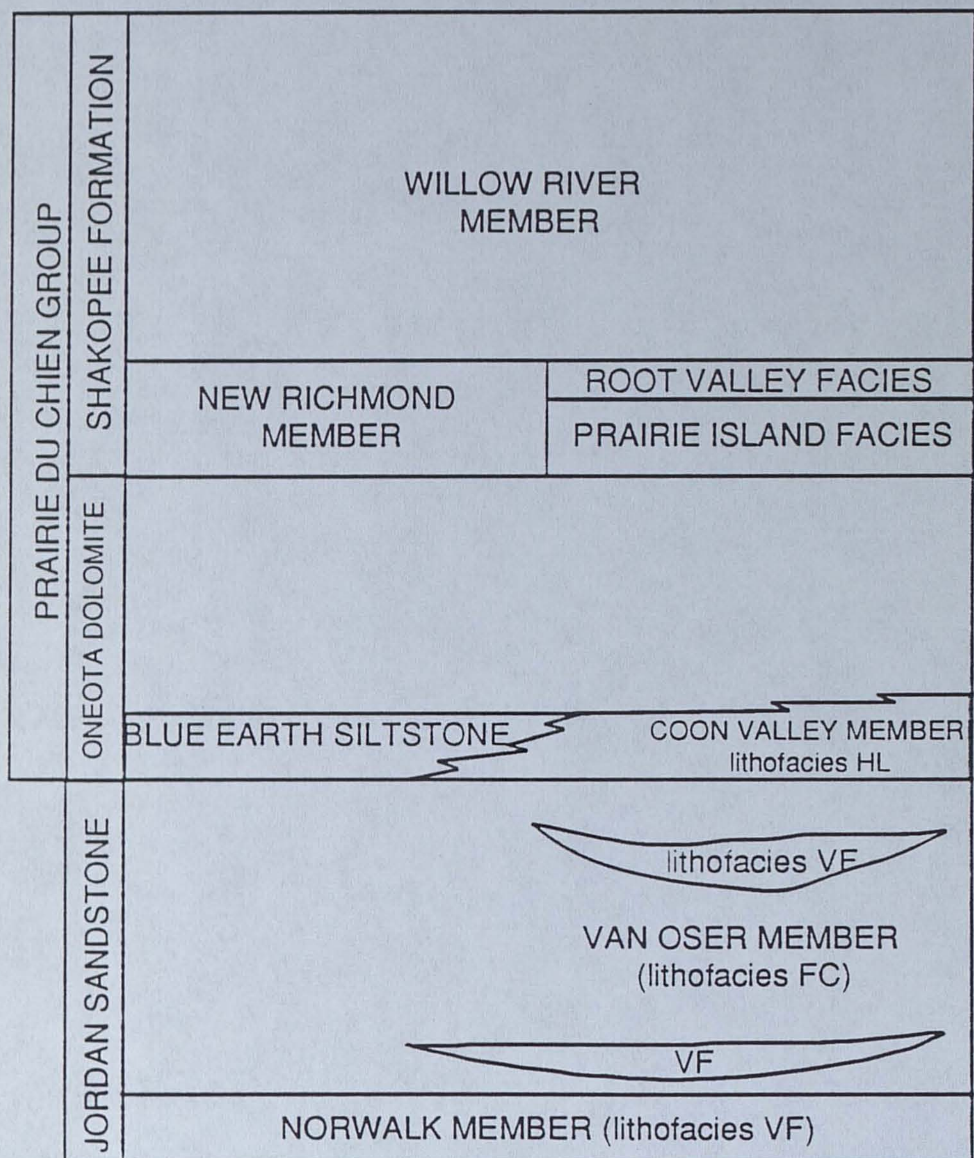


Figure 2. Stratigraphic nomenclature used in this report for the Prairie du Chien Group and Jordan Sandstone.

and gamma logs to recognize the base of these transitional beds in contact with the Jordan Sandstone than it is to recognize their upper, gradational contact with the Oneota Dolomite.

The Shakopee Formation includes a lower sandstone unit, the New Richmond Member, and an upper dolostone unit named the Willow River Member (Fig. 2). The New Richmond Member is subdivided into the Root Valley facies, a fine-grained quartzose sandstone, and the Prairie Island facies, a thinly bedded sandstone with interbeds of sandy dolostone.

Lithostratigraphy

Lithostratigraphic units within the Prairie du Chien Group and Jordan Sandstone were identified and mapped using outcrops, drill cuttings, and borehole geophysical logs (namely, gamma logs). Gamma logging was an integral part of the study because of its usefulness for identifying rock properties and stratigraphic correlation. It is the most widely used nuclear log in ground-water applications and provides useful information for a variety of borehole conditions. Wells with both natural-gamma logs and drill cuttings provided a means of directly comparing two sources of information on rock properties. Similar comparisons were made using outcrops and gamma logs from nearby boreholes. These comparisons facilitated the interpretation of gamma logs in wells without drill cuttings or in areas of sparse outcrop.

Jordan Sandstone

Gamma responses in the Jordan Sandstone are mostly very low, but high readings over intervals up to 40 feet thick are common (Fig. 3). The low gamma responses correspond to sandstone that is mostly fine- to coarse-grained, which is here informally named **lithofacies FC** (fine to coarse grained). This lithofacies is similar to published descriptions of the Van Oser Member of the Jordan Sandstone. It is a trough cross-bedded, moderately sorted, fine- to medium-grained sandstone composed of about 98% quartz (Dott, 1978; Odom and Ostrom, 1978). Except for the uppermost five feet of the Jordan Sandstone, which is mostly strongly cemented with carbonate, lithofacies FC is friable; it is represented in drill cuttings by moderately to poorly sorted, disaggregated grains of quartz. Low gamma responses in the Jordan Sandstone also indicate the presence of dolostone. In southeastern Washington County there are thin dolostone interbeds in the Jordan Sandstone, but these are not thought to be a major major component of the formation here or elsewhere in the study area.

High gamma values in the Jordan Sandstone consistently correlate with intervals of very fine-grained sandstone, siltstone, and rare shale; these intervals are here informally named **lithofacies VF** (very fine grained). Potassium in the detrital component of these rocks or in the cement causes the high gamma values. Lithofacies VF is moderately sorted, bioturbated,

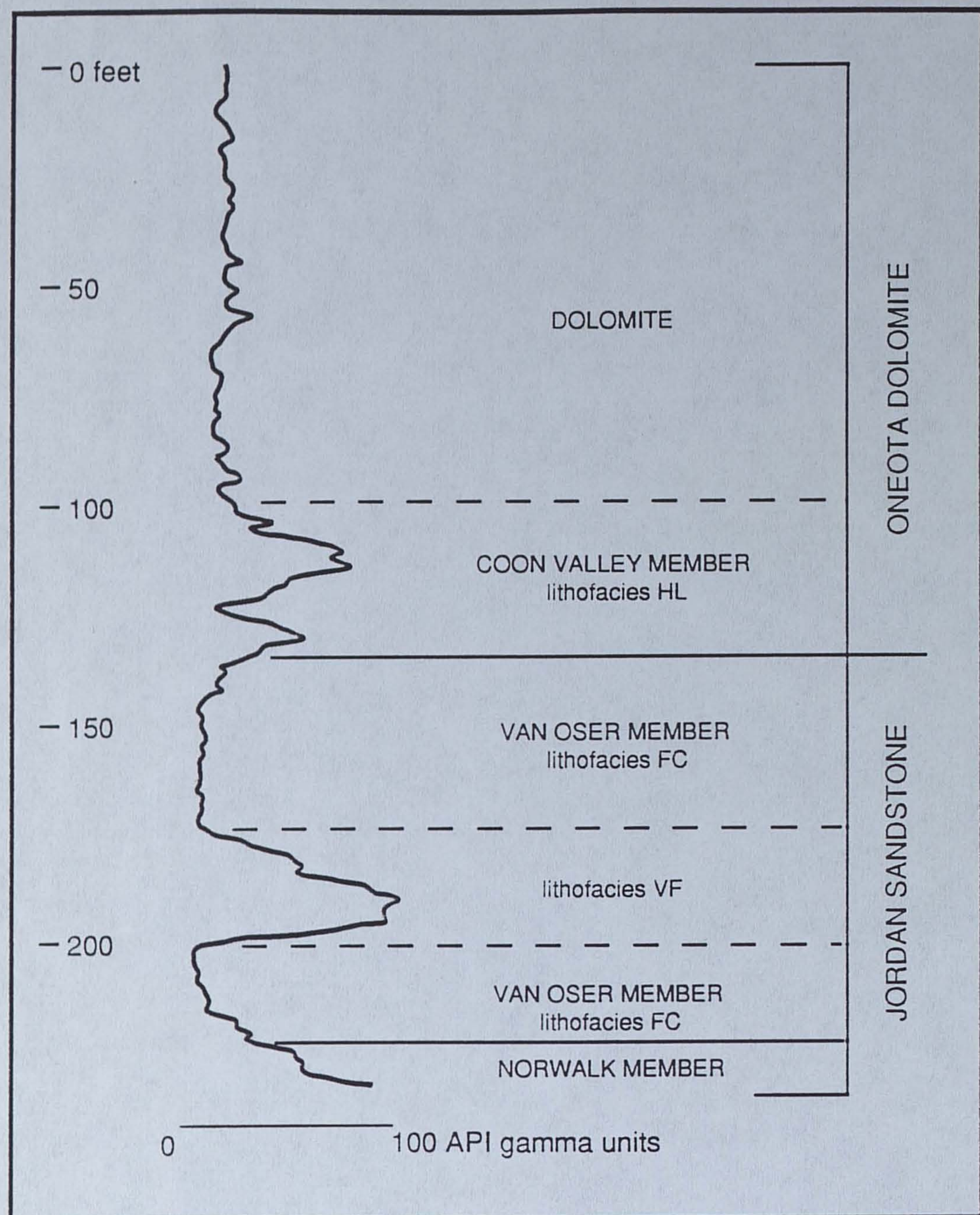


Figure 3. Representative natural gamma signature for the Oneota Dolomite and Jordan Sandstone.

structureless or faintly stratified, very fine-grained sandstone and siltstone; poorly sorted, coarse-grained sandstone and siltstone; and, rarely, moderately sorted, medium- to coarse-grained sandstone. Drill cuttings commonly contain 30–70% aggregates or chips, the presence of which indicates that at least some parts of this lithofacies are firmly to strongly cemented. Lithofacies VF is strongly cemented in places and friable in others. The cement is probably carbonate: all of the cemented samples disaggregated in weak hydrochloric acid. Silica and feldspar cements have also been reported (Dott, 1978; Odom, 1978).

Gamma logging highlights the vertical distribution of lithofacies VF and FC of the Jordan Sandstone. Fence diagrams, which were constructed using the gamma logs, aid the lateral mapping of these facies (Plate 9). Lithofacies VF commonly occurs as lenticular or broad, bowl-shaped bodies across most of the study area. It is as much as 40 feet thick and extends laterally from less than one mile to about 10 miles. The abundance of lithofacies VF varies locally and regionally. Generally, the Jordan Sandstone contains 20–40% of lithofacies VF in the eastern limb of the study area (Dakota to Houston Counties). In the western limb of the study area (Hennepin to Faribault Counties), lithofacies VF comprises less than 10% of the Jordan Sandstone. In Washington County, about 10 to 50% of the Jordan Sandstone can be assigned to this lithofacies.

The high-gamma values typically associated with lithofacies VF of the Jordan Sandstone produce an asymmetrically shaped curve (Fig. 3). The lower boundary of the signal is nearly horizontal, indicating an abrupt change in lithologic character. The upper boundary is diagonal, indicating a gradational change. Grain size coarsens upward within lithofacies VF. Odom and Ostrom (1978) noted a coarsening-upward trend in the Jordan Sandstone of Wisconsin, a trend which is also evident in Minnesota. Over most of the study area, the siltstone of the Lodi Member of the St. Lawrence Formation grades upward to the fine-grained sandstone of the Norwalk Member of the Jordan Sandstone, which in turn grades upward to fine- to medium-grained sandstone (lithofacies FC) in the lowermost 20 feet of the Jordan Sandstone. Medium- to coarse-grained sandstone of lithofacies FC is usually encountered about 30 to 50 feet above the St. Lawrence Formation/Jordan Sandstone contact. Lenses of lithofacies VF may disrupt this pattern slightly. The coarsest part of the Jordan Sandstone is typically the uppermost 5 to 10 feet.

Prairie du Chien Group

The lithostratigraphy of the Prairie du Chien Group has been described in detail by Squillace (1979), Austin (1971), and Stubblefield (1971). Most of the rocks of the Prairie du Chien Group are carbonate, with ground-water flow mostly confined to fractures and solution cavities. These rocks are represented in gamma logs by intermediate to low, variable values. Additional study of the lithologic variations in the carbonate rocks would probably not identify variations in this flow style or associated sensitivity. Several noncarbonate units occur within the Prairie du Chien

Group. Both facies of the New Richmond Member of the Shakopee Formation contain significant detrital components, but because of their porosity, permeability, and thickness these facies would likely not alter the sensitivity of underlying zones of the aquifer. Similarly, thin (1–5 feet) intervals of siltstone to sandstone, sandy and silty dolostone, and rare shale have been encountered in the Shakopee Formation, but these intervals are probably not thick enough to significantly affect the sensitivity of underlying zones. However, interbedded dolostone and fine-grained clastic rocks at the base of the Oneota Dolomite were investigated for this study as a potential factor in variations in flow and sensitivity.

The correlative Coon Valley Member and Blue Earth siltstone of the Oneota Dolomite are here informally named **lithofacies HL** (heterolithic). Lithofacies HL varies in thickness; it includes interbedded, very fine-grained sandstone and siltstone; sandy dolostone; fine- to coarse-grained sandstone; and shale. Gamma values for this lithofacies are moderate to high, and are located between the low constant signature of the Van Oser Member of the Jordan Sandstone below, and the low to moderate, variable signature of the middle to upper Oneota Dolomite above. Lithofacies HL is thickest in Winona, Houston, southern Wabasha, and northern Olmsted Counties, where it is 20–35 feet thick; it thins to the west and northwest (Plates 9–10). In the Twin Cities Metropolitan Area north and west of Dakota County, and in the western limb of the study area from LeSueur to Faribault Counties, lithofacies HL is typically less than five feet thick and in many places absent. Where it is absent, there is a sharp contact between the medium- and coarse-grained sandstone of the Jordan Sandstone below, and the dolostone of the Oneota Dolomite above. Cementation in lithofacies HL is variable. Beds of medium- to coarse-grained sandstone are often friable, but fine-grained sandstone and siltstone are commonly strongly cemented.

Hydrologic Characteristics of the Lithofacies

The hydrologic characteristics of the clastic lithofacies of the Prairie du Chien Group and Jordan Sandstone determine the sensitivity of the aquifer and, perhaps, zones within the aquifer. Where flow has a downward, vertical component, lithofacies HL at the contact of the Prairie du Chien Group and underlying Jordan Sandstone may differentially affect the sensitivity of the aquifer above and below it. Lithofacies VF and lithofacies FC of the Jordan Sandstone presumably cause variations in the sensitivity of the ground water within that formation only—if they affect sensitivity at all.

To address the hydrologic character of the lithofacies VF, FC, and HL, seven samples that represent the three lithofacies and the variations of grain size and cementation within them were collected from outcrop. The samples were tested for porosity and vertical permeability at Core Laboratories in Carrollton, Texas (Table 1). Most measurements of hydraulic conductivity taken from outcrop samples do not represent true field conditions, but they can demonstrate that a wide range of conductivities exists within these rocks. The measured hydraulic conductivities of these rocks vary over four orders of magnitude. The values for lithofacies FC, the dominant rock type of the Jordan Sandstone, indicate that it is a moderately to highly permeable unit, with increased cementation causing a decrease in conductivity. Lithofacies VF yielded a conductivity range of greater than two orders of magnitude, and it can be described as low to very low in relative permeability. Again, increased cementation correlates with decreased permeability. Lithofacies HL, which lies between the Jordan Sandstone and the Prairie du Chien Group, has a low relative permeability.

Table 1. Porosity and permeability values for selected samples from lithofacies FC, VF, and HL
[k, hydraulic conductivity; md, millidarcy; m/day, meters per day]

Sample number	Lithofacies	Permeability (md)	k (m/day)	Porosity (percent)	Cementation
B-1	FC	3000	2.22E+00	26.0	moderate
L-1	FC	52.8	3.91E-02	22.9	strong
J-1	FC	1905	1.41E+00	35.1	moderate to strong
F-1	VF	107	7.93E-02	28.1	moderate
S-1	VF	0.126	9.34E-05	14.6	strong
M-1	HL	97.5	7.22E-02	20.6	moderate
N-1	HL	4.59	3.40E-03	15.0	moderate to strong

These measurements indicate that lithofacies FC constitutes an aquifer, as does most of the Prairie du Chien Group. Lithofacies VF and HL are low-permeability units within the Prairie du Chien–Jordan aquifer that may affect flow patterns and sensitivity. This hypothesis should be hydrologically tested in the field. Because lithofacies VF occurs on a local scale, its effects on ground-water sensitivity, if any, are also likely to be local. Lithofacies HL occurs on a regional scale, and its effects are presumed to be more widespread.

NITRATE DISTRIBUTION AS AN INDICATOR OF SENSITIVITY

Nitrate is probably the most common and the most widespread contaminant in the Prairie du Chien–Jordan aquifer. Most of the nitrate in the ground water of the Midwest comes from sources at the land surface, such as septic tanks, barnyards, manure storage and spreading, and fertilizers (Zaporozec, 1983). Nitrate is stable and soluble in ground water and moves like ground water once it passes the zone of biologic activity (the soil). Its stability and solubility make nitrate a convenient indicator of sensitivity. However, in some places within the study area there are no surface sources of nitrate. The absence of nitrate in the aquifer underlying these places does not indicate a lack of sensitivity. Similarly, in using nitrate as an indicator of sensitivity, it must be understood that nonvertical flow paths can cause nitrate concentrations that are unrelated to the geologic conditions immediately above the contamination.

Because human activities at the land surface have introduced nitrate into the ground for over 100 years, its presence in ground water cannot be related to any shorter unit of time. Other chemicals, such as herbicides and pesticides, that have been applied only more recently are a better indicator of travel time of ground water. However, there are more analyses available for nitrate in ground water than for almost any other chemical constituent. The data are not without problems. The analyses are unevenly distributed over the study area, with an obvious correlation between population density and the number of analyses. There are also disparities in data density that are the result of the testing and record-keeping policies of the various local government units that often support nitrate testing programs. The utility of nitrate distribution as an indicator of sensitivity is tied to the amount of geologic information available for the wells from which water samples are drawn. Some well records have enough detailed information to identify the aquifer; others have at least reliable depth and well-construction information, which can be used in combination with geologic mapping to determine the aquifer that yielded the sample. For some samples, the only information available is the well depth as recalled by the well owner. Again, some inference of the aquifer the well draws from can be made from this depth value, but this information is unreliable. Fortunately, these wells are a minor part of the data set.

Nitrate values vary locally (Zaporozec, 1983). Seasonal and daily fluctuations are also common. Nonetheless, the comparison of regions of anomalous nitrate values with regional geologic conditions remains a valid method of detecting sensitivity. Most of the study area is agricultural land, with the notable exceptions of the large urban and suburban areas of Minneapolis, St. Paul, and Rochester. For this reason the effects of land use on nitrate distribution can probably be regarded as universal except for those noted areas. The nitrate values on Plate 1 were compiled from records at the Minnesota Department of Health, the Minnesota Geological Survey, and county health departments. Information on well location and the nitrate value were entered into the CWI (County Well Index) data base and plotted digitally. Because these nitrate values were collected over many years, and because values can change over time and across even short distances, Plate 1 should not be used as an indicator of expected nitrate concentrations in a particular well or location.

Correlation of Geologic Features and Nitrate Distribution

Glacial Drift

Confinement index values for glacial materials were calculated for every water well finished in the Prairie du Chien–Jordan aquifer for which a nitrate analysis and a well record were available (more than 900 wells). A computer program was written to calculate the confinement index directly from the well log ; these values were then matched with the nitrate concentration value. Nitrate values can be low regardless of the character of the glacial drift, but high nitrate concentrations (greater than 5 ppm) are mostly confined to areas where the glacial drift overlying the aquifer is thin or sandy (low confinement index) (Fig. 4). High sensitivity indicates only a *potential* for contamination, but low sensitivity indicates that contamination through natural flow paths is unlikely. This limiting on the maximum nitrate concentration is illustrated on the plot by a line that represents the upper boundary of the 99% confidence envelope. The position of the line was determined by statistically analyzing the nitrate values for each ten-unit-wide confinement category (0-9, 10-19, 20-29, . . .) and calculating the nitrate value three standard deviations above the mean.

The nitrate data used for this analysis are unevenly distributed over the study area; two-thirds of the data are for wells in Washington and Dakota Counties. However, if the data from those counties are removed from the analysis, the relationship of nitrate concentration and confinement-index values as shown on Figure 4 remains the same. If the data are plotted separately for wells completed in the Prairie du Chien Group versus wells completed in the Jordan Sandstone (Fig. 5), the same general relationship is again unchanged. This is unexpected in that the lithofacies of the Prairie Du Chien Group and Jordan Sandstone can strongly affect the sensitivity of various zones in the aquifer. However, because these lithofacies are not found in the areas most often represented in this data set, no significant differences in sensitivity were detected

The importance of the character of glacial drift in controlling the sensitivity of the Prairie du Chien-Jordan aquifer to contamination is inferred from the strong correlation between the confinement index and the upper limit of nitrate concentration, and the confinement-index mapping method is useful in assessing this sensitivity. Regional flow within the aquifer, which is inferred the potentiometric surface, is generally from areas where the aquifer is overlain by younger bedrock formations toward the subcrop area of the Prairie du Chien Group and Jordan Sandstone (Plate 12). This is particularly true in the areas south of the Twin Cities, and less so in the counties of the Twin Cities Metropolitan Area. These younger formations include regional confining units; if we equate increased confinement with lower sensitivity, then the ground-water flow is likely from areas of lower sensitivity to areas of higher sensitivity. Water quality in the study area is directly related to the amount of mixing of recharge from the study-area surface with flow entering the

Figure 4. Nitrate concentration in the Prairie du Chien-Jordan aquifer versus confinement-index values

(diagonal line represents 99% confidence envelope)

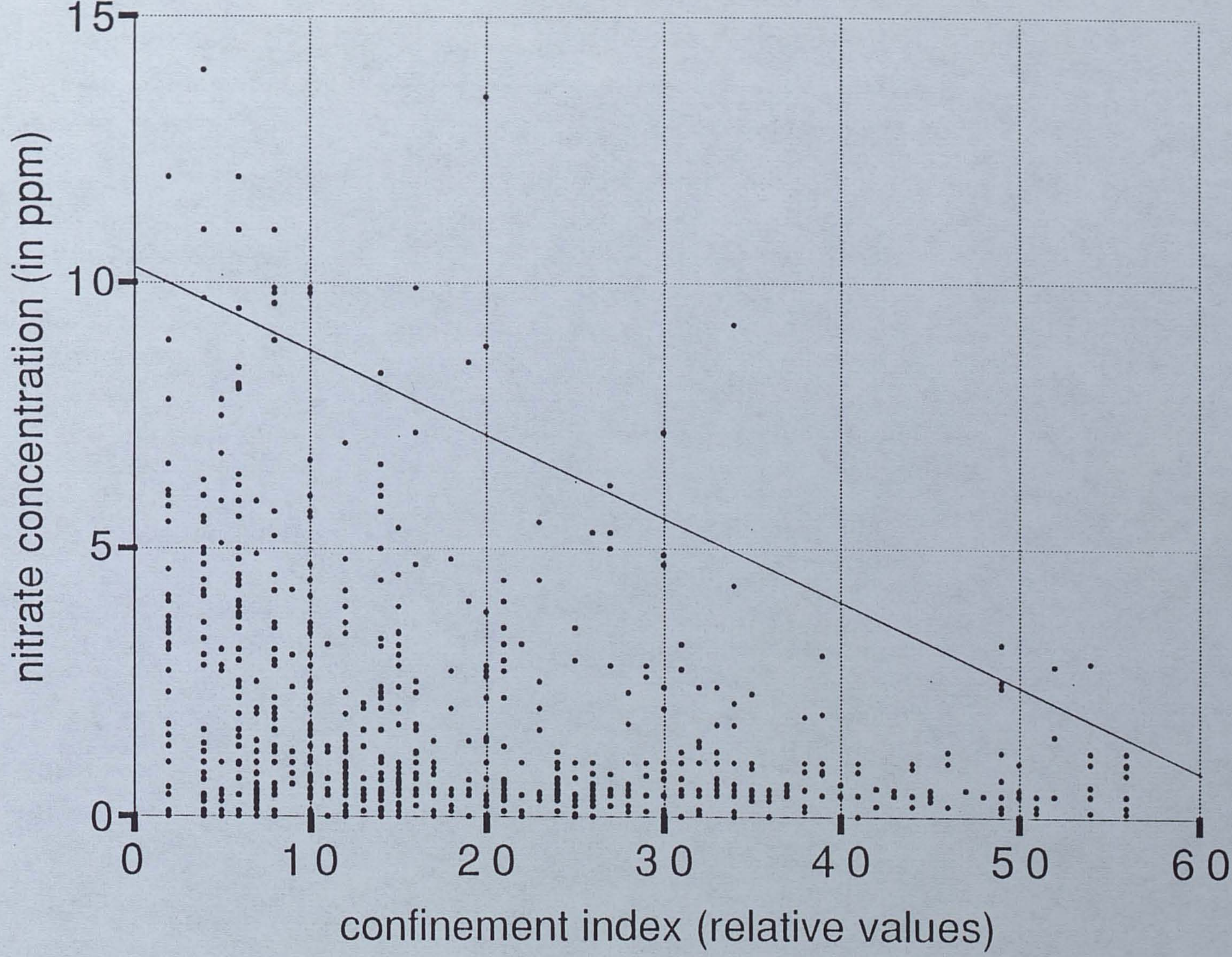


Figure 5a. Nitrate concentration in the Jordan Sandstone versus the confinement index.

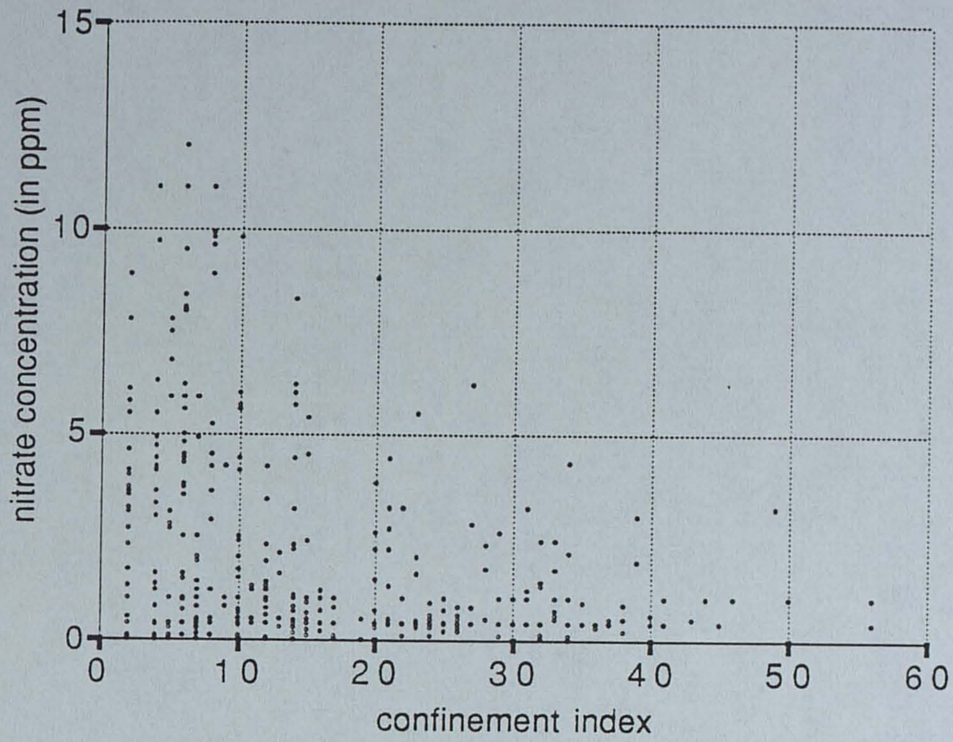
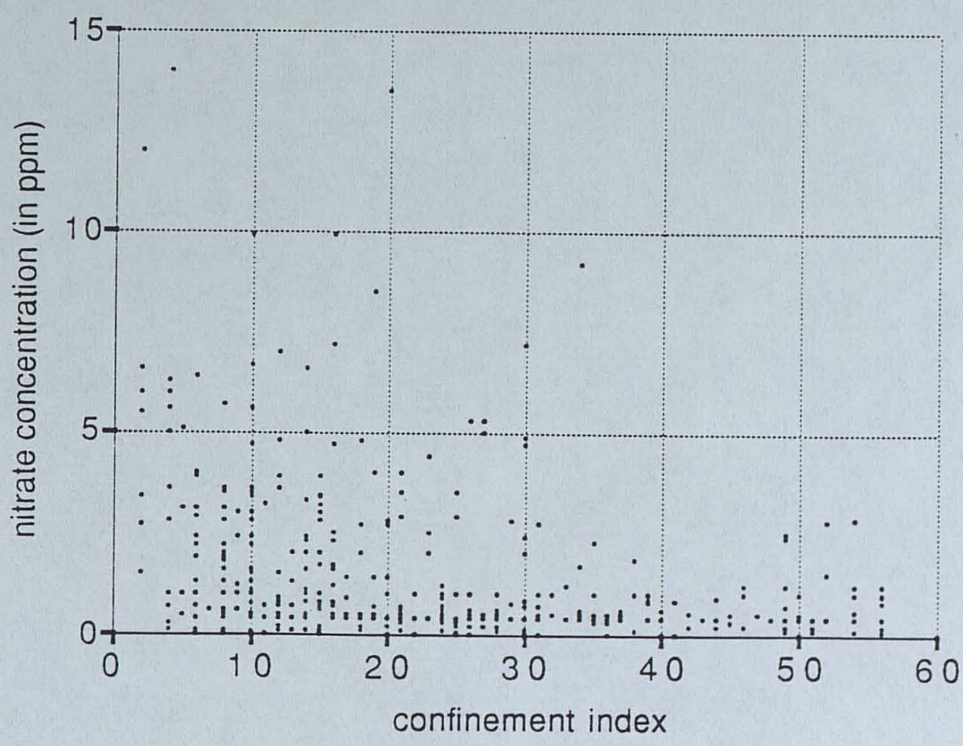


Figure 5b. Nitrate concentration in the Prairie du Chien Group versus the confinement index.



area laterally (see Fig. 6) from less sensitive areas. Glacial materials of low permeability and substantial thickness may limit or delay this local recharge and mixing, thus preserving the quality of the aquifer water entering laterally. If glacial materials of low conductivity are at the land surface, a significant part of the nitrate load will be diverted to surface-water runoff. The remaining nitrate load will slowly percolate into the glacial drift. When nitrate-bearing water passes through the glacial materials of low conductivity and reaches the underlying aquifer, some dilution of the nitrate concentration will be caused by the difference in flow rates between the glacial materials and the aquifer.

We have assumed for the purposes of mapping and analysis that vertical flow is an important factor in assessing the sensitivity of the aquifer. However, because we know that there is also lateral flow within aquifers, contaminants are also assumed to transfer laterally from areas of high sensitivity to areas of low sensitivity; any area down-gradient from an area of high sensitivity is vulnerable to this kind of contamination. To test this hypothesis, the distribution of nitrate could again be used as an indicator of sensitivity if analyses were available where flow is from an area of high vertical conductivity to an area of low vertical conductivity. Unfortunately, our study area and data set did not provide this opportunity. In almost every part of the study area, flow is from areas of low vertical conductivity to areas of high vertical conductivity, or the flow is through an area of relatively homogeneous, hydrologic character (compare Plates 12 and 11). One possible exception is on the western limb of the study area east of Mankato, but in this area too few nitrate analyses are available to warrant a conclusion. Until the opportunity to analyze this phenomenon arises, it is prudent to assume that lateral transport of contaminants within aquifers is a viable factor in controlling the sensitivity of aquifers that is not addressed by the methods used in this investigation.

Lithofacies of the Prairie du Chien Group and Jordan Sandstone

Nitrate concentrations in the Prairie du Chien Group part of the aquifer are commonly higher than nitrate concentrations in the underlying Jordan Sandstone. Because the Jordan Sandstone is the lower part of the aquifer and is commonly overlain by the Prairie du Chien Group, flow paths to the Jordan Sandstone are longer than paths to the Prairie du Chien Group. This suggests that the unequal nitrate distribution may be controlled by depth, and the present distribution of nitrate may simply mark its advancement at this time. However, there is only a weak correlation of nitrate concentration with well depth in the study area (Fig. 7). The effects on aquifer sensitivity of the geologic factors of drift composition and thickness and bedrock type probably overwhelm any effect caused by depth alone.

The hydrologic properties of lithofacies VF suggest that the lithofacies can affect flow, particularly vertical flow, within the aquifer. To test this hypothesis, nitrate concentrations above

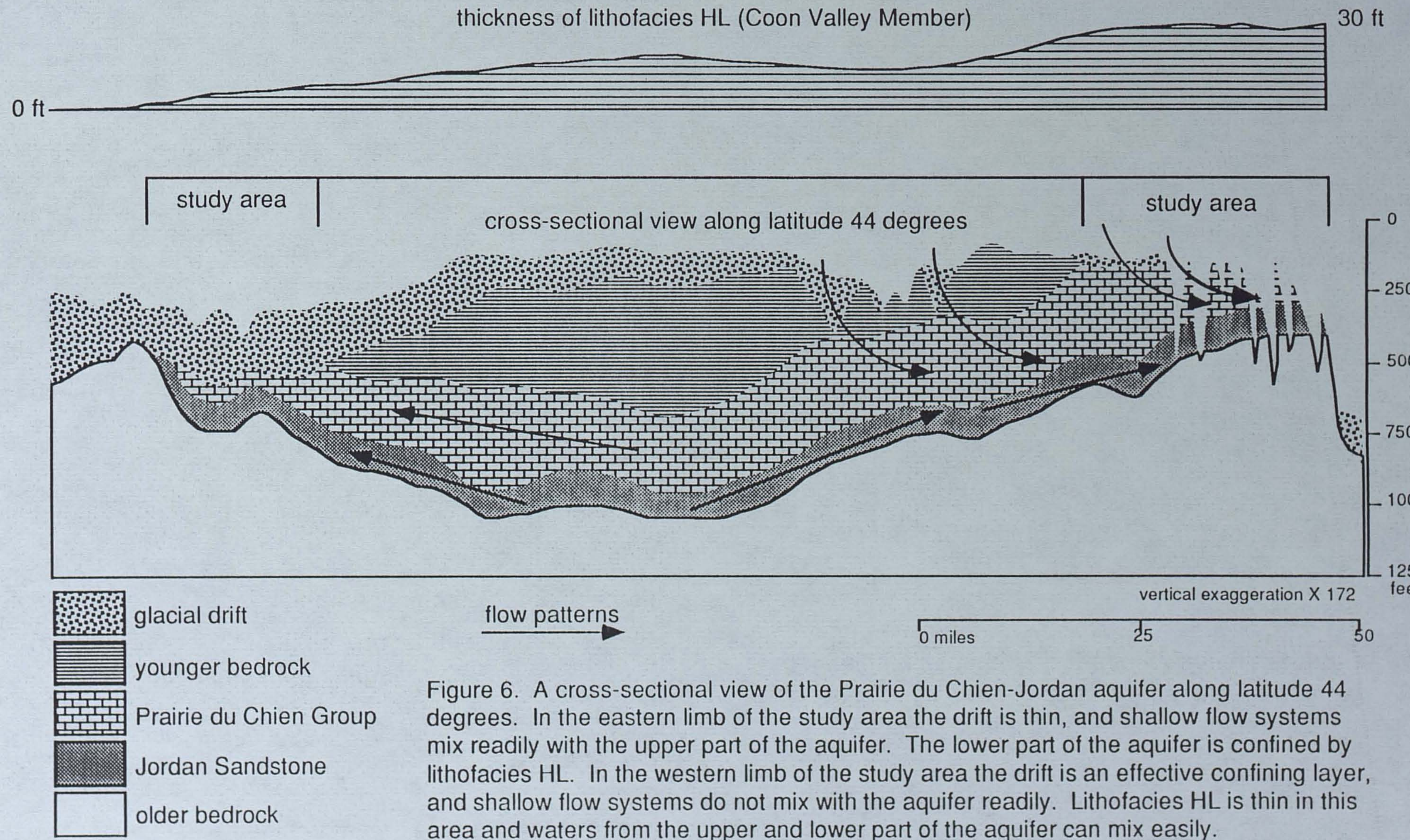
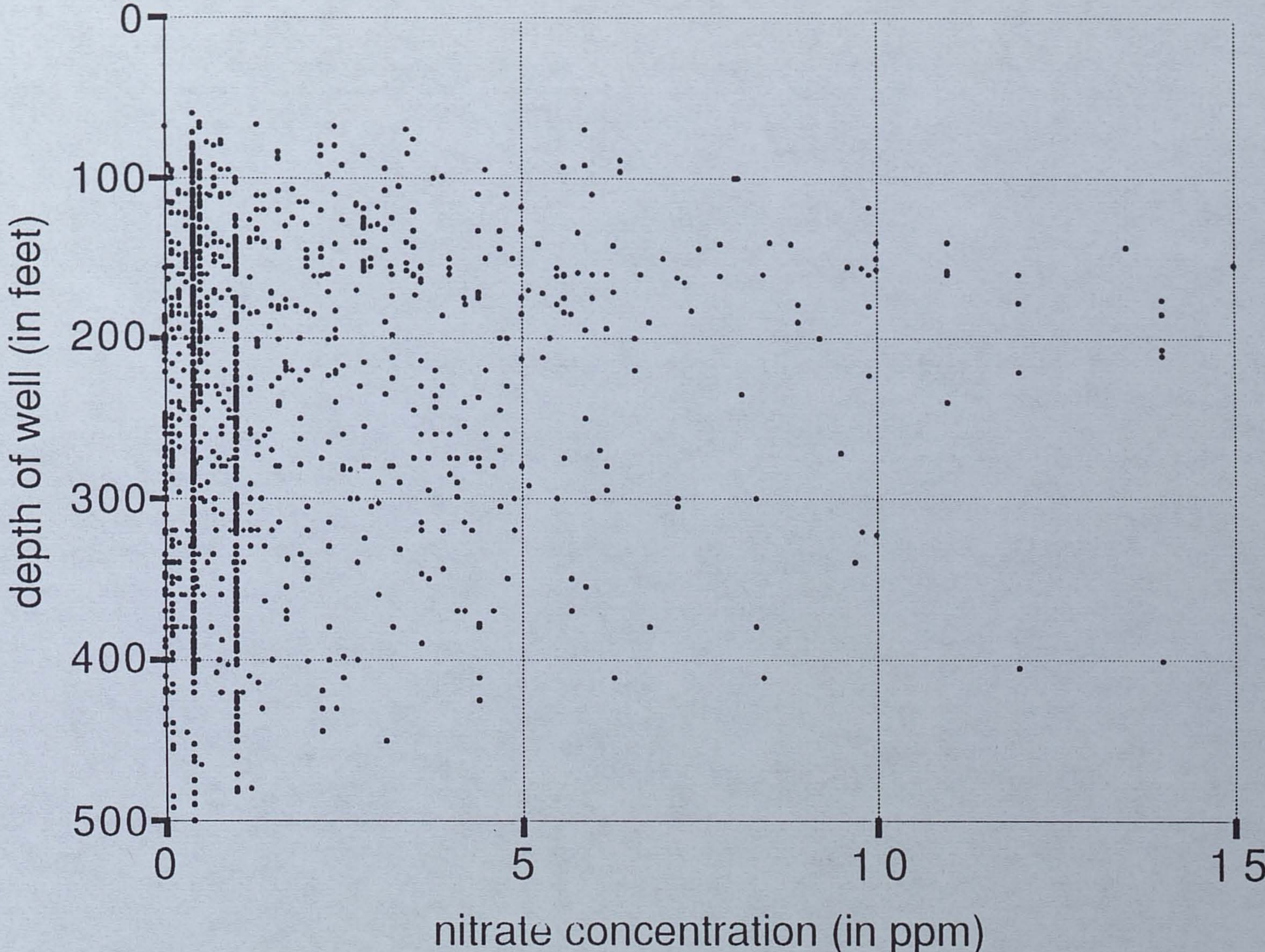


Figure 6. A cross-sectional view of the Prairie du Chien-Jordan aquifer along latitude 44 degrees. In the eastern limb of the study area the drift is thin, and shallow flow systems mix readily with the upper part of the aquifer. The lower part of the aquifer is confined by lithofacies HL. In the western limb of the study area the drift is an effective confining layer, and shallow flow systems do not mix with the aquifer readily. Lithofacies HL is thin in this area and waters from the upper and lower part of the aquifer can mix easily.

Figure 7. Nitrate concentration in the Prairie du Chien-Jordan aquifer versus depth of well.

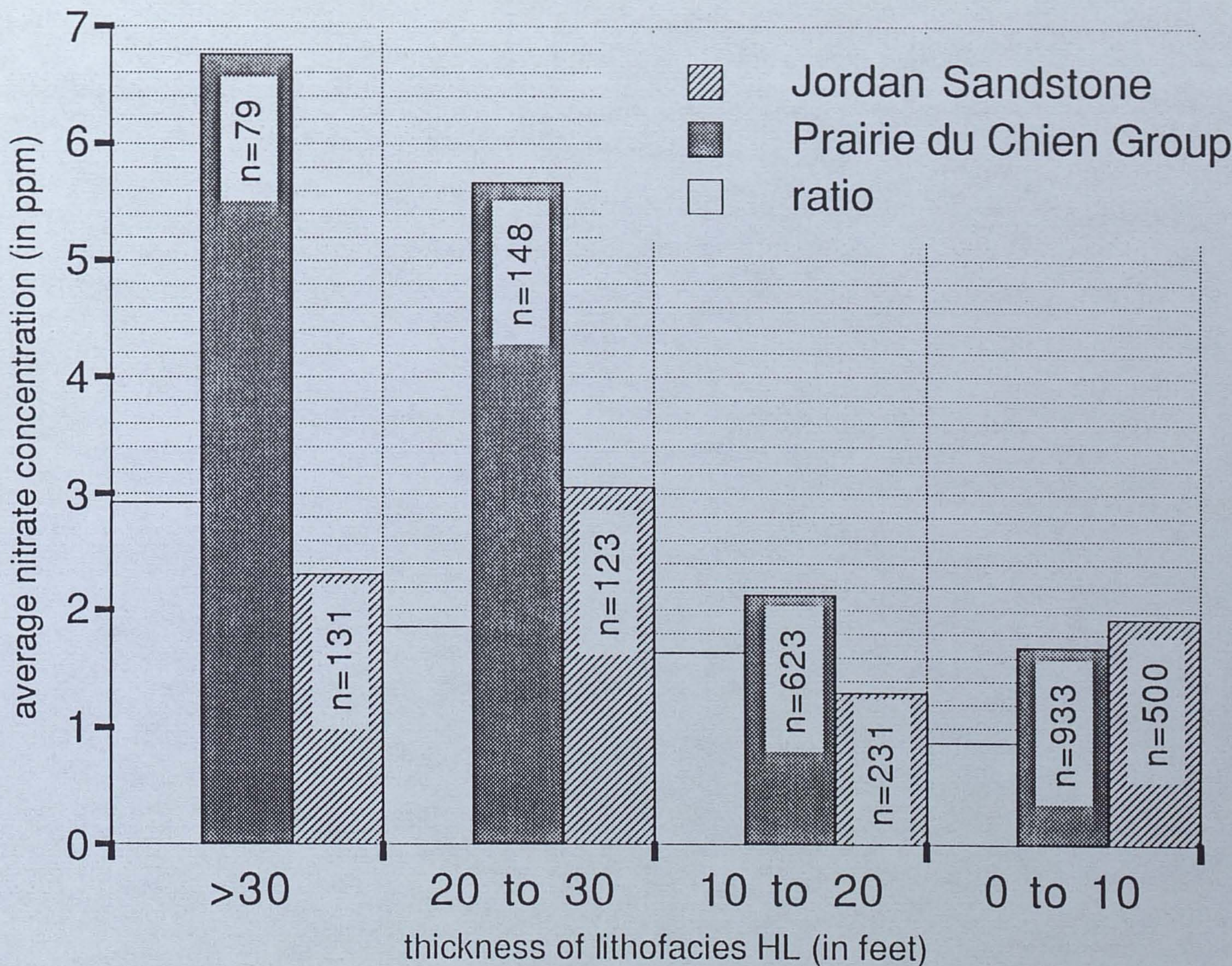


and below this lithofacies should be compared in as many locations as possible. In spite of the large volume of nitrate data available, we were unable to find wells and associated nitrate analyses suitable for this comparison. The identification of lithofacies VF in the rocks penetrated by a well is generally not possible without a gamma log, limiting the available sites for comparison. The number of wells available for comparison is further limited by the lack of variety on a local scale in well construction: wells drilled close together tend to have the same construction with regard to the geologic environment—drilled to the same depth in the same formation, with casing set in the same stratigraphic position, and this also limits opportunities for investigating the effects of local geologic features on water quality.

Lithofacies HL is a regional geologic feature, and sufficient nitrate data exist to correlate nitrate distribution with its occurrence. The position of lithofacies HL at the contact of the overlying carbonate part of the aquifer (Prairie du Chien Group) and the underlying clastic part of the aquifer (lithofacies FC of the Jordan Sandstone) suggests that its potential effect on sensitivity would be reflected in differences in water quality in the two parts of the aquifer. Figure 8 is a summary of nitrate concentrations in the two parts of the aquifer related to the thickness of lithofacies HL between them. There is a clear and strong correlation between the thickness of lithofacies HL and the nitrate concentration above and below it. In areas where lithofacies HL is greater than 10 feet thick nitrate concentrations in the Jordan Sandstone are substantially lower than those in the carbonate portion of the Prairie du Chien Group. The magnitude of the difference in nitrate concentration also increases with the thickness of lithofacies HL . This is graphically displayed in Figure 8 as the ratio between the average nitrate concentration in Prairie du Chien Group samples and the average concentration in Jordan Sandstone samples. The ratio increases with increasing thickness of lithofacies HL.

It should be noted that this apparent relationship of lithofacies HL and nitrate concentrations in the overlying and underlying parts of the aquifer is only a statistical correlation and does not prove a cause-and-effect relationship. Other possible explanations, such as denitrification owing to geochemical and biochemical processes in the aquifer, the effects of rock fracturing, flow patterns, and other unknown phenomena should be considered and investigated. If lithofacies HL does indeed confer protection from contamination to the waters of the Jordan Sandstone, it is not known with certainty how this is accomplished. Because the carbonate, part of the aquifer (Prairie du Chien Group) overlies this lithofacies and because the karstic condition of this part of the aquifer makes it suitable for rapid flow, the carbonate part may be dominated by local, shallow flow systems with localized recharge and discharge areas (Fig. 7). In this way, nitrates that accumulate in the waters of the Prairie du Chien Group may be discharged or transported laterally before any substantial downward transport of water into the Jordan Sandstone takes place. The low permeability of lithofacies HL would enhance this hydrologic separation. In contrast, flow in

Figure 8. Nitrate concentrations in the two parts of the Prairie du Chien-Jordan aquifer versus the thickness of the intervening lithofacies HL



the Jordan Sandstone aquifer may be more regional and recharge may occur in areas with less contaminant input, or greater protection from surface activities. It is also possible that nitrate concentrations in water from the Prairie du Chien disperse slowly into the Jordan Sandstone as they move through the fine-grained clastics of lithofacies HL, and are then diluted by the lateral flow of uncontaminated water within the Jordan Sandstone. Lithofacies HL may also slow the movement of nitrate-rich water toward the Jordan Sandstone; in time, nitrate concentrations in the water of the Jordan Sandstone may be as high as they are in the upper part of the aquifer. Denitrification in the Jordan Sandstone and lithofacies HL may also reduce nitrate concentration. Denitrification occurs in soil zones at or near the land surface where bacteria and organic matter are common, and also in poorly oxygenated zones in the subsurface. Microbial denitrification has been documented in deep, confined aquifers (Vogel and others, 1981); Andersen and others (1980) and Andersen and Kristiansen (1984) reported that in certain fine-grained, semiconfining units the chemical oxidation of ferrous to ferric iron may lead to nitrate reduction. They also believe that the deep aquifers in which this oxidation process occurs may be well protected against nitrate pollution from natural recharge paths. If this process is responsible for the differences in water quality between the two parts of the aquifer, lithofacies HL must be considered a sensitivity factor only with regard to nitrate contamination and not other potential pollutants.

In those areas where lithofacies HL is less than 10 feet thick, nitrate values in the Prairie du Chien Group and Jordan Sandstone are quite similar. The lack of a substantial, low-permeability unit between these rocks probably results in a more integrated flow system that distributes nitrate input more equally.

CONCLUSIONS

The results of this investigation suggest that the thickness and hydrologic properties of the earth materials that overlie the Prairie du Chien–Jordan aquifer are important factors in determining its sensitivity to contamination from surface activities. The hydrologic properties of younger bedrock formations that may overlie the aquifer are relatively consistent and well known. The thickness and character of the glacial sequence over the aquifer can be mapped and its relative effects quantified from water-well records by the methods described in this report. There is a strong correlation between the properties of the glacial materials and the sensitivity of the aquifer as indicated by the distribution of nitrate. There are variations in sensitivity within the different parts of the aquifer as well. The lower, detrital part of the aquifer often has a lower average nitrate concentration than the upper, carbonate part of the aquifer. This difference is mostly in areas where a regionally occurring, low-permeability subunit is present. How this unit causes this difference in sensitivity is unclear, but its low permeability may serve to hydrologically separate the two halves of the aquifer. This hypothesis should be field tested.

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