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Scientific Investigations Report 2004-5136

U.S. Department of the Interior
U.S. Geological Survey

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Gale A. Norton, Secretary

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Cover photograph: Outcrop of Galena-Platteville deposits in northern Illinois. Photograph by Patrick Mills.

Executive Summary

The characterization of ground-water flow and contaminant transport in fractured-rock aquifers is limited by the heterogeneous and anisotropic nature of these aquifers and the inability of many currently available investigative methods to quickly and accurately assess this heterogeneity and anisotropy under a range of hydrogeologic conditions. Investigations performed by the U.S. Geological Survey and the U.S. Environmental Protection Agency in the fractured Galena-Platteville aquifer at Superfund sites in Illinois and Wisconsin indicate that various investigative methods can be used to characterize fractured-rock aquifers. The effectiveness of these methods varies with the hydrogeology of the site. The completeness of the characterization improved with an increase in the amount of data available, in terms of the number of data points, the period of data collection, and the number of methods applied. The characterization also was improved by comparison of data collected with different methods.

Collection and analysis of background information, including data from governmental databases, previous investigations, topographic maps, aerial photographs, and outcrops and quarries prior to the initiation of any investigation is considered essential to obtaining a preliminary understanding of the hydrogeology and water quality. This understanding is essential to understanding the problems associated with the site and for planning the investigation.

The utility of surface geophysical methods for the characterization of the secondary-permeability network was limited by site geology and cultural interference. Surface ground-penetrating radar provided no information. Square-array resistivity provided information on the orientation of vertical fracture sets that may or may not have been accurate.

Lithologic logging was essential to geologic characterization at every site. Core analysis typically was useful for stratigraphic interpretation and providing samples for geotechnical measurements.

Characterization of the site geology was improved by collecting geophysical logs. Natural-gamma logging was best used to identify lithologic variations that, in combination with other data, provided insight into the lithologic factors that affect the location of secondary-permeability features. Three-arm caliper logging was most useful for identifying the presence and location of fractures and solution openings. Neutron logs were effective in evaluating trends in the primary porosity at sites where clay minerals or variable saturation did not substantially affect the log response. Acoustic-televiewer logs identified the largest number of secondary-permeability features, as well as permitting identification of the type and orientation of these features. Televiewer logging was considered the best method for the thorough characterization of the secondary-permeability network. Borehole-camera logs also provided substantial insight into the location of secondary-permeability features in boreholes with clear water. Single-hole, ground-penetrating radar (GPR) surveys appear to have identified lithologic and secondary-permeability features tens of feet beyond the boreholes. However, some of the results of these surveys were not confirmed by other methods. Cross-hole GPR surveys were useful for identifying the location and extent of secondary-permeability features between boreholes as well as porosity variations. Cross-hole GPR logging done in conjunction with tracer testing identified flow pathways and was used to calculate the effective porosity of the aquifer.

Characterization of ground-water flow was accomplished by a number of investigative methods. Water-level measurements and the location of contaminants and other water-quality constituents identified vertical and horizontal directions of ground-water flow over areas of tens to thousands of feet. Water level measurements and water-quality data also provided insight into the distribution of aquifer permeability and the location of permeable fractures in some locations.

Characterization of ground-water flow at the boreholes was improved by collection of lithologic, temperature, spontaneous potential, and fluid-resistivity logging. However, the utility of these logs varied with conditions. At some sites, these logs identified few features, whereas at others, more features were identified. Single-hole flowmeter logging under a combination of

ambient and pumping conditions was the most cost-effective method of identifying the location of permeable features in the Galena-Platteville aquifer of any geophysical method used. The utility of the flowmeter logs in any borehole was affected by uniformly low permeability, an absence of vertical hydraulic gradient, large contrasts in permeability, and the distribution of permeable features. Cross-hole flowmeter logging provided the greatest amount of insight into the location of permeable features in individual boreholes, as well as insight into the hydraulic interconnection of these features.

Characterization of ground-water flow also was improved by performance of aquifer tests. Slug tests provided insight into permeability variations with location and stratigraphy and are the only method that could quantify the horizontal hydraulic conductivity of the entire aquifer. Slug tests performed by use of a packer assembly provided the most complete characterization of the location of permeable (or impermeable) intervals in the aquifer, but are expensive in comparison to flowmeter logging. Specific-capacity tests allowed for quantification of aquifer transmissivity where resources were insufficient for detailed aquifer testing. Multiple-well, constant-discharge aquifer tests identified the presence and location hydraulically interconnected features in the Galena-Platteville aquifer, as well as the presence and orientation of heterogeneity and anisotropy. The amount of information that could be obtained from the multiple-well aquifer tests was increased by the amount of aquifer that could be tested discretely. However, reliable estimates of transmissivity and storage coefficient could not always be obtained because of aquifer heterogeneity. Tracer tests allowed estimation of the effective porosity of parts of the aquifer and indicated the presence of hydraulic interaction between the fractures and matrix. Tracer testing done in conjunction with cross-borehole GRP identified discrete flow pathways within the aquifer.

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Conversion Factors, Vertical Datum, Abbreviated Water-Quality Units, and Abbreviations

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
foot per foot (ft/ft)	0.3048	meter per meter (m/m)
foot per mile (ft/mi)	0.1894	meter per kilomter (m/km)
	Area	
acre	4,047	square meter (m^2)
square inch (in^2)	6.4516	square centimeter (cm^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3.785	million liters (ML)
cubic inch (in^3)	16.39	cubic centimeter (cm^3)
	Velocity	
feet per minute (ft/min)	0.3048	meter per minute (m/min)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Flow rate	
gallon per minute (gal/min)	3.785	liter per minute (L/min)
million gallons per year (Mgal/yr)	3.785	million liters per year (ML/yr)
	Hydraulic conductivity*	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). The NGVD 29 is a geodetic datum derived from a general adjustment of first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929

Altitude, as used in this report, refers to distance above or below NGVD 29.

*Hydraulic conductivity: The standard unit for hydraulic conductivity is cubic foot per day per square foot of aquifer cross-sectional area (ft^3/d)ft^2. In this report, the mathematically reduced form, foot per day (ft/d), is used for convenience.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per foot of head per square foot of aquifer cross-sectional area (ft^3/d)(ft)/ft^2. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance (SC) of water is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C). The unit is equivalent to micromhos per centimeter at 25 degrees Celsius (µmho/cm), formerly used by the U.S. Geological Survey.

Abbreviated water-quality units used in this report: Organic- and inorganic-constituent concentrations, water temperature, and other water-quality measures are given in metric units. Constituent concentrations are given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter are considered equivalent to parts per million at the reported concentrations. Micrograms per liter are considered equivalent to parts per billion (ppb) at the reported concentrations.

Tritium concentrations are given in tritium units (TU). Tritium units may be converted to picocuries per liter (pCi/L) as follows

$$pCi/L = TU \times 3.2$$

Dissolved oxygen (DO) is given in milligrams per liter (mg/L).

Oxidation-reduction potential (ORP) is given in millivolts (mv).

Select abbreviations:

MHz	Megahertz
FANGVD29	Feet above National Geodetic Vertical Datum of 1929
g/cm^3	Grams per cubic centimeter
VOC's	Volatile Organic Compounds
μmho/cm	Micromho per centimeter
Kh	Horizontal hydraulic conductivity
DNAPL	Dense nonaqeous phase liquid
USGS	U.S. Geological Survey
USEPA	U.S. Environmental Protection Agency
ISGS	Illinois State Geological Survey
WGNHS	Wisconsin Geologic and Natural History Survey
PCHSS	Parson's Casket Hardware Superfund Site
SAR	Square-array resistivity
SP	Spontaneous potential
GPR	Ground-penetrating radar
SPR	Single-point resistivity
TCE	Trichloroethene
PCE	Tetrachloroethene

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Abstract

The effectiveness of 28 methods used to characterize the fractured Galena-Platteville aquifer at eight sites in northern Illinois and Wisconsin is evaluated. Analysis of government databases, previous investigations, topographic maps, aerial photographs, and outcrops was essential to understanding the hydrogeology in the area to be investigated. The effectiveness of surface-geophysical methods depended on site geology. Lithologic logging provided essential information for site characterization. Cores were used for stratigraphy and geotechnical analysis. Natural-gamma logging helped identify the effect of lithology on the location of secondary-permeability features. Caliper logging identified large secondary-permeability features. Neutron logs identified trends in matrix porosity. Acoustic-televiewer logs identified numerous secondary-permeability features and their orientation. Borehole-camera logs also identified a number of secondary-permeability features. Borehole ground-penetrating radar identified lithologic and secondary-permeability features. However, the accuracy and completeness of this method is uncertain. Single-point-resistance, density, and normal resistivity logs were of limited use.

Water-level and water-quality data identified flow directions and indicated the horizontal and vertical distribution of aquifer permeability and the depth of the permeable features. Temperature, spontaneous potential, and fluid-resistivity logging identified few secondary-permeability features at some sites and several features at others. Flowmeter logging was the most effective geophysical method for characterizing secondary-permeability features.

Aquifer tests provided insight into the permeability distribution, identified hydraulically interconnected features, the presence of heterogeneity and anisotropy, and determined effective porosity. Aquifer heterogeneity prevented calculation of accurate hydraulic properties from some tests.

Different methods, such as flowmeter logging and slug testing, occasionally produced different interpretations. Aquifer characterization improved with an increase in the number of data points, the period of data collection, and the number of methods used.

INTRODUCTION

Fractured-rock aquifers are characterized by the presence of ground-water flow through secondary-permeability features (fractures, vugs, and solution openings) that form heterogeneities in a rock matrix. Fractured-rock aquifers underlie at least 40 percent of the United States east of the Mississippi River (Quinlan, 1989) and are used extensively for residential and public-water supply throughout the Nation (fig. 1). Industrial chemicals and other anthropogenic compounds contaminate many of these aquifers, rendering the water unsafe for use.

An accurate assessment of ground-water remediation or development scenarios in fractured-rock aquifers requires thorough characterization of the secondary-permeability network in these aquifers, including characterization of the component secondary-permeability features through which water flows (the permeable features) as well as the low-permeability features that transmit smaller amounts of water. An essential component to this characterization is the identification of the geologic properties of the feature, such as its type (vug, fracture, solution opening), location, size, and orientation as well as the hydraulic properties of the feature such as its transmissivity, storage coefficient, horizontal hydraulic conductivity, and water level. Characterization of both the geologic and hydraulic properties of an aquifer is hereafter referred to as hydrogeologic characterization.

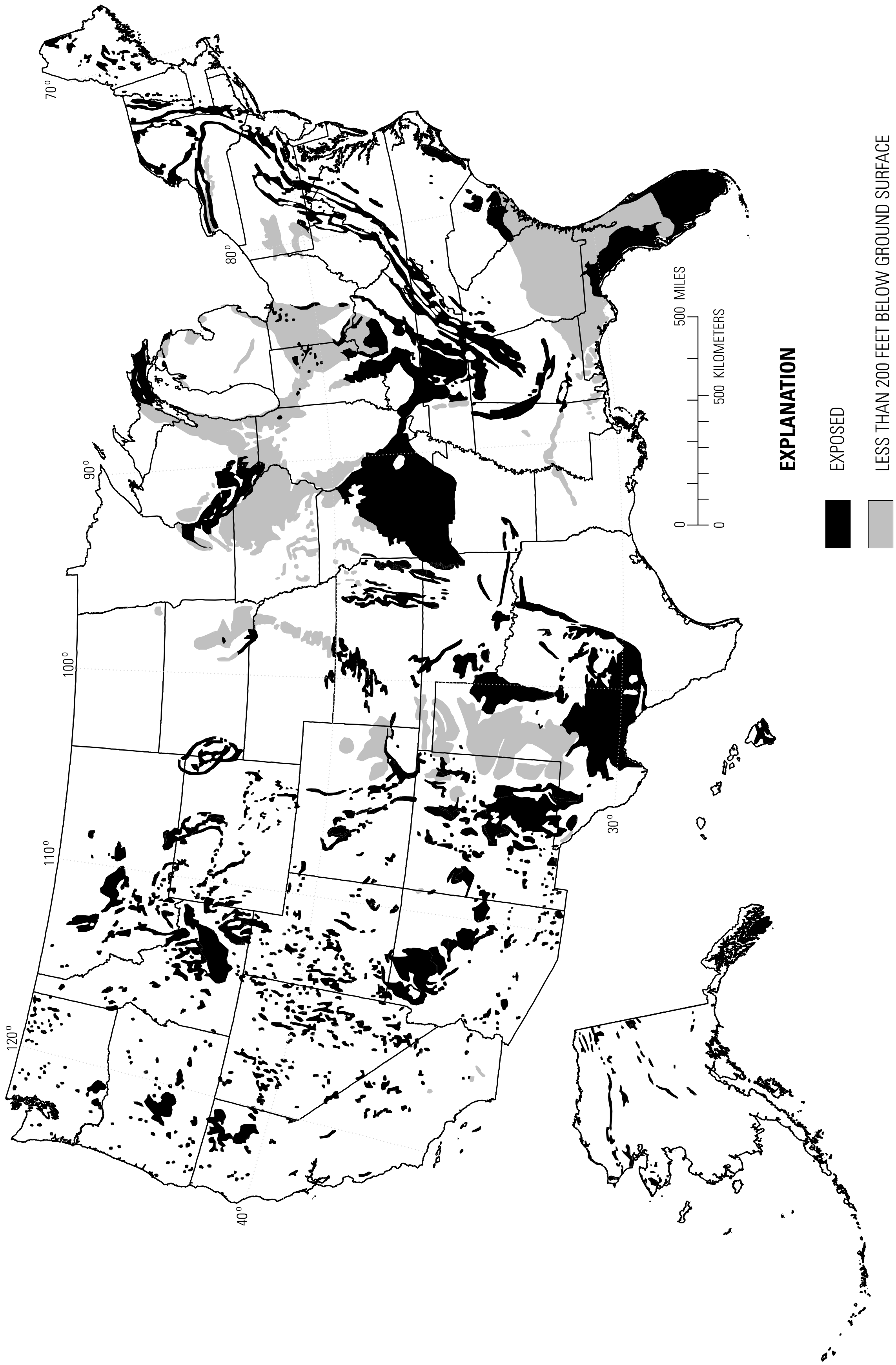


Figure 1. Location of fractured-rock aquifers beneath the United States (modified from National Research Council, 1996).

This hydrogeologic characterization is subject to a number of limitations. The most important limitations relate to the conceptual framework of the ground-water-flow system in the aquifer. Ground-water flow in fractured-rock aquifers can be conceptualized as a discrete flow system, a doubly porous media, or an equivalent porous media. These conceptualizations represent three possible end members of actual aquifers that typically have properties associated with two or all three of these conceptual frameworks. Conceptualization of the flow system is affected by the type, density, and heterogeneity of the secondary-permeability features at the scale of investigation.

In a discrete flow system, ground water flows through individual fractures or solution openings or a small, widely spaced number of such features. These permeable features are considered to be hydraulically isolated from each other and the surrounding rock matrix (Long and others, 1982). In this aquifer conceptualization, the investigative approach is to identify and discretely characterize each of the permeable features (the noncontinuum approach).

In a doubly porous media, the rock matrix has primary porosity that is hydraulically connected to the permeable fractures or solution openings. In this type of flow system, the fractures or solution openings transmit most of the water, but most of the water is stored in the rock matrix. In this aquifer conceptualization, the investigative approach requires identification and characterization of the permeable secondary-permeability features and the rock matrix, as well as the interaction between these features.

In an equivalent porous media, ground-water flow is through a network of secondary-permeability features of sufficient density, interconnection, and uniformity of hydraulic properties so that the aquifer responds as if it were a continuum rather than a series of discrete features (Long and others, 1982). In this conceptualization, the investigative approach is to characterize the aquifer as a whole without regard to individual features, or networks of such features.

Most fractured-rock aquifers are conceptualized as equivalent porous media because this conceptualization is the simplest, and usually the only means of representing and characterizing the aquifer with the available investigative and analytical methods. In most fractured-rock aquifers, the secondary-permeability network is of sufficient density, interconnection, and homogeneity that the assumption of an equivalent porous media is valid if a sufficiently large volume of aquifer is considered. However, smaller volumes of aquifer usually are of interest to problems of contaminant migration or flow to water-supply wells. At the local scale (feet to hundreds of feet), flow through discrete secondary-permeability features may dominate and a noncontinuum approach to aquifer characterization would be required. Therefore, the appropriate conceptual framework (and investigative approach) for any fractured-rock aquifer is dependent of the scale of aquifer requiring characterization. Unfortunately, there is presently (2004) no way to quantitatively determine the volume of aquifer (scale) at which any given fractured-rock aquifer can be represented as an equivalent porous media. Conversely, there also is no way to quantitatively determine the scale at which discrete-flow pathways predominate.

The scale of aquifer requiring characterization and the ease with which the aquifer can be characterized is affected by the degree of heterogeneity (change in hydraulic properties with location) in an aquifer. In theory, a homogenous aquifer has similar properties at all points and at any scale within the aquifer. If the aquifer can be characterized at any scale, any one of various methods (for example, hydraulic testing of core samples, single-well aquifer tests, or multiple-well aquifer tests) performed at a single location anywhere in the aquifer will provide a reasonable estimate of the hydraulic properties of the entire aquifer. Although perfectly homogenous aquifers are not present in nature, many aquifers composed of porous-media (sands, gravels) can be considered homogenous over a variety of scales of interest to investigators. These aquifers can be characterized accurately using any one of various investigative methods with a small number of data points. Because the type, size, interconnection, and density of secondary-permeability features typically varies with location, fractured-rock aquifers usually are heterogeneous at the scale of interest. In addition, multiple scales of investigation are required to address different issues (for example, assessment of a capture zone at a remedial extraction well or understanding the extent of contamination at a site). The heterogeneous nature of many fractured-rock aquifers necessitates that these aquifers be characterized with numerous data points at different investigative scales, which typically requires the use of a variety of investigative methods.

The scale of aquifer requiring characterization and the ease with which the aquifer can be characterized also is affected by the degree of anisotropy (change of hydraulic properties with orientation) in an aquifer. Fractured-rock aquifers typically contain networks of permeable vertical fractures with a preferred orientation that developed in response to tectonic stresses. As a consequence, accurate characterization of fractured-rock aquifers requires assessment of both vertical and horizontal features at the appropriate scale of investigation. For example, an accurate value for the mean orientation (strike) of a network of vertical fractures would require the measurement of numerous fractures in a representative volume of rock.

In addition to affecting the scale of aquifer requiring investigation, the heterogeneous and anisotropic nature of fractured-rock aquifers can affect the accurate quantification of aquifer properties. Analytical methods where it is assumed that the aquifer responds as a homogenous, isotropic, equivalent-porous media sometimes are used in the characterization of fractured-rock aquifers even when flow is predominately through discrete features. Misapplication of analytical methods can result in incorrect estimates of aquifer properties. For example, many methods used to estimate transmissivity from constant-discharge aquifer-test data assume that the aquifer is homogenous and isotropic, and an inverse relation between transmissivity and drawdown at any given distance from the pumped well is expected. However, in many fractured-rock aquifers, heterogeneity and anisotropy results in variable amounts of flow with depth and orientation from the pumped well. Under these conditions, drawdown will be largest in observation wells open to the secondary-permeability features in greatest hydraulic connection with the pumped well because these features transmit the most water to the pumped well. However, the lowest estimates for aquifer transmissivity may be calculated for these wells using analytical methods that assume homogeneity or isotropy.

The heterogeneous and anisotropic nature of fractured-rock aquifers also produces a number of practical difficulties associated with their characterization. One of the fundamental difficulties associated with the characterization of fractured-rock aquifers is related to the need to access permeable features for testing. Access typically is provided by a borehole or well. In this report, a borehole refers to the excavation into which the well is placed, whereas a well refers to a completed monitoring or water-supply well. Because boreholes typically are drilled vertically, they are ideal for penetrating horizontal features, but frequently do not intercept vertical or inclined fractures. Therefore, inclined fractures usually are not intercepted or are underrepresented and their effect on flow and contaminant transport is not adequately understood. A related difficulty is that the amount of aquifer that is accessible from a borehole typically is small and discrete features, such as solution openings, that may be hydraulically important but of limited spatial extent can be undetected. In addition, for most problems of contaminant transport or water-resource development, aquifer characterization requires a focus on permeable features, rather than the aquifer matrix. Many monitoring wells installed in fractured-rock aquifers are completed at pre-determined depths, such as the middle or base of the aquifer, irregardless of whether or not permeable features are present. Even if extensive data collection is performed, the information obtained from these wells may not accurately characterize flow and water quality in the aquifer because these wells do not intercept the features moving most of the water and contaminants.

Because scale is important to the characterization of fractured-rock aquifers, a variety of investigative methods must be used for compete characterization. Therefore, even if a sufficient number of boreholes are installed in the appropriate parts of the aquifer, incomplete characterization of the secondary-permeability network can result if inappropriate methods are used. For example, characterization of contaminant movement from source area to discharge points can require water-level measurements across an area of investigation of 5 mi^2 or more. However, this characterization might not be improved substantially by data from a constant-discharge aquifer test, which even under the best of circumstances likely would characterize flow through a small, potentially non-representative part of the aquifer. Assessment of remedial efficacy at a ground-water extraction well, however, would be improved substantially by a properly located aquifer test, but may not require a site-wide understanding of the aquifer.

Beyond the difficulties of characterization of hydraulic and geologic properties, other aspects of flow and contaminant transport in fractured-rock aquifers are not well understood. The concepts of advection and dispersion in fractured rocks are identical to those in porous media (National Research Council, 1996), and will affect the fate and transport of contaminants. Advection is the movement of a solute caused by the bulk fluid movement. When considered in detail, this movement is extremely complicated as fluid velocity can vary on all scales – across the fracture aperture, in the plane of the fracture, from one fracture to another, and from one part of the fracture network to another (National Research Council, 1996). How to address dispersion in fracture flow is less well established. The classical approach is that dispersion can be treated as a Fickian (diffusive) process, but some investigators (Dagan, 1986; Gelhar, 1986) suggest that this approach is not always valid (National Research Council, 1996). Additional research is needed to determine how fracture geometry results in preferential flow paths and determines the rock-surface area that will affect matrix diffusion and reactive transport.

Because of the complexity of flow and contaminant transport in most fractured-rock aquifers, ground-water flow and contaminant transport in these aquifers typically is difficult to characterize. These difficulties reduce the effectiveness of aquifer remediation or development of water supplies. Even where extensively investigated, fluid flow and contaminant transport in fractured-rock aquifers is difficult to accurately determine because of limitations in current methods of conceptualizing, investigating, assessing, and quantifying these complex processes. As a consequence, there is a great need for determining the most accurate, efficient methods for characterizing fractured-rock aquifers under a variety of hydrogeologic conditions.

Investigations performed by the U.S. Geological Survey (USGS) and the U.S. Environmental Protection Agency (USEPA) characterized the geology of the dolomite deposits of the Galena and Platteville Groups (the Galena-Platteville dolomite) and the hydrology of the Galena-Platteville aquifer at eight locations in Illinois and Wisconsin. These investigations provide an excellent opportunity to assess the effectiveness of many of the methods used to characterize the hydrogeology of fractured-rock aquifers. The Galena-Platteville aquifer was characterized extensively at the Byron and Waupun Superfund sites, as well as at the Parson's Casket Hardware site in the Belvidere area (fig. 2, table 1). Less extensive characterization occurred at the Tipton Farm, ACME Solvents, Winnebago Reclamation Landfill, Southeast Rockford, and Better Brite sites. Multiple methods for hydrogeologic characterization were used at each site and many of the same methods were used. Because the nature of the secondary-permeability network in the Galena-Platteville aquifer varied among the sites, the data obtained from these investigations provide a good opportunity to assess and compare methods of characterization under a variety of conditions and to identify the factors that affect the efficacy of each method.

Purpose and Scope

The purpose of this report is to describe the efficacy of various investigative methods used by the USGS and the USEPA to characterize the hydrogeology of the fractured Galena-Platteville aquifer at six waste-disposal sites in Illinois and two in Wisconsin. The scope is subregional in extent, but the information presented in this report can be applied to the characterization of the Galena-Platteville aquifer where it subcrops in parts of Illinois, Wisconsin, Iowa, and Minnesota as well as to the characterization of fractured-rock aquifers throughout the world. Background information on the hydrogeology of the Galena-Platteville aquifer is provided. Each of the methods used in the hydrogeologic characterization is described, including how the method operates, the information provided by each method, method scale of investigation, and primary method limitations. The utility of each method and the hydrogeologic factors that beneficially or adversely affected the performance of each method at each site are summarized. More detailed discussion of the site hydrogeology and the information gained from each method at each site is presented in the appendixes. Because this report summarizes previous investigations, results and interpretations that could be drawn from data provided in this report typically are not presented if the analysis was not done during the original investigation. A summary of the most effective methods used for the characterization of the hydrogeology of the Galena-Platteville and possibly for other fractured-rock aquifers is provided.

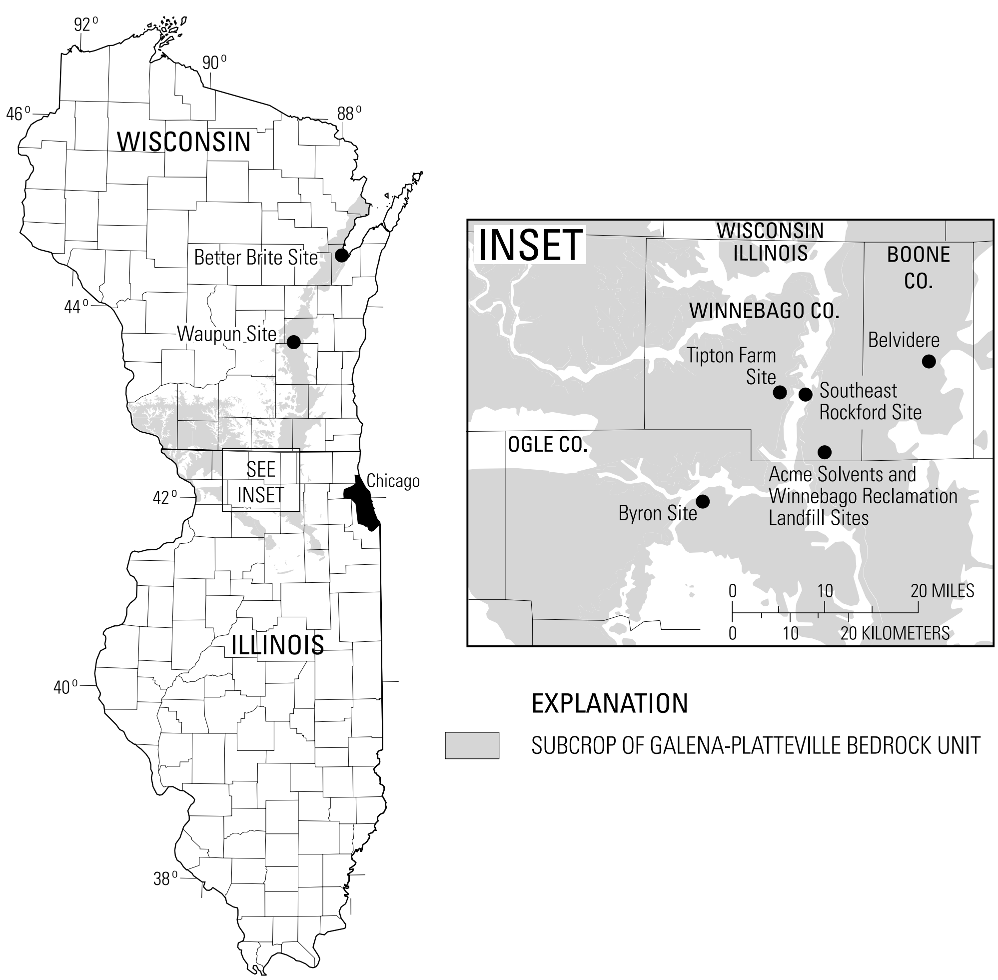


Figure 2. Location of Superfund sites overlying the Galena-Platteville aquifer in Illinois and Wisconsin investigated by the U.S. Geological Survey and U.S. Environmental Protection Agency.

Table 1. Methods used for U.S. Geological Survey and U.S. Environmental Protection Agency investigations of the Galena-Platteville aquifer in Illinois and Wisconsin.

Method	Site Name						
	Byron Salvage Yard	Tipton Farm	ACME Solvents and Winnebago Reclamation Landfill	Southeast Rockford	Belvidere area	Waupun	Better Brite
Previous investigations and database searches	X	X		X	X	X	X
Topographic maps or aerial photographs	X	X	X	X			
Quarry visits	X		X	X	X		
Surface geophysics	X				X		
Lithologic logging	X	X	X	X	X		X
Core analysis	X	X	X		X	X	X
Borehole camera logs	X		X	X	X		X
Caliper logs	X	X	X	X	X	X	X
Natural-gamma logs	X	X	X	X	X	X	X
Spectral gamma logs	X						
Spontaneous-potential logs	X	X			X		X
Normal resistivity logs				X	X	X	
Single-point resistance logs	X	X			X		X
Neutron logs	X		X		X	X	X
Density logs			X				
Acoustic televiewer logs	X			X	X	X	X
Borehole ground-penetrating radar	X				X	X	
Water levels from wells	X	X	X	X	X		X
Water levels using packers	X			X	X	X	X
Temperature logs	X				X		X
Fluid-resistivity logs	X				X	X	X
Flowmeter logs	X			X	X	X	
Hydrophysical logs	X						
Slug tests	X	X	X	X	X	X	X
Specific-capacity tests	X			X	X		
Multiple-well, constant-discharge tests	X		X		X	X	
Tracer tests	X				X		
Contaminant location	X		X	X	X	X	X

Depositional and Post-Depositional History of the Galena-Platteville Deposits

During the early part of the Ordovician period (approximately 300 to 350 million years before present), the area that is now Illinois and Wisconsin was low-lying land near the edge of the North American continent. During the middle and late parts of the Ordovician period, sea level rose and an epeiric sea inundated this area. This epeiric sea was teeming with algae and other marine organisms. As these organisms died, calcium carbonate was deposited, eventually lithifying to limestone. Variable amounts of silt and clay probably derived form the Transcontinental Arch and the Wisconsin Dome (fig. 3) also were deposited.

At some point after deposition of the limestone deposits, movement of water began to transform the limestone (calcium carbonate) into dolomite (calcium-magnesium carbonate), forming what is now the Galena-Platteville dolomite. This transformation was so extensive that between about 80 and 90 percent of Galena-Platteville deposits are now dolomite (Willman and Kolata, 1978: Bakush, 1985). Dolomitization involves the substitution of magnesium for calcium in the carbonate minerals that compose the rock, altering the its texture and increasing its porosity. At least in part because of this process, Galena-Platteville deposits composed of nonargillaceous dolomite tend to be highly vesicular and vuggy (Willman and Kolata, 1978).

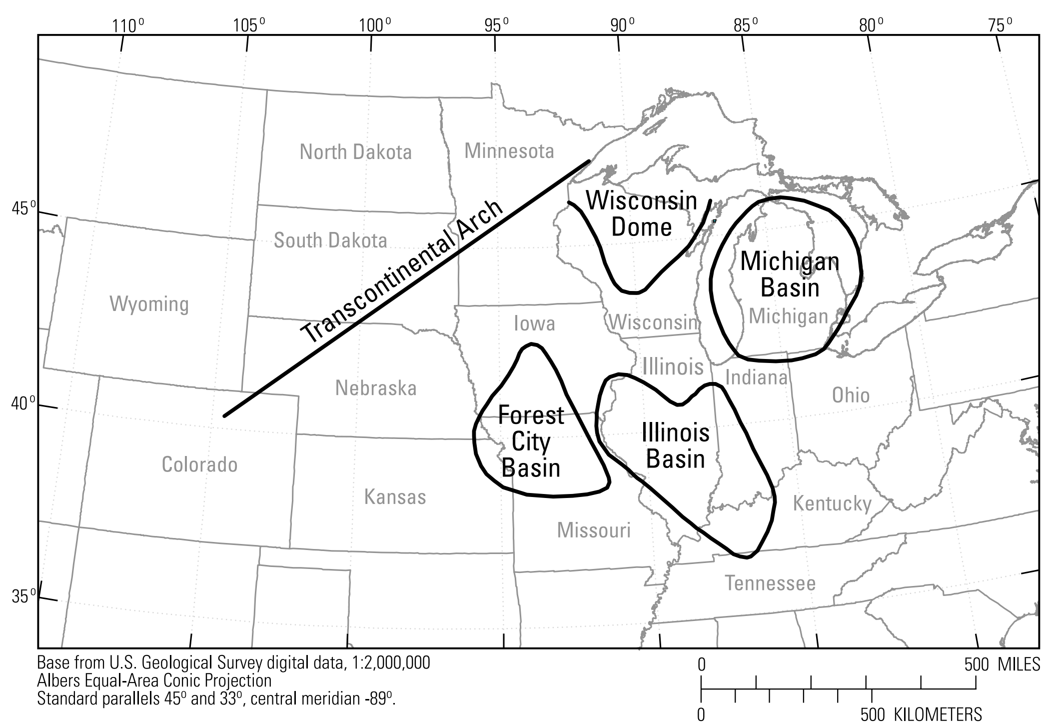


Figure 3. Selected structural features in the central United States.

Over geologic time, movement of meteoric water through the Galena-Platteville deposits resulted in the dissolution of the rock, enlarging openings and thinning calcareous beds (Heyl and others, 1955; Carlson, 1961; Agnew, 1963; Allingham, 1963: Klemic and West, 1964; Taylor, 1964; Whitlow and West, 1966). Because limestone is more soluble than dolomite, the amount of dissolution may be related inversely to the dolomite content of the rock. Dissolution thinning of calcareous beds also may have resulted in the concentration of argillaceous material in parts of the deposits. Dissolution resulted in the structural instability of the rock in some places and the development of fractures, faults, and sinkholes.

The current distribution of the Galena-Platteville deposits in Illinois and Wisconsin is affected primarily by the presence of the Wisconsin Arch, a broad anticlinal structure, which trends approximately 160 degrees through Wisconsin and northern Illinois (fig. 3). The Wisconsin Arch is a topographic upland, which began to form about 1 billion years ago and remained emergent during much of the transgression of the epeiric seas in which the Galena-Platteville deposits were emplaced. The Galena-Platteville deposits dip away from the arch, to the southwest along its western margin, to the south along its southern margin, and to the east along its eastern margin, where they are overlain by younger deposits that infilled the Michigan, Illinois, and Forest City Basins (fig. 3). As a result of these processes, the Galena-Platteville deposits constitute the subcrop (the uppermost bedrock unit) along the eastern, western and southern parts of the Wisconsin Arch in northern Illinois, eastern and southwestern Wisconsin (fig. 4), as well as southeastern Minnesota and northeastern Iowa.

The distribution of the Galena-Platteville deposits in the subcrop areas of Illinois and Wisconsin (which constitutes the study area) is affected by the Plum River and Sandwich Fault zones (fig. 4). The Plum River Fault zone is an east-west trending zone of high-angle faulting (Kolata and Buschbach, 1976; Bunker and others, 1985). The Plum River Fault zone is downthrown to the north, has up to 500 ft of displacement, and probably began development during the Middle Devonian period. The Sandwich Fault zone is a series of high angle faults trending about 120 degrees (Kolata and others, 1978). The Sandwich Fault zone is downthrown to the north, has up to about 800 ft of displacement, and developed after the Silurian period. These faults developed in response to tectonic stresses.

Faulting at the Plum River Fault zone resulted in the presence of younger deposits forming the subcrop in much of northwestern Illinois (fig. 4). Faulting at the Sandwich Fault zone resulted in erosion of the Galena-Platteville deposits in much of the area near the fault zone in north-central Illinois, resulting in the presence of older deposits as the subcrop.

There are numerous smaller structural features—arches, domes, anticlines, synclines, and faults—in the Galena-Platteville deposits. The size of these features ranges from hundreds of feet to tens of miles. These features have little effect on the distribution of the Galena-Platteville deposits as a whole, but can affect the presence and location of individual geologic units and can have a substantial effect on the orientation and density of the fractures and solution openings.

Investigation of the Galena-Platteville deposits in the lead-zinc district of southeastern Wisconsin (Lafayette, Iowa, and Grant Counties) and northern Illinois (Jo Davies County) (fig. 4) identified folds up to 30 mi in length and from 3 to 6 mi in width, with about 100 to 200 ft of amplitude (Heyl and others, 1955; Carlson, 1961; Agnew, 1963; Allingham, 1963: Klemic and West, 1964; Taylor, 1964; Whitlow and West, 1966; Willman and Kolata, 1978). Faulting with up to 200 ft of displacement may have occurred. Folds trend eastward to northeastward or northwestward.

The Galena-Platteville deposits also contain an extensive network of horizontally oriented features includ-

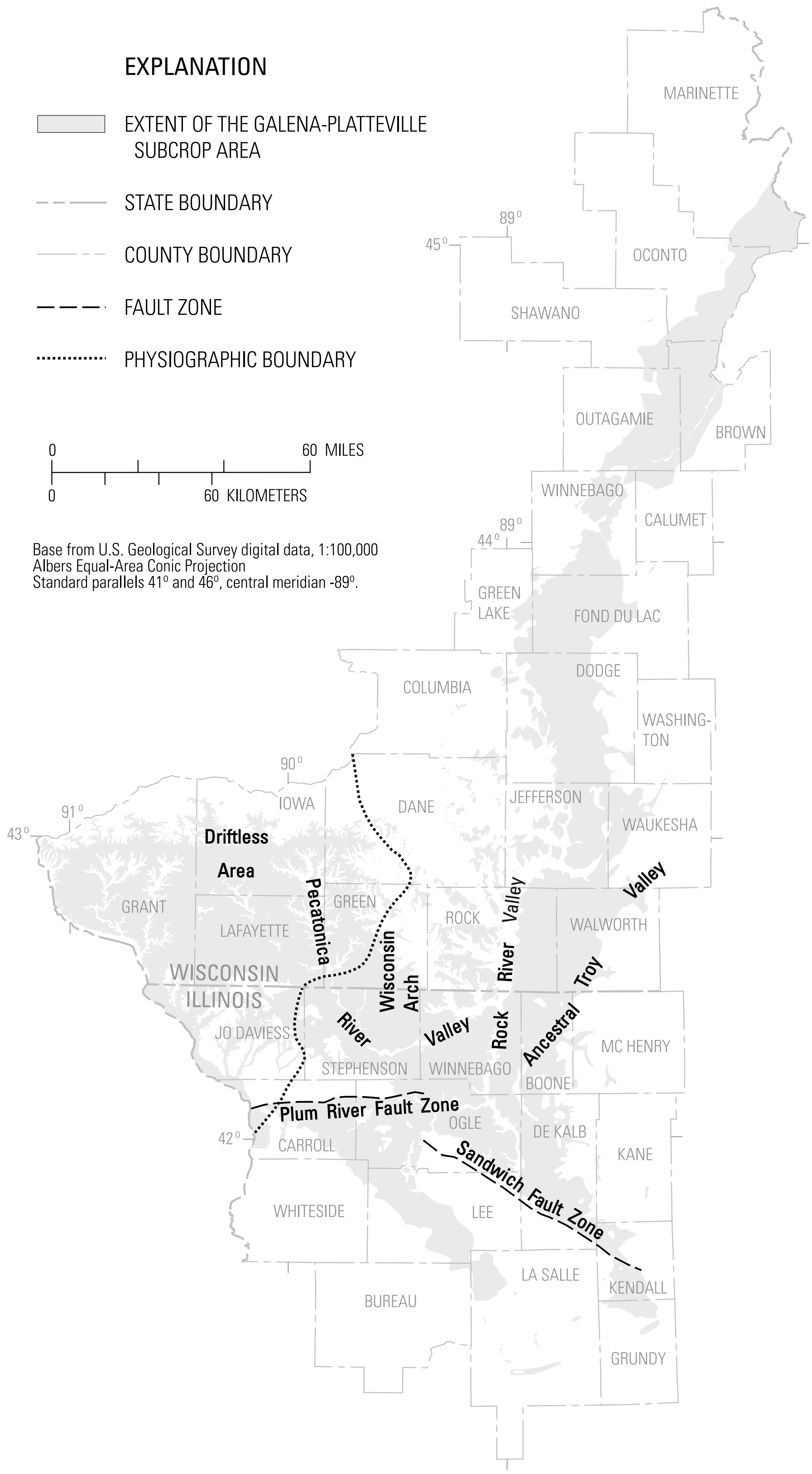


Figure 4. Galena-Platteville subcrop area of Illinois and Wisconsin and select structural and physiographic features.

ing vugs and bedding-plane partings and non-horizontal features such as inclined fractures. The orientations of the inclined fractures in the lead-zinc district in Wisconsin change substantially over distances of hundreds of feet, but tend to be oriented primarily to the northwest with a conjugate set to the northeast (Heyl and others, 1955; Carlson, 1961; Agnew, 1963; Allingham, 1963; Klemic and West, 1964; Taylor, 1964; Whitlow and West, 1966; Willman and Kolata, 1978). Vertical fracture traces in the Galena-Platteville deposits at six quarries in north-central Illinois commonly showed a fracture set oriented at N. 31° W. and a second nearly orthogonal fracture set oriented at S. 64° E. (Foote, 1982). In Boone and Winnebago Counties in Illinois, the predominate orientation of the vertical fractures in the Galena-Platteville deposits is N. 74° W. with a secondary set at N. 30° E. The northwest trending fractures in the upper part of the deposits were shorter and more widely spaced than in the lower part, whereas intensity in the northeast trending fractures was greater in the upper part. Formation of these fracture sets was attributed to tensile cracking (Chris McGarry, Illinois State Geological Survey, written commun., 2000).

Tectonic deformation and chemical dissolution of the rock has resulted in the development of karst features (sinkholes, small caverns) in the Galena-Platteville deposits in parts of the subcrop area (LeRoux, 1963). However, the karst features usually are obscured by the overlying glacial deposits.

Stratigraphy of the Galena-Platteville Deposits

The Illinois State Geological Survey (ISGS) considers the Galena and Platteville deposits to be groups (fig. 5), which are subdivided into 10 formations primarily based on subtle variations in silt and clay content, with other features, such as chert content, fossils, and bedding, also being considered (Willman and Kolata, 1978). The ISGS further divides these formations into members. The Wisconsin Geologic and Natural History Survey (WGNHS) considers these deposits to compose the Sinnipee Group, which is divided into the Platteville Formation, the Decorah Formation, and the Galena Dolomite (fig. 5). These deposits are divided into members by the WGNHS. Because it is the most detailed, the stratigraphic nomenclature used in most of this report is that of the ISGS (Willman and others, 1975, p. 61-80 and 218-230), which does not follow the usage of the USGS. WGNHS nomenclature is used for the discussion of the Waupun site to be consistent with the presentation in the original report.

The basal unit of the Platteville Group is the Pecatonica Formation (Willman and Kolata, 1978; Choi, 1998), which is composed primarily of medium-to-thick bedded, gray-to-brown, mottled, finely vuggy, fine-to-medium crystalline dolomite with few shale partings. This deposit unconformably overlies the Glenwood Formation in much of the subcrop area in Illinois, and conformably overlies the Glenwood Formation in much of Wisconsin. The Pecatonica Formation commonly is

ILLINOIS			WISCONSIN		
Galena Group	Dubuque Formation		Sinnipee Group	Galena Dolomite	Dubuque Member
	Kimmswick Subgroup	Wise Lake Formation			Wise Lake Member
		Dunleith Formation			Dunleith Member
	Decorah Subgroup	Guttenberg Formation		Decorah Formation	Guttenberg Member
		Spechts Ferry Formation			Spechts Ferry Member
Platteville Group	Plattin Subgroup	Quimbys Mills Formation		Platteville Formation	Quimbys Mill Member
		Nachusa Formation			McGregor Member
		Grand Detour Formation			
		Mifflin Formation			
	Pecatonica Formation				Pecatonica Member

Figure 5. Stratigraphic nomenclature of the Galena and Platteville deposits in Illinois and Wisconsin.

about 20-45 ft thick in northern Illinois and Wisconsin and generally thickens from north to south.

The Mifflin Formation is separated by a weathered surface from the underlying Pecatonica Formation. The Mifflin Formation is composed primarily of thinly interbedded light gray and light brown, finely crystalline dolomite and limestone with numerous gray and green shale partings (Willman and Kolata, 1978). The formation is composed predominately of limestone in parts of southwestern Wisconsin and small areas of north-central Illinois and dolomite in the remainder of the study area. The Mifflin Formation commonly is 15-20 ft thick in northern Illinois and southwestern Wisconsin.

The Grand Detour Formation conformably overlies the Mifflin Formation and is composed of a lower, cherty, medium-grained, medium-bedded, mottled dolomite and limestone with small amounts of clay and an upper, thinly bedded, cherty, argillaceous dolomite and limestone with brown-red, gray, or black shale partings. Limestone tends to constitute a larger percentage of the deposits in southwestern Wisconsin than in other parts of the study area. The Grand Detour Formation is part of the McGregor Formation according to WGNHS nomenclature. The thickness of the Grand Detour Formation is about 25-45 ft beneath the northern Illinois part of the study area but is about 15-20 ft thick in southwestern Wisconsin and thickens to the south and east (Willman and Kolata, 1978; Choi, 1998).

The Nachusa Formation conformably overlies the Grand Detour Formation and is composed of brown and gray thickly bedded to massive, fine-to-medium grained, vuggy dolomite with some limestone, mottles, and chert. The middle part of the Nachusa Formation is argillaceous. The Nachusa Formation is the part of the McGregor Formation according to WGNHS stratigraphic nomenclature. This formation is about 15-25 ft thick in north-central Illinois, but thins westward and is absent in western Jo Davies County, Ill. and Grant County, Wis.

The Quimbys Mill Formation is the uppermost deposit of the Platteville Group and conformably overlies the Nachusa Formation where the Nachusa Formation is present. The Quimbys Mill Formation is composed of thin to medium bedded, brown to gray, very fine to finely grained mottled dolomite with some limestone, thin brown shale partings, and some chert. The Quimbys Mill Formation is composed of substantial percentage of limestone in much of southwestern Wisconsin (Allingham, 1963). The Quimbys Mill Formation is about 12 ft thick in most of the northern Illinois and Wisconsin, but thins toward the north and west in southwest Wisconsin and is less than 1 ft thick or absent in much of far southwestern Wisconsin. The variation in the thickness of the Quimbys Mill Formation may result partly from solution thinning of limestone in the formation. The top of the Quimbys Mill Formation is defined by an unconformity that is characterized by fractures and brecciation with vuggy porosity (Choi, 1998).

The Spechts Ferry Formation is the basal unit of the Galena Group and unconformably overlies the Quimbys Mill Formation. The Spechts Ferry Formation is composed predominately of shale, with interbedded limestone and dolomite. This formation is as much as 15 ft thick in extreme northwestern Illinois and southwestern Wisconsin, but thins to the north and east and is absent in most of the study area. In parts of southwestern Wisconsin, the Spechts Ferry is thinner where it is composed of approximately equal parts of limestone and shale than where it is composed predominately of dolomite (Carlson, 1961), presumably because of differential solution.

The Guttenberg Formation is composed of vuggy dolomite or limestone with thin beds of red or brown shale. The Guttenberg Formation is conformable with the Spechts Ferry Formation where the Spechts Ferry is present, but unconformably overlies the Quimbys Mill where the Spechts Ferry is absent. The Guttenberg Formation is about 10-15 ft thick in the western part of the study area, thins to about 1-7 ft in the central and eastern part of the study area near the State line, and is absent along the eastern flank of the Wisconsin Arch (Willman and Kolata, 1978; Choi, 1998). The thickness of the Guttenberg Formation can vary substantially over distances of less than 500 ft, perhaps because of dissolution of the carbonate beds, and the formation locally is absent throughout the study area. The Guttenberg Formation is predominately limestone in parts of northwestern Illinois and southwestern Wisconsin.

The Dunleith Formation disconformably overlies the Guttenberg Formation where the Guttenberg Formation is present. Where the Guttenberg and Spechts Ferry Formations are absent, the Dunleith Formation unconformably overlies the Quimbys Mill Formation, except for a small area of southwestern Wisconsin and northwestern Illinois where the Quimbys Mill is absent and it overlies the Nachusa or Grand Detour Formations. The Dunleith Formation is composed primarily of gray-to-brown, medium to coarsely crystalline mottled dolomite with abundant chert and alternating beds of pure and argillaceous dolomite. The pure dolomite deposits are medium to thickly bedded and vuggy. The argillaceous dolomite deposits are medium to thinly bedded and dense. The argillaceous content of this formation decreases from the bottom to the top. The lower part of the formation usually is composed of limestone in parts of northwestern Illinois and southwestern Wisconsin. The Dunleith Formation is about 120 ft thick in much of the study area where it has not been thinned by erosion. Limestone dissolution in parts of the Dunleith Formation may have resulted in the development of karst features in parts of southwestern Wisconsin.

The Wise Lake Formation conformably overlies the Dunleith Formation and consists of tan and gray, vesicular to vuggy, medium-to-thickly bedded, coarsely crystalline dolomite with some mottles and little chert. The Wise Lake Formation typically is nonargillaceous and is about 45-75 ft thick where it has not been thinned by erosion.

The Dubuque Formation is the uppermost deposit in the Galena Group, and conformably overlies the Wise Lake Formation. The lower part of the Dubuque Formation grades upward from argillaceous, thick bedded dolomite, to shaley dolomite. The upper part of the Dubuque Formation becomes increasingly argillaceous and consists of interbedded argillaceous dolomite and dolomitic shale. Where not eroded, the Dubuque Formation is about 45 ft thick in much of the western part of the study area, thinning to about 20 ft in the east.

In the eastern part of the Wisconsin Arch, the Platteville deposits indicate a trend of increasing shale, coarser dolomite, and more vugs and chert to the north. Within the Galena Group, clay content increases to the north, as does the size of the dolomite crystals and the lithologic heterogeneity of the deposits (Choi, 1998).

Relation Between Glacial Deposits and the Galena-Platteville Deposits

In the Driftless area of southwestern Wisconsin and northwestern Illinois (Leighton and others, 1948)(fig. 4) glacial deposits largely are absent. In this area, the Galena-Platteville dolomite is overlain by soil and loess, which typically are less than 10 ft thick. Fractures in the dolomite that extend to the land surface in the Driftless area can be infilled with unconsolidated rock material to depths more than of 80 ft (Agnew, 1963). Quaternary-aged alluvial deposits are present in the stream and river valleys of the Driftless area. Alluvial deposits are less than 10 ft thick in most of the Driftless area, except near the Mississippi River.

Ground-moraine deposits composed primarily of till overlie the Galena-Platteville dolomite in most of the study area outside of the Driftless area (Olcott and Hamilton, 1973; Cotter and others, 1969; Olcott, 1966). These ground-moraine deposits typically are less than 100 ft thick (Brown and others, 2000). Fluvial and glaciofluvial processes have resulted in the partial to complete erosion of the Galena and Platteville deposits in the valleys of the Pecatonica and Rock Rivers, and in the ancestral Troy Valley (fig. 4). Glaciofluvial processes deposited more than 300 ft of sand and gravel, which partially have filled the bedrock troughs and valleys (Brown and others, 2000). Most of the subcrop consists of the Galena dolomite, although Platteville deposits commonly are the subcrop unit along bedrock valleys (Batten and others, 1997).

Hydrology of the Galena-Platteville Aquifer

The Galena and Platteville deposits at the regional scale are lithologically and hydraulically similar and are considered a single hydraulic unit, the Galena-Platteville aquifer. The Galena-Platteville deposits are unsaturated in the far western parts of the study area (Cline, 1965; LeRoux, 1963). The water table is located within the Galena-Platteville aquifer in much of the study area where the unconsolidated deposits are thin (LeRoux, 1963), and the aquifer typically is completely saturated where the unconsolidated deposits are comparatively thick (Borman and Trotta, 1975, Borman, 1976, Berg and others, 1984). The unconsolidated deposits typically recharge the Galena-Platteville aquifer where the unconsolidated deposits are saturated. Where saturated unconsolidated deposits are absent, precipitation directly recharges the aquifer. Water in the Galena-Platteville aquifer discharges to nearby surface-water bodies or recharges the underlying St. Peter aquifer.

Horizontal hydraulic conductivity (Kh) values for the Galena-Platteville aquifer from a series of specific-capacity tests done in eastern Wisconsin averaged 18 ft/d in the weathered upper 15 ft of the aquifer, 4.0 ft/d in the upper 15 to 40 ft of the aquifer, and 0.15 ft/d below 40 ft (Feinstein and Anderson, 1987). Aquifer tests in Brown County, Wisconsin (fig. 4) resulted in a Kh of 5.3 ft/d in the upper part of the aquifer (Batten and Bradbury, 1996). Kh values from specific-capacity tests in wells open to the aquifer in Jefferson and Walworth Counties, Wisconsin ranged from 1 to 130 ft/d (Borman and Trotta, 1975; Borman, 1976). Results from Jefferson and Walworth Counties probably were biased toward the upper part of the aquifer. Vertical-hydraulic conductivity values (Kv) of 0.003 and 3.4×10^{-5} ft/d were obtained for the Galena-Platteville aquifer in a part of northeastern Wisconsin where the aquifer was confined by the Maquoketa Shale (Krohelski, 1986; Conlon, 1997).

Analysis of the hydrostratigraphy of the Galena-Platteville aquifer at two boreholes in eastern Wisconsin indicates that the Kh distribution varied from about 0.03 to 284 ft/d in one of the boreholes, and typically was about 0.28 ft/d in the other (Stocks, 1998). Stocks observed that the aquifer was poorly permeable where it was composed of homogenous, fine-grained dolomite; was moderately permeable where the dolomite has increased granularity and bioturbation, as well as an increased number of clay beds, vugs and other forms of secondary porosity; and was most permeable in zones with fractures and solution openings. Secondary-permeability features associated with solution along bedding planes were found in intervals with abundant clay beds and at contacts between contrasting lithologies. Fractures and solution features also were concentrated in the weathered deposits near the top of the aquifer.

The correlation between changes in lithology and the enhanced presence of secondary permeability features is consistent with work done by Rovey and Cherkauer (1994). Observations on the concentration of springs in association with the Spechts Ferry Formation (Agnew, 1963) and the presence of solution cavities at the contact between the dolomitic shale of the Quimbys Mill Formation and the underlying limestone of the McGregor (Nachusa) Formation (Allingham, 1963) in southwestern Wisconsin also indicate that areas of lithologic change may be preferential pathways of ground-water flow, areas of enhanced dissolution of the carbonate rock, and increased aquifer permeability (Carlson, 1961). Additionally, lead-zinc deposits in northwestern Illinois and southwestern Wisconsin typically are located in fractures or solution features in the Spechts Ferry or Guttenberg Formations (Heyl and others, 1955; Allingham, 1963; Agnew, 1963; Klemic and West, 1965). As these mineral deposits formed from precipitation of compounds dissolved in meteoric water, their presence indicates that lithologic changes associated with the shaley Spechts Ferry and Guttenberg Formations also may have been associated with the historical presence of preferential ground-water flow through the Galena-Platteville aquifer.

SITE CONDITIONS AND METHOD APPLICATIONS

Characterization of the hydrogeology of the Galena-Platteville aquifer at the Byron Salvage Yard, Tipton Farm, ACME Solvents, Winnebago Reclamation Landfill, Southeast Rockford, Parson's Casket Hardware, Belvidere area, Waupun, and Better Brite sites is based on a variety of standard and innovative investigative methods (table 1). Each of these methods has a variety of uses and limitations (table 2). The focus of this report is on the utility of the methods for identifying and characterizing secondary-permeability features (especially those that were highly permeable) in the Galena-Platteville aquifer. Numerous other methods are available for characterization of fractured-rock aquifers. However, methods not used for these investigations are beyond the scope of this report and are not discussed. More detailed discussion of the individual methods used for these investigations, including how they work, the types of information provided, the scale of aquifer characterized, and the shortcomings of the method are presented in appendix A.

A description of the hydrogeologic conditions at each of the sites investigated, as well as a summary of the investigative methods used and the utility of each method at each site follow. Detailed description of the insights gained from the application of each method at each site is included in appendixes B-H, as well as in the original site documents. The sites are presented in approximate geographic order from southwest to northeast (fig. 2), which generally is coincident with the trends in the permeability of the Galena-Platteville aquifer at the sites investigated. The aquifer is most permeable at the Byron Salvage Yard site in the southwest, least permeable at the Better Brite site to the northeast, and of intermediate permeability at the remaining sites.

Byron Site

The Byron Salvage Yard Superfund site (the Byron site) is located in Ogle County in north-central Illinois (figs. 6 and 7). The Byron site was investigated intensely with 26 different investigative methods used (tables 1 and 3), more than 75 wells penetrating the Galena-Platteville aquifer (table 4) available for characterization, and over 25 years of data available for analysis. Detailed analysis of the data collected at this site is presented in appendix B.

The Byron site consists of two properties, the Byron Salvage Yard (BSY), and the Dirk's Farm Property (DFP) (figs. 6 and 7). Industrial wastes were deposited on the BSY and various locations on the DFP from the 1960's through the early 1970's (fig. 8). These wastes have leached VOCs and cyanide into the Galena-Platteville aquifer, the uppermost aquifer beneath the disposal areas.

The Byron site is characterized by a northwest trending upland dissected by well-developed, narrow drainage ravines (figs. 6 and 7). The upland areas nearly are level or gently rolling, grading to steeply sloping valley walls near the ravines. The Galena-Platteville dolomite is as much as 190 ft thick beneath the topographic ridges in the Byron area (figs. 9 and 10). The topographic ridge also is a bedrock ridge. Pre- and post-glacial erosion along fractures in the dolomite has accentuated the development of the topographic lows associated with the ravines and has reduced the thickness of the dolomite near Woodland Creek, the West Ravine, and the Northwest Ravine. Erosion has removed the Galena-Platteville dolomite in the vicinity of the Rock River (fig. 10). Quaternary-aged deposits unconformably overlie the Galena-Platteville dolomite throughout that part of the Byron site where the dolomite is present (figs. 10 and 11). Alluvial sand-and-gravel deposits generally are present in topographically low areas in the valley of the Rock River and along the lower reaches of Woodland Creek, the Northwest Ravine, and the West Ravine. Loess deposits underlain by sand-and-gravel deposits are located in the topographic depressions in the upper parts of Woodland Creek, the West Ravine, and the Northwest Ravine. Quaternary deposits in the upland areas are composed of loess and till. Quaternary

Table 2. Description of methods used for data collection by the U.S. Geological Survey and U.S. Environmental Protection Agency for investigation of the Galena-Platteville aquifer in Illinois and Wisconsin.

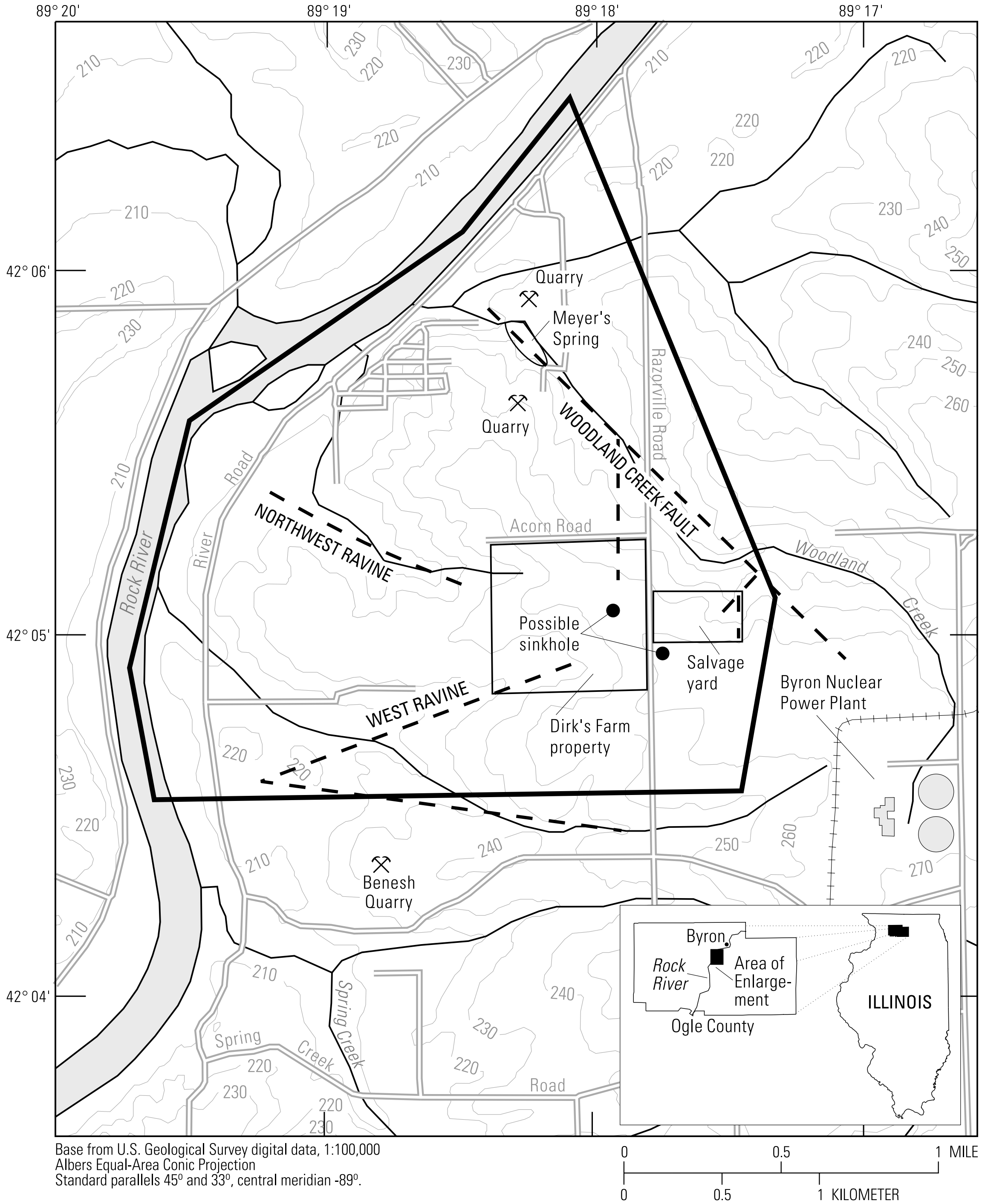
Method	Information Provided	Limitations
Previous investigations	Geology, hydrology, and water quality. Develoment of site conceptual model and identification of data gaps.	Information usually not site specific or pertinent to the problem identified. Can be hard to identify existence of report and obtain copies.
Databases	Geology, hydrology, and water quality. Development of site conceptual model and identification of data gaps	Information generally not site specific or pertinent to the problem identified.
Topographic maps or aerial photographs	Potential location of faults, fracture traces, bedrock ridges, sinkholes, and ground-water-flow direction. Can give a preliminary indication of more and less fractured parts of rock.	Requires field verification. Most useful where unconsolidated deposits are thin and for larger secondary-permeability features.
Quarry visits	Lithology and stratigraphy. Fracture type, location, and orientation. Location of preferential flow paths.	Representativeness of data dependent on proximity to site and extent of excavation. Stress release fractures can be misidentified as representative of in-situ conditions.
Surface geophysics	Location and orientation of secondary-permeability features.	Affected by surficial geology and cultural interference. Data often requries field verification.
Lithologic logging	Lithology, location of secondary permeability features. Location of permeable features.	Descriptions can be subjective. Moderately permeable features can be difficult to identify. Drilling is expensive.
Core analysis	Lithology, stratigraphy, and geotechnical properties.	Breaking and stress release fractures can obscure identification of presence and location of in-situ features. Expensive in comparison to other methods.
Borehole-camera logs	Location and type of secondary-permeability features. Location of permeable features. Can be used above or below the water level in the borehole.	Visibility limited in cloudy water. Data analysis can be time consuming. Orientation of inclined features cannot be identified with some systems. Location of permeable features can be hard to identify.
Natural-gamma logs	Lithology, stratigraphy, location of clay-infilled secondary-permeability features	Affected by drilling fluids. Sometimes cannot distinguish between different non-argillaceous lithologies.
Caliper logs	Location of competent rock as well as potential fractures and solution openings. Location of well casing. Can help identify source of anomalies in flowmeter data.	Cannot identify features. Cannot distinguish between fractures and wash outs from soft rock. Typically not good for identifying vugs or features with small apertures. Cannot determine if feature is permeable. Need uncased borehole.
Spectral gamma logs	Location of clays with differing mineralogy, can be associated with clay-infilled fractures.	Limited utility for characterization of secondary permeability. Data collection can be time consuming.
Acoustic televiewer	Location, apparent size, and orientation of fractures. Location of vugs and solution openings.	Apparent size of fracture at borehole typically not representative. Cannot distinguish between fractures and wash outs from soft rock. Cannot determine if feature is permeable. Must be below the water level in an uncased borehole. Borehole must be nearly vertical for accurate assessment of fracture orientation.
Spontaneous-potential logs	Location of potential secondary-permeability features. Location of permeable features. Can identify differences in water quality in the borehole.	Affected by vertical flow in the borehole and presence of argillaceous deposits in the rock. Requires substantial change in water quality for identification of permeable features. Precise depth of features can be hard to identify. Only can be used below water in uncased boreholes.
Single-point resistance and normal resistivity logs	Location of potential secondary-permeability features. Location of permeable features and some lithologic changes. Can identify differences in water quality.	Affected by vertical flow in the borehole and argillaceous deposits in the rock. Requires fairly substantial change in water quality for identification of permeable features. Precise depth of features can be hard to identify. Only can be used below water in uncased boreholes. Thinner features can be missed.
Density logs	Variation in rock bulk density, which can be related to porosity.	Signal does not relate directly to porosity.
Borehole ground-penetrating radar	Location and orientation of bedding planes and potential secondary-permeability features in rock away from borehole. Cross-borehole tomography can indicate extent of features.	Requires high contrast in conductivity, some features may not be identified. Requires verification. Length of signal penetration is variable. Steel casing prevents use.
Water levels from wells (single measurement)	Identification of flow direction in three dimensions. Can indicate areas of comparatively large and small permeability and boundaries to slow system. Can identify presence and sources of variation in flow.	Can provide inaccurate identification of flow direction, particularly in karstic aquifers. Does not identify changes in flow because of pumping or precipitation.

Table 2. Description of methods used for data collection by the U.S. Geological Survey and U.S. Environmental Protection Agency for investigation of the Galena-Platteville aquifer in Illinois and Wisconsin.--Continued.

Method	Information Provided	Limitations
Water levels from wells (periodic measurement)	Identification of flow direction in three dimensions. Can indicate areas of comparatively large and small permeability and boundaries to flow system. Can identify presence and sources of variation in flow.	More expensive than single measurements. May be too infrequent in highly variable flow systems to define the range of conditions in a timely manner.
Water levels from wells (continuous measurement)	Identification of barometric efficiency, which can be indicative of confined or unconfined aquifer. Identification of response to pumping or precipitation.	More expensive than periodic measurements. Typically, only practical for a limited number of wells.
Temperature logs	Depth of permeable features.	Temperature changes usually small and subtle, particularly below the upper 5-10 feet of the water column. Presence and depth of permeable features can be hard to identify.
Fluid resistivity logs	Depth of permeable features. Trends in water quality.	Resistivity changes often small and subtle, particularly below the upper few feet of the water column. Presence and depth of permeable features can be hard to identify.
Flowmeter logs (single well)	Depth of permeable features.	Lack of ambient flow can be caused by low permeability or lack of vertical variation in water levels. Less permeable features can go unidentified, particularly if permeability variations are large. Requires uncased, unscreened borehole.
Flowmeter logs (cross-hole pumping)	Depth of permeable features. Pathways of hydraulic connection between features. Can estimate transmissivity and storage coefficient.	Limited utility in low-permeability deposits. Method used to calculate transmissivity and storage coefficient requires supporting data and is still being verified.
Hydrophysical logs	Depth of permeable features. Water quality. Can estimate transmissivity and storage coefficient.	Requires deionized water.
Slug tests	Estimates of horizontal hydraulic conductivity. Location of permeable features. Trends in aquifer permeability and hydrostratigraphy.	Assumes uniform flow through the aquifer and can underestimate horizontal hydraulic conductivity. Can vary with increases in saturated thickness in water-table wells. Results affected by length of test interval.
Specific-capacity tests	Estimates of transmissivity. Areal trends in aquifer permeability.	Well loss and inaccurate estimation of effective well radius and aquifer storage coefficient can affect accuracy of transmissivity estimate.
Multiple-well, constant-discharge tests	Estimates of transmissivity, storage coefficient, and vertical and horizontal hydraulic conductivity. Location and orientation of hydraulically interconnected features.	Expensive to perform. Data can be affected by a variety of phenomena. Misapplication of analytical methods can result in inaccurate estimates of hydraulic properties. Long test intervals can result in permeable features not being identified.
Tracer tests	Estimates of effective porosity. Identification of flow pathways if performed in conjunctions with cross-borehole ground-penetrating radar.	Expensive to perform. Data can be affected by a variety of factors. Misapplication of analytical methods can results in inaccurate estimates of hydraulic properties.
Contaminant Location	Verification and identification of flow pathways.	Can be affected by presence of unidentified sources such as nonaqueous phase liquids.
Data collection using packers	Allows detailed vertical characterization of water levels, water quality, and hydraulic properties at a borehole.	Can be expensive and time consuming, especially in low-permeability test intervals. Long packer intervals can result in features being missed.

deposits generally are less than 15 ft thick in along the topographic ridges, usually are greater than 20 ft thick at the ravines, and are more than 130 ft thick near the Rock River (fig. 10). The Galena-Platteville dolomite is underlain by the Harmony Hill Shale Member of the Glenwood Formation, which functions as a semiconfining unit beneath the Byron site. The St. Peter aquifer underlies the Harmony Hill Shale.

The Kh of the Galena-Platteville aquifer beneath the Byron site ranges from 0.0034 to 11,000 ft/d and varies with aerial location and stratigraphy (fig. 12). The dolomite contains karst features and the aquifer as a whole is moderately to highly permeable. Development



EXPLANATION

220 — TOPOGRAPHIC CONTOUR--Shows elevation of land surface, in meters. Contour interval 10 meters. Datum is NGVD 29.

- - - FRACTURE TRACE

━━ BYRON SITE BOUNDARY

Figure 6. Location of the Byron site, salvage yard, Dirk's Farm Property, sinkholes, and fracture traces, Byron site, north-central Illinois.

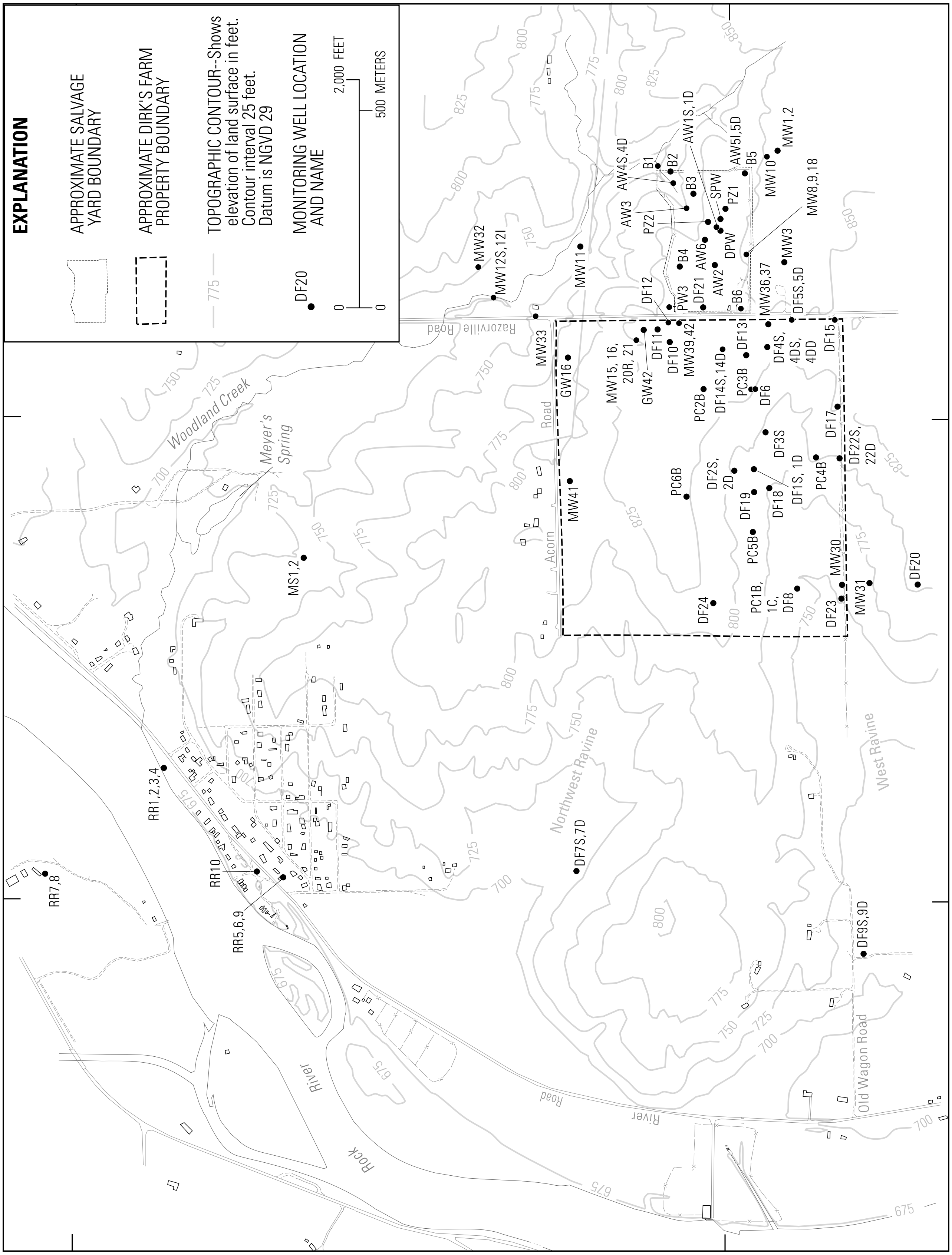


Figure 7. Location of monitoring wells, salvage yard, and Dirk's Farm property, Byron site, Ill.

of karstic features likely was aided by tectonic activity. Part of the Sandwich Fault zone is located approximately 7 mi south of the Byron site, the terminus of the Plum River Fault zone is about 7 mi to the northwest, and the Oregon anticline is present about 3 mi south. Sinkholes are present in the upland areas within and south of the Byron site (fig. 6). These sinkholes are covered with glacial deposits and their surficial expression partly is obscured.

Ground-water flow and contaminant migration at the Byron site is from the uplands westward through the Galena-Platteville aquifer (figs. 13, 14, 15). Flow directions at the site are stable through time. Ground water from beneath the Byron site ultimately discharges into the Rock River. Woodland Creek appears to define the location of a ground-water sink that serves as a boundary to ground-water flow and contaminant migration on the northern part of the site. The hydraulic boundaries south of the Byron site are not well defined.

Virtually all of the methods of investigation provided some useful insight into the geology (table 5) or hydrology (table 6) of the Byron site. Multiple methods usually provided similar information.

Analysis of data from previous investigations, including searches of databases, provided an indication of the location, extent, and thickness of the Galena-Platteville deposits in and near the Byron site as well as information on the presence and orientation of fractures and faults. This information subsequently was verified by a number of site investigative methods.

Analysis of surface topography was useful for identifying the location of the bedrock ridge at the Byron site. Bedrock ridges can be areas of comparatively resistant, unfractured rock, which can have low permeability. Aquifer-test data confirm that the Galena-Platteville aquifer at the bedrock ridge beneath part of the Byron site had lower Kh than in the remainder of the area. Formation of secondary-permeability features associated with sinkholes and fracture traces (also identified by analysis of surface topography) resulted in high permeability beneath other parts of the bedrock ridge.

Orientations of fracture traces were predictive of fracture orientations in the dolomite, as verified by background investigations, quarry visits, and acoustic-televiewer logging. Development of fracture traces and sinkholes in this area was aided by the initial formation of fractures, at least some of which were created in response to nearby tectonic activity (Sargent and Lundy, Inc., and Dames and Moore, Inc., 1975), and enhanced by chemical dissolution of the rock in meteoric water. Identification of fracture traces and sinkholes was aided by their extensive development in this karstic area, and by the comparatively thin (less than 15 ft) unconsolidated deposits overlying much of the bedrock at this site, which did not obscure the traces.

Quarry visits were useful for establishing stratigraphy and orientations of inclined fractures, as well as indicating the potential for the development of permeable features in the Grand Detour Formation. Interpretations initially indicated by the quarry visits were confirmed by analysis of cores, acoustic-televiewer logs, GPR surveys, and aquifer testing.

The high clay content of the unconsolidated deposits in much of this area prevented appreciable penetration of the surface GPR signal in the areas investigated. For this reason, surface GPR was one of the few methods that provided no insight into the hydrogeology of the bedrock deposits at this site.

Lithologic logs provided the initial identification of areas where some of the larger more permeable secondary-permeability features were located as well as some of the less permeable parts of the aquifer. These interpretations subsequently were confirmed and expanded upon by analysis of water-level data, caliper logs, borehole-camera logs, acoustic-televiewer logs, flowmeter logs, and aquifer testing.

Core analysis provided the foundation for the Byron site stratigraphy, which helped provide insight into the lithologic factors that affect the distribution of Kh, water levels, and, perhaps, contaminant movement in the aquifer. Core analysis provided some insight into the location of secondary-permeability features in the aquifer, as well as giving some indication of secondary-permeability features that might be transmitting water. A potential permeable interval first identified from core analysis in borehole DF4D subsequently was confirmed by analysis of flowmeter logs and aquifer tests. Finally, analysis of samples collected from the cores was used to determine the primary porosity of the aquifer.

Three-arm caliper and borehole-camera logs provided insight into the location of fractures and solution openings in the bedrock, as well as areas where these features did not appear to be present. These logs, particularly the caliper, were of little use in identifying vuggy intervals. Camera and caliper logs helped refine interpretations about the type and locations of secondary-permeability features identified with the lithologic logging as well as various features not identified with the lithologic logging. The location of most of these features subsequently was confirmed by acoustic-televiewer logging. Borehole-camera logs also provided some indication of areas where the water level in the Galena-Platteville aquifer was above the water level in the borehole, interpretations confirmed by flowmeter logging and water-level measurement using a packer assembly.

Natural-gamma logs provided a comprehensive depiction of the stratigraphy at the Byron site beyond what could be accomplished with the six cores. This comprehensive stratigraphic framework provided insight into the lithologic factors that affect the distribution of secondary-permeability features, water levels, and, per-

Table 3. Summary of methods of data collection, Byron site, Ill.

Method	Location of data collection	Uses
Previous investigations	South of site.	Orientation of inclined fractures in dolomite.
Topographic maps and aerial photographs	Entire site and surrounding area.	Identification of fracture traces.
Quarry visits	Benesch Quarry and quarry near Meyers Spring.	Identification of fracture orientation, potential presence of solution features and lithology.
Surface geophysics	Salvage Yard, Dirk's Farm Property.	No data obtained.
Lithologic logging	All boreholes.	Identification of lithology, areas of high and low permeability, location of highly permeable features.
Cores	Boreholes MW2, MW20, DF4D, AW1D, AW4S, AW4D.	Identification of stratigraphy, lithology, quantification of primary porosity, location of potentially permeable features.
Borehole-camera logs	Boreholes DF4D, DF5S, DF12, DF15, DF17, GW42, SPW, PZ1, PZ2, PZ3, B6R.	Identification of presence and location of secondary-permeability features, drainage from above water column.
Caliper logs	Boreholes AW1S,D, AW2, AW5D, AW6, B6R, DF1S,D, DF2S,D, DF3S, DF4D, DF5D, DF10, DF11, DF12, DF13, DF17, DF20, DF21, DF22, DF24, GW16, GW42, MW2, MW11, MW18, MW20, MW37, MW39, MW41, PW3, PZ2, PZ3, SPW.	Identification of presence and location of potential fractures and competent parts of rock.
Natural-gamma logs	Boreholes AW1S,D, AW2, AW5D, AW6, B6R, DF1S,D, DF2S,D, DF3S, DF4S,D, DF5S,D, DF9D, DF10, DF11, DF12, DF13, DF17, DF20, DF21, DF22, DF24, DPW, GW16, GW42, MS2, MW2, MW10, MW11, MW18, MW20, MW37, MW39, MW41, PC1C, PC2, PW3, PZ1, PZ2, PZ3, SPW.	Characterization of site stratigraphy, identification of presence and location of potential clay-infilled fractures.
Spectral gamma logs	Borehole SPW.	Verified presence of clay infilled secondary-permeability features.
Spontaneous-potential logs	Boreholes AW1D, AW5D, DF2D, DF4S,D, DF5S,D, DF12, DF17, GW16, MW2, MW18, MW20, PW3.	Identified a few fractures.
Single-point resistance logs	Boreholes AW1D, AW5D, DF2D, DF4S,D, DF5S,D, DF12, DF13, DF17, MW2.	Identified a few fractures.
Neutron logs	Boreholes GW16, GW42, B6R, MS2, MW10, MW11, MW16, MW18, MW20, MW39, MW41, PC2, DPW, SPW.	Identified trends in porosity.
Acoustic-televiewer logs	Boreholes AW1S, B6R, DF4D, DF5D, DF12, DF13, DF17, GW16, GW42, PZ1, PZ2, PZ3, SPW.	Identified location, type, and orientation of secondary-permeability features.
Borehole GPR	Boreholes AW1S, DF4D, DF12, DF17, PZ1, PZ2, PZ3, SPW.	Location of lithologic changes, location and orientation of secondary-permeability features.
Water levels from wells	All wells.	Determined vertical and horizontal directions of flow, indicated distribution of permeability, identified presence of confining layer.
Water levels using packers	Boreholes AW1S, DF2D, DF4D, DF5D, DF6, DF12, DF13, DF14D, DF17, PZ1, PZ2, PZ3, SPW.	Identified vertical directions of flow, location of permeable, and less-permeable features at borehole.
Temperature logs	Boreholes AW1S,D, AW5D, DF2D, DF4D, GW16, MW2, PZ1, PZ2, PZ3.	Measured fluid temperature, identified location of some permeable features.
Fluid-resistivity logs	Boreholes AW1D, AW5D, DF2D, DF4D, DF5D, GW16, MW2, MW11, MW20, MW41, PW3, PZ1, PZ2, PZ3.	Measured fluid resistivity, identified location of some permeable features.

Flowmeter logs	Boreholes AW1S, DF4D, DF5D, DF12, DF13, DF17, PZ1, PZ2, PZ3, SPW.	Identified location of permeable features and pathways of hydraulic interconnection between boreholes.
Hydrophysical logs	Boreholes DF4D, DF12, SPW.	Identified location of permeable features, measured conductivity of formation water.
Slug tests	Almost all wells and boreholes.	Quantification of horizontal hydraulic conductivity, identification of permeable features, distribution of permeability.
Specific-capacity tests	Boreholes DF12, PZ3.	Quantification of transmissivity.
Step-drawdown tests	Boreholes SPW, DF4D.	Sustainable pumping rate.
Multiple-well, constant-discharge tests	Boreholes SPW, DF4D.	Quantification of hydraulic properties of aquifer, identification of ground-water-flow pathways, identification of presence of heterogeneity and anisotropy.
Tracer tests	Borehole SPW.	Identification of ground-water-flow pathways, quantification of effective porosity.
Contaminant location	Entire site.	Identification of ground-water-flow pathways.

haps, contaminant migration. Anomalies in the natural-gamma logs, combined with spectral-gamma logging, identified a number of clay-filled fractures, the presence of which was confirmed by acoustic-televiewer, borehole camera, GPR, and by lithologic and caliper logging in some of the boreholes.

Spontaneous potential (SP) and single-point resistance (SPR) logs provided only limited insight into the geology and presence of secondary-permeability features at the Byron site. Although both methods identified some fractures, they did not identify many of the secondary-permeability features identified with other methods.

Neutron logs provided minimal insight into the geology and presence of secondary-permeability features at the Byron site. The primary reason for this result is the high clay content in much of the Galena-Platteville dolomite at this site, the presence of clay minerals infilling some secondary-permeability features, and perhaps insufficient water in the fractures and solution openings to be clearly distinguishable from the water in the aquifer matrix.

Acoustic-televiewer logs provided the most useful, and largest amount of, information on the location, orientation, and type of secondary-permeability features in the dolomite. These logs tended to confirm results of the analysis of the fracture traces, lithologic logs, cores, borehole-camera logs, caliper logs, and natural-gamma logs on the location and orientation of fractures. Televiewer logs identified the type of feature, such as vugs, and the orientation of the feature that usually was not identified with the other methods.

Single-hole GPR surveys identified various secondary-permeability features associated with the transition to the shaley part of the Grand Detour Formation, as well as possible fractures tens of feet beyond the boreholes being logged. The ability to identify potential secondary-permeability features not intercepted by a borehole is an important improvement in the hydrogeologic characterization. However, poor correlation between the presence and orientation of potential fractures identified by the single-hole GPR logging and the presence and orientation of fractures identified by the acoustic-televiewer and other types of logs is cause for reservation about single-hole GPR logging. These differences may be at least partly attributable to changes in the orientation of the fractures away from the borehole and the potential presence of numerous fractures in the surrounding rock that did not intercept the borehole.

Cross-hole GPR surveys provided a clear depiction of the location of continuous secondary-permeability features between boreholes. These surveys provided important insight into the extent and interconnection of the secondary-permeability network on the BSY, which was verified by cross-hole flowmeter logging and multiple-well aquifer testing to be permeable. Because of variations in the altitude of some of these features,

Table 4. Monitoring well and water-level data, Byron Superfund site, Ill.

Hydrologic unit: GPWT, open to the water table in the Galena-Platteville aquifer; BGP, well open to the base of the Galena-Platteville aquifer; MGP, well open to the middle of the Galena-Platteville aquifer; UAWT, well open to the water table in the unconsolidated aquifer; UAM, well open to the middle of the unconsolidated aquifer; GPSS, well open to the entire thickness of the Galena-Platteville aquifer and the upper part of the St. Peter Sandstone aquifer; SS, well open to the St. Peter Sandstone aquifer; HHS, well open to the Harmony Hill Shale semiconfining unit; GP, well open to most or all of the Galena-Platteville aquifer. Water-level altitude: <, less than; NT, measurement not taken

Well name	Hydrologic unit	Depth of boring (feet below land surface)	Open interval (feet below land surface)	Measuring-point altitude (feet above National Geodetic Vertical Datum of 1929)	Water-level altitude January 27, 1992 (feet above National Geodetic Vertical Datum of 1929)
AW1D	BGP	161	149-161	833.55	753.68
AW1S	GPWT	83	304-98	833.89	806.43
AW2	GPWT	71	262-07	843.13	787.73
AW4D	BGP	118	96-118	783.94	735.07
AW4S	GPWT	50	15-50	783.70	744.46
AW5D	BGP	172	159-172	845.81	753.74
AW5I	MGP	100	93-100	845.79	766.85
AW6	GPWT	35	9-35	828.70	806.61
B1	GPWT	35	14-45	771.81	<736.81
B2	GPWT	60	31-60	792.76	<732.76
B3	GPWT	50	32-50	819.85	775.12
B4	GPWT	90	63-90	834.03	753.76
B5	GPWT	40	21-40	846.82	809.12
B6	GPWT	95	76-95	850.48	NT
B6R	GPWT	102	15-102	851.69	753.68
DF1D	BGP	111	76-94	787.69	727.55
DF1S	GPWT	62	39-62	787.12	728.07
DF2D	BGP	112	104-112	796.24	729.38
DF2S	GPWT	75	52-75	795.29	728.74
DF3	GPWT	66	43-66	792.09	729.28
DF4DS	GPWT	151	41-64	833.22	NT
DF4DD	BGP	151	137-151	833.04	NT
DF4S	MGP	92	78-92	833.26	756.79
DF5D	MGP	168	98-109	844.75	753.97
DF5S	GPWT	65	13-65	844.29	803.72
DF6	BGP	151	113-125	828.11	744.17
DF7D	UAM	53	40-48	712.79	675.13
DF7S	UAWT	27	20-27	712.71	685.99
DF8	BGP	63	55-63	757.73	719.70
DF9D	BGP	51	41-51	707.38	677.12
DF9S	WTUA	20	7-20	707.61	688.22
DF10	GPWT	84	62-84	834.27	753.66
DF11	GPWT	84	65-84	834.38	753.60
DF12	BGP	134	122-134	834.74	753.70
DF13	MGP	158	101-112	839.24	753.92
DF14D	BGP	166	134-147	847.05	753.89
DF14S	GPWT	111	71-88	847.51	<762.11
DF15	GPWT	115	7-115	849.91	745.51
DF17	BGP	123	97-123	820.59	732.04
DF18	GPWT	63	36-63	780.51	727.57
DF19	GPWT	65	48-65	788.87	727.79
DF20	GPWT	80	9-80	804.91	729.79
DF21	GPWT	100	18-100	840.43	758.87
DF22D	BGP	135	99-109	811.77	728.17
DF22S	GPWT	135	67-90	812.06	727.86
DF23	BGP	65	53-65	755.66	719.00

Table 4. Monitoring well and water-level data, Byron Superfund site, Ill.--Continued.

Well name	Hydrologic unit	Depth of boring (feet below land surface)	Open interval (feet below land surface)	Measuring-point altitude (feet above National Geodetic Vertical Datum of 1929)	Water-level altitude January 27, 1992 (feet above National Geodetic Vertical Datum of 1929)
DF24	GPWT	102	19-102	813.94	725.00
DPW	SS	310	190-310	837.06	NT
GW16	GPSS	133	16-133	788.79	NT
GW42	GPWT	101	5-101	838.58	753.16
MS1	BGP	47	34-47	729.27	694.79
MS2	SS	87	72-82	731.14	678.14
MW1	GPWT	71	13-71	862.15	806.50
MW2	SS	231	219-231	861.38	685.75
MW3	GPWT	76	14-76	858.82	789.28
MW8	BGP	180	170-180	853.40	753.57
MW9	GPWT	106	96-106	852.66	758.19
MW10	HHS	189	178-189	854.42	762.98
MW11	BGP	83	68-83	747.89	719.49
MW12I	UAM	52	43-52	726.99	713.44
MW12S	GPWT	33	22-33	728.55	712.58
MW15	GPWT	86	73-86	822.42	752.73
MW16	BGP	147	107-120	823.64	752.68
MW18	SS	237	227-237	853.09	NT
MW20R	SS	191	172-191	822.03	682.44
MW21	SS	234	215-234	821.88	682.47
MW30	GPWT	40	24-37	858.90	819.83
MW31	GPWT	63	50-63	772.96	719.04
MW32	GPWT	46	19-46	755.31	714.03
MW33	GPWT	58	22-58	759.21	712.50
MW36	BGP	156	136-156	843.99	753.93
MW37	SS	206	180-206	843.59	NT
MW39	SS	186	164-186	836.95	682.99
MW41	BGP	146	102-121	817.07	752.48
MW42	BGP	152	135-152	836.57	753.62
PC1B	GPWT	48	32-48	757.60	720.28
PC1C	SS	112	97-112	758.16	680.60
PC3B	GPWT	103	85-103	842.77	757.61
PC3B	GPWT	93	64-83	828.53	760.73
PC4B	GPWT	83	68-83	803.04	727.76
PC5B	GPWT	73	57-73	788.59	725.43
PC6B	GPWT	103	82-103	831.3	746.73
PW3	GPWT	91	8-91	833.38	753.64
PZ1	GP	165	20-165	838.51	NT
PZ2	GP	115	20-115	829.21	NT
PZ3	GP	145	20-145	NT	NT
RR1	UAM	55	40-53	679.99	672.14
RR2	UAM	25	9-25	678.55	NT
RR3	UAWT	15	4-15	679.90	672.11
RR4	UAM	88	70-88	678.24	672.18
RR5	UAM	40	31-40	689.61	672.11
RR6	UAWT	25	13-25	690.33	672.08
RR7	UAWT	44	28-44	709.00	672.71
RR8	UAM	100	87-100	710.19	672.76
RR9	UAM	58	50-58	689.28	672
RR10	UAM	123	103-113	676.27	NT
SPW	GP	150	20-150	836.43	NT

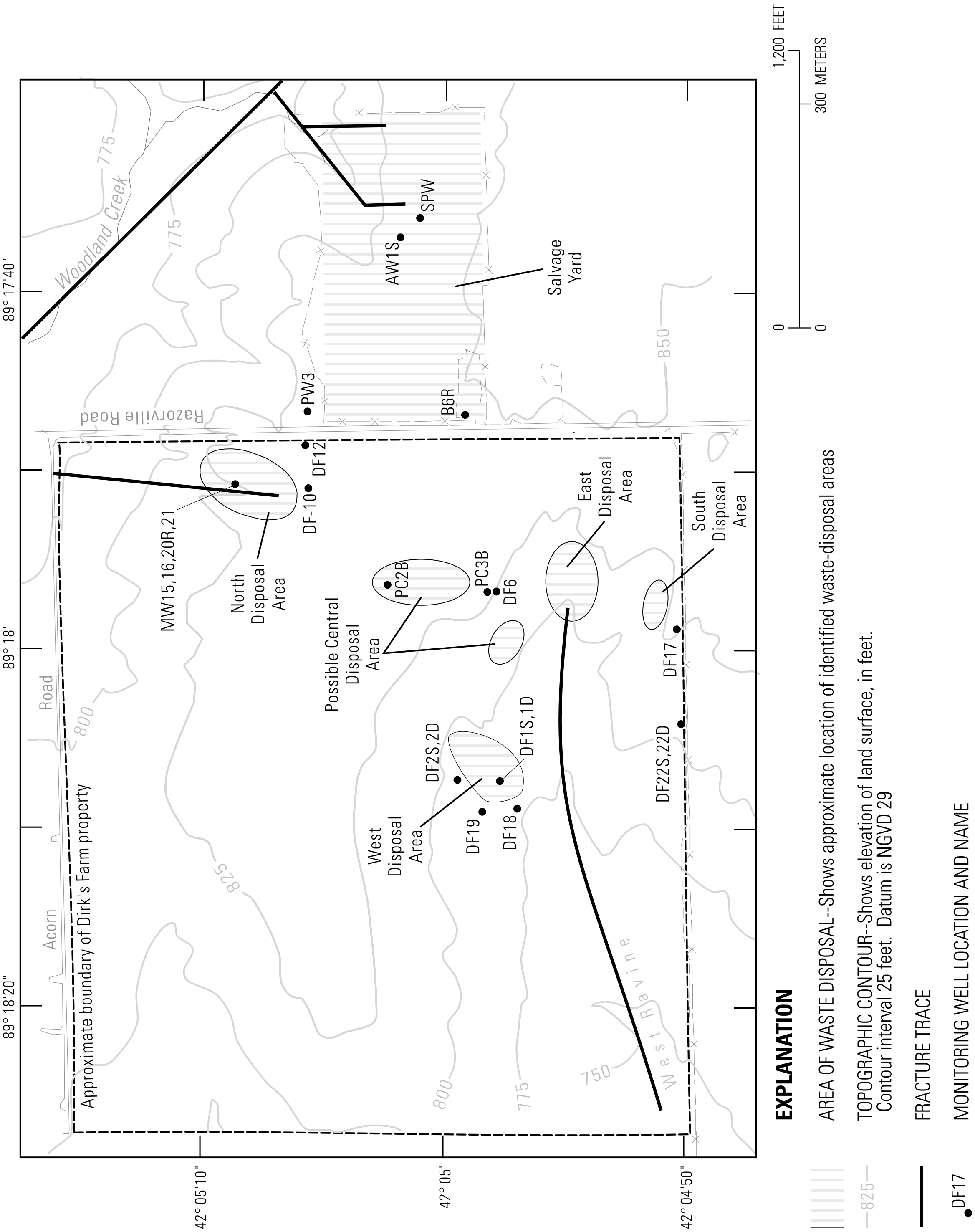


Figure 8. Location of identified waste-disposal areas and select fracture traces, Byron site, Ill.

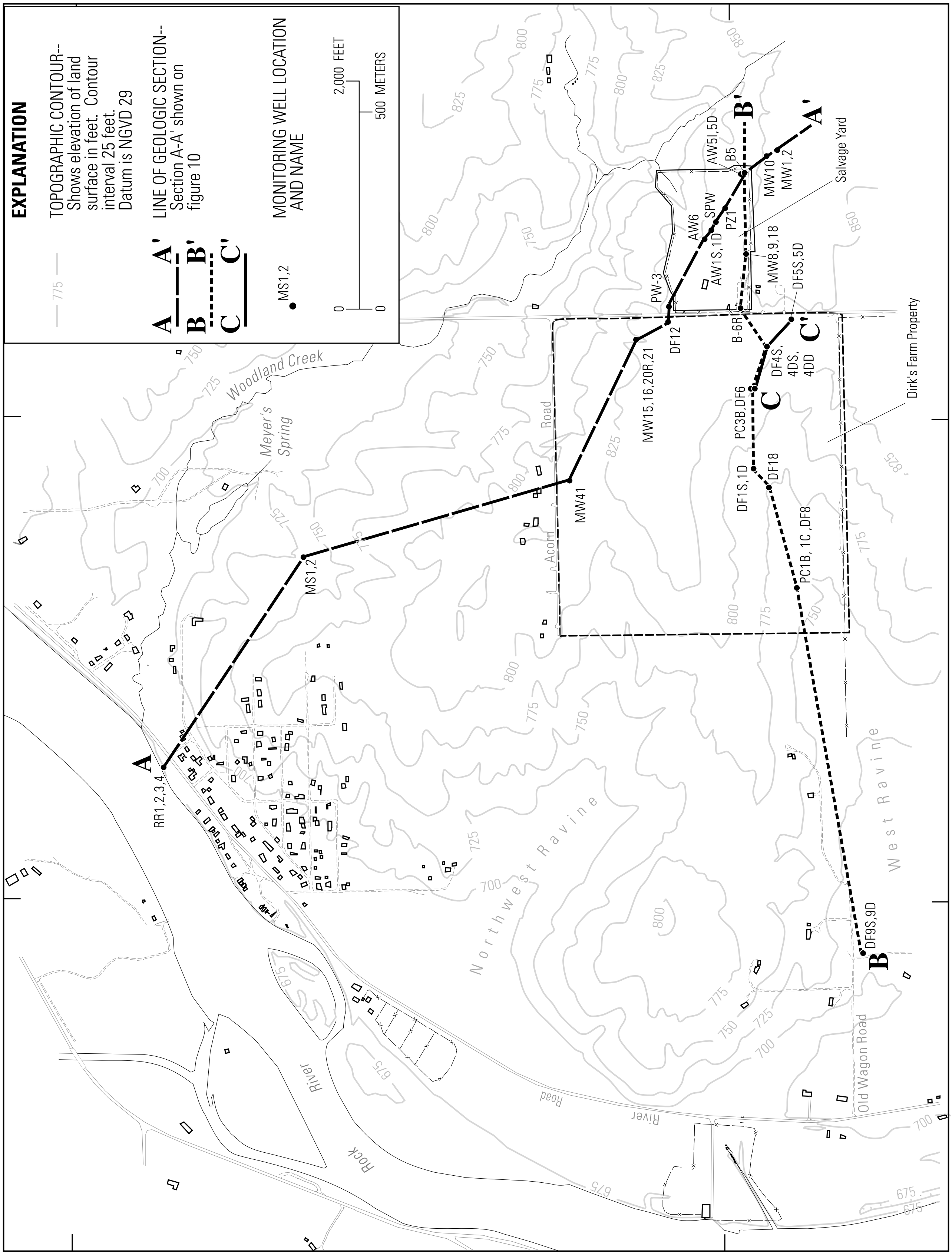


Figure 9. Lines of geologic section, Byron site, Ill.

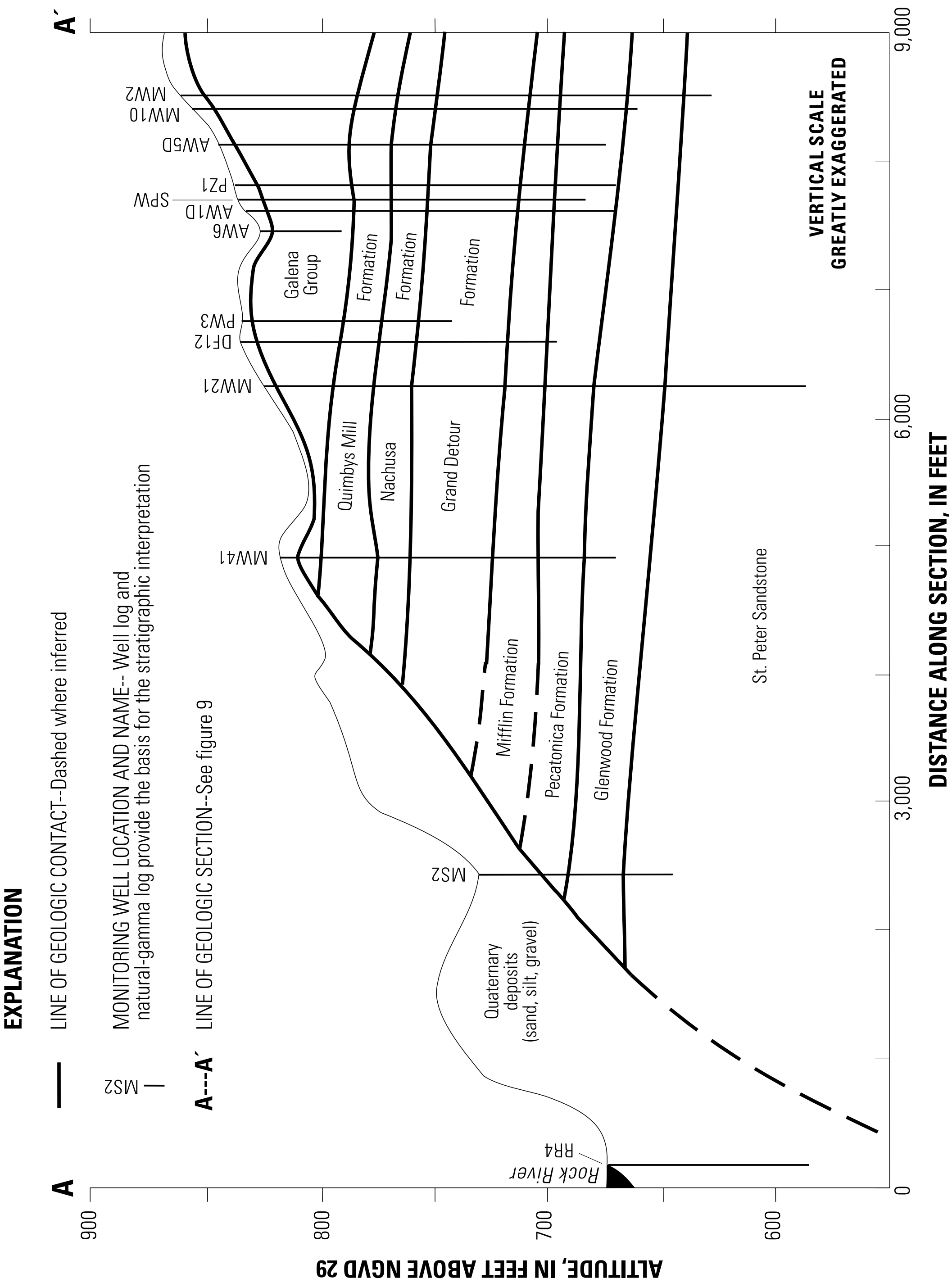


Figure 10. Diagram of geologic section A-A′, Byron site, Ill.

SYSTEM	GROUP	FORMATION	MEMBER	LITHOLOGY	THICKNESS, IN FEET	GEOHYDROLOGIC UNIT	MEDIAN PRIMARY POROSITY, IN PERCENT
QUATERNARY				Alluvium, silty at top, grading downward to sand with occasional gravel	0-20	Un-consolidated aquifer	Unknown
				Loess, windblown silt, leached	0-15		
				Sand and silt, windblown, leached	0-15		
				Outwash, sand and gravel	0-180		
				Till, brown silty clay to clayey silt with few boulders, stiff	0-26		
				Silt, brown to gray, calcareous, stiff	0-10		
				Till, brown silty sand with few boulders, very stiff to hard	0-25		
ORDOVICIAN	GALENA	DUNLEITH		Dolomite, buff, finely crystalline, thin to medium bedded with white and gray chert nodules, green shale partings in lower portion	0-70	Galena-Platteville aquifer	10.3
		GUTTENBERG		Dolomite, vuggy, with red shale partings	0-5		6.4
	PLATTEVILLE	QUIMBYS MILL		Dolomite, buff and gray, occasional white chert, mottled with numerous shale partings	0-20		10.2
		NACHUSA		Dolomite, pure to slighty argillaceous, vuggy, thickly bedded to massive, occasional white chert	0-25		9.5
		GRAND DETOUR		Dolomite, mottled buff and dark gray, finely crystalline, medium to massive bedded, thin gray and reddish-brown shale partings	0-45		11.3
		MIFFLIN		Dolomite, mottled, thinly bedded, thin gray or green shale partings	0-15		9.4
		PECATONICA		Dolomite, mottled, medium bedded	0-33		9
	ANCELL	GLENWOOD	HARMONY HILL	Shale, green, gray, and brown, thinly laminated	0-5	Harmony Hill Shale semi-confining unit	Unknown
			DAYSVILLE	Shale, brown and gray, sandy Dolomite, greenish-gray, fine-grained	0-16		18
			KINGDOM SANDSTONE	Dolomitic sandstone, greenish-gray	0-16	St. Peter aquifer	16
		ST. PETER SANDSTONE		Sandstone, white, coarse- to medium-grained, quartzose, friable	approximately 420		14

Figure 11. Generalized geologic column showing stratigraphy, geohydrologic units, and median primary porosity of Ordovician and Quaternary deposits, Byron site, Ill.

the interconnectivity of this network would not necessarily have been identified using single-hole methods of characterization.

Water-level measurements from packer assemblies and monitoring wells provided substantial insight into the horizontal and vertical directions of ground-water flow, the vertical and horizontal distribution of permeable features, and the possible presence of confined conditions in parts of the aquifer. Water-level data also assisted in the identification of permeable intervals at individual boreholes. In combination with stratigraphic data, analysis of water levels helped identify lithologic factors that may have affected trends in aquifer permeability. Interpretations regarding the distribution of secondary permeability in the aquifer and the location of secondary-permeability features in a borehole subsequently were supported by the results of aquifer testing. Interpretations regarding the overall directions of ground-water flow across the Byron site were confirmed with ground-water-quality data. However, ground-water-quality data indicate that there may be localized areas where flow is opposite to that predicted by water-level measurements. Water-level data provide insight into the permeability distribution because permeability is highly variable both vertically and horizontally across the Byron site. Large variations in permeability result in large, easily identifiable variations in the water levels required to induce steady-state flow through the aquifer. The variable permeability is a function of the location, type, density, size, and connectivity of fractures, vugs, and solution openings, which are, in turn, affected by the tectonic and chemical forces that affected development of karstic and other secondary-permeability features at the site.

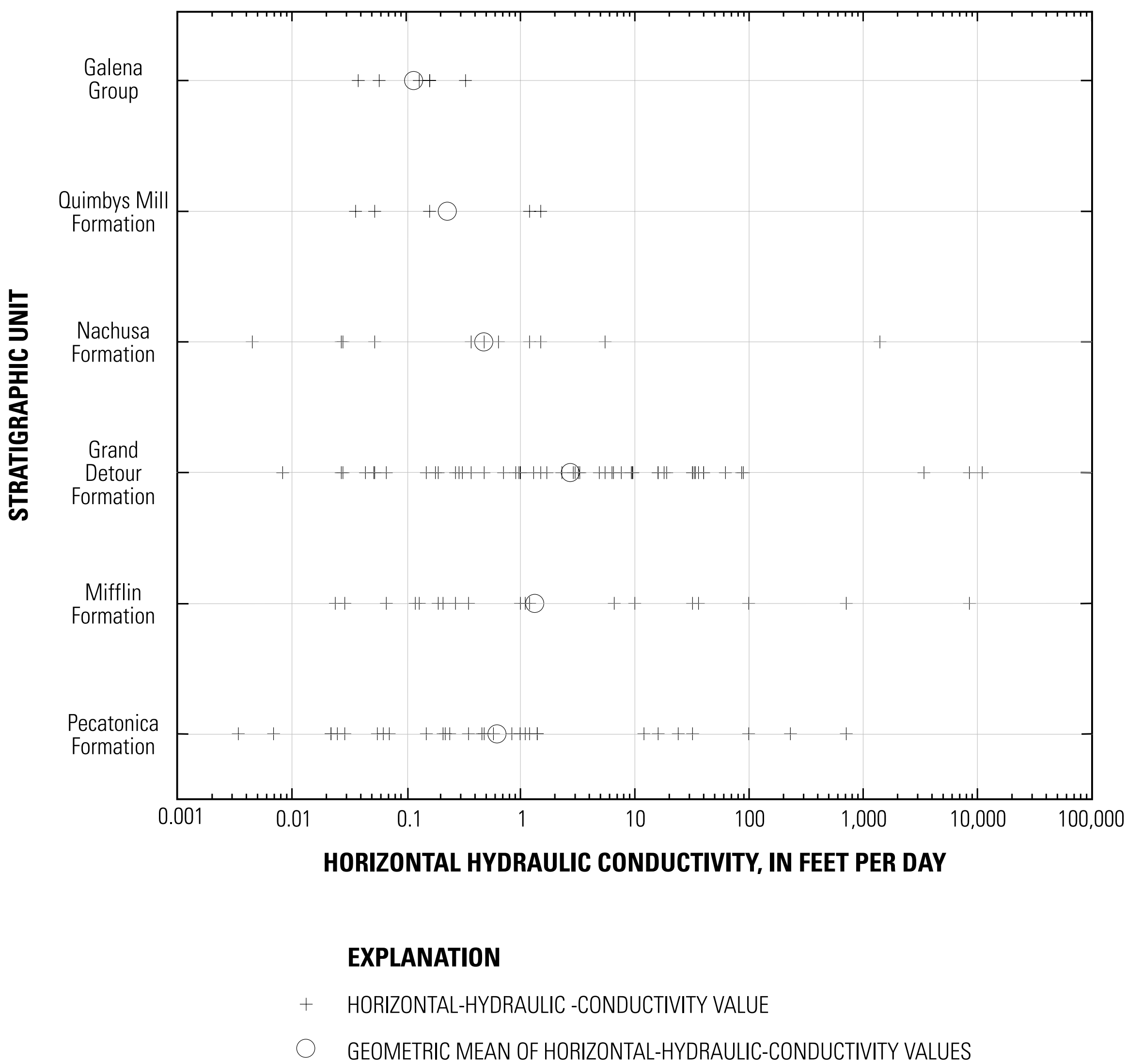


Figure 12. Distribution of horizontal hydraulic conductivity within the stratigraphic units that compose the Galena-Platteville aquifer, Byron site, Ill.

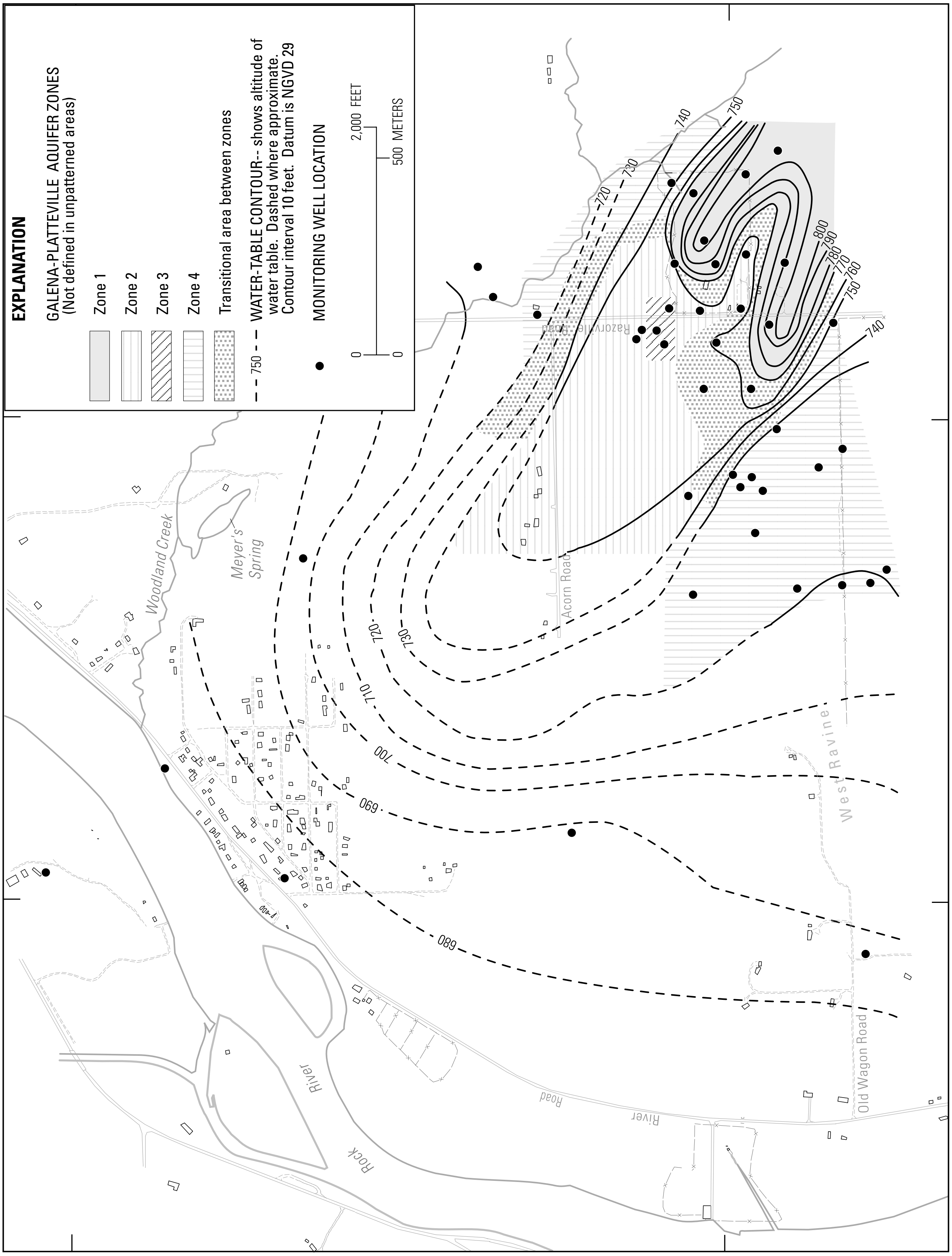


Figure 13. Water-table configuration and zones in the Galena-Platteville aquifer, Byron site, Ill., January 27, 1992.

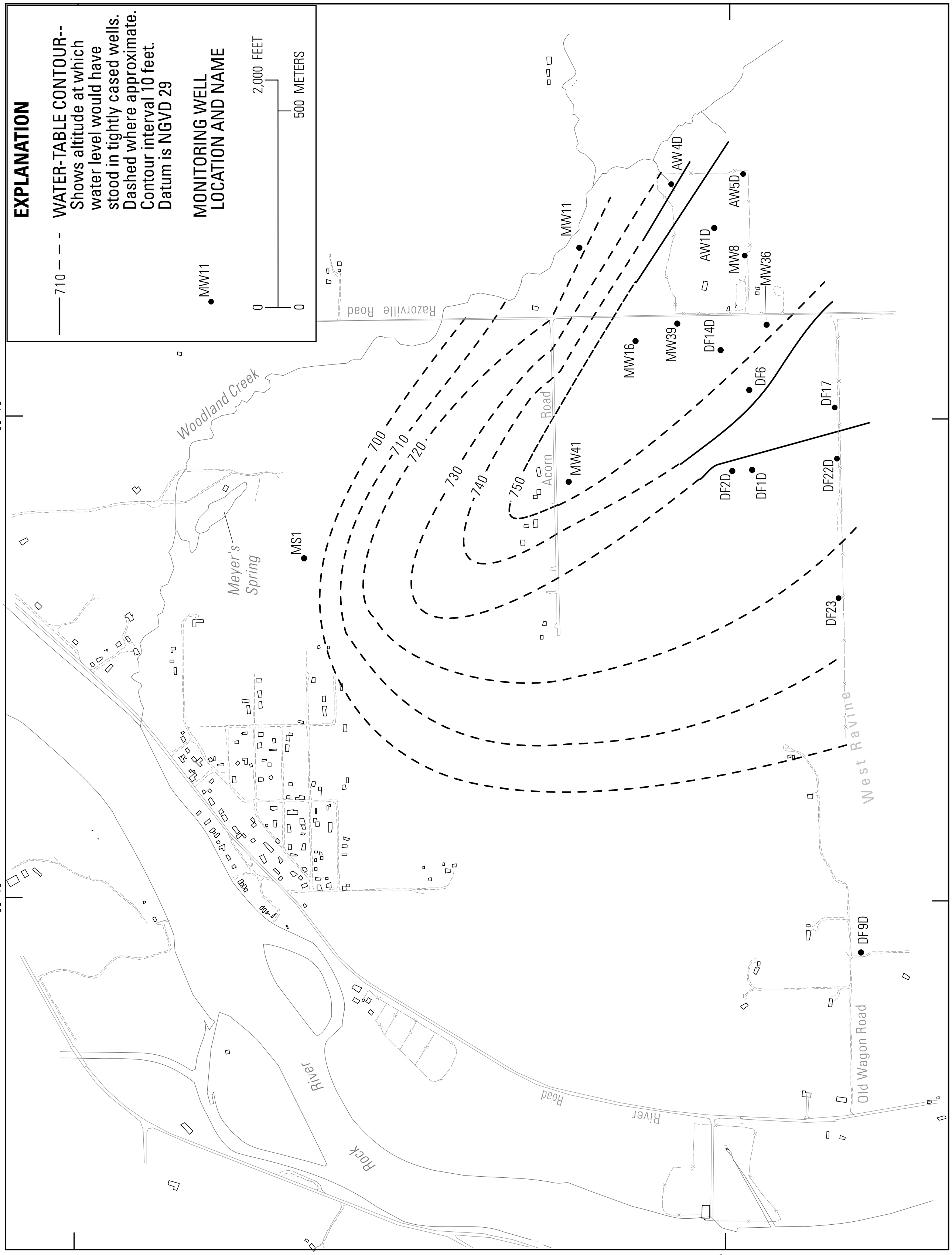
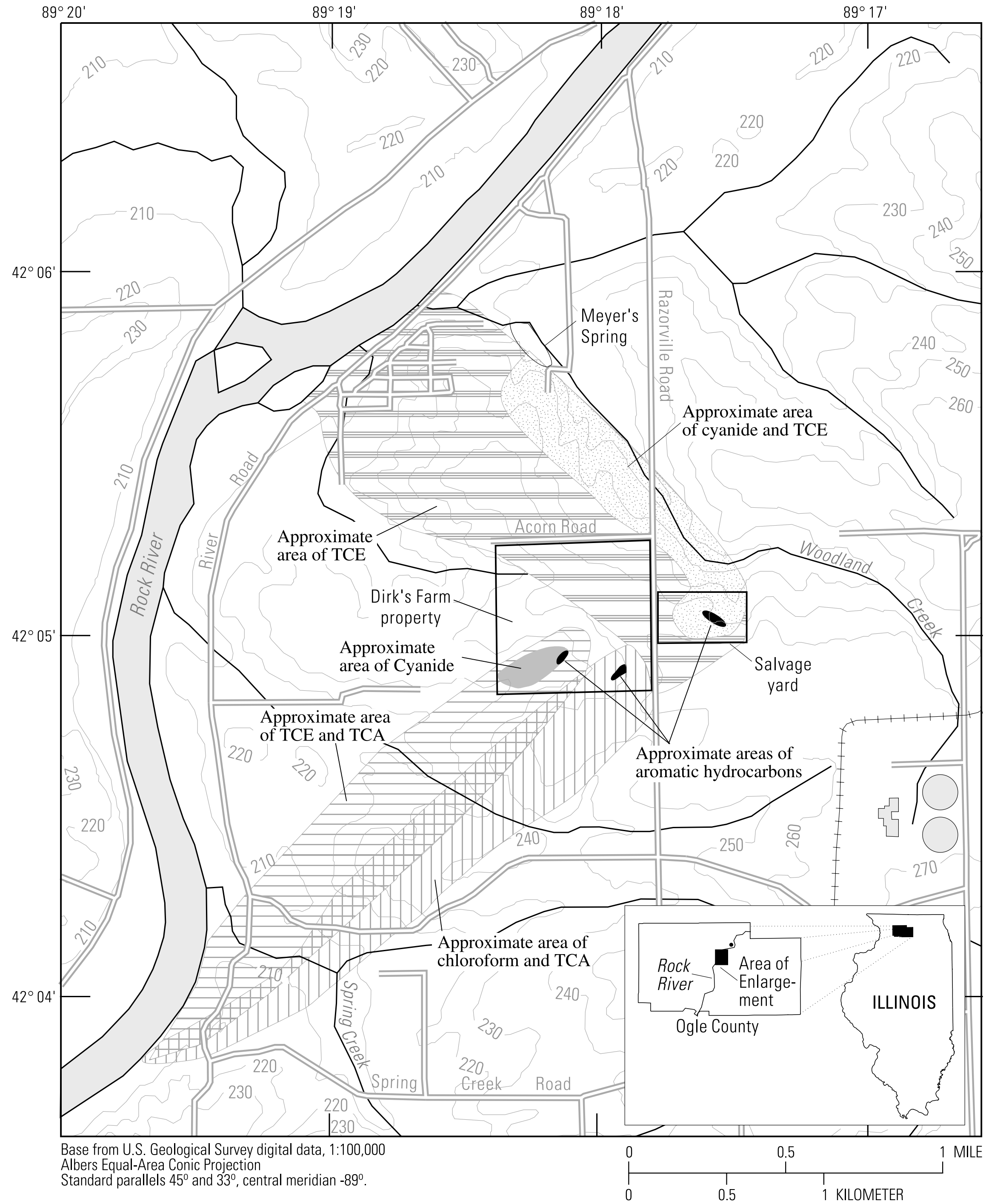


Figure 14. Potentiometric surface of the base of the Galena-Platteville aquifer, Byron site, Ill., January 27, 1992.



EXPLANATION

220	TOPOGRAPHIC CONTOUR--Shows elevation of land surface, in meters. Contour interval 10 meters. Datum is NGVD 29
TCA	TRICHLOROETHANE
TCE	TRICHLOROETHENE

Figure 15. Type and extent of ground-water contamination, Byron site, Ill. (modified from U.S. Environmental Protection Agency, 1994).

Table 5. Summary of altitudes of potential secondary-permeability features in select boreholes by method of detection, Byron site, Ill.

[GPR, ground-penetrating radar]

Borehole	Method	Altitude of secondary-permeability features (feet above National Geodetic Vertical Datum of 1929)
DF4D	Lithologic logging	None Identified.
	Cores	Fractures at 736-742.
	Borehole-camera logs	Fractures at 723 and 748.
	Caliper logs	None Identified.
	Natural-gamma logs	None Identified.
	Spectral gamma logs	Method not used.
	Neutron logs	Method not used.
	Acoustic-televiewer logs	Vugs 693-703, numerous fractures at 703-713, 723-736, 741-758, fractures at about 764 and 768.
	Borehole GPR	Reflectors at 698, 731, 759, 762, possible increase in porosity below 759.
DF12	Lithologic logging	Possible solution opening below about 702, numerous possible fractures at 702-761.
	Cores	Method not used.
	Borehole-camera logs	Fractures throughout borehole, large fractures and solution openings at 702-729, possible solution opening below 702.
	Caliper logs	Enlarged borehole at 702-719, 810.
	Natural-gamma logs	Clay infilling of feature at 709.
	Spectral gamma logs	Method not used.
	Neutron logs	None Identified.
	Acoustic-televiewer logs	Not logged 700-718. Possible solution opening at 718-722, dense fracturing at 722-726, numerous fractures at 729-760, fracture at 765.
	Borehole GPR	Reflectors at 687, 718, 741, 780, point reflector away from borehole at 757.
DF17	Lithologic logging	Fracture or solution opening at 694 ft.
	Cores	Method not used.
	Borehole-camera logs	Fractures over length of borehole, especially at 714-720, 754-759, and 790-805. Solution opening at about 694 to 700.
	Caliper logs	Enlarged borehole from 694 to 708.
	Natural-gamma logs	None Identified.
	Spectral gamma logs	Method not used.
	Neutron logs	None Identified.
	Acoustic-televiewer logs	Borehole not logged below 710, vugs at 710-715, fractures, 715-720, 725-738.
	Borehole GPR	Reflectors at 663, 693, 719, 746, 757.
SPW	Lithologic logging	Fracture at about 712.
	Cores	Method not used.
	Borehole-camera logs	Fractures at 695-700, 710-718, 724, 736-751, 765.
	Caliper logs	Possible fractures at 710, 735, 745, 765, and 789.
	Natural-gamma logs	Clay infilling of fractures at 710 and 738.
	Spectral gamma logs	Clay infilled fractures at 710 and 738.
	Neutron logs	None Identified.
	Acoustic-televiewer logs	Horizontal fractures at 696-700, inclined fractures at about 710, 737-752, about 756, and about 765, vugs at 716-726.
	Borehole GPR	Reflectors at 709, 720, 736, and 765.
PZ1	Lithologic logging	None Identified.
	Cores	Method not used.
	Borehole-camera logs	Fractures at 708-712, 734, 739, 767, 808-809, and 812.
	Caliper logs	None Identified.
	Natural-gamma logs	None Identified.
	Spectral gamma logs	Method not used.
	Neutron logs	Method not used.
	Acoustic-televiewer logs	Fractures at 679, 688-704, 707-718, 729-736, and 739-750.
	Borehole GPR	Reflectors at 708, 718, 736, and 764.

Table 6. Summary of altitudes of permeable features in select boreholes by method of detection, Byron site, Ill.

[GPR, ground-penetrating radar]

Borehole	Method	Altitude of permeable features (feet above National Geodetic Vertical Datum of 1929)
DF4D	Lithologic logging	None identified.
	Water-level measurement	Borehole in transitional area. Packer test water levels not measured.
	Temperature logs	Method not used.
	Fluid-resistivity logs	Method not used.
	Ambient flowmeter logs	Below 693 to 700, 728 to 753, 757, above 766.
	Pumping flowmeter logs	Method not used.
	Cross-hole flowmeter logs	721 to 742 .
	Hydrophysical logs	694 to 698, 729, 739 to 743, 754.
	Slug tests	690 to 700, 721 to 741.
	Specific-capacity tests	Method not used.
	Multiple-well, constant-discharge tests	700 to 745, east-west oriented vertical features in lower part of aquifer, less permeable above about 775.
	Tracer tests	Method not used.
DF12	Lithologic logging	Below 702, 702 to near top of water column at about 770.
	Water-level measurement	Borehole in permeable area. Packer test water levels did not identify permeable features in borehole.
	Temperature logs	Method not used.
	Fluid-resistivity logs	Method not used.
	Ambient flowmeter logs	Below 723, 728 to 741.
	Pumping flowmeter logs	Method not used.
	Cross-hole flowmeter logs	Method not used.
	Hydrophysical logs	Below 713.
	Slug tests	Bottom of hole at about 700 to top of water column at 754.
	Specific-capacity tests	Hydraulically active feature present, altitude could not be identified.
	Multiple-well, constant-discharge tests	Method not used.
	Tracer tests	Method not used.
DF17	Lithologic logging	694
	Water-level measurement	Borehole in permeable area. Packer test water levels did not identify permeable features in borehole.
	Temperature logs	Method not used.
	Fluid-resistivity logs	Method not used.
	Ambient flowmeter logs	Below 710, 730, 735.
	Pumping flowmeter logs	Method not used.
	Cross-hole flowmeter logs	Method not used.
	Hydrophysical logs	Method not used.
	Slug tests	Method not used.
	Specific-capacity tests	Method not used.
	Multiple-well, constant-discharge tests	Method not used.
	Tracer tests	Method not used.
SPW	Lithologic logging	None identified.
	Water-level measurement	Borehole in less permeable part of aquifer. Packer test water levels did not identify permeable features in borehole.
	Temperature logs	Method not used.
	Fluid resistivity logs	Method not used.
	Ambient flowmeter logs	None identified.
	Pumping flowmeter logs	698, 711, above 736.
	Cross-hole flowmeter logs	711, above 736.
	Hydrophysical logs	711, 744.
	Slug tests	706 to 716, 732 to 753.
	Specific-capacity tests	Method not used.
	Multiple-well, constant-discharge tests	Vertical fractures oriented N 60° W, possible hydraulic isolation of part of the aquifer.
	Tracer tests	Vertical fractures, subhorizontal features at 711 and about 750, possible confining unit above 750.

Table 6. Summary of altitude of permeable features in select boreholes by method of detection, Byron site, Ill. --Continued.

Borehole	Method	Altitude of permeable features (feet above National Geodetic Vertical Datum of 1929)
PZ1	Lithologic logging	None identified.
	Water-level measurement	Borehole in less permeable part of aquifer. Packer test water levels identified permeable feature at 742.
	Temperature logs	725.
	Fluid resistivity logs	727.
	Ambient flowmeter logs	Drainage from above the water column at 748, 708.
	Pumping flowmeter logs	Method not used.
	Cross-hole flowmeter logs	708.
	Hydrophysical logs	Method not used.
	Slug tests	704 to 714, 734 to 744.
	Specific-capacity tests	Method not used.
	Multiple-well, constant-discharge tests	Vertical fractures.
	Tracer tests	711 and about 750.

Temperature and fluid-resistivity logging, in combination with caliper and acoustic-televiewer logs, provided only limited insight into the presence of permeable features in the Galena-Platteville aquifer at the Byron site. These logs identified some potentially permeable features, but did not identify some features identified using other methods. Some of the permeable features identified by these logs (at borehole PZ1, for example) were not detected with other methods, indicating that these detections may have been inaccurate. The lack of detection of permeable features with the temperature logs may be related to the small change in temperature (approximately 0.5^{o} C) in the aquifer. Boreholes that did show changes in temperature and resistivity tended to be open to most of the aquifer in zone 1 (fig. 13), where the aquifer appears to be under confined conditions. Hydraulic separation of the upper and lower parts of the aquifer in zone 1 may have produced sufficient contrast in water quality to be identified with the logs. In boreholes open to the more hydraulically interconnected parts of the aquifer, differences in temperature and resistivity may have been too small to produce identifiable changes.

Data collected during single-hole flowmeter logging, particularly when analyzed in conjunction with acoustic-televiewer data, provided substantial insight into the location and type of permeable features in individual boreholes open to the Galena-Platteville aquifer at the Byron site. The utility of these logs, especially when run during ambient conditions, was limited by uniformly low permeability, an absence of vertical-hydraulic gradient, or substantial vertical contrasts in permeability at the borehole being logged. The location of permeable features identified with the flowmeter logging showed moderate to good agreement with the location of permeable intervals identified with slug testing. Characterization of permeable features using flowmeter logging was superior to that provided with slug testing in many instances, especially if the logging was done in conjunction with pumping in the borehole so that vertical flow could be induced.

Data collected during cross-hole flowmeter logging also provided substantial insight into the location and type of permeable features in individual boreholes, as well as insight into the flow pathways between boreholes. Areas of hydraulic connection identified with the cross-hole flowmeter logging showed good agreement with areas of hydraulic connection identified during constant-discharge aquifer testing and tracer testing.

Hydrophysical logging provided identification of permeable features consistent with those identified by the flowmeter logging. Hydrophysical logging identified fewer permeable features than with the flowmeter logs in two of the three boreholes logged using both methods, indicating a lower detection limit for the hydrophysical logging. Water-quality parameters in each of the permeable intervals also were quantified with hydrophysical logging.

Slug tests, particularly when combined with acoustic-televiewer and flowmeter data, provided substantial insight into the location and type of permeable features at a borehole. Slug tests also provided substantial insight into the distribution of permeability at individual boreholes, between stratigraphic formations, and across the Byron site. Slug tests performed in test intervals isolated with a packer assembly typically provided a superior characterization of the location of permeable intervals in boreholes with low permeability, low vertical-hydraulic gradients, or large differences in permeability. Slug tests also have the advantage of being able to quantify the Kh of both permeable and less-permeable features, although the accuracy of the values is questionable. Flowmeter logging tends to provide a superior characterization of permeability when more than one permeable feature is present within the interval of the packer assembly or when the length of the packed interval is greater than about 10 ft.

Specific-capacity tests allowed for quantification of aquifer transmissivity in a part of the Galena-Platteville aquifer too permeable to have been cost effectively characterized by a long-term (days), multiple-well, constant-discharge aquifer test (borehole DF12) and where resources were insufficient for detailed hydrogeologic characterization (borehole PZ3). Transmissivity values calculated from the specific-capacity data were in good agreement with those calculated from slug testing.

Multiple-well, constant-discharge aquifer tests, including tracer tests, allowed quantification of the hydraulic properties of the aquifer (at least from one of the tests), which could not be determined with other methods. These tests verified the presence of hydraulic interaction between the fractures and the matrix; identified the presence, location, and types of hydraulically connected features in the aquifer as well as the presence and location of hydraulically isolated parts of the aquifer; and identified the presence and orientation of heterogeneity and anisotropy in the aquifer. This information was consistent with interpretations made from analysis of fracture traces, acoustic-televiewer logs, single- and cross-hole GPR, slug testing, and flowmeter logging.

The location of contaminants at the Byron site indicates that the ground-water-flow pathways in parts of the Byron site are represented adequately with the water-level data. Contaminant distribution indicates flow south of the DFP and in the middle of the aquifer in the southern part of the BSY, is opposite to the directions indicated by the water-level data. Flow in directions opposite to those indicated by static water levels indicates that the flow pathway in the Galena-Platteville aquifer is complex and may not be adequately assessed with the limited monitoring well network south of the DFP. The complexity of the flow pathways likely is the result of the complex secondary-permeability network in the vicinity of the Byron site.

Tipton Farm Site

The Tipton Farm site is located near Wempletown, about 4 mi northwest of the city of Rockford in the central part of Winnebago County, north-central Illinois (fig. 16). Ten investigative methods were used at the Tipton Farm site (tables 1, 7). Fifteen wells penetrating the Galena-Platteville aquifer were available for characterization (table 8), and about 10 years of data were available for analysis. Information regarding the Galena-Platteville aquifer at the Tipton Farm site is limited because site investigations were restricted to the shallow part of the aquifer. Detailed discussion of the data collected at the Tipton Farm site is presented in appendix C of this report.

The Tipton Farm site contains two disposal areas: a drum-storage area and a landfill in an abandoned stone quarry (fig. 17). The site is approximately 110 acres in size, with the landfill and drum-storage areas occupying about 3 acres.

Wells at the site were surveyed to an arbitrary datum, not to NGVD29. Land-surface altitude for these wells was estimated from topographic maps. As a consequence, the location of most of the secondary-permeability features at a given well are referenced relative to NGVD29, with an accuracy of about 5 ft. Water-level measurements are referenced to an arbitrary datum, which is accurate to within 0.05 ft.

Surface topography at the Tipton Farm site is above 880 ft above NGVD29 (FANGVD29) in the southeastern and far northern parts of the site, and decreases to about 850 FANGVD29 near the landfill (fig. 17). The altitude of the bedrock surface is highest at the topographic highs and lowest at the topographic lows. Between 2 and 15 ft of Quaternary-aged deposits overlie the Galena-Platteville dolomite beneath the site. The Quaternary deposits are thickest in topographically elevated areas and thinnest in topographically low areas (fig. 18).

The Galena-Platteville aquifer is under water-table conditions at the Tipton Farm site. The upper part of the Galena-Platteville aquifer at the Tipton Farm site has low permeability, with a geometric mean Kh value of 0.28 ft/d. The direction of ground-water flow in the Galena-Platteville aquifer varies, but generally is from southeast to northwest (fig. 19). Low concentrations of VOC's stored or disposed of in the drum-storage and landfill areas have migrated into the Galena-Platteville aquifer.

Methods used for hydrogeologic characterization at the Tipton Farm site only were moderately successful. Some lack of success is attributed to the small number of data points available for analysis, the small amount of aquifer penetrated by most of the boreholes and the presence of well screens in the deeper wells, which limits the number of methods that could be used in the investigation.

Background sources of information substantially benefited the site characterization. Data obtained from previous investigations were useful for determining the geology, hydrology and water quality at the site (table 7). However, SAR surveys performed by previous investigators identified a number of potential secondary-permeability features that were not verified by subsequent investigation. Analysis of land-surface topography identified the location of relatively high and low bedrock-surface altitude, which was verified by the lithologic logs collected by previous investigators.

Core analysis identified the lithology and stratigraphy beneath the Tipton Farm site, the location of fractures, and the primary porosity of the dolomite (table 7). Geologic information obtained from the core analysis generally was consistent with the analysis of the lithologic logs provided by the previous investigators.

The three-arm caliper logs indicate numerous small increases in diameter in each of the boreholes that may correspond to small fractures. However, the lack of confirmation from other methods makes this interpretation uncertain.

Natural-gamma logging, in combination with the core description, helped to assess site stratigraphy. The utility of this method was diminished by the availability of this log type for only one shallow well, which prevented interpretation of conditions over the Tipton site as a whole. Data from the SPR and SP logging provided no clear information on the geology or hydrology of the site.

Periodic water-level measurements indicated the overall direction of ground-water flow in three dimensions. Vertical- and horizontal-hydraulic gradients are higher beneath high points in the bedrock near the drum-storage area than beneath low points near the land-

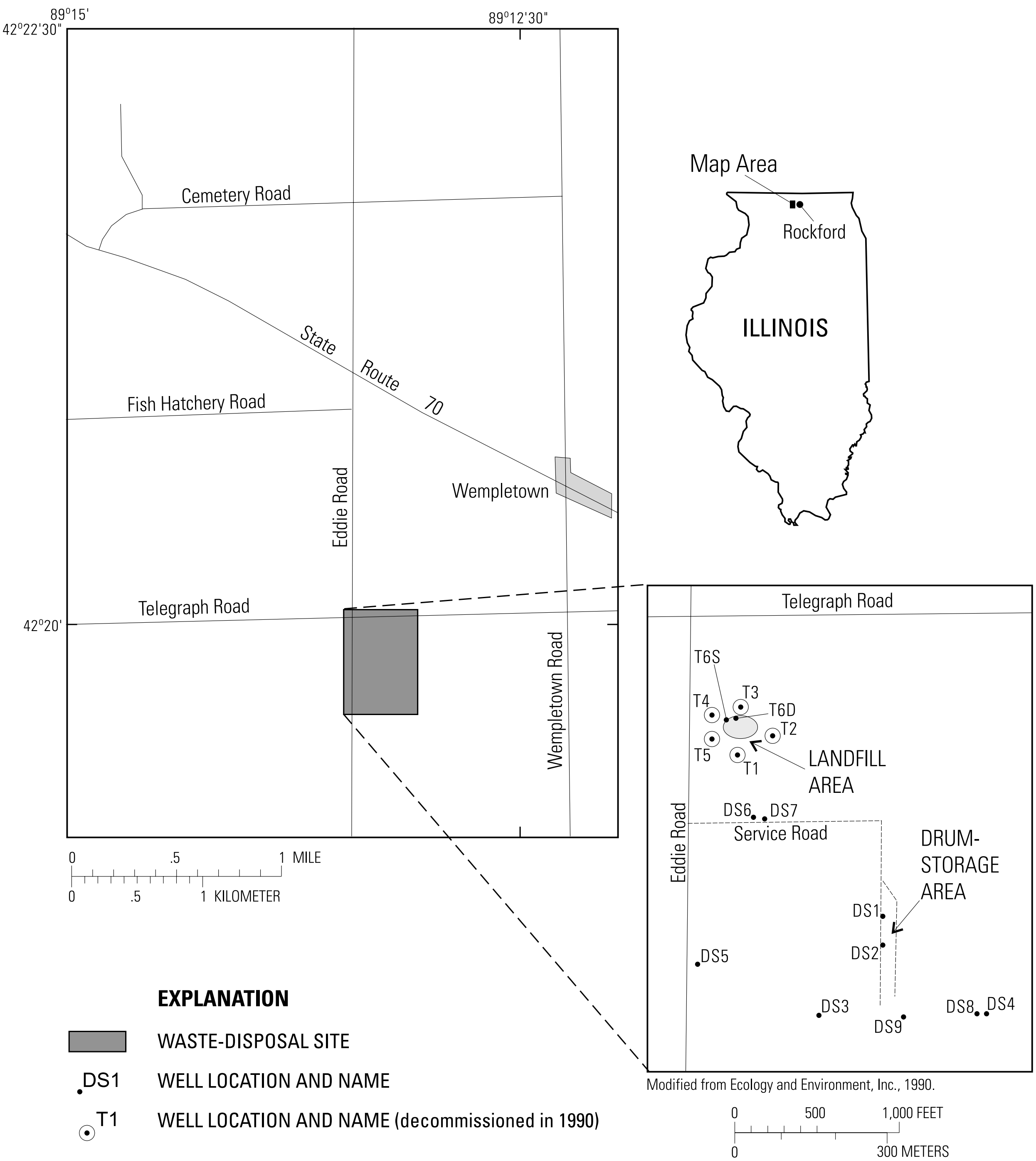


Figure 16. Location of Tipton Farm site and monitoring wells near Wempletown, Illinois.

fill area, indicating that the Galena-Platteville aquifer beneath the bedrock highs may be less permeable than beneath the bedrock lows. If the aquifer beneath the bedrock highs is less permeable, the rock in this area likely has fewer secondary-permeability features than the rock near the lows.

Slug testing quantified the Kh of the aquifer. Slug-test values may have been affected by changes in the saturated thickness of the aquifer between tests. Slug-test data indicated that the Kh of the aquifer is lower near the landfill area than at the rest of the site. This interpretation is contrary to that drawn from analysis of the water-level data described previously. There are a number of potential explanations for this discrepancy including potentially erroneous interpretations of one or both data sets because of the small number of data points, or differences in the amount of aquifer characterized by slug tests (less than 10 ft in the vicinity of the borehole) and water-level measurements (site wide). It is possible that the Galena-Platteville aquifer is more permeable near the landfill, but the wells that were slug tested are not in direct hydraulic connection with the permeable features controlling water levels in this area. It also is possible that the discrepancy in interpretations made from the water level and slug-test data is due partly to the position of wells along the flow path. The area beneath the landfill appears to be associated with a ground-water divide, with possible high vertical-hydraulic gradients in comparison to other parts of the flow system (Toth, 1962).

ACME Solvents and Winnebago Reclamation Landfill Sites

The ACME Solvents site and the Winnebago Reclamation Landfill (WRL) site, hereafter combined and referred to as the ACME/WRL site, are adjacent sites located in north-central, Illinois (figs. 20, 21). Thirteen methods were used in the investigation of the ACME/WRL site (tables 1, 9). More than 60 boreholes and wells penetrating the Galena-Platteville aquifer (table 10) were available for characterization, and 7 years of data were available for analysis at the time these sites were investigated. Details of the results of the investigations are presented in appendix D to this report.

Industrial wastes, including solvents, paints and oils, were deposited in barrels, storage tanks, and unlined disposal pits on the ACME property from about 1960 through 1972. The WRL is an asphalt-lined sanitary landfill, which has been in operation since 1972. Wastes disposed of in the WRL include municipal solid waste, sewage sludge, and various special permitted and industrial wastes prior to 1986. Wastes at both sites have leached a variety of contaminants, including VOCs into the Galena-Platteville aquifer (Kay, 1991).

A bedrock ridge is present beneath the center of the ACME Solvents site, trending south of the WRL toward Killbuck Creek (fig. 22). The Galena-Platteville dolomite is about 230 ft thick beneath this bedrock ridge. Pre- and post-glacial erosion has reduced the

Table 7. Summary of methods of data collection, Tipton Farm site, Ill.

Method	Location of data collection	Uses
Previous investigations	Entire site.	Assessment of geology, hydrology, and water quality. Square-array resistivity interpretations not verified by drilling.
Topographic maps	Entire site and surrounding area.	Identification of bedrock high and low areas. Aquifer at bedrock high may be less permeable than at bedrock low, but interpretations vary with method used.
Lithologic logging	All boreholes.	Identification of lithology.
Cores	Boreholes DS8, T6D.	Identification of stratigraphy and lithology. Quantification of primary matrix porosity. Identified healed fractures at 814-816, 829, and 841 feet above National Geodetic Vertical Datum of 1929 in borehole T6D, and at about 819, 835-837, 842, 847, 849, 856-859, 867, and 869 feet above National Geodetic Vertical Datum of 1929 in borehole DS8.
Caliper logs	Boreholes T2, T, T4, T5.	No potential fractures identified.
Natural-gamma logs	Borehole T5.	Characterization of site lithology and stratigraphy on combination with core description.
Single-point resistance logs	Borehole T4.	No value.
Water levels from wells	Boreholes DS1, DS2, DS3, DS4, DS5, DS6, DS7, DS8, DS9, T2, T3, T4, T5, T6S, T6D.	Determined vertical and horizontal directions of flow, may indicate areas of higher permeability.
Spontaneous-potential logs	Boreholes T2, T4, T5.	Identified possible permeable features near water level in well, likely no value.
Slug tests	Boreholes DS1, DS2, DS5, DS6, DS7, DS9, T4, T5, T6S, T6D.	Quantification of horizontal hydraulic conductivity, possible identification of spatial variation in permeability. Some variation in hydraulic conductivity with height of water column in well, indicating presence of permeable features at and near water table at some locations.

Table 8. Monitoring-well and water-level data for the Tipton Farm site, Ill.

[NA-not available]

Well name	Total depth (feet below land surface)	Open interval (feet below land surface)	Land-surface altitude (feet above arbitrary datum)	Approximate land-surface altitude (feet above National Geodetic Vertical Datum of 1929)	Water-level altitude April 5, 1990 (feet above arbitrary datum)	Water-level altitude April 5, 1991 (feet above arbitrary datum)	Water-level altitude March 5, 1993 (feet above arbitrary datum)	Water-level altitude December 9, 1994 (feet above arbitrary datum)
DS1	43.0	18-43	127	885.0	93.22	107.25	109.25	108.68
DS2	43.5	18-43.5	134	892.0	99.69	113.15	115.49	114.09
DS3	44.0	33-44	130	888.0	NA	98.53	101.82	98.10
DS4	38.5	9-38.5	129.5	887.5	102.75	114.32	117.39	114.88
DS5	43.5	20-43.5	108	866.0	71.64	81.83	84.77	82.06
DS6	43.5	12-43.5	99	857.0	69.09	89.66	85.21	82.63
DS7	72.0	61-72	99	857.0	66.55	77.17	81.50	77.78
DS8	70.0	58-69	129.5	887.5	96.43	106.92	109.50	107.58
DS9	28.5	11-28.5	130.5	888.5	106.24	114.90	117.42	115.33
T6S	28.5	2-28.5	93	851.0	75.17	81.12	84.96	82.29
T6D	58.5	47.5-58.5	93	851.0	68.49	79.19	83.33	79.48
T2	30.0	13-30	NA	852.0	NA	NA	NA	NA
T3	31.0	8.8-31	NA	852.0	NA	NA	NA	NA
T4	32.5	12.8-32.5	NA	852.0	NA	NA	NA	NA
T5	30.0	13-30	NA	852.0	NA	NA	NA	NA

thickness of the dolomite to about 80 ft south and west of the ridge. Quaternary-aged deposits unconformably overlie the Galena-Platteville dolomite throughout the study area where these deposits have not been removed by quarrying. Quaternary deposits typically are less than 10 ft thick near the bedrock ridge, but are in excess of 100 ft thick where the bedrock has been eroded more extensively. Quaternary deposits tend to be coarse grained beneath the ACME Solvents site and the WRL, and fine grained to the south. Sand-and-gravel deposits overlie the bedrock beneath much of the ACME/WRL site. The Galena-Platteville deposits are underlain by the Harmony Hill Shale Member of the Glenwood Formation, which functions as a semiconfining unit beneath the ACME/WRL site. The St. Peter aquifer underlies the Glenwood Formation.

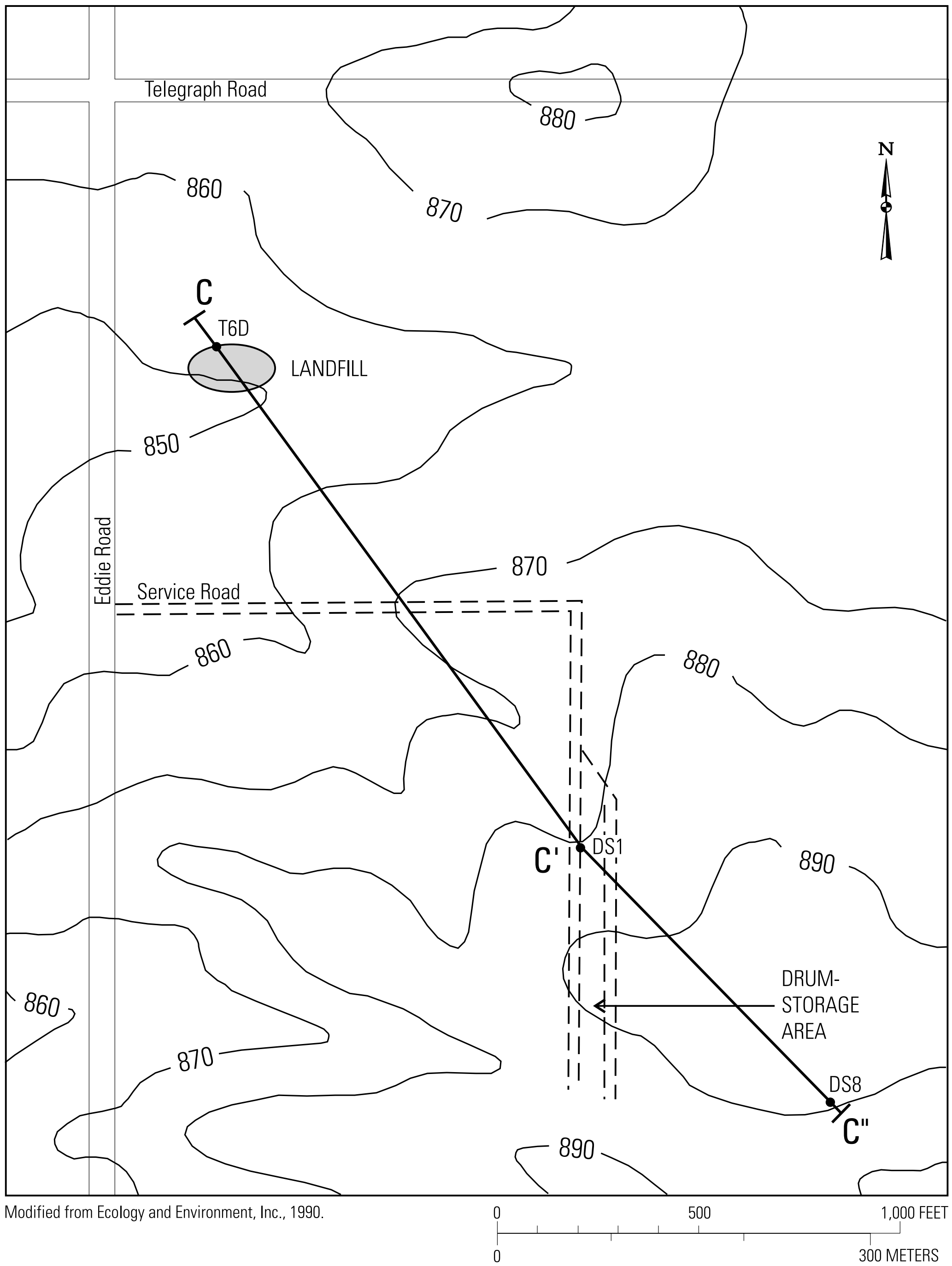
The water table is in the Quaternary deposits west of the line between wells G102, B10, and B13 and south of the line between wells B13, G111, and P8 (fig. 21). North and east of these lines, the water table is located in the Galena-Platteville aquifer.

Ground-water flow and contaminant migration at the ACME/WRL site is from east to west (figs. 23, 24, 25), with periodic local reversals in this direction because of recharge from the intermittent stream between the sites. Ground water discharges into and flows beneath Killbuck Creek. Hydraulic boundaries to ground-water flow and contaminant migration at the ACME/WRL site are not defined clearly. The Galena-Platteville aquifer beneath the ACME/WRL site is moderately permeable, with Kh values having a geometric mean value of 0.72 ft/d. The aquifer has a lower Kh (geometric mean value of 0.15 ft/d) in the area defined approximately by the B6 and 5S/I/D well clusters to the east and well G114 and the G113 well cluster to the west than in the remainder of the site (geometric mean Kh of 2.1 ft/d).

Most of the methods of investigation provided some useful insight into the hydrogeology of the Galena-Platteville aquifer at the ACME/WRL site (tables 9, 11, 12). Multiple methods often provided the same information. However, application of different methods also provided contradictory interpretations.

Analysis of surface topography was useful for identifying the location of the bedrock ridge at the ACME/WRL site (table 9). Aquifer-test data confirm that the Galena-Platteville aquifer, in at least part of the area corresponding to the bedrock ridge, had lower permeability than in the remainder of the area, indicating the presence of comparatively competent rock.

Quarry visits were useful for establishing stratigraphy and fracture orientations (table 9). Stratigraphic interpretations initially indicated with the quarry visits were confirmed and expanded with core analysis. Analysis of contaminant distribution indicates a component of ground-water flow to the south along one of the primary orientations of the inclined fractures measured



EXPLANATION

—— 850 ——	TOPOGRAPHIC CONTOUR -- Shows elevation of land surface in feet Contour interval is 10 feet. Datum is NGVD 29
⊢C–C'–C"⊣	LINE OF GEOLOGIC SECTION (see fig. 18)
● DS1	WELL LOCATION AND NAME

Figure 17. Location of line of geologic section and surface topography at the Tipton Farm site, Ill.

at the quarry.

Lithologic logs were useful for providing the initial identification of areas where hydraulically active and inactive secondary-permeability features were located (tables 9, 11, 12). Some of these interpretations subsequently were confirmed by caliper-log analysis.

Core analysis provided the foundation for the ACME/WRL site stratigraphy, including the potential presence of an unconformity in the dolomite. Core analysis also provided some insight into the location of secondary-permeability features in the aquifer (tables 9, 11). Discrepancies were observed in the stratigraphic interpretations made from different cores by different investigators. It is uncertain if these discrepancies reflect actual variations in the site stratigraphy or differences in opinion between investigators.

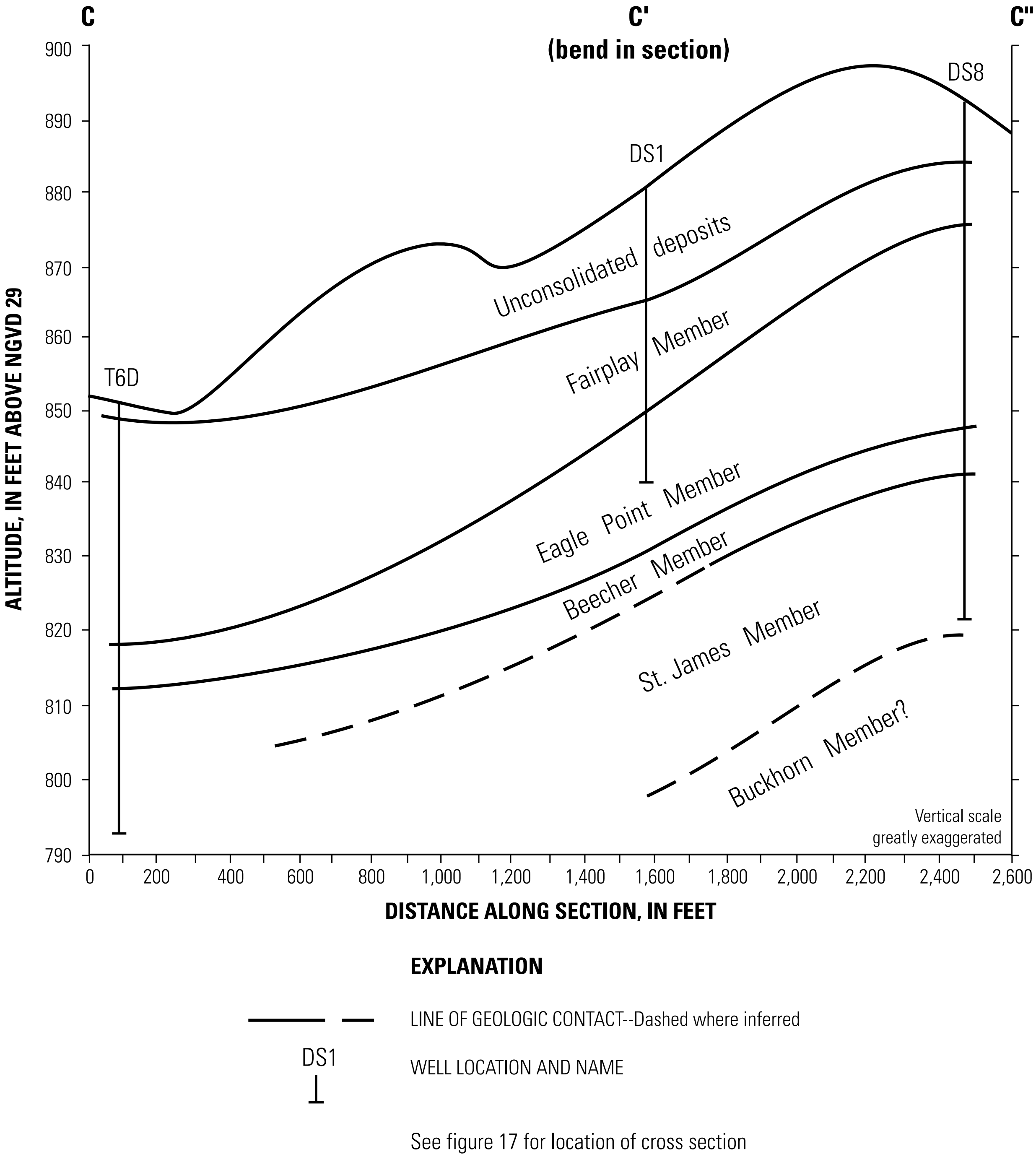
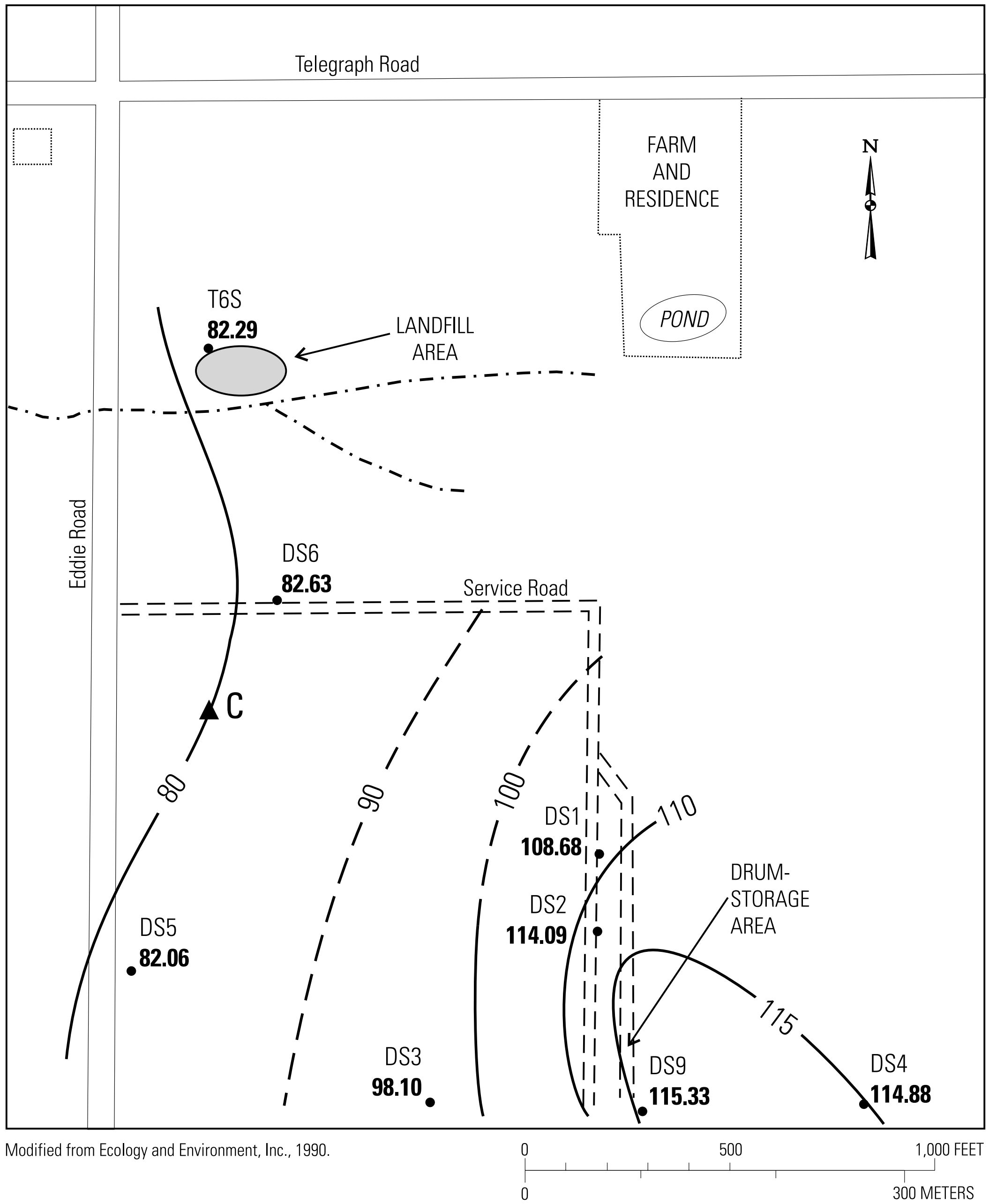


Figure 18. Line of geologic section C-C', Tipton Farm site, Ill.



EXPLANATION

—— 80 — —	WATER-TABLE CONTOUR -- Shows line of equal water level below datum. Dashed where approximate. Contour interval, in feet, is variable. Datum is arbitrary
- · - · - · -	INTERMITTENT STREAM
DS5 •82.06	WELL LOCATION AND NAME -- Altitude of water level in well, in feet above arbitrary datum
▲C	GROUND-WATER TRANSECT ENDPOINT AND DESIGNATION

Figure 19. Water-table configuration in the vicinity of the Tipton Farm site, Ill., December 19, 1994.

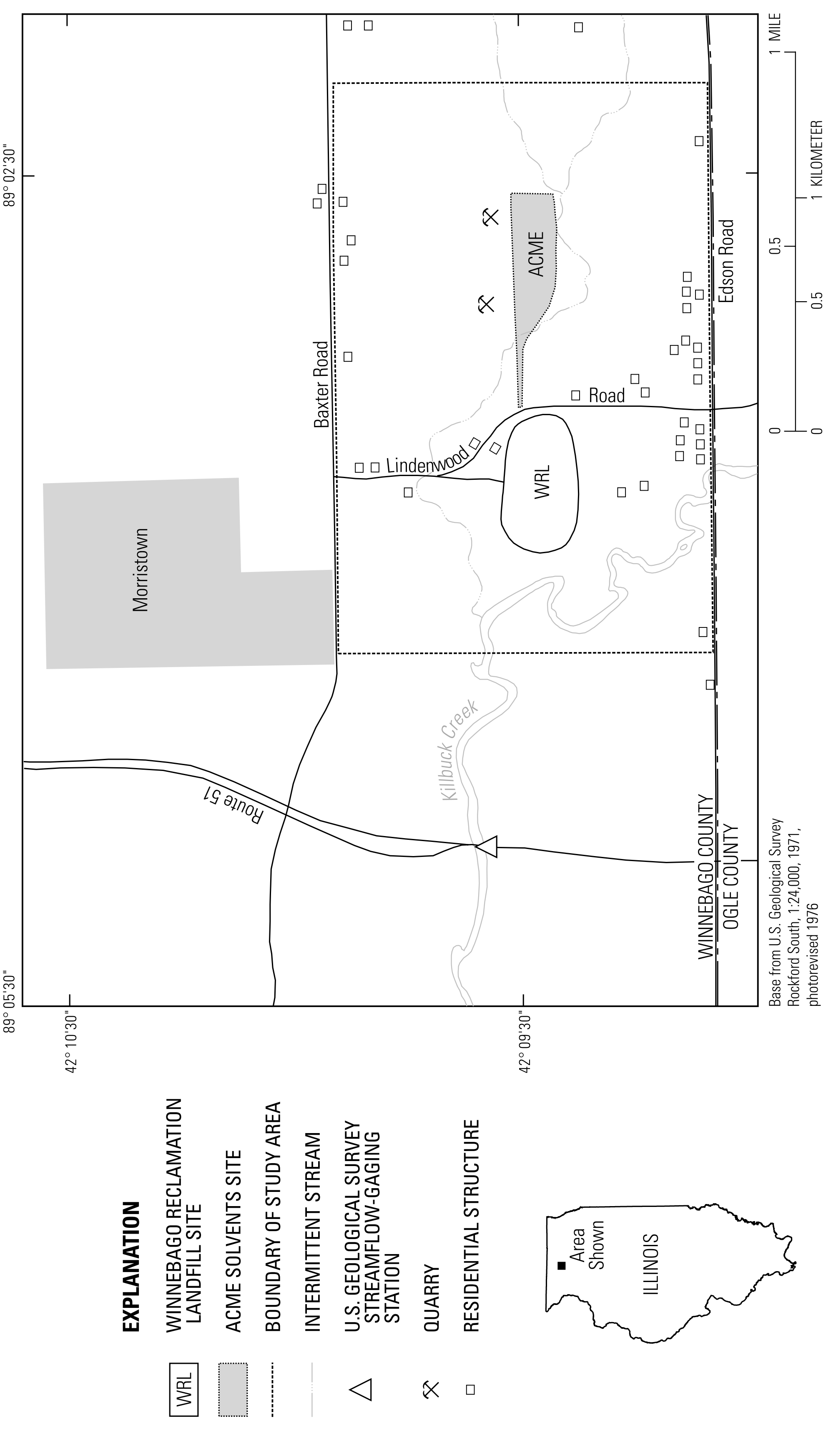


Figure 20. Location of the ACME Solvents and Winnebago Reclamation Landfill sites, Winnebago County, Ill.

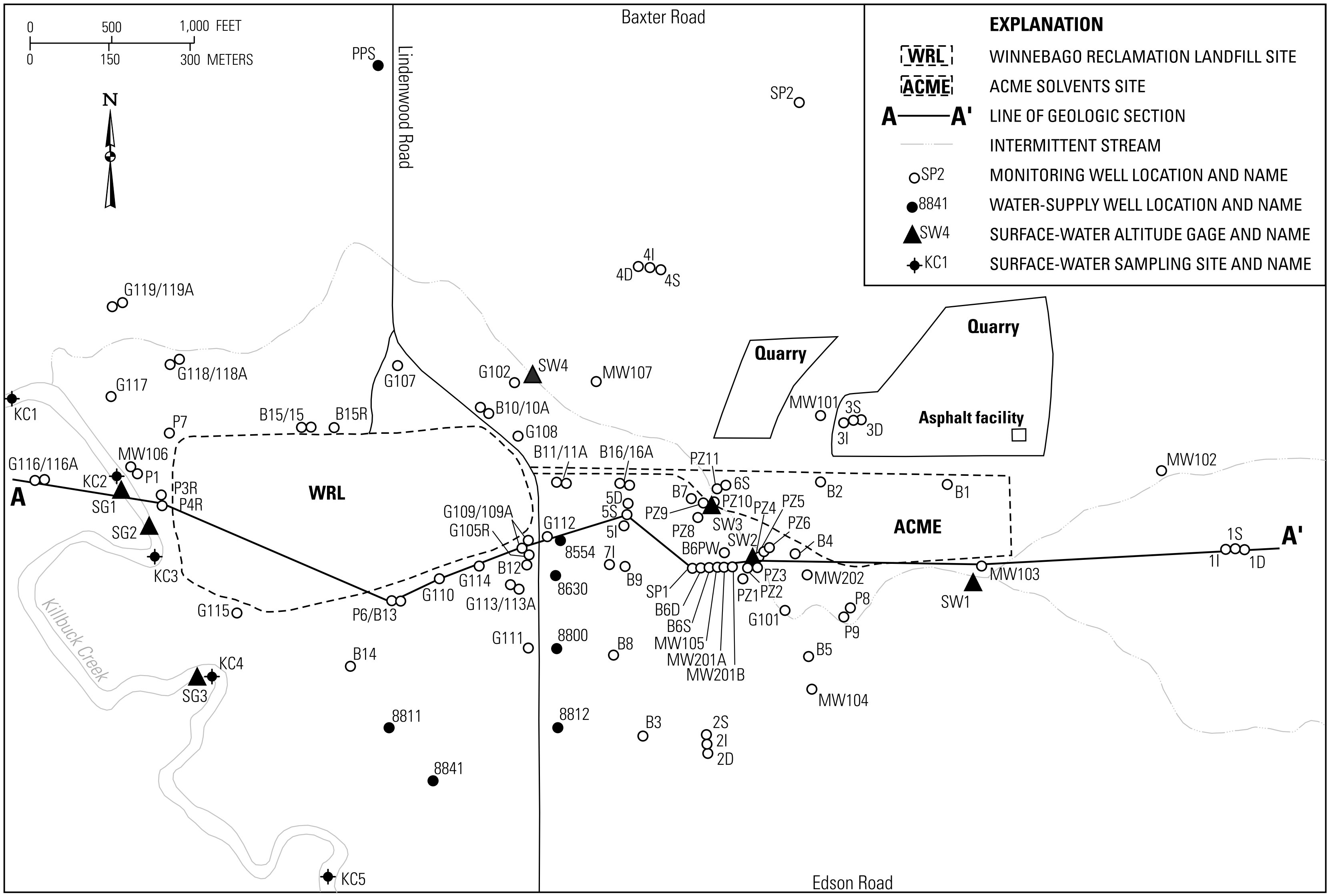


Figure 21. Location of ACME Solvents and Winnebago Reclamation Landfill sites, monitoring wells, and line of geologic section A-A', Ill.

Table 9. Summary of methods of data collection, ACME Solvents and Winnebago Reclamation Landfill sites, Ill.

Method	Location of data collection	Use
Topographic maps and aerial photographs	Entire site and surrounding area.	Identification of bedrock ridge.
Quarry visits	Quarry north of ACME Solvents site.	Identification of fracture orientation and lithology.
Lithologic logging	All boreholes.	Identification of lithology, location of highly permeable features.
Cores	Abandoned location near STI-SP2; completion intervals for STI-I and STI-D boreholes.	Identification of stratigraphy, lithology, location of potentially permeable features including unconformity at top of Mifflin and base of Grand Detour Formations.
Borehole-camera logs	Borehole B6PW.	Identification of presence and location of secondary-permeability features.
Caliper logs	Boreholes STI-SP1, STI-SP2, STI-1D, STI-2D, STI-3D, STI-4D, STI-5D.	Identification of presence and location of potential fractures and competent parts of rock.
Natural-gamma logs	Boreholes TI-SP1, STI-SP2, STI-1D, STI-2D, STI-3D, STI-4D, STI-5D.	Characterization of site stratigraphy.
Neutron logs	Boreholes STI-SP1, STI-SP2, STI-1D, STI-2D, STI-3D, STI-4D, STI-5D.	Identification of trends in porosity.
Density logs	Boreholes STI-SP1, STI-SP2, STI-1D, STI-2D, STI-3D, STI-4D, STI-5D.	Identification of location, type, and orientation of secondary-permeability features.
Water levels	All wells	Determined vertical and horizontal directions of flow, indicated vertical and horizontal distribution of permeability.
Slug tests	Wells B4, B6S, B6D, B7, B9, B10, B10A, B11, B11A, B12, B13, B16, B16A, G101, G113, G113A, G114, MW104, MW105, MW201B, MW202, P8, P9, STI-5S, STI-5I, STI-5D, STI-6S, STI-7I.	Quantification of horizontal hydraulic conductivity, identification of distribution of permeability.
Multiple-well, constant-discharge tests	Well STI-3I, borehole B6PW.	Quantification of hydraulic properties of aquifer, identification of ground-water-flow pathways, identification of the presence of heterogeneity and anisotropy.
Contaminant location	Entire site	Identification of ground-water-flow pathways.

Caliper and borehole camera logs provided insight into the possible location of fractures in the bedrock, as well as areas where these features did not appear to be present (tables 9, 11). These logs helped refine interpretations about the locations of secondary-permeability features identified with the lithologic logs. These logs also helped identify the location of secondary-permeability features not identified with the lithologic logging.

Natural-gamma logs provided a comprehensive depiction of the stratigraphy at the ACME/WRL site beyond what could be accomplished with the cores alone (table 9). Natural-gamma logging also was used to identify trends in the thickness of the Galena-Platteville aquifer. Attempts were made to correlate stratigraphy with Kh values, but the data distribution was too sparse for comparison.

Neutron and density logs indicated general patterns of increasing and decreasing porosity, which showed some correlation with stratigraphy but did not identify any fractures or solution openings (tables 9, 11). These logs were not calibrated to absolute values of porosity, so the magnitude of the variations is unknown. The primary reason for the failure to identify large fractures or solution openings appears to be a lack of sufficiently high porosity in these secondary-permeability features to distinguish them from the matrix porosity.

Periodic water-level measurements collected over 6 years identified the horizontal and vertical directions of ground-water flow and provided some insight into trends in aquifer permeability (and, thereby, the distribution of secondary-permeability features) across the ACME/WRL site (tables 9, 12). Analysis of horizontal hydraulic gradients indicated the presence of an area of lower permeability in the Galena-Platteville aquifer roughly coincident with the bedrock high between the ACME and WRL sites. This interpretation was supported by the results of aquifer testing and water-quality sampling. Horizontal hydraulic gradients could be used to identify trends in permeability partly because large variations in recharge conditions during these investigations resulted in substantial changes in flow directions and because data coverage within and surrounding the low-permeability area was sufficient for this area to be identified. Uniformly low (less than 1.0×10^{-2} ft/ft) vertical-hydraulic gradients tended to indicate the presence of high vertical-hydraulic conductivity in the Galena-Platteville aquifer throughout the ACME/WRL site. However, this interpretation was not supported by interpretations of two constant-discharge aquifer tests. The combination of low vertical-hydraulic gradient and apparently moderate to low vertical-hydraulic conductivity indicates that the amount of vertical flow within the aquifer at the ACME/WRL site is spatially uniform and fairly low.

Table 10. Monitoring well data, ACME Solvents and Winnebago Reclamation Landfill sites, Ill.

Screened interval: NA, not applicable; **Lithology:** D, dolomite; S, sandstone; UC, unconsolidated coarse grained; UF, unconsolidated, fine grained. **Hydrologic unit:** WTGP, water table Galena-Platteville; WTDA, water table drift aquifer; MGP, middle of Galena-Platteville aquifer; BGP, base of Galena-Platteville aquifer; MDA, middle of drift aquifer; LA, lower aquifer.

Well name	Measuring-point altitude (feet above National Geodetic Vertical Datum of 1929)	Open interval (feet below land surface)	Screened interval (feet below land surface)	Lithology	Hydrologic unit
B1	773.15	35-51	40-46	D	WTGP
B2	792.37	54-73	67-73	D	WTGP
B3	744.88	23-40	30-40	D	WTGP
B4	757.66	17-36	25-35	D	WTGP
B5	752.91	20-35	25-35	D	WTGP
B6S	754.07	35-48	37-47	D	WTGP
B6D	754.19	37-100	95-100	D	WTGP
B7	751.90	12-31	25-31	D	WTGP
B8	750.02	25-35	29-35	UF	WTDA
B9	758.38	14-42	36-42	D	WTGP
B10	744.12	16-40	34-40	D	WTGP
B10A	743.78	53-62	57-62	D	MGP
B11	750.63	29-47	42-47	D	WTGP
B11A	758.92	65-75	70-75	D	MGP
B12	760.35	28-49	44-49	D	WTGP
B13	739.33	21-33	27-33	D	WTGP
B15	744.47	15-40	34-40	UC	WTDA
B15P	743.51	50-63	58-63	UC	MDA
B15R	743.70	36-43	38-43	UC	WTDA
B16	762.86	23-45	40-45	D	WTGP
B16A	762.58	61-70	65-70	D	MGP
P1	727.65	27-35	30-35	UC	WTDA
P3R	749.59	35-48	38-48	UC	WTDA
P4R	747.82	60-70	65-70	UC	MDA
P6	739.61	44-50	45-50	D	MGP
P7	728.75	22-30	25-30	UC	WTDA
P8	748.21	30-36	30-36	UC	WTDA
P9	748.71	45-50	45-50	D	MGP
MW101	800.04	76-100	95-100	D	MGP
MW102	760.81	30-54	44-54	D	WTGP
MW103	751.10	23-60	50-60	D	MGP
MW104	756.82	102-135	125-135	D	MGP
MW105	753.00	64-76	70-76	D	MGP
MW106	725.85	47-60	55-60	UC	MDA
MW107	750.00	72-150	145-150	D	MGP
PZ1	747.48	23-30	24-29	D	WTGP
PZ2	745.17	18-25	19-24	UF	WTDA
PZ3	743.85	12-18	13-18	UF	WTDA
PZ4	744.27	13-21	14-19	D	WTGP
PZ5	747.33	13-21	15-20	UF	WTDA
PZ6	749.67	17-30	19-24	D	WTGP
PZ8	752.39	17-24	19-24	D	WTGP
PZ10	754.20	15-24	15-20	UC	WTDA
PZ11	754.53	13-21	14-19	UC	WTDA
1S	766.65	38-53	NA	D	WTGP
1I	766.04	127-147	NA	D	MGP

Table 10. Monitoring well data, ACME Solvents and Winnebago Reclamation Landfill sites, Ill.--Continued.

Well name	Measuring-point altitude (feet above National Geodetic Vertical Datum of 1929)	Open interval (feet below land surface)	Screened interval (feet below land surface)	Lithology	Hydrologic unit
1D	766.86	170-190	NA	D	BGP
2S	748.47	25-50	25-50	UF	WTDA
2I	748.35	116-135	NA	D	MGP
2D	747.89	162-182	NA	D	BGP
3S	768.38	31-46	NA	D	WTGP
3I	767.88	155-175	NA	D	MGP
3D	768.26	212-232	NA	D	BGP
4S	772.83	40-56	NA	D	WTGP
4I	771.52	115-137	NA	D	MGP
4D	770.00	182-201	NA	D	BGP
5S	763.96	23-49	27-47	D	WTGP
5I	762.41	120-140	NA	D	MGP
5D	762.67	180-201	NA	D	BGP
6S	752.07	7-30	11-30	D	WTGP
7I	757.14	77-101	81-101	D	MGP
SP1	752.63	244-264	NA	S	LA
SP2	769.94	294-316	NA	S	LA
MW201A	752.12	216-249	238-248	D	BGP/LS
MW201B	751.15	176-196	184-194	D	BGP
MW202	752.81	87-127	114-127	D	MGP
PPS	785.89	320-600	UNK	S	LA
B6PW	UNK	20-161	NA	D	GP
G101	745.78	UNK	UNK	D	WTGP
G102	738.48	UNK	UNK	D	WTGP
G105R	761.34	28-44	34-44	D	WTGP
G107	739.52	25-36	26-36	UF	WTDA
G108	751.13	27-44	34-44	D	WTGP
G109	760.60	35-52	42-53	D	WTGP
G109A	760.90	70-80	75-80	D	MGP
G110	747.90	30-43	33-43	D	WTGP
G111	740.59	23-36	26-36	UC/D	WTGP
G112	763.37	30-44	34-44	D	WTGP
G113	762.23	35-48	38-48	D	WTGP
G113A	762.86	63-75	70-75	D	WTGP
G114	758.07	30-45	35-45	D	WTGP
G115	729.03	8-20	10-20	UF	WTDA
G116	713.83	4-14	4-14	UC	WTDA
G116A	714.12	30-45	35-45	UC	MDA
G117	723.42	8-25	13-23	UF	WTDA
G118R	717.61	2-13	3-13	UC	WTDA
G118A	718.24	34-45	38-45	UC	WTDA
G119	720.34	8-20	10-20	UC	WTDA
G119A	720.17	40-50	45-50	UC	MDA

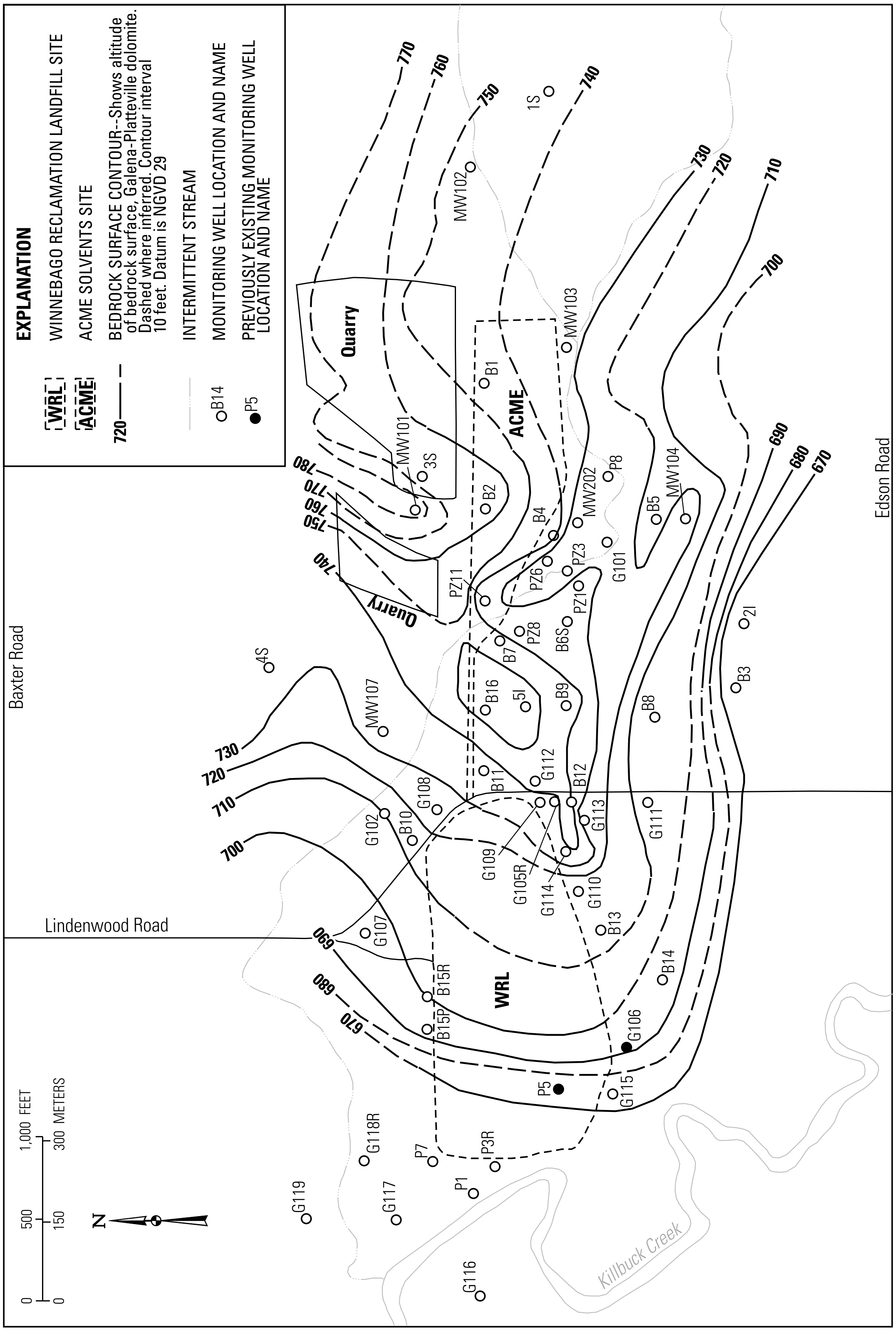


Figure 22. Bedrock-surface altitude at the ACME Solvents and Winnebago Reclamation Landfill sites, Ill.

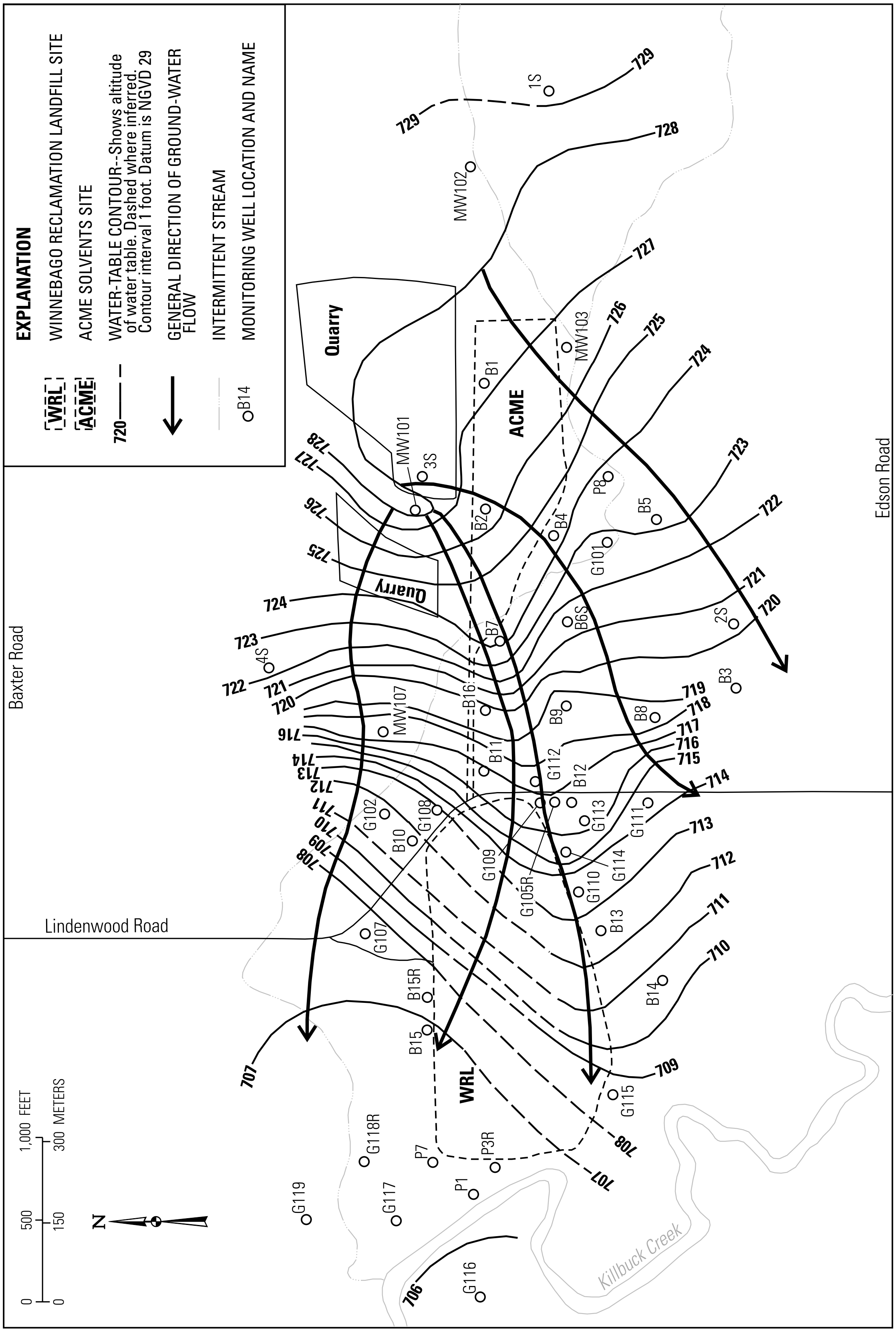


Figure 23. Water-table configuration, ACME Solvents and Winnebago Reclamation Landfill sites, Ill., November 7-9, 1988.

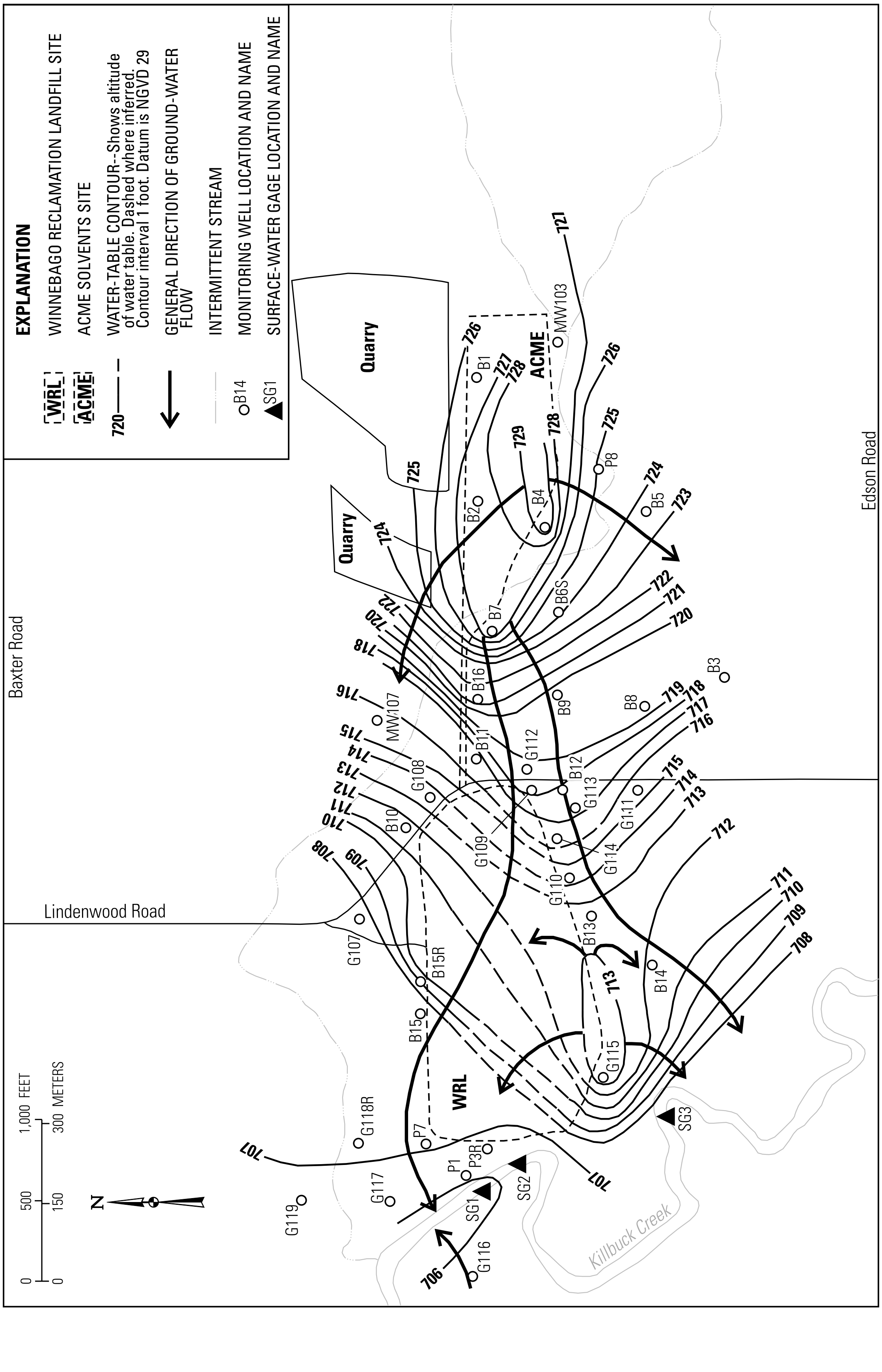


Figure 24. Water-table configuration, ACME Solvents and Winnebago Reclamation Landfill sites, Ill., April 20, 1990.

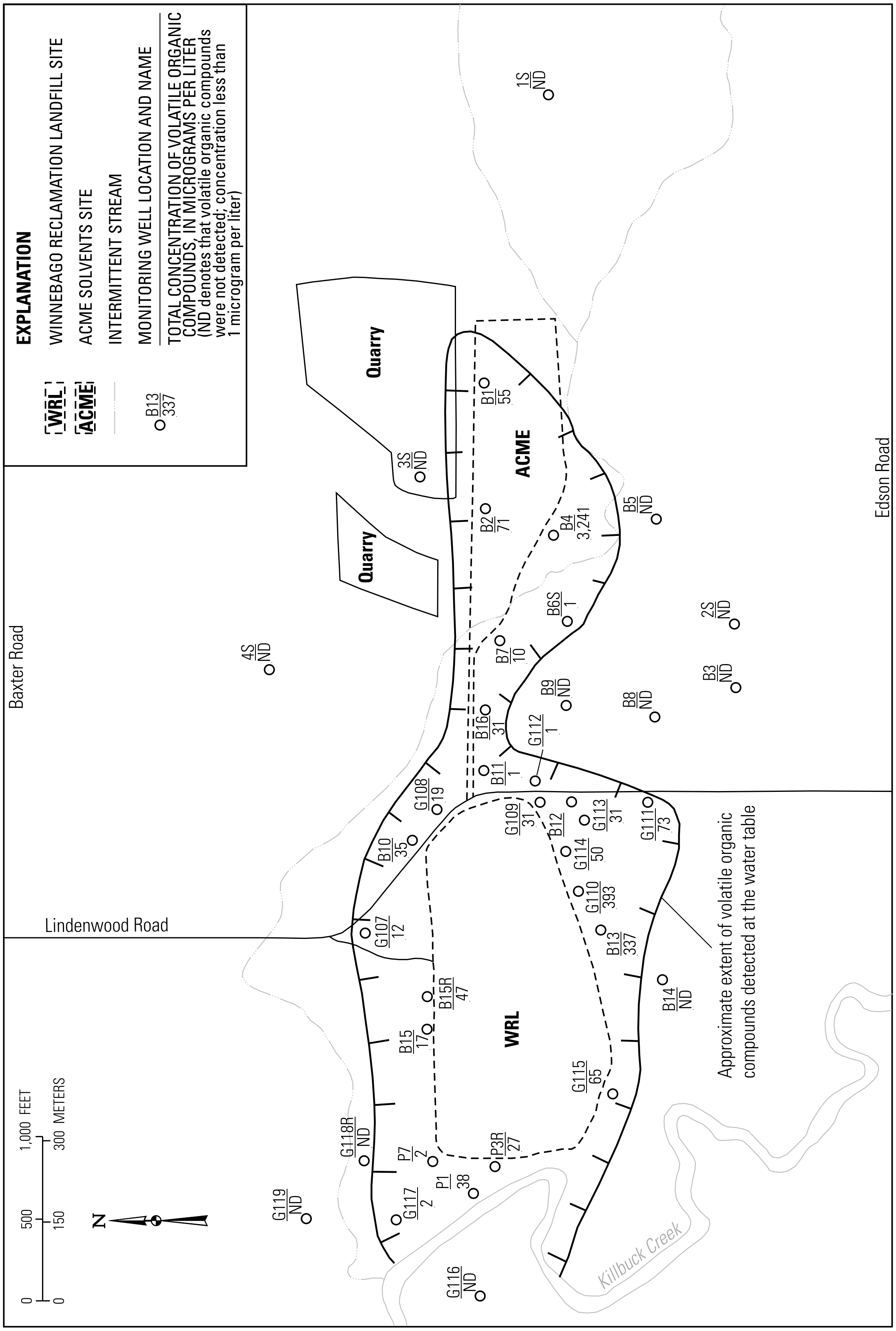


Figure 25. Distribution of volatile organic compounds in water-table wells at the ACME Solvents and Winnebago Reclamation Landfill sites, Ill., summer 1988.

Analysis of slug-test data confirmed the presence of areas of comparatively high and low Kh within the Galena-Platteville aquifer at the ACME/WRL site indicated by analysis of water-level data (tables 9, 12). Slug tests also quantified the Kh of various parts of the aquifer. Results of slug testing were affected by the length of the test interval, with smaller test intervals providing a more accurate depiction of the location of permeable features.

Multiple-well, constant-discharge aquifer tests allowed qualitative and quantitative assessment of the horizontal and vertical hydraulic properties of the aquifer, which could not be determined with other methods (tables 9, 12). However, the calculated transmissivity, storativity, and horizontal and vertical-hydraulic conductivity values may not be accurate because the heterogeneity of the aquifer is not accounted for in the analytical method. Analysis of drawdown data from a pumped well identified the approximate location of hydraulically active features in the well, which were consistent with those identified with borehole camera logging (tables 11, 12).

The location of contaminants at the ACME/WRL site indicates that the ground-water-flow pathways within the Galena-Platteville aquifer in parts of the ACME/WRL site are represented adequately by the water-level data. Contaminant locations also may indicate the presence of preferential flow around the low-permeability area between the ACME Solvents and WRL sites, which is consistent with interpretations about the comparative lack of secondary-permeability features in this area indicated by analysis of the water-level and aquifer-test data.

Table 11. Summary of altitudes of secondary-permeability features in select wells by method of detection, ACME Solvents and Winnebago Reclamation Landfill sites, Ill.

Borehole	Method	Altitude of secondary-permeability features (feet above National Geodetic Vertical Datum of 1929)
STI-1D	Lithologic logging	598, 665, 690.
	Cores	None identified.
	Borehole-camera logs	Method not used.
	Caliper logs	Possible fractures at 667, 684, 734.
	Natural-gamma logs	None identified.
	Neutron logs	None identified.
	Density logs	621.
STI-2D	Lithologic logging	None identified.
	Cores	None identified.
	Borehole-camera logs	Method not used.
	Caliper logs	None identified.
	Natural-gamma logs	None identified.
	Neutron logs	None identified.
	Density logs	None identified.
STI-3D	Lithologic logging	None identified.
	Cores	None identified.
	Borehole-camera logs	Method not used.
	Caliper logs	None identified.
	Natural-gamma logs	None identified.
	Neutron logs	None identified.
	Density logs	Method not used.
STI-SP2	Lithologic logging	None identified.
	Cores	Fractures at 736-742, unconformity at 603.
	Borehole-camera logs	Method not used.
	Caliper logs	None identified.
	Natural-gamma logs	None identified.
	Neutron logs	None identified.
	Density logs	None identified.
B6PW	Lithologic logging	None identified.
	Cores	Method not used.
	Caliper logs	Method not used.
	Natural-gamma logs	Method not used.
	Neutron logs	Method not used.
	Density logs	Method not used.

Southeast Rockford Site

The Southeast Rockford Superfund site (hereafter referred to as the Southeast Rockford site) is located in the southeastern part of the city of Rockford, Winnebago County, north-central Illinois (fig. 26). For the purposes of this report, the Southeast Rockford site is identical to the study area shown on figure 26. The Southeast Rockford site was subjected to moderate investigation with 15 investigative techniques used (tables 1, 13). The focus of the USGS investigation was boreholes BH1, BH2, and BH3 (fig. 26), which penetrate the entire thickness of the Galena-Platteville aquifer (table 14). Data collected over a period of 4 years by other investigators at numerous monitoring wells also are considered. Detailed analysis of the data collected at this site is presented in appendix E of this report.

Industrial wastes were disposed of or had been released from storage containers at various locations within the southeast Rockford area (Camp, Dresser, and McKee, 1992). The source area of concern to the USGS investigation is located west of Alpine Road between O'Connell Street and the railroad tracks (Camp, Dresser, and McKee, 1992) (fig. 26).

Surface topography at the Southeast Rockford site is elevated in the eastern part of the site, and decreases toward an unnamed stream through the west-central part

Table 12. Summary of information regarding permeable features in select boreholes by method of detection, ACME Solvents and Winnebago Reclamation Landfill sites, Ill.

Borehole	Method	Altitude of permeable features (feet above National Geodetic Vertical Datum of 1929)
STI-1D	Lithologic logging	598.
	Water-level measurement	In area of relatively high permeability.
	Slug tests	In area of relatively high permeability, specific permeable features not identified.
	Multiple-well, constant-discharge tests	Method not used.
	Contaminant location	None identified.
STI-2D	Lithologic logging	None identified.
	Water-level measurement	In area of relatively high permeability.
	Slug tests	In area of relatively high permeability, specific permeable features not identified.
	Multiple-well, constant-discharge tests	Method not used.
	Contaminant location	Along secondary orientation of vertical fractures in dolomite from ACME Solvents site.
STI-3D	Lithologic logging	None identified.
	Water-level measurement	In area of relatively high permeability.
	Slug tests	In area of relatively high permeability, specific permeable features not identified.
	Multiple-well, constant-discharge tests	Low vertical hydraulic interconnection, possible permeable feature near borehole.
	Contaminant location	Contaminants not detected.
STI-SP2	Lithologic logging	None identified.
	Water-level measurement	No Galena-Platteville data points in this area.
	Slug tests	In area of relatively high permeability, specific permeable features not identified.
	Multiple-well, constant-discharge tests	Method not used.
	Contaminant location	No Galena-Platteville data points in this area.
B6PW and B6 Well Cluster	Lithologic logging	None identified.
	Water-level measurement	In area of relatively low permeability.
	Slug tests	In area of relatively low permeability, specific permeable features not identified.
	Multiple-well, constant-discharge tests	Low vertical hydraulic interconnection, permeable features at 668-679, largest feature at 677, possibly other features near 640, 662, and 688.
	Contaminant location	In area of little flow in comparison to surrounding area.

of the site (fig. 26). The stream marks the approximate location of an east-west trending bedrock valley (fig. 27). The Galena-Platteville dolomite is as much as 360 ft thick at the bedrock upland and is about 150 ft thick in the bedrock valley (Kay and others, 1994; Camp, Dresser and McKee, Inc., 1992, 1994).

Quaternary-aged deposits unconformably overlie the Galena-Platteville dolomite beneath the Southeast Rockford site. Alluvial sand-and-gravel deposits generally are present in topographically low areas near the unnamed stream. Silt-and-clay deposits are interbedded with the sands and gravels, with more than 35 ft of silt and clay directly overlying the bedrock at boreholes BH1 and BH3. Quaternary deposits generally are about 40 ft thick along the bedrock ridges, and more than 150 ft thick near the bedrock valley.

The Galena-Platteville aquifer is overlain by the sand and gravel aquifer throughout the Southeast Rockford site. The Galena-Platteville aquifer is moderately permeable, with a geometric mean Kh of 2.6 ft/d. The aquifer contains a number of fractures and vuggy intervals whose location appears to be affected by lithology.

The overall direction of ground-water flow in the Galena-Platteville aquifer is from east to west beneath the Southeast Rockford site (fig. 28). VOC's stored or disposed of in this area have leached into the sand and gravel and Galena-Platteville aquifers (fig. 29), and are present in the aquifers from the area west of Alpine Road to the Rock River. A second, smaller, VOC plume is present in the northeastern part of the site.

Most of the methods of investigation provided some useful insight into the geology or hydrology of the Southeast Rockford site (tables 13, 15, 16). Multiple methods sometimes provided the same hydraulic information at this site. However, interpretations made based on one method occasionally were contradicted by interpretations made based on other methods.

Background sources of information were useful to the hydrogeologic characterization of the Galena-Platteville aquifer at the Southeast Rockford site, in part, because of the limited number of data points analyzed as part of the USGS investigation. Results of previous and concurrent investigations were used to determine geology, ground-water-flow directions, aerial distribution of contamination, and Kh of the Galena-Platteville aquifer. Analysis of surface topography was useful for identifying the configuration of the bedrock surface at the Southeast Rockford site. The limited aquifer-test data indicates the Galena-Platteville aquifer, as a whole, may be more permeable near the bedrock valley than near the bedrock ridge.

Observation of the rock at a quarry immediately southwest of Alpine and Sandy Hollow Roads established the lithology and stratigraphy of the exposed rocks (table 13). The utility of the data was limited because only the Wise Lake and Dunleith Formations were exposed at the quarry.

Lithologic logs identified depths of secondary-permeability features, although only one permeable feature was described beneath the site with this method (tables 13, 15, 16). These interpretations subsequently were confirmed by analysis of televiewer and caliper logs. The utility of the lithologic logs was limited by the large amount of water ejected out of the boreholes, which obscured increases in water return associated with permeable features and minimized their identification.

Three-arm caliper, borehole-camera, and acoustic-televiewer logs all provided insight into the location of bedding-plane partings in the dolomite, as well as areas where these features did not appear to be present (tables 13, 15). These logs helped refine interpretations about the locations of secondary-permeability features identified with the lithologic logs and identified secondary-permeability features that were not identified with the lithologic logs. Acoustic-televiewer logs provided the largest amount of information on the location, orientation, and type of secondary-permeability features.

Natural-gamma logs provided a comprehensive depiction of the stratigraphy at the Southeast Rockford site, which could not be accomplished with other methods (tables 13, 15). Natural-gamma logs did not indicate the presence of clay-infilled fractures in the boreholes. Short-normal resistivity logs, which tended to show a response inverse to the natural-gamma logs, also did not indicate the presence of clay-infilled fractures at the Southeast Rockford site, presumably because these features were not encountered.

Periodic water-level measurements collected from monitoring wells, single measurements from test intervals isolated with a packer assembly, and continuous measurements from a borehole, all provided insight into the horizontal and vertical directions of ground-water flow (tables 13, 16). Water-level measurements collected periodically over 3 years did not vary substantially between measurements rounds. Higher horizontal hydraulic gradients indicate the presence of an area of lower permeability in the Galena-Platteville aquifer between bore-

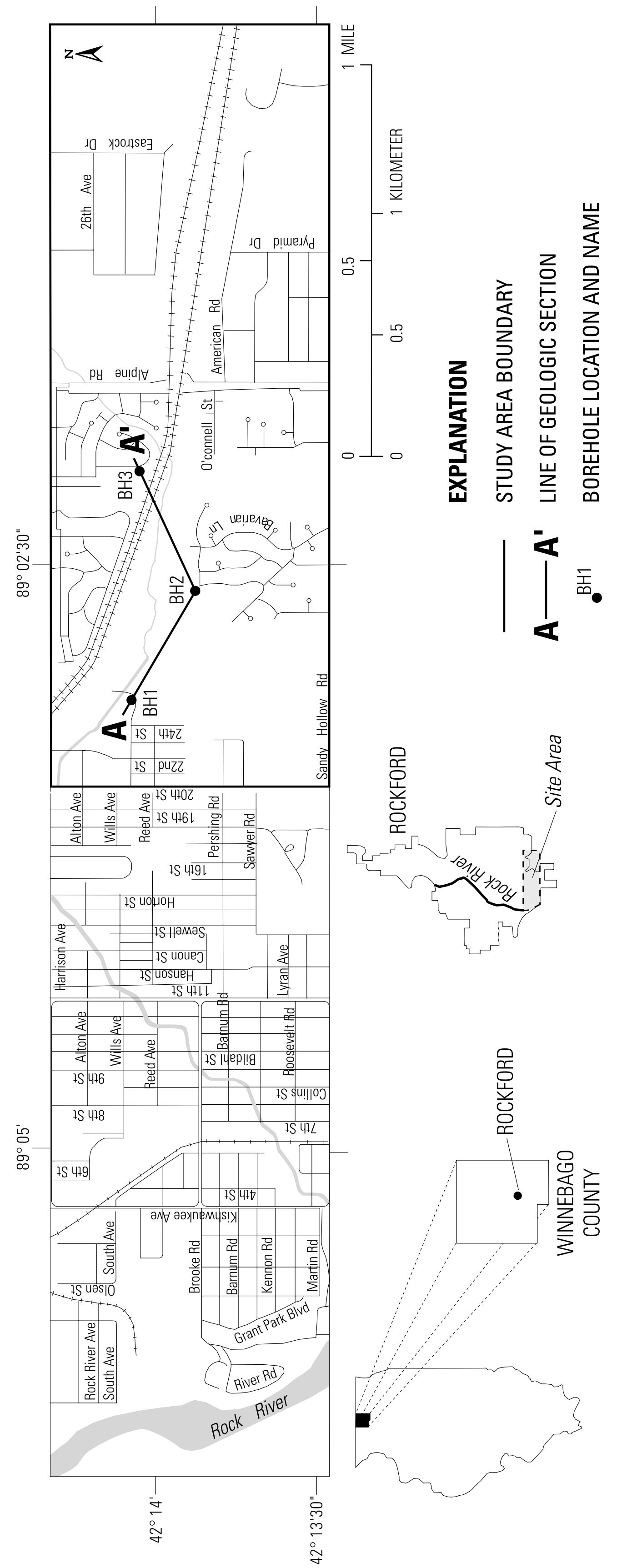


Figure 26. Location of the Southeast Rockford Superfund site, boreholes BH1, BH2, and BH3 and line of section A-A', Winnebago County, Ill.

Table 13. Summary of methods of data collection, Southeast Rockford site, Ill.

Method	Location of data collection	Uses
Previous investigations	Entire site and surrounding area.	Identification of lithology, directions of ground-water flow, water quality.
Topographic maps	Entire site and surrounding area.	Indication of bedrock topography.
Quarry visits	Quarry south of site.	Identification of stratigraphy and lithology in uppermost part of bedrock.
Lithologic logs	Boreholes BH1, BH2, BH3.	Identification of lithology, location of potential secondary-permeability features.
Borehole camera logs	Borehole BH3.	Identification of presence and location of secondary-permeability features.
Caliper logs	Boreholes BH1, BH2, BH3.	Identification of presence and location of potential fractures and competent parts of rock.
Natural-gamma logs	Boreholes BH1, BH2, BH3.	Characterization of site stratigraphy.
Acoustic-televiewer logs	Boreholes BH1, BH2, BH3.	Identification of presence and location of secondary-permeability features and competent parts of rock.
Short-normal resistivity logs	Boreholes BH1, BH2, BH3.	Identification of location of potential fractures.
Water levels from wells	Monitoring wells.	Determined vertical and horizontal directions of flow, indicated vertical and horizontal distribution of permeability.
Water levels using packers	Boreholes BH1, BH2, BH3.	Identification of vertical direction of flow, location of permeable features, vertical distribution of permeability, presence of high vertical-hydraulic gradients.
Flowmeter logs	Boreholes BH1, BH2, BH3.	Identification of vertical direction of flow, location of permeable features, potential for high vertical-hydraulic gradients and vertical distribution of permeability.
Slug tests	Monitoring wells.	Quantification of horizontal hydraulic conductivity, identification of presence of heterogeneity.
Specific-capacity tests	Boreholes BH1, BH2, BH3.	Quantification of hydraulic properties of aquifer, possible identification of areas of elevated permeability.
Contaminant location	Boreholes BH1, BH2, BH3 and monitoring wells.	Identification of ground-water-flow pathways.

holes BH1 and BH2 (fig. 28). However, this interpretation was not supported by the results of aquifer testing. This discrepancy may be related to the differences in the scale of aquifer characterized with the different methods, or the higher hydraulic gradients may be a response to increased ground-water flow in the Galena-Platteville aquifer in the western (downgradient) part of the site because of recharge from the overlying aquifer. Analysis of vertical trends in water levels indicated that the vertical-hydraulic conductivity of the aquifer decreases with depth, and that the vertical-hydraulic conductivity of the underlying confining unit is likely to be low. These vertical water-level trends indicate the presence of fewer, less permeable, less interconnected secondary-permeability features in the deeper part of the Galena-Platteville aquifer than in the shallow part beneath the Southeast Rockford site.

Data collected during flowmeter logging, particularly when analyzed on conjunction with acoustic-televiewer data, identified the location and type of permeable features in each of the boreholes (tables 13, 15). The location of some of these features also was indicated by analysis of the water-level data collected by use of a packer assembly. The utility of these logs may have been limited by the large amount of vertical flow in the boreholes, which may have reduced the ability to identify small changes in the amount of flow associated with potentially unidentified secondary-permeability features. The presence of high volumes of vertical flow through the boreholes can be indicative of poor vertical hydraulic interconnection within the aquifer, an interpretation that also is consistent with analysis of the water-level data collected by use of a packer assembly. Analysis of slug-test data from completed monitoring wells verified that the permeable zones identified by the flowmeter logging had the highest Kh values.

Specific-capacity tests (table 16) indicate that the secondary-permeability network may be more extensively developed in the bedrock valley than in the bedrock uplands; however, results of the slug testing do not clearly support this interpretation. This discrepancy may result because of the small number of specific-capacity tests (3) to support the interpretation, or may be because the specific-capacity tests were performed in boreholes open to the entire aquifer, intercepted permeable frac-

Table 14. Data for boreholes BH1, BH2, and BH3, Southeast Rockford site, Ill.

Borehole name	Depth (feet below measurement point)	Altitude of open interval (feet above National Geodetic Vertical Datum of 1929)	Altitude of measurement point (feet above National Geodetic Vertical Datum of 1929)
BH1	221	544-626	765
BH2	254	537-743	791
BH3	250	560-633	810

tures and vugs, and have a radius of influence of tens or hundreds of feet, whereas slug tests were performed in monitoring wells open to 10-15 ft of (typically) arbitrarily selected parts of the aquifer, in poor hydraulic connection with permeable features, and have a radius of influence of less than 10 ft.

The location of contaminants indicates that the overall ground-water-flow pathways within the Galena-Platteville aquifer in parts of the Southeast Rockford site are represented adequately by the water-level data. Vertical and areal distribution of contamination seems to indicate preferential flow through secondary-permeability features in some parts of the Southeast Rockford site.

Belvidere Area

The Belvidere study area (hereafter referred to as the Belvidere area) encompasses 80 mi² of Boone County, Illinois (figs. 2, 30), in and surrounding the city of Belvidere. The Belvidere area, and particularly the Parson's Casket Hardware Superfund site (figs. 30, 31) was investigated extensively with the application of 25 methods (tables 1, 17), more than 50 boreholes and wells penetrating the Galena-Platteville aquifer available for characterization (table 18), and up to 12 years of data available for analysis at the time these sites were investigated. Details of the results of the investigations are presented in appendix F to this report.

During the past century, waste materials containing VOC's and other potentially hazardous contaminants were disposed of at industrial and commercial facilities in Belvidere and at three nearby landfills (fig. 30). One industrial facility and two landfills in the Belvidere area are designated Superfund sites (Parson's Casket Hardware, Belvidere Landfill No. 1, MIG/DeWane Landfill). VOC's have been detected in samples from municipal, industrial, and residential water-supply wells open to the glacial drift and bedrock aquifers underly-

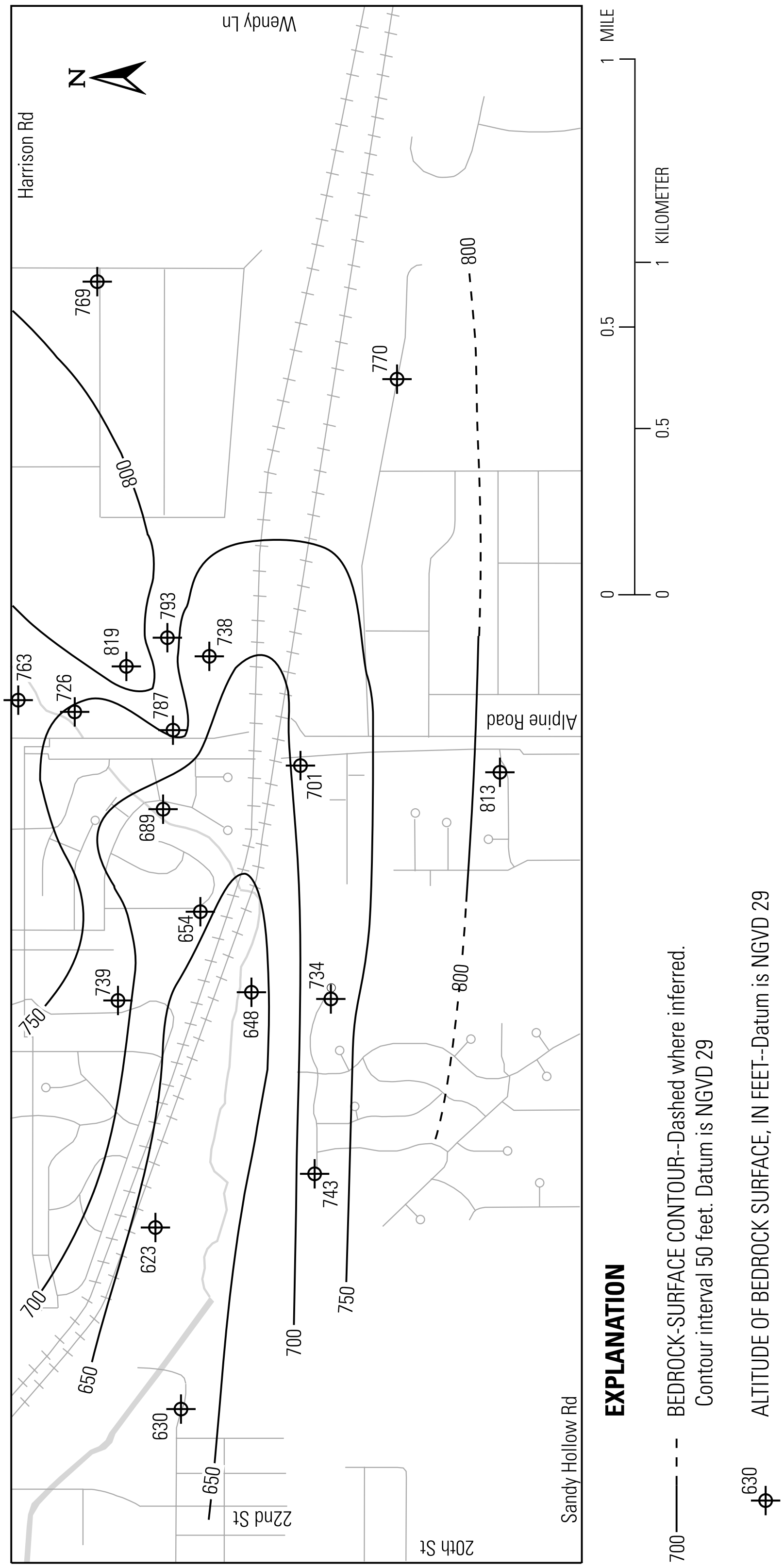


Figure 27. Bedrock surface topography at the Southeast Rockford site, Ill.

ing the Belvidere area, including the Galena-Platteville aquifer (Brown and Mills, 1995; Mills and others, 1998, 1999, 2002a, b). VOC's in ground water also appear to discharge to the Kishwaukee River in the Belvidere area (Roy F. Weston, Inc., 1988; Mills and others, 1999).

The Belvidere area is characterized by an undulating topography. The city of Belvidere is in a broad lowland valley that generally overlies the buried ancestral Troy Bedrock Valley (fig. 32). The axis of the Troy Bedrock Valley is about 1.5 mi west of the city. Surface-water runoff in the area discharges to the Kishwaukee River and its principal tributaries; the Kishwaukee river flows westward through the central part of the study area and Belvidere. The bedrock surface at the uplands that flank the river valley to the north and south are as high as 800 FANGVD29, whereas the bedrock-surface altitude beneath the river valleys is less than 500 FANGVD29.

The Galena-Platteville dolomite is the uppermost bedrock geologic deposit in most of the Belvidere area (fig. 32). The Galena-Platteville dolomite is as much as 300 ft thick beneath the Belvidere area, but has been removed by erosion near the axis of the Troy Bedrock Valley. Locally, in the south-central part of the Belvidere area, the Galena Group is exposed at outcrops.

Quaternary-aged deposits unconformably overlie the Galena-Platteville dolomite. Outwash sand-and-gravel deposits as much as 260 ft thick compose the southern part of the Troy Bedrock Valley and parts of the present Kishwaukee River and Piscasaw Creek Valleys. Outwash and alluvial sand-and-gravel deposits less than about 50 ft thick flank the present valleys. In the northern part of the Belvidere area, including the Troy Bedrock Valley, fine-grained till with interbeds of sand and gravel less than about 10 ft thick predominate. Most of the south-central and southeastern part of the Belvidere area is overlain by glacial till. In the central part of the Belvidere area, where most of the test boreholes and monitoring wells used for this study are located, the glacial-drift deposits generally are about

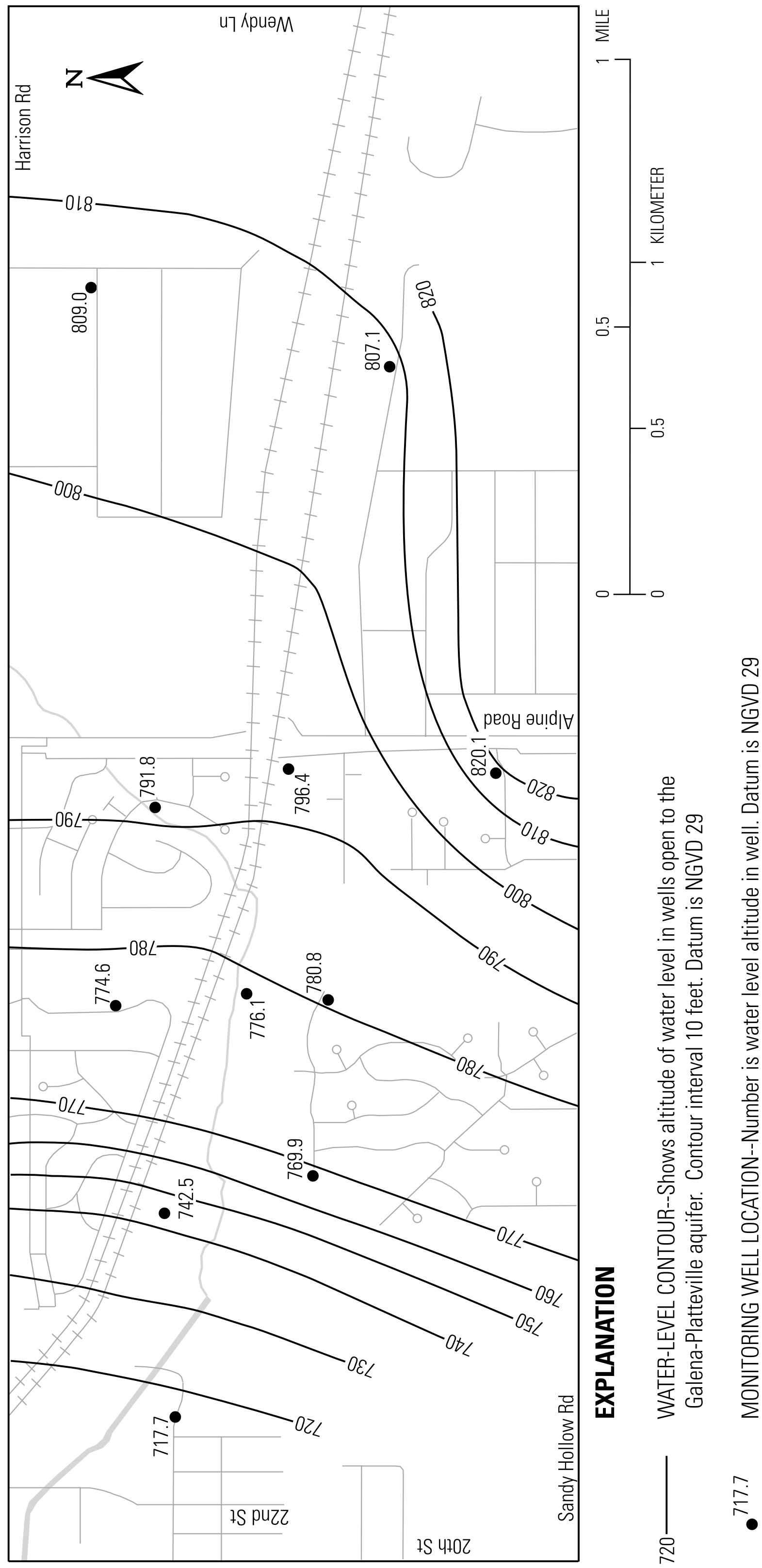


Figure 28. Potentiometric surface of the Galena-Platteville aquifer in the vicinity of the Southeast Rockford site, Ill., October, 1991

40 ft thick and are composed of sand and gravel with interbedded till.

Sand-and-gravel deposits, and in some locations, finer-grained deposits of glacial and alluvial origin, compose a glacial drift aquifer that underlies at least 50 percent of the Belvidere area. The aquifer is thickest in the southern part of the Troy Bedrock Valley (fig. 33) and along Kishwaukee River and its major tributaries. The glacial drift is unsaturated at locations where the bedrock surface is high in the south-central part of the Belvidere area and along northeastward trendlines in the northwestern and southwestern parts of the area (fig. 34a).

Hydraulic connection between the glacial drift aquifer and the underling Galena-Platteville aquifer is greatest where permeable sand-and-gravel deposits directly overlie the weathered upper 5-20 ft of the Galena-Platteville aquifer (Mills and others, 2002a; Kay, 2001). Vuggy intervals are present in some of the Galena-Platteville deposits, as are fractures and bedding-plane partings, but sinkholes and large solution openings do not appear to have been developed. Laterally extensive, permeable bedding-plane fractures are present at about 485, 525, and 660 FANGVD29 (fig. 35). Permeable vertical fractures also are present, particularly in the upper part of the aquifer. The Galena-Platteville aquifer is moderately permeable in the Belvidere area, with Kh values ranging from 0.005 to 2,500 ft/d. Horizontally oriented fractures and solution openings are most permeable in the upper, weathered part of the aquifer and at the bedding-plane fractures. These horizontal intervals are separated by less permeable matrix and connected by permeable vertical fractures.

Lateral ground-water flow in the glacial drift and Galena-Platteville aquifers is from the uplands north and south of the Kishwaukee

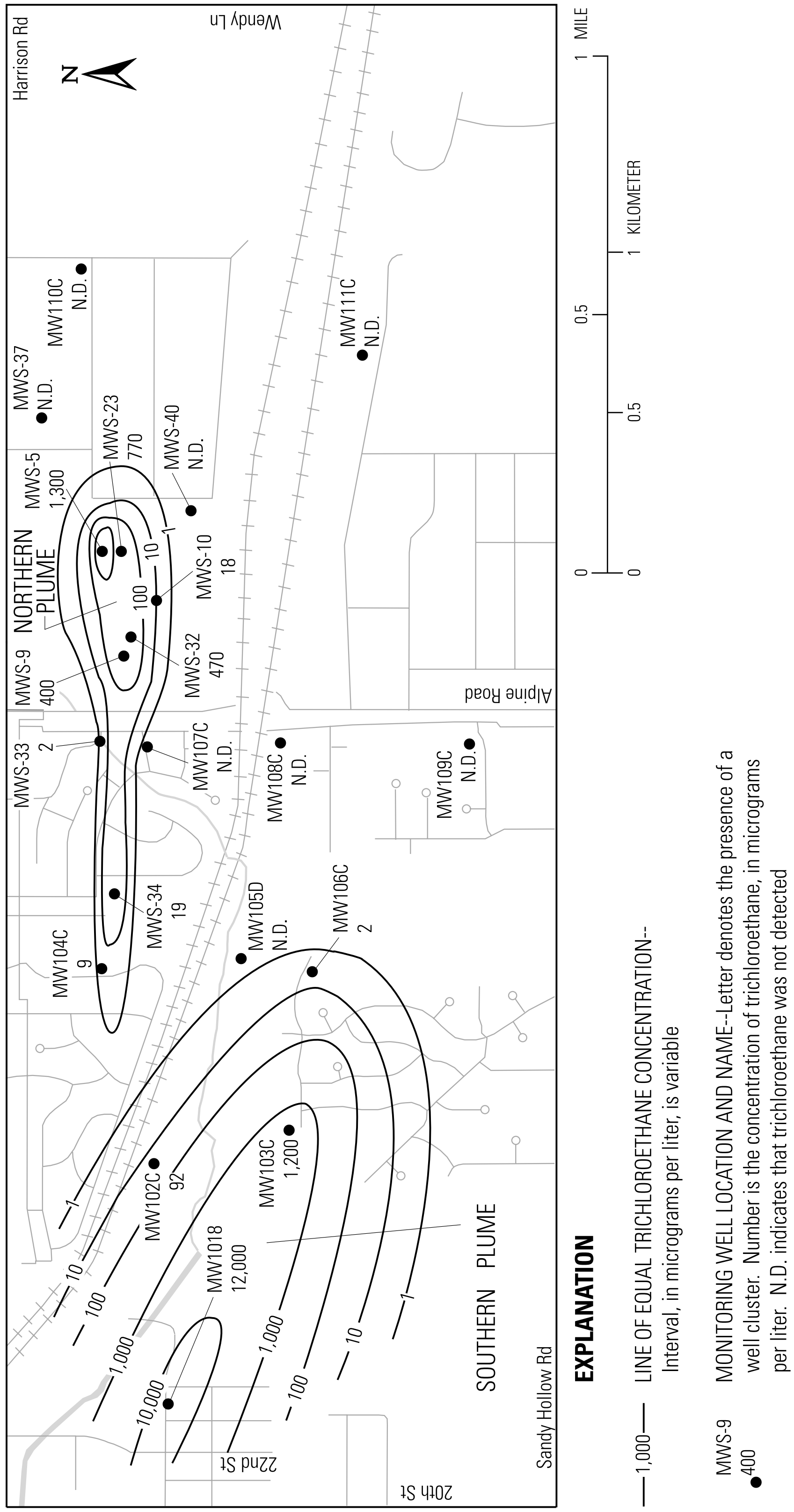


Figure 29. Concentration of trichloroethane in ground water from the Galena-Platteville aquifer at the Southeast Rockford site, Ill., October 1991.

Table 15. Summary of altitudes of secondary-permeability features in select boreholes by method of detection, Southeast Rockford site, Ill.

Borehole	Method	Altitude of secondary-permeability features (feet above National Geodetic Vertical Datum of 1929)
BH1	Lithologic logging	547, 563, 602, 606, 616.
	Borehole-camera logs	Method not used.
	Caliper logs	Potential fractures at 563, 591, 603, 607, 625.
	Natural-gamma logs	None identified.
	Acoustic-televiewer logs	Potential fractures at 549-555, 560, 587, 597-607, 611-625.
	Short-normal resistivity logs	None identified.
BH2	Lithologic logging	598, 608.
	Borehole-camera logs	Method not used.
	Caliper logs	Potential fractures at 543, 600, 663, 743.
	Natural-gamma logs	None identified.
	Acoustic-televiewer logs	Potential fractures at 537, 550, 565, 589, 591-600, 617-669, 695, 731-743.
	Short-normal resistivity logs	None identified.
BH3	Lithologic logging	586, 626, 630, 646.
	Borehole-camera logs	Fractured areas at 566-587, 610-631, individual fractures at 580, 590, 597, 626, 650. Vugs at 572, 581, 589, 594-610, 627, and 633-638.
	Caliper logs	Potential fractures at 580, 590, 597, 626, 650.
	Natural-gamma logs	None identified.
	Acoustic-televiewer logs	Potential fractures at 569, 577, 582, 586, 592-600, 608-615, 620-630, 638-642.
	Short-normal resistivity logs	None identified.

River toward the river (figs. 34a, b). Vertical flow in these aquifers is downward in the uplands and near the city of Belvidere, where ground water is withdrawn for municipal and industrial supply. Upward flow occurs primarily in the southwestern part of the Belvidere area, where ground water discharges from the Galena-Platteville aquifer into the glacial drift aquifer near the Troy Bedrock Valley and the Kishwaukee River. Six municipal-supply wells (BMW2-BMW7) and at least three high-capacity industrial-supply wells that are open, in part, to the Galena-Platteville aquifer, affect flow in the aquifer throughout much of the city of Belvidere (fig. 34b). Locally, flow in the Galena-Platteville aquifer may be affected by low-capacity-well withdrawals in widely distributed rural subdivisions.

VOC's from the waste materials have contaminated the glacial drift and Galena-Platteville aquifers in parts of the Belvidere area. VOC concentrations as high as 1,000 µg/L have been detected in the Galena-Platteville aquifer. VOC's from the Parsons Casket Hardware Superfund site (hereafter referred to as the PCHSS) and perhaps other sites are migrating to residential, municipal, and industrial water-supply wells in the Belvidere area in response to natural hydraulic stresses as well as pumping.

Virtually all of the study methods provided information on the geology or hydrology of the Belvidere area (tables 17, 19, 20). Multiple methods usually provided the same information, but, occasionally, all were necessary to resolve non-unique interpretations.

Review of previous studies was useful for initial conceptualization of the hydrogeology of the Belvidere area. Data gaps were identified, as were important hydrogeologic features on which to focus investigation. The quality and comparability of all available data had to be evaluated. These data generally were considered acceptable for select uses. For example, drillers logs of residential-supply wells were too vague for identification of specific permeable features in the Galena-Platteville aquifer, but did indicate that the aquifer typically was at least moderately permeable, particularly in the upper part where most of the residential-supply wells were finished.

Quarry inspections were useful for establishing stratigraphy and fracture orientations in the Belvidere area (table 17). Quarry inspections also indicated the potential for enhanced permeability above units of low permeability, which were confirmed by analysis of hydraulic and geophysical data.

The SAR surveys indicated the primary orientation of inclined fractures and estimates of secondary porosity (table 17). The fracture orientations varied between the sites, but generally were consistent with those identified from previous investigations of area quarries as well as multiple-well aquifer testing, acoustic-televiewer, and borehole GPR logging performed as part of these investigations. Some discrepancies were noted, however, particularly at the PCHSS, where confirmatory data were most abundant. Estimates of secondary porosity from the SAR surveys varied by more than an order of magnitude between the PCHSS and the other locations. The estimate of secondary porosity at the PCHSS generally was consistent with the primary porosity values for

Table 16. Summary of information regarding aquifer hydrology and location of permeable features in select boreholes by method of detection, Southeast Rockford site, Ill.

Borehole	Method	Altitude of permeable features (feet above National Geodetic Vertical Datum of 1929)
BH1	Lithologic logging	Large amount of water returned, aquifer moderately permeable, hydraulically active feature at 600-606.
	Water-level measurement	Aquifer may be less permeable with depth, borehole may be open to less permeable part of aquifer. Most permeable feature(s) may be located between 601 and 617.
	Flowmeter logging	563-567, 587, 596, 601-605, above 620 . Potentially poor vertical hydraulic interconnection.
	Specific-capacity tests	May be in less permeable part of the aquifer.
	Contaminant location	Potentially moderately good vertical interconnection within the aquifer.
BH2	Lithologic logging	Large amount of water returned from borehole, aquifer moderately permeable.
	Water-level measurement	Aquifer may be less permeable with depth.
	Flowmeter logging	548, 600, 720 . Potentially poor vertical hydraulic interconnection.
	Specific-capacity tests	May be in less permeable part of the aquifer.
	Contaminant location	Potentially moderately good vertical interconnection within the aquifer.
BH3	Lithologic logging	Large amount of water returned from borehole, aquifer moderately permeable.
	Water-level measurement	Specific intervals not identified. Well may be in more permeable part of aquifer.
	Flowmeter logging	597 and 650. Potentially poor vertical hydraulic interconnection.
	Specific-capacity tests	May be open to more permeable part of aquifer.
	Contaminant location	Potentially moderately good vertical interconnection within the aquifer.

the upper part of the dolomite measured from the core samples.

Thick deposits of fine-grained sediments (greater than 30 ft), and multiple fracture orientations and cultural interferences, limited the locations where SAR surverys could be conducted and the quality of the surveys in the Belvidere area. The survey at the PCHSS also was affected by nearby cultural features. Quarry inspections and borehole-geophysical methods provided more reliable and less costly information about the presence and orientation of steeply inclined fractures than the SAR surveys.

Lithologic logs were of limited value for characterizing secondary-permeability features in the Galena-Platteville aquifer (tables 17, 19, 20). Lithologic logs provided the initial identification of some shallow secondary-permeability features, as well as some of the less permeable parts of the aquifer. These interpretations were confirmed by analysis of water-level data, caliper logs, acoustic-televiewer logs, flowmeter logs, and aquifer testing. However, these logs were less successful in identifying secondary-permeability features in the deeper parts of the aquifer than in the shallow parts. This lack of success was partly because by the time these deeper features were encountered, large amounts of water already were being ejected from the borehole. Increases in water return associated with the deeper features were comparatively small in relation to the total volume of water being expelled and, therefore, were difficult to detect. In addition, the deeper secondary-permeability features were thin enough that appreciable changes in drilling rates could not be identified when they were encountered.

Core analysis was the basis for identification of the stratigraphy of the Galena and Platteville Groups in the Belvidere area (table 17). This information was the foundation of the analysis of the lithologic factors that affect the distribution of the permeability, water levels, and, perhaps, contaminant movement in the Belvidere area. Analysis of core samples also was used to determine the primary porosity of the aquifer. Core analysis provided limited information on the location of fractures in the aquifer, but did provide some information to indicate that vertical fracturing decreases with depth, which subsequently was confirmed with borehole GPR logging and water-level measurements. The lack of weathering of the core and need to represent the full thickness of the aquifer with cores from multiple boreholes hindered reliable identification of stratigraphic units and the location of breaks between units so that identification of stratigraphic units at the member level was limited to a few easily distinguished units.

Borehole-camera logs provided information on the location of vugs and fractures in the aquifer (tables 17, 19). The effectiveness of this method was limited partly by the presence of turbid water in parts of some boreholes obscuring the borehole walls. The turbidity may be caused by the presence of soft rock on the borehole wall, but could not be related to the presence of secondary-permeability features, but the bottom of the turbid zones showed some correlation with the presence of permeable features in at least one location. Information provided by these logs generally was confirmed and expanded upon by caliper and acoustic-televiewer logging.

Three-arm caliper logs were used to identify the location of a number of the more prominent secondary-permeability features in the bedrock, including the 525- and 660-ft partings, as well as areas where more competent rock was present (tables 17, 19). Caliper logs tended to confirm interpretations about the locations of shallow secondary-permeability features identified with

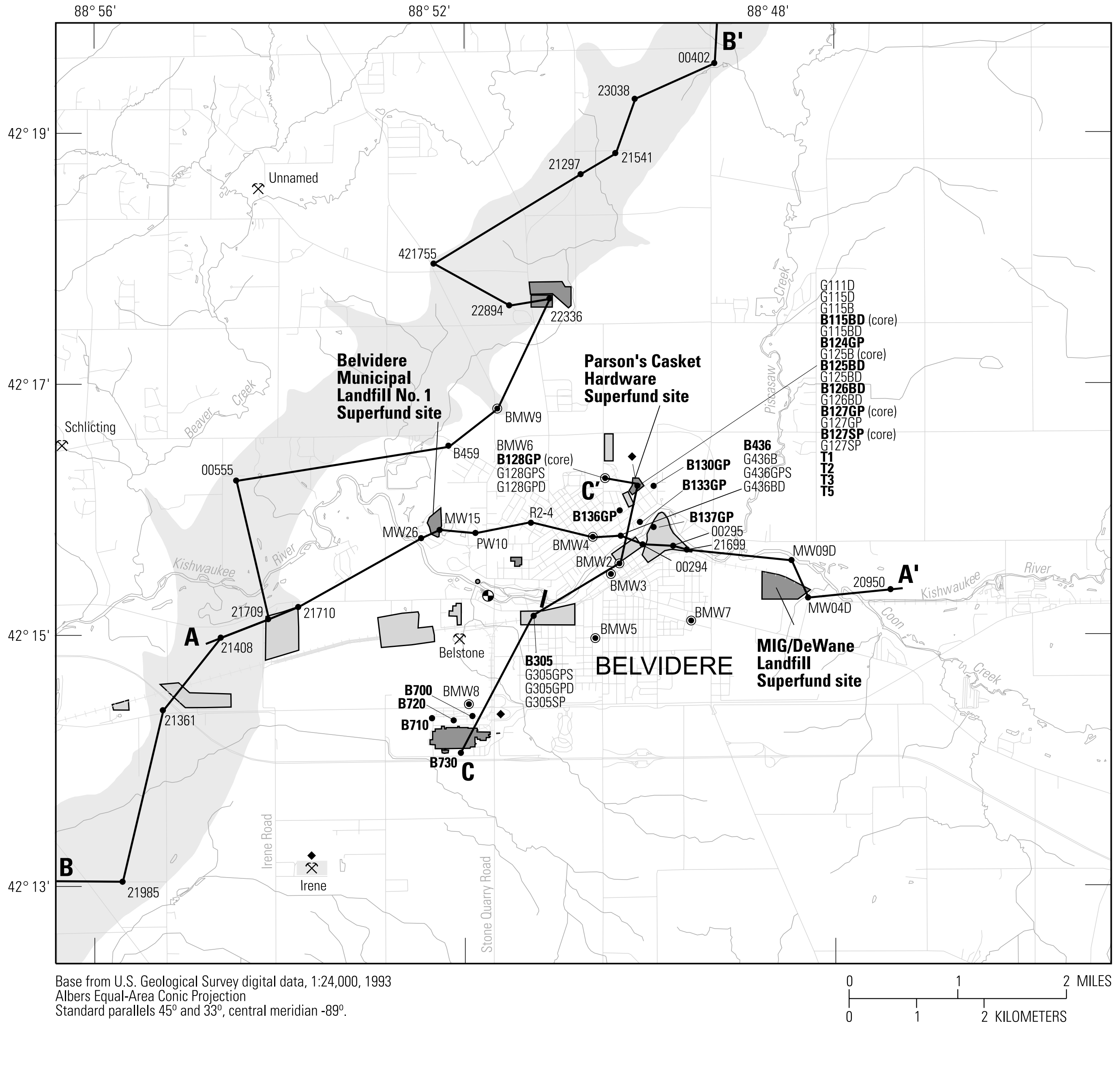
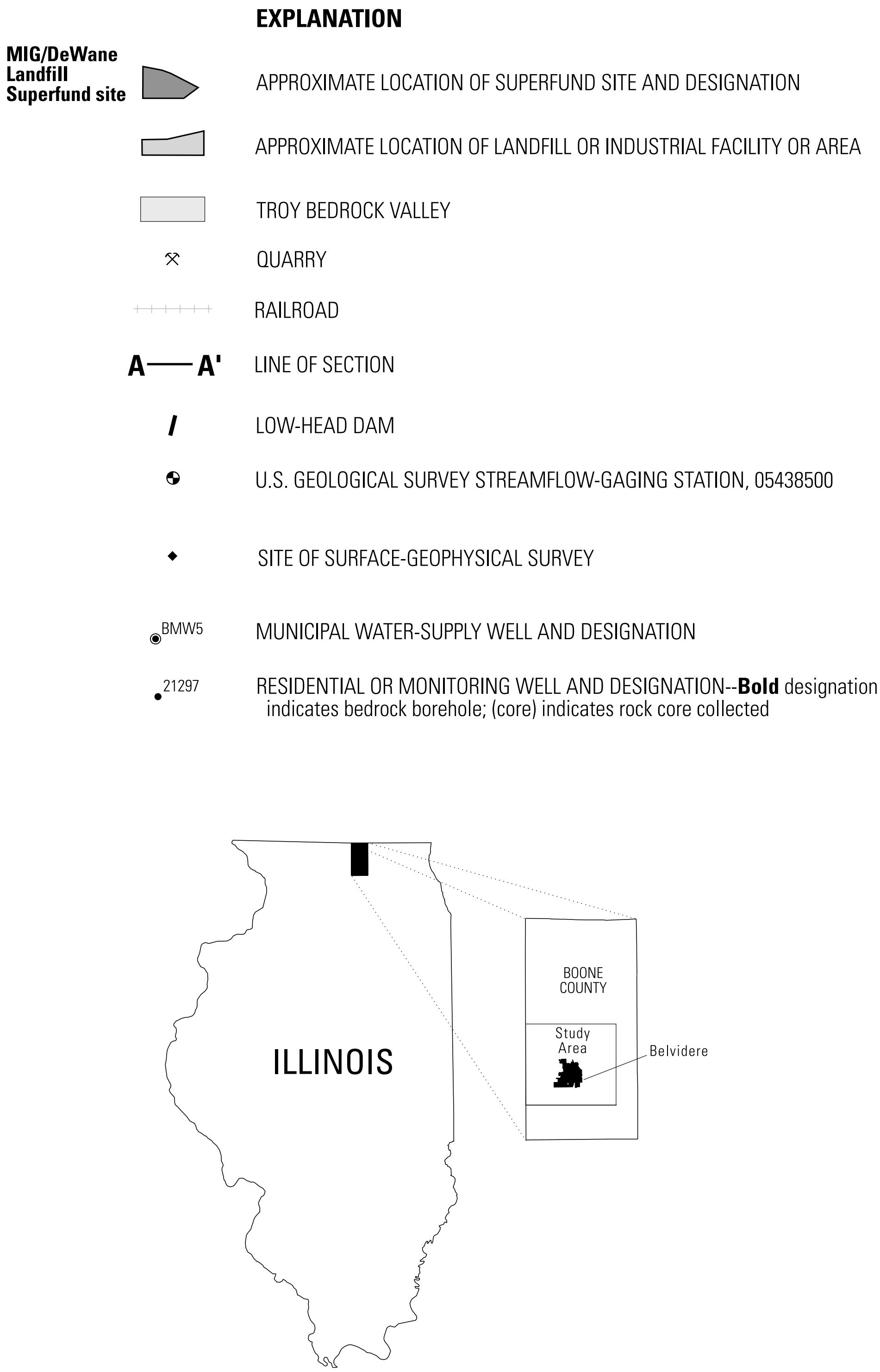


Figure 30. Study area in the vicinity of Belvidere, Ill., including selected hazardous-waste-disposal sites, well locations, quarries, sites of surface-geophysical surveys, and rock cores.



the lithologic and camera logs, and helped identify the presence and location of secondary-permeability features in the deeper part of the bedrock not identified with the lithologic and camera logging. The location of many of these features subsequently was confirmed by acoustic-televiewer logging.

Natural-gamma logs were used to supplement stratigraphic interpretations made from the core data and to provide a comprehensive depiction of the stratigraphy of the Belvidere area beyond what could be accomplished with the comparatively limited number of cores and quarries available for observation (table 17). Better understanding of stratigraphy and variations in lithology were combined with hydraulic information to identify lithologic factors that may have affected the location of permeable features in the aquifer. These features affect flow directions and contaminant movement. For example, as initially indicated by observations in area quarries, the presence of permeable features above argillaceous parts of the Galena-Platteville dolomite, such as the 525-ft and 660-ft partings, may have been created by the retardation of vertical ground-water flow through the argillaceous deposits. Retardation of vertical flow may have resulted in a larger volume of horizontal flow across the top of these deposits, which could have enhanced dissolution of the rock and the formation of these features.

SPR and normal and lateral resistivity logs showed similar response. These logs provided only limited insight into the geology and presence of potential fractures in the Belvidere area (tables 17, 19). Although there was a tendency to increase

Table 17. Summary of methods of data collection, Belvidere, Ill., area study.

Method	Location of data collection	Uses
Quarry inspection	Belstone, Irene Road, Schlicting, unnamed quarries.	Identification of flow pathways, stratigraphy, fracture orientation.
Square-array resistivity	Parson's Casket, Stone Quarry Road, Irene Road quarry sites.	Identification of primary and secondary orientation of vertical fractures, calculation of secondary porosity.
Lithologic logging	Several hundred water-supply wells throughout the area. All boreholes drilled by the U.S. Geological Survey.	Identification of lithology, location of shallow permeable features.
Cores	Boreholes B115BD, B125B, B127GP, B127SP, B128GP.	Identification of stratigraphy, lithology, quantification of primary porosity.
Borehole camera logs	Boreholes B115BD, B125BD, B126BD, B127GP, B128GP, B305, B436, BMW2.	Identification of secondary-permeability features.
Caliper logs	Boreholes T1, T2, T3, T5, T6, T7, T8, B115BD, B124GP, B125BD, B126BD, B127GP, B127SP, B128GPD, B130GP, B133GP, B134GP, B136GP, B137GP, B305, B436, BWM2.	Identification of presence and location of potential fractures and competent parts of rock.
Natural-gamma logs	Boreholes T1, T2, T3, T5, T6, T7, T8, B115BD, B124GP, B125BD, B126BD, B127GP, B127SP, B128GPD, B130GP, B133GP, B134GP, B136GP, B137GP, B305, B436, B700, B710, B720, B730, BMW2, BMW8.	Characterization of stratigraphy.
Single-point resistance logs	Boreholes B115BD, B125GP, B126GP, B127GP, B127SP, B128GP, B305, B436, BMW2.	Identification of fractures.
Normal-resistivity logs	Boreholes T1, T2, T5, T6, T7, T8, B128GP, B130GP, B133GP, B134GP, B136GP, B137GP, B305, B436, BMW2.	Identification of fractures.
Neutron logs	Boreholes B128GP, T1, T8.	Identification of trends in porosity.
Acoustic-televiewer logs	Boreholes T1, T2, T3, T5, T6, T7, T8, B124GP, B127GP, B127SP, B128GPD, B130GP, B133GP, B134GP, B136GP, B137GP, B436, BMW2.	Identification of location, type, and orientation of secondary-permeability features.
Borehole ground-penetrating radar	Single hole at boreholes T1, T3, T6, T8, B127GP. Cross hole at boreholes T2-T7, T2-T8, T2-T3, T3-T8, T3-T7, T7-T8.	Location of lithologic changes. Identification of type, location, and orientation of secondary-permeability features.
Single water-level measurements	Synoptic measurement in approximately 150 water-supply and monitoring wells. Packed intervals in boreholes T1, T2, T3, T5, T6, T7, T8, B115BD, B124GP, B125GP, B126GP, B127GP, B128GP, B130GP, B133GP, B134GP, B136GP, B137GP	Determined vertical and horizontal directions of flow. Identified location of permeable features at a borehole, indicated distribution of vertical hydraulic conductivity. Indicated the presence of large decreases in water level that could be attributed to pumping in parts of the aquifer.
Continuous water-level measurements	Wells G115D, G115B, G115BD, G124GP, G126GP, G127GP, G127SP, G128GPS, G128GPD, G133GP, G134GP, G136GP, G305GPS, G305GPD, G305SP, G436B, T8, BMW4, BMW6.	Identified presence and cause of variability in flow within different parts of the aquifer. Identified hydraulically active features. Determined vertical distribution of permeable features and permeability in the aquifer.
Periodic water-level measurements	Wells G115BD, G125BD, G126D, G127GP, G128GP, G305GPS, G305GPD, G305SP, G436B, G436GPS, G436GPD.	Identified vertical and horizontal flow directions. Indicated variability in flow directions within the aquifer. Indicated presence of pumping effects in deeper part of aquifer.
Spontaneous-potential logs	Boreholes B115BD, B125GP, B126GP, B127GP, B127SP, B128GP, B305, B436, BMW2.	Identification of fractures.
Temperature logs	Boreholes B115BD, B124GP, B127GP, B127SP, B128GPD, B130GP, B133GP, B134GP, B136GP, B137GP, B305, B436, BMW2.	Measured fluid temperature, identified permeable features.
Fluid-resistivity logs	Boreholes B115BD, B124GP, B127GPD, B127SP, B128GP, B130GP, B133GP, B134GP, B136GP, B137GP, B436, BMW2.	Measured fluid resistivity, identified permeable features.
Flowmeter logs	Boreholes T1, T2, T3, T5, T6, T7, T8, B124GP, B127GP, B128GPD, B130GP, B133GP, B134GP, B136GP, B137GP, B436, BMW2.	Identified location of permeable features and pathways of hydraulic interconnection between boreholes.
Slug tests	Approximately 160 wells and test intervals.	Quantification of horizontal hydraulic conductivity, identification of permeable features, and distribution of permeability.
Specific-capacity tests	About 250 residential-supply wells. Boreholes B130GP, B133GP, B134GP, B136GP.	Quantification of transmissivity.

Multiple-well, constant-discharge tests	Borehole B127GP. Test intervals in boreholes T1 and T6.	Quantification of hydraulic properties of the aquifer, identification of ground-water-flow pathways, identification of presence of heterogeneity and anisotropy.
Tracer tests	Borehole T1.	Identification of ground-water-flow pathways, quantification of effective porosity.
Computer modeling	Entire study area.	Flow pathways, capture zones, effect of horizontal hydraulic conductivity and porosity on ground-water velocity, potential variation in aquifer permeability.
Contaminant location	Approximately 150 monitoring and water-supply wells. Boreholes B124GP, B127GP, B128GP, B130GP, B133GP, B134GP, B136GP, B137GP.	Identification of ground-water-flow pathways.

signal response near potential fractures at bedding-plane partings associated with argillaceous deposits, they did not identify many of the secondary-permeability features identified with other methods. It appears likely that the logs were responding to areas of transition between argillaceous and non-argillaceous deposits that happened also to correspond to the location of subhorizontal, bedding-plane partings rather than to the actual partings.

Neutron logs showed a signal response to some bedding-plane partings and, perhaps, an inclined fracture identified with lithologic, caliper, or televiewer logs, but showed no response to other subhorizontal bedding-plane partings and inclined fractures (tables 17, 19). Neutron logs appear to respond more to clay minerals associated with the fractures, rather than to the fractures themselves and this method was not clearly useful for identifying the location of fractures in the Belvidere area. Neutron logs did show changes in signal response that correlated well with general trends in primary porosity identified from the analysis of core samples and cross-borehole GPR logging. This result indicates that the porosity of most of the bedding-plane partings is low in comparison to primary porosity. Limited flow seems to be associated with all intervals of enhanced porosity and water content identified with neutron logging. Other logging methods generally provided more useful information on the location of permeable features and, possibly, contaminant migration pathways. Additionally, hazards associated with the potential loss of the radioactive source during neutron logging limit its desirability as an investigative method.

Acoustic-televiewer logs provided the greatest amount of information on the location, orientation, and types of secondary-permeability features in the Galena-Platteville dolomite. These logs tended to confirm the results of the lithologic logging, core inspections, borehole-camera, caliper, and other geophysical logs regarding the location of bedding-plane partings, inclined fractures, and vugs. Televiewer logs identified numerous bedding-plane partings, inclined fractures, and vuggy intervals not identified with the other methods, as well as the orientation (strike, dip, vertical or horizontal) of many of these features, which could not be determined using other methods (tables 17, 19). Vertical-fracture orientation identified with the televiewer logging was consistent with the vertical-fracture orientation identified with the SAR survey performed at the PCHSS, as well as the predominant orientation of inclined fractures in the area as determined at local quarries. Comparison of televiewer results with caliper and natural-gamma logs indicates that some of the bedding-plane partings may be wash outs of shale partings and bentonite layers rather than fractures.

Single-hole GPR surveys enabled identification of apparent fractures, bedding-plane partings, and cavities at distances up to about 50 ft from the boreholes. The location of many of the bedding-plane partings was confirmed with other geophysical methods (tables 17, 19). However, comparison of the orientation of potential inclined fractures identified with the single-hole GPR survey in a number of boreholes located within about 150 ft of each other with inclined fracture orientations determined for those boreholes by acoustic-televiewer logging, the SAR survey, and the drawdown distribution from a constant-discharge aquifer test indicated moderate agreement (appendix F). In addition, a number of inclined fractures projected to intersect the boreholes did not appear to be present based on televiewer and other logs. One of the prominent inclined fractures identified with the lithologic, caliper, and televiewer logs also was identified during GPR logging in a nearby borehole, but was not identified with GPR logging in the borehole where the fracture was observed. GPR logging did uniquely produce the important conclusion that the size of this fracture decreased with depth in the dolomite deposits. The ability to identify secondary-permeability features located tens of feet from the borehole represents an important improvement in the ability to characterize fractured-rock aquifers and a number of important interpretations resulted from the GPR logging. However, the occasional discrepancies between the results of the GPR logging and other investigative methods indicate the results of the GPR logs should be interpreted with caution. The apparent discrepancies between the results of the of GPR and other investigative methods in this study may be related to the difficulties in identifying weakly developed fractures, the variability of fracture orientation with location, and termination of the fractures before they intercept the borehole. GPR logging may prove more beneficial in karstic settings or where fractures are more fully developed.

Cross-hole GPR surveys identified trends in the competence and porosity in the Galena-Platteville dolomite. Patterns in porosity, identified with the cross-borehole GPR logging, were consistent with those identified with core analysis and neutron logging. Porosity values obtained during the GPR survey were consistent with those measured from the core samples and the SAR survey at the PCHSS.

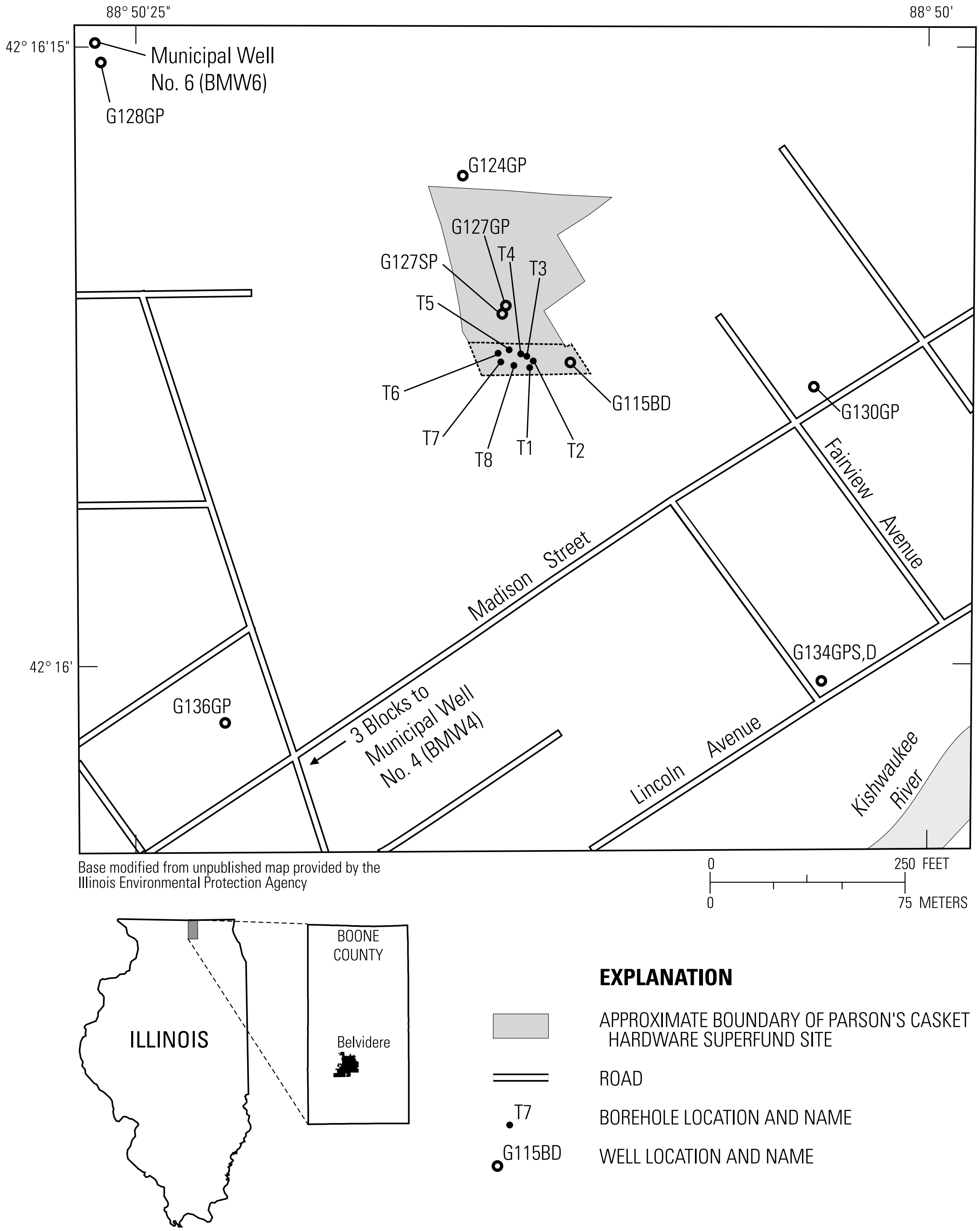


Figure 31. Location of the Parson's Casket Hardware Superfund site and vicinity, including location of select boreholes and monitoring wells, Belvidere, Ill.

Table 18. Description of selected wells and borings used in the Belvidere, Ill. area study.

[NA, not applicable; GP, Galena-Platteville aquifer; GD, glacial drift aquifer; GF, Glenwood Formation; SP, St. Peter aquifer; OR, Ordovician aquifer (Galena-Platteville and St. Peter Sandstone); CO, Cambrian-Ordovician aquifer]

Borehole name	Well name	Hydrogeologic Unit	Altitude of measurement point (feet above National Geodetic Vertical Datum of 1929)	Altitude of open interval of borehole (feet above National Geodetic Vertical Datum of 1929)	Altitude of open interval of well (feet above National Geodetic Vertical Datum of 1929)
NA	G111D	GP	783	NA	748-753
NA	G115D	GP	783	NA	745-750
NA	G115B	GP	784	733-745	733-745
B115BD	G115BD	GP	784	630-747	630-641
B124GP	G124GPS	GP	782	515-747	733-743
B124GP	G124GPD	GP	782	515-747	718-726
NA	G125BD	GP	782	NA	746-751
B125BD	G125BD	GP	782	631-751	634-645
B126BD	GH126BD	GP	784	633-755	748-751
B127GP	G127GP	GP	785	484-744	490-495
B127SP	G127SP	GP	785	390-749	408-413
B128GP	G128GPD	GP	785	472-752	524-529
B128GP	G128GPS	GP	782	472-752	661-666
B130GP	G130GP	GP	788	558-747	560-570
B133GP	G133GP	GP	778	510-733	518-528
B134GP	G134GPD	GP	784	516-728	516-526
B134GP	G134GPS	GP	784	516-728	718-728
B136GP	G136GP	GP	782	499-754	499-754
B137GP	G137GPD	GP	762	487-704	719-726
B305	G305GPS	GP	766	172-744	662-667
B305	G305GPD	GP	766	172-744	526-531
B305	G305SP	SP	766	172-744	419-424
B436	G436B	GP	766	551-738	731-736
B436	G436GPS	GP	766	551-738	659-664
B436	G436GPD	GP	766	551-738	566-571
NA	MW04D	GP	776	NA	746-751
NA	MW09D	GP	772	NA	711-716
NA	MW15	GD	767	NA	730-746
NA	MW26	GP	750	NA	608-613
NA	PW10	GP	773	NA	707-717
NA	R2-4	GP	780	NA	684-740
T1	NA	GP	784	569-735	NA
T2	NA	GP	784	569-736	NA
T3	NA	GP	784	569-734	NA
T4	NA	GP	784	734-739	NA
T5	NA	GP	784	569-747	NA
T6	NA	GP	783	569-747	NA
T7	NA	GP	784	569-749	NA
T8	NA	GP	784	569-744	NA
NA	00294	CO	760	NA	-108-521
NA	00295	CO	770	NA	143-707
NA	00402	GF	835	NA	481-500
NA	00555	GF	775	NA	469-495
NA	20950	GP	765	NA	615-708
NA	21297	SP	841	NA	401-456
NA	21361	GF	757	NA	427-497

Table 18. Description of selected wells and borings used in the Belvidere, Ill. area study.--Continued.

Borehole name	Well name	Hydrogeologic Unit	Altitude of measurement point (feet above National Geodetic Vertical Datum of 1929)	Altitude of open interval of borehole (feet above National Geodetic Vertical Datum of 1929)	Altitude of open interval of well (feet above National Geodetic Vertical Datum of 1929)
NA	21408	GD	765	NA	615-617
NA	21541	SP	850	NA	440-484
NA	21699	GP	783	NA	638-722
NA	21709	SP	775	NA	385-496
NA	21710	OR	766	NA	346-500
NA	21985	GD	752	NA	642-667
NA	22336	SP	811	NA	411-499
NA	22894	SP	815	NA	410-502
NA	23038	SP	842	NA	402-472
NA	421755	SP	830	NA	432-478
NA	B459	GD	774	NA	554-555
NA	B700	GP	786	NA	462-777
NA	B710	GP	790	NA	436-771
NA	B720	GP	790	NA	446-771
NA	B730	GP	788	NA	434-766
NA	BMW2	CO	759	NA	-1101-709
NA	BMW3	CO	763	NA	-1037-708
NA	BMW4	CO	777	NA	-1023-625
NA	BMW5	CO	799	NA	189-647
NA	BMW6	CO	782	NA	-86-672
NA	BMW7	CO	839	NA	-130-647
NA	BMW8	CO	783	NA	-607-421
NA	BMW9	CO	781	NA	661-711

Single water-level measurement during synoptic surveys provided substantial information on the horizontal and vertical directions of ground-water flow in the Belvidere area, and gave some indication that water levels in parts of the Galena-Platteville aquifer were affected by pumping stresses from quarries and water-supply wells (fig. 34; tables 17, 20). Water levels measured periodically over periods of months to years also provided substantial information on the vertical directions of ground-water flow, indicated that the aquifer responded to climatic stresses as a single aquifer, indicated that water levels in the deeper parts of the aquifer were affected by pumping from water-supply wells, and provided some indication on the vertical distribution of aquifer permeability. Water levels measured continuously over periods of days or weeks provided the largest amount of information on the location of permeable features and the vertical distribution of permeability within the aquifer. Single water-level measurements taken from test intervals isolated by use of packer assemblies also provided substantial insight into the vertical directions of ground-water flow, the location of some permeable features, and trends in vertical-hydraulic conductivity within the aquifer. These interpretations were supported to varying degrees by the analysis of cores, slug tests, borehole-geophysical logs (especially flowmeter logging and borehole GPR) and water-quality data.

The utility of water-level measurements for the characterization of the Galena-Platteville aquifer in the Belvidere area results from the presence of laterally extensive secondary-permeability features in the Galena-Platteville aquifer, such as the 525-ft parting, and the presence of water-supply wells that induce substantial hydraulic stresses on the aquifer. These stresses, when transmitted through the extensive secondary-permeability network, result in large, easily identifiable, changes in water levels in most of the aquifer. If pumping did not induce these large changes in water level, and if the 525-ft parting was not present to transmit the hydraulic stress over large areas, the amount of interpretation that could have been made from the measurements would have been reduced substantially. In addition, the utility of the water-level measurements for the characterization of the Galena-Platteville aquifer in the Belvidere area was linked directly to the frequency of measurements. Single water-level measurements allowed limited characterization of the aquifer, periodic measurements provided greater characterization, and continuous measurements provided substantial insight into flow direction and permeability distribution.

SP, temperature, and fluid-resistivity logging identified a number of permeable features in the Galena-Platteville aquifer, which also were identified with use of other methods in the Belvidere area (tables 17, 20). The change in signal response associated with many of these permeable features was subtle, and these interpretations often were aided with other data. These logs (particularly the SP log, which tended to respond to argillaceous materials) identified potential permeable features not identified with other methods and did not identify many permeable features that were identified using other methods, particularly flowmeter logging. As a consequence, SP, temperature, and fluid-resistivity logs only were moderately effective in identifying permeable features in the Belvidere area and tended to be most effective in deep boreholes. Part of the reason for the effectiveness of these logs for secondary-permeability characterization in the Belvidere area (in comparison to the Byron site,

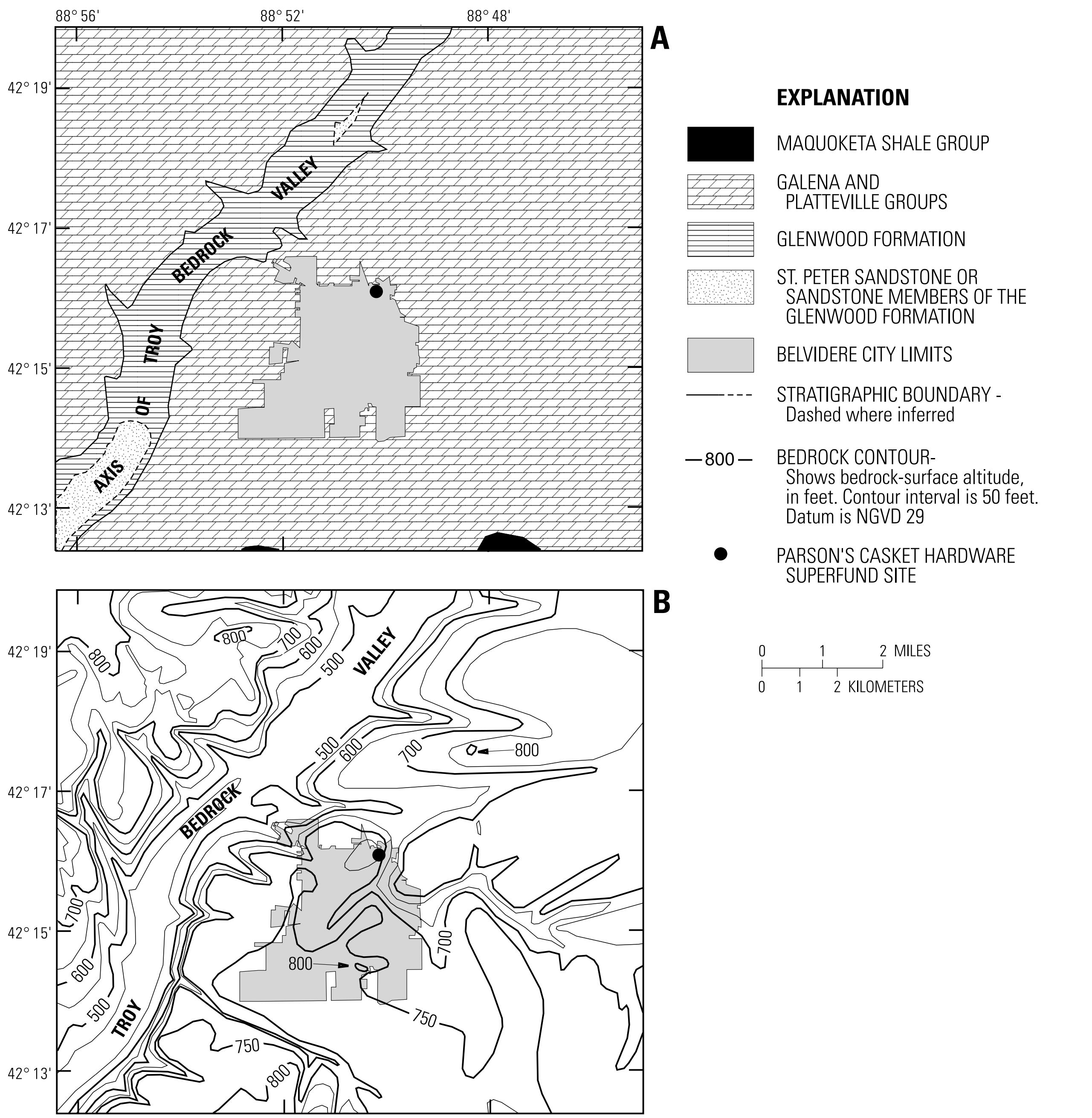


Figure 32. Geology and topography of the bedrock surface in the vicinity of Belvidere, Ill.: (A) stratigraphic units that compose the bedrock surface, (B) topography of the bedrock surface

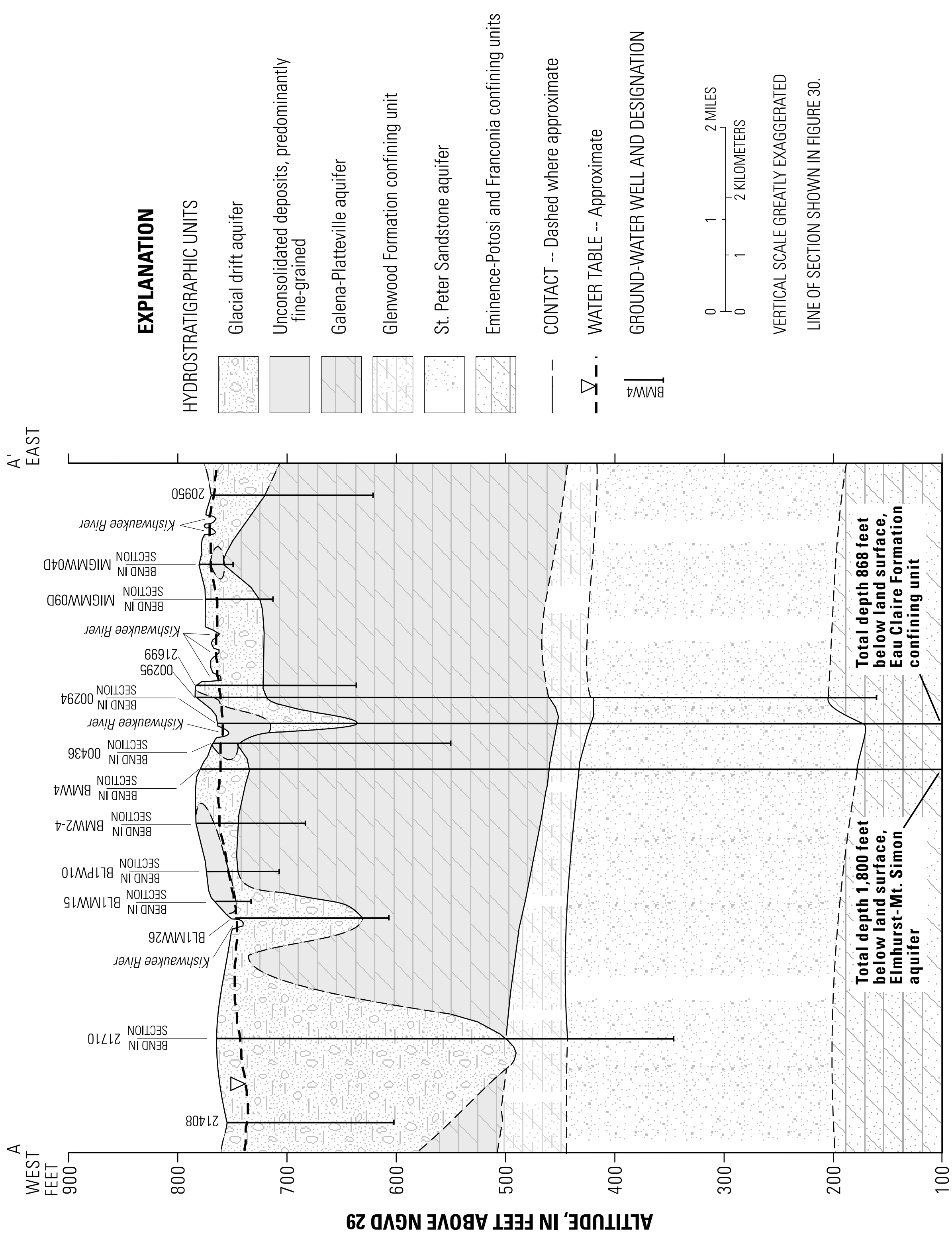
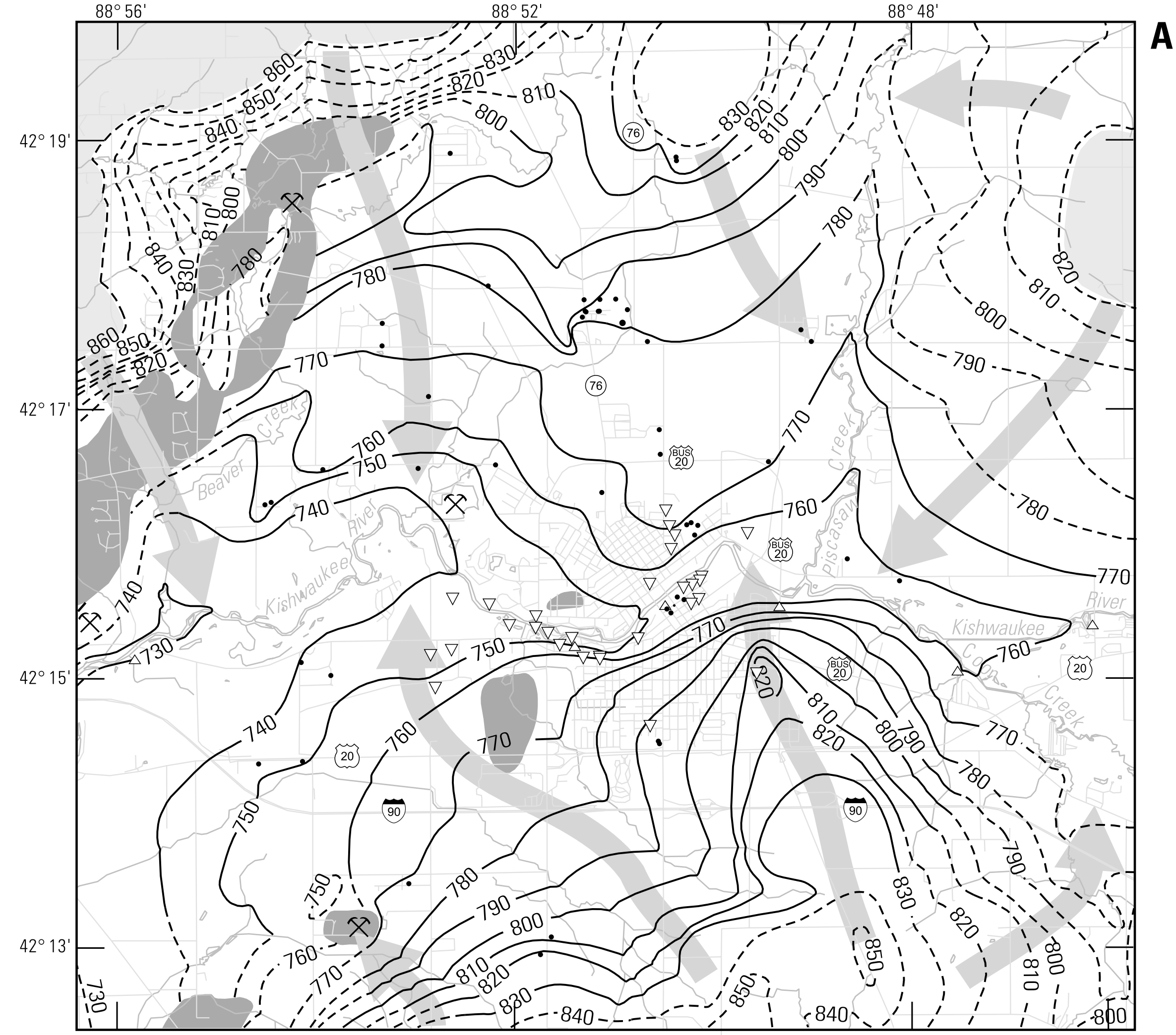


Figure 33. Hydrogeologic section A-A' through the vicinity of Belvidere, Ill.



Base from U.S. Geological Survey digital data, 1:24,000, 1993
Belvidere North, Belvidere South, Calcedonia, and Cherry Valley
Albers Equal-Area Conic Projection
Standard parallels 45° and 33°, central meridian -89°.

0 1 2 MILES
0 1 2 KILOMETERS

EXPLANATION

APPROXIMATE AREA WHERE GLACIAL DRIFT IS UNSATURATED

NOT CONTOURED BECAUSE OF LIMITED WATER-LEVEL-CONTROL DATA

GENERALIZED DIRECTION OF GROUND-WATER FLOW

— 750 - - - POTENTIOMETRIC CONTOUR - Shows altitude at which water would have stood in tightly cased wells. Dashed where inferred. Contour interval is 10 feet. Datum is NGVD 29

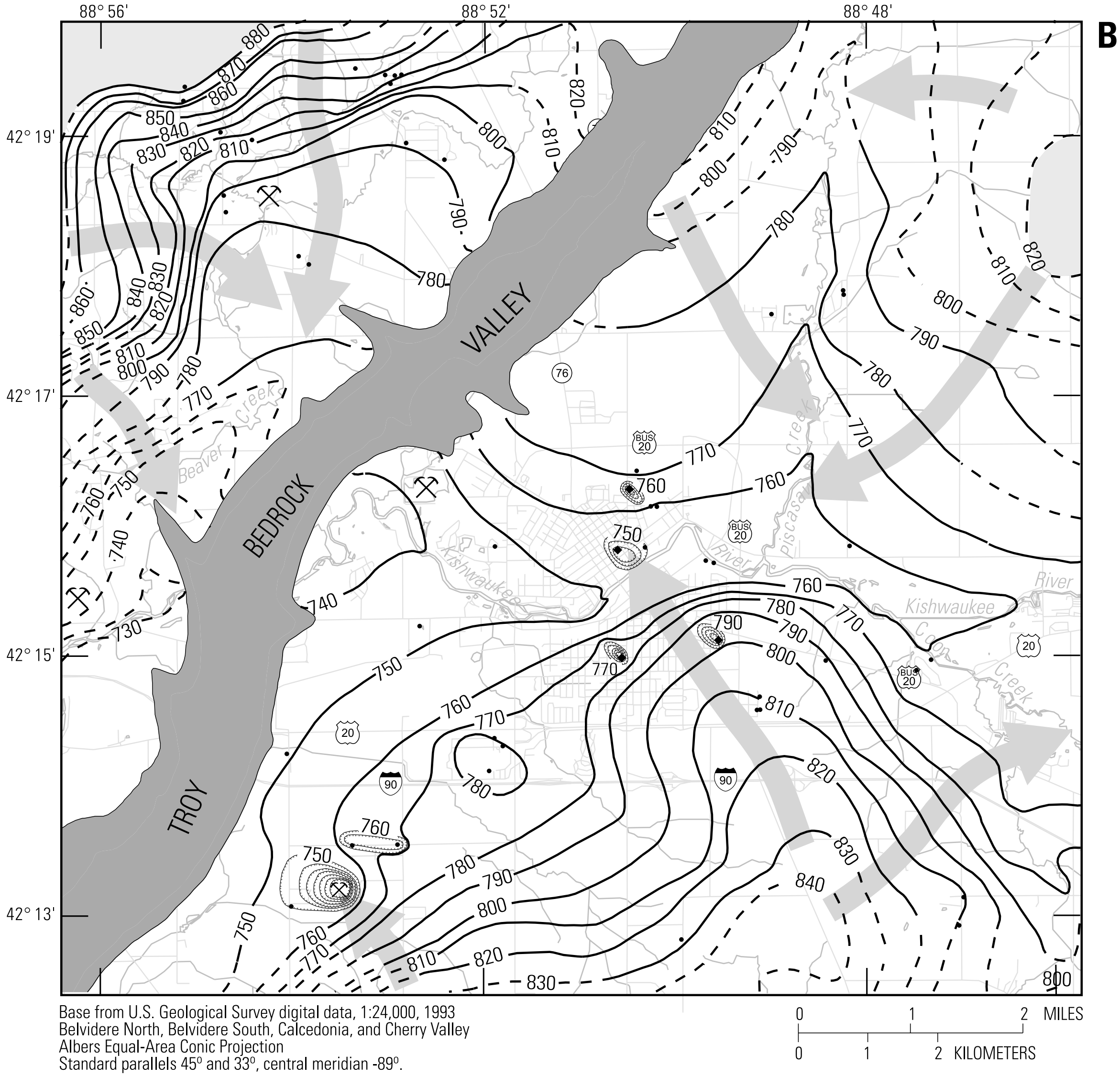
• MONITORING OR WATER-SUPPLY WELL

▽ TEMPORARY WELL

△ SITE OF SURFACE-WATER MEASUREMENT

⚒ QUARRY

Figure 34. Potentiometric levels and horizontal-flow directions in the (A) glacial drift and (B) Galena-Platteville aquifers underlying Belvidere, Ill., July 1993.



EXPLANATION

APPROXIMATE LOCATION WHERE THE GALENA-PLATTEVILLE AQUIFER IS ABSENT IN THE TROY BEDROCK VALLEY

NOT CONTOURED BECAUSE OF LIMITED WATER-LEVEL-CONTROL DATA

GENERALIZED DIRECTION OF GROUND-WATER FLOW

750 POTENTIOMETRIC CONTOUR - Shows altitude at which water would have stood in tightly cased wells. Dashed where inferred. Contour interval is 10 feet. Datum is NGVD 29

MONITORING OR WATER-SUPPLY WELL

BELVIDERE MUNCIPAL WATER-SUPPLY WELL - Open to the Galena-Platteville aquifer and deeper bedrock aquifers

QUARRY

Figure 34. Potentiometric levels and horizontal-flow directions in the (A) glacial drift and (B) Galena-Platteville aquifers underlying Belvidere, Ill., July 1993.--Continued

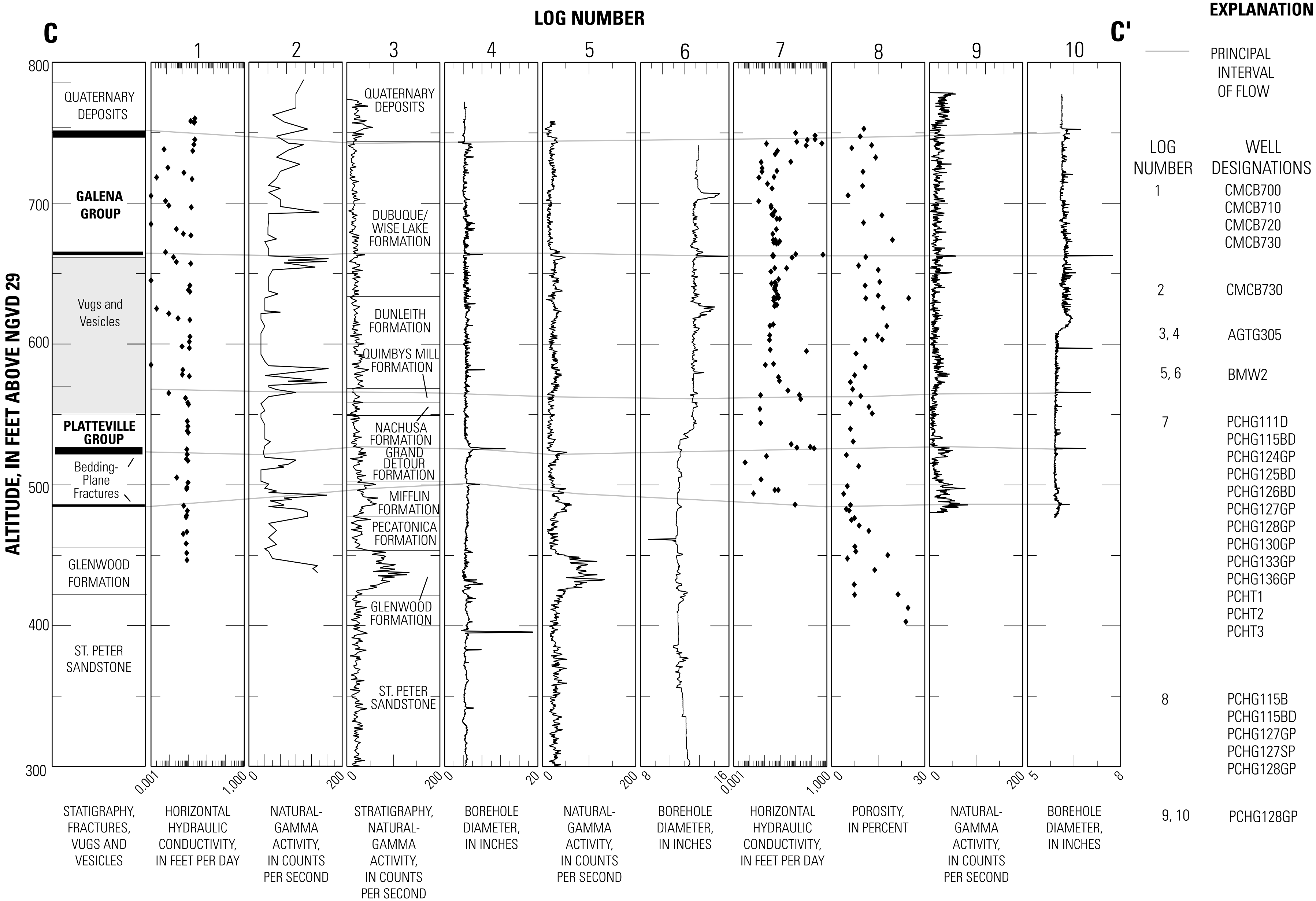


Figure 35. Hydrogeologic section C-C′ through Belvidere, Ill., showing rock-stratigraphic units and principal intervals of ground-water flow in the Galena-Platteville aquifer (line of section and location of boreholes shown in figure 30).

Table 19. Location of potential secondary-permeability features in select boreholes identified by method of detection, Belvidere, Ill.

Borehole	Method	Altitude of secondary-permeability features (feet above National Geodetic Vertical Datum of 1929)
G127GP	Lithologic logging	None identified.
	Cores	None identified.
	Borehole-camera logs	None identified.
	Caliper logs	525.
	Natural-gamma logs	None identified.
	Normal-resistivity logs	None identified.
	Spontaneous-potential logs	Possible features at 524 and 662.
	Single-point resistance logs	None identified.
	Neutron logs	Method not used.
	Acoustic-televiewer logs	Subhorizontal bedding-plane partings at about 495, 525, 564, 566, 660, 680, 732, and 739. Vugs at 569-606, 614, 624-654, 674-709.
	Borehole ground-penetrating radar	Reflectors interpreted above and below borehole. Numerous fractures, bedding-plane partings, and possible cavities identified.
T1	Lithologic logging	About 709.
	Cores	Method not used.
	Borehole-camera logs	Method not used.
	Caliper logs	700-709.
	Natural-gamma logs	None identified.
	Normal-resistivity logs	None identified.
	Spontaneous-potential logs	None identified.
	Single-point resistance logs	Method not used.
	Neutron logs	Low porosity at 569-594 and 699-734, elevated porosity at 599-624, 664-699.
	Acoustic-televiewer logs	Subhorizontal bedding-plane partings at about 601, 629, 651, 662 . Inclined fracture at about 699-709. Vugs from 569 to 709.
	Borehole ground-penetrating radar	Reflectors interpreted above and below borehole. Reflectors identified at about 574, 577, 631, 632, 640, 641, 658, 664, 729 and 753. Higher porosity at 605-615, 667, and 681-693.
T6	Lithologic logging	742.
	Cores	Method not used.
	Borehole-camera logs	Method not used.
	Caliper logs	745.
	Natural-gamma logs	None identified.
	Normal-resistivity logs	None identified.
	Spontaneous-potential logs	None identified.
	Single-point resistance logs	Method not used.
	Neutron logs	Locally elevated porosity at about 599, 610-620, 659-674, 684-709, 714-722, and 744.
	Acoustic-televiewer logs	Subhorizontal bedding-plane partings at about 662, 734, and 744 . Inclined fracture from about 614 to 624 . Vugs at 631-640 and 654-602.
	Borehole ground-penetrating radar	Several reflectors intercept above and below well. Reflectors identified at about 627, 627, 650, 657, 664, 676, and 687. See table 4. Higher porosity at about 605-615, 667, and 681-693.
G124GP	Lithologic logging	None identified.
	Cores	Method not used.
	Borehole-camera logs	Method not used.
	Caliper logs	None identified.
	Natural-gamma logs	None identified.
	Normal-resistivity logs	None identified.
	Spontaneous-potential logs	Method not used.
	Single-point resistance logs	Method not used.
	Neutron logs	Method not used.
	Acoustic-televiewer logs	Subhorizontal bedding-plane partings at about 495, 525, 564, 660, 682 and 739. Vugs at 569-606, 614, 624-654, 674-709.
	Borehole ground-penetrating radar	Method not used.

Table 19. Location of potential secondary-permeability features in select boreholes identified by method of detection, Belvidere, Ill.--Continued.

Borehole	Method	Altitude of secondary-permeability features (feet above National Geodetic Vertical Datum of 1929)
G128GP	Lithologic logging	None identified.
	Cores	Possible fracture at about 530.
	Borehole-camera logs	Fractures at 525 and 660 , possibly at 485.
	Caliper logs	525, 563, 595, 660.
	Natural-gamma logs	None identified.
	Normal-resistivity logs	None identified.
	Spontaneous-potential logs	Possible fractures at about 500 and 525.
	Single-point resistance logs	Possible fractures at 525, 565, 649, and 660.
	Neutron logs	Possible fractures at 502, 525, 597, 646, and 732. Generally elevated porosity at 590-700.
	Acoustic-televiewer logs	Subhorizontal bedding-plane partings at about 481, 492, 525, 534, 562, 579, 643, 645, 660, 682, 707, 742, and 744. Vugs at 502-512, 525-530, 542-562, 572-602, 617-740.
	Borehole ground-penetrating radar	Method not used.

for example) appears to be related to the moderate-to-large amount of change in these properties within the aquifer, which made these features easier to identify. For example, temperature changes of about 2.0^{o} C typically were observed. The moderate-to-large changes in fluid properties likely resulted from the combination of the large aquifer thickness (greater than 250 ft), the presence of discrete permeable features that partly were separated hydraulically by less permeable rock, and the active flow through the aquifer that was enhanced by pumping from the municipal wells.

Data collected during single-hole flowmeter logging under both ambient and pumping conditions provided substantial information on the location, and in conjunction with acoustic-televiewer data, the type of permeable features in individual boreholes open to the Galena-Platteville aquifer in the Belvidere area (tables 17, 20). These logs also provided some insight into the vertical-hydraulic gradient within the aquifer. Comparison of single-hole flowmeter data between boreholes also provided information about the lateral extent of many of these features. Flowmeter logging under ambient and pumping conditions did not yield appreciably different interpretations, presumably because of the high vertical-hydraulic gradients within the aquifer. The location of permeable features identified with flowmeter logging was superior to those provided with lithologic, caliper, SP, temperature, and fluid resistivity logs, and, generally, was consistent with those identified with slug testing, water-level measurements, and GPR tomography performed in conjunction with tracer tests. The utility of these logs was limited by substantial vertical contrasts in permeability in some of the boreholes being logged as well as the relative depths of the features. For example, single-hole flowmeter logging in the T series of boreholes at the PCHSS detected inflow associated with a highly permeable fracture near the bedrock surface at about 742 FANGVD29 and outflow associated with vugs of low-to-moderate permeability near the bottom of these boreholes at about 585-645 FANGVD20. Single-hole flowmeter logging in borehole B127GP, located about 150 ft from the T series boreholes, identified inflow from fractures near the bedrock surface and the 660-ft parting, but no flow was identified in the vugs at 585-645 FANGVD29 because outflow was through the deeper, more permeable 525-ft parting in this borehole.

Data collected during cross-hole flowmeter logging also provided substantial insight into the location and type of permeable features in individual boreholes, as well as insight into the flow pathways between boreholes in the Belvidere area. In addition, cross-hole flowmeter logging allowed quantification of the hydraulic properties of these features. The permeable features identified with the cross-hole flowmeter logging generally were consistent with those identified with lithologic, caliper, and single-hole flowmeter logging, as well as water-level measurements and slug tests in test intervals isolated with a packer assembly and constant-discharge aquifer tests and tracer tests done in conjunction with cross-borehole GPR. Areas of hydraulic interconnection identified with the cross-hole flowmeter logging showed good agreement with areas of hydraulic connection identified during constant-discharge aquifer testing and tracer testing. Estimates of the hydraulic properties of the permeable intervals obtained from the cross-hole flowmeter logging showed variable agreement with estimates based on aquifer tests. Where differences were observed, the differences are partly because of differences in the volume of aquifer tested with the different methods.

Slug-test data provided substantial information on the location of permeable features and comparatively low-permeability parts of the aquifer (tables 17, 20). Slug tests also allow quantification of the Kh of individual features within the aquifer, as well as assessment of the distribution Kh at borehole locations, between stratigraphic units, and across the Belvidere area. Slug

Table 20. Location of permeable features in select boreholes identified by method of investigation, Belvidere, Ill.

Borehole	Method	Altitude of permeable features (feet above National Geodetic Vertical Datum of 1929)
G127GP	Lithologic logging	No specific features identified, but borehole produces moderate amounts of water.
	Water-level measurement	Fracture at 522 identified by continuous monitoring.
	Spontaneous-potential logs	Fractures at 522 and 659, possible fractures and vugs from 659 to 744.
	Fluid-resistivity logs	Method not used.
	Single-point resistance logs	None identified.
	Normal-resistivity logs	None identified.
	Temperature logs	Fracture at 522 , possible vugs above 702.
	Ambient flowmeter logs	Fracture at 522 , possible bedding-plane parting at 662 and vugs at 744.
	Pumping flowmeter logs	Method not used.
	Cross-hole flowmeter logs	Method not used.
	Slug tests	No interval had a horizontal hydraulic conductivity greater than 1.0 foot per day.
	Specific-capacity tests	Method not used.
	Multiple-well, constant-discharge tests	Orientation of inclined fractures may change with depth.
	Tracer tests	Method not used.
	Water quality	Fractures at 482 and 522 , possible vugs and bedding-plane partings above 682.
T1	Lithologic logging	Fracture at about 709.
	Water-level measurement	Fracture at about 709.
	Spontaneous-potential logs	Method not used.
	Fluid-resistivity logs	Method not used.
	Single-point resistance logs	None identified.
	Normal-resistivity logs	None identified.
	Temperature logs	Method not used.
	Ambient flowmeter logs	Vugs at 602-642. Inclined fracture at 699-709.
	Pumping flowmeter logs	Method not used.
	Cross-hole flowmeter logs	Vugs at 602-642 and 682-692. Inclined fracture at 699-709. Hydraulic properties of each of these features were estimated.
	Slug tests	Inclined fracture at 699-709.
	Specific-capacity tests	Method not used.
	Multiple-well, constant-discharge tests	Inclined fracture has low transmissivity but is hydraulically interconnected with overlying and underlying permeable intervals. Vuggy interval at 618-638 hydraulically interconnected with overlying and underlying permeable intervals.
	Tracer tests	Vuggy interval at 618-638. Inclined fracture at 699-709.
	Water quality	None identified.
T6	Lithologic logging	Subhorizontal fracture at 742.
	Water-level measurement	Subhorizontal fracture at 742. Continuous monitoring indicates network of vertically interconnected features above 524.
	Spontaneous-potential logs	Method not used.
	Fluid-resistivity logs	Method not used.
	Single-point resistance logs	None identified.
	Normal resistivity logs	None identified.
	Temperature logs	Method not used.
	Ambient flowmeter logs	Vugs at 589-647 and 682-692, subhorizontal fracture at 742.
	Pumping flowmeter logs	Method not used.
	Cross-hole flowmeter logs	Vugs at 602-642 and 682-692. Subhorizontal fracture at about 742 . Hydraulic properties of each of these features were estimated.
	Specific-capacity tests	Method not used.
	Slug tests	Subhorizontal fracture at about 742.
	Multiple-well, constant-discharge tests	Subhorizontal fracture at about 742 is highly permeable and hydraulically interconnected to overlying unconsolidated aquifer.
	Tracer tests	Vuggy interval at 618-638 , hydraulic interconnection with overlying and underlying permeable units.
	Water quality	None identified.
G124GP	Lithologic logging	No specific features identified, but borehole produces moderate amounts of water.
	Water-level measurement	Vertical hydraulic conductivity higher above 662 than below 662. Fracture at about 524 identified by continuous monitoring.
	Spontaneous-potential logs	Method not used.
	Fluid-resistivity logs	Fracture at 563 and fracture or vugs at 728.

Table 20. Location of permeable features in select boreholes identified by method of investigation, Belvidere, Ill..--Continued.

Borehole	Method	Altitude of permeable features (feet above National Geodetic Vertical Datum of 1929)
G124GP (continued)	Single-point resistance logs	Method not used.
	Normal-resistivity logs	None identified.
	Temperature logs	Fractures at about 524 and 563, fracture or vugs at 728.
	Ambient flowmeter logs	Fracture at about 524 and 564, vugs above 662.
	Pumping flowmeter logs	Fracture at about 524 and 564, vugs above 662.
	Cross-hole flowmeter logs	Method not used.
	Slug tests	Fractures at about 524 and 563.
	Specific-capacity tests	Method not used.
	Multiple-well, constant-discharge tests	Method not used.
	Tracer tests	Method not used.
	Water quality	None identified.
G128GPD	Lithologic logging	No specific features identified, but borehole produces moderate amounts of water.
	Water-level measurement	Water movement associated with fracture at 485.
	Spontaneous-potential logs	Fracture at about 524 identified by continuous monitoring.
	Fluid-resistivity logs	Possibly fractures at about 500 and 524.
	Single-point resistance logs	None identified.
	Normal-resistivity logs	None identified.
	Temperature logs	Fractures at about 525, 565, and 750.
	Ambient flowmeter logs	Fractures at about 483, 565, and 750.
	Pumping flowmeter logs	Fractures or bedding-plane partings at 485, 524, 662 and 750.
	Cross-hole flowmeter logs	Method not used.
	Slug tests	Method not used.
	Specific-capacity tests	Fractures or bedding-plane partings at about 483, 524, 565, 750.
	Multiple-well, constant-discharge tests	Method not used.
	Tracer tests	Method not used.
	Water quality	Method not used.

tests performed in test intervals isolated with a packer assembly showed moderate to good agreement with the location of permeable features identified with water-level measurements, lithologic logging, geophysical logging (especially flowmeter logging), constant-discharge aquifer testing, and tracer tests. Slug tests typically provided a superior characterization of the location of permeable intervals at a borehole compared to lithologic logging, single water-level measurements in test intervals isolated with a packer assembly, and most of the geophysical logs because of the ability to test specific, discrete parts of the aquifer and the use of a consistent test-interval length at this site. Slug testing typically provided an inferior characterization of the presence and distribution of permeable features in the aquifer that were not intercepted by a borehole in comparison to continuous water-level measurements, constant-discharge aquifer testing, and tracer tests because of the small amount of aquifer investigated with slug tests.

Slug tests and flowmeter logs were the two most effective methods available for the identification of permeable features, with each method having advantages and disadvantages. Slug tests that profile most or all of the aquifer by use of a packer assembly typically were superior for characterizing the location of intervals with moderate to low permeability, particularly in boreholes with low vertical-hydraulic gradients, large differences in permeability over the length of the borehole, or if the less permeable feature(s) were located between two more highly permeable features. Aquifer characterization with flowmeter logging was substantially quicker and cheaper than with slug testing. Flowmeter logging tended to characterize permeable intervals better than slug tests when more than one permeable feature (fracture or parting) was present in a packer-isolated test interval or when test intervals were long (greater than about 10 ft).

Specific-capacity information reported by drillers from residential-supply wells in the Belvidere area allowed for the quick and easy quantification of the transmissivity and Kh of the Galena-Platteville aquifer in a larger part of the Belvidere area than otherwise would have been feasible (tables 17, 20). These data are not suitable for identifying the location of secondary-permeability features and the wells used in this investigation had geographic and depth restrictions, which limited the ability to assess spatial trends in aquifer permeability with this method. Estimates of transmissivity and Kh typically were greater than those determined with aquifer tests.

Multiple-well, constant-discharge aquifer tests allowed quantification of the hydraulic properties of the Galena-Platteville aquifer over a multi-acre area and identification of directions of flow anisotropy, the presence of vertical-hydraulic connection in the aquifer, vertical trends in aquifer permeability, and the presence of heterogeneity (tables 17, 20). This information, in conjunction with water-level data, can be used to assess the average rate and direction of ground-water flow and contaminant migration. Orientations of anisotropy indicated with the aquifer test generally approximated fracture orientations indicated by quarry inspections, SAR, and borehole geophysical logging. Directions of ground-water and contaminant flow did not correlate well with orientations of anisotropy indicated by the aquifer test, presumably because flow that most affects contaminant movement was through the 525-ft bedding-plane parting and the observation wells (wells used to measure drawdown during a multiple-well aquifer test) were open to shallower (about 100 ft or less) parts of the aquifer. Interpretation of the constant-discharge aquifer tests were affected to varying degrees by pumping in nearby water-supply wells, hydraulic interaction with the glacial drift aquifer, and the small number of observation wells (three each in the upper and middle parts of the aquifer) available.

Tracer testing done in conjunction with cross-hole GPR tomography at the PCHSS identified permeable features in the Galena-Platteville aquifer and allowed calculation of the effective porosity of the vuggy interval that, otherwise, would not have been possible (tables 17, 20). The permeable features identified with the tracer tests are consistent with those identified with flowmeter logging, continuous water-level monitoring, slug tests, and constant-discharge aquifer tests. The effective porosity of the test interval estimated from this test is substantially lower than the mean effective porosity measured from core samples. The difference in the calculated porosity may result because of the differences in the features (vugs, small fractures) through which water is flowing at the different scales of investigation (inches for the cores and tens of feet for the tracer test).

Ground-water-flow modeling provided useful verification of the conceptualized flow system underlying the Belvidere area, including bulk-hydraulic properties of aquifers, regional directions of flow, and discharge locations. Data gaps also were identified with model simulation. Model simulation provided virtually no information on site-scale flow conditions or distribution of hydraulic properties of specific aquifers.

The location of contaminants and other water-quality constituents in the Belvidere area, and especially in the vicinity of the PCHSS, provided some insight into the ground-water-flow pathways and directions within the Galena-Platteville aquifer (tables 17, 20). Interpretations made from analysis of the water-quality data indicated flow from the PCHSS, and perhaps other sites in the area, primarily toward the southeast to the Kishwaukee River, with flow components toward the east, west, and north in response to pumping from water-supply wells (Kay, 2001). VOC data also indicate flow in the deeper part of the Galena-Platteville aquifer beneath the Kishwaukee River. These interpretations confirm interpretations made from analysis of continuous water-level measurements, but would have contradicted interpretations of flow direction based on the single or periodic water-level measurements.

Concentrations of tritium, VOC's, and some inorganic constituents indicate the presence of at least moderate vertical hydraulic interconnection within the Galena-Platteville aquifer in the Belvidere area, with water less than 50 years old present throughout the aquifer (tables 17, 20). VOC distribution indicates that, in addition to flow through interconnected fractures, flow occurs through permeable parts of the aquifer matrix.

Waupun Site

The Waupun site (Smedema Farm) is located in Fond du Lac County in east-central Wisconsin (fig. 36). The Waupun site was subjected to moderate investigation with 13 investigative methods used (tables 1 and 21). The focus of the USGS and USEPA investigation was boreholes FL-800, FL-801, and FL-802 (fig. 37). Detailed analysis of the data collected at this site is presented in appendix G.

A 275-gal underground storage tank (UST) was used for gasoline storage on the Smedema Farm property of the Waupun site (fig. 37) until its removal in 1988. The same tank was used as an above-ground storage tank until 1991, when it was removed because of evidence of petroleum contamination in the domestic well on the Smedema Farm, and in a nearby private well. Both these wells were completed in the Ordovician Sinnipee Group aquifer (the Galena-Platteville aquifer using Illinois stratigraphic nomenclature).

Because of the evidence of petroleum contamination, the farm site was added to the list of Wisconsin Department of Natural Resources Underground Storage Tank sites in 1991. An investigation was performed during which benzene was detected in the Smedema Farm well and the nearby residential-supply well.

In 1995, the USGS and the USEPA began a cooperative study of the Ordovician Sinnipee Group aquifer at the Waupun site. As a part of the study, three boreholes were drilled: FL-800, FL-801 and FL-802. Borehole FL-800 was cored, the core described, and laboratory tests were conducted on selected core samples (table 22). A suite of geophysical logs was run in each borehole, including heat-pulse flowmeter. A borehole-radar survey was conducted in boreholes FL-800 and FL-802. Static water levels were measured in selected test intervals isolated with a packer assembly. The vertical distribution of Kh was determined from slug tests and multiple-well, constant-discharge aquifer tests. Water-quality analysis was conducted for common inorganic constituents, trace metals, and organic compounds.

Most of the methods applied at the Waupun site provided insight to the geology and hydrology (tables 23 and 24). The rock core recovered from FL-800 was essential for identifying the stratigraphic units that made up the Sinnipee Group at the site (table 21). The core data were useful for determining the location of fractures in the dolomite, quantifying its porosity and bulk density, and providing insight into the lithologic factors that affect the distribution of secondary-permeability features beneath the site.

In general, there is good correlation among the geophysical logs, porosity and density analyses, and core descriptions. For instance, the described shale content of the Decorah Formation (table 22) is reflected on the natural-gamma logs as a zone of higher gamma counts per second between 796 and 810 FANGVD29 (geophysical log depths appear to be about 2 ft deeper than correlative core depths). The more massive, less argillaceous Galena Dolomite and Platteville Formation have lower gamma counts per second. The shaley nature of the Decorah Formation also is reflected in lower resistance on the normal resistivity log. The higher porosity of the Decorah Formation compared to the rest of the Sinnipee Group measured from the core samples is reflected in the neutron-porosity log.

Because of the massive and uniform nature of the dolomite encountered in the test hole, the natural gamma, SP, and normal resistivity logs were of limited use in identifying secondary-permeability features in borehole FL-800. However, the caliper log shows that there are four intervals in the borehole where the diameter is greater than 6 in (table 23). Both the televiewer

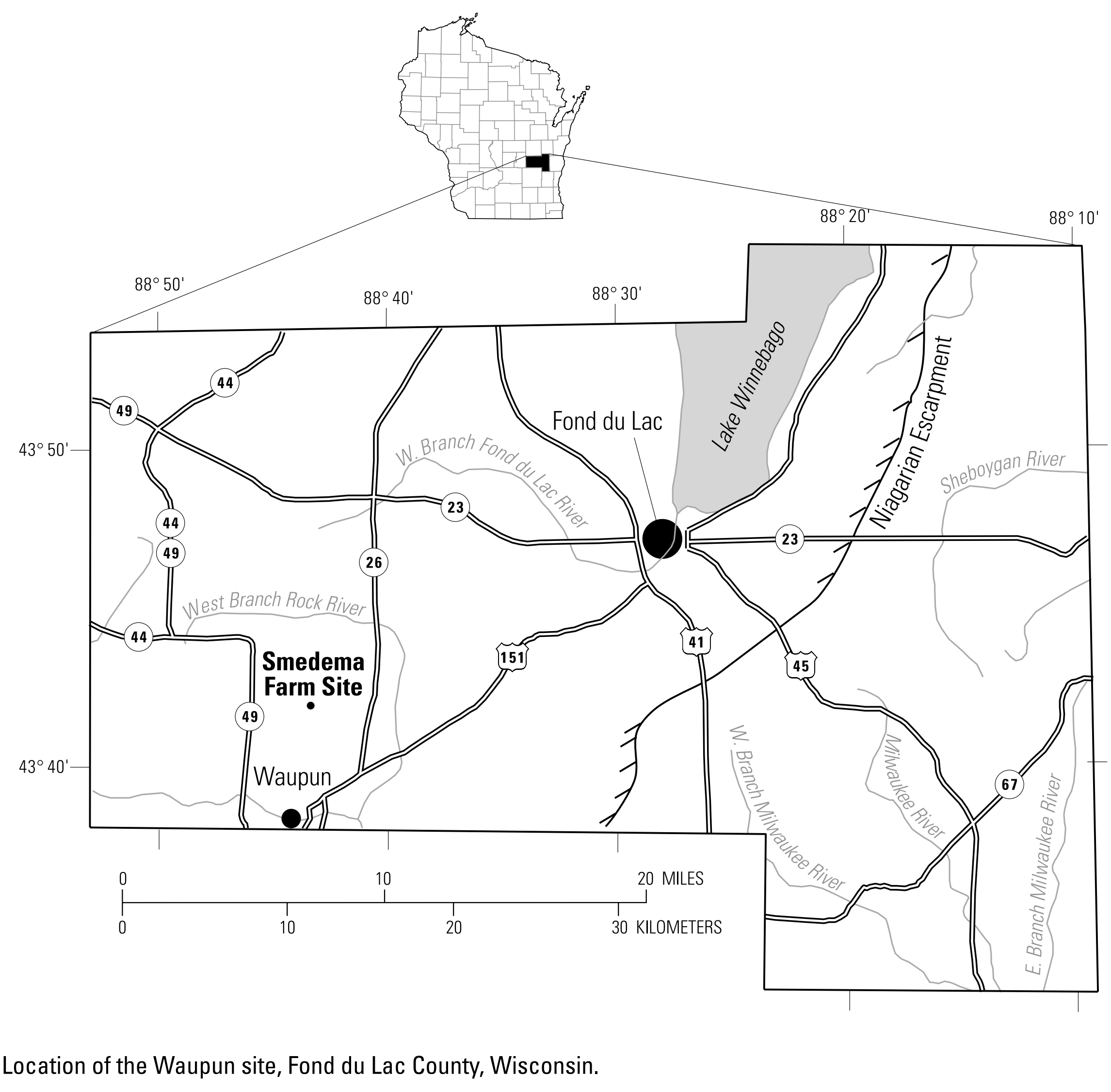


Figure 36. Location of the Waupun site, Fond du Lac County, Wisconsin.

Table 21. Summary of methods of data collection, Waupun site, Wis.

Method	Location of data collection	Uses
Previous investigations	Consultant (Natural Resource Technology) conducted site evaluation, general geologic and hydrologic study carried out by Thomas Newport.	Thickness, character, and areal extent of the water-bearing beds underlying Fond du Lac County were determined.
Cores	Borehole FL-800.	Identification of stratigraphy, lithology, quantification of primary porosity, location of potentially permeable features.
Caliper logs	Boreholes FL-800, FL-801, and FL-802.	Identification of presence and location of potential fractures and bedding-plane fractures, and intervals larger than drilled because of caving.
Natural-gamma logs	Boreholes FL-800, FL-801, and FL-802.	Characterization of site stratigraphy, identification of presence and location of potential clay-infilled fractures. In particular, the shale content of the Decorah Formation described in core is reflected in the natural-gamma log.
Normal-resistivity logs	Boreholes FL-800, FL-801, and FL-802.	Characterization of site stratigraphy.
Neutron logs	Borehole FL-800.	Identified trends in porosity.
Acoustic-televiewer logs	Boreholes FL-800, FL-801, and FL-802.	Identified location, type, and orientation of secondary-permeability features.
Borehole ground-penetrating radar	Cross-hole radar tomography conducted between boreholes FL-800 and FL-802.	Location of lithologic changes, location, and orientation of secondary-permeability features.
Water levels using packers	Boreholes FL-800, FL-801, and FL-802.	Determined vertical gradients, indicated distribution of permeability.
Fluid-resistivity logs	Boreholes FL-800, FL-801, and FL-802.	Measured fluid resistivity, identified location of some permeable features.
Flowmeter logs	Boreholes FL-800, FL-801, and FL-802.	Identified location of permeable features and pathways of hydraulic interconnection between wells, confirmed flow direction driven by vertical gradients.
Slug tests	Boreholes FL-800, FL-801, and FL-803.	Quantification of horizontal hydraulic conductivity, identification of permeable features, distribution of permeability.
Multiple-well, constant discharge tests	Boreholes FL-800, FL-801, and FL-802	Quantification of hydraulic properties of aquifer, identification of ground-water-flow pathways, identification of presence of heterogeneity and anisotropy.
Contaminant location	Borehole FL-800.	Suggested low concentration of petroleum contaminants and/or conclusion of consultant that natural attenuation of petroleum contaminants was occurring.

image and description of the rock core indicate that these intervals are the result of bedding-plane partings, at least one of which is related to lithologic variations. Heat-pulse flowmeter logging indicates that three of the four partings are permeable (table 24).

Analysis of the borehole GPR data supports the interpretation of lithology from the core and geophysical logs. The single-hole directional reflection survey in FL-800 indicates that a group of reflectors at the site have strikes from magnetic north of 40 degrees to 60 degrees, with a conjugate set at 130 to 150 degrees. Cross-hole GPR surveys indicate the presence of high-porosity, electrically conductive rocks coincident with the shaley Decorah Formation.

Water-level measurements taken from zones isolated by packers provided an estimate of the vertical gradient between adjacent intervals and across the entire borehole (tables 21 and 24). Vertical gradients were found to be almost all downward.

Fluid-resistivity logs identified permeable intervals in each borehole (table 24). However, these logs did not identify permeable intervals detected by flowmeter logging, were imprecise in the identification of the exact depth of the permeable features that were identified, and the log response typically was so small that the many of the identified features could have been overlooked easily without confirming analyses.

Flowmeter logging was the most useful method for identifying the location of the permeable features in the aquifer. In combination with the caliper and acoustic-televiewer logs, flowmeter logging enabled identification of the specific permeable feature. The flowmeter has the added capacity to permit estimation of the relative permeability of each permeable feature in the borehole.

Slug tests quantified the Kh of the aquifer in the test intervals. Results of the slug testing confirmed the location of the permeable intervals identified with the flowmeter logging (table 24).

The cross-borehole aquifer tests were useful in determining that the permeable bedding-plane parting at about 870 FANGVD29 is more permeable that the bedding-plane parting at about 810 FANGVD29. This work confirms the interpretation of the heat-pulse flowmeter, which identified the bedding-plane parting at about 870 FANGVD29 as being the most permeable feature intercepted by the boreholes. The cross-borehole data indicate that the permeability of each bedding-plane parting varies between the boreholes and that the bedding-plane partings are isotropic.

Water-quality data were of no value to the charac-

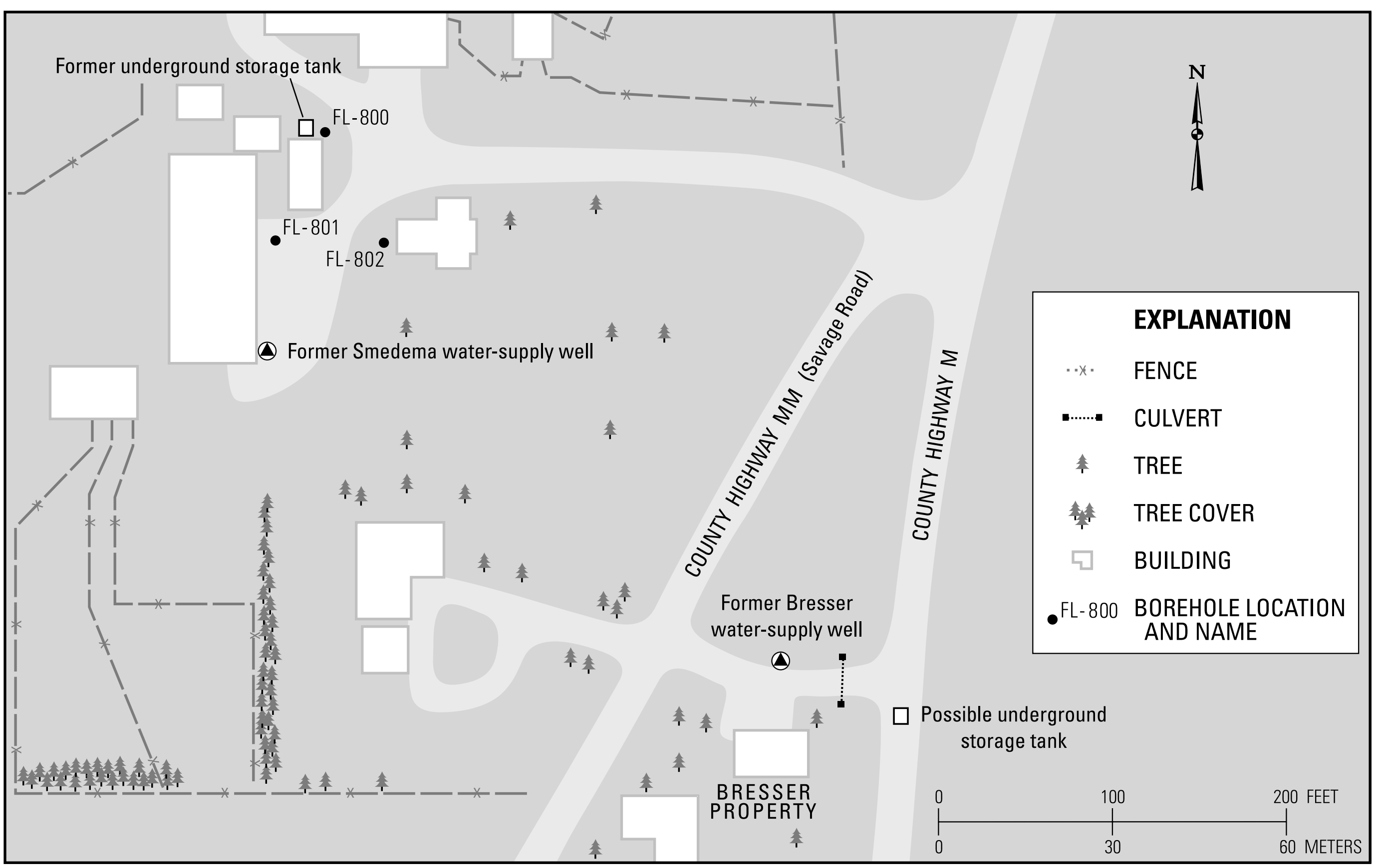


Figure 37. Location of gasoline storage tank and boreholes at the Waupun site, Wis.

Table 22. Abbreviated lithologic description and stratigraphic interpretation of core and drill cuttings from borehole FL-800 at the Waupun Site, Fond du Lac County, Wis. (Modified from Michael L. Sargent and Zakaria Lasemi, Illinois State Geological Survey, written commun., 1997).

[NGVD of 1929, National Geodetic Vertical Datum of 1929; ft, feet; %, percent]

Altitude, in feet above NGVD of 1929	Stratigraphic and lithologic description of core and drill cuttings
950.0 – 930.5	Undifferentiated glacial deposits and soil, not described.
930.5 – 827.8	Galena Dolomite – Wise Lake and Dunleith Dolomite Members; mostly pinkish gray to yellowish gray, from pinkish at the base (827.8) they progressively become very slightly more gray upward to 853.85 ft. From 853.83 ft upward to 876.6 ft there are about seventeen upward-fining cycles in which the rocks generally become more argillaceous and darker gray, some cycles then terminate with a hardground that can range from medium gray to dark gray, overlying each hardground is a lighter-colored pinkish-gray to yellowish-gray purer dolomite that sometimes contains some olive-gray shale partings and shadowy gray mottling; the gray zone, which is topped by a hardground and ranges from 853.85 to 855.5 ft, could be interpreted as the upper phase of a cycle for which the underlying, purer dolomite phase extends from 850.3 to 853.85 ft; the seventeen cycles range from about 0.4 to 2.0 ft thick.
827.8 – 824.3	Galena Dolomite – Wise Lake and Dunleith Dolomite Members; nearly all pinkish gray with a little medium light gray to light gray mottling, mostly along styolites, as at 825.0 and 825.1 ft; one weak very faint hardground marked by flat gray line in calcarenite at 827.3 ft; mostly medium grained and slightly porous, the more pure beds have spongy porosity and vugs up to about 0.5 inches across, some vugginess seems to be fossil moldic; Hormatoma-like fossil mold at 827.5 ft, fracturing in the interval at 827.0 ft and 826.6 ft appears to be mechanical; cherts
824.3 – 811.9	Galena Dolomite – Wise Lake and Dunleith Dolomite Members; mostly pinkish gray to yellowish gray slightly argillaceous dolomite interbedded and interlaminated with olive gray to brownish gray paper-thin wavy-bedded shales (3-5%), several distinct beds of light gray to very light gray slightly vuggy to vuggy dark-gray specked calcarenite beds 0.5-3.0 ft thick, the less argillaceous they are the lighter their color and more vuggy they appear, these beds are medium to coarsely crystalline; most of this interval is fine- to medium-crystalline dense dolomite, some beds are medium to coarsely crystalline and porous to vuggy, these coarser beds are quite pure dolomite and generally grade upward into finer more argillaceous and shaley dolomite.
811.9 – 798.2	Decorah Formation – Spechts Ferry Shale; Dolomite and shale and intermixtures of these two dolomite ranges from light gray to medium-light gray with much darker gray very fine “salt and pepper” speckling, very light gray to white dolomitized bryzoan fossils; shales range from grayish olive green to dark greenish gray; dolomite is predominately medium-grained calcarenite. Overall the formation grades upward from a 60:40 dolomite to shale ration at the base to an least 95% dolomite at the top. Within this 13.7-ft-thick upward-increasing carbonate cycle there are several second-order cycles that begin with a relatively flat bottomed carbonate phase and grade upward into a shale mixed with dark-gray-speckled nodular-dolomite phase.
798.2 – 770.3	Platteville Formation – Quimbys Mill Member; Dolomite, virtually all light brownish gray, the upper foot is very light olive gray mottled with olive gray, burrow mottling of light gray to medium light gray is most prominent in zone from 790.0 to 795.5 ft and at the base of the unit, 770.3 to 771.5. A very prominent well-developed hardground at the top of the Platteville Formation indicates that the Decorah unconformably overlies the Platteville.
770.3 – 754.8	Platteville Formation – McGregor Member; Dolomite, 95% fine-grained dolomite that is very light pinkish gray streaked with argillaceous and shaley beds that range form light olive gray to olive gray; the several calcarenite beds, which range from ½ to 2 ft ft thick, range from medium light gray to very light gray to pinkish gray and generally show mottling and speckling of tones as dark as dark gray
754.8 – 747.2	Platteville Formation – Pecatonica Member; Dolomite, mostly very light brownish gray, in the basal foot becoming mottled on a background of light gray to yellowish gray also some medium light gray to medium dark gray mottling in the lower part above the basal foot, becomes less sharp and lighter toward the top, top foot has very little mottling except in the top one inch, which is as dark as dark gray around the edges of the 0.5-0.75 ft deep carries on the well-developed hardground at the top of the member.
747.2 – 744.0	Ancell Group - Glenwood Formation; Sandstone, light gray to very light gray “salt and pepper” near top (approximately upper 2 ft) becoming more light gray streaked on light gray toward bottom of the core. The top 2 inches of core is light gray horizontally streaked with much darker tones of grayish black to olive black , this 2-ft section also contains pebble and smaller clasts ranging from pinkish brown, many of these clasts are mantled with pyrite cement in the surrounding sandstone of by a much thinner black mantle.

Table 23. Summary of altitudes of secondary-permeability features in select boreholes by method of detection, Waupun site, Wis.

Borehole	Method	Altitude of secondary-permeability features (National Geodetic Vertical Datum of 1929)
FL-800	Cores	Potential inclined fracture at 874 ft. Numerous subhorizontal fractures and bedding-plane partings.
	Caliper logs	Potential fractures at 810, 870, 881, 890, and 913.
	Natural-gamma logs	None identified
	Normal-resistivity logs	None identified.
	Spontaneous-potential logs	None identified.
	Neutron logs	Elevated primary porosity associated with the Decorah Formation. Possible increase at about 809.
	Acoustic-televiewer logs	Inclined fractures at 888 and 910. Numerous subhorizontal features throughout borehole, including at 770, 778, 794-808, 847, 870, 871 and 894.
	Borehole ground-penetrating radar	Fourteen inclined reflectors identified from about 745 to above the borehole. Subhorizontal reflector identified at about 870. Interval of low velocity and high attenuation primarily associated with Decorah Formation.
FL-801	Cores	Method not used.
	Caliper logs	Potential inclined fractures at about 890 and 900. Numerous subhorizontal features throughout borehole, including at 771, 778, 794-808, 852-894, and 905.
	Natural-gamma logs	None identified
	Normal-resistivity logs	None identified.
	Spontaneous-potential logs	None identified.
	Neutron logs	Method not used.
	Acoustic-televiewer logs	Inclined fracture at 890.
	Borehole ground-penetrating radar	Method not used.
FL-802	Cores	Method not used.
	Caliper logs	Potential fractures at 810, 870, 881, 890, and 913.
	Natural-gamma logs	None identified
	Normal-resistivity logs	None identified.
	Spontaneous-potential logs	None identified.
	Neutron logs	Method not used.
	Acoustic-televiewer logs	Numerous subhorizontal features throughout borehole, including at about 771, 778, 794-808, 810, 847, 869, 871, 880, 891, and 908.
	Borehole ground-penetrating radar	Interval of low velocity and high attenuation primarily associated with Decorah Formation.

terization of the aquifer at the Waupun site. The lack of characterization provided with this method is because of the absence of detectable concentrations of water-quality parameters that can be used to trace water movement in the aquifer.

Better Brite Site

The Better Brite Plating facility is located in Brown County, Wisconsin, in the city of De Pere, a suburb of Green Bay (fig. 38). The Better Brite site was subjected to limited investigation, with 16 investigative methods used (table 1) in one borehole for a period of less than 1 year. The focus of the USGS and USEPA investigation was borehole BN-483. Detailed analysis of the data collected at this site is presented in appendix H.

During operation from the late 1960's until 1989, the facility consisted of a zinc-plating shop and a chrome-plating shop located about 0.5 mi apart (fig. 38). These shops compose the Better Brite Superfund site (hereafter referred to as the Better Brite site). Trace metals and organic compounds were detected in soil samples and ground water at both locations, posing a threat to the St. Peter aquifer that supplies De Pere municipal wells (Simon Hydro-Search, Inc., 1995: Batten and others, 1997).

For this investigation, borehole BN-483 was drilled through the entire thickness of the Galena Dolomite, Decorah Formation, and Platteville Formation and into the underlying sandstones of the Ancell Group (figs. 38, 39). Borehole BN-483 is about 1,500 ft northwest of the chrome-plating shop and about 1,900 ft southwest of the zinc-plating shop.

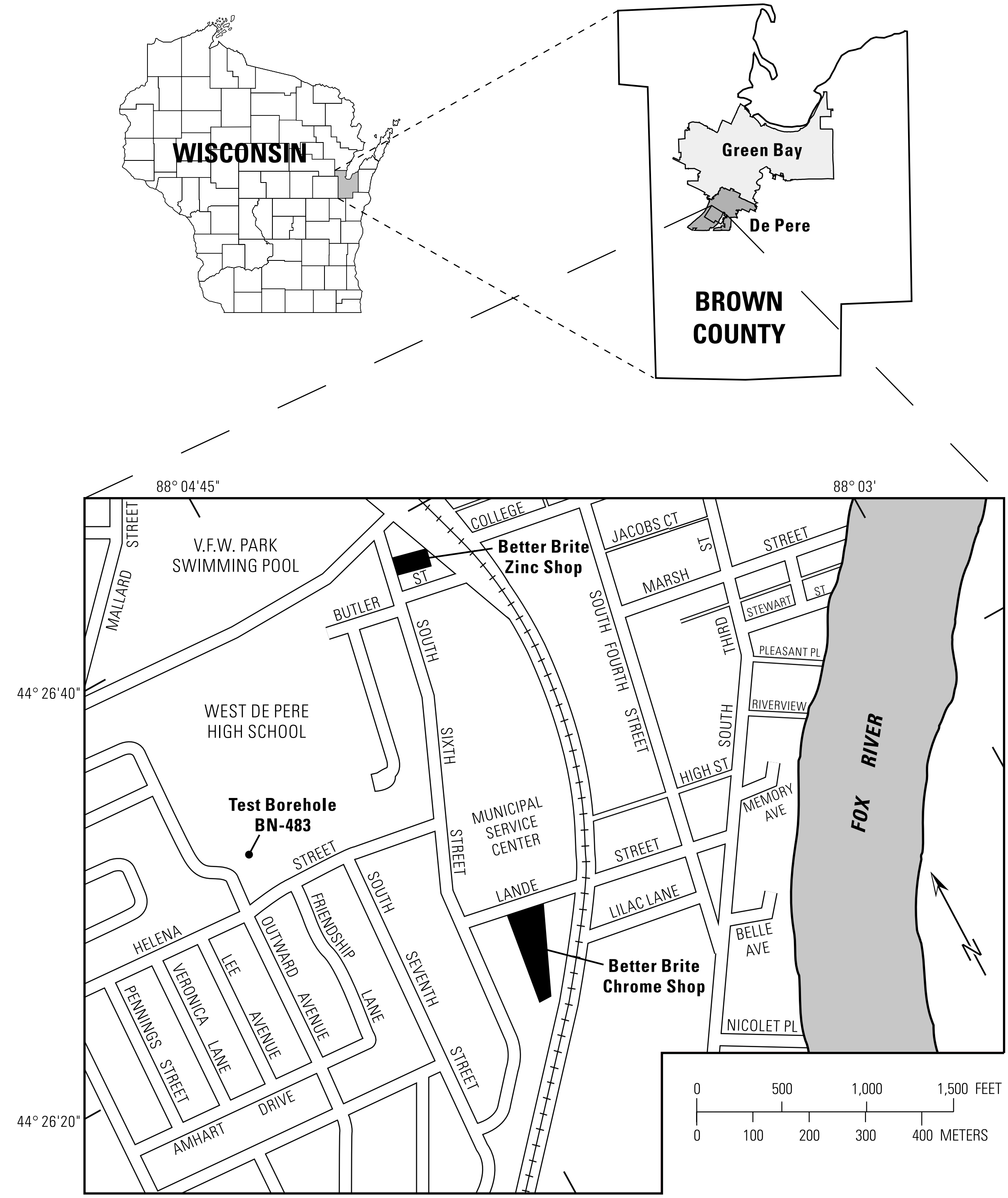
Land surface at borehole BN-483 was not surveyed, but is estimated at about 601 FANGVD29 based on topographic maps. Land surface at the chrome-plating shop is about 610-615 FANGVD29 and at the zinc-plating shop is about 600-605 FANGVD29. The altitude of the Fox River, located 1,500 to 2,000 ft east of the Better Brite shops (fig. 38), is about 590 FANGVD29. Unconsolidated deposits at the Better Brite site typically are from 25 to 30 ft thick and composed of Pleistocene-age lacustrine clay and silt (Simon Hydro-Search, Inc., 1992). The unconsolidated deposits are about 44 ft thick at borehole BN-483 and are underlain by 125 ft of unweathered Galena-Platteville dolomite (Batten and others, 1997), with very low permeability, except in the

Table 24. Summary of altitudes of permeable features in select boreholes by method of detection, Waupun site, Wis.

Borehole	Method	Altitude of permeable features (feet above National Geodetic Vertical Datum of 1929)
FL-800	Cores	None identified.
	Neutron logs	None identified.
	Water levels using packers	None identified.
	Fluid-resistivity logs	Potential features near 810-820 and 870.
	Flowmeter logs	Below 750, at about 809, 870, and 908 and near top of water column at about 915.
	Slug tests	Horizontal hydraulic conductivity greater than 1.0 feet per day associated with features at about 810, 870, 882-892, and 906. Horizontal hydraulic conductivity less than 0.75 feet per day in remaining test intervals.
	Multiple-well, constant discharge tests	Feature at 870 feet most permeable here. Feature at 810 least permeable here.
	Contaminant location	Few contaminants identified. Data could not identify permeable features.
FL-801	Cores	None identified.
	Neutron logs	None identified.
	Water levels using packers	None identified.
	Fluid-resistivity logs	Potential features at 807 and 870.
	Flowmeter logs	At about 778, 809, 869, 890, and near top of water column at about 915.
	Slug tests	Horizontal hydraulic conductivity 19 feet per day associated with feature at about 870. Horizontal hydraulic conductivity of 2.0 feet per day in test interval associated with feature at about 810.
	Multiple-well, constant discharge tests	Feature at 810 most permeable here. Feature at 870 least permeable here.
	Contaminant location	Method not used.
FL-802	Cores	None identified.
	Neutron logs	None identified.
	Water levels using packers	None identified.
	Fluid-resistivity logs	Potential features at 870.
	Flowmeter logs	Below 750, at about 778, 810, 870, 890, 908 and near top of water column at about 915.
	Slug tests	Horizontal hydraulic conductivity of 55 feet per day associated with features at about 870. Horizontal hydraulic conductivity of 0.7 feet per day in remaining test interval at 803-813.
	Multiple-well, constant discharge tests	Features at 810 and 870 feet of intermediate permeability here.
	Contaminant location	Method not used.

upper 5-10 ft of the deposit. The Kh of the Galena-Platteville aquifer in borehole BN-483 ranged from a high of 0.2 ft/d near the bedrock surface to less than 0.001 ft/d in the remainder of the aquifer. In some test intervals isolated with a packer assembly, water levels did not equilibrate after periods of 12 hours to 4 days, indicating that the Galena-Platteville deposits have a low permeability, and may be unsaturated near the bottom of the deposit. The Galena-Platteville dolomite is underlain by Ordovician-age sandstones of the Ancell Group, which include the Glenwood and St. Peter Sandstone Formations. Two monitoring wells were constructed in borehole BN-483. The monitoring wells are open at different altitudes within the Galena-Platteville dolomite to determine vertical gradients. Water-level data from the wells constructed in borehole BN-483 indicate the lower part of the Galena-Platteville aquifer may be unsaturated.

Investigation at the Better Brite site was performed in a portion of the Galena-Platteville aquifer that is much less permeable than at the other sites investigated in this report. The available slug-test and water-level data, coupled with the extremely long time (weeks) required for water levels to reach apparent hydraulic equilibrium, indicate that most of the Galena-Platteville aquifer is of low permeability beneath the Better Brite site. Low permeability indicates that there are few secondary-permeability features in the aquifer and that flow primarily is through the aquifer matrix. The large downward vertical-hydraulic gradients indicate the presence of unsaturated intervals and low vertical-hydraulic conductivity in most of the aquifer. The presence of unsaturated intervals in the aquifer may explain the discrepancy between the patterns in porosity identified with the analysis of the core samples and the neutron logs. The various geophysical logs confirmed the lithologic inter-



Base modified from Hydro-Search Inc.,
Milwaukee, WI, September, 1991.

Figure 38. Location of test borehole BN-483, and zinc and chrome shops at the Better Brite Superfund site, DePere, Wis.

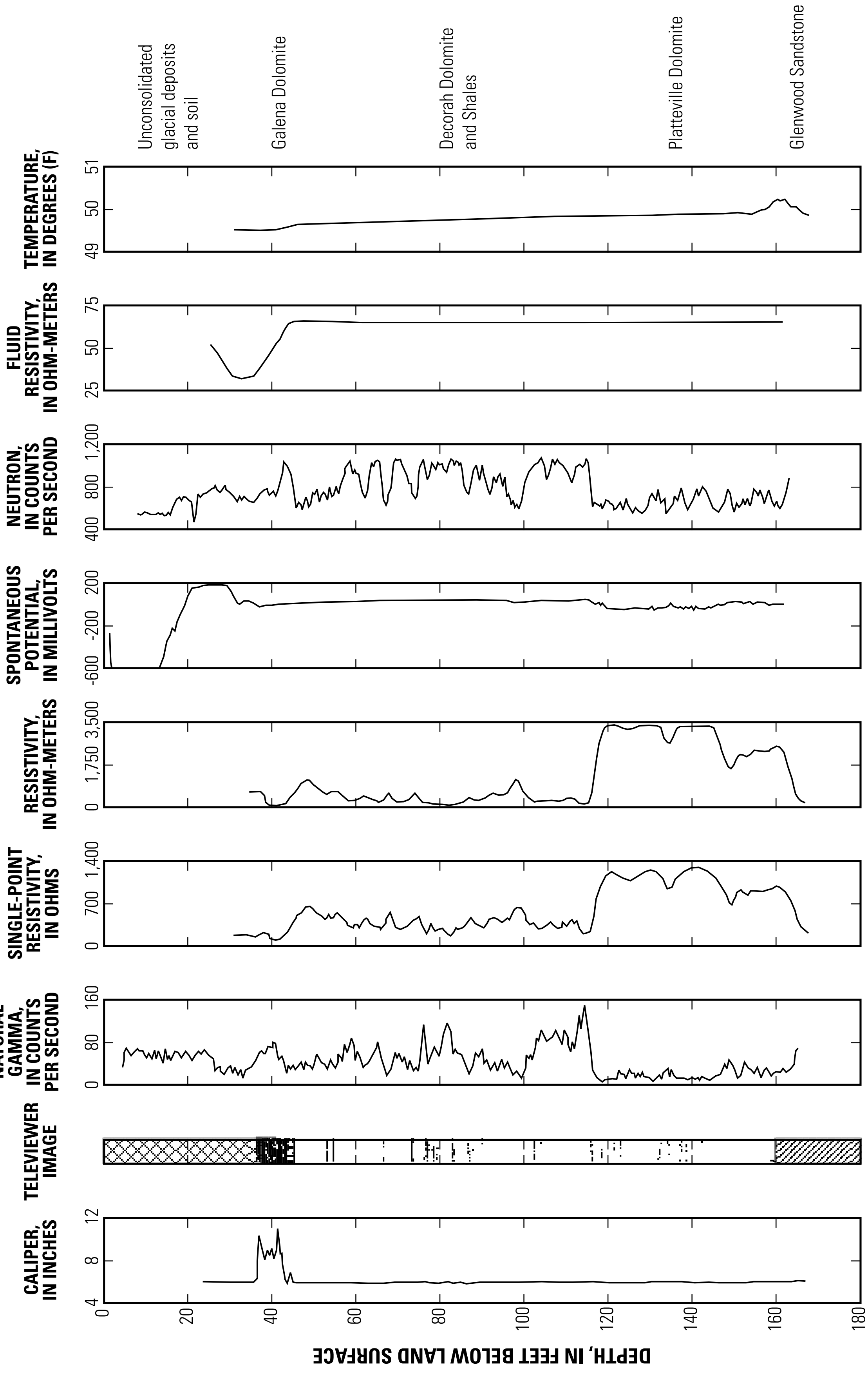


Figure 39. Geophysical logs from test borehole BN-483 at the Better Brite site, DePere, Wis.

pretations made from the rock core, but natural-gamma logs alone could not be used to determine the lithologic breaks at the formation level. The temperature and fluid-resistivity logs indicate flow from a wash out of weathered dolomite below the casing down into the St. Peter aquifer. No contribution from the lower part of the Galena-Platteville aquifer was identified, which is consistent with the results of the slug testing and water-level measurements. Water-quality data were collected only from the uppermost part of the aquifer, and did not contain contaminants. The absence of contamination likely is at least partly because borehole BN-483 hydraulically is upgradient of the potential source areas. As a consequence, water-quality data provided no insight into the presence or location of secondary-permeability features in the Galena-Platteville aquifer at the Better Brite site.

CROSS-SITE COMPARISON OF METHODS USED FOR HYDROGEOLOGIC CHARACTERIZATION AND SUGGESTIONS FOR THEIR USE

Virtually all of the methods of investigation provided some insight into the secondary-permeability network in of the Galena-Platteville aquifer, with multiple methods providing similar characterization in many instances. The amount of information that can be provided with each method is affected by the geologic and hydraulic properties of the aquifer at a given location as well as the heterogeneity of those properties. The hydrogeologic assessment improves as the amount of data available for analysis increases, as defined by the number of boreholes and wells available for investigation, the number of methods used, and the duration of data collection.

Analysis of available sources of information was useful for obtaining a preliminary assessment of the geology and hydrology at most of these sites and such analysis should be useful at all sites prior to the initiation of field activities (table 25). Of particular value in the assessment of the Galena-Platteville aquifer was obtaining information (such as lithologic logs) from database searches and reports from previous investigators, as well as analyzing topographic maps and aerial photographs.

Database searches provided geologic information such as the depth to bedrock and thickness of the aquifer at all of the sites investigated. Hydraulic information, such as depth to water, rough estimates of transmissivity, and some indication of aquifer yield also were provided at all of the sites, although these data were used most fully in the Belvidere area. Because of the interests and needs of the persons providing the information (especially drillers logs) the databases were of little value in the identification of secondary-permeability features and, occasionally, contained information errors.

Previously performed area and site-specific investigations provided geologic information such as the depth to bedrock and thickness of the aquifer at all of the sites investigated. Hydraulic information, such as depth to water, estimates of aquifer properties, and flow directions also were provided at many of the sites investigated. However, even during site-specific investigations detailed characterization of the secondary-permeabilty network in the aquifer usually was not performed, typically because of funding limitations on the investigations.

Analysis of surface topography was useful for predicting overall ground-water-flow directions at all of the sites investigated. However, some local variations in flow direction from that predicted by analysis of surface topography were present at the Byron site, the ACME/WRL site, and in parts of the Belvidere area. These variations resulted because of aquifer heterogeneity (Byron), changes in the distribution of recharge and discharge (ACME/WRL), and pumping from high-capacity wells (Belvidere).

Analysis of surface topography was useful for identifying the location of the bedrock ridges and valleys at the Byron, Tipton Farm, ACME/WRL, Southeast Rockford and Belvidere area sites, but was of no value in assessing the bedrock topography at the PCHSS in the Belvidere area, and at the Waupun and Better Brite sites. Bedrock ridges were confirmed by aquifer testing to be areas of comparatively low permeability at the ACME/WRL site, beneath part of the Byron site, and perhaps the Southeast Rockford and Tipton sites. Bedrock valleys were confirmed by aquifer testing to be areas of comparatively high permeability at these sites. Data from the Tipton Farm site were contradictory for identifying trends in aquifer permeability with bedrock topography. Data from the Belvidere area sites were insufficient for identifying trends in aquifer permeability with bedrock topography.

Analysis of surface topography also was useful for identifying the location of the fracture traces and sinkholes at the Byron site, but did not identify these features at any of the other sites. The utility of this method at the Bryon site likely resulted because these features present in the bedrock and from hundreds to thousands of feet in extent. Also, the small thickness of the overlying glacial deposits at this site did not obscure these features. Orientations of fracture traces were predictive of fracture orientations in the dolomite at the Byron site identified with other methods. Analysis of surface topography should be done at all sites prior to the initiation of field activities (table 25).

Observations made during quarry visits were useful for establishing stratigraphy and orientations of inclined

Table 25. Conclusions regarding use of methods for hydrogeologic characterization of fractured-rock aquifers.

Method	Conclusions
Previous investigations	Should be performed prior to investigations at all sites.
Database search	Should be performed prior to investigations at all sites.
Topographic maps or aerial photographs	Should be performed prior to investigations at all sites. Likely to be most effective where overburden deposits are thin and where large secondary-permeability features are present.
Quarry visits	Should be performed prior to investigations at all sites if nearby quarries are available.
Surface geophysics	Should be considered prior to drilling at sites with minor cultural interference and appropriate surficial materials (thin, nonargillaceous) if finances are available.
Lithologic logging	Collection of detailed lithologic logs, including detailed observations of water return and drilling rate should be done by a geologist using standardized descriptors at every borehole at every site.
Core analysis	Should be performed only at sites where knowing geotechnical properties or stratigraphy is important and financial resources permit.
Borehole camera	Should be performed if televiewer logging is unavailable or cost prohibitive or if features near or above the water level in the borehole are of interest. Should not be performed in boreholes with turbid water.
Natural-gamma logs	Should be performed for select boreholes for all sites with some variation in clay content. Permeable horizontal features show some tendency to associate with the top of argillaceous intervals. Deepest holes provide the most useful data.
Caliper logs	Should be performed at all sites if televiewer or borehole-camera logs are unavailable or cost prohibitive. If these methods are available, the primary utility of the caliper log is to determine if the borehole environment poses a danger for losing the televiewer or camera tools. Should be performed if features above the water level in the borehole are of interest and borehole-camera logs are not available.
Spectral gamma logs	Should be performed only at sites where clay infilling of fractures is likely (typically a karstic environment)
Acoustic-televiewer logs	Should be performed in select boreholes at all sites
Spontaneous-potential logs	Should not be performed if flowmeter or hydrophysical logs or vertical profiling of hydraulic conductivity by use of a packer is available. If these logs are unavailable, should be considered at sites with a long water column, generally low argillaceous content, and potentially large changes in water quality and hydraulic separation within the aquifer. Should not be performed for sites with a small water column, substantial argillaceous content, good vertical hydraulic interconnection, or where features of interest are expected to be present near the top of the water column.
Single-point resistance and normal-resistivity logs	Should not be performed.
Neutron logs	Should be performed only at sites where argillaceous content of rock is low and trends in matrix porosity are important, such as sites where flow is predominately through vugs. Generally not useful for fracture identification.
Density logs	Should be performed only at sites where trends in matrix porosity are important and neutron logs are not available.
Borehole ground-penetrating radar	Both single-hole reflection and cross-hole tomography should be considered at sites with available boreholes but in need of additional characterization. Should be considered at sites with and where moderate to large contrasts in rock conductivity because of vuggy intervals or moderate-to-large fractures can be expected at depths more than 5-10 feet below the well casing. Not useful for highly argillaceous deposits.
Water levels from wells (single measurement)	Should be performed at all sites pending collection of periodic data
Water levels from wells (periodic measurement)	Should be performed at all sites on a quarterly basis for a period of at least 1 year. Periodic measurements over a longer period should be considered where seasonal or longer-term variations in recharge or anthropogenic features such as pumping are substantial enough to alter flow directions.
Water levels from wells (continuous measurement)	Should be performed for sites where water levels change rapidly enough in response to precipitation (karstic environments) or pumping where frequent, short-term variations in flow are present.
Temperature logs	Should not be performed if flowmeter or hydrophysical logs or vertical profiling of hydraulic conductivity by use of a packer is available. If these logs are unavailable, this method should be considered at sites with a long water column, potentially large changes in temperature and hydraulic separation within the aquifer. Should not be performed at most sites with a small water column, good vertical hydraulic interconnection, or where features of interest are expected to be present near the top of the water column.
Fluid-resistivity logs	Should not be performed if flowmeter or hydrophysical logs or vertical profiling of hydraulic conductivity by use of a packer is available. If these logs are unavailable, should be considered at sites with a long water column, potentially large changes in fluid resistivity and hydraulic separation within the aquifer. Should not be performed at most sites with a small water column, good vertical-hydraulic interconnection, or where features of interest are expected to be present near the top of the water column.
Flowmeter logs (single well)	Should be performed at all sites not underlain by rock of uniformly low permeability. Both ambient and in-well pumping should be considered for all holes. In-well pumping should be performed for sites with low vertical-hydraulic gradients.

Table 25. Conclusions regarding use of methods for hydrogeologic characterization of fractured-rock aquifers.--Continued.

Method	Conclusions
Flowmeter logs (cross-hole pumping)	Should be performed at all sites with sufficient permeability to support pumping if financial resources permit. Both ambient and pumping profiles should be performed in all boreholes.
Hydrophysical logs	Only used at one site, so assessment was limited. However, data indicate method can be useful at sites not underlain by rock of uniformly low permeability. Utility of this method compared to flowmeter logging is expected to be specific to the data needs at the individual site.
Slug tests	Should be performed at all sites. Multiple tests should be considered in water-table wells if the height of the water column in the well varies by more than 5 feet.
Specific-capacity tests	Should be performed at all sites as part of borehole and well development. Should not be performed as a stand-alone activity unless there is a need for estimates of hydraulic properties and other aquifer tests are not feasible because of factors such as high aquifer permeability.
Multiple-well, constant-discharge tests	Should be considered if financial resources permit at all sites with permeability high enough to support pumping but not so high as to present problems with water disposal or inducing sufficient drawdown for analysis. Final decision should be based on analysis of the well network (number of wells, depth of open intervals, distance from pumped well), the degree of heterogeneity in the aquifer, and the objectives of the testing.
Tracer tests	Should be considered if financial resources permit at all sites with permeability high enough to support pumping if effective porosity is important to the investigation. Tracer testing in conjunction with borehole ground-penetrating radar logging should be considered if detailed assessment of the flow pathway is necessary and cannot be provided by flowmeter logging, slug testing, multiple-well aquifer testing, or analysis of contaminant location.
Contaminant location	Should be performed at all sites
Data collection using packers	Should be performed for vertical profiling of water levels, water quality, and horizontal hydraulic conductivity at all sites with sufficient aquifer permeability and financial resources to make data collection practical. Test interval should be 10 feet or less in most cases. Test results likely to be improved if test-interval selection is augmented by televiewer/camera and flowmeter data.

fractures at the Byron, ACME/WRL, Southeast Rockford, and Belvidere area sites, as well as indicating the potential for lithologic controls on permeability at the Byron site and in the Belvidere area. Stratigraphy and lithologic control on permeability was confirmed by other methods at the Byron site and in the Belvidere area (as well as at the Waupun site). The utility of a quarry visit was improved by the proximity of the quarry to the site and the amount of rock exposed. Quarry visits should be done prior to the initiation of field activities if acceptable quarries and outcrops are available (table 25).

Surface-geophysical methods were of some use. Surface GPR did not provide useful information at the Byron site because the high clay content of the unconsolidated deposits prevented penetration of the GPR signal to the bedrock. SAR did not provide useful information at the Byron site probably because of cultural interference from power lines and perhaps because the high clay content of the unconsolidated deposits prevented penetration of the signal to the bedrock. SAR investigations resulted in the identification of inclined-fracture orientations in the Galena-Platteville dolomite in the Belvidere area, which showed variable agreement with those identified with other methods, including televiewer logging and constant-discharge aquifer testing. SAR investigations resulted in the identification of porosity values in the Galena-Platteville dolomite at the PCHSS in the Belvidere area, which were consistent with those identified with core analysis. Potentially permeable features identified with SAR surveys performed by other investigators at the Tipton Farm site were not verified as being present by drilling. SAR surveys should be considered prior to the initiation of drilling activities if other sources of information on fracture orientation (such as quarries and fracture traces) are not available, if fracture orientation is thought to have an important effect on flow direction, and if cultural interference can be avoided.

Lithologic logs provided the foundation for the geologic interpretation and allowed identification of depths of some permeable features in the Galena-Platteville aquifer at the Byron, ACME/WRL, Southeast Rockford, and Belvidere area sites. Lithologic logging also allowed identification of generalized areas of more competent and less competent rock at the Byron site. Many of these interpretations subsequently were confirmed with other methods. Lithologic logs were more useful for identifying secondary-permeability features at the Byron site because of the large number of boreholes drilled, the large variability in the competence of the rock across the site, and the small thickness of the aquifer in comparison to the other sites. Lithologic logs were more useful for identifying secondary-permeability features in the shallower parts of the aquifer in the Belvidere area (and perhaps the Southeast Rockford site) than in the deeper part of the aquifer because of the difficulty in identifying the comparatively small changes in drilling speed and volume of water returned from the deeper parts of the aquifer at these sites. Lithologic logs from boreholes drilled using a pneumatic hammer at the ACME/WRL site were more useful in identifying secondary-permeability features than logs obtained from drilling with a tricone roller bit because of the more dramatic contrasts in drilling rate and volume of water returned from the borehole when secondary-permeability features are encountered using the pneumatic hammer. Detailed lithologic logs are an essential part of any investigation and should be made for all boreholes drilled at any site (table 25).

Core analysis provided the foundation for site stratigraphy at the Byron, Tipton Farm, ACME/WRL, Belvidere area, Waupun, and Better Brite sites. Stratigraphic interpretation appeared to be most certain at the Byron, Tipton Farm, and Waupun sites, but less uncertain or contradictory at the ACME/WRL, Belvidere area, and Better Brite sites, where differentiating stratigraphic units usually was difficult and interpretations varied between investigators. The uncertainty associated with the stratigraphic interpretation arises primarily from the lack of weathering features in the cores, which are the clearest means of differentiating the Galena-Platteville deposits in outcrop. This uncertainty particularly is great for the younger formations in the Galena Group, which tend to be more homogeneous with smaller contrasts in clay content and bedding features than the formations in the Platteville Group.

Core samples also were used to determine the primary porosity of the Galena-Platteville dolomite at the Byron, Tipton Farm, Belvidere area, Waupun, and Better Brite sites. These measurements provided an upper limit for effective porosity and enabled analysis of variations in porosity with stratigraphic unit.

Core analysis combined with other methods provided insight into the lithologic and stratigraphic factors that affect the distribution of vugs and subhorizontal bedding-plane partings in the Galena-Platteville dolomite, particularly at the Byron, Belvidere area, and Waupun sites. Insight gained from core analysis of the effect of lithology and stratigraphy on the distribution of secondary-permeability features improved assessment of the location of secondary-permeability features in the aquifer, as well as the pathways of ground-water flow and contaminant migration. However, at least partly because of mechanical breakage, core loss, and the vertical orientation of most of the cores, core analysis alone usually did not identify fractures or solution openings in the dolomite. Core analysis also did not clearly identify permeable features at any of the sites investigated. In addition, lithologic features, such as variation in the clay content of the dolomite and the presence of argillaceous layers, appear to have a greater effect on the location of the permeable features in the Galena-Platteville aquifer than do stratigraphic features such as unconformities. Core analysis was not considered an essential component of the characterization of the Galena-Platteville aquifer during these site investigations (table 25).

Three-arm caliper logging identified the presence and location of secondary-permeability features in the Galena-Platteville deposits, as well as the location of more competent rock at each of the sites. Many of these features subsequently were determined to be permeable. Caliper logs also identified the presence of a wash out below the surface casing at the Better Brite site. Caliper logs refined interpretations about the location of secondary-permeability features identified with the lithologic logs and identified the location of various secondary-permeability features not identified with the lithologic logging. The location of many of these features subsequently was confirmed by borehole-camera or acoustic-televiewer logging. Caliper logs were of limited value in identifying vuggy intervals and also did not identify a number of secondary-permeability features subsequently determined to be permeable. Caliper logs should be run in any application if there are concerns about the security of downhole equipment because of obstructions in the borehole or the potential for the borehole to collapse; if there is a need to know the borehole diameter or the depth of the well casing or screen; or if more comprehensive methods of identifying fractures or solution openings are not available (table 25). Caliper logs are inexpensive and easy to run compared to other methods and have some value for the identification of secondary-permeability features, particularly those with large openings (such as the solution openings at the Byron site). However, caliper logs only were of moderate value for the identification and characterization of secondary-permeability features for the sites studied during these investigations and comprehensive characterization of fractured-rock aquifers should not rely on this method as the primary means for identification of secondary-permeability features.

Borehole-camera logs provided substantial insight into the location of vugs, fractures, solution openings, and wash outs in the Galena-Platteville dolomite at the Byron, ACME/WRL, Southeast Rockford, Belvidere area, and Better Brite sites, as well as identifying areas where competent bedrock was present. In general, camera views that looked down the borehole typically provided a superior characterization of the location of fractures and solution openings than side views, whereas side views tended to be better than down views for observing vuggy intervals. Camera logs refined and expanded upon interpretations about the type and location of secondary-permeability features identified with the lithologic and caliper logs. The locations of most of these features subsequently were confirmed with acoustic-televiewer logging. Borehole-camera logs also identified areas where the water table was above the water level in the borehole at the Byron site and directly identified a permeable interval in one borehole in the Belvidere area. These interpretations subsequently were confirmed with flowmeter logging and water-level measurement using a packer assembly. The camera did not provide data in parts of boreholes at the Byron and Belvidere area sites because of high turbidity. Camera logs should be considered for the characterization of the type and location of secondary-permeability features at all sites where water clarity and borehole diameter is adequate for viewing the sides of the borehole and televiewer logs are not available (table 25). Camera logs should be considered for the characterization of the type and location of secondary-permeability features at sites where such features are located near or above the water level in the borehole.

Natural-gamma logs, in combination with the core analysis and lithologic logging, provided a comprehensive description of the stratigraphy and lithology in the Galena-Platteville deposits at each of the sites investigated, although their utility was limited by the small depth of the wells at the Tipton Farm site. This description, in combination with other geophysical and hydraulic data, provided insight into the lithologic factors that affect the location of vugs and subhorizontal fractures in the Galena-Platteville aquifer at the Byron, Belvidere area, and Waupun sites, and possibly the Southeast Rockford and ACME/WRL sites. Because of its uniformly low permeability, lithologic factors within the Galena-Platteville aquifer do not appear to affect the presence or location of secondary-permeability features at the Better Brite site.

Anomalies in the natural-gamma logs that subsequently were identified as clay-infilled fractures and solution openings with other methods, including spectral-gamma logging, were detected in a number of boreholes at the Byron site. Prominent anomalies in the natural-gamma logs that could be attributed to secondary-permeability features were not identified at any of the other sites. The presence of clay-infilled fractures and solution openings at the Byron site likely is the result of the comparatively advanced development of karstic features in the Galena-Platteville dolomite at this site providing pathways for movement of clay-sized particles from the land surface into and through the network of secondary-permeability features. Natural-gamma logging should be done to characterize lithology at any site investigated, providing variability in the argillaceous content of the rock is expected (table 25). Although natural-gamma logs alone are of minimal value for the direct identification and characterization of secondary-permeability features, comparison of natural-gamma logs with caliper and televiewer logs, as well as hydraulic data, should be done to determine the location of permeable vugs and subhorizontal bedding-plane partings at any site investigated.

Single-point-resistance, density, and normal resistivity logs provided limited insight into the geology and presence of fractures in the Galena-Platteville dolomite at every site where these methods were applied. Although each of these methods were used to identify a small number of fractures, no secondary-permeability features were identified that were not identified using other methods and these logs did not identify most of the secondary-permeability features identified with other methods. This lack of response partly results because of the variable clay content of the Galena-Platteville dolomite, which tends to obscure the response of these logs to other features that might be more readily identified if the clay content were more uniformly low. In addition, because most of the features were thin, less than an inch in size, a small signal change likely resulted in most of the logs. Most of these logs are designed to find features larger than an inch in size. These logs are not considered important to the characterization of the Galena-Platteville dolomite.

Neutron logs provided only minimal insight into the presence of fractures or solution openings at the Byron, ACME/WRL, Belvidere area, Waupun, and Better Brite sites. Neutron logs were effective in evaluating trends in primary porosity at the ACME/WRL, Belvidere area, and Waupun sites, but were less effective at the Byron and Better Brite sites. Analysis of porosity trends in boreholes at the Waupun site and in the Belvidere area showed a good agreement with porosity trends identified from analysis of core samples. Thorough analysis of porosity trends in the borehole at the Better Brite site showed poor-to-moderate correlation with porosity trends identified from analysis of core samples. The primary reason for the lack of response of the neutron logs to the fractures appears to be a lack of sufficient water in the fractures to be clearly distinguishable from the water in the aquifer matrix or areas of increased borehole diameter. The variable clay content in the Galena-Platteville deposits appears to be obscuring the relation between the neutron log and the aquifer porosity at the Byron site. The possible presence of unsaturated zones in parts of the Galena-Platteville deposits at the Better Brite site also may be obscuring the relation between porosity and the neutron log. Neutron logging should be considered for determination of trends in primary porosity at sites with low argillaceous content of the rock, but this logging probably should not be done to identify fractures and solution openings (table 25).

Acoustic-televiewer logs identified the largest number of secondary-permeability features in the Galena-Platteville dolomite at each site where the method was used, as well as permitting identification of the type (vugs, fractures, solution openings) and orientation of these features. Acoustic-televiewer and borehole-camera logs were the only methods with the capacity of unambiguously identifying the type of secondary-permeability feature. Televiewer logging was the only method used in these investigations with the capacity of determining the orientation of non-horizontal secondary-permeability features. Televiewer logging confirmed the location of many of the secondary-permeability features in the Galena-Platteville dolomite identified with other methods, identified the type of most of these features, and identified a number of features, such as small subhorizontal bedding-plane partings and vuggy intervals that frequently were not identified with other methods. Televiewer logging should be done at all sites where there is a need to thoroughly characterize the secondary-permeability network (table 25). However, this method may be of limited or no use if there is a need to characterize features near or above the water level in the borehole, such as parts of the Waupun and Byron sites.

Single-hole GPR surveys appear to have identified lithologic and secondary-permeability features in the Galena-Platteville dolomite tens of feet beyond the boreholes at each site where the method was applied. Borehole GPR is the only method used for this investigation that allowed direct identification of lithologic and secondary-permeability features not intercepted by the borehole. However, some features identified with single-hole GPR surveys were not identified with other methods and some important secondary-permeability features identified with televiewer logging were not identified in some of the GPR surveys. The depth and orientation of a number of features identified with the GPR logs typically did not correlate with their depth and orientation as identified with other methods. These discrepancies were observed at every site where single-hole GPR surveys were performed and likely are related to the requirement for a large change in conductivity for a feature to be detected by the GPR (which tends to be associated with larger features), changes in fracture orientation with location the dolomite, and the termination of many of the features before they intercept the borehole. Single-hole GPR surveys are a valuable tool for the comprehensive characterization of fractured-rock aquifers, particularly at sites where the number of boreholes available for site characterization is limited and during the early stages of investigation where there is a need for information to guide the placement of additional boreholes (table 25). Careful interpretation of the data collected with these methods is required.

Cross-hole GPR surveys provided a clear picture of the location and extent of hydraulically connected, secondary-permeability features at the Byron, Belvidere area, and Waupun sites. Because of variations in the altitude of some of these features, particularly at the Byron site, the connection of some of these features would not necessarily have been identified using single-hole characterization methods. Cross-hole GPR logging identified porosity variations in the Galena-Platteville dolomite in the Belvidere area and at the Waupun site, which were consistent with porosity variations defined by neuron logging and core analysis. Cross-hole GPR logging done in conjunction with saline tracer testing at the PCHSS in the Belvidere area identified flow pathways and the effective porosity in the Galena-Platteville aquifer. Cross-hole GPR surveys are considered to be a valuable tool for more comprehensive characterization of fractured-rock aquifers and should be considered for use at all sites.

Single water-level measurements from test intervals isolated with a packer assembly provided substantial insight into the vertical directions of ground-water flow within most of the boreholes tested at the Byron, Southeast Rockford, Belvidere area, Waupun, and Better Brite sites. Assessment of vertical flow directions was complicated in some test intervals at the Byron, Southeast Rockford, and Better Brite sites by the practical difficulty of waiting an hour or more for water levels to reach hydraulic equilibrium. Assessment of vertical flow directions was complicated in various boreholes in the Belvidere area by the effects of pumping on water levels in the aquifer. Interpretations regarding flow directions were supported by the results of flowmeter logging and measurements from monitoring wells completed in the boreholes.

Single water-level measurements from test intervals isolated with a packer assembly also provided substantial insight into the distribution of vertical-hydraulic conductivity within many of the boreholes tested at the Byron, Southeast Rockford, and Belvidere area sites. Assessment of the distribution of vertical-hydraulic conductivity with this method was aided by the presence of large variations in vertical-hydraulic conductivity and water levels (frequently greater than 5 ft) within many of the boreholes at the Byron, Southeast Rockford, and Belvidere area sites, as well as by the uniform vertical-hydraulic conductivity and small (less than 0.25 ft) differences in water levels within two of the boreholes at the Byron site. Large withdrawals from water-supply wells open to a widespread, permeable fracture near the lower part of the Galena-Platteville aquifer in the Belvidere area also aided the analysis of the vertical differences in water levels at this site. In addition, the difficulties in waiting for water levels to equilibrate in most of the test intervals at the Better Brite site provides information regarding the low vertical-hydraulic conductivity of the Galena-Platteville aquifer at this site.

Single water-level measurements from test intervals isolated with a packer assembly identified the depth of permeable vugs, fractures, and solution openings in boreholes at the Byron and Belvidere area sites, and provided some indication of the depth of a permeable feature in one borehole at the Southeast Rockford site. Packer measurements did not provide insight into the depth of secondary-permeability features at many of the other boreholes at these sites. Boreholes in which this method proved successful in the identification of permeable features tended to be those where large vertical-hydraulic gradients were coupled with the presence of a single interval with a horizontal hydraulic conductivity roughly one order of magnitude or higher than the rest of the borehole. Interpretations regarding the distribution of secondary permeability in the aquifer and the location of secondary-permeability features in a borehole usually were confirmed by the results of aquifer testing and flowmeter logging. Analysis of water-level measurements to determine the presence of permeable features was not performed at the Waupun site, and could not be performed in most of the test intervals at the Better Brite site because of the low permeability of the Galena-Platteville deposits.

Single water-level measurements from test intervals isolated with a packer assembly provided important insight into ground-water-flow directions and the location and distribution of secondary-permeability features (or lack thereof) in the Galena-Platteville aquifer. Collection of water levels from the open borehole and the zones above, within, and below the test interval should be done at all sites where packer testing is performed (table 25).

Single and periodic water-level measurements in monitoring wells provided substantial insight into the horizontal and vertical directions of ground-water flow at the Byron, Tipton Farm, ACME/WRL, Southeast Rockford, Belvidere area, and Better Brite sites. A single, comprehensive set of measurements appears to have been sufficient to characterize flow directions at the Byron site and, perhaps, the Tipton Farm site. However, multiple measurements were required to characterize the range of flow directions at the ACME/WRL site and could not fully characterize flow in some parts of the Belvidere area. Because only one or two sets of measurements were available at the Southeast Rockford and Better Bite sites, the adequacy of a single measurement could not be fully evaluated. Multiple periodic measurements, though more informative than a single measurement, were inadequate to assess the range of flow directions at the Belvidere area site because of the frequent and rapid changes in flow directions induced by pumping from water-supply wells in the area. Multiple measurements were required to assess the range of flow directions at the ACME/WRL site because of the changes in flow directions induced by drought conditions and perhaps recharge from an intermittent stream in the area. Interpretations regarding the overall directions of ground-water flow from single measurements across the Byron, ACME/WRL, and Southeast Rockford sites, based on analysis of water-level data, were confirmed by ground-water-quality data collected at each site. Water-quality data at the Byron site indicate that ground-water-flow directions may not be fully represented with the water-level data because of the karstic nature of the aquifer underlying this site. Water-quality data in the Belvidere area indicate that ground-water-flow directions, based on a small number of available measurements, is not fully represented with the water-level data because pumping creates highly variable flow directions in parts of this site.

Single and periodic water-level measurements in monitoring wells provided substantial insight into the distribution of permeability within the aquifer as a whole at the Byron and ACME/WRL sites and to a lesser degree at the Tipton Farm, Belvidere area, and Better Brite sites. Analysis of vertical-hydraulic gradients in monitoring wells at the Byron, ACME/WRL, Belvidere area, and Better Brite sites (and perhaps the Tipton Farm site) allowed identification of the vertical distribution in aquifer permeability in various parts of the aquifer. Analysis of horizontal hydraulic gradients in monitoring wells at the Byron and ACME/WRL sites, and perhaps the Tipton Farm site, allowed the areal distribution in aquifer permeability to be identified. This method was not effective in identifying the areal distribution of permeability at the Southeast Rockford or Belvidere area sites. Spatial variations in the water-table altitude, vertical-hydraulic gradients, and changes in water-level altitude through time throughout the Byron site are the result of large variations in the size, number, and type of secondary-permeability features, as well as the degree of connection of these features in the karstic Galena-Platteville aquifer at this site. Analysis of the water-level data allowed the spatial distribution of vertical and horizontal permeability in the aquifer at this site to be easily identified. More subtle variations in the horizontal hydraulic gradient at the ACME/WRL site, which are the result of the less extensive, less variable secondary-permeability network (in comparison to Byron) also enabled identification of a low-permeability area within the Galena-Platteville aquifer at the site. These interpretations subsequently were confirmed by aquifer testing. Visual analysis of the water-table configuration at the Southeast Rockford site identified areas of lower and higher horizontal hydraulic gradient. However, these gradients do not show a systematic variation with the distribution of horizontal hydraulic conductivity based on the available aquifer-test data and this interpretation cannot be confirmed. Analysis of vertical and horizontal hydraulic gradients at the Tipton Farm site indicate the possibility of differences in vertical and horizontal hydraulic conductivity within the site, which has not been confirmed with other methods. The absence of water in wells open to the deeper part of the Galena-Platteville aquifer at the Better Brite site indicates that the lower part of the deposit is at least partly unsaturated and has low permeability, with few or no secondary-permeability features.

Analysis of long-term changes in flow directions within the aquifer in response to drought conditions was made possible by periodic water-level measurements in monitoring wells at the ACME/WRL site. These changes could not be attributed clearly to differences in the distribution of secondary-permeability features at the site, and, therefore, did not provide any insight into the secondary-permeability network.

Continuous water-level measurements from packer assemblies and monitoring wells provided substantial insight into the presence (or absence) of permeable features at the Belvidere area and Southeast Rockford sites. Continuous water-level measurements at the Southeast Rockford site showed no response to pumping in nearby municipal-supply wells, indicating that the base of the Galena-Platteville aquifer in this area is composed of unfractured dolomite with low vertical-hydraulic conductivity. Continuous water-level measurements at the Belvidere area site indicated substantial response to pumping in nearby water-supply wells. Continuous water-level measurements allowed analysis of the aquifer response to the pumping stress, which would not have been possible using a single measurement, and would have required months or years to fully characterize using periodic measurements. Analysis of the aquifer response to the pumping enabled identification of a widespread permeable fracture, as well as inferential identification of the presence of a hydraulically connected network of flow pathways capable of vertical transmission of water within the Galena-Platteville aquifer that was not observed readily using other methods.

Continuous water-level measurements from monitoring wells, in combination with climatic data, indicated areas where the secondary-permeability network was comparatively developed and undeveloped within the Byron site. These interpretations are consistent with the results obtained with the application of other metods.

Water-level measurements always should be performed to determine flow directions and potential variations in permeability distribution (table 25). However, interpretations about the distribution of permeability distribution, based on analysis of water levels, should be made with caution and verified with aquifer-test data, if possible. The measurement frequency should depend on the type of information to be drawn from the data, as well as the expected variation in water levels because of changes in climatic conditions, recharge from surface water, and pumping in the area. Collection of water-level data on a quarterly basis for a period of 1 year appears to be a reasonable minimum frequency for sites where water-level variations can be expected to be small. These data then can be evaluated for anomalies to determine if a greater measurement frequency is needed.

Temperature, SP, and fluid-resistivity logging provided only limited insight into the presence of permeable features at the Byron and Better Brite sites, but identified a larger number of permeable features at the Belvidere area and Waupun sites. Identification of permeable features usually were based on subtle changes in these logs that may not have been identified if other methods, such as flowmeter logging, did not confirm their presence. At no site did temperature, SP, and resistivity logs identify all of the permeable features identified with other methods. In addition, the depth at which permeable features were identified with these methods tended to be offset, usually by 5-10 ft, from the location of the permeable feature as identified with the flowmeter logs. Part of the reason for the lack of information provided by these logs at the Byron and Better Brite sites appears to be related to the degree of hydraulic interconnection within the aquifer. Because identification of secondary-permeability features is dependent on changes in the temperature and electrical properties of the fluid in the borehole, a lack of contrast in these properties in the borehole water minimizes the utility of the temperature, SP, and fluid-resistivity logs. An absence of change in temperature or SP and resistivity can be produced by the presence of only one permeable feature at the borehole, or a lack of change in these properties in the aquifer monitored by the borehole. At the Better Brite site, the aquifer has low permeability and poor vertical connection. With only one interval supplying water to the borehole, the water in the borehole is of uniform resistivity, SP, and temperature. Over much of the Byron site, the aquifer is less than 100 ft thick and in good vertical connection, which results in well-mixed water of uniform quality throughout the aquifer. As a consequence, there may be little contrast in fluid resistivity, SP, and temperature between the secondary-permeability features that contribute the water to the borehole. In those parts of the Byron site where the confining unit is present, hydraulic separation of the upper and lower parts of the aquifer may have produced sufficient contrast in water temperature, SP, and resistivity to be identified. In the Belvidere area, the aquifer is more than 200 ft thick with variable vertical hydraulic interconnection and enhanced vertical and horizontal movement of water through the aquifer in response to pumping from the municipal-supply wells. These factors have combined to create contrasts in the temperature, SP, and fluid resistivity in the Galena-Platteville aquifer beneath the Belvidere area, making these logs comparatively useful for the identification of permeable features in this area. Temperature, SP, and fluid-resistivity logs should be considered as a means of characterizing the presence and location of permeable features in fractured-rock aquifers only where other, more comprehensive methods, such as flowmeter logs or detailed aquifer-test data, will not be used (table 25).

Single-hole flowmeter logging, particularly in combination with acoustic-televiewer data, was the most cost-effective method of identifying the location and type of permeable features in individual boreholes open to the Galena-Platteville aquifer at every site where this method was used. This method also helped identify the effect of lithology on the location of permeable features at the Byron, Belvidere area, and Waupun sites, and perhaps at the Southeast Rockford site. The utility of the flowmeter logs was reduced in boreholes with uniformly low permeability, little or no vertical-hydraulic gradient (potentially a result of uniformly high permeability), contrasts in permeability of two orders of magnitude or more within the borehole, or variability in flow resulting from pumping and the cessation of pumping. The utility of these logs also was affected by the distribution of permeable features within the borehole. Identification of permeable features using flowmeter logging was superior to that provided by slug testing in some boreholes, especially if the logging was done in conjunction with pumping in the borehole, when more than one permeable feature is present within the interval of the packer assembly, or where the length of the packed interval is large (generally greater than 10 ft).

Single-hole flowmeter logging performed in conjunction with pumping in the tested borehole also was effective in identifying the location and relative permeability of permeable features, as well as providing some indication of the distribution of vertical-hydraulic gradients within the borehole and, in every instance, improved on the characterization provided with logging under ambient conditions alone. Estimates of relative permeability based on comparison of flow under ambient and pumping conditions at the Waupun site showed good agreement with estimates provided with aquifer testing. This method allows for identification of the permeable features in boreholes with no ambient flow because of low vertical-hydraulic gradients. Single-hole flowmeter logging under both ambient and pumping conditions should be done at all sites where there is a need to investigate fractured-rock aquifers (table 25).

Data collected during cross-hole flowmeter logging provided substantial insight into the location and type of permeable features in individual boreholes, as well as insight into the hydraulic interconnection of these features between boreholes at each of the sites where this method was used. Locations of hydraulically connected secondary-permeability features identified with the cross-hole flowmeter logging showed good agreement with areas of hydraulic interconnection identified during constant-discharge aquifer testing and tracer testing at the Byron and Belvidere sites. Cross-borehole flowmeter logging also identified small secondary-permeability features not identified with other methods, including constant-discharge aquifer tests and single-hole flowmeter logging at these sites. Estimates of hydraulic properties in the Belvidere area made from analysis of cross-hole flowmeter data showed variable agreement with estimates made from slug and constant-discharge aquifer tests. Where the two methods showed poor agreement, the discrepancy may be partly related to the volume of aquifer tested with the different methods and boundary conditions assumed for each method. This method should be used for fractured-rock aquifer characterization wherever appropriate boreholes are available and funding is sufficient.

Hydrophysical logging provided identification of permeable features consistent with those identified with the flowmeter logging at the Byron site. Also, water-quality parameters in each of the permeable intervals were quantified. Hydrophysical logging was not performed at the remaining sites, so the utility of this method under a range of hydrogeologic conditions could not be evaluated. The data available from this investigation indicate that hydrophysical logging provides comparable results to flowmeter logging and one or the other of these methods should be used at all sites. Based on study experiences, flowmeter logging was quicker and easier to perform than hydrophysical logging, whereas hydrophysical logging provides water-quality information not provided with flowmeter logging.

Slug tests performed by use of a packer assembly provided substantial insight into the location and type of permeable features within the boreholes at the Byron, Belvidere, Waupun, and Better Brite sites. The utility of these tests for identifying features at a borehole was improved substantially with acoustic-televiewer and flowmeter data, which helped refine and confirm the interpretations and provided a means of focusing the depths for data collection. Slug tests performed by use of a packer assembly at the ACME/WRL site were less successful in identifying permeable features, because these features may not have been present, because the long test intervals at this site (and at some locations at the Byron site) obscured the response of higher-permeability features that may have been present, and because other types of data that would have confirmed the results of the slug-test analysis were not available. Slug tests were not performed using the packer assembly in some test intervals at the Byron and Better Brite sites because it was impractical to wait for water levels to stabilize. Slug tests performed by use of a packer assembly provided superior aquifer characterization in comparison to flowmeter logs in boreholes with uniformly low permeability, low vertical-hydraulic gradients, and large differences in permeability within the borehole. Slug tests performed by use of a packer assembly also provided a superior characterization in boreholes where features of intermediate permeability were located between more permeable features, providing that most or all of the borehole could be tested. Slug tests with a packer assembly should be used for characterization of all fractured-rock aquifers if funding permits (table 25).

Slug tests from packer assemblies and monitoring wells also provided substantial insight into the aerial permeability distribution across the Byron, Tipton Farm, ACME/WRL, and Belvidere area sites, and allowed identification of lithologic and stratigraphic effects on the location of permeable features at the Byron, Belvidere area, and Waupun sites. Slug testing is the only method that enabled quantification of the hydraulic properties of the entire aquifer at all of the sites and always should be performed.

Specific-capacity tests allowed for quantification of aquifer transmissivity in a part of the Galena-Platteville aquifer too permeable to have been characterized cost-effectively with a long-term, multiple-well, constant-discharge aquifer test at the Byron site, and in boreholes where resources were insufficient for detailed aquifer characterization at the Southeast Rockford and Belvidere area sites. Transmissivity values calculated from the specific-capacity data were consistent with the maximum values calculated from slug testing at the Byron and Belvidere area sites, but could not be verified at the Southeast Rockford site. Specific-capacity tests should be considered in all boreholes that are pumped for development. There is less need for analysis of these data if the borehole is to be used for slug testing or multiple-well, constant-discharge aquifer testing.

Multiple-well, constant-discharge aquifer tests identified the presence and location hydraulically interconnected features in the Galena-Platteville aquifer, as well as the presence and orientation of heterogeneity and anisotropy in the aquifer at the Byron, ACME/WRL, Belvidere area, and Waupun sites. These interpretations typically were consistent with those made using a combination of other methods, including televiewer, cross-borehole GPR, flowmeter logs, and slug tests. The amount of information that could be obtained from these aquifer tests was increased by the amount of aquifer that could be tested discretely. Constant-discharge aquifer tests utilizing numerous boreholes for measurement of drawdown, where flowmeter logging also is done, or with multiple test intervals in the boreholes used for measurement of aquifer response, allowed a superior aquifer characterization in comparison to tests involving only a small number of partially or fully penetrating boreholes. Although reliable estimates of the hydraulic properties of the Galena-Platteville aquifer were obtained from some of these tests, heterogeneities in the aquifer precluded calculation of a reliable estimate of hydraulic properties from at least one test at the Byron and ACME/WRL sites. Large changes in ambient water levels in response to recharge from precipitation and offsite pumping also precluded or complicated estimation of hydraulic properties determined from some of the aquifer tests at the Byron and Belvidere area sites. Multiple-well, constant-discharge aquifer tests should be considered for all sites where there is a need to quantify the hydraulic properties of the aquifer and the aquifer likely is homogenous at the test scale (table 25).

Tracer tests allowed estimation of the effective porosity of parts of the Galena-Platteville aquifer at the Byron and Belvidere area sites and provided some idea of the presence of hydraulic interaction between the fractures and matrix. Estimates of effective porosity obtained from the tracer tests at the Byron and Belvidere sites were less than estimates of total porosity at these sites obtained from core analysis. Estimates of effective porosity obtained from the tracer tests at the Belvidere site also were less than estimates of total porosity obtained from the SAR survey and neutron logging, indicating that tracer tests should be done if there is a need to determine the effective aquifer porosity (table 25). The tracer test performed in conjunction with cross-borehole GRP at the Belvidere area site also identified flow pathways within the aquifer. However, these pathways also were identified in combination with other methods, primarily cross-borehole flowmeter logging and multiple well, constant-discharge aquifer testing. The availability of data obtained with other methods should be considered before tracer testing is done, if the sole study objective is the identification of flow pathways.

The location of contaminants and other water-quality constituents was useful in the identification of horizontal and vertical flow directions, the presence of vertical-hydraulic connection within the aquifer, and the location (or absence) of hydraulic boundaries at the Byron, ACME/WRL, Southeast Rockford, and Belvidere area sites. The lack of substantial contamination at the Tipton Farm, Waupun, and Better Brite sites precluded use of this method. Many of the interpretations about flow directions based on the distribution of contaminants were not identified readily with other methods and analysis of contaminant locations should be done at all sites as a means of characterizing the secondary-permeability network (table 25).

Contaminant location may indicate the potential for ground-water flow counter to the directions indicated by water-level measurements in parts of the Byron site. Contaminant locations at the ACME Solvent/WRL, Southeast Rockford, and Belvidere area sites indicate ground-water flow is represented adequately with water-level measurements, providing those measurements were detailed sufficiently in time and location to identify variations in water levels. The potential inadequacy of water-level measurements to depict flow directions at the Byron site appears to be related to the presence of the highly complex, secondary-permeability network underlying this site, which is a function of the well developed (in comparison to the other sites investigated) karst features at this site. Karst features at the remaining sites are not as developed (for example, Byron is the only site where solution openings and sinkholes were identified) and, therefore, the secondary-permeability network is less developed.

Contaminant location indicated the presence of low-permeability deposits in parts of the ACME/WRL site, an interpretation consistent with water-level and aquifer-test data. Contaminant location tended to confirm water-level data indicating the potential for flow toward municipal-supply wells at the Belvidere area site. Contaminant location also confirmed water-level data indicating the potential for flow beneath the Kishwaukee River at the Belvidere area site. Water-quality data tended to confirm interpretations about the elevated vertical-hydraulic connection within the upper part of the Galena-Platteville aquifer at the Belvidere area site. Contaminant locations present in deeper parts of the aquifer tended to indicate moderate to high vertical hydraulic interconnection within the Galena-Platteville aquifer at the Byron, ACME/WRL, and Southeast Rockford sites, and the Belvidere area. This interpretation is consistent with interpretations based on water-level data at much of the Byron site, at the ACME/WRL site, and in the Belvidere area, but is contrary to the interpretation of low vertical-hydraulic interconnection within the aquifer based on water-level data at the Southeast Rockford site.

SUMMARY

The characterization of ground-water flow and contaminant transport in fractured-rock aquifers is complicated by the heterogeneous and anisotropic nature of these aquifers and the inability of many investigative methods to quickly and accurately assess secondary-ermeability features under a range of hydrogeologic conditions. Investigations performed by the U.S. Geological Survey and the U.S. Environmental Protection Agency in the fractured Galena-Platteville aquifer at the Byron, Tipton Farm, ACME Solvents, Winnebago Reclamation Landfill, Southeast Rockford, Belvidere area, Waupun, and Better Brite sites in Illinois and Wisconsin indicate that there are a number of investigative methods that can be used to characterize fractured-rock aquifers. The effectiveness of these methods varies depending on the hydrogeologic conditions of the site. The completeness of the characterization improved with an increase in the amount of data available, in terms of the number of data points, the period of data collection, and the number of methods applied. The characterization also was improved by comparing the data collected with different methods.

Collection and analysis of background information, including data from governmental databases and reports of previous investigations is considered essential to obtaining a preliminary understanding of the hydrogeology and water quality in the area to be investigated. This understanding is essential to understanding the problems associated with the site and for planning an investigation.

Topographic maps and aerial photographs provided preliminary information about hydraulic conditions as well as the potential type, location, and orientation of individual faults, fractures, and sinkholes as well as the location of areas with comparatively high and low densities of secondary-permeability features at a number of the sites investigated. The utility of the maps and photos was greatest where the overburden deposits were thin and where secondary-permeability features were large.

Observations at outcrops and quarries provided information about the geology and stratigraphy at the sites, the orientation of vertical fractures, and the presence of preferential flow pathways. The utility of the data from the outcrops and quarries was reduced where only small parts of the Galena-Platteville deposits were exposed or where the outcrops were not near the site.

The high clay content of the unconsolidated deposits at the Byron site prevented penetration of the ground-penetrating radar (GPR) signal to the bedrock. Square-array resistivity identified the orientation of inclined fractures in the Belvidere area. However, these orientations showed variable agreement with those identified with other methods.

Lithologic logging provided essential hydrogeologic information wherever detailed logs were available. The characterization of fractured-rock aquifers would be improved by detailed lithologic logging performed by a competent geologist for every borehole at every site.

Core analysis provided the foundation for stratigraphy at the sites where cores were collected and also were used to provide samples for geotechnical analysis. However, stratigraphy from the cores was interpreted differently by different investigators at some sites, indicating uncertainty about the accuracy of some of the interpretations. Core analysis also provided insight into the lithologic and stratigraphic factors that affect the distribution of vugs and subhorizontal bedding-plane partings in the Galena-Platteville dolomite and improved assessment of the location of secondary-permeability features in the aquifer. However, core analysis usually did not identify fractures of solution openings in the dolomite.

Natural-gamma logging helped expand the interpretation of stratigraphy and, in combination with other data, provided insight into the lithologic factors that affect the location of secondary-permeability features at most of the sites investigated. Anomalies in the logs defined the location of clay-infilled fractures at the Byron site, which likely resulted from the development of karstic features in the Galena-Platteville dolomite at this site.

Three-arm caliper logging identified the presence and location of large secondary-permeability features in the Galena-Platteville deposits in addition to the location of more competent rock at each of the sites. However, caliper logs were of limited value in identifying vuggy intervals, and also did not identify a number of smaller secondary-permeability features subsequently determined to be permeable by flowmeter logging and slug testing. Comprehensive characterization of fractured-rock aquifers should not rely on these logs as the primary means for identification of secondary-permeability features.

Neutron logs provided minimal insight into the presence of fractures or solution openings in the Galena-Platteville aquifer. The primary reason for the lack of aquifer response to the neutron logs appears to be a lack of sufficient water in the fractures to be clearly distinguishable from the water in the aquifer matrix. Neutron logs were effective in evaluating trends in the primary porosity of the aquifer at most of the sites tested. The log was less effective at sites where a substantial portion of the aquifer had variable clay content or where variably saturated conditions were present.

Acoustic-televiewer logs identified the largest number of secondary-permeability features in the dolomite at each site where the method was used and permitted identification of the type and orientation of these features. Televiewer logging is considered the best geophysical technique for the identification of secondary-permeability features in the Galena-Platteville dolomite. However, this method was of limited use for characterizing features near or above the water level in the borehole.

Borehole-camera logs also provided substantial insight into the location of vugs, fractures, solution openings, and wash outs in the Galena-Platteville dolomite at each site where the method was used. Borehole-camera logs could be used to identify features above the water level in the borehole, but could not be used in parts of some boreholes because of high turbidity.

Single-hole GPR surveys appear to have identified lithologic and secondary-permeability features in the Galena-Platteville dolomite tens of feet beyond the boreholes at each site where the method was applied. However, some features identified with single-hole GPR surveys were not identified with other methods and some important secondary-permeability features identified with televiewer logging were not identified in some of the GPR surveys. The depth and orientation of a number of features identified with the GPR logs typically did not correlate with their depth and orientation as identified with other methods. These discrepancies likely are related to changes in fracture orientation with location the dolomite and the termination of many of the features before they intercept the borehole. Cross-hole GPR surveys provided a clear picture of the location and extent of hydraulically connected, secondary-permeability features as well as porosity variations wherever this method was used. Cross-hole GPR logging done in conjunction with tracer testing in the Belvidere area identified flow pathways and the effective porosity in the Galena-Platteville aquifer.

Single-point-resistance, density, and normal resistivity logs provided limited insight into the geology and presence of fractures in the Galena-Platteville dolomite at every site where these methods were applied. Although each of these methods identified a small number of fractures, they identified no secondary-permeability features that were not identified using other methods and they did not identify most of the secondary-permeability features identified with other methods.

Water-level measurements provided substantial insight into the vertical and horizontal directions of ground-water flow at each site as well as into the natural and anthropogenic factors that can affect the directions of flow in the aquifer. In addition, water-level measurements provided substantial insight into the horizontal and vertical distribution of aquifer permeability at some of the sites as well as identifying the depth of permeable features in some boreholes. The number of measurement periods required to (presumably) fully assess the variability of flow directions in the Galena-Platteville aquifer differed among the sites. A single, comprehensive set of measurements appears to have been sufficient to characterize flow directions at the Byron site and perhaps the Southeast Rockford, Better Brite, and Tipton Farm sites. However, multiple measurements were required to characterize the range of flow directions at the ACME/WRL site because of the effects of precipitation and drought. Continuous measurements collected over a period of weeks were required to assess the range of flow directions at the Belvidere area site because of the frequent and rapid changes in flow directions induced by pumping from water-supply wells in the area.

Temperature, spontaneous potential, and fluid-resistivity logging provided variable insight into the presence of permeable features at the different sites. At some sites, these logs identified few features, whereas at others sites, more features were identified. At no site did these logs identify all of the permeable features identified with other methods. Part of the reason for the variation in the amount of information provided by these logs appears to be related to differences in the degree of vertical-hydraulic connection within the aquifer among the sites, with these methods being of limited value at the sites where the aquifer either has low or high interconnection.

Single-hole flowmeter logging under a combination of ambient and pumping conditions, particularly in combination with acoustic-televiewer data, was the most cost-effective method of identifying the location and type of permeable features in the Galena-Platteville aquifer at every site where this method was used. The utility of the one of both types of flowmeter logs was reduced in boreholes with uniformly low permeability, little or no vertical-hydraulic gradient, or contrasts in permeability of two orders of magnitude or more within the borehole, and by the distribution of permeable features within the borehole. Single-hole flowmeter logging performed in conjunction with pumping in the tested borehole also was effective in identifying the location and relative permeability of permeable features. This logging also provided some indication of the distribution of vertical-hydraulic gradients within the borehole and, in every instance, improved the characterization provided by logging under ambient conditions alone.

Data collected during cross-hole flowmeter logging provided substantial insight into the location and type of permeable features in individual boreholes, as well as insight into the hydraulic interconnection of these features between boreholes at each of the sites where this method was used. Cross-borehole flowmeter logging also identified small secondary-permeability features not identified with other methods, including constant-discharge aquifer tests and single-hole flowmeter logging at these sites. Estimates of hydraulic properties made from analysis of cross-hole flowmeter data showed variable agreement with estimates made from aquifer-test results.

Hydrophysical logging provided identification of permeable features consistent with those identified with the flowmeter logging at the Byron site. Also, water-quality parameters in each of the permeable intervals were quantified. Hydrophysical logging was not performed at the remaining sites, so the utility of this method under a range of hydrogeologic conditions could not be evaluated.

Slug tests performed in packer assemblies and monitoring wells provided insight into the permeability distribution with location and stratigraphy of every site where a sufficient amount of data was available for analysis. Slug testing is the only method that enabled quantification of the hydraulic properties of both permeable and less-permeable features. The utility of slug tests for identifying permeable features was improved by the use of test intervals of 10 feet or less. Slug tests performed by use of a packer assembly provided superior hydrogeologic characterization in comparison to flowmeter logs in boreholes with uniformly low permeability, low vertical-hydraulic gradients, and large differences in permeability within the borehole. Slug tests performed by use of a packer assembly also provided a superior characterization in boreholes where features of intermediate permeability were located between more permeable features, providing that most or all of the borehole could be tested.

Specific-capacity tests allowed for quantification of aquifer transmissivity in highly permeable parts of the Galena-Platteville aquifer and in wells where resources were insufficient for detailed hydrogeologic characterization. Specific-capacity tests should be performed in all boreholes that are pumped for development.

Multiple-well, constant-discharge aquifer tests identified the presence and location of hydraulically interconnected features in the Galena-Platteville aquifer, as well as the presence and orientation of heterogeneity and anisotropy. The amount of information that could be obtained from these aquifer tests was increased by the amount of aquifer that could be tested discretely. However, reliable estimates of the hydraulic properties of the aquifer could not be obtained from some tests because of heterogeneities and water-level fluctuations related to factors other than pumping.

Tracer tests allowed estimation of the effective porosity of parts of the Galena-Platteville aquifer and provided information on the presence of hydraulic interaction between the fractures and matrix at the sites where these tests were done. Tracer testing performed in conjunction with cross-borehole GRP also identified flow pathways within the aquifer. However, these pathways also were identified with a combination of other methods, primarily cross-borehole flowmeter logging and multiple well, constant-discharge aquifer testing.

The location of contaminants and other water-quality constituents was useful in the identification of horizontal and vertical flow directions, the presence of vertical-hydraulic connection within the aquifer, and the location (or absence) of hydraulic boundaries at the Byron, ACME/WRL, Southeast Rockford, and Belvidere area sites. The lack of identified contaminant plumes at the Tipton Farm, Waupun, and Better Brite sites precluded use of this method. Many of the interpretations about flow directions based on the distribution of contaminants were not identified with other methods because of the effects of pumping at the in the Belvidere area and (possibly) karst hydrology at the Byron site.

REFERENCES CITED

Agnew, A.F., 1963, Geology of the Platteville quadrangle, Wisconsin: U.S. Geological Survey Bulletin 1123-E, p. 245-275.

Allingham, J.W., 1963, Geology of the Dodgeville and Mineral Point Quadrangles, Wisconsin: U.S. Geological Survey Bulletin 1123-D, p. 169-244.

Bakush, S.H., 1985, Carbonate microfacies, depositional environments and diagenesis of the Galena Group (Middle Ordovician) along the Mississippi River (Iowa, Wisconsin, Illinois and Missouri), United States: unpublished PhD Thesis, University of Illinois at Urbana-Champaign, 233 p.

Barenblatt, G.E., Zheltov, I.P., and Kochina, I.N., 1960, Basic concepts in the theory of seepage of homogeneous liquids in fissured rocks: Journal Applied Mathematical Methods (USSR), v. 24 p. 1286-1303.

Batten, W.G., and Bradbury, K.R., 1996, Regional ground-water flow system between the Wolf and Fox Rivers near Green Bay Wisconsin: U.S. Geological Survey Information Circular 75, 28 p.

Batten, W.G., Brown, T.A., Mills, P.C., and Sabin, T.J., 1997, Rock-stratigraphic nomenclature, lithology, and subcrop area of the Galena-Platteville bedrock unit in Illinois and Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 97-4054-B, 1 plate.

Berg, R.C., Kempton, J.P., and Stecyk, A.N., 1984, Geology for planning and Boone and Winnebago Counties: Illinois State Geological Survey Circular 531, 69 p.

Borman, R.G., and Trotta, L.C., 1975, Ground-water resources and geology of Jefferson County, Wisconsin: U.S. Geological Survey Information Circular 33, 31 p.

Borman, R.G., 1976, Ground-water resources and geology of Walworth County, Wisconsin: U.S. Geological Survey Information Circular 34, 44 p.

Boulton, N.S., and Streltsova-Adams, T.D., 1978, Unsteady flow to a pumped well in an unconfined fissured aquifer: Journal of Hydrology, v. 37, p. 349-363.

Brown, T.A., Dunning, C.P., and Sharpe, J.B., 2000, Altitude, depth, and thickness of the Galena-Platteville bedrock unit in the area of Illinois and Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 97-4054-C, 4 plates.

Brown, T.A., and Mills, P.C., 1995, Well-construction, hydrogeologic, and ground-water-quality data in the vicinity of Belvidere, Boone County, Illinois: U.S. Geological Survey Open-File Report 94-515, 34 p.

Bunker, B.J., Ludvigson, G.A., and Witzke, B.J., 1985, The Plum River Fault zone and Stratigraphic framework of eastern Iowa: Iowa Geological Survey Technical Information Series Number 13, 126 p.

Camp, Dresser, and McKee, Inc., 1992, Technical Memorandum for Phase I field activities, Southeast Rockford groundwater contamination project, Rockford, Illinois: Prepared for the Illinois Environmental Protection Agency, Springfield Illinois, variously paginated.

Camp, Dresser, and McKee, Inc., 1994, Remedial investigation report, Southeast Rockford groundwater contamination study: Prepared for the Illinois Environmental Protection Agency, Springfield Illinois, variously paginated.

Carlson, J.E., 1961, Geology of the Monfort and Linden quadrangles, Wisconsin: U.S. Geological Survey Bulletin 1123-B, p. 95-137.

Choi, Y.S., 1998, Sequence stratigraphy and sedimentology of the middle to upper Ordovician Ancell and Sinnipee Groups, Wisconsin: Unpublished Ph.D. Thesis, University of Wisconsin Madison, 284 p.

Cline, D.R., 1965, Geology and ground-water resources of Dane County, Wisconsin: U.S. Geological Survey Water-Supply Paper 1779-U, 64 p.

Conlon, T.D., 1997, Hydrogeology and simulation of ground-water flow in the sandstone aquifer, northeastern Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 97-4096, 60 p.

Cotter, R.D., Hutchinson, R.D., Skinner, E.L., and Wentz, D.A., 1969, Water resources of Wisconsin, Rock-Fox River Basin: U.S. Geological Survey Hydrologic Investigations Atlas HA-360, 4 p.

Dagan, G., 1986, Statistical theory of groundwater flow and transport: Pore to laboratory, laboratory to formation, and formation to regional scale: Water Resources Research, v. 22, no. 9, p. 120S-134S.

Ecology and Environment, Inc., 1990, Hydrogeologic report for Rockford-Tipton, Rockford, Illinois, vol. 1: Prepared for the U.S. Environmental Protection Agency, Chicago, Illinois, variously paginated.

Feinstein, D.T., and Anderson, M.P., 1987, Recharge to and potential for contamination of an aquifer system in northeastern Wisconsin: University of Wisconsin Madison Water Resources Center Technical Report WIS WRC 87-01, 112 p.

Foote, G.R., 1982, Fracture analysis in northeastern Illinois and northwestern Indiana: unpublished M.S. Thesis, University of Illinois at Urbana-Champaign, 193 p.

Gelhar, L.W., 1986, Stocastic subsurface hydrology from theory to applications: Water Resources Research, v. 22 no. 9, p. 135S-145S.

Heyl, A.V., Lyons, E.J., Agnew, A.F., and Behre, C.H., 1955, Zinc-lead-copper resources and general geology of the upper Mississippi valley district: U.S. Geological Survey Bulletin 1015-G, p. 227-243.

Kay, R.T., 1991, Geology, hydrology, and ground-water quality in the vicinity of two Waste-disposal sites near Morristown, Illinois: U.S. Geological Survey Administrative Report for the U.S. Environmental Protection Agency, 67 p.

Kay, R.T., Prinos, S.T., and Paillet, F.L., 1994, Geohydrology and ground-water quality in the vicinity of a ground-water-contamination site in Rockford, Illinois: U.S. Geological Survey Water-Resources Investigations Report 94-4187, 28 p.

Kay, R.T., 2001, Geology, hydrology, and ground-water quality of the Galena-Platteville aquifer in the vicinity of the Parson's Casket Hardware Superfund site, Belvidere, Illinois, 1999: U.S. Geological Survey Water-Resources Investigations Report 00-4152, 34 p.

Klemic, H., and West, W.S., 1964, Geology of the Belmont and Calamine quadrangles, Wisconsin: U.S. Geological Survey Bulletin 1123-G, p. 361-433.

Kolata, D.R., and Buschbach, T.C., 1976, The Plum River fault zone of northwestern Illinois: Illinois State Geological Survey Circular 491, 20 p.

Kolata, D.R., Buschbach, T.C., and Treworgy, J.D., 1978, The Sandwich fault zone of northern Illinois: Illinois State Geological Survey Circular 505, 26 p.

Krohelski, J.T., 1986, Hydrology and ground-water use and quality, Brown County, Wisconsin: Wisconsin Geologic and Natural History Survey Information Circular 57, 42 p.

Leighton, M.M., Ekblaw, G.E., and Hornberg, Leland, 1948, Physiographic divisions of llinois: Journal of Geology, v. 56, p. 16-33.

LeRoux, E.F., 1963, Geology and ground-water resources of Rock County, Wisconsin: U.S. Geological Survey Water-Supply Paper 1619-X, 49 p.

Long, J.C., Remer, J.S., Wilson, C.R., and Witherspoon, P.A., 1982, Porous media equivalents for networks of discontinuous fractures: Water Resources Research, v. 18, no. 3, p. 645-658

Mills, P.C., Yeskis, D.J., and Straub, T.D., 1998, Geologic, hydrologic, and water-quality data from selected boreholes and wells in and near Belvidere, Illinois, 1989-96: U.S. Geological Survey Open-File Report 97-242, 151 p.

Mills, P.C., Thomas, C.A., Brown, T.A., Yeskis, D.J., and Kay, R.T., 1999, Potentiometric levels and water quality in the aquifers underlying Belvidere, Ill., 1993-96: U.S. Geological Survey Water-Resources Investigations Report 98-4220, 106 p.

Mills, P.C., Nazimek, J.E., Halford, K.J., and Yeskis, D.J., 2002a, Hydrogeology and simulation of ground-water flow in the aquifers underlying Belvidere, Illinois: U.S. Geological Survey Water-Resources Investigations Report 01-4100, 103 p.

Mills, P.C., Halford, K.J., and Cobb, R.P., 2002b, Delineation of the Troy Bedrock Valley and particle-tracking analysis of ground-water flow underlying Belvidere, Illinois: U.S. Geological Survey Water-Resources Investigations Report 02-4062, 46 p.

National Research Council, 1996, Rock fractures and fluid flow, contemporary understanding and applications: National Academy Press, Washington, D.C., 551 p.

Olcott, P.G., 1966, Geology and water resources of Winnebago County, Wisconsin: U.S. Geological Survey Water-Supply Paper 1814, 61 p.

Olcott, P.G., and Hamilton, G.E., 1973, Water Resources of Wisconsin, Menominee-Oconto-Peshtigo River Basin: U.S. Geological Survey Hydrologic Investigations Atlas HA-470, 4 p.

Quinlan, J.F., 1989, Ground-water monitoring in karst terranes: recommended protocols and implicit assumptions: Las Vegas, Nev.: U.S. Environmental Protection Agency, Environmental Monitoring Systems Laboratory, EPA/600/X-89/050, 100 p.

Rovey, C.W., and Cherkauer, D.S., 1994, Relation between hydraulic conductivity and texture in a carbonate aquifer: Ground Water, v. 32, no. 1, p. 53-62.

Roy F. Weston, Inc., 1988, Remedial investigation report for Belvidere municipal No. 1 landfill site, Belvidere, Illinois: Report to the Illinois Environmental Protection Agency, Springfield, Illinois, variously paginated.

Sargent and Lundy, Inc., and Dames and Moore, Inc., 1975, Fault specific geotechnical investigations, Byron, Station: Prepared for Commonwealth Edison Corp., Chicago, Ill., 40 p.

Simon Hydro-Search, Inc., 1992, Remedial investigation/Feasibility study, Better Brite sites, DePere, Wisconsin: Report to the Wisconsin Department of Natural Resources, Madison, Wis., variously paginated.

Stocks, D.L., 1998, Hydrostratigraphy of the Ordovician Sinnipee Group dolomites, eastern Wisconsin: Master's Thesis, University of Wisconsin, Madison, 183 p.

Taylor, A.R., 1964, Geology of the Rewey and Mifflin quadrangles, Wisconsin: U.S. Geological Survey Bulletin 1123-F, p. 279-359.

Toth, J., 1962, A theory of groundwater motion in small drainage basins in central Alberta, Canada: Journal of Geophysical Research, v. 67, no. 11, p. 4375-4387.

U.S. Environmental Protection Agency, 1994, Remedial investigation report for the Byron Salvage Yard Superfund site: Prepared for the U.S. Environmental Protection Agency, Chicago, Ill., variously paginated.

Whitlow, J.W., and West, W.S., 1966, Geology of the Potosi quadrangle, Grant County, Wisconsin, and Dubuque County, Iowa: U.S. Geological Survey Bulletin 1123-I, p. 533-571.

Willman, H.B., and Kolata, D.R., 1978, The Platteville and Galena Groups in northern Illinois: Illinois State Geological Survey Circular 502, 75 p.

Willman, H.B., Atherton, Elwood, Buschbach, T.C., Collinson, Charles, Frye, J.C., Hopkins, M.E., Lineback, J.A., and Simon, J.A., 1975, Handbook of Illinois stratigraphy: Illinois State Geological Survey Bulletin 95, 261 p.

APPENDIXES