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A Cross-Site Comparison of Methods Used for Hydrogeologic Characterization of the Galena-Platteville Aquifer in Illinois and Wisconsin, With Examples From Selected Superfund Sites

Scientific Investigations Report 2004-5136

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

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By Robert T. Kay, Patrick C. Mills, Charles P. Dunning, Douglas J. Yeskis, James R. Ursic, and Mark Vendl

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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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by Robert T. Kay, Patrick C. Mills, Charles P. Dunning, Douglas J. Yeskis, James R. Ursic, and Mark Vendl

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.

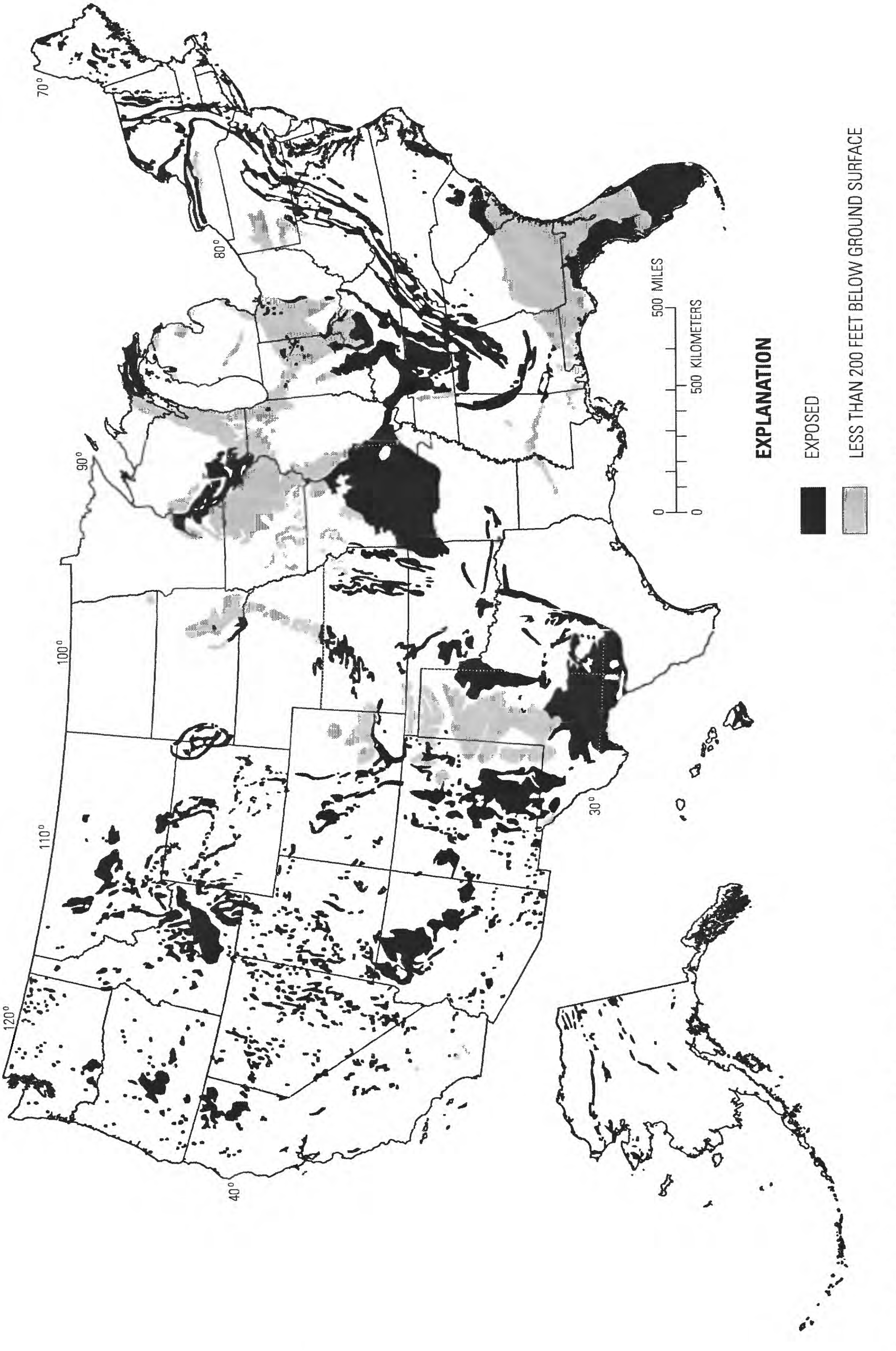


Figure 1. Location of fractured-rock aquifers beneath the United States (modified from National Research Council, 1996).

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.

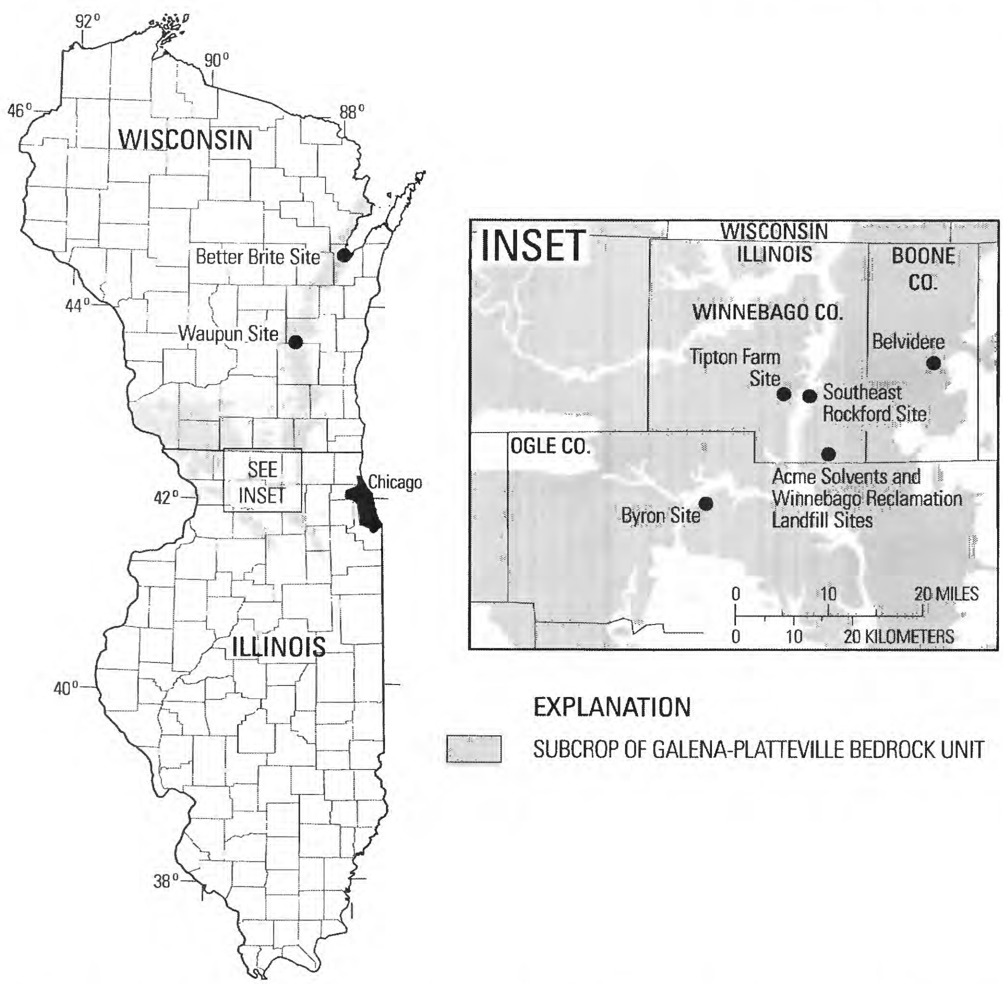


Figure 2. Location of Superfund sites overlying the Galena-Platteville aquifer in Illinois and Wisconsin investigated by the U.S. Geological Survey and U.S. Environmental Protection Agency.

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).

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

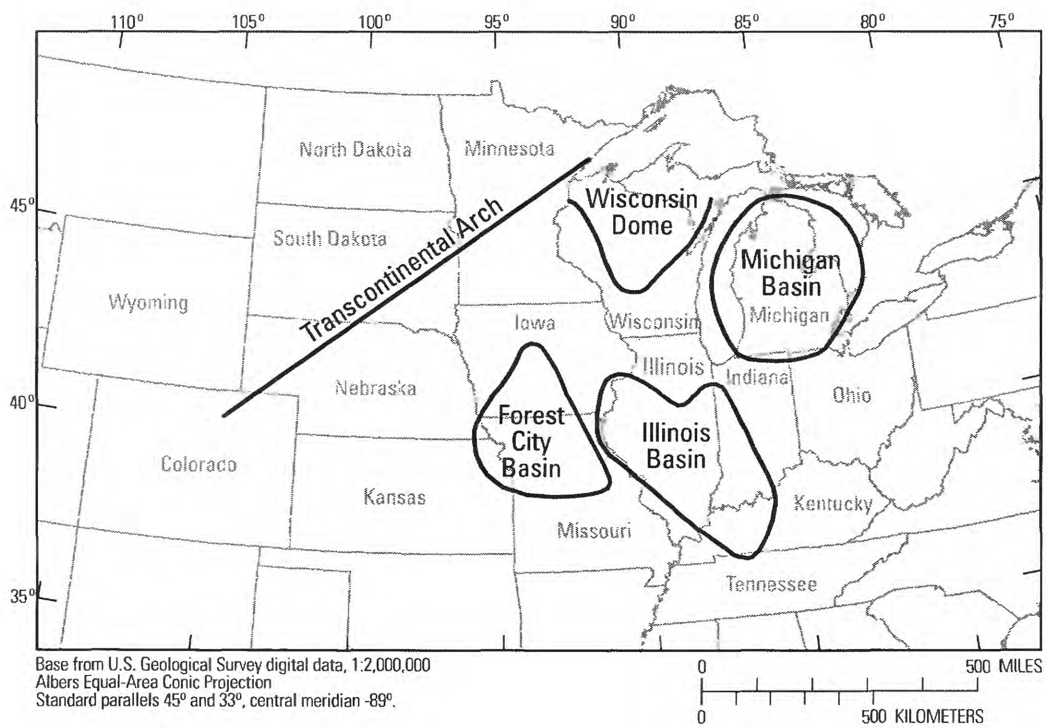


Figure 3. Selected structural features in the central United States.

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-

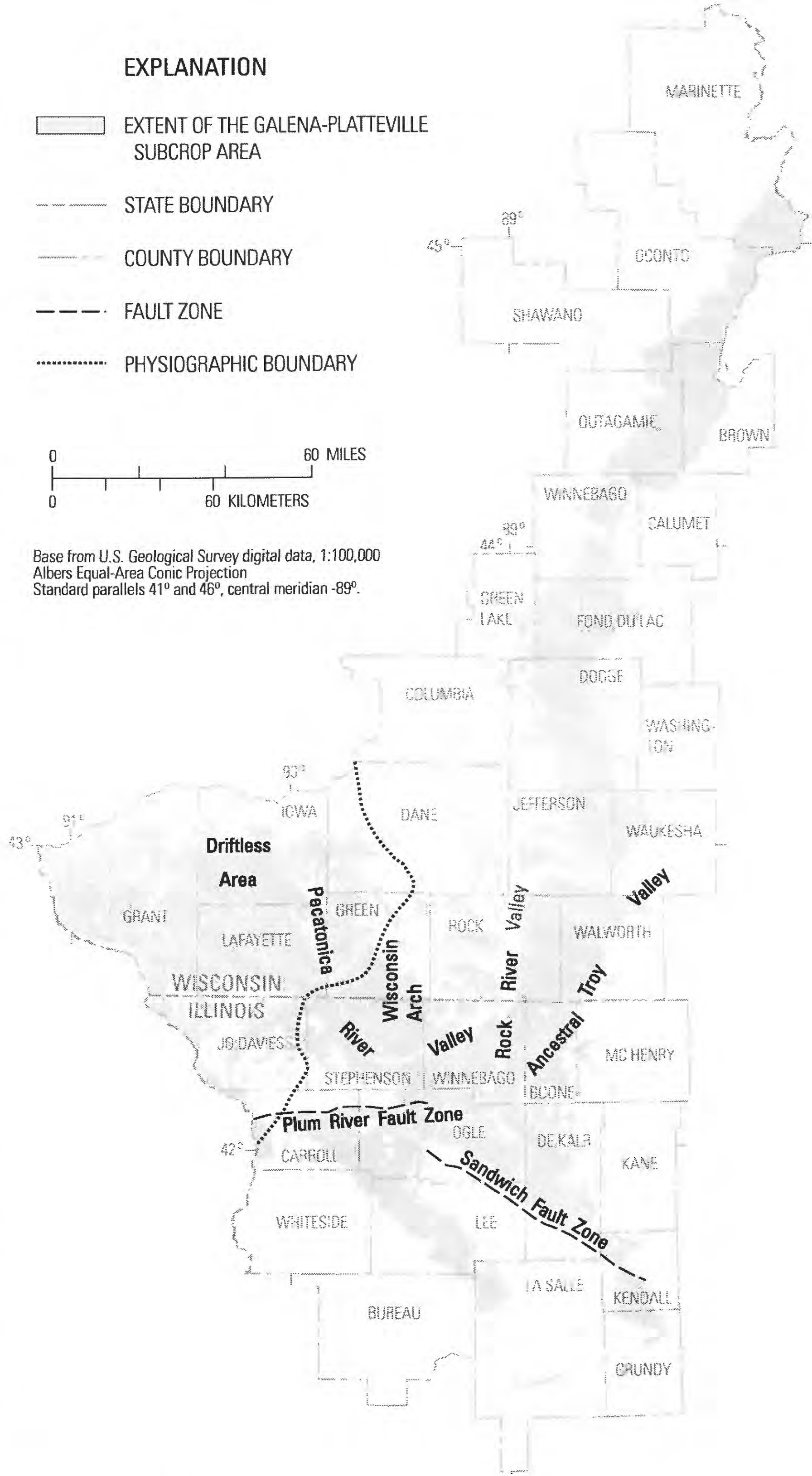


Figure 4. Galena-Platteville subcrop area of Illinois and Wisconsin and select structural and physiographic features.

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

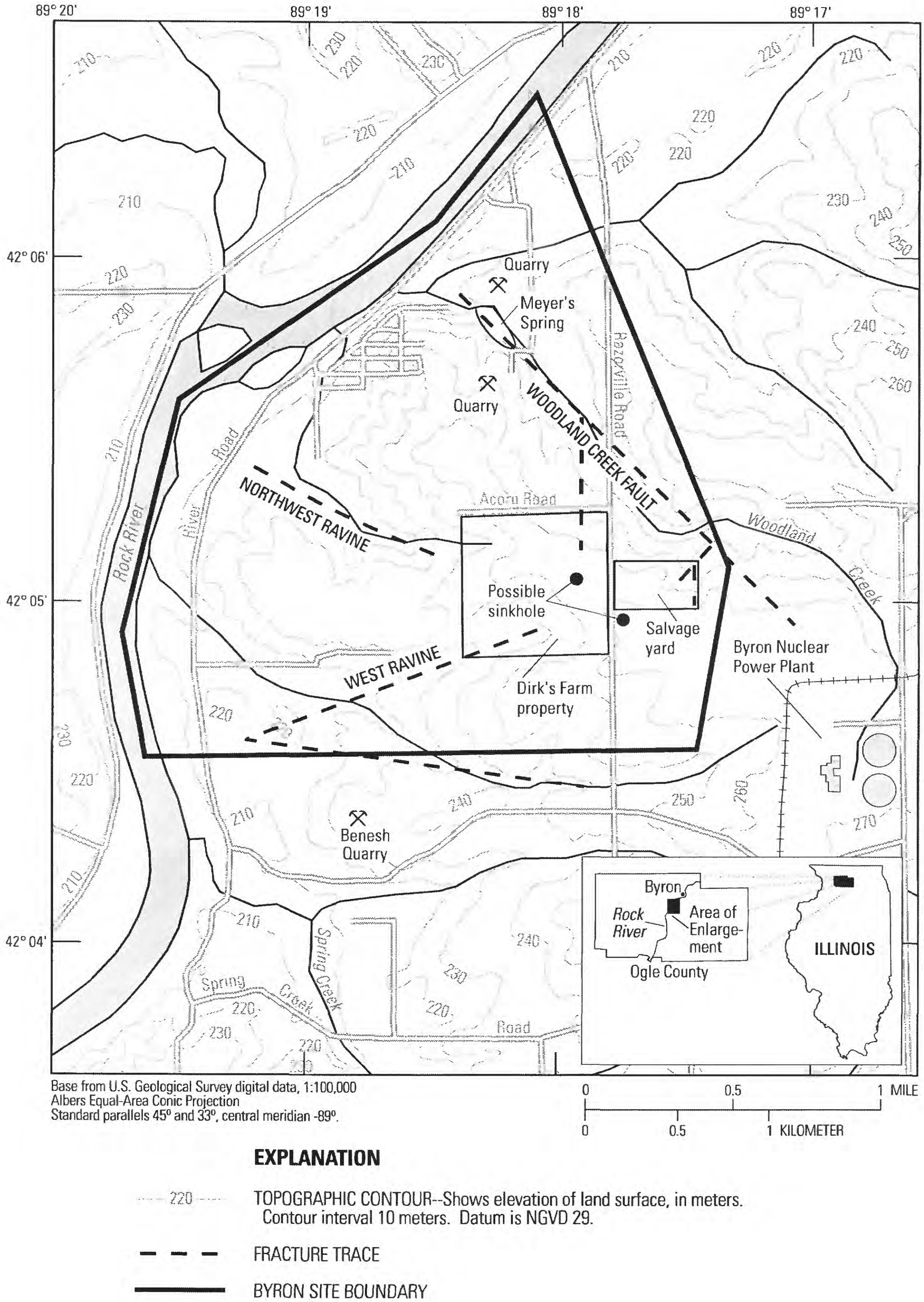


Figure 6. Location of the Byron site, salvage yard, Dirk's Farm Property, sinkholes, and fracture traces, Byron site, north-central Illinois.

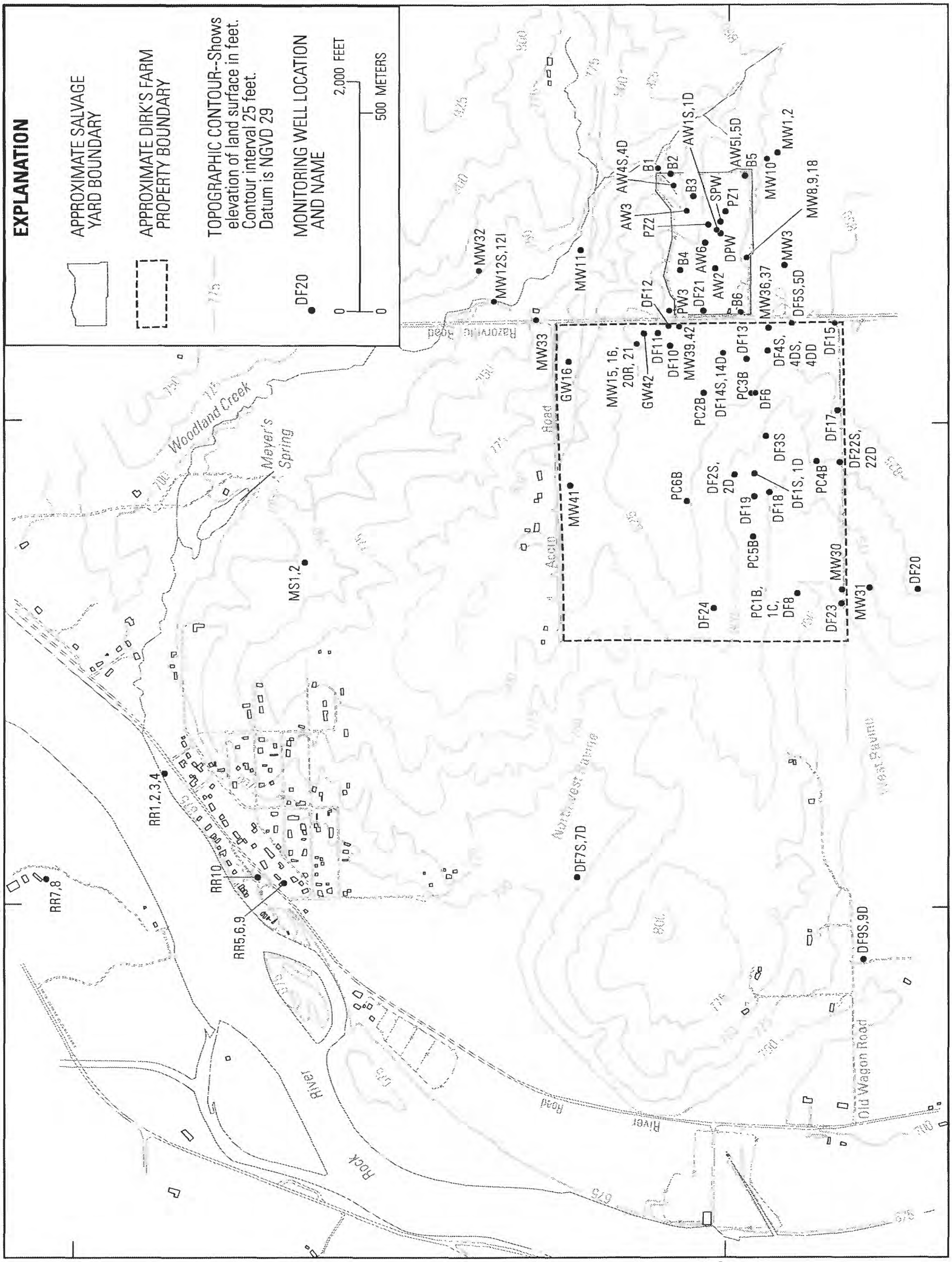


Figure 7. Location of monitoring wells, salvage yard, and Dirk's Farm property, Byron site, Ill.

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,

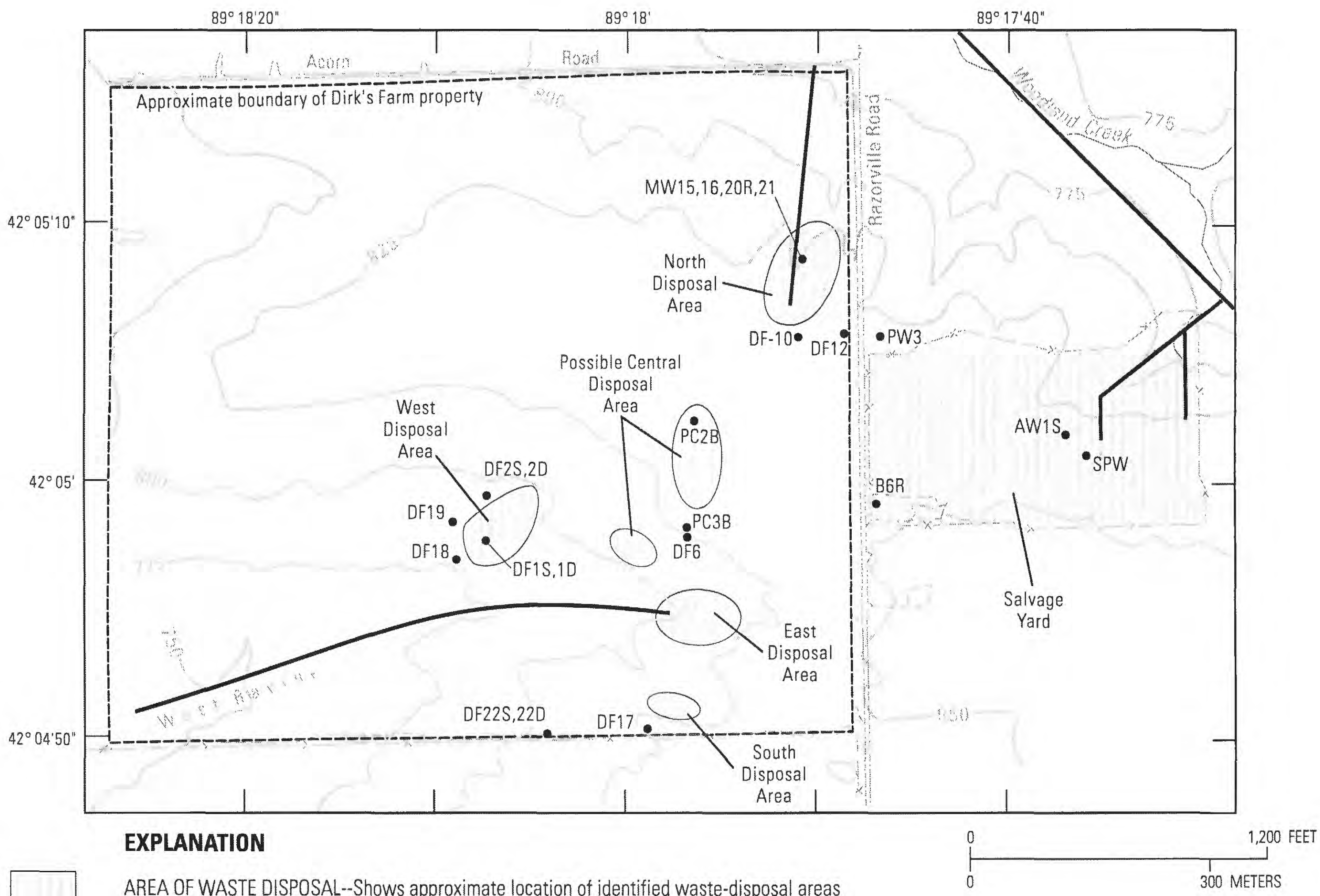
Table 4. Monitoring well and water-level data, Byron Superfund site, Ill.

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



EXPLANATION

AREA OF WASTE DISPOSAL--Shows approximate location of identified waste-disposal areas

TOPOGRAPHIC CONTOUR--Shows elevation of land surface, in feet. Contour interval 25 feet. Datum is NGVD 29

FRACTURE TRACE

DF17 MONITORING WELL LOCATION AND NAME

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

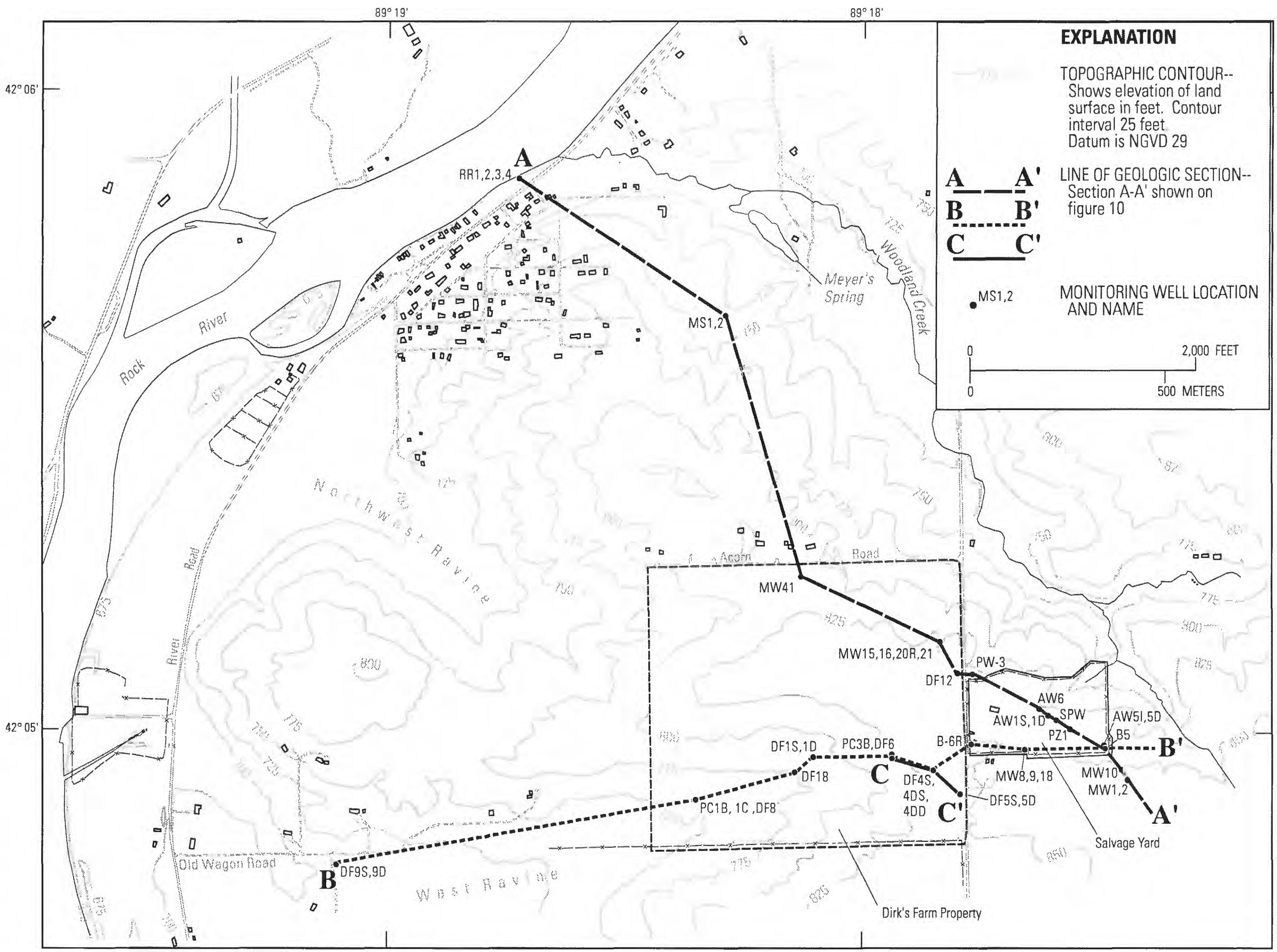


Figure 9. Lines of geologic section, Byron site, Ill.

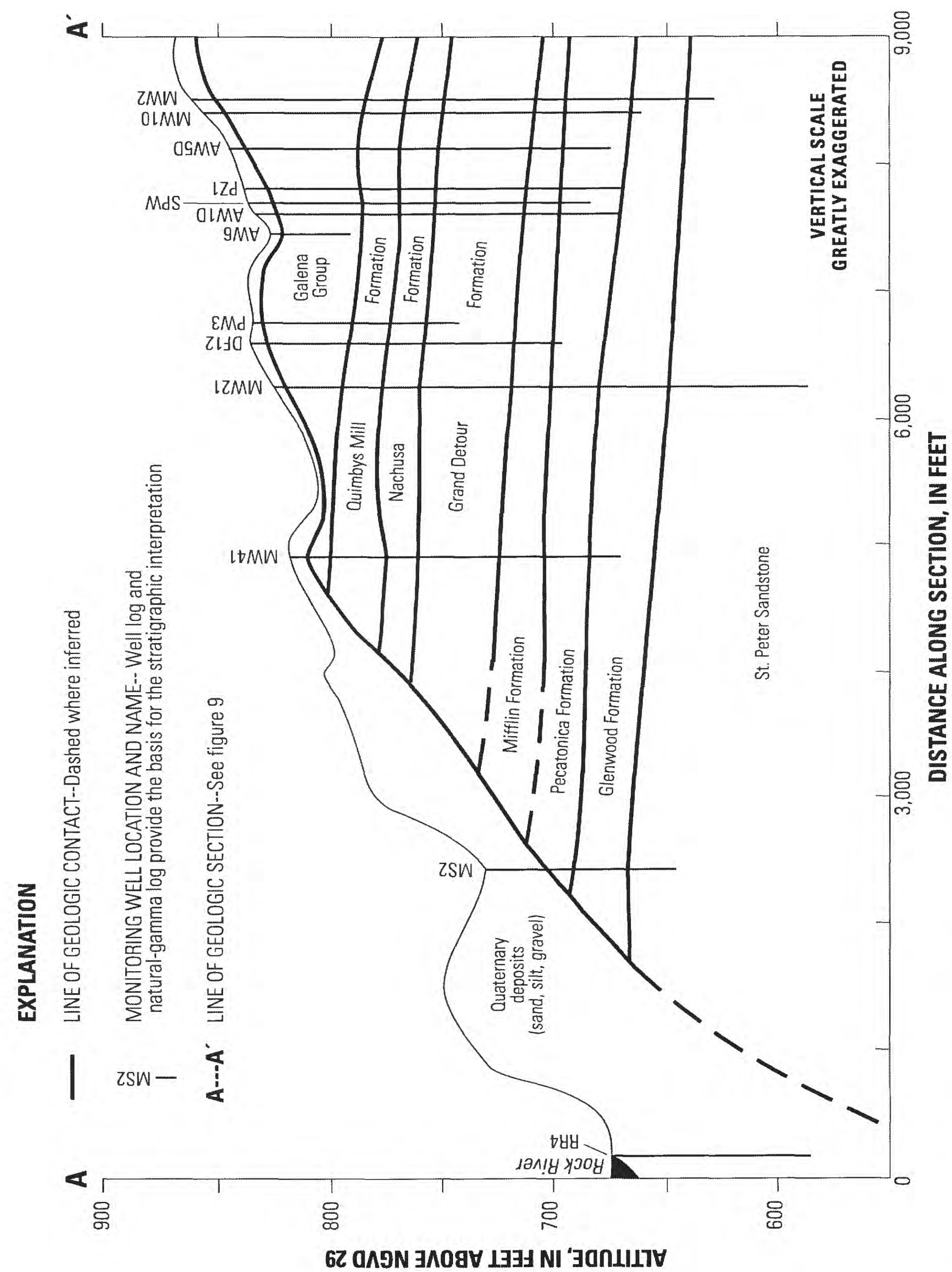


Figure 10. Diagram of geologic section A-A´, Byron site, Ill.

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	Unconsolidated aquifer	Unknown
QUATERNARY				Loess, windblown silt, leached	0-15	Unconsolidated aquifer	Unknown
QUATERNARY				Sand and silt, windblown, leached	0-15	Unconsolidated aquifer	Unknown
QUATERNARY				Outwash, sand and gravel	0-180	Unconsolidated aquifer	Unknown
QUATERNARY				Till, brown silty clay to clayey silt with few boulders, stiff	0-26	Unconsolidated aquifer	Unknown
QUATERNARY				Silt, brown to gray, calcareous, stiff	0-10	Unconsolidated aquifer	Unknown
QUATERNARY				Till, brown silty sand with few boulders, very stiff to hard	0-25	Unconsolidated aquifer	Unknown
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
ORDOVICIAN	GALENA	GUTTENBERG		Dolomite, vuggy, with red shale partings	0-5	Galena-Platteville aquifer	6.4
ORDOVICIAN	PLATTEVILLE	QUIMBYS MILL		Dolomite, buff and gray, occasional white chert, mottled with numerous shale partings	0-20	Galena-Platteville aquifer	10.2
ORDOVICIAN	PLATTEVILLE	NACHUSA		Dolomite, pure to slighty argillaceous, vuggy, thickly bedded to massive, occasional white chert	0-25	Galena-Platteville aquifer	9.5
ORDOVICIAN	PLATTEVILLE	GRAND DETOUR		Dolomite, mottled buff and dark gray, finely crystalline, medium to massive bedded, thin gray and reddish-brown shale partings	0-45	Galena-Platteville aquifer	11.3
ORDOVICIAN	PLATTEVILLE	MIFFLIN		Dolomite, mottled, thinly bedded, thin gray or green shale partings	0-15	Galena-Platteville aquifer	9.4
ORDOVICIAN	PLATTEVILLE	PECATONICA		Dolomite, mottled, medium bedded	0-33	Galena-Platteville aquifer	9
ORDOVICIAN	ANCELL	GLENWOOD	HARMONY HILL	Shale, green, gray, and brown, thinly laminated	0-5	Harmony Hill Shale semiconfining unit	Unknown
ORDOVICIAN	ANCELL	GLENWOOD	DAYSVILLE	Shale, brown and gray, sandy Dolomite, greenish-gray, fine-grained	0-16	Harmony Hill Shale semiconfining unit	18
ORDOVICIAN	ANCELL	GLENWOOD	KINGDOM SANDSTONE	Dolomitic sandstone, greenish-gray	0-16	St. Peter aquifer	16
ORDOVICIAN	ANCELL	ST. PETER SANDSTONE		Sandstone, white, coarse- to medium-grained, quartzose, friable	approximately 420	St. Peter aquifer	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.

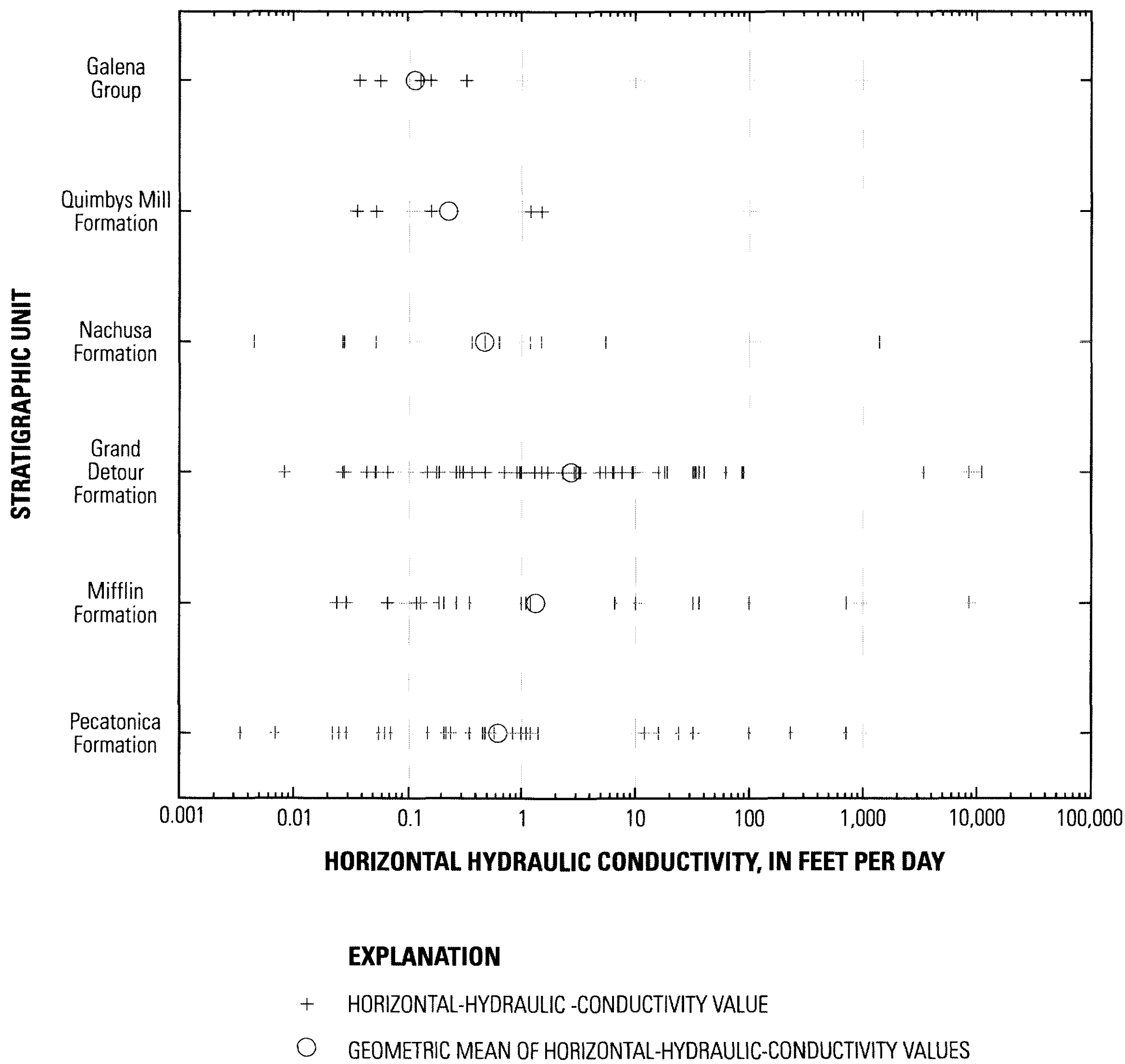


Figure 12. Distribution of horizontal hydraulic conductivity within the stratigraphic units that compose the Galena-Platteville aquifer, Byron site, Ill.

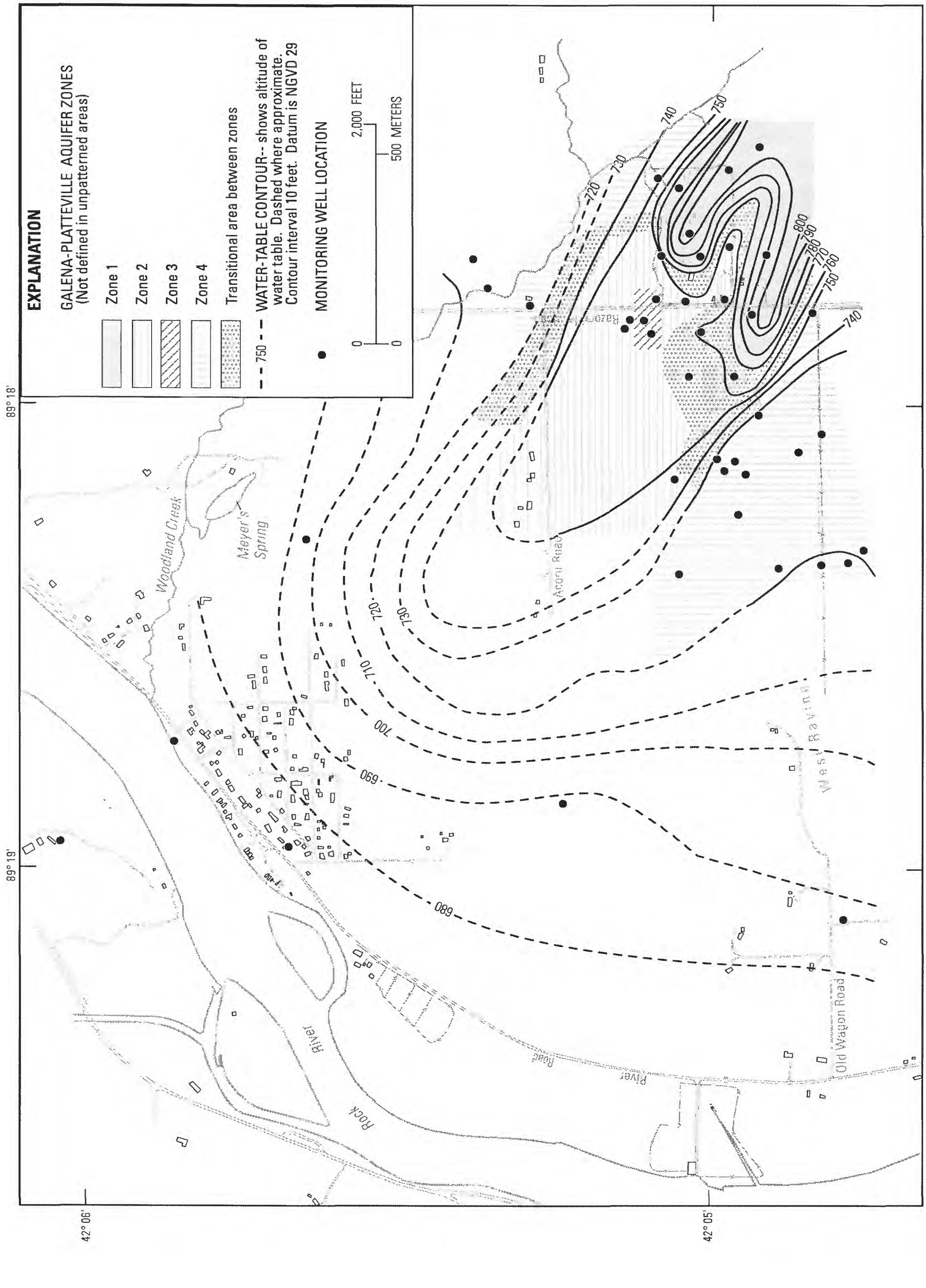


Figure 13. Water-table configuration and zones in the Galena-Platteville aquifer, Byron site, Ill., January 27, 1992.

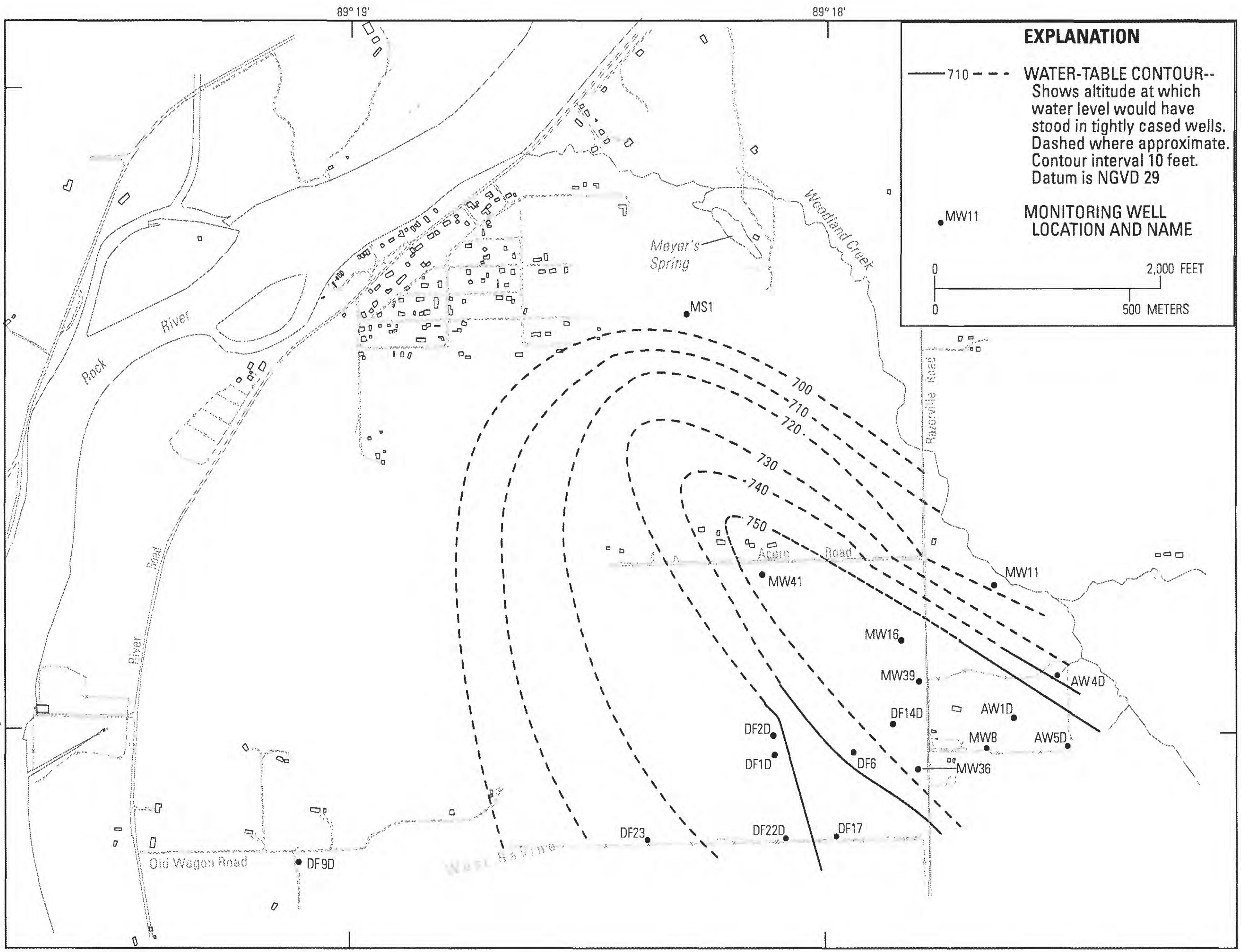
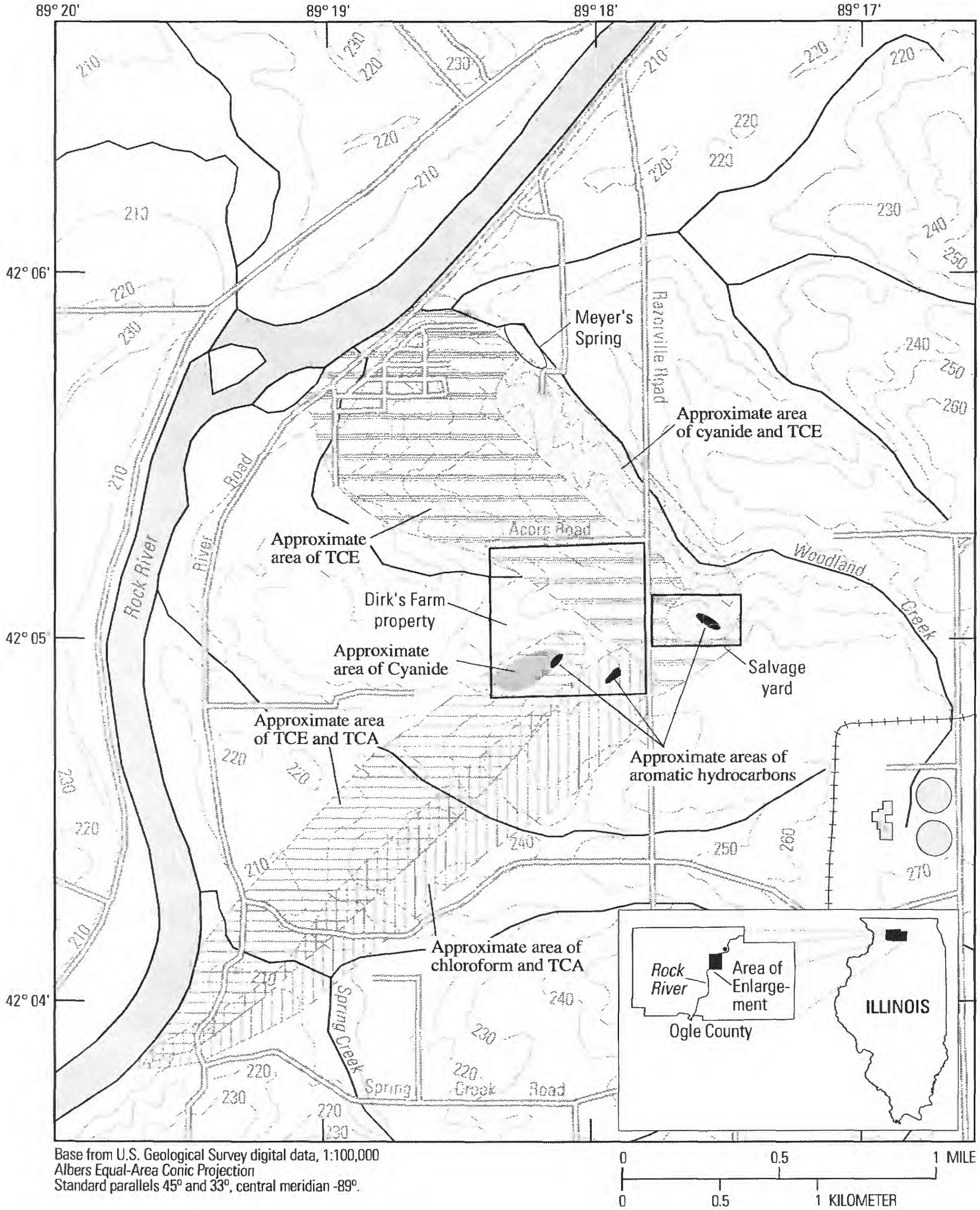


Figure 14. Potentiometric surface of the base of the Galena-Platteville aquifer, Byron site, Ill., January 27, 1992.



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° 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-

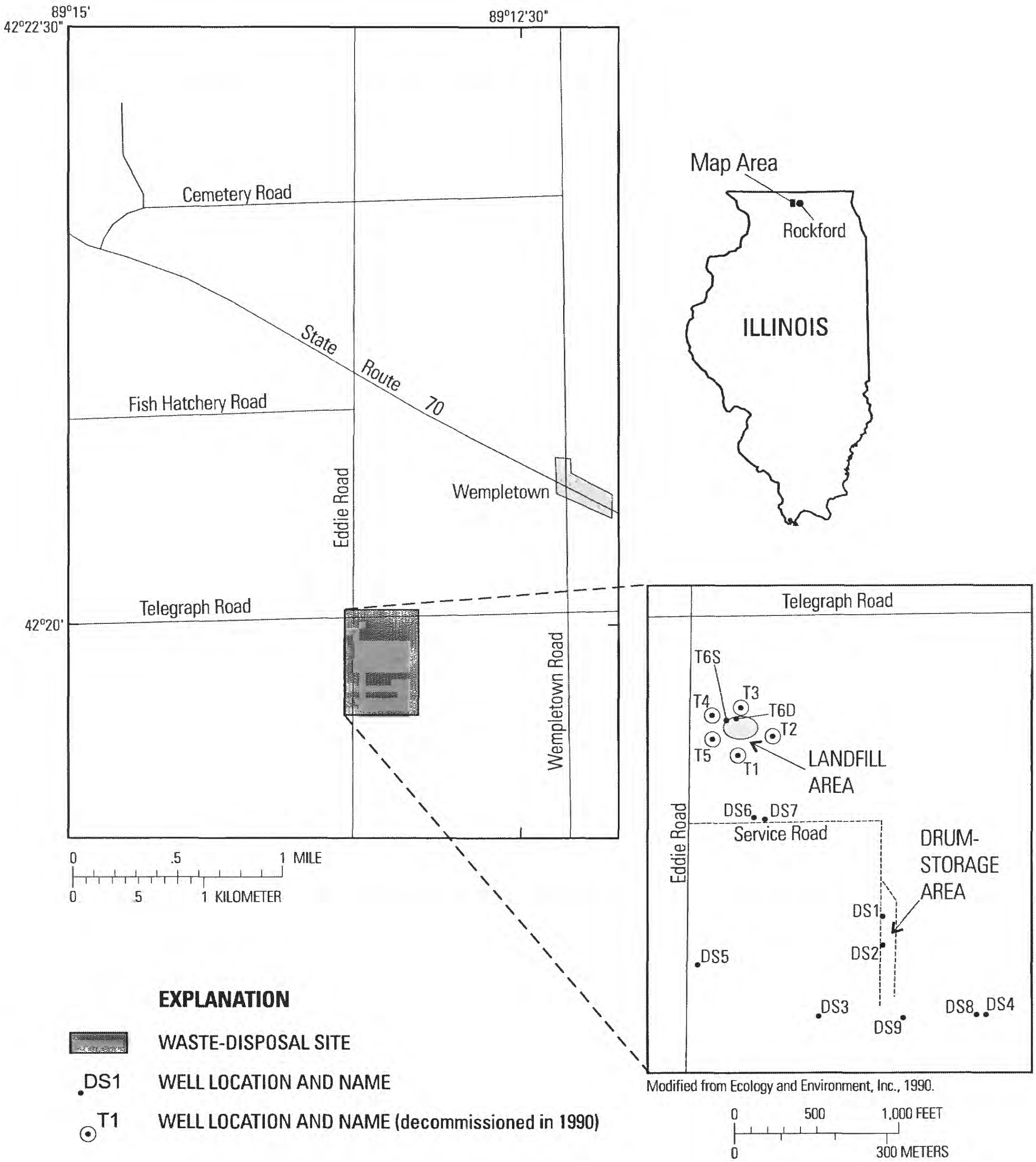


Figure 16. Location of Tipton Farm site and monitoring wells near Wempletown, Illinois.

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.

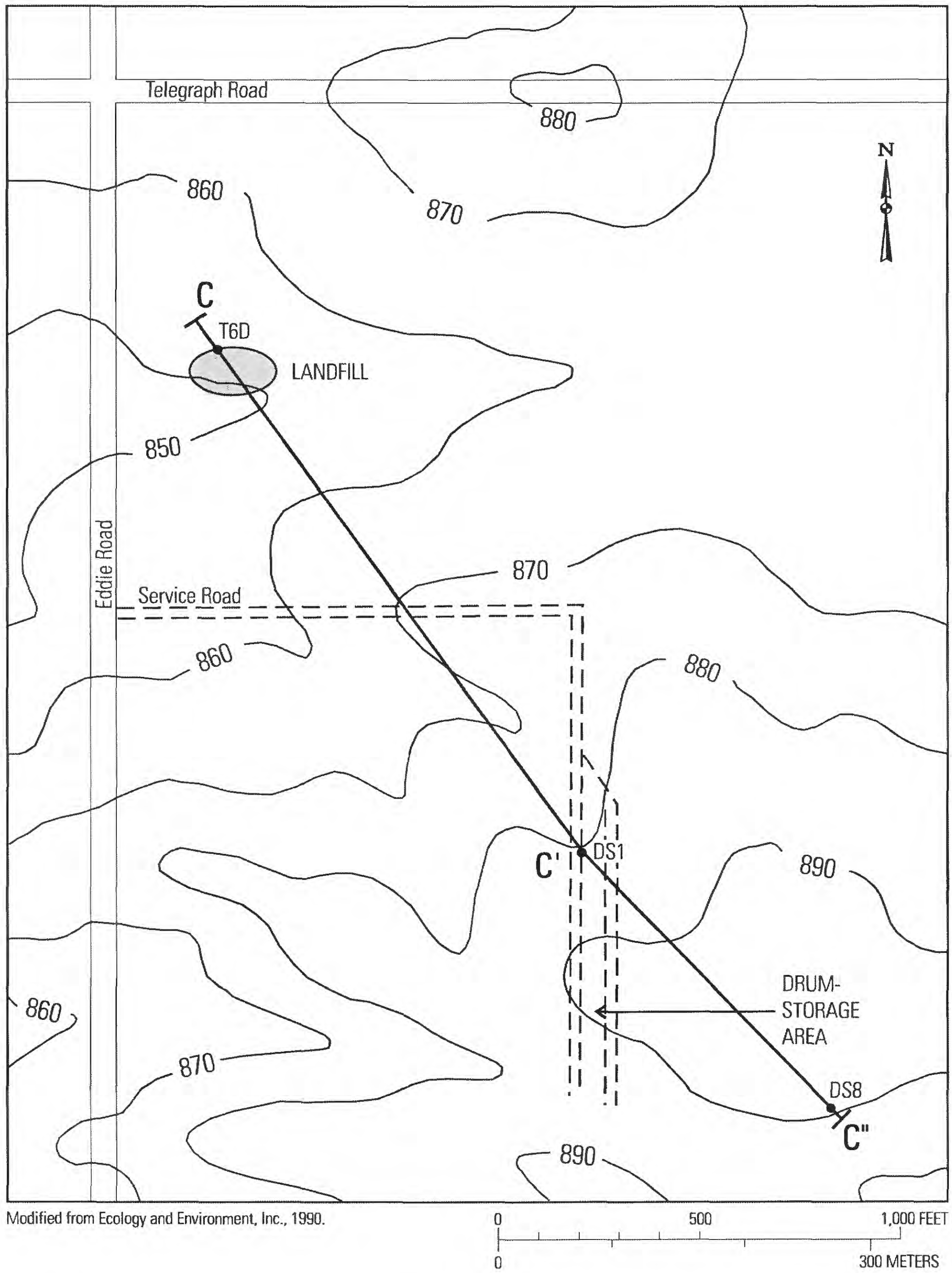
The water table is in the Quaternary deposits west of the line between wells G102, B10, and B13 and south of the line between wells B13, G111, and P8 (fig. 21). North and east of these lines, the water table is located in the Galena-Platteville aquifer.

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.

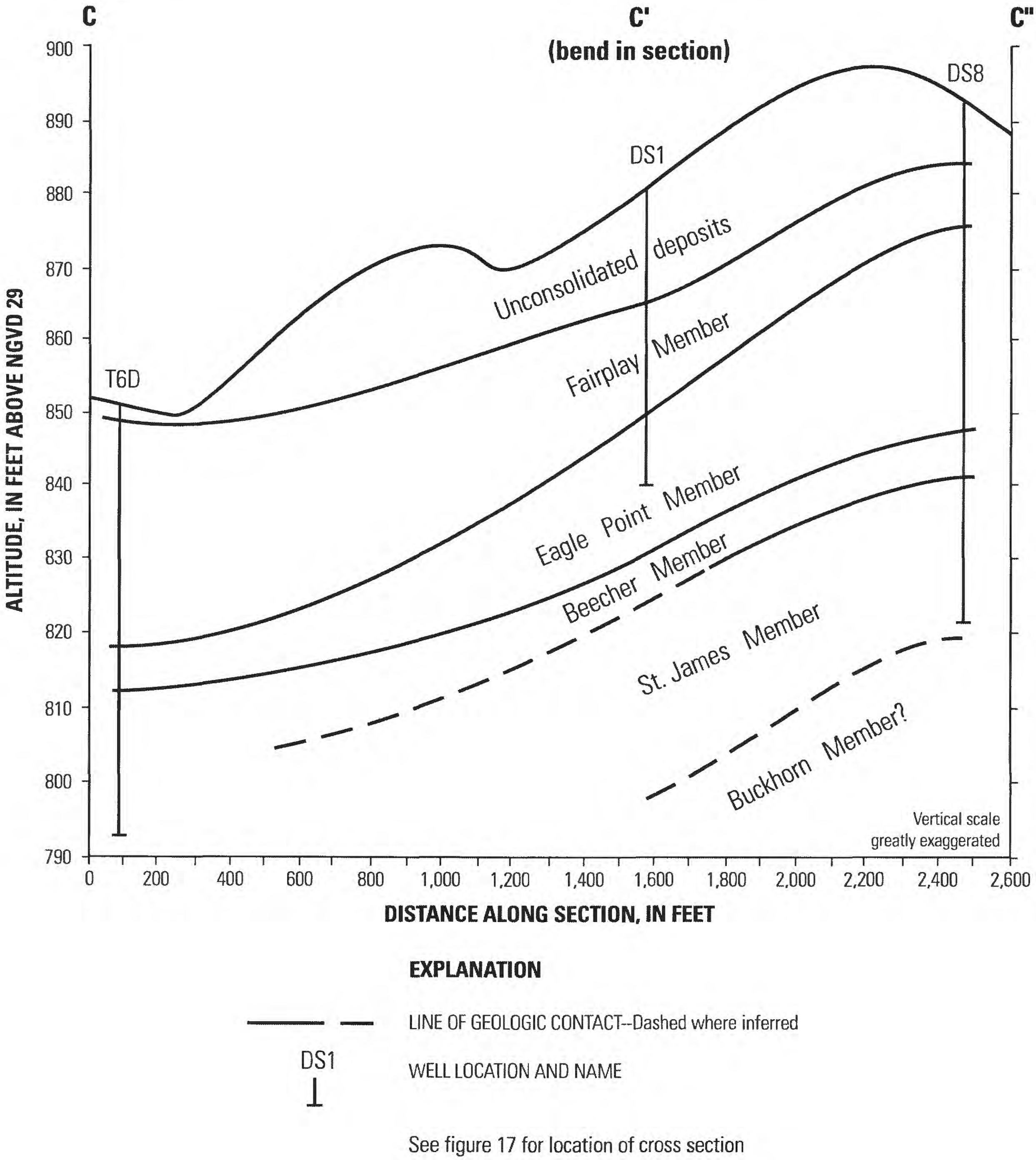


Figure 18. Line of geologic section C-C', Tipton Farm site, Ill.

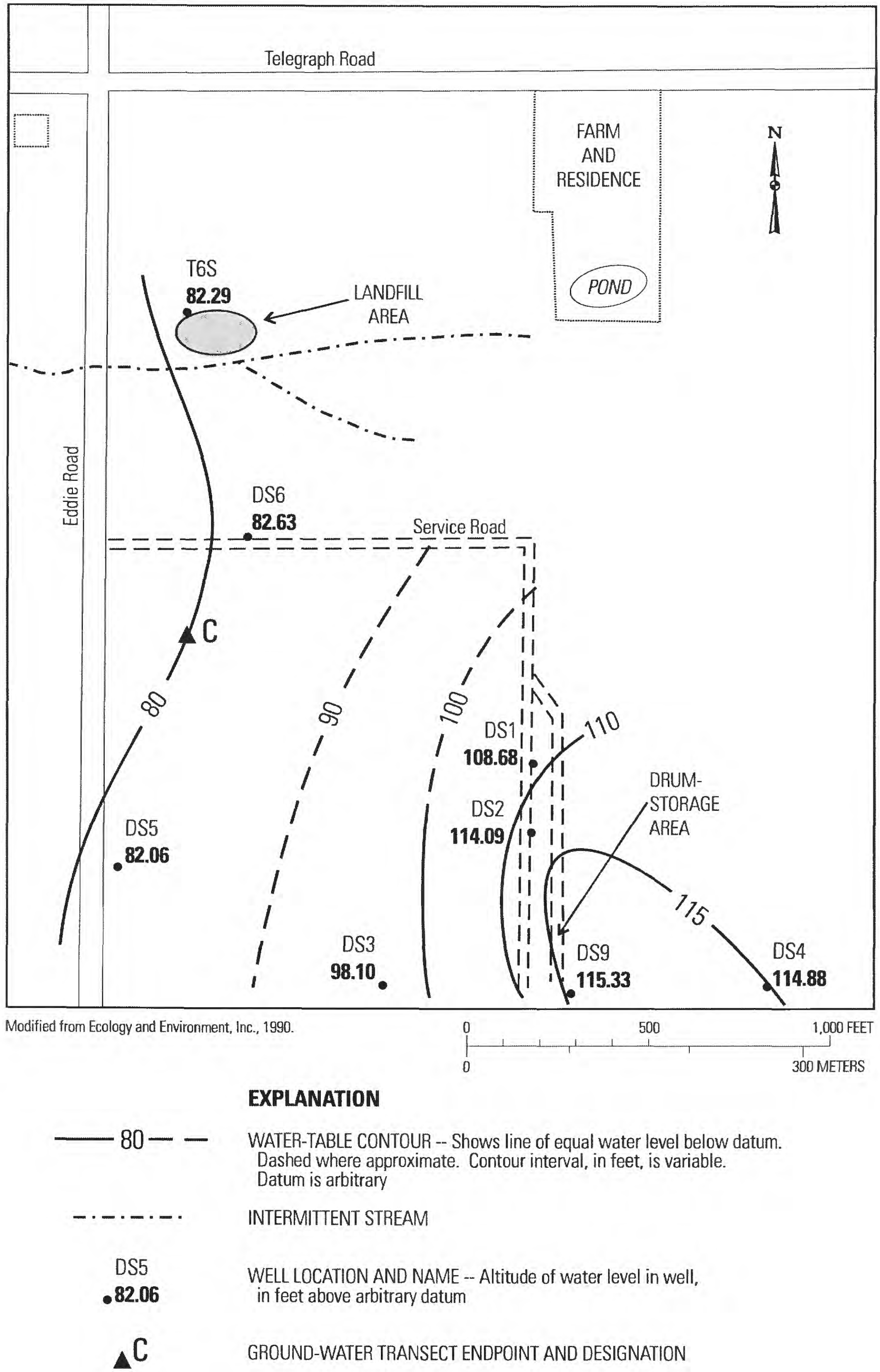


Figure 19. Water-table configuration in the vicinity of the Tipton Farm site, Ill., December 19, 1994.

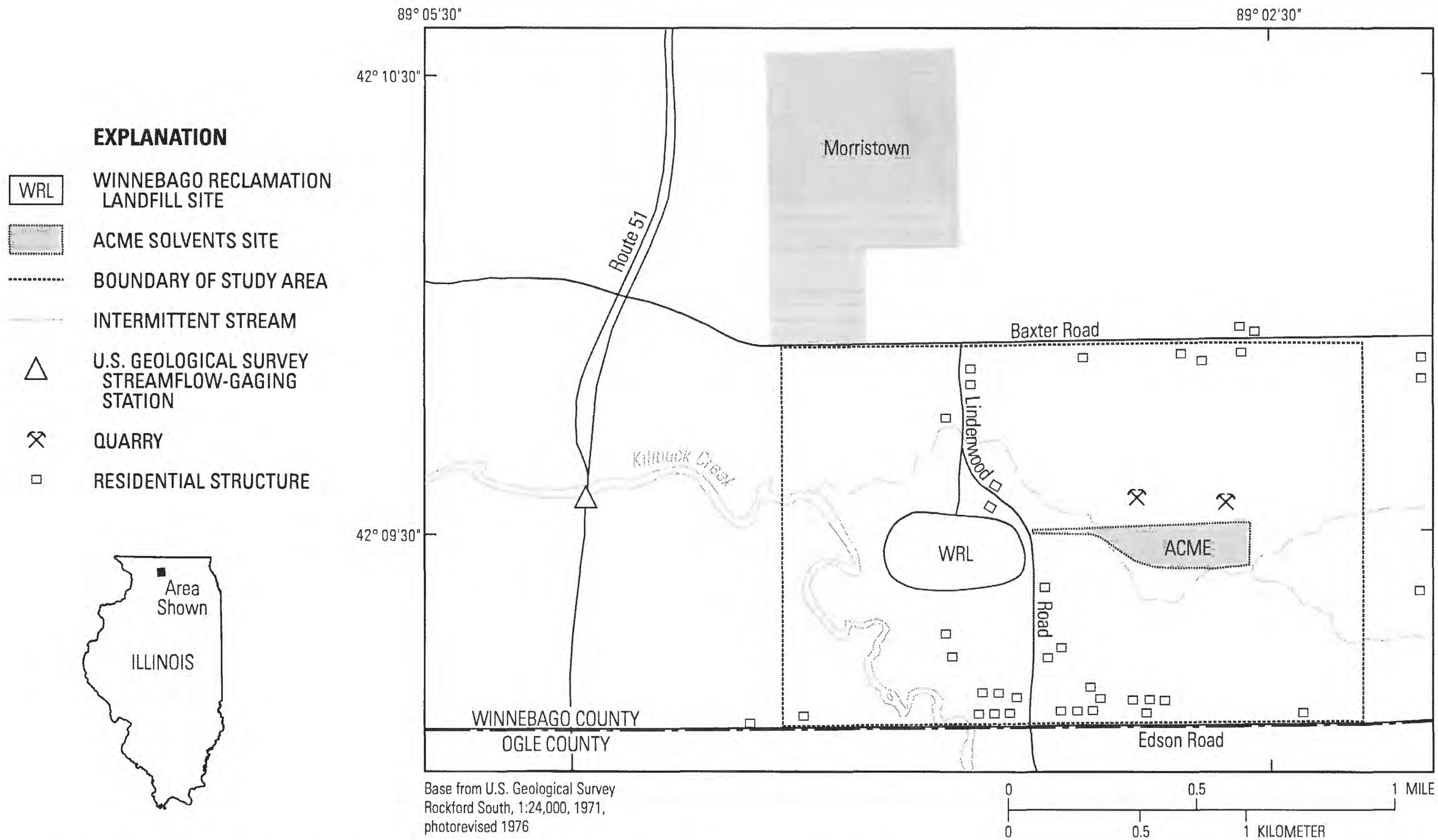


Figure 20. Location of the ACME Solvents and Winnebago Reclamation Landfill sites, Winnebago County, Ill.

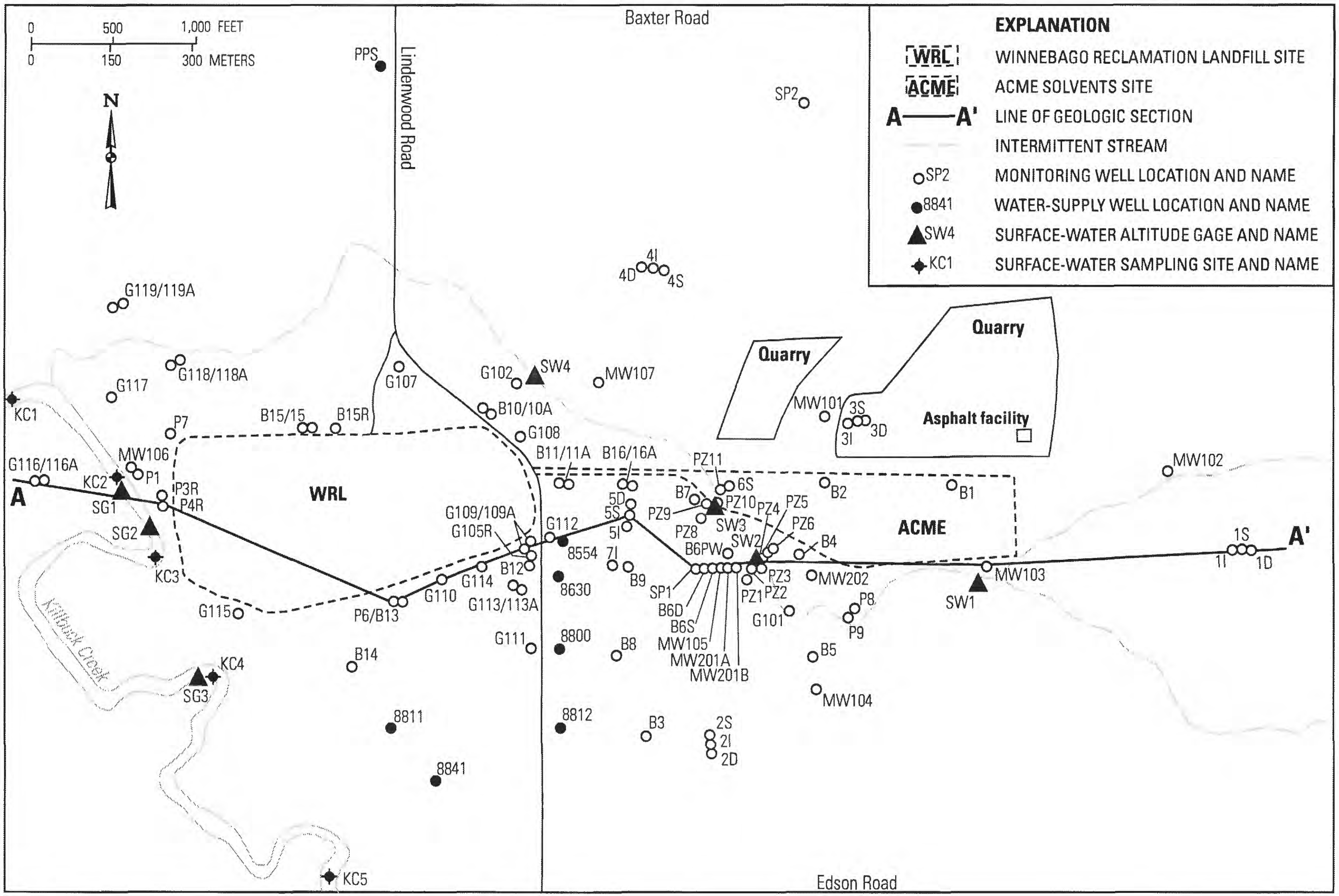


Figure 21. Location of ACME Solvents and Winnebago Reclamation Landfill sites, monitoring wells, and line of geologic section A-A', Ill.

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

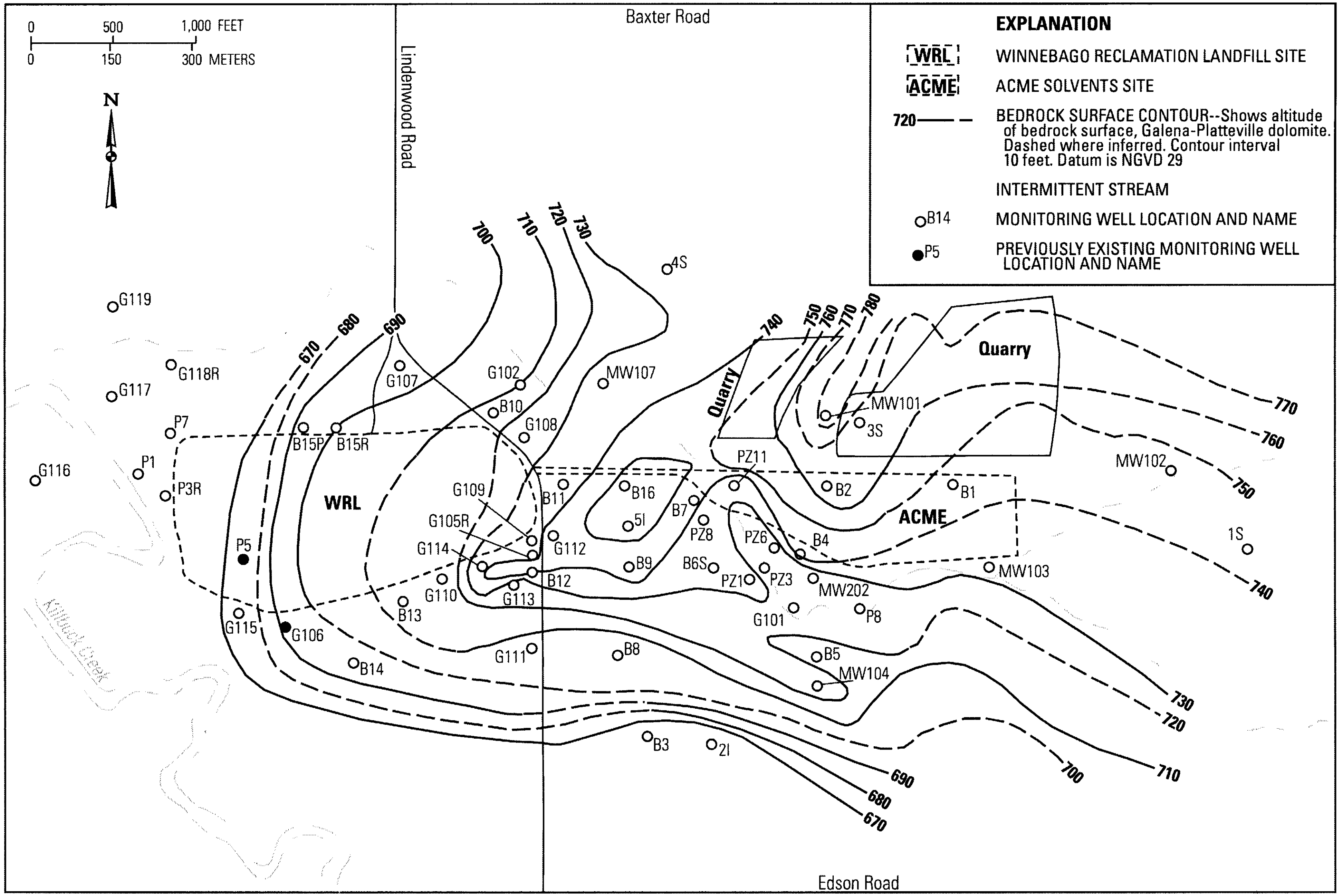


Figure 22. Bedrock-surface altitude at the ACME Solvents and Winnebago Reclamation Landfill sites, Ill.

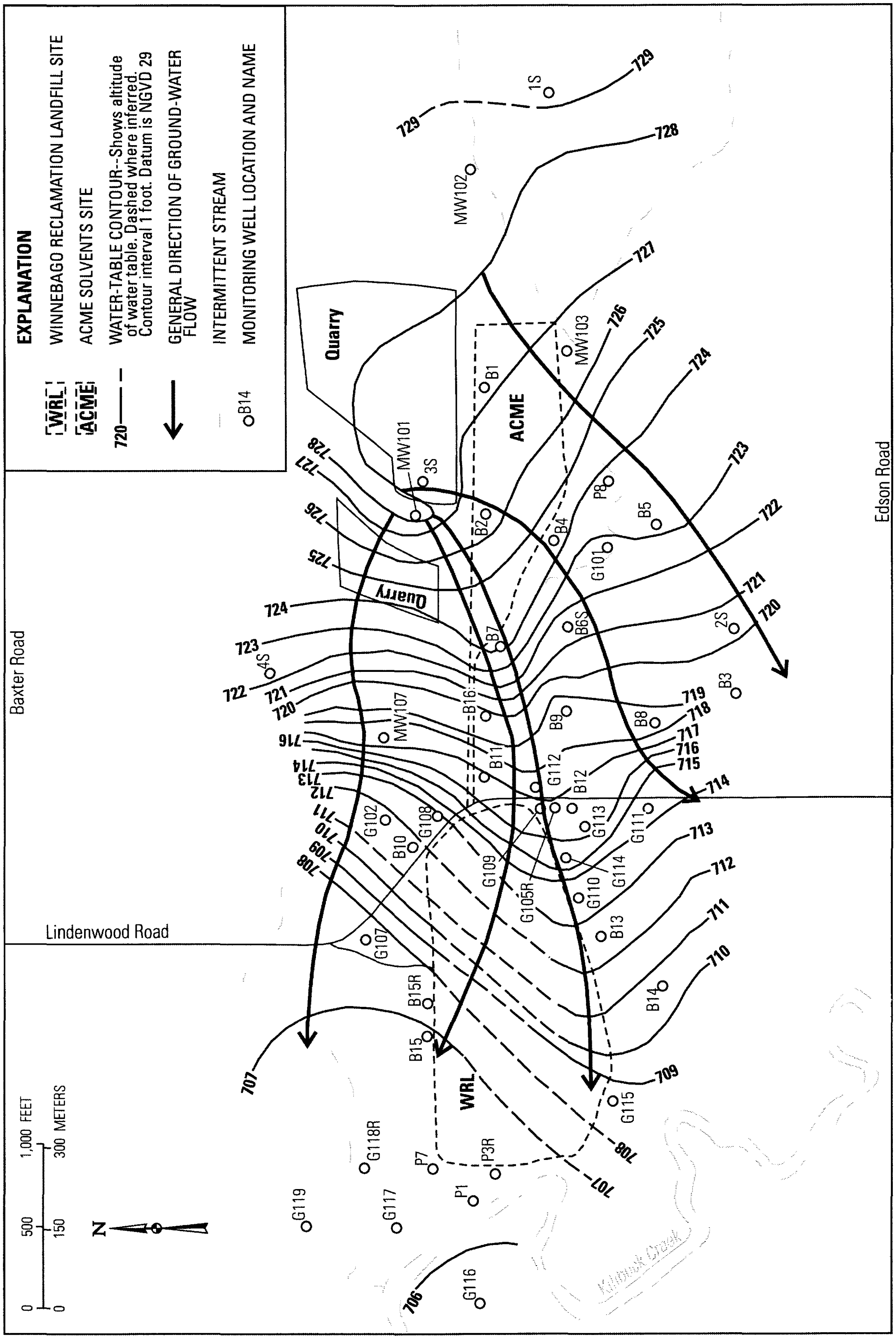


Figure 23. Water-table configuration, ACME Solvents and Winnebago Reclamation Landfill sites, Ill., November 7-9, 1988.

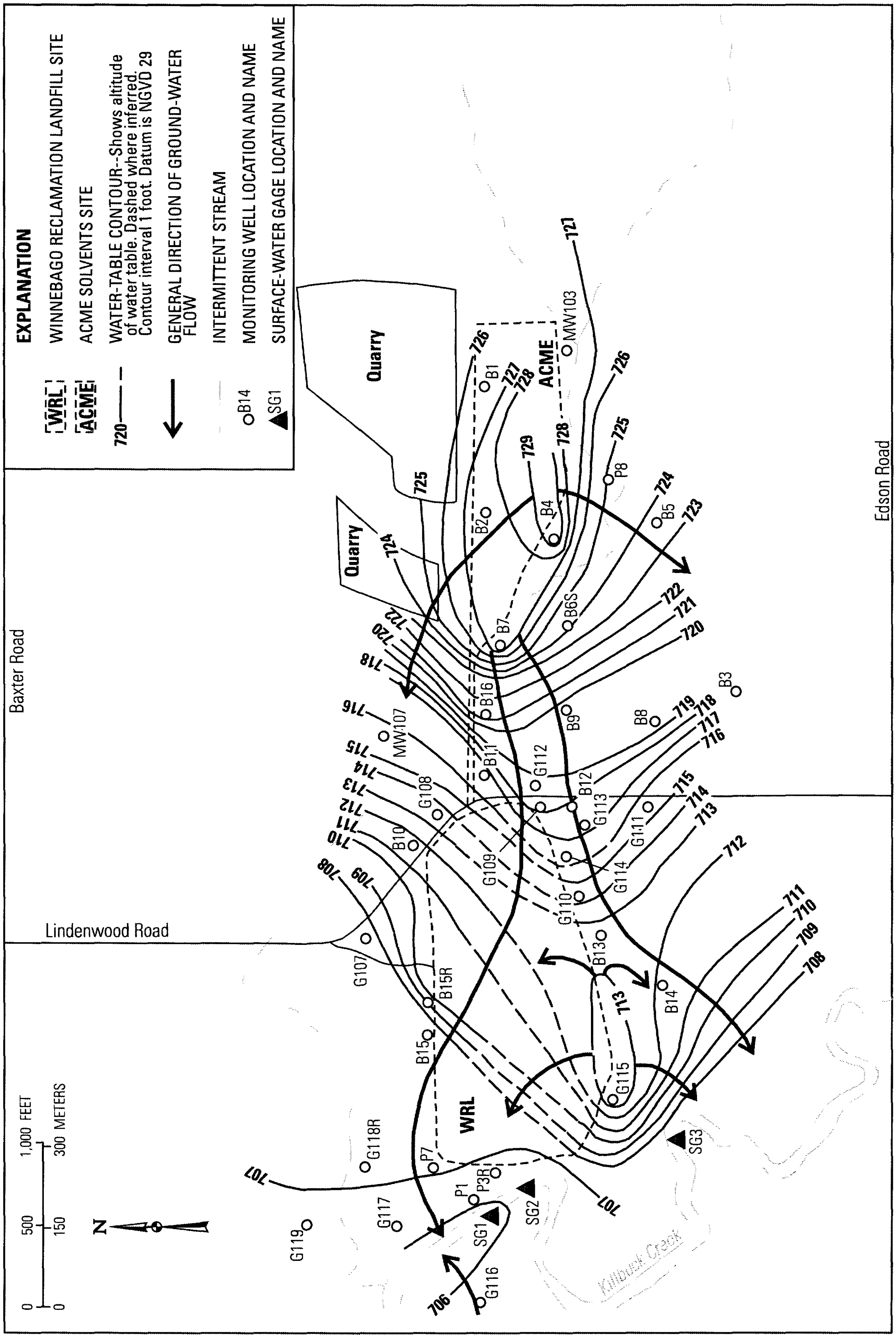


Figure 24. Water-table configuration, ACME Solvents and Winnebago Reclamation Landfill sites, Ill., April 20, 1990.

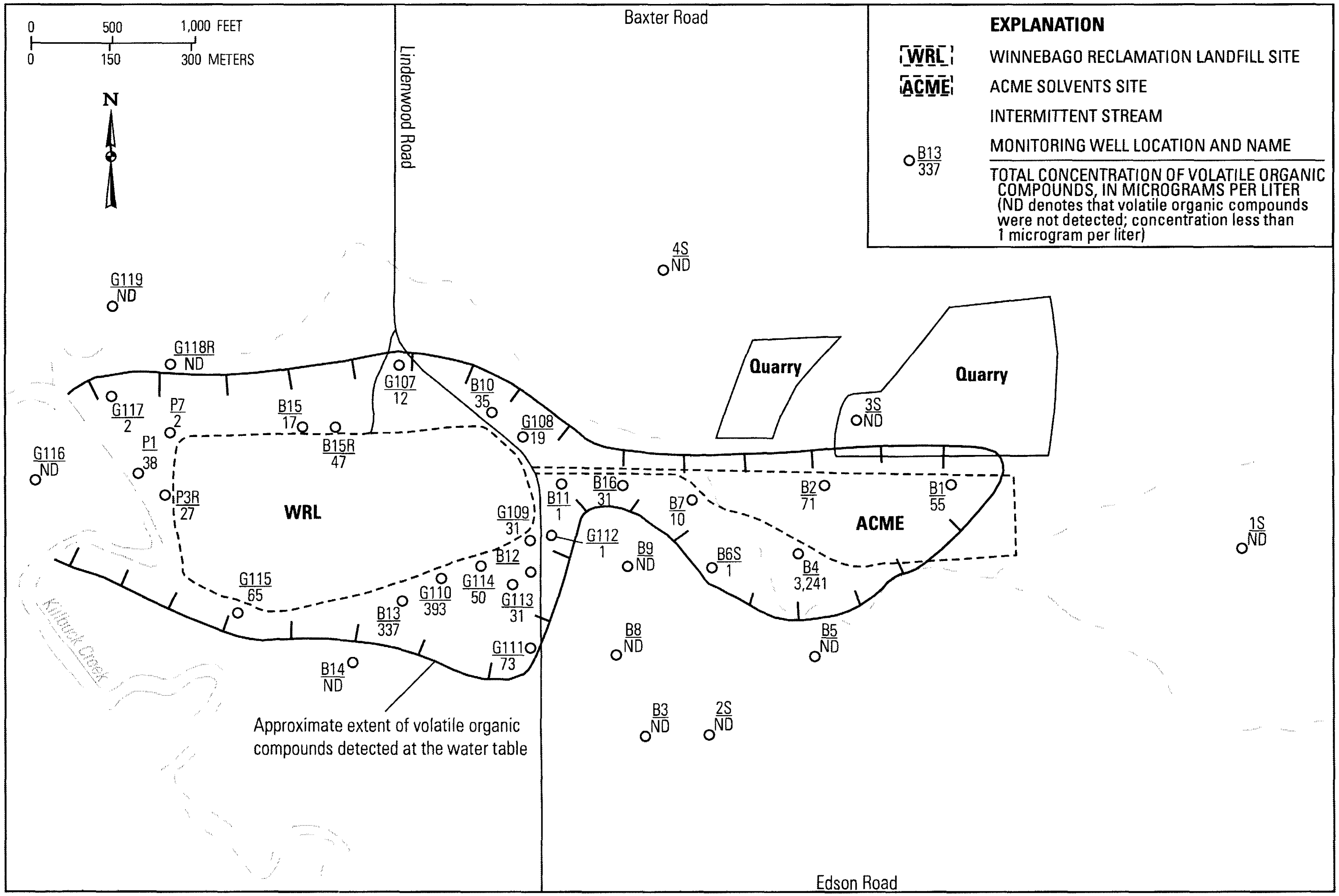


Figure 25. Distribution of volatile organic compounds in water-table wells at the ACME Solvents and Winnebago Reclamation Landfill sites, Ill., summer 1988.

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.

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 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.

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-

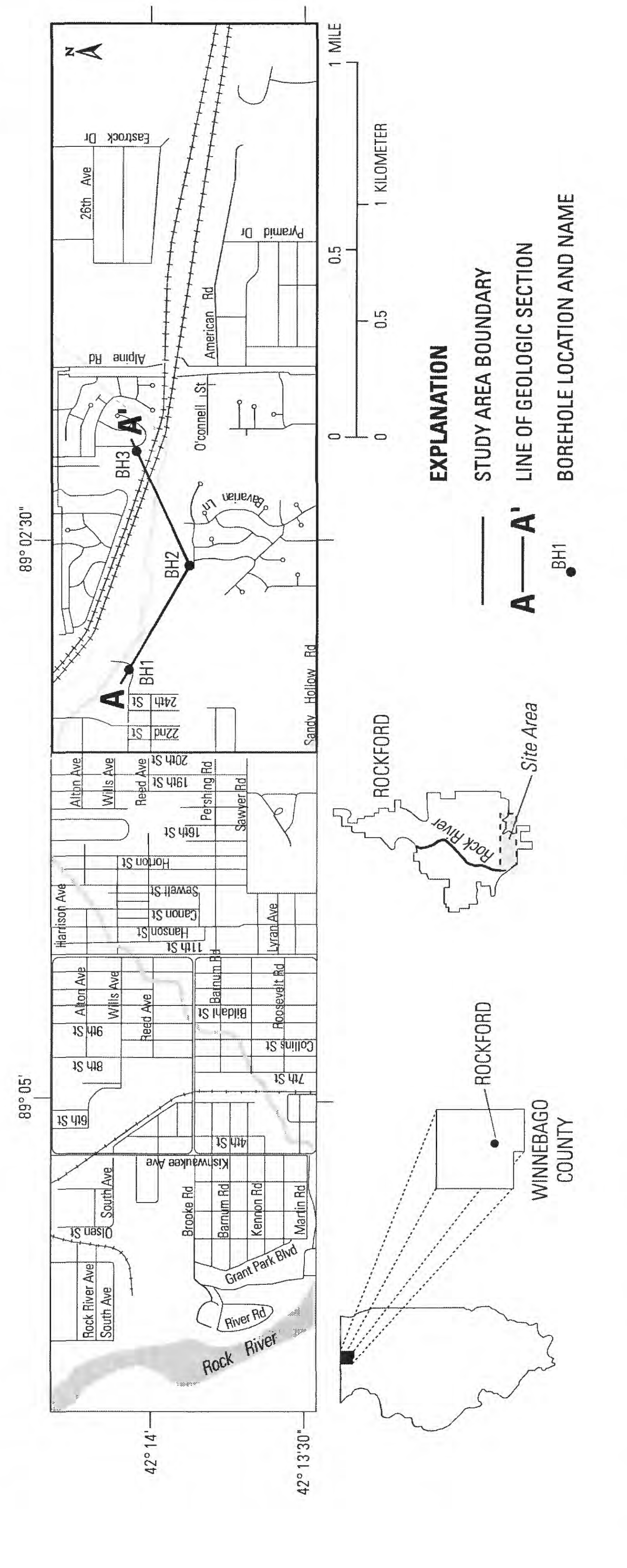


Figure 26. Location of the Southeast Rockford Superfund site, boreholes BH1, BH2, and BH3 and line of section A-A', Winnebago County, Ill.

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 mi^2 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-

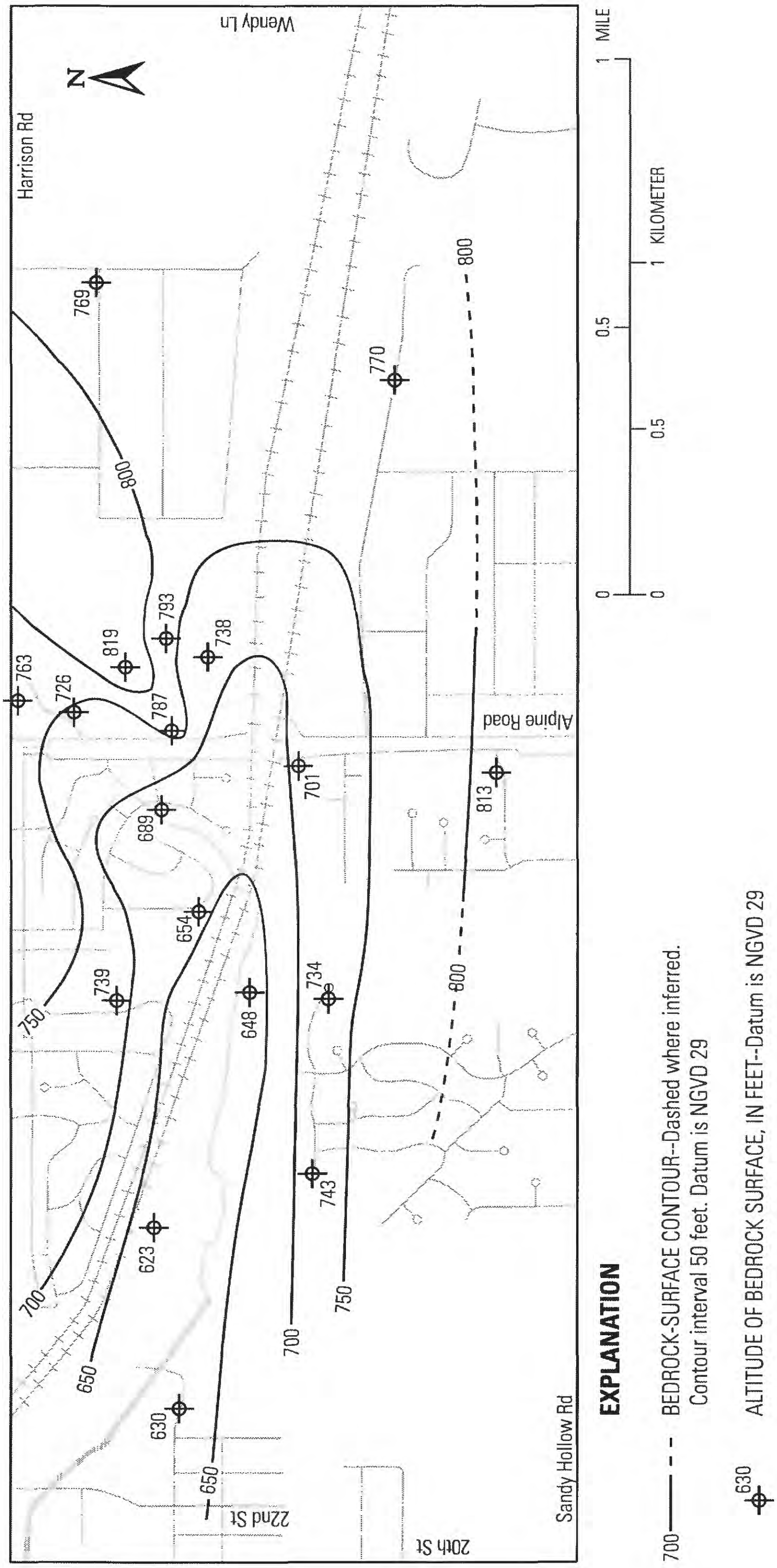


Figure 27. Bedrock surface topography at the Southeast Rockford site, Ill.

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

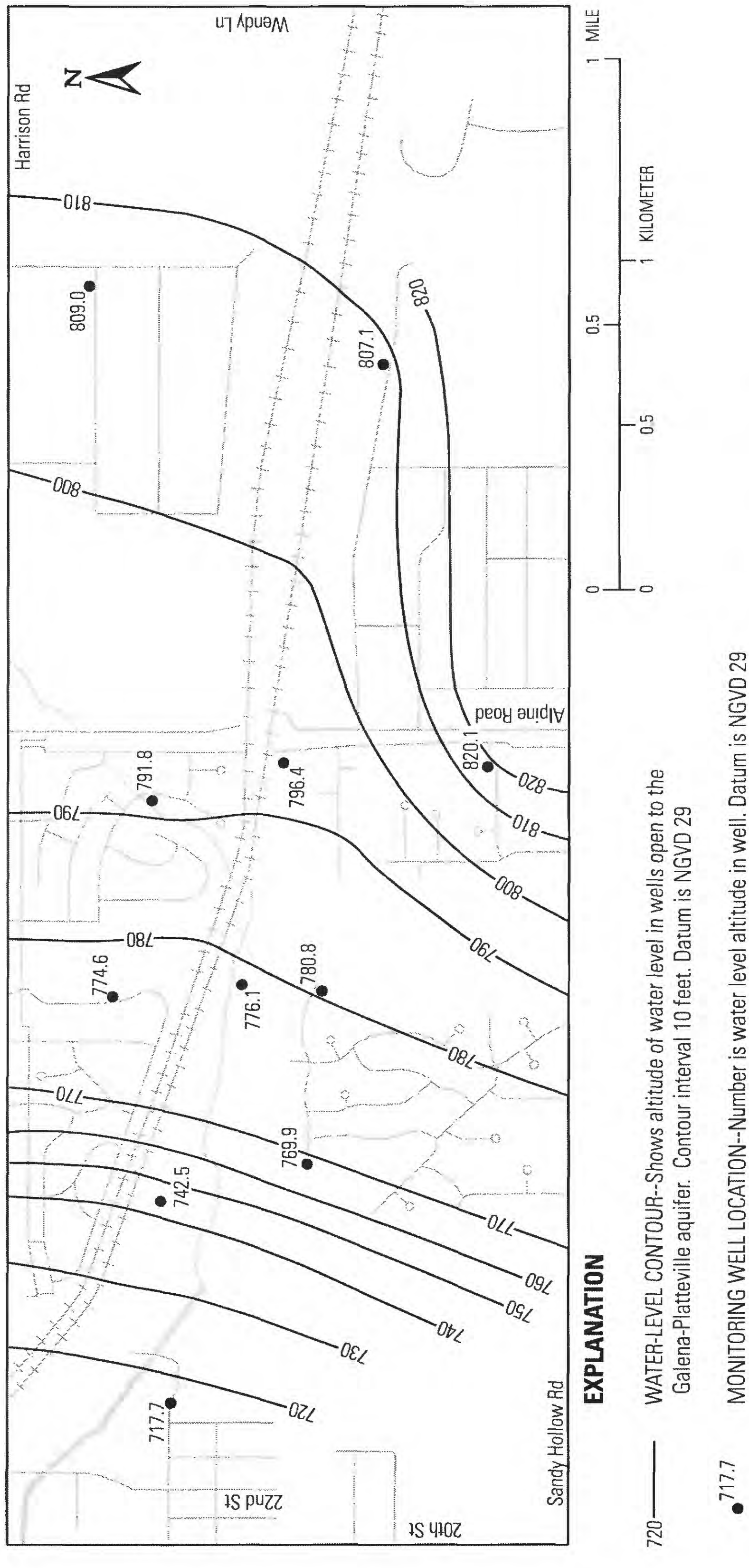


Figure 28. Potentiometric surface of the Galena-Platteville aquifer in the vicinity of the Southeast Rockford site, Ill., October, 1991

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

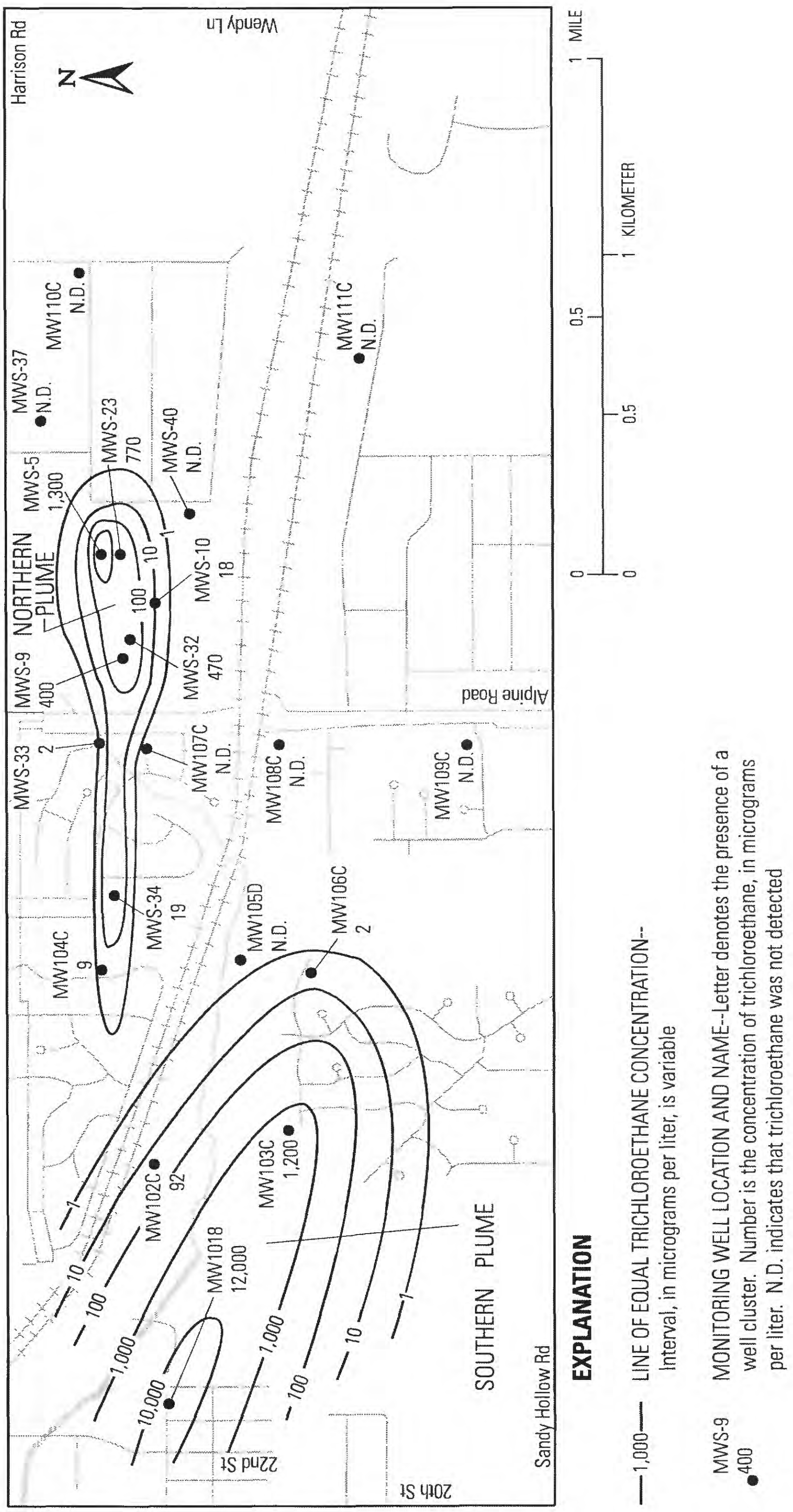


Figure 29. Concentration of trichloroethane in ground water from the Galena-Platteville aquifer at the Southeast Rockford site, Ill., October 1991.

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

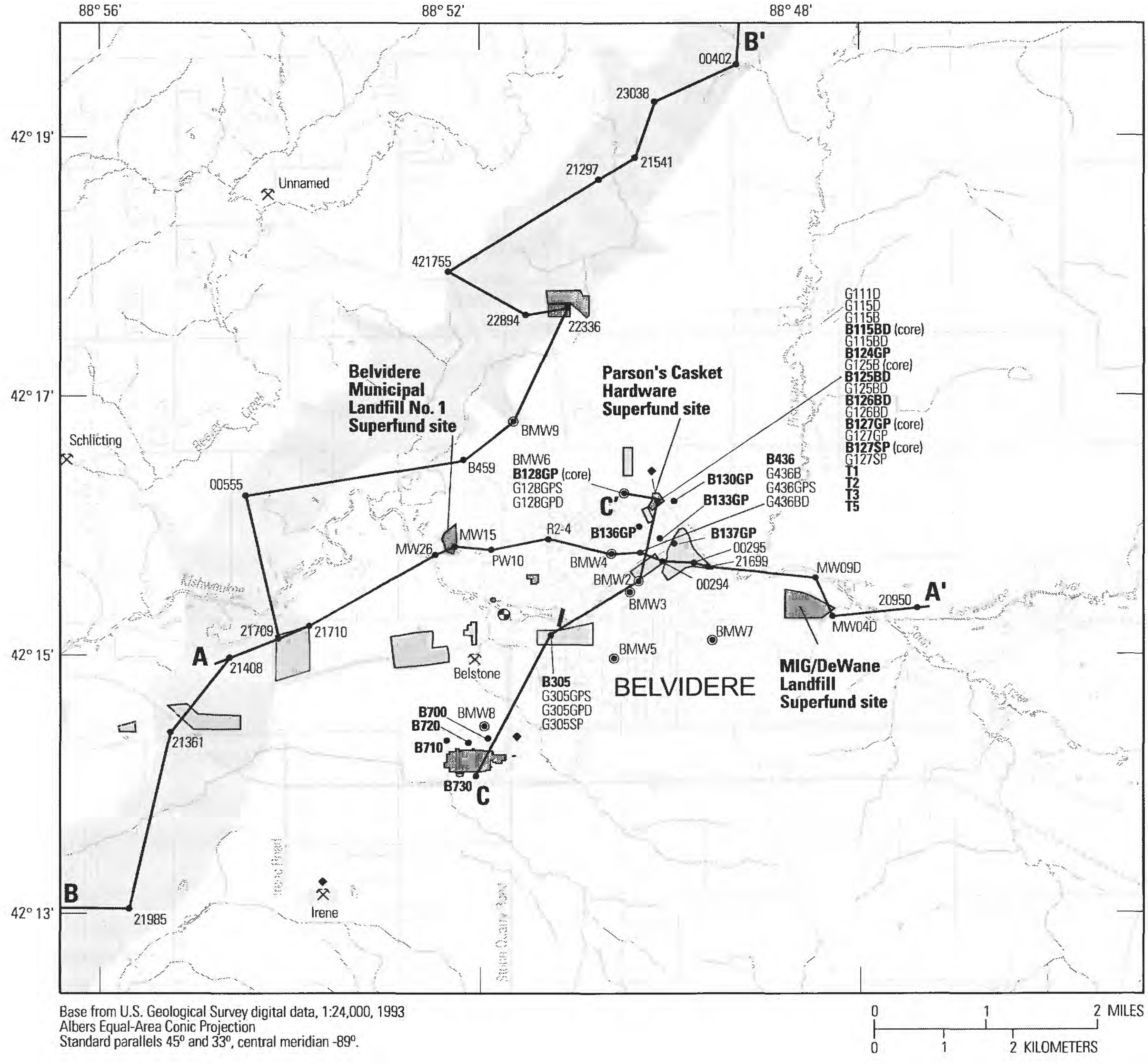


Figure 30. Study area in the vicinity of Belvidere, Ill., including selected hazardous-waste-disposal sites, well locations, quarries, sites of surface-geophysical surveys, and rock cores.

EXPLANATION

MIG/DeWane Landfill Superfund site — APPROXIMATE LOCATION OF SUPERFUND SITE AND DESIGNATION

APPROXIMATE LOCATION OF LANDFILL OR INDUSTRIAL FACILITY OR AREA

TROY BEDROCK VALLEY

QUARRY

RAILROAD

A—A' LINE OF SECTION

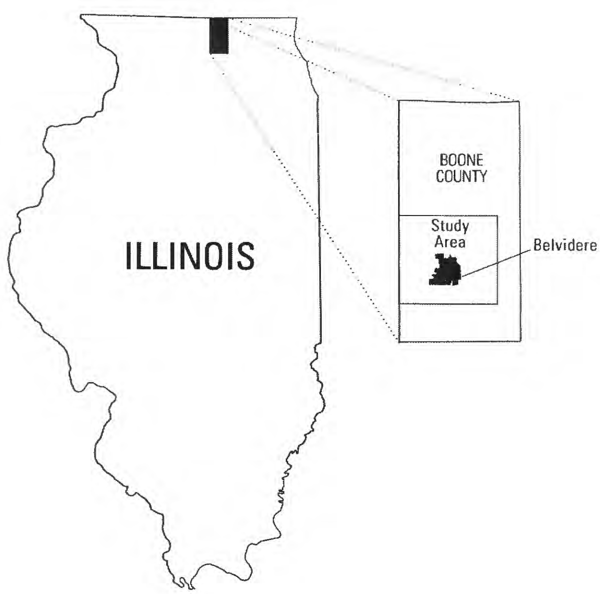
LOW-HEAD DAM

U.S. GEOLOGICAL SURVEY STREAMFLOW-GAGING STATION, 05438500

SITE OF SURFACE-GEOPHYSICAL SURVEY

BMW5 MUNICIPAL WATER-SUPPLY WELL AND DESIGNATION

21297 RESIDENTIAL OR MONITORING WELL AND DESIGNATION--**Bold** designation indicates bedrock borehole; (core) indicates rock core collected



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.

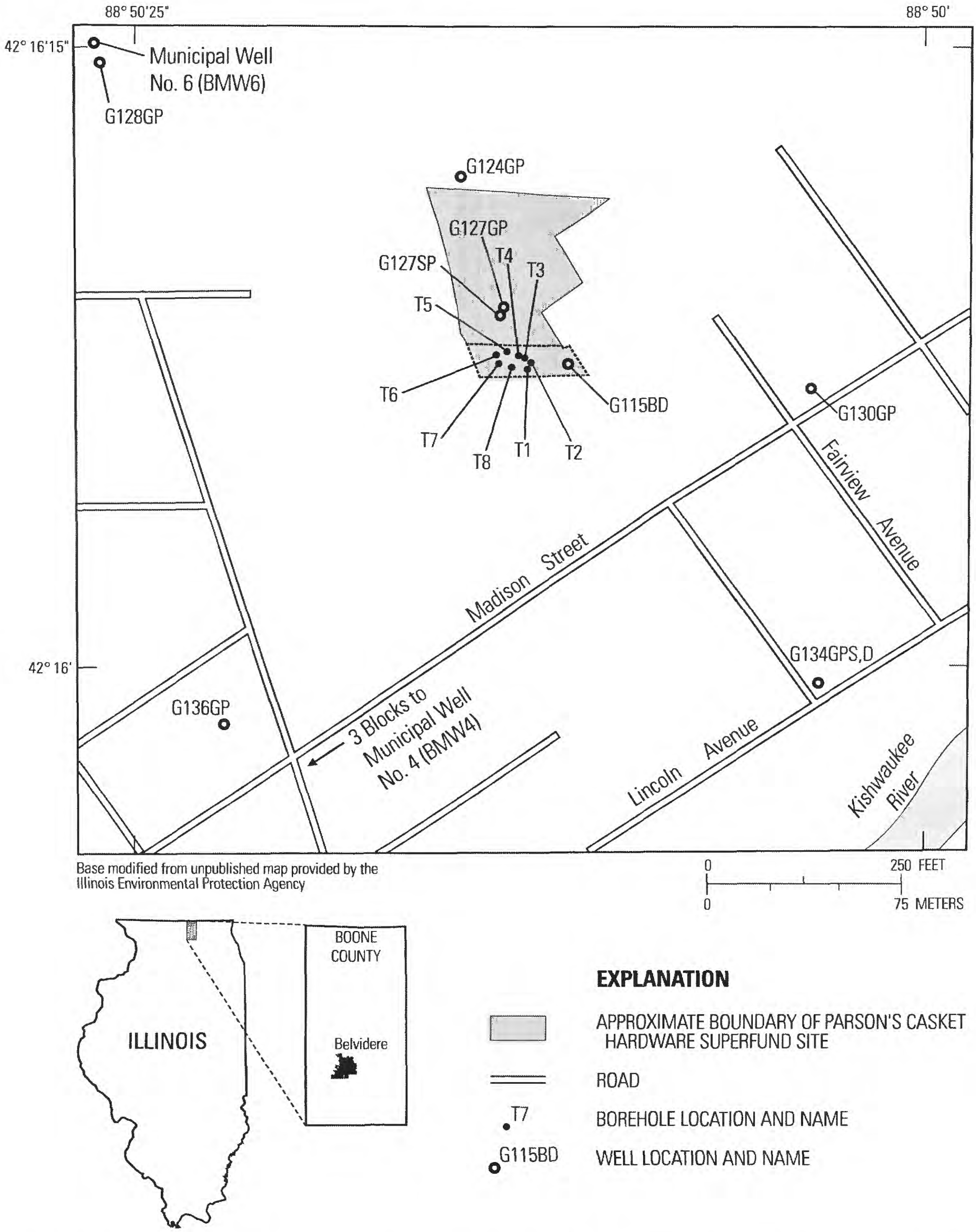


Figure 31. Location of the Parson's Casket Hardware Superfund site and vicinity, including location of select boreholes and monitoring wells, Belvidere, Ill.

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,

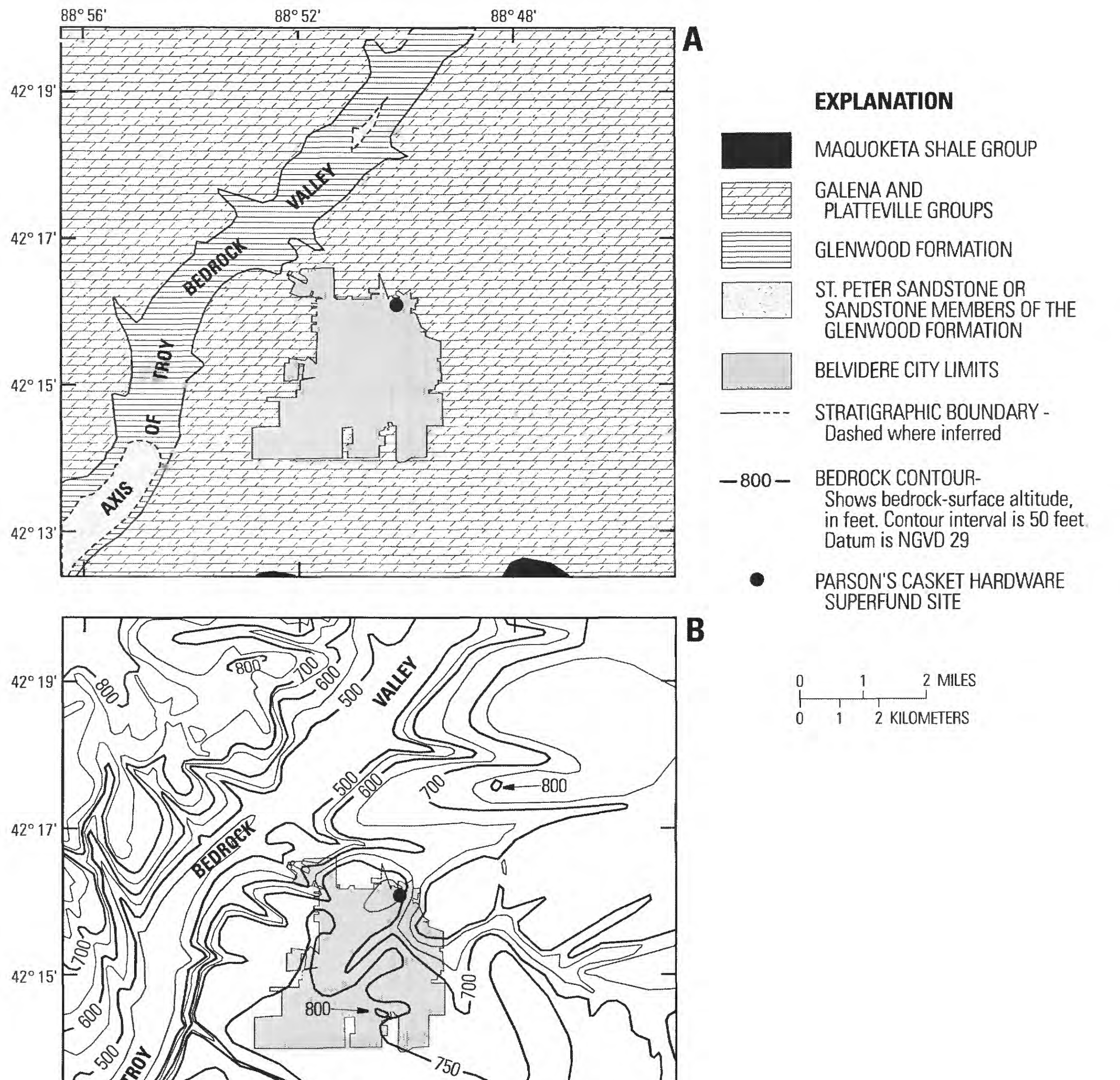


Figure 32. Geology and topography of the bedrock surface in the vicinity of Belvidere, Ill.: (A) stratigraphic units that compose the bedrock surface, (B) topography of the bedrock surface

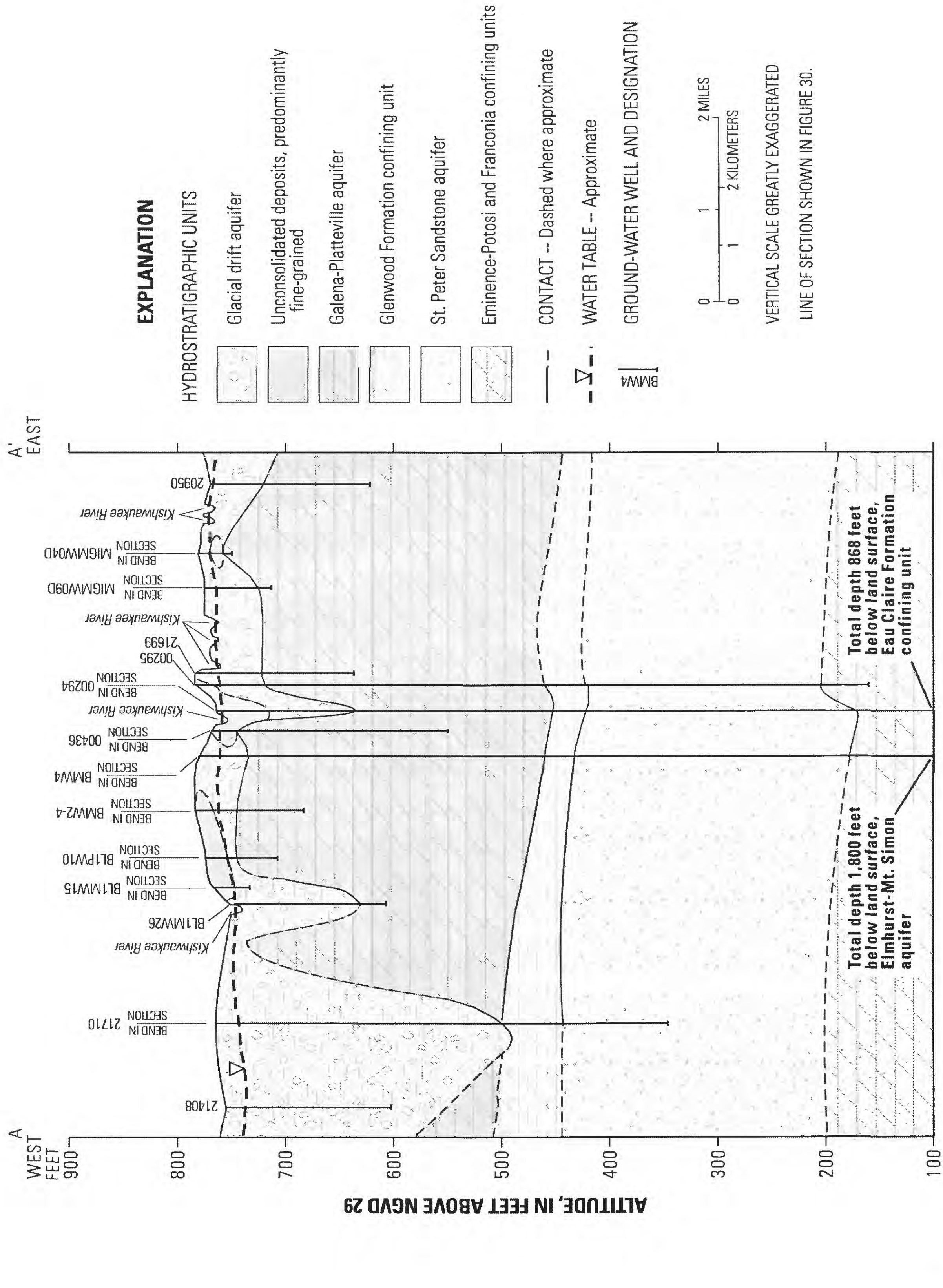


Figure 33. Hydrogeologic section A-A' through the vicinity of Belvidere, Ill.

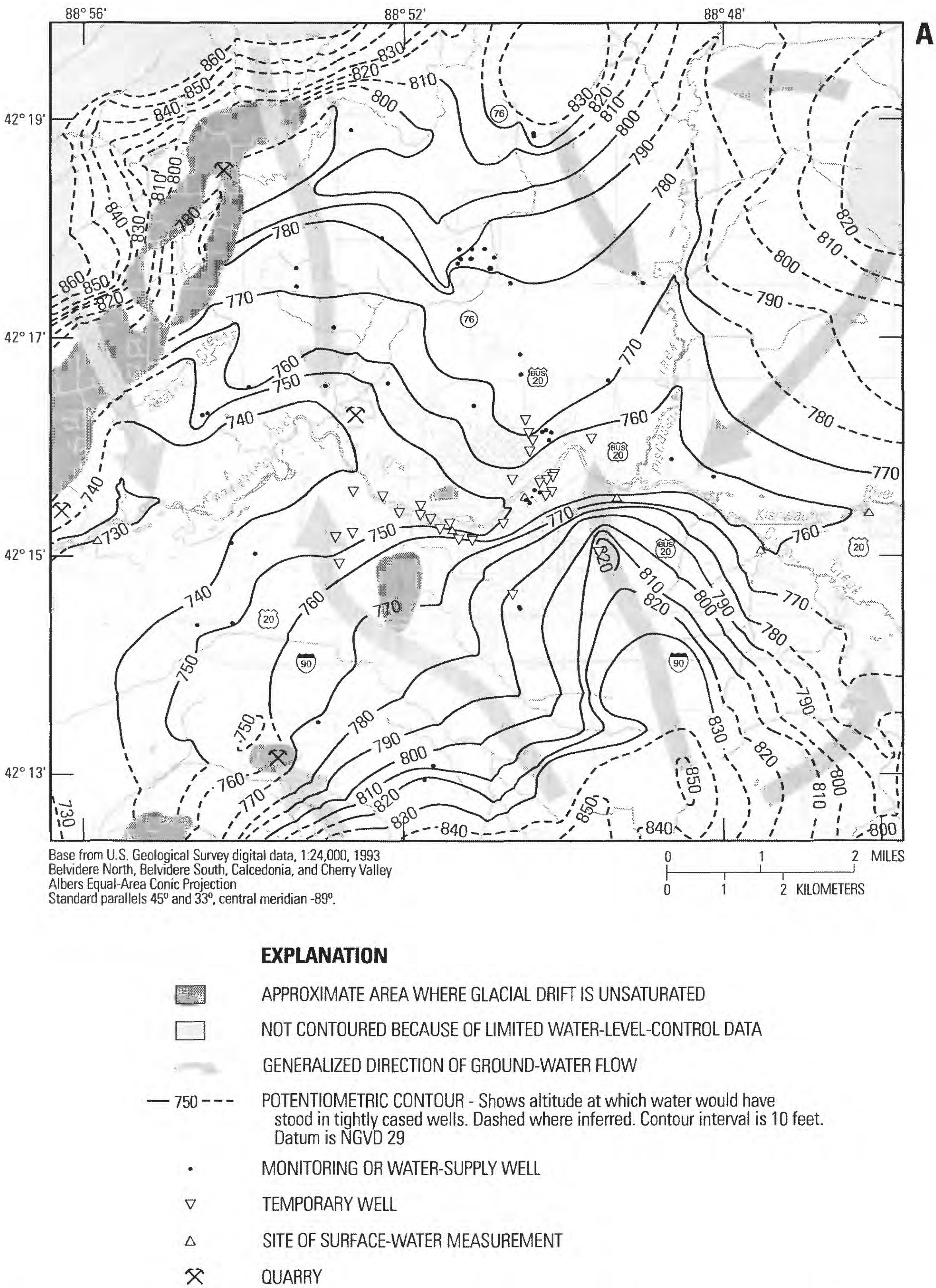
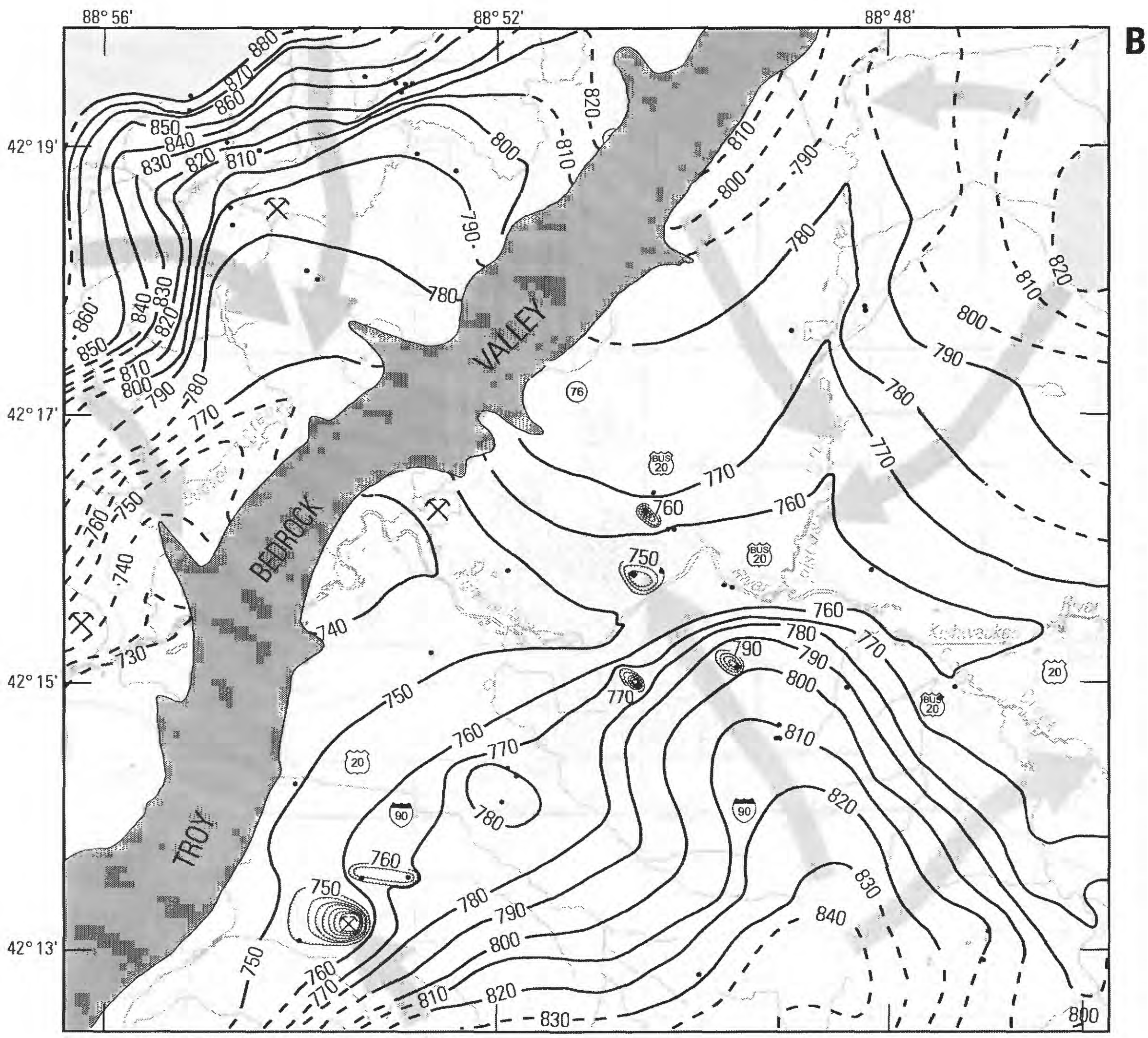


Figure 34. Potentiometric levels and horizontal-flow directions in the (A) glacial drift and (B) Galena-Platteville aquifers underlying Belvidere, Ill., July 1993.



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°.

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

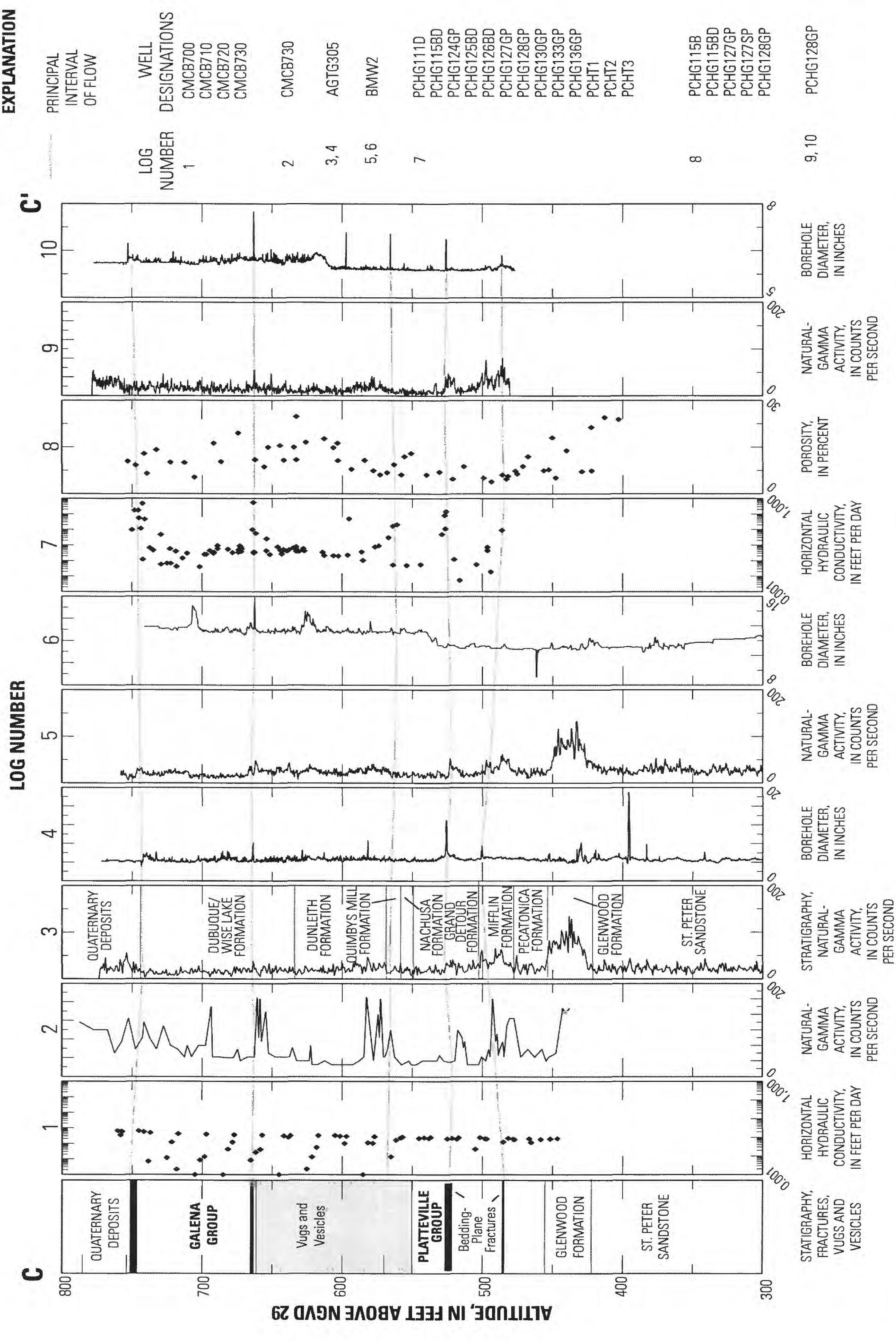


Figure 35. Hydrogeologic section C-C' through Belvidere, Ill., showing rock-stratigraphic units and principal intervals of ground-water flow in the Galena-Platteville aquifer (line of section and location of boreholes shown in figure 30).

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° 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 Kishwakuee 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

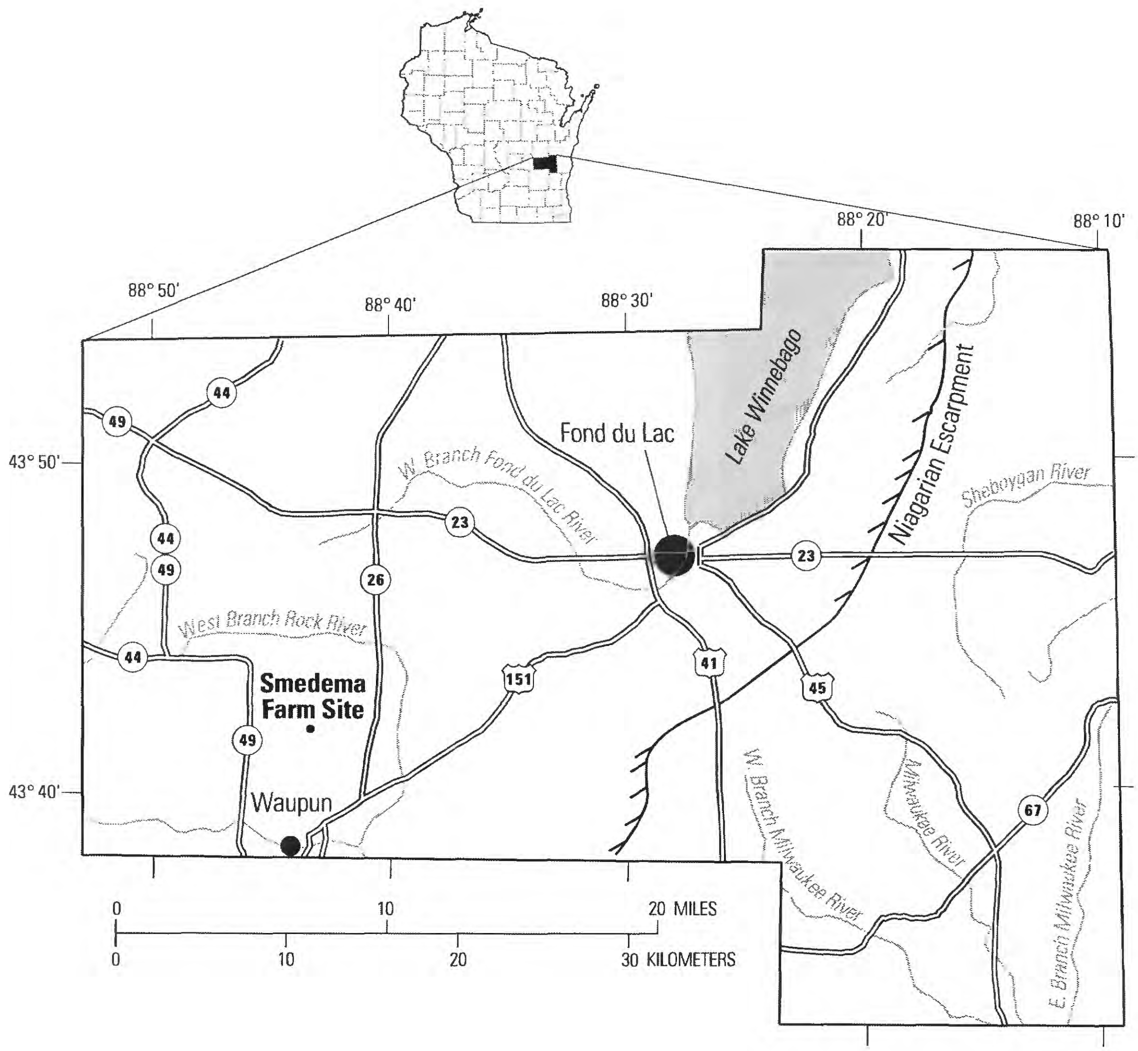


Figure 36. Location of the Waupun site, Fond du Lac County, Wisconsin.

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-

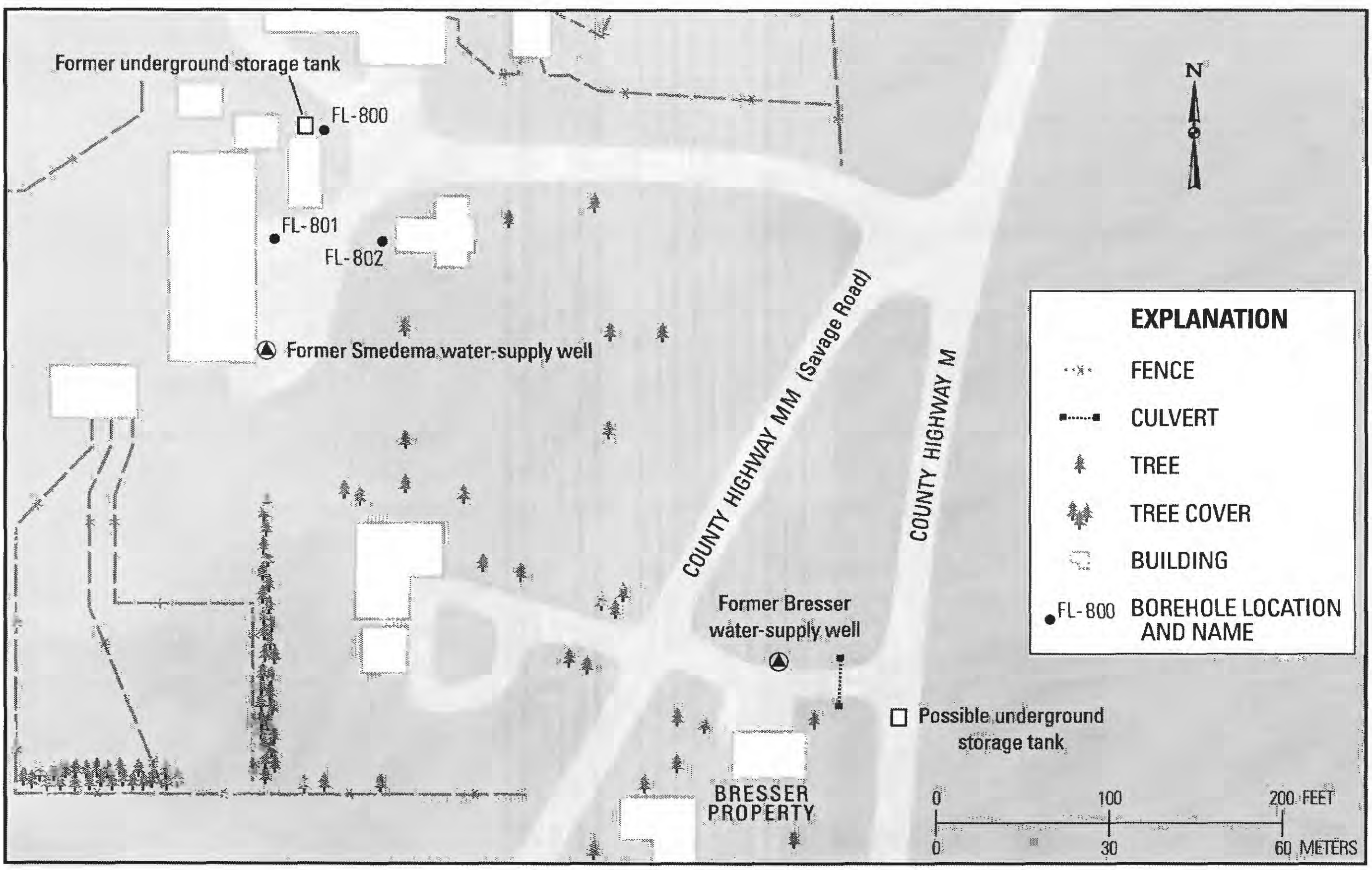


Figure 37. Location of gasoline storage tank and boreholes at the Waupun site, Wis.

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-

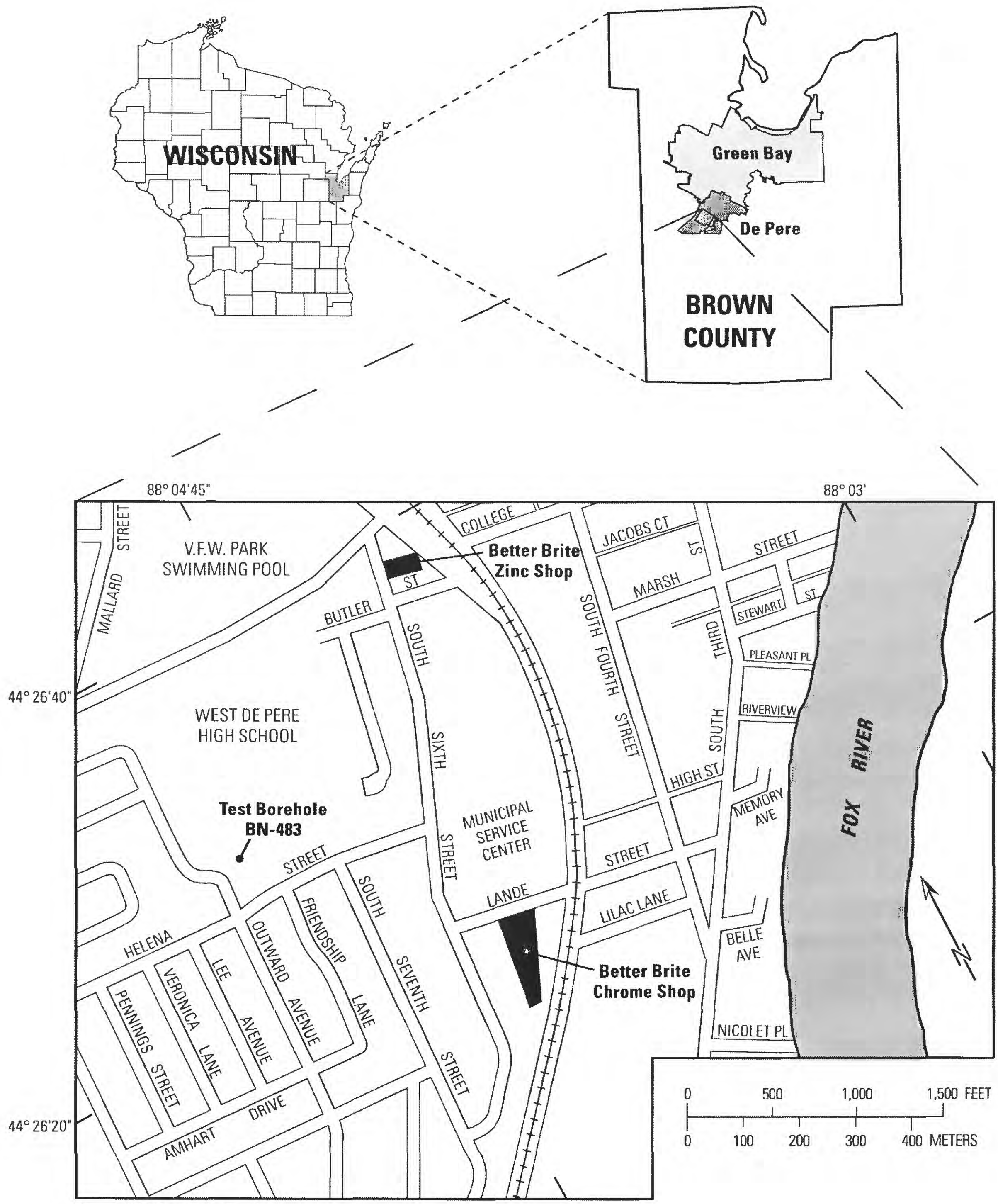


Figure 38. Location of test borehole BN-483, and zinc and chrome shops at the Better Brite Superfund site, DePere, Wis.

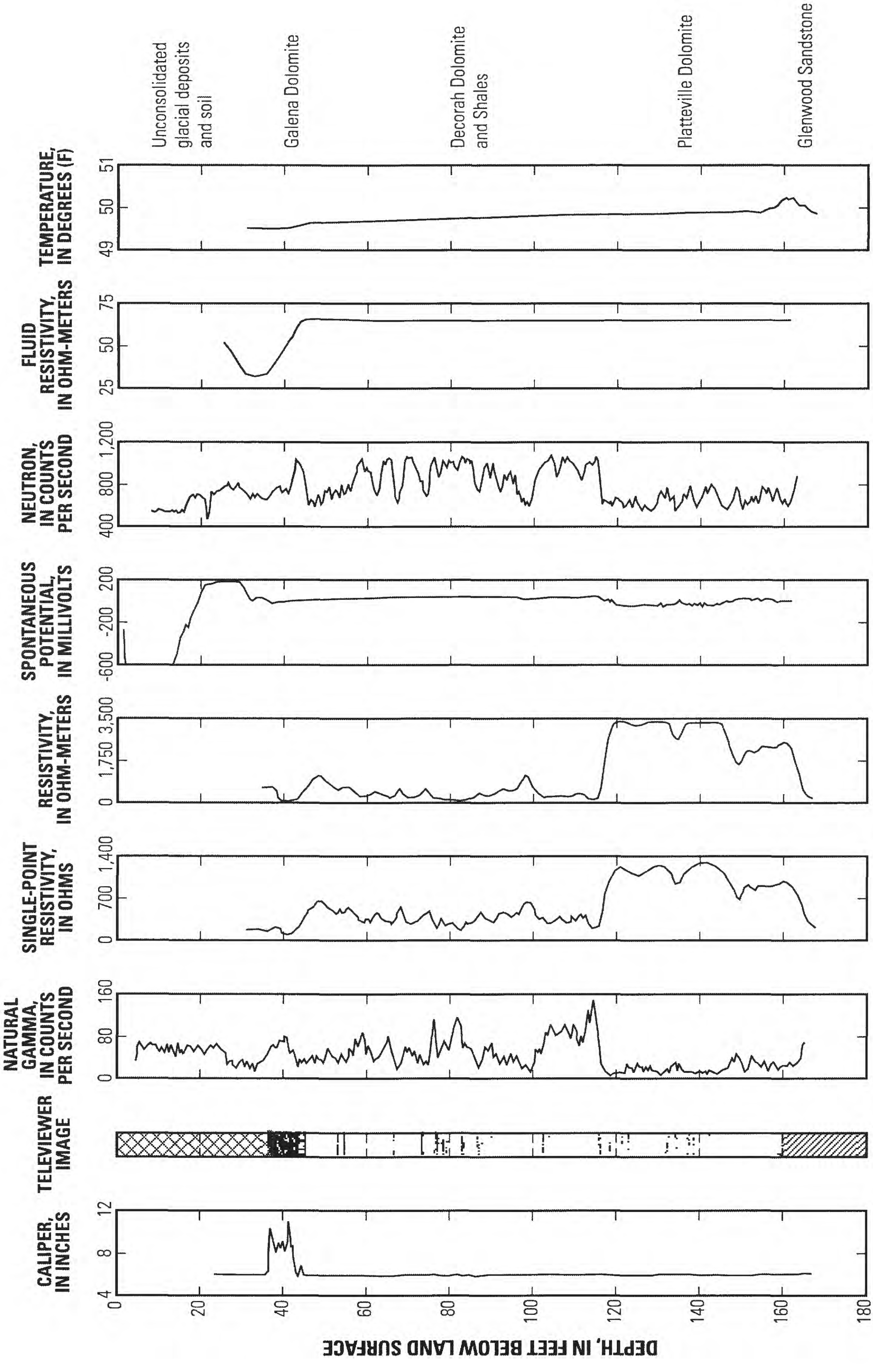


Figure 39. Geophysical logs from test borehole BN-483 at the Better Brite site, DePere, Wis.

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.

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APPENDIXES

Appendix A—Methods of Characterization

A total of 29 methods were used by the USGS and the USEPA for the geologic and hydraulic characterization of the Galena-Platteville deposits in Illinois and Wisconsin (table 1). This discussion is meant to provide more information on the methods, the types of information they provide, and some of the limitations to their use (table 2) so that a better understanding of the study results can be obtained. A full discussion of each method is beyond the scope of this report and persons wishing to obtain a detailed understanding of each method are referred to the references cited in this appendix.

Background Information

Data from numerous background sources were used for the investigations of the Galena-Platteville aquifer and much of that data formed the foundation for the discussion on the geology and hydrology of the aquifer presented in the report. However, the utility of background information obviously is not restricted to investigations of the Galena-Platteville aquifer and a review of available geologic, hydrologic, topographic, and water-quality data will benefit any hydrogeologic investigation.

Federal and State Databases

A primary source for background hydrogeologic data is Federal and State databases. The most comprehensive Federal database used here is the USGS National Water Information System (NWIS). Geologic, hydrologic, and well-construction data can be found in the Ground-Water Site Inventory (GWSI) component of NWIS. Geologic data in GWSI includes lithology and thickness of rock units; hydrologic data include aquifers penetrated by the wells, water levels, and the hydraulic properties of the aquifer. Water-quality data can be found in the Water-Quality database (QWDATA) component of NWIS. NWIS data can be obtained from USGS offices or through the World Wide Web at *http://waterdata.usgs.gov/nwis/qw*. Extensive water-quality data also are available in the database, STORET, maintained by the USEPA. STORET data can be obtained through the World Wide Web at *http://www.epa.gov/STORET/*. Similar data also are available from various State-maintained databases.

Previous Studies

Previous studies and reference bibliographies for locations in and near planned areas of investigation are sources of valuable basic and interpreted hydrogeologic and water-quality data. Previous investigations generally fall into two categories, area and site specific. Area investigations typically present data from a large geographic area that includes or is near the site of interest. Area investigations are best suited for development of conceptual models and to plan initial data collection. Previous site-specific investigations typically are used to identify gaps in the understanding of hydrogeologic or chemical conditions at a site.

The types of previous investigations and availability of information is variable. Reports pertaining to investigations performed by the USGS or State scientific surveys can be identified with comparative ease by a reference search. For example, Brown and others (1997) compiled the listing of readily available reports pertaining to the geology, hydrology, and water quality of the Galena-Platteville deposits in the subcrop area. Investigations performed by the USGS and State scientific surveys typically are available readily from the agencies and university libraries. Reports prepared by or for the USEPA or State environmental protection agencies, such as for Superfund sites, generally are public documents, but their distribution typically is limited and their availability usually is not widely known. Reports prepared by other Federal and State agencies, such as a State department of transportation, usually have similar distribution limitations and these reports may need to be requested specifically from the agency. For example, investigations regarding leaking underground storage tank sites in Illinois only can be accessed through a Freedom of Information Act request. Another valuable source of background data is reports prepared by private geotechnical firms for corporate clients. However, these reports commonly are not publicly available.

Analysis of Topographic Maps and Aerial Photographs

Large faults, inclined fractures, and zones of carbonate solution, in some cases, can be identified at land surface in aerial photographs and in topographic maps (Lattman and Matzke, 1961). The surficial expression of these features may provide information on their orientations, locations of preferential flow, anisotropy within the bedrock, and boundaries of ground-water-flow systems. Features may be visible as patterns of stream drainage or vegetation, for example. Potential for misidentification of anthropogenic features (such as hedge rows and power lines) as natural linear features requires that identified features be field verified.

Extensive subsurface solution of carbonate deposits can result in development of sinkholes and other karst features that can be identified on topographic maps and aerial photographs as dry or water-filled circular depressions and centripetal drainage patterns (drainage lines converge into a central depression). Development of sinkholes and other karstic features can be indicative of an extensive network of secondary-permeability features in the subsurface.

Because ground water typically discharges to surface-water bodies, ground water usually flows from areas of higher surface topography to areas of lower surface topography. As a consequence, analysis of surface topography and the location of surficial hydraulic features can provide a preliminary identification of the direction of ground-water flow. Areas of elevated surface topography usually correspond to areas of elevated bedrock topography, which may be associated with comparatively competent impermeable rock.

Topographic analysis is a potentially useful method for obtaining a preliminary indication of the permeability distribution and directions of preferential flow in the bedrock. This method is best suited for identification of large features in areas where glacial deposits are thin or absent.

Topographic maps at a scale of 1:24,000 and photographs at a scale of 1:12,000 can be obtained from the USGS through the World Wide Web at *http://geography.usgs.gov/www/products/1product.html*. Other topographic maps and aerial photographs also may be available from various Federal and State agencies, and private vendors.

Observations at Quarries and Outcrops

Quarry and outcrop exposures provide an opportunity for inspection of the lithologic composition, texture, bedding, secondary-permeability features (vugs, bedding-plane partings, faults, fractures), and weathering characteristics of the exposed deposits (fig. A1), which form the basis for their stratigraphy. The spacing, location, and orientation (strike and dip) of these features can be measured and the connectivity of the features estimated. Rock exposed in quarries can be affected by stress release, which produces fractures that are not indicative of in-situ conditions, potentially resulting in an inaccurate estimation of the density and orientation. Also, weathering, erosion, and vegetation growth potentially can obscure the presence and orientation of some features.

Hydrologic information also can be obtained from quarry and outcrop observations (fig. A1). Seeps along the face of quarries and outcrops can be used to locate preferential-flow paths associated with secondary-porosity features and geologic deposits (beds or larger stratigraphic units) that restrict vertical flow. If a quarry intersects the water table and the water is not withdrawn by pumping, the vertical position of the water table can be approximated.

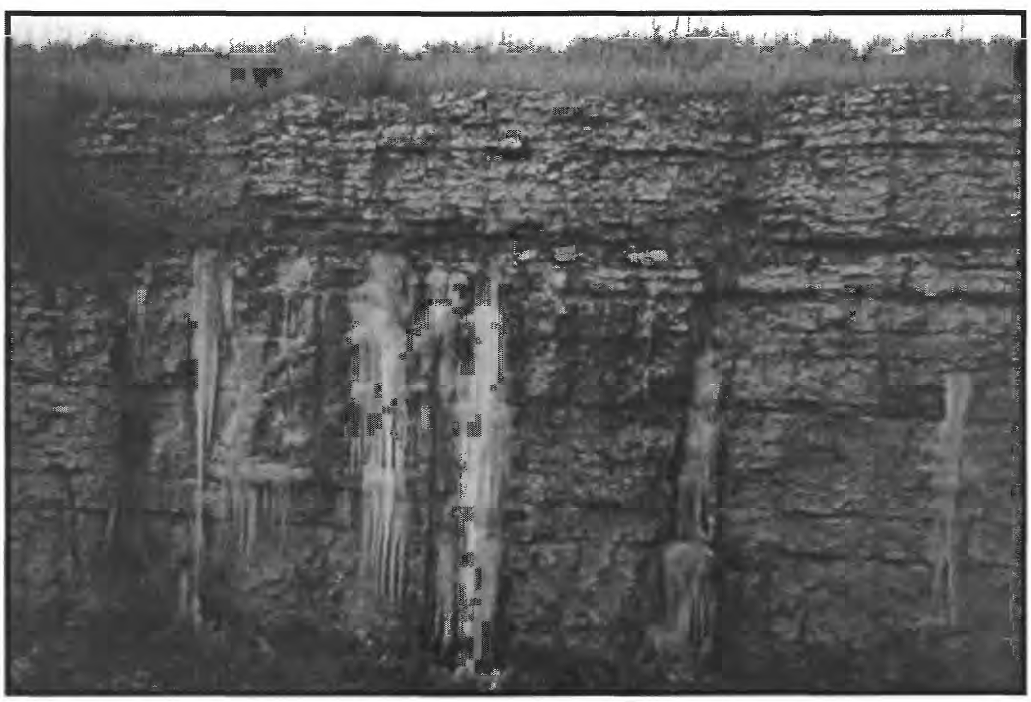


Figure A1. Outcrop of Galena-Platteville deposits in northern Illinois. Photograph by Patrick Mills.

Surface Geophysics

Surface-geophysical methods can provide additional information on hydrogeologic conditions at a site prior to drilling. Surface-geophysical methods, such as square array resistivity and ground-penetrating radar, can provide a quick and inexpensive (in comparison to drilling) preliminary assessment of geologic conditions at a site, including the location and orientation of fractures and sinkholes. However, the utility of surface-geophysical methods is dependent highly on a contrast between the properties of the secondary-permeabilty feature and the surrounding geologic media, as well as the properties of the media between the feature and the land surface. This dependency limits the utility of surface-geophysical methods in the identification of small or deep secondary-permeability features, which may be important to flow and contaminant transport. In addition, surface-geophysical methods usually require data collection from boreholes or wells to verify interpretations. Surface-geophysical methods used to characterize the Galena-Platteville aquifer during these investigations were limited to square-array resistivity and ground-penetrating radar.

Square-Array Resistivity

Electrical resistivity is a physical property of rock and is dependent on a number of factors including lithology, porosity, degree of water saturation, and concentration of dissolved solids. Azimuthal square-array resistivity (SAR) measurements involve sending an electrical current into the earth and measuring changes in apparent rock resistivity to the electrical current with respect to orientation of electrodes and induced current paths. This measurement is done by rotating four electrodes arranged in a square about a center point in 15° increments for a total of 90°. The center point of the square is considered the measurement location and, as a rule of thumb, the side length is approximately equal to the depth of penetration. The array is expanded symmetrically about the center point, in defined increments so that the SAR data also can be interpreted as a function of depth.

Apparent resistivity is measured along perpendicular sides of each square and across the diagonals of each square. Changes in apparent resistivity with direction and depth are measured at a single location. The apparent resistivity data are plotted against the azimuth of that measurement and the principal fracture strike direction is perpendicular to the direction of maximum apparent resistivity (fig. A2).

Variations in resistivity readings can be caused by many factors such as slope of the bedrock surface, dip of bedding or foliation, and overburden thickness. The depth of penetration also is affected by the conductivity of subsurface materials—the more conductive the subsurface material the smaller the depth of penetration—and cultural interference such as overhead power lines and buried cables. To correctly interpret azimuthal resistivity data over fractured rock, the bedrock also must act as an anisotropic medium.

Surface Ground-Penetrating Radar

Ground-penetrating radar (GPR) is a high-frequency electromagnetic (EM) method that has been developed for shallow (typically less than 50 ft), high-resolution investigations of the subsurface. GPR can be used to map hydrogeologic conditions that include depth to bedrock, depth to the water table, depth and thickness of overburden, lithologic contacts, and the location of subsurface cavities and fractures in bedrock. Environmental applications of GPR include locating objects such as pipes, drums, tanks, and utilities; and mapping contaminants.

The GPR system pulses high frequency EM waves into the ground from the transmitting antenna (Annan, 1992, Daniels, 1989). When the transmitted radar energy encounters a subsurface feature with contrasting EM properties, a portion of the energy is reflected back to a receiving antenna and the remaining energy is transmitted downward to deeper material. As the antenna(s) are moved along a survey line, a series of scans are collected at discrete points along the line. These scans are positioned side by side to form a display profile of the subsurface. When GPR data are collected on closely spaced profiles (less than 3 ft), these data can be used to generate three-dimensional views of the subsurface.

The principle-limiting factor in depth of penetration of the GPR method is attenuation of the EM signal in the subsurface materials. Scattering of EM energy may become a dominant factor in attenuation if the subsurface is highly heterogeneous. GPR depth of penetration can be more than 100 ft in less conductive materials. However, penetration commonly is less than 30 ft in most soil and rock and can be less than 3 ft in clay and material with conductive pore fluid.

GPR provides the highest lateral and vertical resolution of any surface-geophysical method. Various frequency antennas (from 10 to 1,000 megahertz) can be selected so that the resulting data can be optimized to the projects needs. Lower frequency provides greater penetration with less resolution. Higher frequencies provide less penetration with higher resolution. Vertical resolution ranges from 1-2 in. to about 1 ft. Horizontal resolution is determined by the distance between station measurements, the sample rate, and the towing speed of the antennae.

GPR has been used to locate and characterize fractures and faults (Benson, 1995). The detectability of these features increases with the size of the feature and with the presence of distinctive pore fluids or conductive fill material. GPR can be used to detect subsurface features from less than an inch to 5 or more feet in size (Martinez and others, 1989).

Lithologic Logging of Wells

After a preliminary assessment has been performed through analysis of background information and, perhaps, collection of surface-geophysical data,

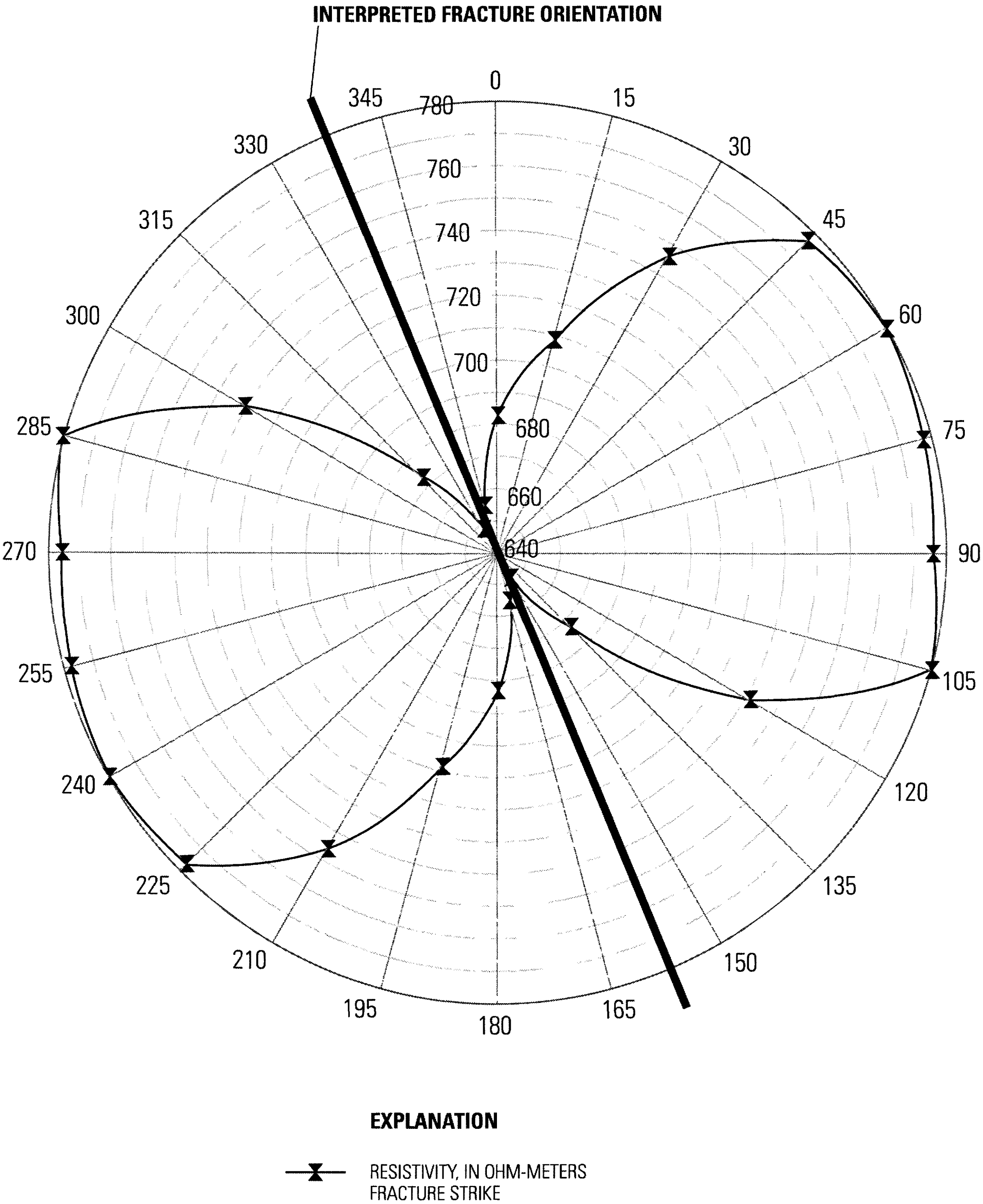


Figure A2. Example results of a square-array resistivity survey (223-foot square) at the Irene Road quarry site near Belvidere, Ill.

well drilling usually is the next step for hydrogeologic investigation. Description of the rock cuttings expelled from the borehole, as a function of depth during drilling, including lithology, presence or absence of fossils, mineralogy, weathering features, forms the primary basis for geologic interpretation at a site. Observation of the drilling speed and the amount of water ejected from the borehole also can provide important insight into the location of secondary-permeability features. For example, comparatively slow drilling rates associated with unweathered rock and minimal increases in the amount of water ejected from a borehole is indicative of competent, unfractured rock. A moderate increase in drilling rate associated with vuggy or weathered cuttings and a small increase in the amount of water ejected from the borehole can be indicative a vuggy deposits or zones of multiple fractures of low to moderate permeability. A sudden increase in drilling speed over an interval of a foot or less associated with an appreciable increase in the amount of water ejected from the borehole can be indicative of a permeable fracture. A sudden increase in drilling speed over an interval of a foot or less associated with argillaceous cuttings and no increase in the amount of water ejected from the borehole may indicate argillaceous deposits or fractures that have been infilled with clay minerals. A sudden increase in drilling speed coupled with the termination or a substantial decrease in the amount of water or cuttings ejected from the borehole may indicate a solution opening.

Identification of the geologic material ejected from the borehole and the depths of water-producing intervals is a standard part of the drilling and serves as the cornerstone of any hydrogeologic assessment. This information can be used to provide a preliminary assessment of the location of high, moderate, and low permeability features in the aquifer and the factors that may affect the permeability distribution. However, a thorough characterization of the hydrogeology of any aquifer, and particularly a fractured-rock aquifer, requires collection of more detailed data.

Core Analysis

Rock coring involves the extraction of (comparatively) undisturbed rock material and allows for its visual inspection. Core inspection can identify lithologic composition, texture, matrix porosity, bedding thickness, erosion and corrosion surfaces developed between depositional cycles, bedding-plane partings, and fractures (opened by stress release and dissolution). From this information, stratigraphy can be determined. Changes in color, such as iron staining, and mineralization (dolomitization), may represent past or present pathways of preferential flow of water and possibly recent contaminant transport. Rock samples obtained from coring can be tested for a variety of geotechnical properties, such as matrix porosity and permeability.

Cores allow detailed inspection of many features that cannot be observed in drill cuttings or are destroyed by the drilling process, making cores particularly useful for detailed analysis of in-situ geology. Cores can allow observation of many geologic features that also can be observed at quarries and outcrops, but because cores have limited spatial coverage, they typically don't provide information on large-scale features (such as vertical fractures) or the spatial variability of features. Laboratory analysis of core samples provides only point-scale information. Cores will not provide information on recent weathering of carbonate units; which for some of the Galena-Platteville deposits is necessary for accurate stratigraphic determination (Willman and Kolata, 1978; Mills and others, 2002a, b). Generally, cores should be greater than 3 in. in diameter for effective construction of a conventional 2-in.-diameter monitoring well in the resulting core hole. Cores should be no smaller than about 2 in. for reliable laboratory analysis of porosity. Collection of cores using angle drilling, as opposed to vertical drilling, will improve greatly the likelihood of encountering vertical and inclined fractures.

Core samples are expensive to obtain and commonly are broken in situ, making it difficult to determine the depth of certain features, particularly fractures, and whether or not the fractures are representative of in-situ conditions or created by the drilling process. As a consequence, limited coring is done in most investigations.

Geophysical Logging

Drilling and coring are the only means of providing direct access to an aquifer. Drilling and coring are expensive, and lithologic logging and core analysis can be subjective, depending on the skill, objectives, and resources of the person providing the description. In addition, drilling and coring gives information only on conditions in the immediate vicinity of the borehole. To maximize and standardize the information that can be obtained from the borehole, geophysical logging usually is performed. Geophysical logging involves continuous or point measurements of geophysical properties, either directly or indirectly, that can help identify geologic, hydraulic, or fluid properties within the borehole. Most geophysical logs convey data by means of a graph with depth scale (Y-axis) and the measured values (X-axis). The utility of the geophysical logs for lithologic and stratigraphic analysis is improved by comparison to detailed lithologic descriptions and results of geotechnical testing.

Natural Gamma

Natural-gamma logs record the amount of radiation emanating from naturally occurring radionuclides, including uranium, thorium, and potassium, in the rock. The amount of radiation emitted by most sedimentary rocks (including the Galena-Platteville dolomite) is related directly to its clay content. Natural-gamma logs can provide data concerning changes in the clay content, which can be related to lithology, stratigraphy, and the presence of clay infilling of fractures and solution openings (figs. 35, 40, A3). These features usually can be correlated across a site and are an important part of any hydrogeologic assessment.

A natural-gamma log can be used in cased or open boreholes, in the presence of clear or opaque fluids, and above or below the water column. The response of the natural-gamma log can be affected by the presence of clays in materials used for drilling or well sealing. The area of investigation is approximately a 1-ft radius from the center of the logging tool.

Spectral Gamma

A spectral gamma log is used to define the specific source (uranium-238, thorium-232, and potassium-40) of the natural-gamma radiation emanating from the geologic formation. By identifying the source of the radiation, some generalizations can be made about the clay mineralogy and the environment of deposition, which can be used to identify the presence of clay-infilled fractures or solution openings. For example, the uranium content in clay-infilled fractures usually is elevated in comparison to that of the bulk of the rock (Fertl, 1979; Fertl and Rieke, 1980). Spectral gamma logging requires measurements be taken at discrete depths in the borehole, rather than continuous profiling and typically can require up to 30 minutes to take a single measurement.

Three-Arm Caliper

The three-arm caliper is a mechanical device that records the inside diameter of the borehole (figs. 35, A3). Caliper tools are calibrated through objects of a known diameter and (depending on the tool) can be sensitive to changes as small as 0.15 in. This type of tool can be used in cased or open holes, in clear or opaque fluids, and above or below the water column. However, an open borehole is required for identification of secondary-permeability features.

Changes in borehole diameter identified with the caliper logs can be associated with a variety of features, including fractures, wash outs, cave ins, solution openings, vugs, well screens, well casing, and cracks in the casing. Caliper logs also can be used to locate intervals of competent rock for setting packers for aquifer and flowmeter tests. Because borehole diameter can affect the response of other geophysical logs, the caliper log also is useful in the analysis of other geophysical logs, including interpretation of flowmeter logs. Although caliper logs can identify variations in wellbore diameter associated with a variety of well construction and secondary-permeability features, it cannot uniquely identify the type of feature, its size, orientation, or if it is permeable. In addition, features with a small aperture at the borehole wall can produce a minimal response on the log.

Borehole Camera

A borehole camera essentially is a small television camera that takes video images of the borehole wall. These images can be viewed on a television monitor and recorded on video tape. Because no natural light is present in a borehole, these cameras have built-in light sources. Two camera lens options typically are available; one lens obtains a down hole view (vertical axis) and the second type of lens provides a horizontal view of the side of the borehole. The side view lens can be rotated 360 degrees to view the entire borehole.

Borehole-camera logs can identify the type and location of secondary-permeability features, depth to water, the presence of cascading water, areas of clear and turbid water, changes in borehole diameter, borehole smoothness or ruggosity, casing conditions, location of foreign objects, as well as identifying some permeable features. The camera can be used in or out of water. The image quality is dependent on water clarity and the tool provides poor results where sediment, algae, or iron flocculate result in opaque water. The camera logs used for the investigations described here could not determine the strike and dip of inclined fractures. Viewing and analysis of camera logs after the initial data collection occurs in real time, which can be time consuming in comparison to other types of logs.

Acoustic Televiewer

The acoustic-televiewer tool scans the borehole wall with an acoustic beam generated by a rotating, rapidly pulsed piezoelectric source as the tool is moved up or down the borehole and the amplitude and travel time of acoustic signals reflected from the wall are measured. A magnetic sensor is used to orient the images. A smooth and hard borehole wall produces a uniform acoustic reflection. The intersection of a fracture, vuggy interval, or solution feature with the borehole scatters the acoustic waves, producing a dark feature on the televiewer image, which can be identified (figs. 40, A3). Because the

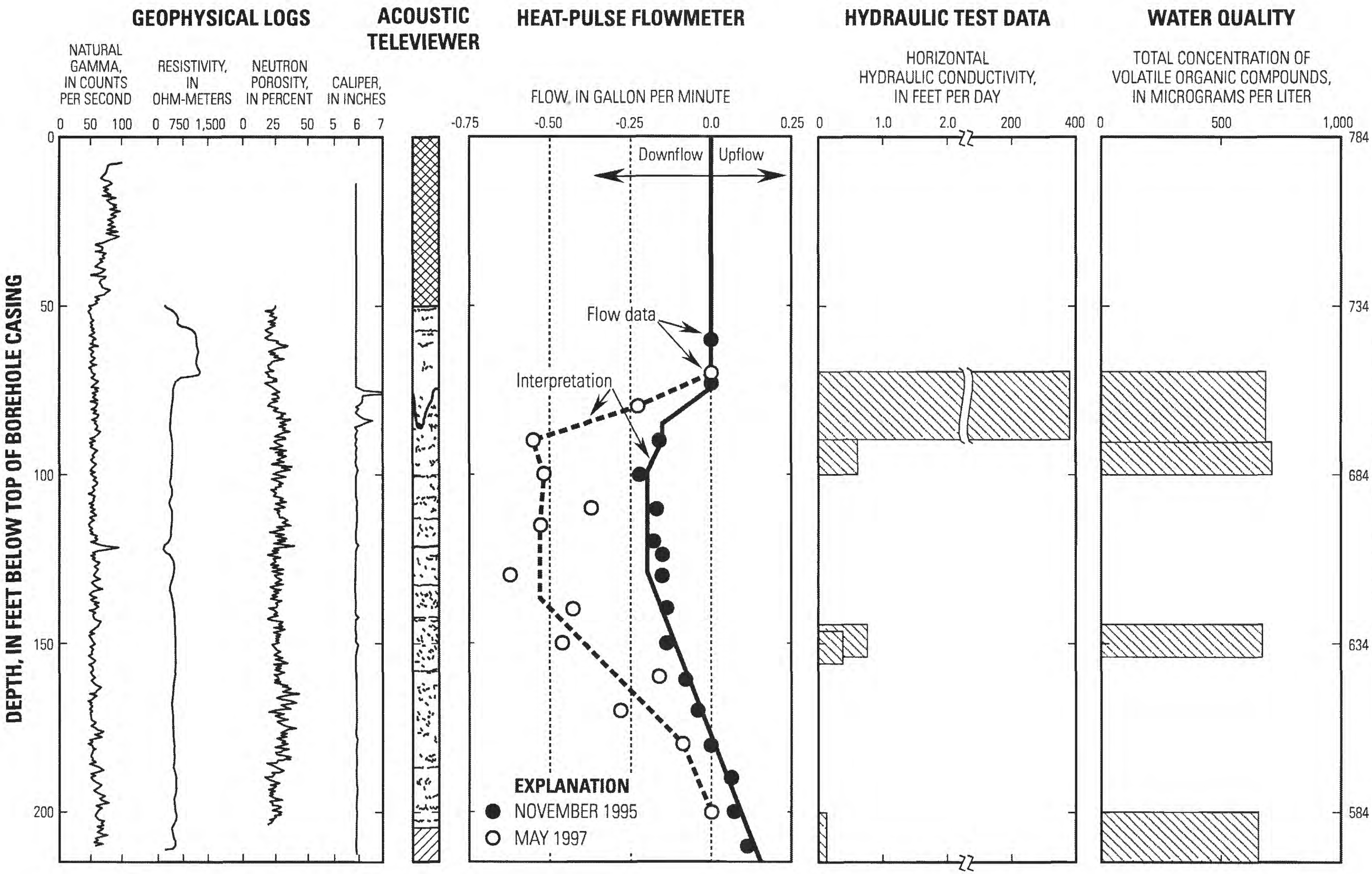


Figure A3. Stratigraphy, select geophysical logs, and horizontal-hydraulic-conductivity data for borehole T1 in Belvidere, Ill.

televiewer image is oriented magnetically, the orientation of the feature can be determined. The televiewer has an advantage over borehole-camera tools because the televiewer can be operated in boreholes with opaque fluids, although certain types of drilling mud in the borehole can affect the log. Successful operation of the tool is dependent on tool centralization, appropriate logging speed and formation/borehole conditions. Tool centralization is required to maintain equal distance travel time for the signals to reach the borehole wall. Because the tool samples 256 travel times and reflection amplitudes per rotation, a logging speed between 2 and 5 ft/min is required to insure effective scanning of the borehole wall. Signal response is affected adversely in boreholes greater than 14 in. in diameter. Some problems may be encountered because of formation characteristics and density. In "softer" formations, the sonic signal may not be strong enough to be received by the acoustic sensor. The more dense formations reflect the acoustic signal, and the log is better imaged. Because a magnetic declination sensor is used in the tool, measurements near metal casing cannot be made. Possible inconsistencies in graphic representation of acoustic-televiewer log signals, such as a non-vertical borehole, are given in Cohen (1995).

Televiewer images can identify the type, apparent size, and orientation of secondary-permeability features intercepting the uncased part of a borehole below the water column. However, these features are not necessarily permeable, and the size, and to a lesser degree the orientation of the feature at the borehole, may not be representative of formation conditions. In addition, televiewer images may detect wash outs of comparatively soft rock (shale, bentonite beds) or impressions in the borehole wall caused by drilling that can be misidentified as fractures.

Spontaneous Potential

The spontaneous potential (SP) log is one of a group of log types categorized as electric logs because they are based on the flow of electric current (fig. 40). The log measures the natural difference in electrical potential between an electrode in the borehole and a reference electrode at land surface. SP logging only can be done in the uncased portion of water- or mud-filled boreholes.

Small spontaneous differences in electrical potential are created by differences in salinity or pressure within the borehole and between the borehole fluid and the formation water (Rider, 1986). The major source of SP is the difference is electrochemical potential produced by differential rates of movement of dissolved ions through shale or through the mixing of water with differing salinity. Changes of SP voltages requires the presence of water with differing chemical properties in the aquifer, a means of segregating these waters within the aquifer, and a point where the waters mix. A lesser source of SP is the physical movement of water, which can generate "streaming potentials" because of differences in the flow of ions through the rock and chemical reactions in the vicinity of the borehole. Changes of SP voltages usually are strongest between contacts of differing lithology, particularly argillaceous and non-argillaceous deposits, or between waters of differing salinity. Changes in SP voltage can be associated with depths where water chemistry in either the borehole or the formation has changed, which can be caused by (among other things) inflow of water into the borehole. Therefore, SP logs can be used to identify secondary-permeability features as well as permeable features in a borehole. Similar to most electric logs, SP logs are affected by the presence of vertical flow of water within a borehole, which can obscure or eliminate differences in the electrical potential between the water in the borehole and the formation. These differences complicate log interpretation.

Single-Point Resistance and Normal Resistivity

Single-point resistance (SPR) logs measure the resistance (opposition of the material to the passage of an electrical current) between an electrode in the tool moving up the borehole and an electrical ground at land surface (figs. 40, A3). The current is induced by a generator and is emitted from an electrode on the SPR tool into the formation. The electrode also measures the resistivity of the formation to the current. Because the electrode spacing is small, thin beds and laminations can be sharply delineated, but investigation depth of the SPR log has no inherent lower resolution limit.

Normal resistivity logs measure millivolt response, calibrated to apparent resistivity (electrical resistance times unit length per unit area) of the formation to an electric current between an electrode on the tool moving up the borehole and an electrical ground at land surface, whereas resistivity is measured between another electrode on the tool and a reference electrode at the land surface. The spacing between the current emitting and potential-measuring electrodes on the tool typically is set at 16 in. (short normal) or 64 in. (long normal), which corresponds to about half the theoretical distance of signal penetration of each log. Although the depth of investigation increases with electrode spacing, the resolution decreases so that the signal associated with a feature (such as a fracture) with a thickness less than the electrode spacing may not be readily identifiable.

Generally, resistance decreases with increasing porosity, borehole diameter, fracture density, and dissolved solids concentration in the water. SPR and normal resistivity logging can provide information on changes in lithology and water quality that can be indicative of the presence of secondary-permeability features. However, these logs only can be done in the uncased portion of water or mud-filled boreholes. As with the other electric logs, the effectiveness of these logs is affected by vertical flow within a borehole obscuring differences in the electrical resistivity and conductivity of the water.

Neutron

The neutron log is one of a group of logs categorized as nuclear logs. A radioactive source in the tool emits neutrons into the formation. These neutrons then interact with hydrogen in the formation and sensors in the tool record the energy degradation of the neutrons as they pass through the formation and back to the sensor. The larger the amount of hydrogen encountered, the larger the amount of neutron adsorption from source to receptor, and the smaller the number of neutrons detected by the sensor (figs. 35, 40, A3). The log is, therefore, principally a measure of the hydrogen content of the formation, which typically is a function of its water content. Water can be present in pore space, or bound in the structure of formation minerals (Rider, 1986).

During ground-water investigations, neutron logs typically are used for estimation of porosity (figs. 35, A3). Although it is possible to calibrate the response of the neutron log to absolute values of porosity, neutron logs typically provide estimates of apparent porosity and typically are used only to evaluate porosity trends with depth.

Depth of investigation into an aquifer is dependent on the porosity but can range from about 2 ft with 0-percent porosity to 0.5 ft with 30-percent porosity (Serra, 1979). Generally, the neutron tool penetrates approximately 6-12 in. into the aquifer (Keys, 1990). The tool can be used in uncased or cased wells, in or out of water; however, the response of the neutron log is affected by whether the tool is in or out of the water column, differences in well diameter, and well construction. The use of a nuclear source for this log can pose regulatory difficulties related to transport and potential loss of the tool in a borehole. Calibration and interpretations of the response of the neutron logs to porosity frequently is complicated by the presence of clay minerals, which contain water molecules in their mineral structure, and shale deposits. These deposits have high total porosity but low effective porosity. Neutron-log calibration assumes that neutron flux is inversely proportionate to the log of the total formation porosity. As a result, the log is less sensitive to porosity at higher values.

Density

Density logs usually are used in combination with neutron logs to determine porosity. Density logs emit gamma rays, which are attenuated by collisions with electrons in the surrounding rock before being detected by a sensor on the logging tool. The counts detected by the probe is affected by the electron density in the formation, and is assumed to be inversely proportionate to the logarithm of the bulk density of the rock. Density logs can be calibrated to absolute values of bulk density for homogenous geologic materials. If the bulk density of the rock minerals is known (a pure dolomite with no pore space has a bulk density of about 2.85 grams per cubic centimeter) and the density of water is assumed to be 1 gram per cubic centimeter, calibrated bulk-density logs can be used to estimate the porosity of the deposit (Schlumberger, 1989). However, calibration is subject to a number of simplifying assumptions and density logs usually are used only to determine vertical trends in porosity for hydrologic applications. Density logs can be run in open or cased holes above or below the water column. Density logs do not provide a direct indication of porosity and are affected by the presence of shale that can be variably compacted.

Borehole Ground-Penetrating Radar

The borehole ground-penetrating radar (BGPR) tool can detect secondary permeability features, including fractures, at distances from 10 to 100 ft away from the borehole. Radar measurements can be made in a single borehole reflection (transmitter and receiver in the same borehole) or by cross-hole tomography (transmitter and receiver in separate boreholes). Single-hole, directional radar can be used to identify the location and orientation of fracture zones and other secondary-permeability features. Cross-hole tomography can be used to estimate the orientation, location, and extent of these features between the boreholes. The movement of a saline tracer through permeable features can be monitored by BGPR.

BGPR uses the reflection and transmission of radar-frequency electromagnetic waves to detect variation in subsurface properties. The principles of borehole-radar reflection logging are similar to those of surface-radar profiling, except that antennas are connected together and lowered down the borehole. A radar pulse is transmitted into the bedrock surrounding the wellbore and moves into the formation until it encounters material with different electromagnetic properties, such as a fracture, void, or different lithology (fig. A4). At this location, some of the energy of the pulse is reflected back to the receiver, whereas the rest continues to penetrate the rock. A radar reflection profile along the wellbore is created by taking a radar scan as the antennas are moved up or down the wellbore. Different features produce a different reflection on the logs.

Cross-hole tomography is the process by which a two-dimensional model of physical properties in the plane between two wells is made. For these tomographic surveys, the transmitter antenna is placed in one well and the receiver antenna in the other. Numerous radar scans are made for each position by moving the receiver along the well at regular intervals. For each scan, the travel time and amplitude of the radar pulse is measured as it travels between the transmitter and receiver. These data then are used to create tomograms that map the radar-propagation velocity and attenuation properties of the rock between the boreholes (figs. A5, A6). Variations in velocity and attenuation can be interpreted to identify fractures, vugs, solution openings, differences in fluid properties, and lithologic contacts in the image plane.

Subsurface conditions and the available equipment limit the use of BGPR methods. In electrically conductive rocks, such as shale, or in saline water, radar waves may penetrate only 3-5 ft (Singha and others, 2000). In electrically resistive rock, the waves may penetrate 100 ft or more. Radar antennae capable of reading higher frequencies provide a more detailed image than those with lower frequencies, but are capable of a smaller distance of penetration. BGPR logs can provide data above and below the water table, but cannot penetrate through metal casing.

Temperature

Temperature logs record water temperature in the borehole (fig. 40). Abrupt temperature changes or subtle changes in the temperature gradient can be associated with inflow of water to the borehole through permeable features. Temperature is a common, easily performed geophysical measurement and can be used to identify permeable features under ambient conditions in the borehole being logged. Temperature logs also can be run in conjunction with pumping in another borehole to identify flow pathways between the pumped and logged boreholes (Robinson and others, 1993). Temperature logs must be run below the water level in an open borehole. Temperature gradients tend to be largest in the upper 5-10 ft of the water column because of interaction with the atmosphere, complicating identification of permeable features near the top of the water column. Changes in temperature and temperature gradients below the upper part of the water column usually are small and hard to identify, as are the precise depths of change.

Fluid Conductivity and Fluid Resistivity

The fluid-conductivity/resistivity log records both the electrical conductivity and resistivity of water in the borehole (fig. 40). Changes in fluid conductivity and resistivity reflect differences in concentration of dissolved solids in the borehole water. Changes in the conductivity or resistivity in the borehole water may be associated with inflow of formation water with different chemical properties and can be used to identify the location of permeable features. Fluid conductivity and resistivity logs must be run below the water column in an uncased borehole. The utility of these logs for identification of permeable features is affected by vertical flow in the borehole and requires water of differing chemical properties. The precise depth of the features also can be difficult to identify.

Borehole Dilution

Borehole dilution or hydrophysical logging is based on profiling changes in the fluid conductivity within a well or borehole through time after the water has been replaced or diluted with deionized water (Tsang and others, 1990; Pedlar and others, 1992). Measurements usually are performed in conjunction with pumping from the top of the water column to induce flow. Measurement of the changes in conductivity with depth through

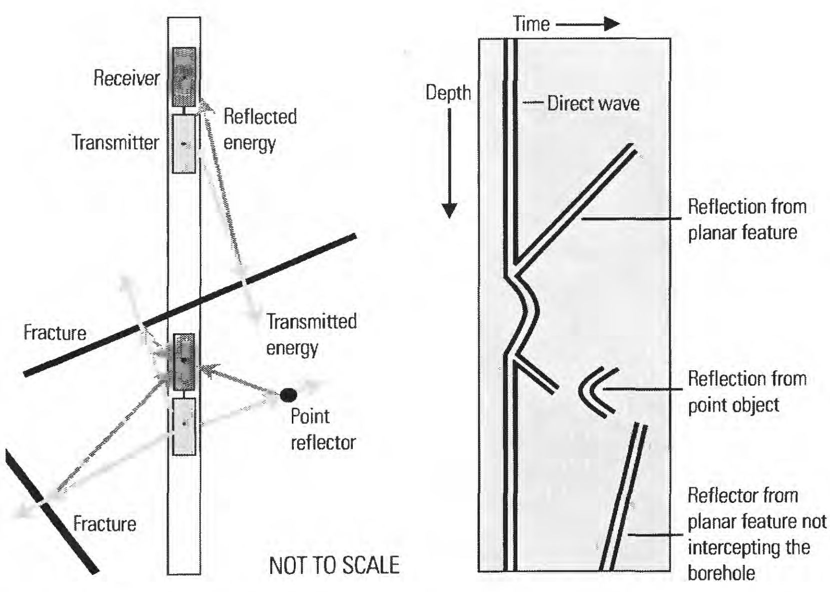


Figure A4. Orientation of borehole ground-penetrating radar transmitter and receiver in a single borehole and the resultant radar record from a fracture and a point reflector.

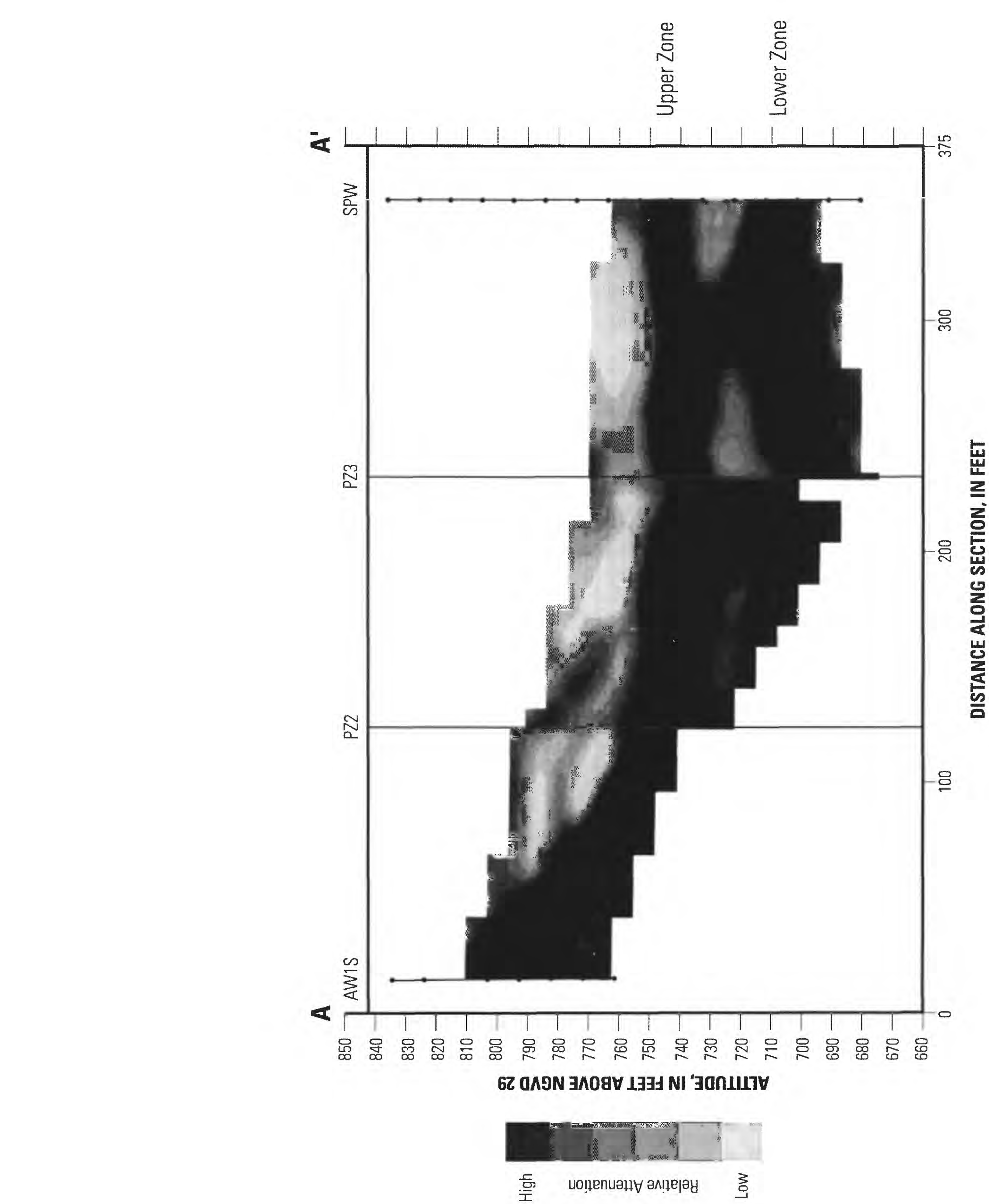


Figure A5. Attenuation tomogram between boreholes AW1S-PZ2, PZ2-PZ3, and PZ3-SPW, Byron site, Ill.

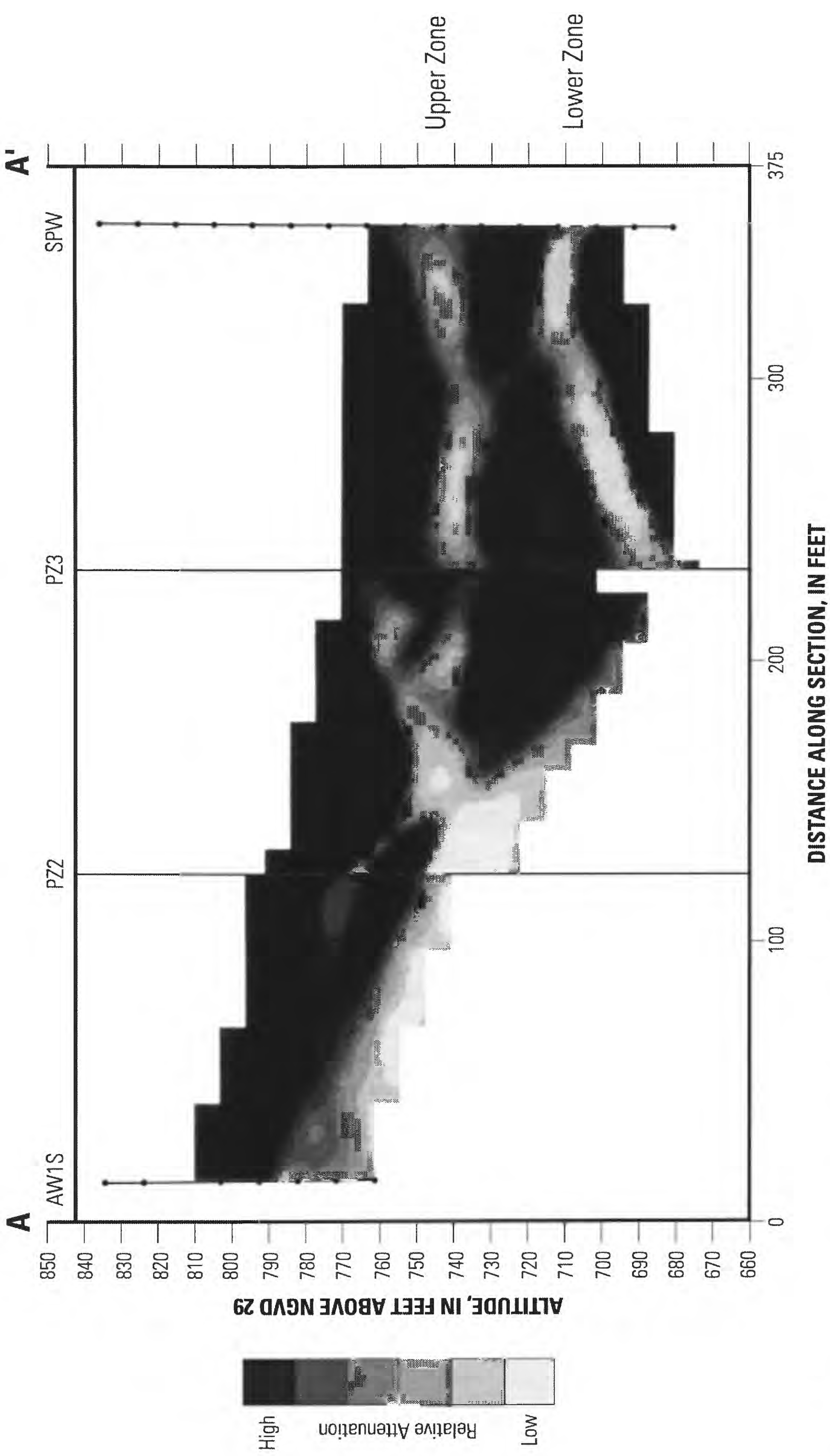


Figure A6. Velocity tomogram between boreholes AW1S-PZ2, PZ2-PZ3, and PZ3-SPW, Byron site, Ill.

time allow identification of the location of permeable intervals, the vertical direction of flow, and the rate of flow for each permeable interval. If reliable estimates of effective well radius can be obtained, hydrophysical logging results can be used to provide estimates of the transmissivity of each of the permeable intervals identified. In addition, hydrophysical logging can be used to interpret the fluid electrical conductivity of the formation water associated with each permeable interval and can be used in combination with other sampling devices to collect water-quality data from the formation at discrete intervals.

Hydrophysical logging can be used in detecting permeable intervals in both low- and high-permeability deposits that intercept the borehole and may have the capacity of detecting smaller amounts of flow (and less permeable features) than heat-pulse and impeller flowmeters can detect (Vernon and others, 1993). Hydrophysical logging can be performed below the water levels in an open borehole or the screened portion of a well. However, the need for deionized water for the logging increases the amount of time and effort required for this method.

Flowmeter

There are a number of different types of flowmeters, including heat pulse, impeller, and electromagnetic induction, each of which operate by different principals, all of which measure the velocity and direction (up or down) of vertical flow at various depths in a borehole. In a borehole of known diameter, water velocity can be converted to flow volume, which can be plotted to profile the vertical distribution of flow (fig. A3). Depth intervals where there are appreciable changes in the volume of flow between measurement stations are interpreted as intervals over which there is inflow to or outflow from the borehole (outflow being hereafter represented as negative inflow). These intervals frequently contain permeable vugs, fractures, or solution openings. In combination with acoustic televiewer logs, flowmeter logs can identify specific permeable features intersecting the borehole. Depending on the type of flowmeter being used and the configuration of the flowmeter measurement section, flowmeter logs can be used to measure discharge rates as low as 0.01 gal/min and as high as 100 gal/min. Flowmeter logs have a scale of investigation of about 10 borehole diameters, or about 5 ft for a 6-in. diameter borehole.

Open boreholes can create hydraulic connections between otherwise isolated fractures, solution openings and permeable beds, causing ambient hydraulic-head differences to drive flow along the borehole. Flow logging under ambient conditions can be an effective way to identify permeable zones in these boreholes. However, ambient flowmeter profiles can be ambiguous. For example, the absence of measurable vertical flow can be attributed to either the absence permeable features at the borehole or the absence of ambient hydraulic-head differences to drive the flow. In general, a single ambient flow profile is not sufficient to estimate the relative hydraulic conductivity of permeable intervals because the amount of inflow in any interval depends on the product of zone transmissivity and hydraulic-head difference driving the flow into the borehole. Furthermore, the water level in an open borehole tends to equilibrate near the hydraulic head of the most permeable feature intercepted by the borehole, minimizing the hydraulic-head difference between the water level in that feature and the water level in the borehole. Thus, natural hydraulic equilibrium can disguise the most transmissive features intersecting a borehole in any single flow profile.

The effects of hydraulic head can be separated from those of zone transmissivity in flowmeter log interpretation by obtaining flowmeter profiles under two hydraulic conditions (usually ambient and steady pumping or injection) (fig. A3). Molz and others (1989) and Paillet (1995) recommend subtracting the zone inflows measured under each of the two hydraulic conditions. This subtraction of inflows method effectively subtracts out the effects of background hydraulic-head variation, so that the differences (expressed as a percentage of the sum of all such differences) gives the relative transmissivity of each inflow zone. This relative transmissivity then can be converted to a quantitative estimate of zone transmissivity if another measurement is used to estimate total borehole transmissivity. Also note that it is assumed with this method that pumping or injection occurs at a rate small enough that "pipe" or friction flow losses associated with vertical flow in the actual borehole can be neglected in comparison with the hydraulic-head differences driving the flow.

A more quantitative approach to flow log interpretation is to simulate borehole flow using a borehole flow model (Paillet, 1998). This method requires that two parameters be estimated for each inflow zone (transmissivity and hydraulic head), and the model used to simulate the flow under ambient and stressed conditions (pumping or injection) and the measured drawdown (change in water level associated with the change from ambient to stressed conditions)(Paillet, 2000). The model parameters then are adjusted systematically until there is minimum difference between computed and measured borehole flow. The modeling method yields direct quantitative estimates of hydraulic head and transmissivity for each zone, but requires a definite estimate of the drawdown associated with the stressed part of the test. If cascading water during injection, lack of appreciable stress during pumping, or interference effects from other pumping in the area prevent accurate measurement of drawdown, the modeling method cannot be used. Although the model results appear to be equivalent to the results of slug testing of discrete intervals isolated by packers, measurement error associated with measurements made in the open borehole restricts the accuracy of model simulation. This result means that inflow associated with less permeable zones cannot be identified within the scatter in the flowmeter data. Paillet (1998) documents that zones with transmissivity two orders of magnitude less than that of the most transmissive zone in a borehole could not be detected in a comparison of flowmeter log interpretation with a set of straddle-packer hydraulic tests in the same boreholes.

Another application of flowmeter logging is cross-borehole testing. Cross-borehole flow logging involves flow logging in an observation borehole during pumping at a constant rate from an adjacent borehole. It is assumed with this method that inflow zones in observation and pumped boreholes already have been identified. Measurements are made in the borehole with the flowmeter held stationary, and the variation in flow with time (flow transient) is recorded as the pump is turned on and off. If there are N flow zones in the observation borehole, the flow transients are recorded at N-1 depth stations between the N zones, and at a depth station above all zones. Thus, there always will be as many data sets recorded as there are water-producing zones to quantify. Data analysis is performed by matching type curves computed with a borehole flow model with the measured transients. The shape of the type curve is used to indicate the nature of the fracture connections in the formation, and the matching of the type curves to the data yields estimates of transmissivity and storage coefficient for each zone (Paillet, 2001). The cross-borehole flowmeter logging is capable of identifying the presence of fractures not intersecting the borehole, and evaluates the properties of the flow path between the boreholes. Although this method is new and relatively few case histories provide independent verification of the method, one recent study indicates that the cross-borehole flow logging yielded results comparable to those obtained with straddle-packer hydraulic tests in the same formation (Williams and Paillet, 2002).

Flowmeter logging must be performed below the water level in an unscreened borehole. The efficacy of flowmeter logging is limited in low-permeability deposits and the representativeness of the flowmeter data are reduced by poor hydraulic connection between the borehole and the surrounding aquifer. Flowmeter logs are capable of detecting inflow though vugs, fracture, or solution openings where the permeability is within two orders of magnitude of the most permeable feature intercepted by the borehole (Paillet, 2001). As a consequence, less permeable features may not be detected in some boreholes. Flowmeter logging is not as widely available as many of the more conventional geophysical-logging methods. Flowmeter logging can be more time consuming and expensive to perform in comparison with other geophysical methods.

Water-Level Measurements

In addition to the hydrogeologic information provided with lithologic and geophysical logging, any assessment of hydrogeology and water quality requires, at a minimum, a thorough understanding of the direction of ground-water flow in three dimensions, as well as definition of the boundaries of the ground-water-flow system, including points of discharge to surface water. The water-level elevation measured in a properly constructed and located well represents the hydraulic head in the aquifer at the open interval of the well and is the principal source of information about the hydrologic stresses acting on an aquifer and how these stresses affect the ground-water system (Taylor and Alley, 2001). Because ground water flows from areas of high to low water-level elevation, plotting water-level elevations within the aquifer through space (the potentiometric surface) can be used to determine directions of ground-water flow and the boundaries of the flow system. In an aquifer with constant discharge through a uniform flow area, there is an inverse relation between hydraulic gradient and permeability of the aquifer. Therefore, variations in the horizontal or vertical-hydraulic gradients within an aquifer may indicate areas where there are variations in the horizontal or vertical-hydraulic conductivity of the aquifer. The scale of information provided by potentiometric-surface maps is dependent on the extent of the well coverage, but typically is on the order of tens to thousands of feet, resulting in the identification of large-scale features in the aquifer.

Limitations are inherent in the interpretation of potentiometric-surface maps. The first is that the development of a potentiometric-surface map usually assumes that the aquifer responds as a porous media, where flow can result in all directions, with the geologic materials affecting flow. In a flow system predominantly affected by a complex network of fractures, flow may not be fully represented with a potentiometric-surface map. Documented cases are present where flow may move in directions up to 180° to what potentiometric-surface maps would indicate as the expected flow direction (Quinlan, 1989). A second limitation is that ground-water systems are dynamic and adjust continually to short-term and long-term changes in climate, ground-water withdrawal, and land use. As a result, ground-water levels vary through time and hydraulic conditions never are fully described. This variation makes the frequency of measurement one of the most important considerations in the design of water-level monitoring programs (Taylor and Alley, 2001). Infrequent water-level measurements at a subset of the total number of available wells at a site or at a single well may provide less insight into details of the site hydrogeology in comparison to more frequent measurements from a larger number of wells, but practical factors, such as budget constraints, may require fewer measurements. The necessary frequency of measurement should be considered in relation to the goals of the investigation as well as the presence of extraneous factors that can affect water levels, such as pumping from the aquifer or if measurements were taken during a period of abnormally low or high precipitation.

Single Measurement

A single measurement of many or all of the wells at a site can provide an accurate depiction of the water-level distribution if the measurements are taken over a sufficiently short time period (Taylor and Alley, 2001)(figs. 13, 19, 23, 24, 28). A single measurement of water levels allows the general direction of ground-water flow, the boundaries of the flow system, and potential variations in aquifer permeability to be identified for the measurement period. In combination with other data types, the water levels also can be used to estimate ground-water velocity. Single measurements are less expensive to collect than periodic measurements and may be adequate to assess hydraulic conditions if not collected during periods of abnormally high or low precipitation, if there is no substantial pumping from the aquifer, and if measurements were taken from an adequate number of properly located wells. However, a single measurement reveals nothing about seasonal or longer-term changes in hydraulic conditions and may not be representative of the full range in flow directions or flow velocities in an aquifer.

Periodic Measurement

Periodic water-level monitoring requires measurement of many or all wells at a site at some time interval, usually quarterly. Periodic measurement of water levels allows for variation or stability in the general direction of ground-water flow to be identified (figs. 23 and 24), can allow identification of the factors that affect variations in flow direction, allows for a realistic range of ground-water velocities to be calculated, can be used to help identify vertical and horizontal variations in aquifer permeability, and can provide a more accurate assessment of the variability of aquifer saturated thickness, which can affect flow and permeability. Periodic measurements are more expensive than single measurements but periodic measurements may be necessary to assess site conditions if flow directions vary because of pumping or seasonal variations in recharge from precipitation.

Continuous Measurement

Continuous water-level monitoring requires the installation of automatic water-level sensing and recording instruments that are programmed to make ground-water measurements at a specified frequency, usually at least daily. Continuous water-level measurements typically are obtained to determine the effects of variations in barometric pressure (fig. A7), nearby pumping, or recharge from precipitation on water levels.

Changes in barometric pressure can affect water levels in wells, the magnitude of water-level change being directly related to the barometric efficiency of the well (fig. A7). Barometric efficiency typically is high in confined aquifers (Todd, 1963; McWhorter and Sunada, 1977) and low in unconfined aquifers. Determination of the barometric efficiency of numerous wells in different parts of an aquifer has allowed previous investigators to identify the presence and location of confined and unconfined parts of an aquifer (Rasmussen and Crawford, 1996).

Offsite pumping may affect flow directions in an aquifer over a period of minutes to years, depending on the hydrogeology of the site and pumping rates. Variations in the water level in a well over a period of minutes or hours, because of offsite pumping, can be used to identify the presence and magnitude of changes in flow direction within an aquifer, as well as provide insight into flow pathways in the aquifer.

The distribution of recharge to a fractured-rock aquifer is affected by the degree to which the fracture network is connected to the ground surface. Water levels in wells that respond quickly to precipitation events are likely to be located in permeable parts of the aquifer, whereas wells that show little response to precipitation events may be located in less permeable parts of the aquifer.

Aquifer Tests

In addition to the hydraulic characterization that can be provided by water-level measurements, more detailed and more quantitative assessment of the aquifer and the secondary-permeability network can be provided by use of aquifer tests. Aquifer tests typically involve stressing the aquifer then monitoring water levels or water quality to enable identification of flow pathways and quantification of the physical properties that affect ground-water flow through specific secondary-permeability features as well as the aquifer as a whole.

Slug Tests

Slug tests involve instantaneous displacement of a volume of water from a well then monitoring water-level response through time as the water level returns to its equilibrium level. These data are analyzed to provide an estimate of horizontal hydraulic conductivity or transmissivity of the aquifer in the vicinity of the borehole. Methods used for data analysis depend on the aquifer type (confined or unconfined) and the manner in which the aquifer responds to the displacement of water.

Horizontal-hydraulic-conductivity estimates can be combined with porosity and water-level information to estimate ground-water velocity. Providing that a sufficient number of locations are available for testing, slug tests can be used to identify vertical and horizontal trends in aquifer permeability.

Slug tests are easy, quick, and inexpensive to perform once a well or borehole has been installed and developed. Estimates of hydraulic properties in deposits of all variations in permeability can be determined with slug tests. Data analysis requires hydrostatic conditions in the aquifer at the start of the test. Waiting for hydrostatic conditions to stabilize can be time consuming and expensive in a low-permeability deposit isolated by use of a packer assembly. Results of slug testing from water-table wells can vary over time because of changes in the saturated/unsaturated state of permeable features at the well. Slug tests also only monitor a small part of the aquifer, typically within 10 ft of the borehole. Analysis of slug-test data requires knowledge of well construction and aquifer geometry, including the length of aquifer open to the well, which typically is assumed to equal the saturated thickness of the well screen or the sand pack. Calculation of horizontal hydraulic conductivity typically assumes uniform flow into the aquifer along the entire saturated open interval of the well. In reality, most flow into the well in a fractured-rock aquifer will be through permeable fractures and solution openings, which usually have a thickness that is orders of magnitude less than that of the well screen. As a result,

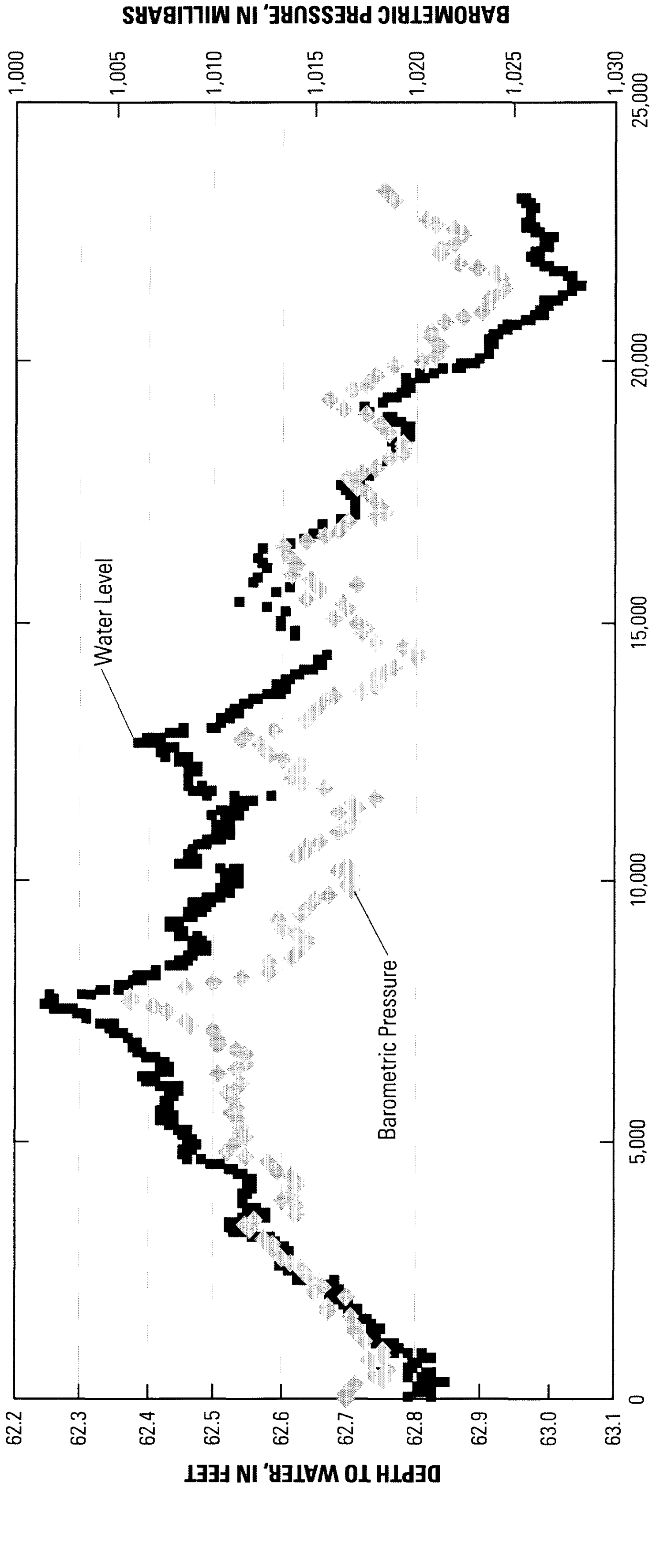


Figure A7. Water levels and barometric pressure in well AW5I, Byron site, Ill., June 30-July 16, 1993.

the calculated horizontal hydraulic conductivity (and dependent ground-water velocity) values appear to be orders of magnitude too low to represent the aquifer.

Conventional analysis of slug test data is based on an assumption that the tested interval can be conceptualized as a porous media. In cases where slug tests are used to evaluate isolated intervals containing fractures, this conceptualization holds most appropriately where the density of conductive fractures is high and where there either is virtually no fluid exchange between fractures and matrix or the rate of exchange is extremely rapid (Butler, 1998). If these conditions are not met, other aquifer conceptualizations must be used. The discrete fracture model (Wang and others, 1977; Karasaki and others, 1988), or the double-porosity model (Moench, 1984) usually are utilized in the alternate conceptualization.

Specific-Capacity Tests

Specific-capacity aquifer tests involve extraction of water from a well at a known, constant rate (Q) and taking a single measurement of the amount of water-level decline in that well (s) at some known time (t) after the initiation of pumping. The specific capacity (Q/s) is the ratio of the discharge rate to the total decline in water level in the well. Specific capacity is a measure of the productivity of the well and the aquifer. The higher the specific capacity, the more productive the well and the aquifer.

Specific-capacity data can be manipulated to provide an estimate of transmissivity (T), and by extension horizontal hydraulic conductivity, of the aquifer in the vicinity of the borehole using the Theis equation (Todd, 1963), where

$$T = [Q/(s)][2.3/4\pi][\log(2.25Tt)/(r_e^2S)]. \qquad (1)$$

Because the T term appears twice in this equation, solution for T involves an initial estimation for the value of T, then iterative solving of equation (1) for Q/s using refined estimates of T until the observed value of Q/s is approximated.

If the value for the storage coefficient (S) of the aquifer is unknown (as frequently is the case), both T and S are estimated for solution of equation (1). The effective radius of the well (r_e) typically is assumed to be equal to the nominal radius of the well (r_w). However, r_e can be substantially larger than r_w, particularly in fractured-rock aquifers (Mace, 1997). Specific-capacity analyses typically assume that well loss is negligible. Calculated transmissivity values are moderately insensitive to large changes in the assumed values of r_e and S. However, uncertainty regarding the true values for S and r_e, and assumptions regarding the absence of well loss and the presence of a fully penetrating well in a confined, homogenous, isotropic aquifer results in T estimates from specific-capacity tests that usually are substantially greater than estimates obtained with other methods (Huntley and others, 1992).

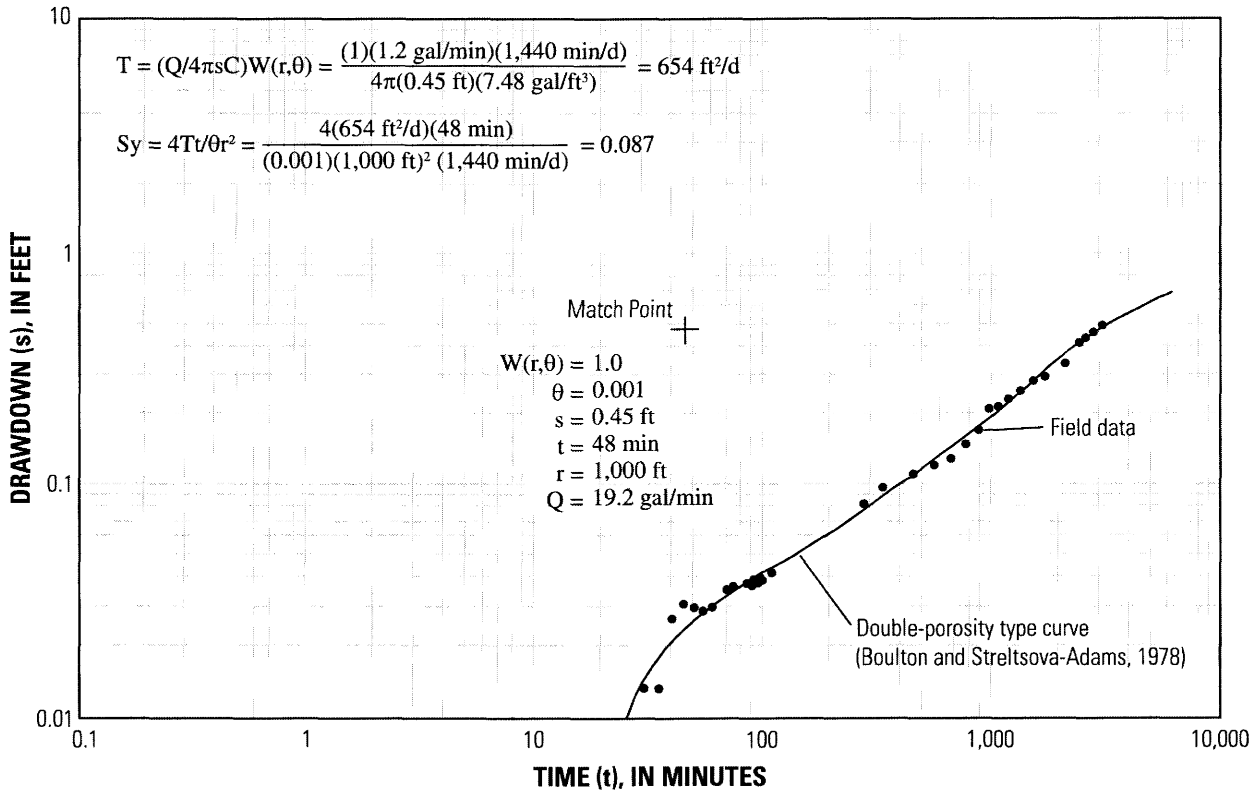
If a sufficient number of specific-capacity tests are available, these data can be used to identify spatial variations in the hydraulic properties of the aquifer. Specific-capacity tests cannot be used to identify vertical variations in aquifer properties without additional information. Specific-capacity data frequently are reported on well logs for water-supply wells on file with various agencies and can be used to obtain preliminary estimates of aquifer transmissivity. Specific-capacity tests typically are easy, quick, and inexpensive to perform if pumping already is being done for well development and the test can be performed in conjunction with or immediately after development. Specific-capacity tests as a stand-alone procedure typically are moderately easy, quick, and expensive to perform. These tests can be difficult and expensive to perform if treatment of the discharge water is required. Although specific-capacity tests theoretically can be performed at any realistic permeability range, as a practical matter the requirement for sustainable drawdown limits the effectiveness of this method when applied to deposits of low and high permeability. Specific capacity in wells cased above the water table can vary over time because of changes in the saturated/unsaturated state of permeable features in the upper part of a well. Additionally, dewatering productive intervals during pumping can result in increased drawdown in the well and an underestimation of aquifer transmissivity. The extent of the aquifer stressed by a specific-capacity test depends on the aquifer properties, the pumping rate, and the pumping duration; these tests typically stress the aquifer between about 100 and 1,000 ft from the pumped well.

Multiple Well Tests

Multiple-well, constant-discharge tests involve extraction of water from a well at a known, constant, rate while monitoring the amount of drawdown through time in the pumped and observation wells (wells where drawdown is measured). Plots of drawdown with time in the observation wells on a log-log scale can be compared with type curves of the theoretical aquifer response to quantify the transmissivity, storage coefficient, and horizontal hydraulic conductivity of the aquifer (Todd, 1963)(fig. A8). Analysis of the spatial distribution of drawdown at a given time during the test can be used to identify the presence and orientation of horizontal and vertical flow anisotropy in the aquifer caused by the orientation and distribution of secondary-permeability features in the aquifer.

The amount of the aquifer stressed with a multiple-well aquifer test depends on the hydraulic properties of the aquifer, the pumping rate, and the duration of pumping, but these tests typically provide information on aquifer properties between 100 and 2,000 ft from the pumped well. Therefore, multiple well, constant-discharge aquifer tests allow the calculation of hydraulic properties over the largest area of the aquifer possible with current methods. These aquifer tests also provide the most comprehensive direct insight into the three-dimensional pathways of ground-water flow.

Multiple-well tests require extensive planning, typically are performed for at least 1,000 minutes, and large amounts of manpower and equipment are required. In addition to measurement of water levels and discharge, water-level data collected during long-term, multiple-well tests typically must be adjusted to correct for water-level fluctuations caused by ambient effects, such as changes in barometric pressure, pumping from offsite wells, and recharge to ground water. As a consequence, these tests are the most difficult, time-consuming, and expensive types of aquifer tests to perform and analyze. The degree of time and expense increase substantially if the extracted water requires treatment prior to disposal or additional wells need to be drilled to support the testing. The requirement for sustainable drawdown in the pumping well and transmission of drawdown from the pumping well to observation wells effectively precludes the use of this method in deposits of low permeability. The requirement for measurable drawdown in the observation wells and the expense associated with treatment and disposal of contaminated water also may limit the use of



ABBREVIATIONS

T = Transmissivity, in ft^2/d (feet squared per day)
Q = Discharge, in gal/min (gallons per minute)
s = Drawdown, in ft (feet)
C = Conversion factor, converts gallons to ft^3 (cubic feet)
$W(r,\theta)$ = Double porosity type curve well function
r = Radial distance from the pumped well, in ft (feet)
θ = A value defined as equal to $(4Tt)/(Syr^2)$
Sy = Specific yield (dimensionless)
t = Time since the start of pumping, in minutes

Figure A8. Logarithmic plot of drawdown as a function of time for borehole PW-3 matched with theoretical double-porosity type curve, Byron site, Ill.

this method in high-permeability deposits. Aquifer-test results in water-table aquifers can vary with time because of changes in the saturated/unsaturated state of permeable features in the upper part of the aquifer. Additionally, dewatering productive intervals during pumping can result in a decrease in the amount of water discharged to the well from some parts of the aquifer with a concomitant increase in the discharge to the well from other parts of the aquifer. Depending on the configuration of the fracture network in the aquifer, these changes in discharge can affect the drawdown data and invalidate their use for calculation of aquifer hydraulic properties.

There are numerous methods for analysis of multiple-well, constant-discharge aquifer-test data. The most appropriate method depends on whether the aquifer is confined or unconfined, the degree to which the aquifer approximates an equivalent porous medium, whether the aquifer functions as a double-porosity media, and the presence of a preferred orientation of the vertical fractures in the aquifer. An overview of each of these methods is beyond the scope of this report. Although many methods can be applied in anisotropic aquifers, it is assumed in all methods that the aquifer is homogenous at the scale of the test.

In a homogenous, isotropic aquifer, drawdown occurs in a circular pattern centered on the pumped well, with the amount of drawdown being dependent on the distance from the pumped well and independent of direction. The presence of vertical fractures in many fractured-rock aquifers results in an anisotropic response to pumping with the amount of drawdown being dependent on both the orientation and distance from the pumped well (fig. A9). Pumping in an anisotropic aquifer produces an elliptical drawdown distribution where the direction of maximum drawdown typically is parallel to the primary orientation of the vertical fractures in the aquifer, with the direction of minimum drawdown oriented perpendicular to this direction. A minimum of three wells penetrating the entire thickness of the aquifer is required to identify the shape of the drawdown ellipse in two dimensions.

In addition to vertical anisotropy in the aquifer, horizontal variations in aquifer permeability and hydraulic interconnection also may produce variations in drawdown at a given location at different depths in the aquifer (fig. A9). Because variations in drawdown with depth in the aquifer cannot be identified in fully penetrating boreholes, important information regarding vertical and horizontal hydraulic interconnection within the aquifer as well as the hydraulic properties of specific secondary-permeability features may not be determined. Cross-hole testing, where packers are used to isolate specific intervals of both the pumped and observation boreholes, can be used to provide a more detailed aquifer assessment.

Tracer Tests

Tracer tests involve the injection of a compound (tracer) into the aquifer in sufficient amounts to raise the concentration of the tracer substantially above its ambient level and monitoring the tracer concentration with time in the aquifer downgradient of the point of injection. For most applications, the tracer is a non-reactive dye or ion, such as chloride or bromide, and it is assumed that the rate of tracer migration is identical to the rate of ground-water flow. There are two basic types of tracer tests; natural gradient (tracer moves in response to natural hydraulic conditions) and induced gradient (tracer moves in response to hydraulic conditions induced by pumping or injection). Only induced-gradient tracer tests are discussed here.

Induced-gradient tracer tests require pumping at a known, constant rate from an extraction well and injection of the tracer in an observation well. Analysis of tracer-test data requires measurement of the distance between the extraction and injection wells, and measurement of the water-level altitude in the extraction and injection wells (converted from measured time-drawdown data) during the test period. Analysis of tracer-test data requires that the flow regime in the aquifer be approximately stable prior to and after tracer injection. A stable flow regime requires an absence of pumping or recovery from offsite wells, approximately steady-state conditions prior to and after tracer injection, tracer injection at a rate slow enough to induce minimal water-level increase at the injection well, and tracer concentrations low enough so that density-driven flow is not induced.

A short-term injection tracer test involves addition of a slug of tracer over a small time period (minutes) at the injection well then plotting tracer concentration with time in the water from the extraction well (fig. A10). Depending on the goals of the investigation, tracer testing in fully penetrating boreholes can be performed to assess the hydraulic properties of the bulk aquifer, or tracer testing can be done in discrete intervals to assess the hydraulic properties of specific features. The time required for the peak concentration of tracer to move through the measured length of aquifer under the measured horizontal hydraulic gradient (dh/dl) provides a direct measurement of the velocity of the water through the aquifer under the conditions induced by the pumping and injection. Determination of ground-water velocity (v) permits solution of the Darcy equation

$$v = (Kh/n_e)(dh/dl), \qquad (2)$$

for either Kh or n_e (effective porosity), depending on which parameter already is known. Typically, Kh can be determined readily from analysis of the time-drawdown data collected during the tracer tests or from aquifer tests done in different parts of the aquifer, so tracer tests are typically used to estimate n_e.

Assessment of the tracer concentration in the extracted water through time can provide insight into the degree of hydraulic interconnection and tortuosity of the secondary permeability network (dispersion), as well as the degree of hydraulic interaction between the secondary and primary porosity in the aquifer (diffusion). In an aquifer dominated by secondary permeability, dispersion largely results from variations in the fluid velocity

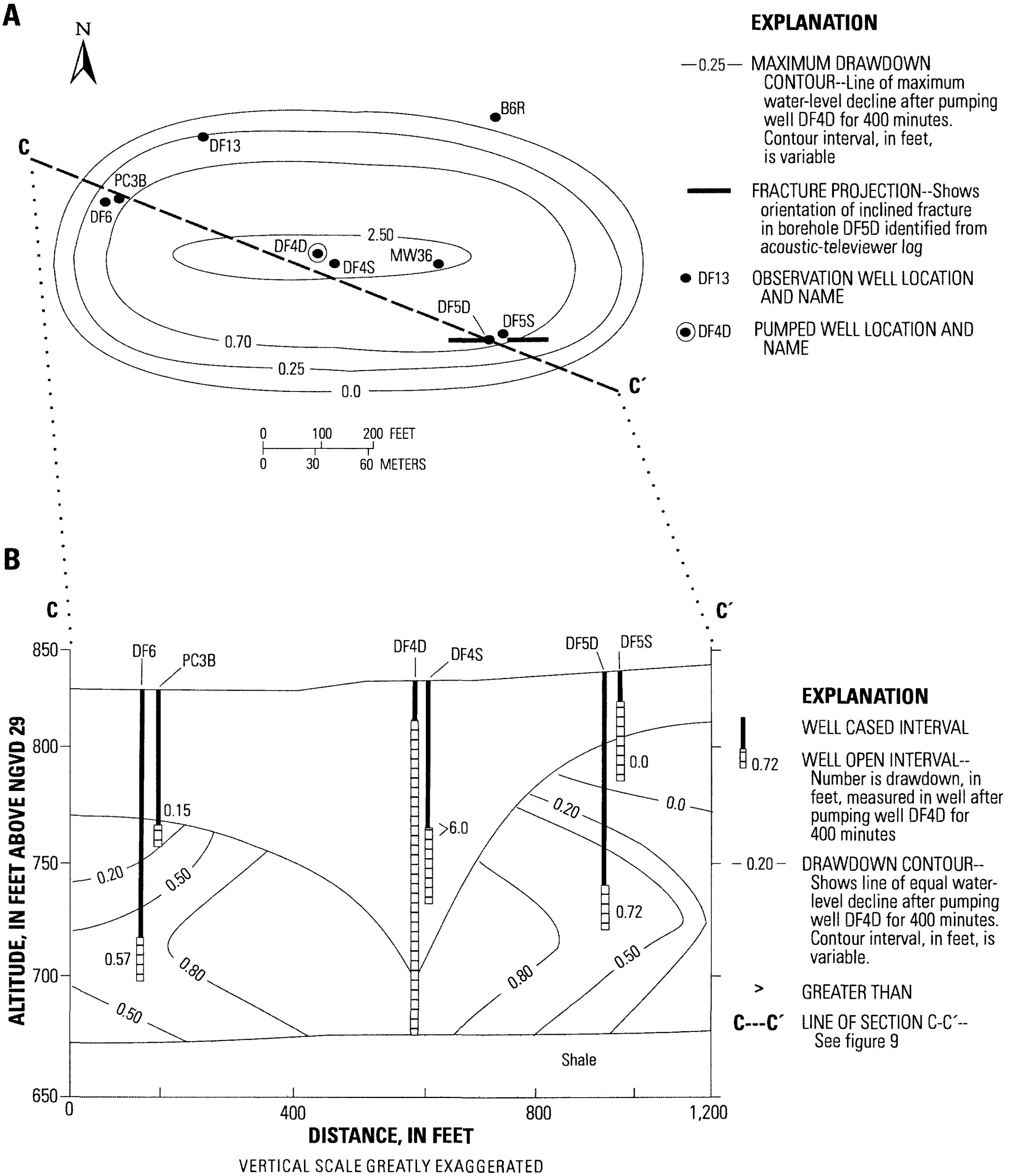


Figure A9. Distribution of drawdown in the Galena-Platteville aquifer after pumping borehole DF4D for 400 minutes, Byron site, Ill., February 2, 1992, A) maximum drawdown in the aquifer; B) drawdown in the aquifer along line of section C-C′.

within a fracture or solution opening and differences in water velocity through different fractures or solution openings. Tracer concentrations that increase rapidly above background concentrations to a maximum value, then decrease rapidly to background concentrations, indicate a low dispersion coefficient and flow through a single fracture or solution opening, or a simple network of fractures or solution openings, with uniform hydraulic properties. Tracer concentrations that increase slowly to a maximum value, then decrease slowly to background concentrations, indicate a comparatively large dispersion coefficient and flow through a complicated network of fractures or solution openings, with variable hydraulic properties.

An accurate value for dispersion and diffusion coefficients is important for a thorough characterization of ground-water flow and contaminant transport, and these coefficients only can be calculated from tracer-test data. For this reason, tracer tests are a useful method for the characterization of fractured-rock aquifers. Short-term injection tracer tests typically are expensive to perform and require extensive understanding of the secondary-permeability network and the flow pathways between the injection and extraction wells to maximize the amount of information that can be obtained from the test. Tracer tests performed in conjunction with pumping usually provide information on the hydraulic properties of the aquifer over a length of tens to hundreds of feet. Because the coefficient of dispersion tends to increase with an increase in the length (scale) of the aquifer being studied (Xu and Eckstein, 1995), the representativeness of any given dispersion coefficient is uncertain.

A continuous injection tracer test involves continuous injection of tracer at a constant concentration during a substantial portion (hours or days) of the test. As is the case for a short-term injection tracer test, the time required for the tracer to move through the measured length of aquifer under the measured horizontal-hydraulic gradient provides a direct measurement of ground-water velocity through the aquifer, which allows equation 2 to be solved for n_e. Because continuous injection of tracer does not allow for analysis of variation in tracer concentration through time as the tracer slug migrates through the aquifer, continuous-injection tests cannot be used to estimate coefficients of dispersion and diffusion and have little value for quantifying the hydraulic properties of an aquifer. However, continuous injection of a chloride tracer of sufficient concentration will result in the flow pathways between the injection and extraction wells being filled with tracer water substantially more conductive than that of the ambient water. Cross-borehole radar tomography can be run in boreholes straddling that part of the aquifer through which the tracer is to move before and during injection. Comparison of the tomograms before and during injection will identify the location of the highly conductive water in the aquifer, thereby identifying the flow pathways and secondary-permeability features in the aquifer (fig. A11). Cross-borehole radar tomography run while the tracer is migrating from the injection well to the extraction

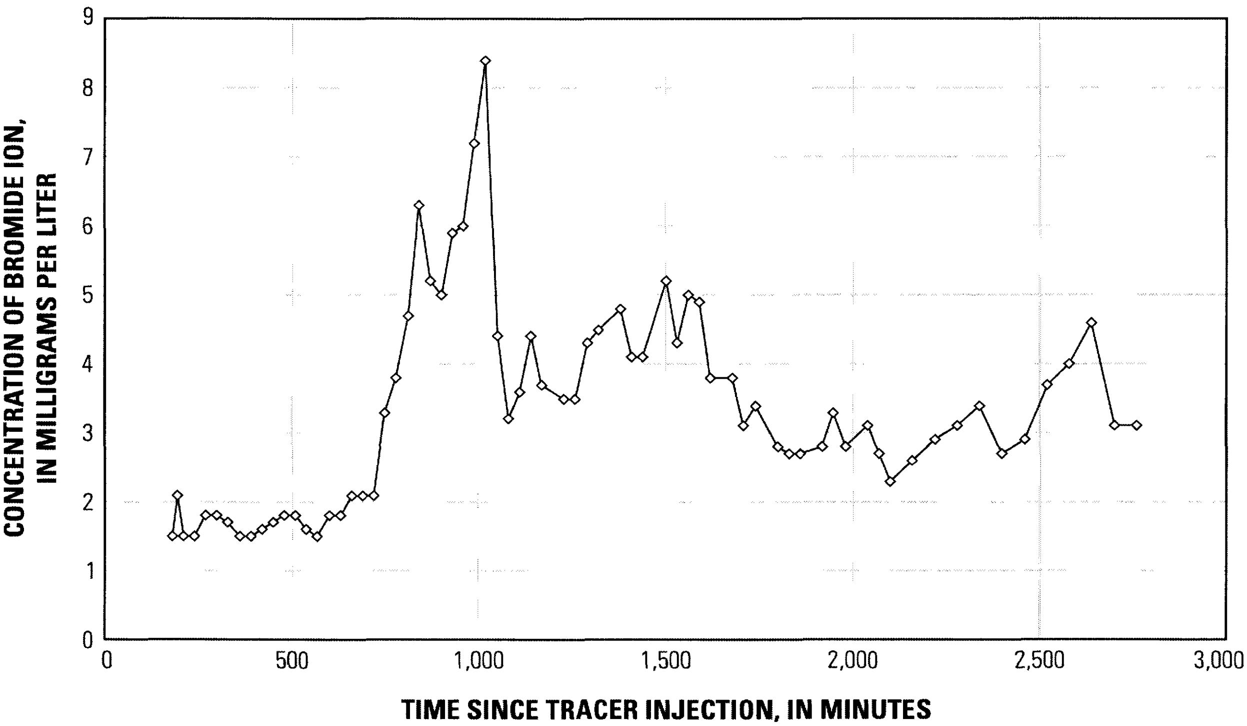


Figure A10. Concentration of bromide ion tracer in water pumped from borehole SPW, Byron site, Ill., July 12-14, 1992.

well also can be used to determine the approximate rate of flow through the aquifer in response to the hydraulic conditions induced by pumping and injection.

Continuous injection tracer tests performed in conjunction with cross-borehole radar tomography, along with multiple-well, constant-discharge aquifer tests and flowmeter logging performed in conjunction with pumping from nearby wells, are capable of providing a comprehensive assessment of the specific pathways for ground-water flow in fractured-rock aquifers. Borehole tomography also allows assessment of specific flow pathways within the aquifer without the need to isolate discrete intervals of the aquifer. In addition to the extraction and injection wells, and the equipment needed to for the tracer tests, long-term injection tracer tests performed in conjunction with cross-borehole radar tomography may require installation of boreholes to allow access to the aquifer, may require extensive aquifer characterization prior to beginning the testing, and may require intensive personnel commitments. Additionally, borehole ground-penetrating radar equipment and personnel experienced in analysis of these data are not readily available and the need to induce an appreciable contrast between the pre- and post-tracer conductivity of the water can result in ambiguous identification of some flow pathways. Long-term injection tracer tests performed in conjunction with cross-borehole tomography are expensive to perform. These tracer tests usually provide allow aquifer characterization over a length of about 20 to 300 ft.

Water Chemistry

Assessment of an aquifer and its secondary-permeability network usually can be obtained by analysis of spatial or temporal patterns in the concentration of a given chemical, or group of chemicals in the aquifer. Because dissolved chemicals are transported in the ground water, they can provide a more direct depiction of flow pathways than usually can be obtained using hydraulic and geophysical methods, which usually represent generalized flow directions.

The location and extent of natural and anthropogenic constituents dissolved in ground water can be used to identify the pathways of ground-water flow (fig. 15). This method of analysis differs from a tracer test in that the chemical constituent used to identify the flow pathway is present in the aquifer as the result of natural or anthropogenic processes, not introduced into the aquifer as part of an investigative method. Because the surficial location of the contaminant source material at most waste-disposal sites is well defined, and because many of the contaminants are not found in nature, identifying the distribution of one or more contaminants in the aquifer can be used to define the pathways of ground-water flow through the fractured rock. The distribution of contaminants in a fractured-rock aquifer can be used to identify specific pathways of ground-water flow, hydraulic interconnection within the aquifer, and hydraulic boundaries of the flow system. Analysis of contaminant distribution also can be used to determine if offsite pumping or temporal variations in precipitation substantially affects flow directions.

Implicit in the analysis of water chemistry is the assumption that contaminants are derived from known source areas and contaminant migration is solely in the dissolved phase. The presence of unidentified surface source areas or nonaqueous phase liquids in an aquifer may result in erroneous interpretations about flow in the aquifer. Because identification of the three-dimensional nature and extent of contamination usually is a requirement for investigation of any waste-disposal site, analysis of the distribution of contamination in an aquifer as a means of aquifer characterization can be considered as both inexpensive and expensive to perform. Analysis of the distribution of contamination in an aquifer allows characterization of the aquifer over the length and width of the plume, typically a distance of hundreds to thousands of feet.

Analyses of the spatial distribution of contaminants and other chemical constituents and indicators of water quality can be useful in identifying pathways of preferential flow within fractured-rock aquifers and the extent of hydraulic interconnection within and between secondary-permeability features in the aquifers. For example, delineation of the distribution of volatile organic compounds (VOC's) with depth in an uncased borehole may identify a substantial increase in VOC concentrations that is restricted to a specific depth. Similarly, delineation of the distribution of water temperature or dissolved oxygen concentration with depth may identify a change in one of these indicators of water quality. These depth-specific changes may represent locations of preferential flow pathways in the aquifer.

Analyses of major ions to determine water chemistry or concentration of selected constituents, such as tritium, may be used to determine to what extent an aquifer, or part of an aquifer, is confined. Differences in water chemistry among sample locations may indicate that a low permeability unit separates flow in different parts of the aquifer, thus, limited movement of contaminants between these locations is expected. Tritium is a radioisotope of hydrogen that can be used to estimate relative age of ground water and extent of confinement and vulnerability of aquifers to contamination. Beginning in 1954, with the onset of above-ground nuclear-weapons testing, naturally occurring levels of atmospheric tritium were increased from about 5 tritium units (Kauffman and Libbey, 1954)(TU's; equivalent to 16 pCi/L) to over 1,000 TU's. Tracking the pulse of tritium-enriched water recharging aquifers allows the time since initiation of recharge to be estimated. Presently (2002), ground water with levels at or less than 1 TU represents recharge that originated before about 1954. Water with tritium levels at or less than 1 TU are considered to be derived from a confined aquifer; thus, the aquifer is not vulnerable to contamination (Illinois Environmental Protection Agency, 1999). Water with tritium levels at or greater than natural levels of 5 TU's are considered to be derived from unconfined aquifers; thus, vulnerable to contamination.

Numerical Modeling

Computer numerical modeling of fractured-rock aquifers can be useful to understanding flow and contaminant transport at various spatial scales. Because of the heterogeneity of fractured-rock aquifers, consideration of model selection in regards to scale and study objectives and evaluation of model uncertainty is important. Development of numerical models requires integration of data from various scientific disciplines, including geology, geophysics, hydrology, and hydrogeochemistry. At all scales of application, models should be considered simplified characterizations of

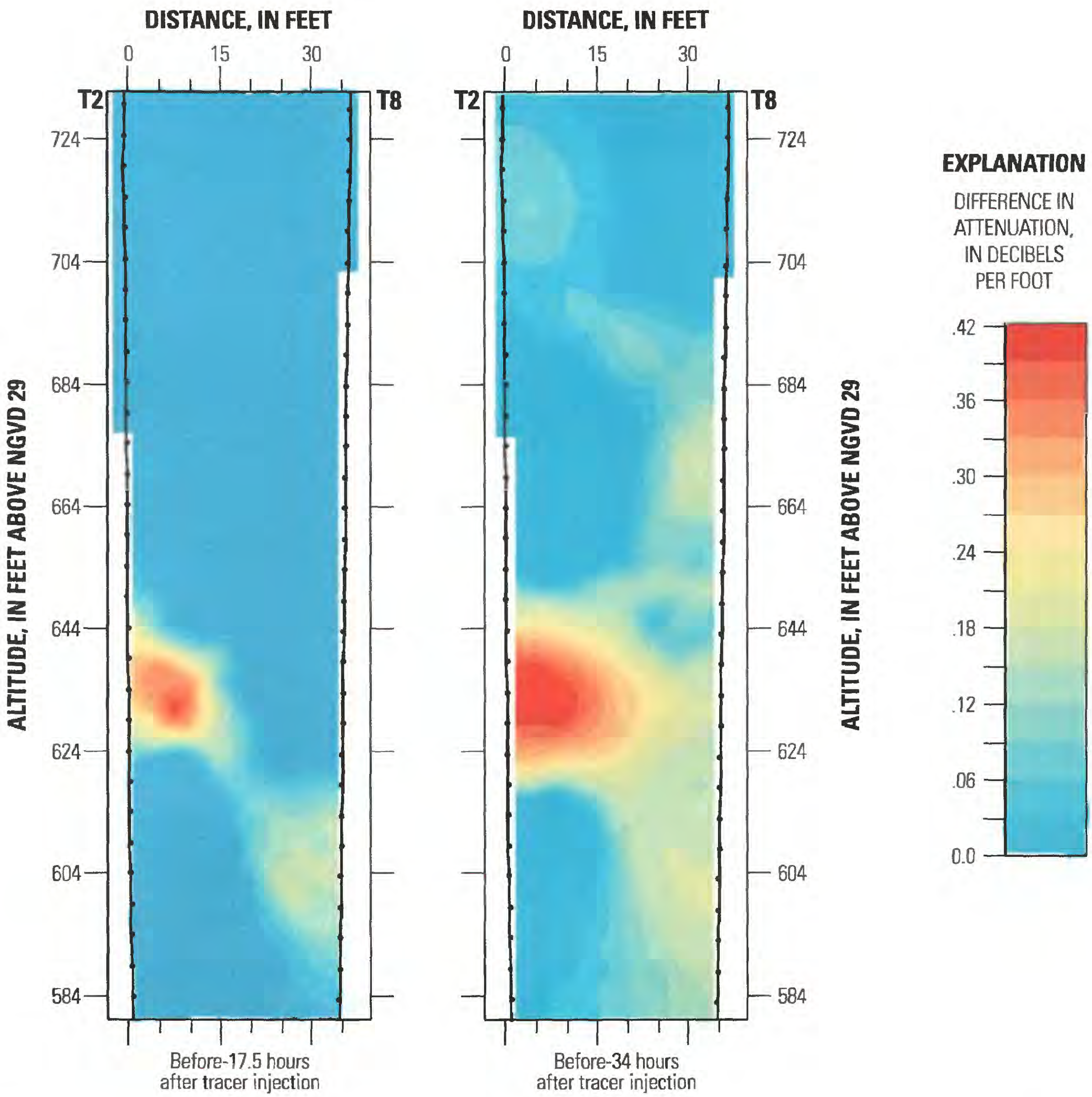


Figure A11. Borehole-radar difference tomogram showing changes in attenuation between boreholes T2 and T8, 17.5 and 34 hours after tracer injection in borehole T1, Belvidere, Ill.

complex ground-water systems. Development and limitations of numerical models, particularly as applied to fractured-rock aquifers, are discussed in detail by the National Research Council (1996).

For large-scale evaluations of aqueous flow, (regional to subregional) continuum-based (porous-media) models, such as MODLFLOW (McDonald and Harbaugh, 1988; Harbaugh and others, 2000) have been used successfully (Mercer and Faust, 1986). In such applications, the scale of investigation is considered large enough for the aquifer to be represented as an equivalent porous media. Post-processing routines, such as MODPATH (Pollock, 1989; 1994) using particle tracking, can aid visualization of the simulated flow patterns. However, because flow patterns are generalized over large areas and property values averaged over large areas usually are estimated on the basis of small-scale measurements, the spatial accuracy typically is unacceptable for subsequent simulation to detail the distribution, travel times, and concentrations of contaminants associated with preferential flow paths or over areas smaller than designated model-cell sizes (National Research Council, 1996). Research also indicates that application of porous-media models may not be appropriate at any scale of investigation, because fracture features that preferentially affect flow are present at all scales of interest (National Research Council, 1996).

Continuum-based models also have been applied to fractured-bedrock systems in which a proportion of flow is through the matrix (doubly-porous media). These dual-porosity models (Glover, 1987, for example) are treated as overlapping continuum models that generally are applied to smaller-than-regional scale settings (Mercer and Faust, 1986). For these models, the hydraulic properties of the matrix (low permeability and high porosity) and fractures (high permeability and low porosity) are considered; the geometry of the fracture network generally is represented in a simplified fashion. Whereas these models can approximate steady-state, matrix-to-fracture leakage, these models are considered most useful for assessing transient flow over periods of tens of years, thus, accounting for the differences in timing of hydraulic response in matrix and fractures. Three principal limitations to these models are (1) the geometry of fracture networks is oversimplified, (2) accurate representative estimates of the hydraulic properties are difficult to obtain, and (3) uncertainty in identifying the scale at which continuum assumptions are valid (National Research Council, 1996).

For small-scale (site to fracture scale) evaluations of aqueous flow, discrete-flow pathway models are best applied. Each fracture is considered discretely with these models. These models require that the heterogeneity of the geometry (aperture, orientation, length, connectivity, density) and hydraulic properties (hydraulic conductivity) of the fracture(s) be well characterized. Particularly difficult aspects of the data requirements for application of these models are field-determination of the geometry of the conductive parts of fracture networks and fracture transmissivity (National Research Council, 1996). Development of these models was limited until the late 1980's, when interest in characterizing and remediating contaminated fractured-rock aquifers expanded rapidly. Since that time, various deterministic (property values generally are known) and stochastic (property values randomly distributed and described by a probability distribution) models have been developed. Aquifers with a well-developed network of fractures may be best suited to stochastic modeling. The most favorable conditions for application of these models include: (1) statistically uniform fracture pattern, (2) obtainable statistically representative sample, (3) simple fracture distribution, and (4) statistically described fractures are fluid filled (National Research Council, 1996).

Discrete-flow pathway models are not readily available and have not been fully verified in the field. Additionally, resources generally are unavailable for the accurate characterization of complex fractured-bedrock systems that is necessary for preparation of accurate local-scale models. Presently (2004), these models are considered by many users to be research tools used for theoretical evaluation of fractured flow; most of their use has been limited to this application. The models have been used successfully in some field-scale studies over lengths less than about 300 ft (National Research Council, 1996). Future advances in aquifer characterization and model development are expected to result in improved accuracy and increased use of these models.

Hybrid models incorporate the approaches and capabilities of continuum and discrete-flow pathway models. Hybrid models are considered most useful in estimating large-scale continuum properties (which generally cannot be measured) based on field-scale, discrete-fracture determinations (National Research Council, 1996).

The complexities of simulating contaminant distribution in fractured-rock aquifers are greater than that of simulating ground-water flow in these aquifers. Pathways for contaminant movement must be delineated accurately and factors that affect advective flow (including effective porosity) and dispersion (mechanical mixing and molecular diffusion of contaminants) in fractures must be estimated accurately. Complex chemical or biochemical reactions, or radioactive decay that can result in changes in contaminant mass usually need to be considered. In these cases, fluid and rock chemistry need to be well determined. Data requirements are more substantial if dual-porosity conditions are present and contaminant movement between fractures and matrix must be simulated. A partial listing of presently developed models of aqueous and contaminant flow in fractured-rock aquifers is given by the National Research Council (1996).

Packer Tests

Characterization of fractured-rock aquifers through the use of open boreholes has a number of disadvantages related to the inability to measure the hydraulic and chemical properties of individual secondary-permeability features intercepted by the borehole. First, the precise location of the permeable features usually cannot be identified without a flowmeter survey or other type of investigation. Second, if multiple fractures are present, water quality and hydraulic response will be a composite of each permeable feature, possibly resulting in an inaccurate characterization. Third, wellbore-storage effects may dominate response if the matrix is of low permeability (National Research Council, 1996). Borehole packers are pneumatic or mechanical devices that isolate sections of a borehole by sealing against the borehole wall, leaving an isolated zone above or below a single packer, or between two packers separated by some distance (fig. A12). The use of packers to isolate specific parts of the borehole reduces or eliminates the effects of these shortcomings by allowing collection of hydraulic and water-quality data from discrete intervals over the entire length of the wellbore. Packers also prevent cross contamination resulting from vertical flow within the wellbore.

Water-quality sampling or hydraulic testing using a packer assembly typically is expensive and time consuming to perform. The large amount of time required for low-permeability intervals to reach hydrostatic conditions or recharge from pumping may serve as a practical barrier to packer testing in some boreholes. Vertical flow within a borehole also can transport contamination within the aquifer from zones of higher to lower head (Williams and Conger, 1990). This transport can produce sampling results indicating contaminant distribution within the aquifer that may not represent in-situ conditions. As a consequence, analysis of water-quality data from discrete intervals in open holes can be ambiguous or erroneous (Johnson and others, 2001). Installation of a packer system soon after drilling minimizes cross contamination and helps ensure collection of representative water-quality samples (Johnson and others, 2001).

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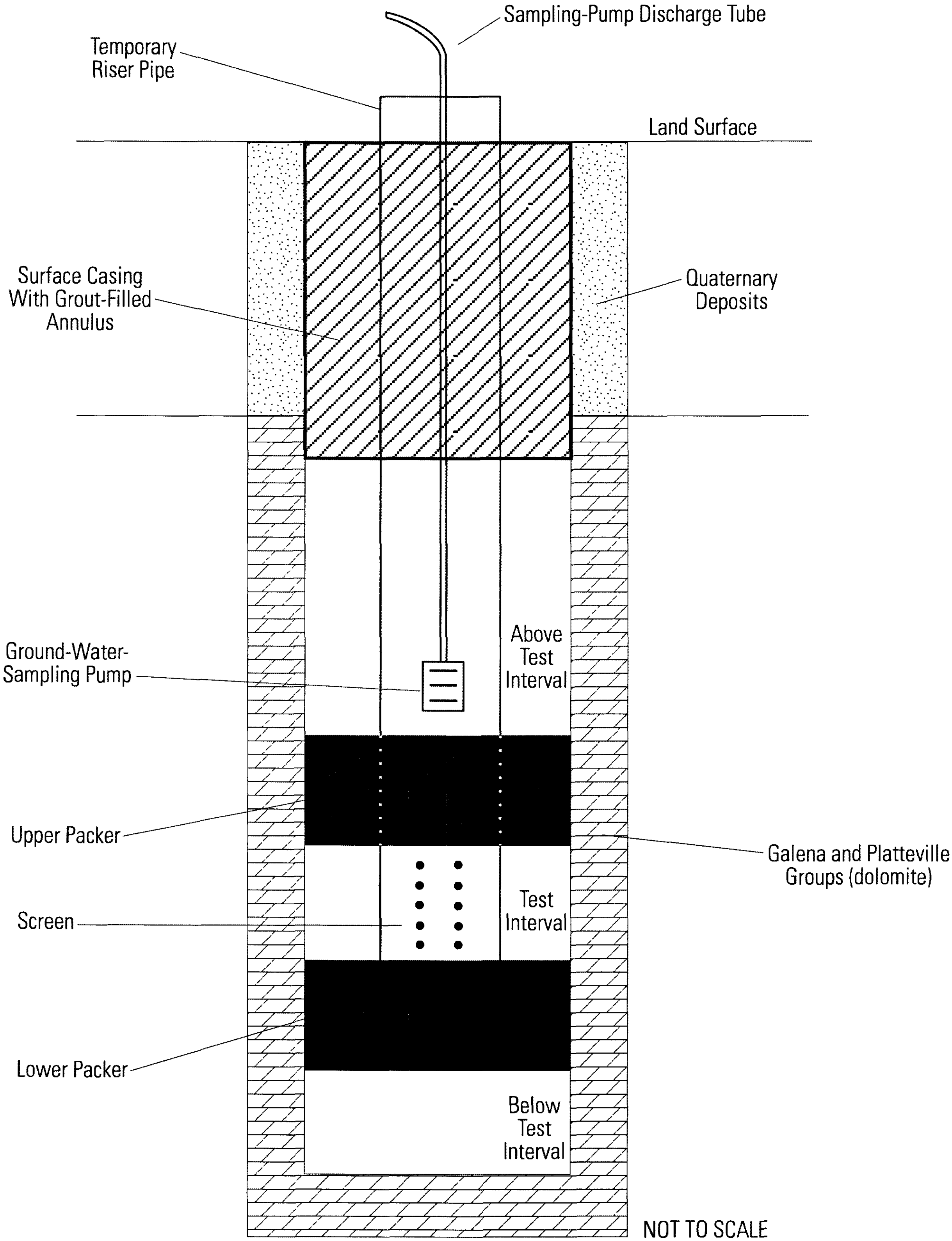

Figure A12. Packer assembly and ground-water sampling pump in a borehole.

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Appendix B—Byron Site Data

The Byron site has been the subject of a series of environmental investigations from 1974 through 1993, with the collection of data for routine monitoring continuing to the present (2002). The investigations that form the primary basis for this discussion were conducted from 1987 through 1993 and are presented in Kay and others, 1989; U.S. Environmental Protection Agency, 1994; Kay and others, 1997; and Kay and others, 1999. These reports provide a detailed discussion of the methods used for, and results of, the hydrogeologic investigations at the Byron site performed by the USGS and USEPA. A total of 26 investigative methods were used to develop the hydrogeologic framework for the Byron site (table 3).

Previous Studies

Sargent and Lundy, Inc., and Dames and Moore, Inc. (1975) investigated fracture orientations in the Galena-Platteville dolomite in and around the Byron site. The investigation identified two primary directions of strike of the vertical fractures: N. 60° W. to N. 75° W. and N. 15° E. to N. 30° E. The trend from N. 60° W. to N. 75° W. is the dominant structural trend. The investigation also identified a fault in the Galena-Platteville dolomite south of the Byron site. Part of the fault is outlined by the topographic low associated with Woodland Creek (fig. 6). The fault has a measured maximum vertical displacement of 6 in. and is oriented N. 60° W. Faulting and fracture development was attributed to movement along the Sandwich Fault zone.

Topographic and Aerial Photographic Analysis

Analysis of land-surface topography during site visits, topographic maps, and aerial photographs defined a prominent bedrock ridge associated with the topographic upland as well as the presence of various depressions potentially associated with fracture traces at the Byron site (U.S. Environmental Protection Agency, 1994) (figs. 6, 7) (table 2). The most prominent fracture trace is associated with the potential fault defined by Woodland Creek. Additional fracture traces also were identified at the BSY and the DFP. The fracture traces tend to be oriented approximately parallel to the dominant vertical fracture orientation at about N. 60° W. (Woodland Creek and the Northwest Ravine), orthogonal to the dominant vertical fracture orientation at N. 30° E. (West Ravine and Northeast Ravine), or approximately due north.

Two circular depressions about 60 ft across were identified near the BH14 well cluster and approximately halfway between wells MW3 and DF15 (fig. 6) during site visits. These circular depressions are interpreted as being sinkhole locations.

Quarry Visits

The Galena-Platteville dolomite at the Benesh Quarry and the quarries near Meyer's Spring (fig. 6) is composed of generally massive dolomite with a network of vertical and horizontal fractures. The orientation of the vertical fractures in the quarry near Meyer's Spring was measured and found to be consistent with the fracture orientations reported by Sargent and Lundy and Dames and Moore, Inc., (1975).

Collapse features 10-15 ft wide were observed in the dolomite deposits at the Benesh Quarry. The collapse features appear to have been formed by the dissolution of dolomite in the upper part of the Grand Detour Formation (Dennis Kolata, Illinois State Geological Survey, oral commun., 1994). Collapse features do not appear to extend to the overlying deposits, indicating that the Grand Detour Formation may have greater secondary permeability than the other formations in the Platteville and Galena Groups at this site.

Surface Geophysics

GPR surveys were conducted in 1988 and 1991 at various locations in the upland part of the Byron site to determine if buried objects were present. A secondary objective of the GPR surveys was to identify fractures and sinkholes. The high clay content in the soil limited the depth of penetration of the GPR signal to approximately 5 ft, which is less than the depth to bedrock. A radio transmission tower in the area also was a source of signal interference during the GPR surveys. Therefore, surface GPR was not of use in the characterization of the Galena-Platteville dolomite at the Byron site.

An azimuthal square-array resistivity survey was conducted on the northeastern part of the DFP to determine the orientation of fractures in the dolomite. The results from this survey did not indicate a preferred fracture orientation. It is possible that the survey lines were too short to obtain measurements that penetrated the overburden and measured properties of the bedrock. The use of resistivity was not investigated further at the Byron site.

Lithologic Logs

Lithologic logs were prepared for all of the wells drilled during environmental investigations at the Byron site (table 3). Lithologic logs indicate that the Galena-Platteville deposits in the upland areas tend to be primarily competent dolomite yielding small amounts of water interspersed with small hydraulically productive zones indicative of fractures and vugs. Softer, more hydraulically productive dolomite was identified beneath much of the West Ravine. Loss of cuttings and formation water near the bottom of wells DF12, DF24, B6R, at the AW4 well cluster (fig. 7), and at an abandoned well between wells MW39 and DF12 indicated the presence of high-permeability fractures or solution openings at these locations (tables 5, 6). Cuttings returned during drilling of well DF14 contained large amounts of silt and clay and little water, indicating infilling of the sinkhole in this area.

Core Analysis

Cores collected at wells MW2, MW20, DF4D, AW1D, AW4S, and AW4D were described and analyzed for stratigraphy (Michael Sargent, Illinois State Geological Survey, written commun., 1992). The Pecatonica, Mifflin, Grand Detour, Nachusa, Quimbys Mill, Guttenberg, and Dunleith Formations were identified from the cores (fig. 11). The Galena-Platteville deposits primarily are dolomite with variable amounts of limestone. The Guttenberg Formation was identified as approximately 5 ft thick at wells MW2 and AW1D, but was about 0.5 ft thick at well MW20.

Vertical fractures, many of which were healed or infilled with clay minerals, and vuggy intervals were identified throughout the Galena-Platteville deposits underlying the site. Although fractures were identified throughout each of the cores, fractured and weathered zones indicative of permeable features were identified in the cores at about 795 and 773 FANGVD29 in well AW1D, at about 750 FANGVD29 in well AW4S, at 736-742 FANGVD29 in well DF4D, and at about 691-703 FANGVD29 in well MW20.

The porosity of the Galena-Platteville deposits determined from analysis of 79 rock samples collected from the cores ranged from about 4 to 22 percent with a median value of about 10 percent (Patrick Mills, U.S. Geological Survey, written commun., 1993). The median porosity value was 6.4 percent for the Guttenberg Formation (fig.11), ranged from 9 to 10.3 percent for the Pecatonica, Mifflin, Nachusa, Quimbys Mill and Dunleith Formations, and was 11.3 percent for the Grand Detour Formation.

Geophysical Logs

Geophysical logging was invaluable in expanding the geologic framework of the Byron site and providing foundation for the hydraulic framework (table 3).

Borehole Camera

Borehole camera logs were run in 11 wells and boreholes, primarily located on or near the Salvage Yard (table 3). Results of camera logging were not discussed in the previous reports on the site, and, therefore, are discussed in greater detail in this report than many of the other logging methods.

Camera logging in borehole PZ1 indicated generally competent rock throughout the borehole. Small fractures were indicated above the water surface at about 767, 800, 808, 809, and 812 FANGVD29 and below the water surface at about 749 and 734 FANGVD29 (table 5). Various large fractures were identified at 708-712 FANGVD29. Water was observed cascading down the sides of the borehole from about 793 ft to the water surface at 761 FANGVD29.

Camera logging in borehole PZ2 indicated generally competent rock throughout the borehole. Small fractures were indicated above the water surface at 806-814 FANGVD29 and below the water surface at about 794 and 790 FANGVD29. Heavy iron flocculate in the water below 763 FANGVD29 obscured clear identification of features, but various possible fractures were identified from 684 to 696 FANGVD29. Water was observed cascading down the sides of the borehole from about 798 FANGVD29 to the water surface at 794 FANGVD29.

Camera logging in borehole PZ3 indicated generally competent rock throughout the borehole. Subhorizontal planar features were identified at 739-741 and 753-756 FANGVD29. Small fractures were observed at about 747 and 749 FANGVD29. Heavy iron flocculate in the water column and algae on the sides of the borehole prevented identification of features below about 725 FANGVD29, with the exception of a possible fracture at about 698 FANGVD29. Water was observed cascading down the sides of the borehole from about 794 FANGVD29 to the water surface.

Cascading water observed above the water surface in the PZ boreholes appeared to drain from the aquifer matrix and was not associated with identifiable secondary-permeability features. Cascading water indicates that the water table is more than 10 ft above the water surface in the PZ boreholes.

Camera logging in borehole SPW indicated numerous vuggy intervals and fractures over most of the borehole (table 5). Vertical fractures were identified above the water surface at about 765 FANGVD29, and below the water surface between about 736 and 751

FANGVD29, and about 710-718 FANGVD29. A series of horizontal planar features were identified at about 724 FANGVD29 and at 695-700 FANGVD29. Water was observed dripping from the sides of the borehole from about 794 FANGVD29 down to the water surface.

Camera logging in borehole DF4D indicated generally competent rock throughout the borehole. Fractures were identified at about 723 and 748 FANGVD29 (table 5). Camera logging in this borehole was terminated at about 718 FANGVD29, above the bottom of the borehole. Camera logging in borehole DF5S indicated competent rock throughout the borehole.

Camera logging in borehole DF15 indicated generally competent rock. Numerous subhorizontal fractures were identified between 747 and 754 FANGVD29, and at about 761 FANGVD29.

Camera logging in borehole DF17 indicated numerous fractures over the length of the borehole (table 5). Fractures especially were concentrated at 714-720, 754-759, and 790-805 FANGVD29. A large solution opening was recorded near the bottom of the borehole at about 694-700 FANGVD29.

Camera logging in borehole DF12 indicated numerous vugs, fractures, and solution openings throughout the length of the borehole (table 5). Fractures and solution openings were observed from about 729 FANGVD29 to the bottom of the borehole at 702 FANGVD29, with a cavern identified at 702 FANGVD29.

Camera logging in boreholes B6R and GW42 indicated numerous fractures over the length of the boreholes. Solution opening was present in borehole B6R at 749-753 FANGVD29.

Caliper

Three-arm caliper logs indicate enlargements in borehole diameter of more than 1 in. at about 689 and 754 FANGVD29 in borehole AW5D; from the bottom of the borehole to 758 FANGVD29 in borehole B6R; at about 757 FANGVD29 in borehole DF1S; at about 739 FANGVD29 in borehole DF2D; at about 731 FANGVD29 in borehole DF3; at about 755 and 790-813 FANGVD29 in borehole DF10; from the bottom of the borehole to about 719 FANGVD29 and at 810 FANGVD29 in borehole DF12; from the bottom of the borehole to about 708 FANGVD29 in borehole DF17; at about 782 and 752 FANGVD29 in borehole DF20; at about 795 FANGVD29 in borehole DF21; at about 700 FANGVD29 in borehole DF22; at about 717 FANGVD29 in borehole DF24; at about 750 FANGVD29 in borehole MW2; at about 767, 753,and 747 FANGVD29 in borehole PW3; and at about 789, 765, 745, 735, and 710 FANGVD29 at borehole SPW (table 5). Many of these enlarged areas are likely to be fractures or solutions openings. Fractures and solution openings indicated by caliper data usually also were indicated by lithologic and borehole camera logging. Caliper logs run in the remaining boreholes indicated little variation in diameter, indicating largely unfractured dolomite (U.S. Environmental Protection Agency, 1994).

Natural Gamma

Natural-gamma logs run in boreholes MW2, MW20, DF4D (fig. B1), DF11, and AW1D were compared to the stratigraphic descriptions for these boreholes obtained from analysis of the cores so the natural-gamma signal of the formations could be identified. Natural-gamma logs from these boreholes then were compared with natural-gamma logs from other boreholes so the stratigraphy across the Byron site could be determined. Comparison of the natural-gamma response with stratigraphy for each of the boreholes indicates that the Guttenberg Formation is approximately 5 ft thick beneath much of the southeastern part of the Byron site, but is reduced in thickness or absent in the western part of the BSY and the eastern part of the DFP, presumably because of erosion during the Ordovician system. Comparison of natural-gamma logs with stratigraphic delineation between boreholes indicates that the Galena-Platteville deposits dip to the south beneath the Byron site (figs. 9, 10).

Although the natural-gamma response typically shows a clear correlation with stratigraphy, anomalous responses were observed in some boreholes. Atypically high counts per second readings were detected at elevations of about 710 and 738 FANGVD29 in borehole SPW (fig. B2), 749 FANGVD29 in borehole B6R, and 709 FANGVD29 in borehole DF12 (fig. B3), which do not reflect the original bedrock stratigraphy. Anomalous responses on the natural-gamma logs correspond to areas where the borehole camera and caliper logs indicated the borehole was enlarged, indicating that these might be locations where fractures have been infilled with clays.

Spectral Gamma

Spectral-gamma logging in borehole SPW indicated amounts of uranium and thorium above background at 710 and 738 FANGVD29, whereas potassium was the dominant source of gamma radiation in other parts of the borehole (Frederick Paillet, U.S. Geological Survey, written commun., 1991). The difference in the clay mineralogy between the dolomite and the locations of the anomalous responses in the natural gamma logs indicates that the anomalous responses are caused by clay minerals infilling fractures (table 5).

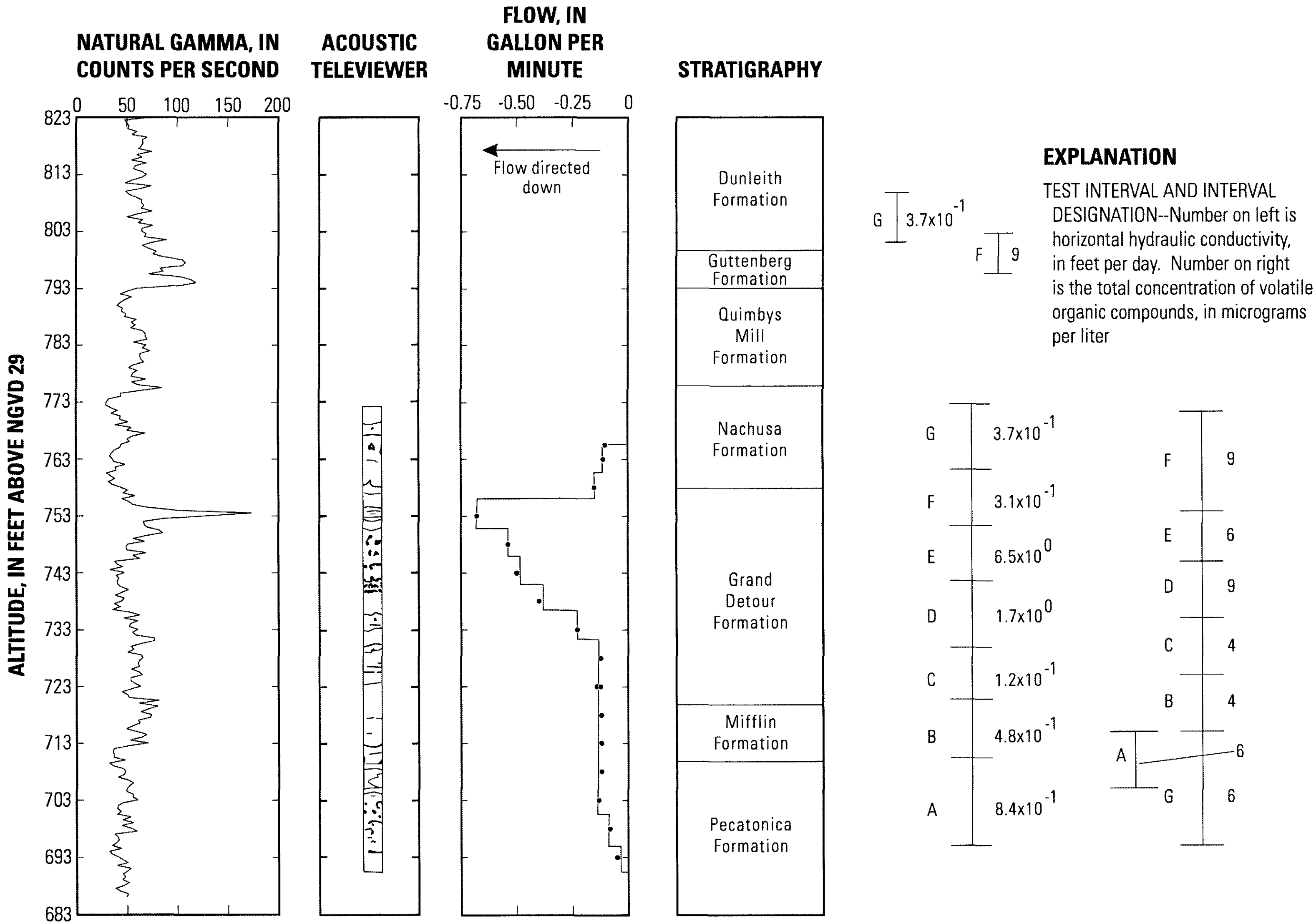


Figure B1. Natural-gamma, acoustic-televiewer, and flowmeter logs, stratigraphy, and horizontal-hydraulic-conductivity values and total concentration of volatile organic compounds in the test intervals isolated with a packer assembly for borehole DF4D, Byron site, Ill.

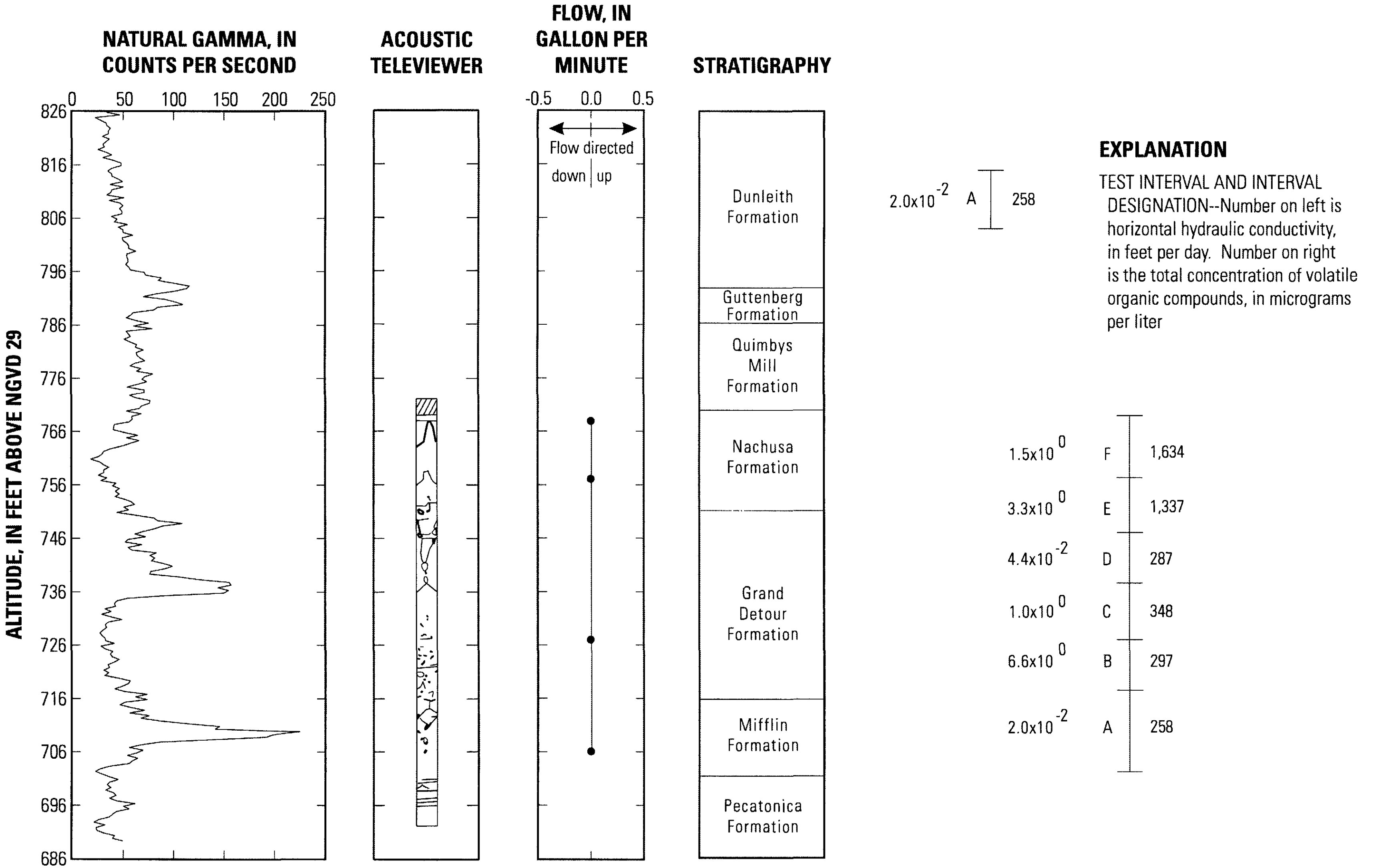


Figure B2. Natural-gamma, acoustic-televiewer, and flowmeter logs, stratigraphy, and horizontal-hydraulic-conductivity values and total concentration of volatile organic compounds in the test intervals isolated with a packer assembly for borehole SPW, Byron site, Ill.

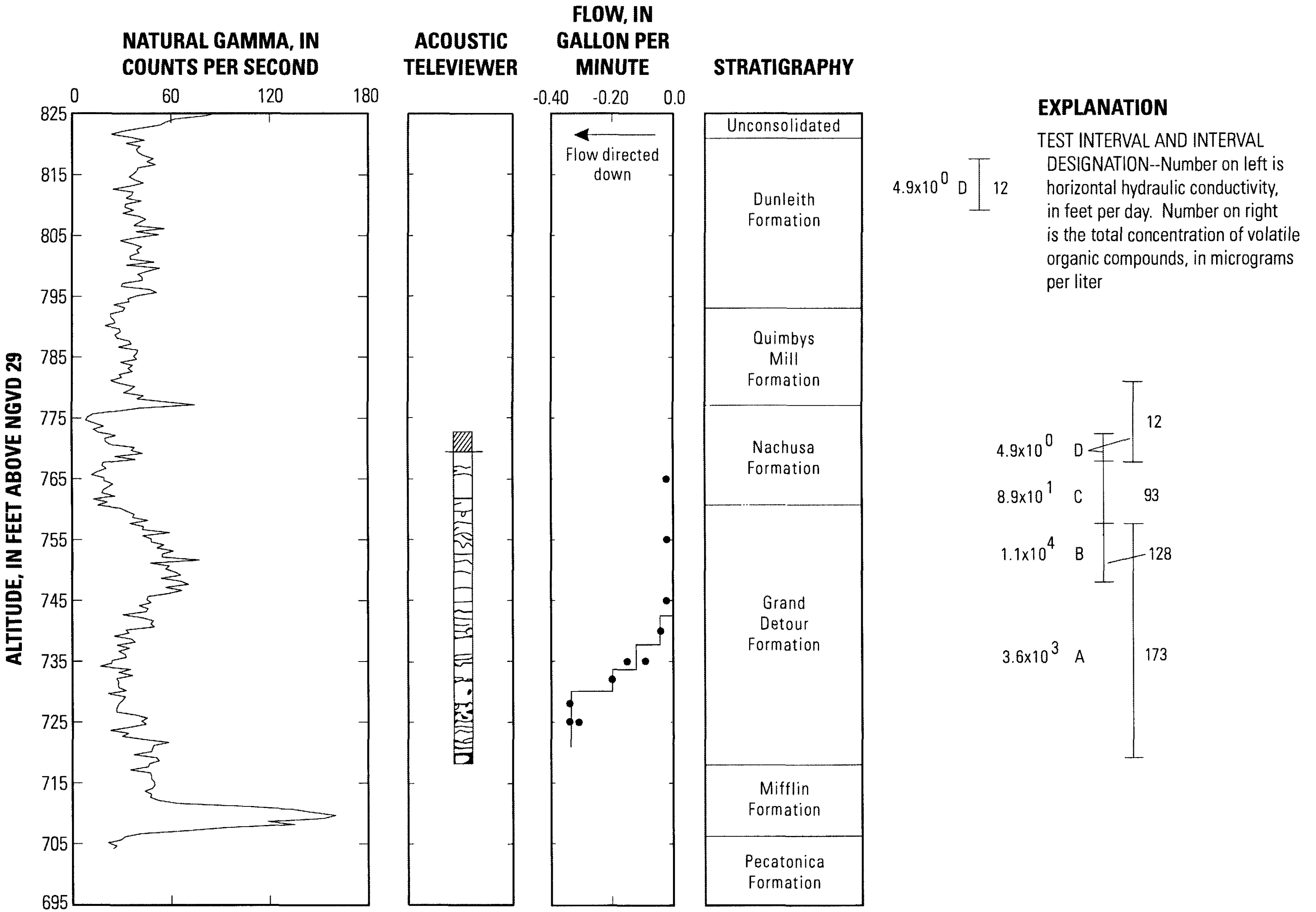


Figure B3. Natural-gamma, acoustic-televiewer, and flowmeter logs, stratigraphy, and horizontal-hydraulic-conductivity values and total concentration of volatile organic compounds in the test intervals isolated with a packer assembly for borehole DF12, Byron site, Ill.

Spontaneous Potential

SP logs indicated a gradual increase in signal response with depth below the top of the water surface in boreholes DF2D, DF4D, DF5D, DF12, DF17, and MW2, and a gradual decrease with depth in borehole PZ1 (U.S. Environmental Protection Agency, 1994). These logs indicated depths of alternating increasing and decreasing signal response in boreholes DF4S, DF5S, AW1D, and AW5D. SP logs tended to mirror natural-gamma logs, having high readings where natural-gamma values were high and low readings where natural-gamma values were low. Except for a large increase in signal associated with the possible fracture identified with the caliper logs at about 689 FANGVD29 in borehole AW5D, and a small increase associated with the possible fracture identified with lithologic and caliper logs near the bottom of borehole DF17, SP logs indicated no clear response to possible secondary-permeability features (table 5).

Single-Point Resistance

SPR logs indicated essentially no change in signal response in boreholes DF4D and DF5D; a gradual decrease in signal response with depth in boreholes DF4S, DF5S, DF12, and PZ3; and a sharp decrease near the possible fracture identified near the bottom of borehole DF17 (U.S. Environmental Protection Agency, 1994). Depths of alternating increasing and decreasing signal were identified in boreholes DF2D, DF4D, AW1S, AW1D, AW5D, PZ1, and MW2. Single-point-resistance logs tended to show an inverse relation with spontaneous-potential and natural-gamma logs, usually showing lower readings in areas where spontaneous-potential and natural-gamma values were higher and higher readings where spontaneous-potential and natural-gamma values were lower. Except for sharp decreases associated with the possible fracture identified with the caliper logs at about 689 FANGVD29 in borehole AW5D and near the bottom of borehole DF17, single-point-resistance logs indicated no clear response to areas of possible fractures (table 5).

Neutron

Neutron logs were run in boreholes MS2, B6R, GW16, GW42, MW10, MW11, MW16, MW18, MW20, PC2, DPW and SPW (table 3). Comparison of neutron logs and porosity measured from core samples at borehole MW20 indicated the expected inverse relation between porosity and neutron counts, but the neutron readings did not show a clear response at the depths of secondary-permeability features identified with other methods. This lack of identifiable response can be attributed partly to the effects of the variation in the clay mineral content of the dolomite. For example, the clay minerals that infilled some of the fractures in borehole SPW appear to have resulted in an increase in the counts per second response of the neutron log. Variations in the amount of condensate on the borehole walls above the water table, and variations in the moisture content in the unsaturated rock above the water table also may have affected the response of the neutron log in such a way as to obscure identification of secondary-permeability features. It also is possible that the porosity associated with many of the secondary-permeability features at the logged boreholes is small relative to the primary porosity, and the neutron log is not sensitive to these small porosity changes.

Acoustic Televiewer

Acoustic-televiewer logs indicate the presence of numerous thin (typically less than 0.25 ft thick), bedding-plane partings through the entire thickness of the Galena-Platteville aquifer below the water table. These bedding-plane partings likely are a combination of subhorizontal fractures related to carbonate solution or stratigraphic changes, and shale partings that have been removed from the borehole wall during drilling and borehole development. The goal of this and other investigations in the Galena-Platteville aquifer was to characterize permeable features and no effort was made to distinguish between subhorizontal fractures and bedding-plane partings. It is assumed, however, that bedding-plane partings are not appreciable pathways for ground-water flow and that fractures may be.

Acoustic-televiewer logging identified inclined fractures at various boreholes (tables 5, B1), including boreholes SPW (fig. B2), PZ1, PZ2, PZ3, AW1S, DF4D (table 5, fig. B1), and DF12 (table 4, fig. B3). Inclined fractures were identified at about 748, 738, and 698 FANGVD29 in borehole DF5D and at about 737 FANGVD29 in borehole DF13.

The inclined fractures at borehole DF13 and boreholes SPW, PZ1, PZ2, PZ3, and AW1S, which are located near the center of the BSY, have strikes that roughly are parallel to the dominant fracture orientation in the Galena-Platteville dolomite (N. 60° W) identified by Sargent and Lundy Inc., and Dames and Moore, Inc., (1975). Various fractures in the boreholes on the BSY are oriented parallel to the north-south and northeast-southwest trending fracture traces on the BSY (figs. 6, 8). The strike of the inclined fractures at boreholes DF4D and DF5D is about N 90° E, roughly parallel to the orientation of the nearby West Ravine (figs. 6, 8). The strike of the inclined fractures at borehole DF12 is roughly north-south, parallel to a nearby fracture trace (fig. 8).

Lithologic, caliper, and borehole-camera logs indicate the largest solution openings in boreholes DF12 and DF17 were near the bottom of the borehole. The bottom 5-10 ft of these boreholes was not logged because of concerns over the safety of the televiewer tool. As a consequence, solution openings were not identified with the televiewer logs in these boreholes in table 5.

Borehole Ground-Penetrating Radar—Single Hole

Single-hole directional GPR reflection surveys were done in eight boreholes (table 3) that were capable of about 30-60 ft of signal penetration into the dolomite (Niva, 1991a; Lane and others, 1994). The distance of signal penetration decreased with increasing depth, indicating increased conductivity with depth. Between three and six reflectors were identified from the processed data in the vicinity of the boreholes (table B1) (John Lane, U.S. Geological Survey, written commun., 1994). The reflectors identified at borehole AW1S are weak and may not actually be present in the rock.

The altitude of many (but not all) of the reflectors identified with the reflection surveys corresponded to the approximate altitude of stratigraphic contacts or fractures identified with other methods, indicating that many of the reflectors represent fractures or changes in lithology. The lithologic change is associated with the shale layer in the Grand Detour Formation. The absence of an identified fracture or lithologic change in a borehole at the altitude indicated by interpretation of the GPR reflection data does not necessarily indicate that the reflector is not present. The fracture or variation in lithology associated with the reflector may terminate before it intersects the borehole, its orientation may change, or the intersection may be above or below the bottom of the borehole.

The dip of the reflectors identified with the GPR reflection surveys ranges from about 24 to 65 degrees (table B1). The strike of the reflectors tends to be randomly oriented. Reflector orientation typically shows poor agreement with the orientation of the associated fractures determined with the acoustic-televiewer logs. Dip values determined from the reflection surveys tend to be substantially less than the values determined with the acoustic-televiewer logs. Strike values determined with the reflection surveys typically vary by more than 40 degrees from the strike values identified with the acoustic televiewer. These differences partly may be attributable to the differences in the amount of rock tested with the different methods, which could combine with variations in fracture extent and orientation in the rock so that features identified with the GPR may not be present, or may be present in the boreholes at different locations and orientations.

Borehole Ground-Penetrating Radar—Cross-Hole

Cross-hole GPR surveys done between the AW1S-PZ2, PZ2-PZ3 and PZ3-SPW borehole pairs indicate an upper zone of low velocity and high attenuation along all three profiles at about 735-740 FANGVD29 (figs. A5, A6). A lower zone of low velocity and high attenuation is present at about 710 FANGVD29 at borehole SPW, decreasing to about 690 ft near borehole PZ3 (Lane and others, 1994). The AW1S-PZ2 and PZ2-PZ3 borehole pairs are not deep enough to determine if the lower zone is present in these areas. The upper zone approximately corresponds to the argillaceous deposits in the upper part of the Grand Detour Formation. The lower zone approximately corresponds to a clay-filled fracture at borehole SPW (fig. B2) and a fractured parts of the Pecatonica Formation at borehole PZ3 identified with the geophysical logs. The lower zone appears to be continuous between boreholes SPW and PZ3.

Water-Level Measurements

Water levels were measured in monitoring wells and test intervals isolated with a packer assembly in select boreholes. Analysis of these measurements resulted in an improved characterization of the Galena-Platteville aquifer.

Continuous Measurements

During the investigations performed at the Byron site, water levels were measured in various wells on at least an hourly basis for periods of days or weeks to establish the processes affecting ambient water levels. Water levels in wells open to the Galena-Platteville aquifer in and near the BSY responded to changes in recharge from precipitation (Kay and others, 1999). Although an exhaustive analysis was not performed, water levels at well B3 essentially were unchanged during a period of unusually heavy precipitation in June and July 1993, whereas water levels in most of the other wells in the vicinity of the BSY rose between about 4 and 10 ft. Additionally, water levels in well B3 declined by less than 0.25 ft over a 10-day span as the aquifer recovered from the high water levels. Water levels in wells AW3 and B5 declined by more than 1.5 ft, and water levels in wells SPW, AW1S, AW1D, AW5D, B4, PW3, MW8, and MW9 declined by 2.5-5.5 ft during this 10-day period. The lack of response to precipitation in well B3 indicates that the part of the aquifer open to this well may be in poor hydraulic connection with the rest of the aquifer.

Table B1. Summary of inclined fracture orientations and reflectors in select boreholes by method of detection, Byron Superfund site, Ill.

[F, reflector interpreted to be a fracture; U, cause of reflection unknown; G, reflector interpreted to be a geologic contact; NI, not identified; NA, not analyzed; DNI, not projected to intercept borehole]

Borehole name (fig. 7)	Altitude or projected altitude of intersection with borehole (feet above National Geodetic Vertical Datum of 1929)	Fractures identified by acoustic televiewer		Reflectors identified by single-hole ground-penetrating radar		
		Strike (degrees from magnetic north)	Dip (degrees from horizontal)	Strike (degrees from magnetic north)	Dip (degrees from horizontal)	Interpreted cause of reflection
SPW	765	324	87	320	24	F
	756	270	83	NI	NI	
	752	315	39	NI	NI	
	745	120	87	NI	NI	
	737	288	77	100	37	F
	720	NI	NI	NA	53	U
	711	126	77	250	44	F
	703	135	87	NI	NI	
PZ1	764	NI	NI	120	61	U
	750	108	39	NI	NI	
	749	108	22	NI	NI	
	746	126	31	NI	NI	
	740	270	45	NI	NI	
	735	171	72	210	32	F
	718	NI	NI	70	51	F
	708	NI	NI	190	27	F
	688	198	31	NI	NI	
PZ2	787	NI	NI	10	37	G
	775	216	85	260	44	F
	763	315	86	NI	NI	
	715	288	73	40	46	G
PZ3	784	NI	NI	200	46	U
	768	0	11	NI	NI	
	744	0	31	90	44	F
	741	315	54	NI	NI	
	737	315	58	NI	NI	
	719	306	77	NI	NI	
	716	153	84	NI	NI	
	709	333	67	NI	NI	
	702	153	78	NI	NI	
	694	153	80	NI	NI	
	681	NI	NI	250	58	U
	677	NI	NI	280	33	G
	643	NI	NI	170	65	
AW1S	787	NI	NI	NA	27	G
	777	18	63	NI	NI	
	776	117	76	NA	34	G
	766	27	80	80	42	F
	DNI	NI	NI	270	89	U

Water levels in wells open to the Galena-Platteville aquifer in and near the BSY also responded to changes in barometric pressure (U.S. Environmental Protection Agency, 1994; Kay and others, 1999). Water levels in well AW5I indicated instantaneous fluctuations in response to changes in barometric pressure during monitoring in July 1993 (fig. A7). The barometric efficiency of well AW5I varied substantially depending on which data measurements used, but averaged 107 percent. Wells B3, B5, AW3, AW6, MW8, and MW9 indicated less response to barometric changes. Additional monitoring of barometric pressure and water levels over a 3-day period in October 1989 indicates that water levels in well AW1S show a substantial response to variations in barometric pressure, well B3 less so, and well AW1D appears to be unaffected by the 15 millibar change in barometric pressure. The barometric efficiency of a well is inversely related to its storage coefficient (Jacob, 1940), which is affected by whether the aquifer is confined or unconfined (Rasmussen and Crawford, 1996). Therefore, the response to barometric pressure indicates the storage coefficient of the Galena-Platteville aquifer is low at well AW5I, which is indicative of a confined part of the aquifer. The moderate response to barometric pressure indicates the storage coefficient of the Galena-Platteville aquifer is intermediate at water-table wells AW1S, B5, AW3, AW6, MW9, and B3, and deep well MW8, indicating that the aquifer may be unconfined at the screened interval of these wells. The response to barometric pressure indicates the storage coefficient of the Galena-Platteville aquifer is high at well AW1D, indicating unconfined conditions. However, other data indicate that the aquifer is confined at well AW1D and the lack of water-level response to barometric pressure at this well may be because of well storage, skin effects, or low aquifer permeability.

Periodic Measurements

Water levels were collected periodically from the available wells from 1985 to 1999. The most frequent monitoring occurred during 1985-92. With the exception of wells B3 and MS1, water levels in the wells with a period of record prior to 1990 varied by 10-20 ft. Water levels in wells B3 and MS1 varied by less than 10 ft from 1985 to 1999, whereas annual variations typically were about 10 ft for the remaining wells (fig. B4). The data are insufficient to clearly evaluate seasonal trends or the relation between water levels and precipitation. The small fluctuation in water levels at well MS1 may be related to its position in the downgradient part of the Galena-Platteville aquifer at the Byron site. The small fluctuation in water levels at well B3 indicates that this well may monitor an area in poor hydraulic connection with the rest of the aquifer.

Water levels at well clusters open to the water table and the middle or base of the Galena-Platteville aquifer typically increased and decreased at the same time and typically by similar amounts (fig. B4). These patterns indicate that the Galena-Platteville aquifer has sufficient hydraulic interconnection to respond to hydraulic effects as a single aquifer.

Water levels from most of the periods of measurement were used to construct the water-table configuration and the potentiometric surface at the bottom of the Galena-Platteville aquifer so that a three-dimensional representation of flow directions could be obtained. Water-level data collected on May 11 and 12, 1992 (figs. 13, 14), are representative of typical hydraulic conditions and are used to illustrate ground-water-flow directions and gradients.

The water-table configuration in the Galena-Platteville aquifer generally mirrors surface topography. The overall direction of flow is toward the Rock River, with components of flow toward the topographic lows at Woodland Creek and the West Ravine (fig. 13). Water-level data indicate that a ground-water divide is present along the topographic ridge, a ground-water sink is present at the topographic lows at Woodland Creek and the West Ravine, and the Rock River is the point of discharge. Based on the water-table configuration, the Galena-Platteville aquifer underlying the southeastern part of the Byron site can be divided into four zones on the basis of the altitude and configuration of the water table (fig. 13). Transitional areas are present between zones.

Zone 1 corresponds primarily to the part of the aquifer where the water table is above 770 FANGVD29 beneath much of southeastern part of the Byron site (fig. 13). Zone 2 is characterized by a flat part of the water table from about 745 to 770 FANGVD29. Zone 2 is located northwest of zone 1 and intersects with zone 1 in the southwestern part of the BSY. Zone 3 is a subset of zone 2, and consists of a small area northwest of the BSY, where water levels virtually are identical. Zone 4 is defined by water-level altitudes typically less than 750 FANGVD29 near Woodland Creek and less than 730 FANGVD29 near the West Ravine. Zone 4 is an area of lower land-surface altitude.

Variations in the water-table altitude in fractured-rock aquifers reflect variations in the permeability distribution and topography (LeGrand and Stringfield, 1971). The high water table at zone 1 indicates that this is a zone of low permeability and a low degree of fracture interconnection, requiring high hydraulic gradients to move water. This interpretation is consistent with the results of geophysical and lithologic logging, which indicate that the Galena-Platteville aquifer is composed of generally competent dolomite in this zone, particularly in the upper part of the aquifer, although permeable features are present locally. Geophysical logs and core analysis indicate zone 1 may correspond to areas where the Guttenberg Formation is thickest and most competent. Intermediate water levels in zones 2 and 3 and data from lithologic and geophysical logging indicate a well-developed system of permeable interconnected fractures and solutions openings (karstic features) in these zones, particularly in zone 3. Ground-water flow in this area is through a well-developed system of fractures and solution openings requiring low hydraulic gradient to move water. The low water table in zone 4 coupled with comparatively large decreases in surface topography and data from the lithologic logging, core analysis, and presence of the fracture traces indicate ground-water flow in zone 4 also is through a well-developed fracture network.

The potentiometric surface at the base of the Galena-Platteville aquifer indicates the same general horizontal flow directions are present as shown in the water-table surface (fig.14). However, the potentiometric surface at the base of the aquifer is not as complex as the water-table configuration, indicating that the bottom of the aquifer is more homogenous than the upper part.

Vertical changes in water level between the water table and the base of the Galena-Platteville aquifer typically are more than 50 ft in zone 1, but always are less than 10 ft, and typically less than 2 ft in the other zones. With the exception of the area of wells DF22S and D in the southern part of the DFP (fig. 14), water levels indicate the potential for downward flow (table 4). High vertical-hydraulic gradients at zone 1 indicate that the vertical-hydraulic conductivity of the aquifer in this area is high in comparison to zones 2, 3, and 4 and that a confining unit may be present in zone 1.

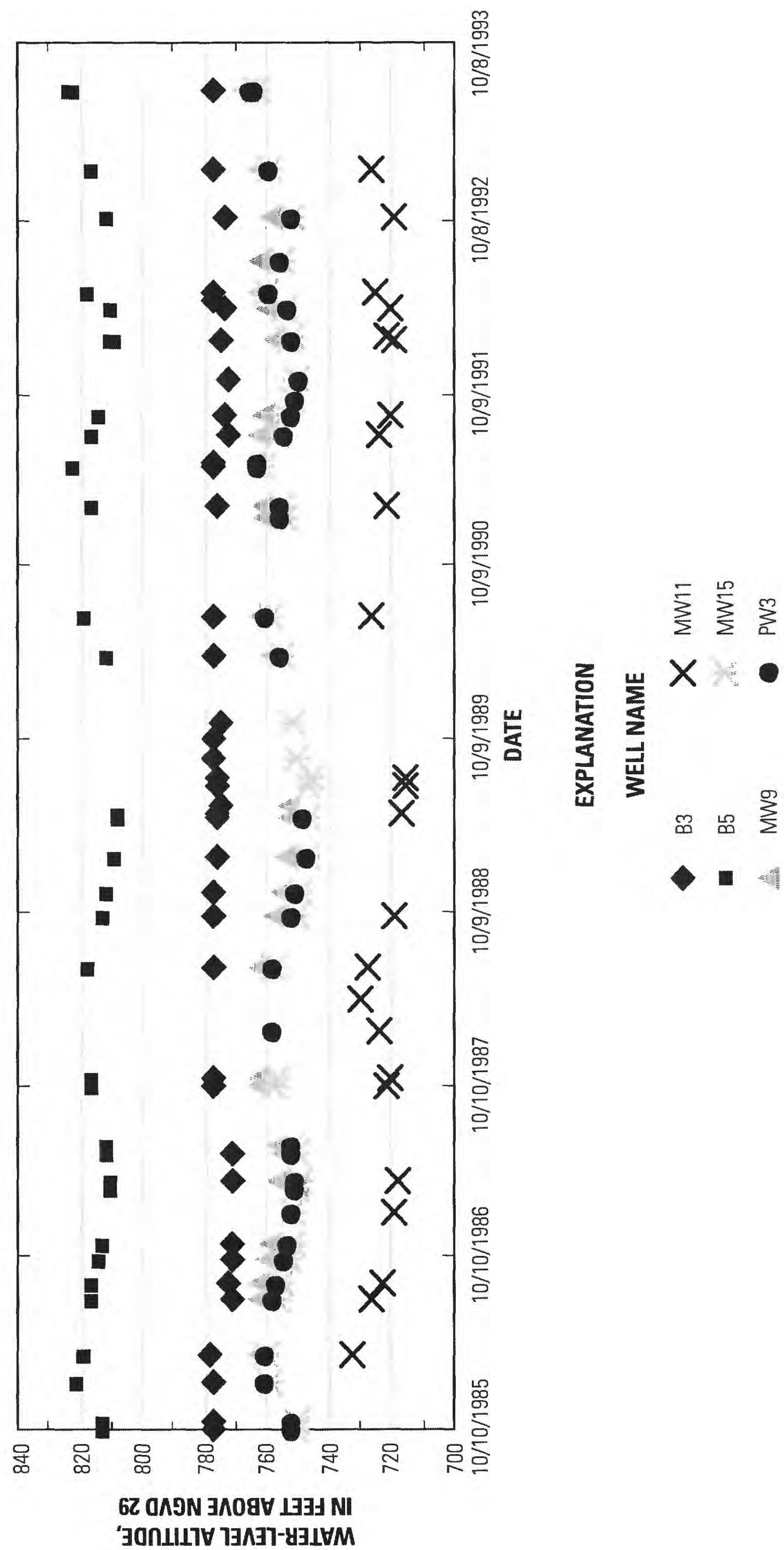


Figure B4. Water-levels in select monitoring wells, Byron site, Ill., October 1985-July 1993.

Single Measurements-Packers

Test intervals isolated with the packer assembly sampled most or all of the saturated thickness of the aquifer at boreholes DF5D, DF12, DF13, SPW, AW1S, and PZ1. Water levels did not equilibrate during testing in various intervals from boreholes DF2D, DF4D, DF6, and DF14D because of slow recovery rates and data from these boreholes could not be used. Slow recovery rates in these boreholes indicate low aquifer permeability.

Water levels measured above, within, and below the test intervals indicate the potential for downward flow within the aquifer at boreholes DF5D, DF12, DF13, SPW, AW1S, and PZ1 and the potential for upward flow near borehole DF17 (table B2). Water levels above and below the test intervals typically differed by more than 20 ft in at least one test interval in boreholes DF5D, AW1S, and PZ1. Water levels above and below the test intervals differed by about 2 ft in the one test interval from borehole DF17 and by at least 0.40 ft at borehole DF12. Water levels above and below the test intervals typically differed by less than 0.15 ft in all of the test intervals in boreholes DF13 and SPW.

Water levels measured in some boreholes differed substantially from the water levels measured in test intervals isolated with a packer assembly. Borehole AW1S is open to the aquifer from 826 to 750 FANGVD29. The water level in this borehole was 780.99 FANGVD29 prior to insertion of a packer assembly. When test interval A (from 765 to 750 FANGVD29) was isolated, the water level in the test interval fell about 13 ft to 767.63 FANGVD29, whereas the water level above the test interval rose about 23 ft to 803.93 FANGVD29 (table B2). These data indicate that the water level in borehole AW1S is lower than the actual water-table altitude. It is probable that water levels in wells MW3, AW2, and MW1 also do not accurately reflect the actual water table.

Borehole DF5D is open to the Galena-Platteville aquifer from about 690 to 830 FANGVD29. Water levels in the borehole and in that part of the aquifer above the test interval were about 756 FANGVD29, when the test intervals below about 739 FANGVD29 were isolated (test intervals A-D)(table B2). This water level (756 FANGVD29) is similar to the water level within the test interval when the test intervals included that part of the borehole between 726 and 739 FANGVD29 (test intervals E-G). The water level above (for interval G) or within (for intervals H and I) the test intervals increased to over 767 FANGVD29 when that part of the aquifer above 739 FANGVD29 was isolated. Similar results were observed in the packed intervals above 742 FANGVD29 at borehole PZ1.

Because the water level in an open borehole is affected by the vertical distribution of water levels and Kh in the aquifer along the open interval of the borehole (Sokol, 1963), water-level data from test intervals isolated with a packer assembly can provide insight into the secondary-permeability network at a site. The high vertical-hydraulic gradients in the upper part of the aquifer at boreholes AW1S, DF5D, and PZ1 indicate parts of the aquifer with low vertical hydraulic conductivity and the presence of few secondary-permeability features with minimal vertical interconnection. The effect of secondary-permeability features at 726-739 FANGVD29 in borehole DF5D and at 742 FANGVD29 in borehole PZ1 on the water level in these boreholes indicates that these are the most permeable features at these boreholes, and that these features are in poor hydraulic connection with the overlying parts of the aquifer (table B2). The low (less than 0.10 ft/ft) vertical hydraulic gradients observed during packer testing at boreholes DF12, DF13, DF17, and SPW (table B2) indicate that the Galena-Platteville aquifer has good vertical hydraulic connection at these boreholes. These conclusions are consistent with the analysis of the periodic water-level monitoring at the Byron site. Boreholes PZ1 and DF5D are in that part of the aquifer corresponding to zone 1. Boreholes DF12, DF13, and DF17 are in zones 3, 4, or transitional areas of the aquifer. Borehole SPW is located in zone 1; however, this borehole intercepts a vertical fracture, which likely transmits water vertically through the aquifer.

Geophysical Logs

Geophysical logs also were run in various boreholes to determine the presence of permeable features (fractures, vugs, solution openings) in the Galena-Platteville aquifer beneath the Byron site (table 3).

Temperature

Water temperatures measured with the geophysical logs indicated little variation, ranging from about 10.5 to 11.0°C in most boreholes. Water temperature in boreholes AW1S and MW2 increased gradually with depth, but indicated no changes indicative of inflowing or outflowing water. Water temperature indicated a slight change in gradient at about 702 FANGVD29 and perhaps at about 674 FANGVD29 in borehole AW1D and at about 690 FANGVD29 in borehole PZ3. These altitudes might correspond to the location of permeable features. Water temperature indicated an abrupt increase with depth just below a possible fracture identified on the caliper log at about 690 FANGVD29 in borehole AW5D, and at about 725 FANGVD29 in borehole PZ1 (table 6), indicating that these features are permeable.

Table B2. Water-level data in select test intervals isolated with a packer assembly, Byron Superfund site, Ill.

(NA, not applicable; NT, not taken; >, greater than; NE, not equilibrated)

Borehole name (fig. 7)	Test interval	Altitude of test interval (feet above National Geodetic Vertical Datum of 1929)	Water-level altitude (feet above National Geodetic Vertical Datum of 1929)		
			Above test interval	In test interval	Below test interval
AW1S	A	751-766	803.93	767.63	NA
AW1S	B	785-804	NA	804.12	NT
DF5D	A	674-691	756.32	754.41	NA
DF5D	B	691-701	756.28	756.12	755.14
DF5D	C	701-711	756.31	756.17	756.14
DF5D	D	711-721	756.35	NT	756.20
DF5D	E	721-731	756.22	756.19	756.05
DF5D	F	731-753	NA	756.24	756.20
DF5D	G	731-741	767.92	756.02	756.02
DF5D	H	745-777	NA	776.02	755.79
DF5D	I	770-778	NA	777.42	765.07
DF12	A	702-741	759.87	759.87	NA
DF12	B	731-741	759.87	759.83	NT
DF12	C	741-751	>760.30	759.91	NT
DF12	D	751-755	NA	759.85	NT
DF13	A	680-695	764.02	763.95	NA
DF13	B	695-705	NE	NE	NE
DF13	C	705-715	763.58	763.54	763.52
DF13	D	715-725	763.67	763.64	763.61
DF13	E	725-735	NT	763.60	763.54
DF13	F	735-745	NE	NE	NE
DF13	G	736-766	NA	764.80	764.50
DF17	A	698-715	736.78	738.73	NA
DF17	B	715-725	736.87	NT	738.74
DF17	C	725-733	NA	736.79	NT
PZ1	A	671-687	753.85	754.00	NA
PZ1	B	687-697	753.91	753.81	754.23
PZ1	C	694-704	753.93	753.83	754.41
PZ1	D	704-714	754.31	753.86	753.80
PZ1	E	714-724	754.39	754.04	754.05
PZ1	F	724-734	759.58	755.03	755.03
PZ1	G	734-744	758.64	755.09	755.14
PZ1	H	744-754	791.54	758.84	>755.51
SPW	A	686-702	NT	NT	NT
SPW	B	702-712	754.13	754.05	NA
SPW	C	712-722	753.68	753.58	NT
SPW	D	722-732	753.58	753.56	NT
SPW	E	732-742	NT	NT	NT
SPW	F	742-751	NA	753.56	NT

Fluid Resistivity

Fluid-resistivity values measured in boreholes DF2D, AW1S, AW1D, AW5D, MW2, PZ1, and PZ3 typically were about 1,500 to 2,000 µmho/cm. Resistivity values in boreholes DF2D and MW2 decreased gradually with depth and indicated no changes indicative of water flowing into or out of the borehole. Resistivity values indicated an increase of about 20 µmho/cm at 792 ft at borehole AW1S, and a slight change in slope at about 727 FANGVD29 in borehole PZ1 (table 6) and at about 796 FANGVD29 in borehole PZ3. These depths may correspond to permeable features. Resistivity values indicated an abrupt decrease of approximately 25 µmho/cm with depth near a possible fracture identified on the caliper log at about 690 FANGVD29 in borehole AW5D, indicating that the possible fracture is permeable. Fluid-resistivity values indicated a gradual decrease of approximately 50 µmho/cm with depth at about 727 FANGVD29 at borehole AW1D, increased by about 2,000 µmho/cm to a maximum value at about 687 ft, then decreased steadily by about 1,500 µmho/cm to the bottom of the borehole at 672 ft. There may be permeable features at 672-687 FANGVD29, and 687-727 FANGVD29 at borehole AW1D.

Flowmeter Logging—Single Hole

Flowmeter logging under conditions of ambient flow in borehole DF4D indicates downward flow in the borehole with water cascading down the borehole to the top of the water column at 766 FANGVD29 and inflow along a subhorizontal bedding-plane parting near the top of the Grand Detour Formation at 757 FANGVD29 (table 6)(fig. B1). Outflow was detected through a series of bedding-plane partings, inclined fractures, and vugs in the upper to middle parts of the Grand Detour Formation between about 753 and 728 FANGVD29 and the middle part of the Pecatonica Formation below about 700 and 690 FANGVD29.

Flowmeter logging under ambient-flow conditions in borehole DF5D indicates downward flow in the borehole with water draining down the borehole to the top of the water column at 762 FANGVD29 and, possibly, inflow from one or more bedding-plane partings between 762 and 759 FANGVD29. Outflow was detected through a series of bedding-plane partings, inclined fractures, and vugs in the lower half of the Grand Detour Formation between about 739 and 729 FANGVD29. No flow was detected below 729 FANGVD29.

Flowmeter logging under ambient-flow conditions in borehole DF12 indicates downward flow in the borehole with inflow through vugs and fractures in the lower part of the Grand Detour Formation from about 741 through 728 FANGVD29 (table 6)(fig. B3). Concerns over equipment safety prevented obtaining a flowmeter measurement below 723 FANGVD29 in this borehole, but in order for inflow to be present in the upper part of the borehole, outflow must have been present below 723 FANGVD29.

Vertical flow was not detected under ambient-flow conditions in borehole DF13. Water-level data collected during packer testing identified less than 0.10 ft difference in water levels between the upper and lower parts of this borehole (table B2), indicating that the lack of ambient flow results from an absence of vertical hydraulic gradient within the borehole. Flowmeter logging done in conjunction with pumping from borehole DF13 identified flow associated with bedding-plane partings in the Grand Detour Formation at 759 and 734-732 FANGVD29, a vuggy part of the Grand Detour Formation at 747 FANGVD29, and bedding-plane partings in the Pecatonica Formation at about 702 FANGVD29.

Flowmeter logging under ambient-flow conditions in borehole DF17 indicates upward flow in the borehole with inflow through permeable fractures or solution openings in the Pecatonica Formation below 710 FANGVD29. Outflow is through bedding-plane partings in the Grand Detour Formation at about 730 and 735 FANGVD29 (table 6).

Vertical flow was not detected under ambient-flow conditions in borehole SPW (fig. B2). Water-level data collected during packer testing identified less than 0.11 ft difference in water levels between the upper and lower parts of this borehole (table B2), indicating that the lack of ambient flow results from an absence of enough vertical variation in water level within the borehole to drive flow. The lack of vertical variation in water level at borehole SPW may be attributed to good vertical hydraulic connection within the inclined fractures that intercept the borehole. Flowmeter logging done in conjunction with pumping in borehole SPW identified measurable flow through the inclined fractures in the Grand Detour Formation above 736 FANGVD29 and through the inclined fracture in the Mifflin Formation at about 711 FANGVD29 (Frederick Paillet, U.S. Geological Survey, written commun., 1993). About 0.03 gal/min of flow occurred through one or more bedding-plane partings in the Pecatonica Formation at about 698 FANGVD29. Single-hole reflection surveys identified a reflector at about 711 FANGVD29 in borehole SPW, but no reflectors were identified near the other permeable intervals. The interval at 711 FANGVD29 approximately corresponds to the depth of the lower zone identified at borehole SPW on the cross-hole tomograms. This result indicates the lower zone is a permeable subhorizontal fracture and that it may extend from boreholes PZ3 and SPW to borehole PZ1. This fracture shows no clear relation to changes in lithology.

Flowmeter logging under ambient-flow conditions in borehole PZ1 indicates downward flow, with water cascading down the borehole to the top of the water column and, possibly, inflow from fractures at or near the highest point of flow measurement at 748 FANGVD29 (Frederick Paillet, U.S. Geological Survey, written commun., 1993, 1997)(table 6). Outflow was through a vuggy, fractured part of the aquifer in the Mifflin Formation (fig. 11) at an altitude of about 708 FANGVD29. The altitude of the outflow interval corresponds to one of the reflectors identified from the single-hole radar survey (table B1). The altitude of the outflow interval also is consistent with the altitude of the lower zone identified at borehole SPW on the cross-hole tomograms (figs. A5, A6; table 5).

Flowmeter logging under ambient-flow conditions in borehole PZ2 indicates downward flow, with water draining down the borehole to the top of the water column and, possibly, inflow from a series of fractures above the highest point of measurement at 784 FANGVD29. Outflow was through inclined or horizontal fractures in the Nachusa Formation at an altitude of about 761 FANGVD29, one or more horizontal fractures in the Grand Detour Formation between 748 and 754 FANGVD29, and a fracture at about 723 FANGVD29. Single-hole reflection data identified a reflector at 787 FANGVD29 in this borehole but no reflectors were identified at the other depths of flow (table B1).

Flowmeter logging under ambient-flow conditions in borehole PZ3 indicates downward flow, with water draining down the borehole to the top of the water column and, possibly, inflow from some of the horizontal fractures near 764 FANGVD29. Inflow was through a horizontal fracture in the Grand Detour Formation at 750 FANGVD29. Outflow was through horizontal and inclined fractures in the Pecatonica Formation at about 694 FANGVD29. Single-hole reflection data identified a reflector at 746 FANGVD29 in this borehole, but no reflectors were identified that clearly correspond to depths of measurable flow. The outflow interval near 694 FANGVD29 approximately corresponds to the altitude of the lower zone identified at borehole PZ3 on the cross-hole tomograms.

Flowmeter logging under ambient-flow conditions in borehole AW1S gave inconsistent readings between multiple measurements at the same depth and at different depths in the borehole, but indicated less than 0.10 gal/min of downflow in the borehole. The small amount of flow coupled with the lack of consistent readings precludes identification of specific depths of flow into or out of this borehole. The large water-level differences measured during packer testing in this borehole indicate that the small amount of flow measured is the result of uniformly low aquifer permeability at this borehole.

Flowmeter Logging—Cross-hole

Flowmeter logging in boreholes PZ1, PZ2, and AW1S was done in conjunction with pumping in borehole SPW at 22 gal/min, and in borehole PZ3 at 32 gal/min (Frederick Paillet, U.S. Geological Survey, written commun., 1993). Analysis of changes in flow in response to pumping resulted in identification of flow pathways between boreholes.

Analysis of changes in the flow in borehole PZ1 during pumping in borehole SPW indicates hydraulic connection between the permeable feature at about 708 FANGVD29 in borehole PZ1 and one or more fractures supplying the water pumped from borehole SPW (table 6). Analysis of flow in borehole PZ2 during pumping in borehole SPW indicates hydraulic connection between the fractures from 748 to 754 FANGVD29 and, possibly, the horizontal or inclined fracture at about 761 FANGVD29 in boreholes PZ2 and SPW. Analysis of changes in flow in borehole PZ3 during pumping in borehole SPW indicates hydraulic connection between the fractures at about 764, 750, and 694 FANGVD29 at borehole PZ3 and one or more fractures supplying water to borehole SPW. No changes in flow were observed in borehole AW1S during pumping in borehole SPW.

Analysis of changes in the flow in borehole PZ2 during pumping in borehole PZ3 indicate hydraulic connection between the horizontal fractures above 784 FANGVD29, and at 748-754 FANGVD29 in borehole PZ2 and one or more fractures supplying the water pumped from borehole PZ3. No changes in flow were observed in borehole AW1S, SPW, and PZ1 during pumping in borehole PZ3.

Flowmeter, acoustic televiewer, and borehole-radar data in the vicinity of boreholes SPW, PZ1, PZ2, PZ3, and AW1S indicate inclined fractures that intercept the borehole above 736 FANGVD29 and at 711 FANGVD29 supply most of the water to borehole SPW. These fractures are connected hydraulically to an upper flow pathway at about 750 FANGVD29 and a lower flow pathway below 711 FANGVD29 (figs. A5, A6). The upper flow pathway appears to correspond to a number of horizontal fractures in the upper part of the Grand Detour Formation. These fractures are above the argillaceous deposits of the Grand Detour Formation identified as the upper zone by the cross-borehole tomography and are overlain by a low-permeability interval. The upper flow pathway may be absent near borehole AW1S. The lower flow pathway appears to correspond to a fractured interval that extends between boreholes SPW and PZ1, between 711 and 708 FANGVD29, and between boreholes SPW and PZ3, between 711 and about 694 FANGVD29. The lower flow pathway appears to correspond to the lower permeable zone identified with the cross-hole logging and corresponds to the Mifflin and Pecatonica Formations.

Flowmeter logging was done in boreholes DF13 and DF5D during pumping in borehole DF4D at 6.5 gal/min. Borehole DF13 had a slight increase in flow between 742 and 721 FANGVD29, indicating flow between the permeable features supplying water to borehole DF4D and permeable features in the lower portion of the Grand Detour Formation at borehole DF13. Borehole DF5D did not respond to pumping in borehole DF4D.

Hydrophysical Logging

Hydrophysical logging under ambient-flow conditions in borehole DF4D indicated flow down the borehole wall to the top of the water column, flow into the borehole through subhorizontal bedding-plane partings at about 754, 739-743, 729, and 694-698 FANGVD29 (GZA Geoenvironmental, Inc., 1991)(table 6). Hydrophysical logging indicates the specific conductance of the permeable features above 729 ft was about 840 µS/cm, whereas the specific conductance of the permeable feature from 694 to 698 ft was about 600 µS/cm. This interpretation is consistent with that made from analysis of the single-borehole GPR survey, which indicated decreased fluid conductivity with depth at this borehole.

Hydrophysical logging under ambient-flow conditions in borehole DF12 identified inflow through the fractures and solution openings below about 713 FANGVD29 (table 6). Hydrophysical logging under conditions of ambient flow in borehole SPW did not detect vertical flow, presumably because of a lack of vertical variation in water level within the aquifer. Hydrophysical logging, done in conjunction with simultaneous pumping and fluid injection in borehole SPW, identified inflow through inclined fractures at about 711 and 744 FANGVD29 (table 6). Hydrophysical logging indicates the specific conductance of the permeable feature at 711 FANGVD29 was about 1,035 µS/cm, whereas the specific conductance of the permeable feature at 744 FANGVD29 was about 725 µS/cm. This interpretation is different from that made from analysis of the single-borehole GPR survey that indicated decreased fluid conductivity with depth at this borehole.

Aquifer Tests

Slug tests, specific-capacity tests, step-drawdown tests, multiple-well tests, and tracer tests were performed at the Byron site (table 3). The results of these tests confirm and expand upon interpretations of hydrogeologic conditions determined with the application of other methods.

Slug Tests

Kh values were obtained from slug tests in 55 monitoring wells open to the Galena-Platteville aquifer at the Byron site and in 55 test intervals isolated with a packer assembly that sampled most of the aquifer thickness at wells AW1S, DF2D, DF4D, DF5D, DF6, DF12, DF13, DF14D, PZ1, and SPW. Kh values ranged from a high of 11,000 ft/d in test interval B of borehole DF12 to a low of 0.0034 ft/d in test interval A of borehole DF14D. The large variation in Kh supports the conclusion that the Galena-Platteville aquifer is highly heterogeneous.

The geometric mean of the Kh values was calculated for each of the four zones in the Galena-Platteville aquifer identified from analysis of the water-table configuration (fig. 13). The mean Kh in zones 1,2,3, and 4 was 0.31, 5.2, 240, and 8.0 ft/d, respectively. The median Kh in the upper part of zone 1 is 0.11 ft/d, slightly lower than the mean Kh in the lower and middle parts of zone 1 (0.48 ft/d). These conclusions are consistent with those drawn from analysis of the lithologic and flowmeter logs, water levels in test intervals isolated with a packer assembly, and the water-table configuration.

Kh values obtained from the slug tests in the intervals isolated with a packer assembly in a borehole or in the finished monitoring wells were compared to the stratigraphic unit to which the well or test interval was open. The geometric mean of the Kh for the Galena Group is 0.12 ft/d (fig. 12). The geometric mean of the Kh for the Pecatonica, Nachusa, and Quimbys Mill Formations varied from 0.23 to 0.62 ft/d. The geometric mean of the Kh for the Mifflin and Grand Detour Formations is 1.3 and 2.7 ft/d, respectively. If the values determined for wells DF12 and MW16 northwest of the BSY are excluded, the mean Kh of the Mifflin Formation is calculated to be 0.71 ft/d, indicating the Kh of the Mifflin Formation is not appreciably higher than that of the Pecatonica, Nachusa, and Quimbys Mill Formations beneath most of the Byron site. The higher mean Kh of the Grand Detour Formation across the Byron site is consistent with the presence of collapse features in this formation observed at the Benesh Quarry.

Comparison of Kh values for test intervals obtained by use of the packers with the elevation of permeable features identified from the flowmeter logs generally show good to moderate correlation (table 6)(figs. B1, B2, B3). The correlation was more consistent between intervals of low permeability identified from the slug tests and the flowmeter logs. For example, Kh values in borehole AW1S are less than 0.05 ft/d, and no permeable intervals were identified with the flowmeter logs.

Flowmeter logs and slug-test values show generally good agreement at borehole DF5D, where flowmeter logs indicate the presence of permeable features between about 739 and 729 FANGVD29 and, perhaps, 762 and 759 FANGVD29. A Kh of 18 ft/d was calculated between 721 and 731 FANGVD29, and a value of 3.2 ft/d was calculated between 731 and 741 FANGVD29. Kh values for the remaining test intervals were less than 0.10 ft/d, including the test interval corresponding to the possible permeable feature at about 762 FANGVD29. The differences in interpretation in aquifer permeability at about 762 FANGVD29 can be attributed to the flowmeter log measuring inflow of water cascading down the borehole to the top of the water column, not inflow from a permeable fracture in this interval.

Flowmeter logs indicate the presence of permeable features at borehole DF4D at 690-700, 728-753, and 757 FANGVD29 (table 6)(fig. B1). Kh values greater than 1.5 ft/d were calculated between 721 and 741 FANGVD29, whereas Kh values less than 0.90 ft/d were calculated in the 683-698 interval, and Kh values less than 0.50 ft/d were calculated in all of the remaining test intervals, including the 751-762 interval. The presence of measureable flow in intervals of comparatively low Kh near the top and the bottom of borehole DF4D may be a reflection of the large variation in water level over the length of the borehole.

Although the saturated thickness of the Galena-Platteville aquifer at borehole DF12 was about 12 ft less during slug testing than during flowmeter logging, analysis of slug tests and flowmeter logs both indicate the presence of permeable features from approximately 728-741 FANGVD29 and between the bottom of the borehole at 703 FANGVD29 and the lowest flowmeter measurement at 723 FANGVD29 (fig. B3). Slug-test results indicate high (greater than 4.0 ft/d) Kh above 741 FANGVD29, whereas a change in flow in this interval was not detected by the flowmeter log. This discrepancy is most likely because the Kh of the aquifer above 741 FANGVD29 is more than two orders of magnitude less than it is from 731 to 741 FANGVD29 (11,000 ft/d), precluding effective measurement of changes in flow. Additionally, the Kh at the 703-740 FANGVD29 interval is approximately an order of magnitude less than that at the 730-740 FANGVD29 interval, indicating that the aquifer at 703-730 FANGVD29 is less permeable than at 730-740 FANGVD29.

Kh values exceeded 2.0 ft/d in the interval from 727 to 747 FANGVD29 at borehole DF13, even though the flowmeter log failed to detect flow, and, thereby, identify permeable intervals, under ambient-flow conditions because of the low vertical hydraulic gradient within the borehole. Areas of elevated permeability were identified at 702, 732-734, 747, and 759 FANGVD29 during flowmeter logging done in conjunction with pumping. The permeable features identified at 702 and 759 FANGVD29 correspond to areas where the Kh was calculated to be less than 0.50 ft/d. The low Kh calculated for the permeable feature at 759 FANGVD29 can be explained, at least partially, by the atypically long (20 ft) packer-test interval at this depth. Flowmeter measurements typically were collected at intervals of 5 ft or less, whereas slug tests were done at intervals of 10 ft or more. Because it is assumed in the slug-test analysis that the tested part of the aquifer is homogenous, the response of the thick low-permeability matrix is combined with the response of the high-permeability fractures and solution openings, resulting in low-permeability estimates for the entire interval. Flowmeter measurements allow for the characterization of permeable features at numerous discrete points within the aquifer, permitting the assembly of a more detailed permeability profile than is possible with a 10-ft packer assembly.

Kh values from test intervals B, C, E, and F in borehole SPW (at 700-720 and about 730-755 FANGVD29) were 1.0 ft/d or greater (fig. B2). Each of these zones is either in or near permeable intervals identified with the flowmeter logs done in conjunction with pumping from the borehole (table 6). Kh values from test intervals D, F and G in borehole PZ1 (at 703-713 and 723-743 FANGVD29) were greater than 0.90 ft/d. Only the 703-713 FANGVD29 interval in this borehole corresponds to a permeable feature identified with the flowmeter log (table 6).

Specific-Capacity Tests

Borehole DF12 was pumped at 13, 33, and 71 gal/min on three different occasions in an attempt to determine the feasibility of a multiple-well, constant-discharge aquifer test. After pumping the borehole at 71 gal/min for 112 minutes, 0.14 ft of drawdown was measured in borehole DF12 and no drawdown was measured in nearby wells PW3, DF10, or MW39. A multiple-well aquifer test was determined to be infeasible for this borehole, leaving a specific-capacity test the only method available for estimation of hydraulic properties for the aquifer at this borehole. The transmissivity of the aquifer at borehole DF-12 was estimated to be 1.30 X 10^5 ft^2/d. This value is consistent with the results of the slug testing from this borehole.

Borehole PZ3 was pumped at 33 gal/min in an attempt to perform a multiple-well, constant-discharge aquifer test. After pumping borehole PZ3 for 100 minutes, about 22 ft of drawdown was measured the borehole, but no drawdown measured in nearby wells AW1S, AW1D, AW3, SPW, B3, PZ1, and PZ2 (fig. 7). The transmissivity of the aquifer at borehole PZ3 was estimated to be 130 ft^2/d.

Multiple-Well Aquifer Tests

Multiple-well aquifer tests were done in the vicinity of borehole SPW and borehole DF4D (table 3). These test provided substantial insight into the flow pathways within the aquifer.

Borehole SPW

A multiple-well, constant-discharge aquifer test was done in June 1987 by pumping 20 gal/min from borehole SPW over a period of 3,140 minutes. Borehole PZ1 was 115 ft deep when this test was done and boreholes PZ3, AW1S, AW1D, and AW3 had not yet been drilled. The data from this test indicate that the Galena-Platteville aquifer is anisotropic and unconfined in this area and acts as a double-porosity medium (Kay and others, 1989). Drawdown preferentially was oriented N. 60° W. from borehole SPW, parallel to the dominant regional fracture orientation and the orientation of inclined fractures identified in borehole SPW (fig. B5). Aquifer transmissivity was at a maximum of 670 ft^2/d directed N. 60° W. from borehole SPW and at a minimum of 490 ft^2/d perpendicular to the N. 60° W. direction. Kh values ranged from 5.8 to 8.0 ft/d, and the specific yield ranged from 0.017 to 0.148. After initially dropping, water levels in observation wells B3, B5 and PZ2 began to rise about 1,000 minutes into the test and were about 0.10 to 0.60 ft higher at the end of the test (3,140 minutes) than at about 1,000 minutes. Water levels in observation wells PW3, MW8, MW9, PZ1, and B4 dropped during the entire test. The increase in water levels in wells B3, B5, and PZ2 could not be correlated with background water-level fluctuations, indicating that the upper part of the aquifer in the vicinity of wells B3, B5, and PZ2 may have become hydraulically isolated from the fractures supplying water to borehole SPW during the test, presumably due to localized desaturation of the upper fractured zone identified by the cross-hole GPR surveys. Wells B5 and PZ2 are located in zone 1, a part of the aquifer characterized by low permeability, especially in the upper part of the aquifer and low vertical hydraulic interconnection. Well B3 is located in a part of the aquifer that appears to be in poor hydraulic connection with the rest of the aquifer. It is presumed that the water level did not increase in borehole PZ1 because the part of the aquifer monitored by borehole PZ1 remained hydraulically connected to borehole SPW by flow through vertical fractures connected to the lower fractured zone (figs. A5, A6).

Borehole DF4D

A multiple-well, constant-discharge aquifer test was done in February 1992 by pumping 8 gal/min from borehole DF4D for 1,440 minutes. Borehole DF4D was open to the entire thickness of the Galena-Platteville aquifer during the test. Observation wells DF5D, DF6, DF13, and DF14D were screened in the most permeable parts of the aquifer identified from the slug testing and the flowmeter logging.

The data from this test indicate that the Galena-Platteville aquifer is heterogeneous and anisotropic in this area. Drawdown preferentially was oriented N 90° E from borehole DF4D, parallel to the orientation of inclined fractures identified with the televiewer logs in boreholes DF4D and DF5D and roughly parallel to the orientation of the West Ravine in this area (fig. A9). Drawdown also was greater in the middle of the aquifer than at the water table (fig. A9), indicating that the zone of elevated permeability between 730 and 760 FANGVD29 identified with the slug testing and flowmeter logging is the primary pathway for horizontal ground-water flow (Kay and others, 1997)(table 6). A large amount of drawdown was measured at the bottom of the Galena-Platteville aquifer at well MW36, indicating the presence of hydraulically connected secondary-permeability features, most likely inclined fractures, in the lower part of the aquifer in this area. Measurable drawdown in the shallow part of the Galena-Platteville aquifer at well PC3B indicates that the aquifer has some vertical hydraulic connection in upper part of the aquifer in this area, possibly because of the presence of inclined fractures. The absence of drawdown in the shallow part of the Galena-Platteville aquifer at well DF5S indicates that there are few, if any, permeable inclined fractures in the upper part of the aquifer in this area. These results are consistent with the interpretations made from the water-level data that indicated high vertical hydraulic gradients in the aquifer near wells DF4S/4D and DF5S/5D, and lower gradients at wells PC3B/DF6 (tables 4, B2).

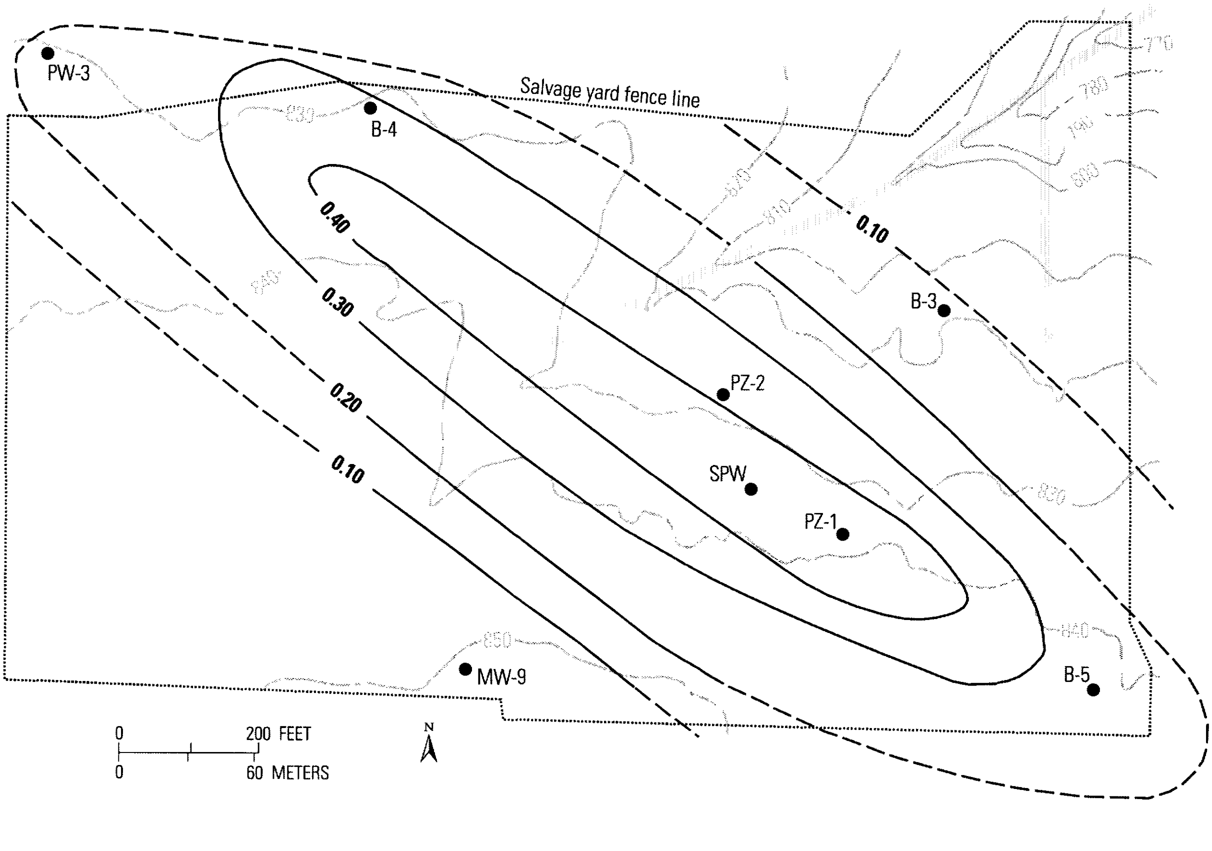
Transmissivity values calculated from the constant-discharge aquifer-test data for wells MW36 and DF6D, located along or nearest the direction of maximum drawdown in the aquifer, were about 90 ft^2/d. These values are approximately an order of magnitude lower than transmissivity values of about 725 ft^2/d calculated for wells DF5D and DF13 located furthest from the direction of maximum drawdown in the aquifer. The specific-yield values indicated no clear spatial patterns. The distribution of transmissivity values is contrary to what would be expected for an anisotropic aquifer, where the wells closest to the direction of maximum drawdown have the highest transmissivity, whereas the wells closest to the direction of minimum drawdown have the lowest transmissivity. No curve match could be made for the data from wells DF4S and PC3B. Attempts to calculate a transmissivity tensor using the Papadopulos (1965) method and the method of Hsieh and others (1985) yielded a negative value, indicating that the aquifer is heterogeneous in this area. Aquifer heterogeneity in the vicinity of well DF4D is consistent with the interpretations about aquifer heterogeneity in this area resulting from the analysis of the water-level data. The water-level data indicate borehole DF4D is located in zone 1 but also near transitional areas and zone 2.

Tracer Testing

A constant-discharge aquifer test was conducted as part of a tracer test done in borehole SPW in June and July 1993 (Kay and others, 1999). The tracer test was done to characterize the hydraulic properties of the aquifer in the vicinity of borehole SPW, with specific emphasis on the lower flow pathway identified with the cross-borehole tomography, slug testing, and flowmeter logging done in this area.

Hydrologic conditions for data collection differed between the 1987 and 1993 tests in borehole SPW. Boreholes PZ3, AW1S, AW1D, and AW3 were not present in 1987, but were available for the 1993 test (fig. 7). Borehole PZ1 had been deepened from 115 to 167 ft for the 1993 test. Packers were installed in boreholes PZ1 and PZ3 to provide a more detailed depiction of aquifer response. As a result of abnormally high amounts of precipitation immediately prior to the tracer test, the saturated thickness of the aquifer was about 16 ft higher during the 1993 tracer test than during the 1987 aquifer test.

Borehole SPW was pumped at a constant rate of 20 gal/min for 3,068 minutes while monitoring water levels in observation wells (wells expected to have detectable drawdown) and background wells (wells not expected to respond to pumping stresses). This pumping rate was selected to duplicate conditions during the 1987 aquifer test. The discharge rate was increased to 28 gal/min after 3,068 minutes of pumping and gradually decreased



EXPLANATION

—— 0.10 – – LINE OF EQUAL DRAWDOWN OF THE WATER TABLE, IN FEET-- Dashed where inferred. Contour interval 0.10 foot

840 TOPOGRAPHIC CONTOUR -- Shows elevation of land surface, in feet. Contour interval 10 feet. Datum is NGVD 29

FRACTURE TRACE

● MW-9 WELL LOCATION AND NAME

Figure B5. Drawdown of the water table after pumping borehole SPW for 1,000 minutes, Byron site, Ill., June 1987.

to about 25 gal/min by 4,365 minutes. Pumping from borehole SPW stopped after 4,365 minutes. The tracer-injection phase of the test began 150 minutes after the initiation of pumping from borehole SPW when 7.5 gal of tracer water with a concentration of about 20,000 mg/L of bromide was injected into the packed interval in borehole PZ1 (PZ1P) open to the aquifer from 708 to 718 FANGVD29.

Background declines in water levels caused by fluctuations in barometric pressure and recovery from the abnormally high water levels present in the aquifer were more than 2 ft in most of the wells during the tracer test. These background declines in water level were so high that drawdown could not be reliably quantified in the observation wells. Therefore, transmissivity and storativity values were not calculated. The data were analyzed qualitatively to obtain a general understanding of the flow pathways in the vicinity of the tracer test.

Comparison of the trends in water levels with pumping changes clearly indicate that drawdown was observed in boreholes PZ2 and AW1D, and in the packed intervals in boreholes PZ1 and PZ3. These boreholes are close to the pumped borehole and the timing and magnitude of drawdown in these boreholes could be separated easily from background fluctuations for short time periods. Drawdown may have been observed in wells DF21, PW3, B4, AW5D, and AW6, however, the water-level changes were difficult to pick out from the background water-level declines and amount of drawdown, if present, could not be accurately determined at these boreholes over even short time spans. Drawdown was not indicated in the remaining wells, including wells (MW8, MW9, B3) that contained measurable drawdown during the 1987 aquifer test.

Flowmeter and borehole-radar data indicate that water flows to the inclined fracture at borehole SPW primarily through the upper flow pathway around 750 FANGVD29 and the lower flow pathway at about 711 FANGVD29. Because most of the flow is through these pathways, it can be assumed that wells in good hydraulic connection with these pathways will have the largest drawdown, whereas observation wells in poor hydraulic connection with these pathways will have the smallest drawdown. More than 0.90 ft of drawdown was measured at intervals PZ1A (1.35 ft), PZ1P (0.95 ft), and PZ3A (1.15 ft) 100 minutes after the start of pumping. All of these intervals are in good hydraulic connection with the flow pathways supplying water to in borehole SPW. Intervals PZ3P (0.07 ft), PZ3B (0.10 ft), PZ1B (0.32 ft), and wells AW1D (0.08 ft) and PZ2 (0.06 ft) appear to be have moderate hydraulic connection with the flow pathways. Drawdown may have resulted 100 minutes after the start of pumping at wells DF21, PW3 (0.05 ft), and AW5D (0.07 ft). The aquifer in the vicinity of these wells may be hydraulically connected to the flow pathways supplying water to borehole SPW. The absence of detectable drawdown in wells B5 and AW1S, located in the upper part of the aquifer clustered with deeper wells (AW5D and AW1D) that may have had measurable drawdown, indicates that the upper part of the aquifer is not in hydraulic connection with borehole SPW in these areas.

The maximum amount of drawdown measured in boreholes PZ1 (1.35 ft) and PZ3 (1.15 ft) 100 minutes after the start of pumping was above the packed interval, which monitored the upper flow pathway. Drawdown in the test intervals in borehole PZ1 was greater than in the test intervals in borehole PZ3. Because borehole PZ3 is about 10 ft closer to the pumped borehole than borehole PZ1, the larger drawdown in borehole PZ1 indicates that flow is preferential along the orientation of the inclined fractures (N. 60° W.) from borehole SPW to borehole PZ1.

Measurable drawdown in the various packed intervals in borehole PZ3 100 minutes after the start of pumping in borehole SPW during the tracer test contrasts with the absence of hydraulic connection identified at borehole SPW 100 minutes after the start of pumping in borehole PZ3 during the flowmeter logging. The dissimilarity in the response to pumping in this borehole pair, although borehole PZ3 was pumped at a substantially greater rate (33 gal/min as opposed to 20 gal/min), indicates that boreholes PZ3 and SPW are supplied, at least in part, by different secondary-permeability features. The presence of separate permeable features supplying water to boreholes in different parts of the Byron site indicates that the Galena-Platteville aquifer is heterogeneous. The most likely pathway for flow to borehole PZ3 that does not appear to contribute substantial flow to borehole SPW is the vertical fracture between boreholes AW3 and PZ1 outlined by the fracture trace shown in figure 8. However, boreholes AW3 and PZ1 did not clearly show hydraulic connection to borehole PZ3 when it was pumped, so the importance of this fracture on flow cannot be determined.

Monitoring of the concentration of bromide ion with time in the water pumped from borehole SPW (fig. A10) indicated the velocity of the tracer through the lower flow pathway between boreholes PZ1 and SPW under the hydraulic gradient imposed by the pumping was about 152 ft/d. Solution of the Darcy velocity equation results in a calculated effective porosity for the lower flow pathway from 2.6 to 3.5 percent. Combining the effective porosity determined from the tracer test with the water-level and Kh data obtained by use of the packer assembly, solution of the Darcy equation (4) yielded an average ground-water velocity through the lower flow pathway of about 15.4 ft/d under hydrostatic conditions.

The effective porosity of the lower flow pathway is lower than the median primary porosity of the Galena-Platteville deposits of about 10 percent (fig. 11) and exceeds typical effective porosity values for fractures of less than 1 percent. An effective porosity value for the lower flow pathway that is higher than those typical of fractures and lower than those typical of the aquifer matrix indicates that the fractures and matrix in the Galena-Platteville aquifer in this area are connected hydraulically. Hydraulic connection between fractures and matrix is expected for a double-porosity medium such as the Galena-Platteville aquifer.

Location of Contaminants

The concentration and distribution of cyanide and VOC's in the ground water beneath the Byron site was determined by sampling in test intervals isolated with a packer assembly and from completed monitoring wells. As these compounds are not present in nature, their distribution was used as a tracer to define migration pathways through the Galena-Platteville aquifer.

Concentrations of VOC's in the test intervals isolated with a packer assembly in boreholes DF4D (fig. B1), DF5D, DF12 (fig. B3), DF13, and DF17 tended to be higher in the more permeable parts of the aquifer than in the less permeable parts of the aquifer. These patterns indicate preferential flow through the secondary-permeability features in the aquifer and smaller amounts of flow through the less permeable parts of the aquifer.

The distribution of VOCs and cyanide in monitoring wells at the Byron site shows two general areas of VOC's, one at the BSY and downgradient, and another derived from two areas on the DFP (fig. 15). The types of contaminants were variable spatially within the aquifer, making their distribution useful for tracking the movement of water in different parts of the aquifer.

The plume emanating from the BSY is composed primarily of trichloroethene, which migrates northwest to the Rock River along the direction of ground-water flow in this area, and also along the dominant vertical fracture orientation in the dolomite. The plume emanating from the BSY also contains cyanide; however, cyanide largely is confined to the fracture traces in the eastern part of the BSY and Woodland Creek, as well as at Meyer's Spring (fig. 15). Woodland Creek appears to define the extent of contamination in the northeastern part of the Byron site, and appears to be a ground-water sink.

The presence of VOC's in water at monitoring well AW5I in the southeast corner of the BSY upgradient of the source areas is difficult to explain (U.S. Environmental Protection Agency, 1994)(fig. 7). Well AW5I is open to the middle of the Galena-Platteville aquifer immediately above the shaley layer near the top of the Grand Detour Formation, and the well is hydraulically upgradient of disposal areas on the BSY. Wells B5, open to the water table, and AW5D, open to the base of the Galena-Platteville aquifer, are clustered with well AW5I, and do not contain VOC's. The presence of contaminant in the middle of the aquifer hydraulically upgradient of the defined disposal areas indicates one of two possibilities. There may be components of flow in the aquifer opposite to the northerly direction of flow indicated by the water-level data. Alternatively, contaminants (presumably in the form of a dense nonaqueous phase liquid) may have migrated at depth from the disposal areas to the area of well AW5I, presumably along the top of the shaley layer at the top of the Grand Detour Formation. The shale layer dips to the south in this area (fig. 10).

Two plumes are present in separate areas on the southern part of the DFP (fig. 15). The first is composed primarily of trichloroethene (TCE) and trichloroethane (TCA). The second is composed of TCA and chloroform. Both plumes migrate southwest to the Rock River along the West Ravine and approximately along the direction of the secondary vertical fracture orientation identified in the dolomite. Although water-level and water-quality data are not available in much of the area south of the DFP water-level data indicate that flow is from the area south of the DFP is northward toward the West Ravine. The presence of VOC's in the Galena-Platteville aquifer south of the DFP indicates flow opposite to the direction indicated by the water-level data.

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Appendix C—Tipton Farm Site Data

The hydrogeologic characterization of the Tipton Farm site is based on data collected and interpreted by the USGS and USEPA (Robinson and Yeskis, 1998). In addition, a substantial amount of data obtained by previous investigators (Ecology and Environment, 1985, 1986, 1990) also was summarized and subjected to analysis by the USGS and USEPA for this investigation. A total of 10 investigative methods were used to develop the hydrogeologic framework for the Tipton Farm site (table 7). Most of these methods contributed to the characterization.

Previous Studies

In 1985 and 1986, Ecology and Environment installed five monitoring wells (T1 - T5)(fig. 16) around the landfill area, collected ground-water-level measurements, performed a SAR survey, and sampled ground water. Ground-water-level data collected as part of this investigation indicated a northwestern direction of flow around the landfill area, with a more northerly component during periods of low water levels. A number of high and low resistivity anamolies were detected with the SAR survey, which could indicate the presence of unsaturated caverns/fractures (high resistivity) or saturated caverns/fractures (low resistivity). Four of the five wells were installed in areas with suspected karst features based on the SAR survey, however, only one small fracture was found in one well (Ecology and Environment, 1985). Analysis of water samples from the five wells indicated 24 parts per billion (ppb) of 2,4-dimethylphenol in the sample from well T1 and 5 ppb of trans-1,2-dichloroethene in the samples from well T5. Water from both wells contained phenolic compounds (Ecology and Environment, 1985, 1986).

A follow-up to the previous investigation by Ecology and Environment (1990), included the installation of 11 monitoring wells (DS1 - DS9, T6S, T6D)(fig. 16), ground-water-level measurements, soil sampling and ground-water-quality sampling. The investigation indicated that the ground-water flow generally mirrors surface topography (fig. 17). The major component of ground-water flow was to the west-northwest with seasonal variations and possible local variations because of fractures. Ground-water-quality samples collected in December 1987 and April 1988 indicated the presence of phenolic compounds and other organic compounds in water from wells T1 and T5 (Ecology and Environment, 1990).

Topographic Maps

Analysis of land-surface topography during site visits and from topographic maps (fig. 17) did not clearly indicate the presence of fracture traces or sinkholes at the Tipton Farm site. Comparison of surface topography with bedrock topography from lithologic logs obtained during previous investigations did indicate that topographic highs corresponded to locations where the bedrock surface is elevated in comparison to the rest of the site (fig. 18).

Lithologic logs

Because all of the wells were drilled during previous investigations, USGS analysis of the lithologic logs was restricted to the information on the logs, which was limited to identification of lithology. This analysis indicated the Galena-Platteville dolomite is overlain by 10-15 ft of unconsolidated material near the drum-storage area (figs. 17, 18) and less than 5 ft of unconsolidated material near the landfill.

Core Analysis

Core samples of the bedrock from wells DS8 and T6D were inspected by personnel from the ISGS (Mike Sargent and Steve Lasemi, Illinois State Geological Survey, written commun., 1992). Wells at the Tipton Farm site appear to penetrate the St. James, Beecher, Eagle Point, and Fairplay Members of the Dunleith Formation (fig. 18). These deposits, or at least the Eagle Point and Fairplay Members, appear to vary in thickness beneath the Tipton Farm site. Horizontal and healed vertical fractures were noted at about 814-816, 829, and 841 FANGVD29 in well T6D, and at about 819, 835-837, 842, 847, 849, 856-859, 867, and 869 FANGVD29 in well DS8.

Porosity values for three samples of the Fairplay Member ranged from 18 to 24 percent. Porosity values for four samples of the Eagle Point Member ranged from 9 to 31 percent. Porosity values for two samples of the Beecher Member ranged from 16 to 18 percent. Porosity values for two samples of the St. James Member ranged from 14 to 18 percent (Robinson and Yeskis, 1998).

Geophysical Logs

Caliper, natural gamma, and SPR logs were used for geologic characterization at the Tipton Farm site (table 7).

Caliper

Three-arm caliper logs indicate numerous small increases in diameter in each of the boreholes, most of which are above the water level. Large (greater than 1 in.) increases in diameter indicative of fractures were not detected. Increases in borehole diameter tend to correspond to fractured areas identified by the core analysis.

Natural Gamma

The natural-gamma log for well T5 shows a decrease in gamma activity below about 827 FANGVD29. This activity decrease may represent the location of the top of the Eagle Point Member at this location. The small interval of this well available for logging limits the utility of the log.

Single-Point Resistance

The SPR log resistance values from well T5 decreased slightly with depth. This log provided no conclusive information on site geology or the location of secondary-permeability features.

Water-Level Measurements

Water-level measurements were made in April 1990, November 1992, March 1993, and December 1994 (table 8). Water-level data indicate that the water-table configuration generally mirrors surface topography (fig. 19). Ground-water flow is from a ground-water divide near the drum-storage area toward low points west and northwest of the drum-storage area and the topographic low at the intermittent stream south of the landfill area (fig. 19). North of the intermittent stream, ground-water flow typically is west-southwest, although the direction of ground-water flow around the landfill is affected by seasonal changes in precipitation and also can be to the north and south.

Vertical hydraulic gradients at the DS4/DS8, DS6/DS7, and T6S/T6D well clusters indicate the potential for downward flow in the Galena-Platteville aquifer. Vertical gradients at the DS6/DS7 and T6S/T6D well clusters typically were about 0.05 ft/ft. These wells are located in the northern part of the site where the altitude of the bedrock surface is low in comparison to the rest of the site. Vertical hydraulic gradients at the DS4/DS8 cluster typically were about 0.2 ft/ft. The DS4/DS8 cluster is located in the southern part of the site where the bedrock surface is high. These gradients may indicate that the vertical hydraulic conductivity of the upper part of the Galena-Platteville aquifer is higher in the southern part of the site near the bedrock ridge than in the northern part of the site near the bedrock lows.

Vertical hydraulic gradients for well nest DS4/DS8 are fairly consistent over time. From 1990 to 1994, the average vertical gradient of 0.194 for well nest DS4/DS8 is near the 0.216 ft/ft average measured in 1987 and 1988 (Ecology and Environment, 1990). From 1990 to 1994, vertical hydraulic gradients for well nest T6S/T6D are larger during periods of lower water levels with the largest gradient (0.220 ft/ft) occurring in 1990 (Robinson and Yeskis, 1998).

Horizontal hydraulic gradients typically were about 0.03 ft/ft throughout the site. Horizontal hydraulic gradients were about 0.008 ft/ft near the landfill, indicating that the aquifer is this area may be more permeable than the rest of the site.

Geophysical Logging

SP logs were analyzed in an attempt to provide insight into the location of permeable features. The SP readings in wells T2, T4, and T5 indicated a large decrease in about the upper 8 ft of the water column, then decreased slightly with depth. The interval of large signal response may correspond to a permeable feature, but more likely was caused by the tool acclimating to water.

Aquifer Tests

Slug tests were performed on wells DS1, DS2, DS5, DS6, DS7, DS9, T6S, T6D, T4 and T5 in 1988 and 1990 (table C1). Slug tests were performed by the USGS on wells DS1 through DS9 in 1994. Water levels in 1988 and 1990 were from 7.1 to 15.5 ft lower than water levels in 1994 (Robinson and Yeskis, 1998). Kh values calculated from the slug tests ranges from 0.01 to 1.00 ft/d (table C1).

Those wells around the landfill area (T6S, T6D, T4, T5) typically had the lowest Kh values, indicating few saturated fractures during testing in 1990. Comparison of Kh values from wells tested in 1988 or 1990, and again in 1994, show that five wells had similar Kh and two wells had higher Kh values during 1994, when water levels were higher. The higher Kh at these wells might be due to higher water levels in 1994 resulting in saturated fractures being intercepted by the well that were not within the water column in 1988 or 1990 (Robinson and Yeskis,1998).

Table C1. Horizontal hydraulic conductivity values and date of testing, Tipton Farm site, Ill.

Well name (fig. 16)	Date of test (month and year)	Height of static water column (feet)	Horizontal hydraulic conductivity value (feet per day)
DS1	Apr-90	4.11	0.10
	Dec-94	19.58	1.00
DS2	Apr-90	6.56	.60
	Dec-94	20.96	.50
DS3	Dec-94	10.00	.40
DS4	Dec-94	22.54	.70
DS5	Apr-90	6.58	.50
	Dec-94	17.00	.50
DS6	Mar-88	20.13	.50
	Dec-94	20.38	.40
DS7	Mar-88	55.38	.30
	Mar-88	55.38	.30
	Dec-94	55.63	.30
	Dec-94	55.63	.30
DS8	Dec-94	53.94	.50
	Dec-94	53.94	.50
	Dec-94	53.94	.50
DS9	Apr-90	4.11	.30
	Dec-94	13.20	1.00
T6S	Jan-90	9.67	.10
T6D	Jan-90	33.27	.40
T4	Jan-90	7.44	.01
T5	Jan-90	12.72	.10

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Appendix D—ACME Solvents and Winnebago Reclamation Landfill Sites Data

The ACME Solvents and Winnebago Reclamation Landfill sites (the ACME/WRL site) were the location of a series of environmental investigations between 1982 and 1990, with collection of data for routine monitoring ongoing. The investigations of concern for this discussion were conducted from 1988 through 1990 by Warzyn Engineering, Inc., and Harding-Lawson Associates. The USGS provided field oversight and an independent analysis of the data for the USEPA. Results of these investigations are presented in Warzyn Engineering, Inc, 1990; Harding-Lawson Associates, 1990; and Kay, 1991. These reports provide a detailed discussion of the hydrogeologic investigations at the ACME/WRL site. A total of 13 investigative methods were used to develop the hydrogeologic framework for the ACME/WRL site (table 9). Most of these methods contributed to the characterization.

Topographic and Aerial Photographic Analysis

Analysis of land-surface topography during site visits, and from topographic maps and aerial photographs, did not indicate the presence of fracture traces or sinkholes at the ACME/WRL site. It is presumed that these features were not identified because they are absent within the area of investigation, though the thick (more than 20 ft) unconsolidated deposits in parts of the ACME/WRL site may be masking their presence. Comparison of surface topography with bedrock topography indicated that topographic highs (not associated with the landfill) corresponded to areas where the bedrock is near the land surface.

Quarry Visits

The Dunleith Formation of the Galena Group is the only bedrock deposit exposed at the quarry north of the ACME Solvents site (fig. 21). Solution features were not observed, but vertical fractures were present. The strike of these vertical fractures ranged from N. 53° W. to N. 67° W., with a second set oriented between N. 18° E. to N. 44° E.

Lithologic Logs

Lithologic logs were done for all of the boreholes drilled during environmental investigations at the ACME/WRL site (tables 9, 10). The STI well series at the ACME site and the G well series at the WRL site were drilled for these investigations. The other wells were drilled as part of previous investigations. The only lithologic logs of use for characterization of secondary-permeability features were those for the STI series of wells drilled for the investigation at the ACME site, which were drilled using an air hammer. The remaining wells were drilled using a tricone roller, which tended to obscure the presence of permeable features because of its slow drilling rate in comparison to other drilling methods. It is impractical to recount the particulars of the logs for each well, but the logs indicate that the Galena-Platteville deposits primarily were competent dolomite yielding small amounts of water interspersed with occasional permeable zones indicative of fractures and vugs. The lithologic log for well STI-1D indicated fractures at 598, 665, and 690 FANGVD29 (table 11). The lithologic log for well STI-3D indicated fractures at about 633 and 713 FANGVD29. The lithologic log for well STI-4D indicated fractures at 666 and 700 FANGVD29. A dramatic decrease in the amount of rock return was observed below about 731 FANGVD29 at wells STI5I and 5D, with a complete loss of water and rock return at 641 FANGVD29, indicating the presence of a large fracture or solution opening near 731 FANGVD29. Vugs or fractures also were indicated at 707 FANGVD29 in well STI-5D. Secondary-permeability features were not identified from the remaining lithologic logs.

Core Analysis

The entire thickness of the Galena-Platteville dolomite (519-679 FANGVD29) was cored at a location about 50 ft east of well STI-SP2 (fig. 21). In addition, 20-ft sections of core were collected at the completion intervals for each of the STI-I and STI-D series of wells (table 9). Stratigraphic analysis of these cores (Harding-Lawson Associates, 1990; Michael Sargent, Illinois State Geological Survey, written comun., 1998) indicates that the Platteville and Galena Groups beneath the ACME/WRL site are composed of the Pecatonica (about from 519 to 543 FANGVD29 at well STI-SP2), Mifflin (about from 543 to 564 FANGVD29), Grand Detour (about from 564 to 603 FANGVD29), and Dunleith Formations (603 FANGVD29 to the bedrock surface)(figs. D1 and D2). The Nachusa, Quimbys Mill and Guttenberg Formations are not described in any of these cores, indicating the presence of an unconformity at about 603 FANGVD29 at well STI-SP2.

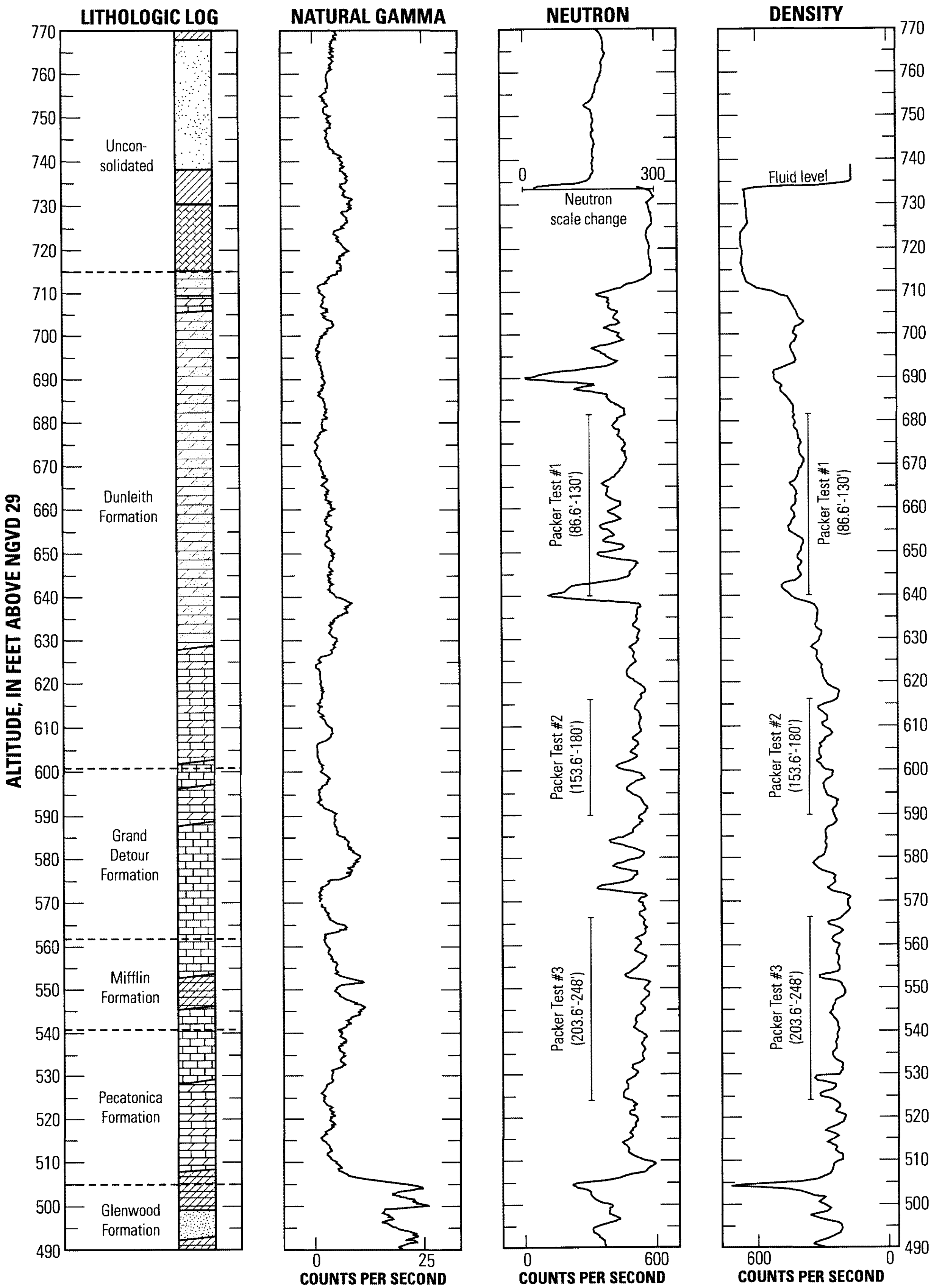

Figure D1. Lithology, stratigraphy, select geophysical logs, and packer-test intervals for borehole STI-SP2, Acme Solvents/Winnebago Reclamation Landfill sites, Ill.

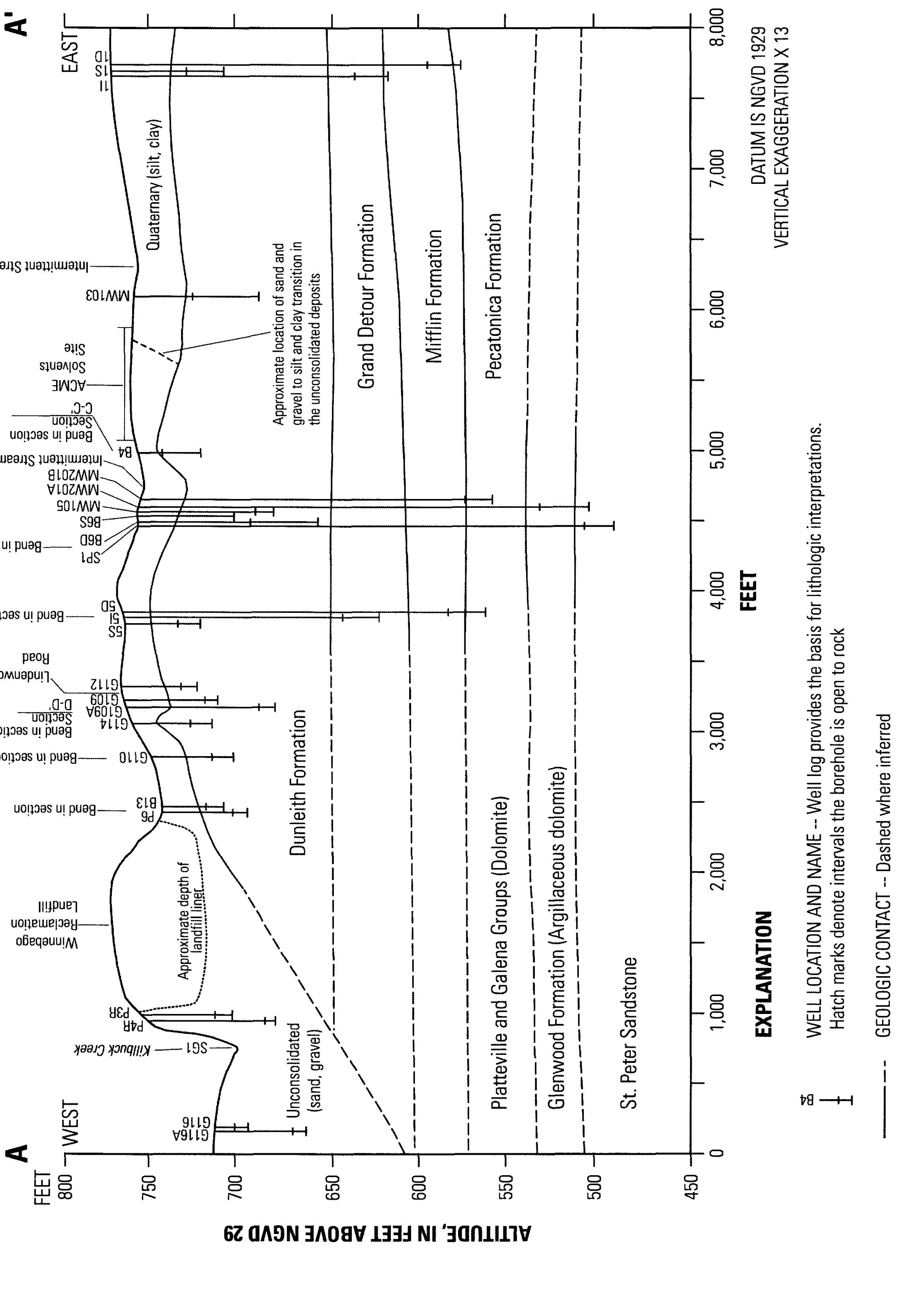

Figure D2. Geologic section A-A' at the ACME Solvents/Winnebago Reclamation Landfill sites, Ill. Line of section shown in figure 21.

Description of the core taken near well STI-SP2 indicates that the Galena-Platteville dolomite contains vertical and horizontal fractures at about 576-583 FANGVD29 (Grand Detour Formation), 625-634, 657-684, and 697-710 FANGVD29 (Dunleith Formation) with vuggy intervals at 625-634, 657-684, and 697-710 FANGVD29 (Dunleith Formation)(fig. D1). Comparatively competent dolomite was indicated for the uppermost 30 (Dunleith Formation) and lowermost 60 ft (Pecatonica and Mifflin Formations) of the Galena-Platteville dolomite.

Although not part of this investigation, a core was drilled in the quarry north of the ACME Solvents site and analyzed for stratigraphy by the quarry operator (Rockford Sand and Gravel, written commun., 2000). The reference altitude of this core was not provided, so the altitude of the features cannot be determined. The Dunleith Formation is about 150 ft thick at the quarry and is described as being underlain by about 4 ft of Guttenberg Formation, and by about 4 ft of the Quimbys Mill Formation. The Quimbys Mill Formation is underlain by the Grand Detour Formation. It is unclear if the discrepancy regarding the presence or absence of the Quimbys Mill and Guttenberg Formations at the quarry and at well STI-SP2 is related to the actual presence or absence of these formations in different parts of the ACME/WRL site, or differences between the interpretation of the persons doing the descriptions. However, lithologic logs from well STI-3D in the quarry indicate the presence of shale beds at about 603, 613, and 653 FANGVD29, which were not described in the other STI wells. The two deeper shale beds are about 165 and 155 ft below land surface, which is consistent with the depths described from the quarry core.

Geophysical Logs

Geophysical logs were run primarily at the deep well in the STI clusters at the ACME/WRL site (table 9). These logs expanded the geologic framework of the ACME/WRL site and provided part of the foundation for the hydraulic framework.

Borehole Camera

Borehole-camera logging in well B6PW generally showed competent rock with clearly identifiable subhorizontal fractures at about 609 and 677 FANGVD29 (table 11). Smaller, less distinctive fractures or bedding-plane partings were present between 668 and 679 FANGVD29 and between 700 and 720 FANGVD29. An inclined fracture was identified at about 650 FANGVD29.

Caliper

Single-arm caliper logs show enlargements in well diameter at about 667, 684, and 734 FANGVD29 in well STI-1D (table 11), at 732 FANGVD29 in well STI-4D, and at 729 FANGVD29 at well STI-5D. Single-arm caliper logs in well STI-3D tended to show general areas of enlarged wellbore diameter from 583 to 593, 664 to 676, at 719, and from 730 to 740 FANGVD29, as opposed to distinct, individual features. Single-arm caliper logs in wells STI-2D tended to show areas of enlarged wellbore diameter from 583 to 593, 664 to 676 , at about 719, and from 730 to 740 FANGVD29. Many of these enlarged areas may be fractures or solution openings, but it is more likely that these areas were enlarged during drilling (wash outs) and are not representative of secondary-permeability features. Areas where caliper data indicate potential fractures in a well usually are the same locations where lithologic logs indicate the presence of permeable features (table 11). Caliper logs run in the remaining logged wells showed little variation in diameter, indicating competent, unfractured, dolomite.

Natural gamma

Natural-gamma logs run in well STI-SP2 were compared to the stratigraphic description from the nearby core so the natural-gamma signal of the formations could be identified (fig. D1). Natural-gamma logs from wells STI-1D, 2D, 3D, 4D, 5D, and SP1 then were compared with natural-gamma logs from well STI-SP2 so the stratigraphy across the ACME/WRL site could be determined (fig. D2). Comparison of the natural-gamma signal with the stratigraphic interpretations for each of the wells indicates that the altitude of the contacts between the various formations in the Galena and Platteville Groups is variable. The contact between the Glenwood and Pecatonica Formations is at about 543 FANGVD29 at wells STI-SP1 and STI-3D, but decreases to about 505 FANGVD29 at well STI-SP2. The natural-gamma log from well STI-3D does not indicate that the Guttenberg and Quimbys Mills Formations are present near this well.

Neutron

The neutron log run in the borehole for well STI-SP1 prior to well installation shows an overall increase in counts per second (cps) from the top to the bottom of the Dunleith Formation, a slight decrease from the top to the bottom of the Grand Detour Formation, generally consistent response throughout the Mifflin Formation, decreasing cps in the upper part of the Pecatonica Formation, and similar cps in the lower part of the Pecatonica Formation. Neutron logs run in the borehole for well STI-SP2 (fig. D1) also show an overall increase in cps from the top to the bottom of the Dunleith Formation, a slight increase from the top to the bottom of the Grand Detour Formation, consistent response throughout the Mifflin Formation, and a small decrease in cps with depth in the Pecatonica Formation. Neutron logs run in the borehole for well STI-1D show a slight overall increase in cps from the top to the bottom of the Dunleith Formation, but generally were unchanged from the bottom part of the Dunleith Formation through the end of the log near the top of the Mifflin Formation. Neutron logs run in the borehole for well STI-2D also show little change from the lower part of the Dunleith Formation (the upper part is eroded in this area) through the Grand Detour Formation, then a slight decrease toward the Mifflin Formation near the bottom of the borehole. Neutron logs run in the borehole for well STI-3D show little change in the upper part of the Dunleith Formation, were elevated in the lower 20 ft of this formation, decreased with depth in the Grand Detour Formation, and generally were unchanged with depth in the Mifflin Formation at the end of the log. Neutron logs run in the borehole for well STI-4D show little change in the Dunleith Formation and increased slightly with depth through the Grand Detour Formation to the top of the Mifflin Formation at the bottom of the borehole. Neutron logs run in the borehole for well STI-5D show little change in the upper part of the Dunleith Formation, increase slightly in the lower 30 ft of this formation, and decrease slightly with depth in the Grand Detour Formation and the top of the Mifflin Formation at the end of the log.

Neutron logs at the ACME/WRL site showed no large, abrupt changes in cps readings that could be attributed clearly to fractures identified with the caliper or lithologic logs. Neutron logs showed some correlation with natural-gamma response, but this response was not evident in all of the wells, or at all depths within a given well. This lack of identifiable response to secondary-permeability features probably can be attributed to the effects of the variation in the clay mineral content of the dolomite and a lack of secondary-permeability features containing enough water to be detected over the ambient response.

Water-Level Measurements

Water levels were measured on a periodic basis. These measurements resulted in an improved understanding of the hydrology of the Galena-Platteville aquifer.

Periodic Measurements

Water levels were collected periodically from December 1984 through April 1990, with the most intensive effort from October 1988 through August 1989. Water levels were used to construct the water-table configuration and to determine the horizontal and vertical-hydraulic gradients within the Galena-Platteville aquifer so that a three-dimensional depiction of flow directions could be obtained. A major drought occurred in 1988-89 affecting water-table configuration from May 1989 through February 1990.

Water levels varied by less than 5 ft from April 1988 through April 1990. The largest variation (4.47 ft) was measured at well STI-3S. The smallest variation (1.79 ft) was measured at well B6D.

Water levels in wells open to the water table, the middle, and the base of the Galena-Platteville aquifer typically increased and decreased at the same time and typically by similar amounts during the period of measurement (fig. D3). These patterns indicate that the Galena-Platteville aquifer has sufficient vertical hydraulic interconnection to respond to ambient hydraulic effects as a single aquifer.

During typical (non-drought) conditions, such as were present at the site in November 1988, the water-table configuration indicates the direction of flow in the Galena-Platteville aquifer generally is from east to west toward Killbuck Creek, with a component of flow to the southwest (fig. 24). A ground-water divide is located north of the ACME Solvents site trending to the southeastern corner of the WRL. This divide corresponds to the location of the bedrock ridge (fig. 22).

During drought conditions, ground-water flow generally was from east to west toward Killbuck Creek (fig. 24), but the ground-water divide shifted south of the ACME site. This shift in the location of the ground-water divide appears to be in response to the comparatively large decline in water level north of the ACME Solvents site near well STI-3S, and the comparatively small decline south of the ACME Solvents site as indicated by the smaller change in water levels near well B6S. These differences in the amount of water-level decline may indicate that aquifer permeability north of the ACME Solvents site is higher than the aquifer permeability south of the site.

Examination of the water-table configuration for November 1988 (fig. 23) indicates that the horizontal hydraulic gradients, where the water table is in the Galena-Platteville aquifer, tend to be highest between the ACME Solvents and WRL sites (about 1×10^{-2} ft/ft) and lowest in the eastern part of the ACME Solvents site (about 6.5×10^{-4} ft/ft). These patterns in the horizontal hydraulic gradients indicate that the Galena-Platteville aquifer may be less permeable, and contain fewer interconnected secondary-permeability features in the area between the two sites than in the surrounding area.

Vertical differences in water level between the water table and the middle of the Galena-Platteville aquifer and between the middle and base of the Galena-Platteville aquifer typically are less than 10 ft. Vertical flow directions vary with depth and location, but flow is directed downward from the water table to the base of the aquifer beneath most of the area near the ACME Solvents site and beneath the southeastern part of the WRL. Flow is directed upward from the base of the aquifer to the water table south of the ACME Solvents site and northeast of the WRL. Not considering direction, vertical hydraulic gradients between the water table and the middle of the Galena-Platteville aquifer ranged from -8.1×10^{-4} to 2.4×10^{-2} ft/ft (table D1). Vertical-hydraulic gradients between the middle and base of the Galena-Platteville aquifer ranged from -1.4×10^{-4} to -1.3×10^{-2} ft/ft.

Vertical-hydraulic gradients in the Galena-Platteville aquifer at the ACME/WRL generally are low, which tends to indicate high vertical hydraulic conductivity within the aquifer. Analysis of these limited data does not indicate a substantial systematic variation in vertical hydraulic gradient with location or depth in the aquifer, indicating that the secondary-permeability network in this area does not vary substantially.

Aquifer tests

Slug tests and multiple-well constant-discharge aquifer tests were performed at the ACME/WRL site (table 9). Analysis of these tests provided the primary hydrogeologic insight into the nature of the secondary-permeability network at the site.

Slug tests

Kh values were obtained from slug tests performed in 33 monitoring wells open to the Galena-Platteville aquifer (table D2). Kh values obtained from the monitoring wells ranged from 0.024 ft/d in well STI-5D to 68 ft/d in well G111, with a geometric mean value of 0.72 ft/d. This range indicates that the Galena-Platteville aquifer is heterogeneous at the ACME/WRL site.

Kh values in the area defined approximately by well G114 and the B6, STI-5, and G113 well clusters (fig. 21) have a lower geometric mean value (0.15 ft/d) than the rest of the Galena-Platteville aquifer (2.1 ft/d). This area, hereafter referred to as the Low Permeability Area, is associated with a part of the bedrock ridge (fig. 22) and is likely to have a small number of interconnected secondary-permeability features in comparison to the remainder of the ACME/WRL site. This conclusion is consistent with the analysis of the spatial distribution of horizontal hydraulic gradients at the site.

Kh values determined from slug tests in 13 test intervals in boreholes open to the Galena-Platteville aquifer and isolated with a packer assembly ranged from 0.00022 to 26 ft/d, with a geometric mean value of 0.057 ft/d (table D3). The geometric mean and range of values from the test intervals isolated with a packer assembly are both substantially lower than the Kh values determined from the slug tests in the monitoring wells.

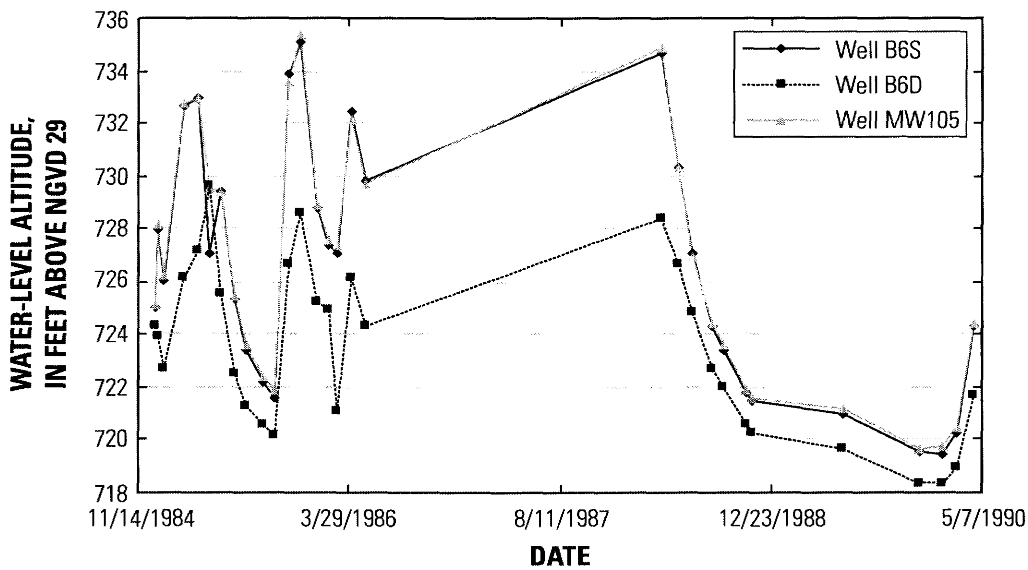

Figure D3. Hydrograph for wells B6S, B6D, and MW105, ACME Solvents/Winnebago Reclamation Landfill sites, Ill., November 14, 1984-May 7, 1990.

Table D1. Vertical hydraulic gradients, ACME Solvents and Winnebago Reclamation Landfill sites, Ill., November 1988.

[-, denotes potential for downward flow; ft/ft, foot per foot]

	Calculated vertical hydraulic gradient (ft/ft)
Well cluster	**Water-table/middle of Galena-Platteville aquifer**
STI1-S/1I	-6.5×10^{-3}
STI-2S/2I	1.9×10^{-3}
STI-3S/3I	-8.1×10^{-4}
STI-4S/4I	-1.7×10^{-2}
P8/P9	3.0×10^{-3}
B6S/B6D	-2.0×10^{-2}
B10/B10A	2.4×10^{-2}
B11/B11A	-1.1×10^{-2}
B13/P6	-1.5×10^{-2}
B16/B16A	-2.4×10^{-3}
G109/G109A	-1.8×10^{-3}
G113/G113A	-3.0×10^{-3}
Well cluster	**Middle/base of Galena-Platteville aquifer**
STI-1I/1D	7.2×10^{-3}
STI-2I/2D	4.0×10^{-3}
STI-3I/3D	-1.3×10^{-2}
STI-4I/4D	-1.4×10^{-3}
STI-5I/5D	-1.4×10^{-4}

Areas of high Kh values identified from the test intervals isolated with a packer assembly indicated a lack of correlation with potential permeable features identified by geophysical or lithologic logs at these boreholes. For example, the high Kh at 668-720 FANGVD29 at borehole STI-3D (table D2) is not indicated clearly with any other method (tables 11, 12). This result indicates the need to use methods that measure permeability directly. This lack of correlation, and the difference between Kh values obtained by use of a packer assembly and those calculated from the monitoring wells, results partly because of the comparatively large number of packer-test intervals in the Low Permeability Area where secondary-permeability features largely are absent, partly because some potential features (such as the potential fracture at 598 FANGVD29 at borehole STI-1D) were not subjected to aquifer testing, and partly because the long (typically 20 ft or more) test intervals isolated with the packer assembly may have obscured areas of elevated Kh within the test interval.

Multiple-Well, Constant Discharge Aquifer Tests

Multiple-well, constant-discharge aquifer tests were performed in wells STI-3I and B6PW.

Well STI-3I

The multiple-well, constant-discharge aquifer test was done in well STI-3I in June 1989. Water levels were monitored for 24 hours prior to the start of pumping in well STI-3I and for 24 hours after the cessation of pumping. Well STI-3I was pumped for 48 hours at a rate of about 4.9 gal/min with a water-level decline of about 60 ft. Water levels were measured in wells STI-3S, STI-3D, B1, B2, STI-1S, STI-1I, STI-1D, STI-4S, STI-4I, STI-4D, B6S, MW201B, and STI-SP1 during all phases of the test.

Aside from well STI-3I, drawdown was not detected in any well, including wells STI-3S and 3D. Wells STI-3S and 3D are open to the Galena-Platteville aquifer about 110 ft above and 37 ft below the open interval at well STI-3I, respectively. The absence of drawdown at wells STI-3S and 3D indicates moderate to high vertical hydraulic conductivity in the Galena-Platteville aquifer at this well cluster, which is contrary to interpretations drawn from analysis of vertical hydraulic gradient data.

A semi-log analysis of the water-level data from well STI-3I (Cooper and Jacob, 1946) resulted in a calculated transmissivity of about 42 ft^2/d and a Kh of 2.1 ft/d (Harding-Lawson Associates, 1990). The semi-log plot of the drawdown data indicated that the drawdown rate decreased during the later stages of the test. This decrease could indicate a lessening of well loss because of well development resulting from pumping, or the induction of flow to the well from a permeable fracture or vuggy zone away from the test interval.

Well B6PW

The multiple-well, constant-discharge aquifer test was done in well B6PW in September 1989. Water levels were monitored for 18 hours prior to the start of pumping, and for 48 hours after the cessation of pumping. Well B6PW was pumped for 48 hours at a rate of about 1.9 gal/min. Well B6PW was open to the Galena-Platteville aquifer from about 589 to 722 FANGVD29. Water levels were measured in wells B6S, B6D, MW105, MW201A, MW201B, STI-SP1, STI-5I, STI-5D, B4, B7, B9, G101, MW202, STI-3S, STI-3I, and STI-3D during all phases of the test.

Analysis of the water-level data in well B6PW indicated about 100 ft of drawdown during pumping. Substantial increases in the rate of drawdown were observed when water levels in the well were about 688, 662, and 640 FANGVD29 (fig. D4). These increases are

Table D2. Horizontal hydraulic conductivity values calculated from slug testing in monitoring wells open to the Galena-Platteville aquifer, ACME Solvents and Winnebago Reclamation Landfill sites, Ill.

Well name (fig. 21)	Calculated horizontal hydraulic conductivity (feet per day)
B4	1.3
B6S	.49
B6D	.030
B7	1.5
B9	1.1
B10	.20
B10A	5.4
B11	1.5
B11A	.32
B12	.16
B13	4.0
B16	1.5
B16A	.48
G101	40
G108	7.9
G109	.60
G109A	.015
G110	4
G111	68
G113	.40
G113A	.15
G114	.19
MW104	2.9
MW105	.22
MW201B	.058
MW202	1.8
P8	5.1
P9	1.5
STI-5S	.48
STI-5I	.039
STI-5D	.024
STI-6S	3.7
STI-7I	.037

attributed to the effects of dewatering fractures intercepting the pumped well near or above these altitudes. The precise features that were dewatered to produce the increase in drawdown cannot be identified from these data. However, analysis of the borehole camera log indicated that one or more of the subhorizontal fractures from 700 to 720 FANGVD29, 668 to 679 FANGVD29 and an inclined fracture at about 650 FANGVD29 (tables 11, 12) may be the contributing features.

Drawdown was measured in wells B6S (1.5 ft), B6D (1.8 ft), MW105 (5.3 ft), and MW201B (0.25 ft) during the aquifer test. Well MW105 reached maximum drawdown about 5.7 hours into the test, then rose slightly for the remainder of the pumping phase. Well MW105 is

Table D3. Horizontal hydraulic conductivity values calculated from slug testing in test intervals isolated with a packer assembly, ACME Solvents and Winnebago Reclamation Landfill sites, Ill.

Borehole name (fig. 21)	Altitude of test interval (feet above National Geodetic Vertical Datum of 1929)	Calculated horizontal hydraulic conductivity (feet per day)
STI-1D	675-687	0.12
	616-637	.12
STI-3D	688-720	26
	639-660	.20
STI-4D	663-680	.12
STI-5D	661-681	.019
	622-672	.0093
	582-615	.45
STI-SP1	623-665	.0081
	572-597	.00022
STI-SP2	640-681	.30
	590-616	.0066
	524-566	.026

open to the Galena-Platteville aquifer between 654 and 690 FANGVD29 (table 10). Well B6D is open to the aquifer between 654 and 717 FANGVD29. Well B6S is open to the aquifer between 706 and 719 FANGVD29. Well MW201B is open to the base of the Galena-Platteville aquifer between 555 and 575 FANGVD29. The drawdown pattern illustrates that most of the flow to the well was through the fractures between 668 and 679 FANGVD29, and probably primarily through the fracture at 677 FANGVD29 identified with the borehole camera log at well B6PW (tables 11, 12).

The remaining observation wells, including wells MW201A and STI-SP1 in the B6 well cluster, did not respond to pumping. Wells MW201A and STI-SP1 are open to the Glenwood Formation semiconfining unit and the St. Peter aquifer, respectively.

Transmissivity values calculated from the time-drawdown data from wells B6S, B6D, and MW105 were 46, 61, and 10 ft^2/d, respectively (Harding-Lawson Associates, 1990), with a geometric mean value of 30 ft^2/d using the method of Black and Kipp (1981). Because the well with the largest amount of drawdown, and (presumably) the best hydraulic communication with the fracture network had the lowest calculated transmissivity, the assumption of aquifer homogeneity for the Black and Kipp (1981) method appears to have introduced error to the transmissivity estimate. The geometric mean value for the storage coefficient was 7.8×10^{-4}.

The mean Kh value calculated from the well B6PW aquifer-test data was 0.2 ft/d. This value is consistent

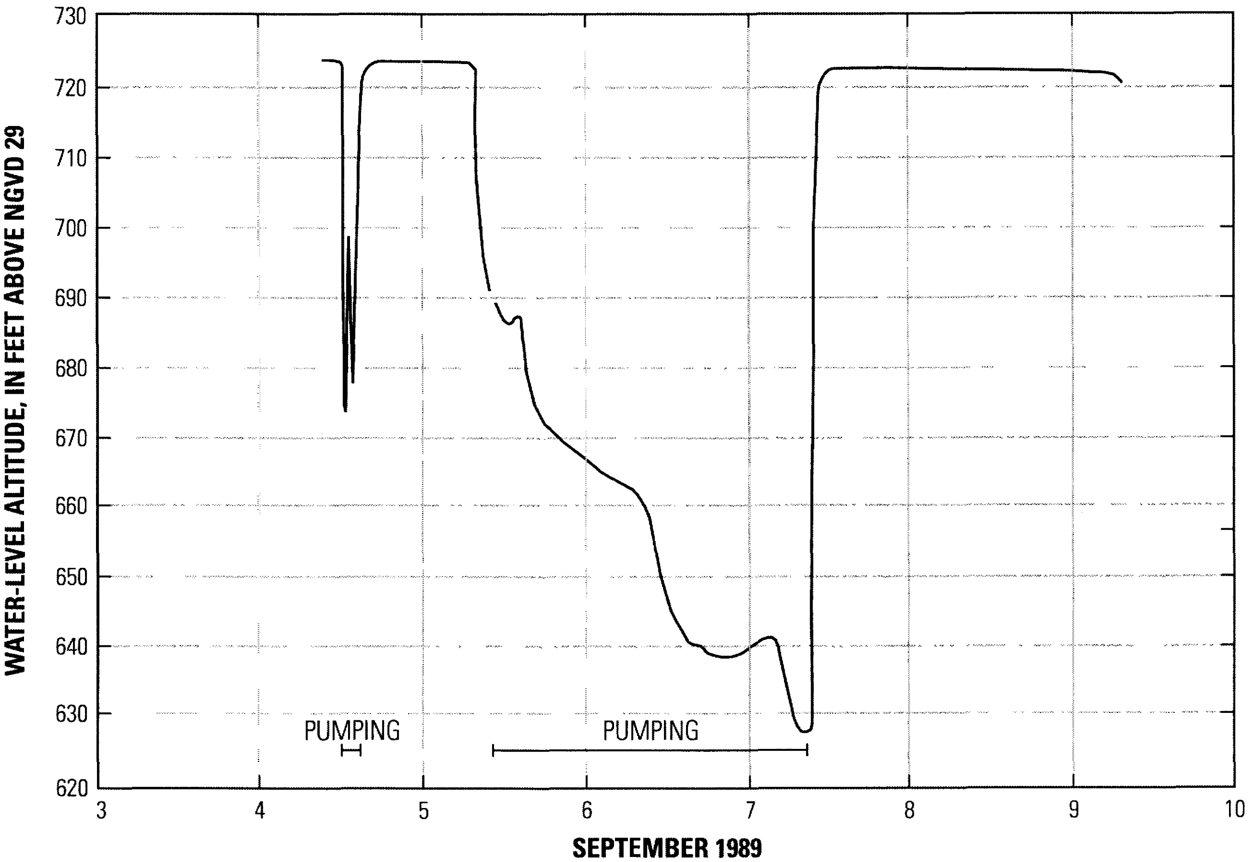

Figure D4. Hydrograph of well B6PW during aquifer testing, ACME/Water Reclamation Landfill site, Ill., September 1989.

with the geometric mean Kh (0.15 ft/d) obtained from the slug tests in the Low Permeability Area.

Well B6PW is within the Low Permeability Area defined by the slug testing. The low transmissivity and large of drawdown in response to a low pumping rate confirms the low permeability of the aquifer in this area.

The presence of drawdown at well MW201B (open about 15 ft below the bottom of well B6PW) indicates some vertical hydraulic interconnection within the aquifer in this area. An analytical solution was used to simulate the time-drawdown data from well MW201B. The model-simulated ratio of horizontal to vertical hydraulic conductivity in the Galena-Platteville aquifer is between 5 and 100 (Harding-Lawson Associates, 1990). Coupled with the low Kh of the area, this ratio indicates the presence of minimal vertically transmissive features in the lower part of the aquifer near well B6PW. These results are inconsistent with the interpretations drawn from the water-level data, which indicate moderate to high vertical hydraulic connection in the Galena-Platteville aquifer.

Location of Contaminants

Water-quality data shows VOC's in ground water from the northeastern part of the ACME Solvents site west to Killbuck Creek (fig. 25). This movement of VOC's is in the general direction of ground-water flow defined with the water-level measurements. VOC's are present at depth at the STI-2 cluster, which also is located in the general direction of ground-water flow and along one of the primary directions of the vertical fractures in the Galena-Platteville aquifer. The area between the ACME Solvents site and the WRL corresponding to a part of the Low Permeability Area tends to have lower concentrations of VOC's near the water table and in the upper part of the Galena-Platteville aquifer. The low concentration of VOC's between the ACME Solvents site and the WRL may be attributed to dilution from periodic recharge from the intermittent stream south of ACME Solvents and variations in aquifer permeability resulting in preferential ground-water flow around the Low Permeability Area.

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Appendix E—Southeast Rockford Site Data

The Southeast Rockford site has been the location of environmental investigations performed in the late 1980's and early 1990's (Camp, Dresser and McKee, Inc., 1992, 1994). The USGS investigation that forms the basis for most of this discussion involved drilling and testing of boreholes BH1, BH2, and BH3 in the eastern part of the site during the winter of 1992-93 (fig. 26)(table 13). Detailed discussion of the methods used for, and results of, the hydrogeologic investigation performed by the USGS is presented in Kay and others (1994). Geologic and hydrologic data collected by Camp, Dresser and McKee, Inc. (1992, 1994) also was analyzed for this investigation. For ease of discussion, the data collected as part of other investigations are integrated into the discussion of the specific methods, rather than as a separate discussion of the previous investigations.

Topographic Analysis

Analysis of land-surface topography during site visits and from topographic maps did not indicate the presence of fracture traces or sinkholes at the Southeast Rockford site. It is assumed that these features were not identified because they are not present. However, the thick (40-150 ft) unconsolidated deposits present beneath most of the Southeast Rockford site may be masking the presence of secondary-permeability features in the Galena-Platteville dolomite. Comparison of surface topography with bedrock topography indicates that topographic highs correspond to bedrock highs, whereas topographic lows correspond to areas where the bedrock was more extensively eroded.

Quarry Visits

The Galena-Platteville dolomite is exposed about 0.75 mi south of borehole BH2 (fig. 26). About 5 ft of the Wise Lake Formation is present at the top of the quarry with the Dunleith Formation exposed below. The quarry did not extend below the Dunleith Formation at the time of this study. Vertical fractures also were observed in the dolomite, but their orientation was not measured.

Lithologic Logs

Lithologic logs were completed for the boreholes drilled for each of the environmental investigations performed at the Southeast Rockford site. Lithologic logs for boreholes BH1, BH2, and BH3 indicate that the Galena-Platteville dolomite primarily is competent rock interspersed with small intervals of fractures and vugs. Each of the boreholes produced substantial quantities of water during drilling, indicating moderate or high aquifer permeability. Lithologic logging identified various possible fractures in each of the boreholes (table 15), but only the feature at about 600-606 FANGVD29 in borehole BH1 (table 16) was described as being associated with an increase in water return during drilling.

Geophysical Logs

A variety of geophysical logs were run in boreholes BH1, BH2, and BH3. These logs improved the understanding of the geology of the Southeast Rockford site and provided additional foundation for the hydraulic framework.

Borehole Camera

A borehole-camera log was run in borehole BH3 (table 15). Camera logging showed competent rock with large fractures just below the bottom of the casing at about 650 FANGVD29. Subhorizontal bedding-plane partings were present throughout the borehole, with these features concentrated between 610-631 and 566-587 FANGVD29. Prominent individual subhorizontal bedding-plane partings were observed at about 580, 590, 597, 626, and 650 FANGVD29. Vuggy intervals were observed at about 572, 581, 589, 594-610, 627, and 633-638 FANGVD29.

Caliper

Three-arm caliper logs show enlargements in the borehole diameter of about 1 in. below the bottom of the casing at about 625, 743, and 652 FANGVD29 in boreholes BH1, BH2, and BH3, respectively. Smaller (0.5 in. or less) but distinct enlargements in the borehole diameter also were observed at 563, 591, 603, and 607 FANGVD29 at borehole BH1; 543, 600, and 663 FANGVD29 in borehole BH2; and at about 626 FANGVD29 in borehole BH3. The caliper log for borehole BH3 indicates that the borehole is enlarged at altitudes similar to those of the bedding-plane partings identified by the borehole camera logging (table 15).

Natural Gamma

Natural-gamma logs run in boreholes BH1, BH2, and BH3 showed consistent response (fig. E1) and indicated about 1 degree of dip toward the east. The lack of detailed stratigraphic information at the Southeast Rockford site prevented comparison of the natural-gamma logs with the local Galena-Platteville stratigraphy. However, natural-gamma logs correlated with stratigraphy at the ACME/WRL site show good correlation with the natural-gamma logs for boreholes BH1, BH2, and BH3, allowing stratigraphy to be determined from the natural-gamma logs from these boreholes. The natural-gamma log for borehole BH2 indicates that the Dunleith Formation is present above about 637 FANGVD29, the Guttenberg, Specht's Ferry, Quimbys Mill, and Nachusa Formations are very thin or absent, the Grand Detour Formation is present at about 595-637 FANGVD29, the Mifflin Formation is present at 572-595 FANGVD29, and the Pecatonica Formation is present from about 542 to 572 FANGVD29.

Acoustic Televiewer

Acoustic-televiewer logs identified subhorizontal bedding-plane partings through the entire thickness of boreholes BH1, BH2, and BH3 (fig. E2). Bedding-plane partings were identified at about 549-555, 560, 587, 597-607, and 611-625 FANGVD29 in borehole BH1 (table 15). Bedding-plane partings were identified at about 537, 550, 558, 565, 589, 591-600, 617-669, 695, and 731-743 FANGVD29 in borehole BH2. Bedding-plane partings were identified at about 569, 577, 582, 586, 592-600, 608-615, 620-630, and 638-642 FANGVD29 in borehole BH3. Some of the partings correlate between at least two of boreholes (fig. E2). Trends in the altitude of many bedding-plane partings show a good correlation with trends in the natural-gamma logs, indicating stratigraphic control on the distribution of the bedding-plan partings (compare figures E1 and E2). Bedding-plane partings correspond to areas of both high and low counts per second on the natural-gamma logs, indicating that many of them are not wash outs of shale partings.

Acoustic-televiewer logs identified an inclined fracture at about 551 FANGVD29 at borehole BH2. This feature is interpreted to be a subhorizontal fracture that appears to be inclined on the televiewer log because of borehole deviation.

Acoustic-televiewer logs identified vuggy intervals in each of the boreholes. Vuggy intervals tended to concentrate in the less argillaceous parts of the dolomite.

Short-Normal Resistivity

As expected, short-normal resistivity logs typically showed an inverse relation with the natural-gamma logs. Short-normal resistivity logs showed no clear response to possible secondary-permeability features identified with lithologic, borehole camera, caliper, or acoustic-televiewer logging (table 15).

Water-Level Measurements

Single, periodic, and continuous water-level measurements were collected as part of the investigations of the Southeast Rockford site.

Periodic Measurements

Water levels were measured in monitoring wells open at various depths in the Galena-Platteville aquifer three times in 1991, once in 1993, and once in 1994 (Camp Dresser and McKee, Inc., 1992, 1994). Measurements indicate that flow in the aquifer is from east to west, from the uplands toward the Rock River (fig. 28). Flow directions were consistent between measurements. Although horizontal hydraulic gradients were not calculated, visual inspection of the water-level altitude in the Galena-Platteville aquifer indicates low gradients in the northeastern part of the Southeast Rockford site and much of the area near borehole BH3 west of Alpine Road. These might be areas of elevated aquifer permeability. Higher horizontal hydraulic gradients are present in the western part of the study area defined by the 717.7 and 769.9 FANGVD29 water levels (fig. 28). There is no clear correlation between the configuration of the potentiometric surface of the Galena-Platteville aquifer and the configuration of the top of the Galena-Platteville dolomite (compare figures 27 and 28).

Water levels in the upper part of the Galena-Platteville aquifer typically exceed water levels in the middle or deeper parts of the aquifer by less than 5 ft, indicating good vertical hydraulic interconnection between the upper and middle parts of the aquifer beneath most of the Southeast Rockford site. However, water levels in the upper and middle part of the aquifer at the MW103 well cluster (fig. 29) were about 20 ft higher than water levels at the base of the aquifer, indicating lower vertical hydraulic conductivity in the lower part of the aquifer at this location. Water levels at the top of the Galena-Platteville aquifer near the MW106 well cluster (fig. 29) were about 105 ft higher than the water level at the top of the St. Peter Sandstone aquifer. This large difference in water level indicates low vertical hydraulic conductivity within the Galena-Platteville aquifer or the Glenwood semiconfining unit beneath the Southeast Rockford site.

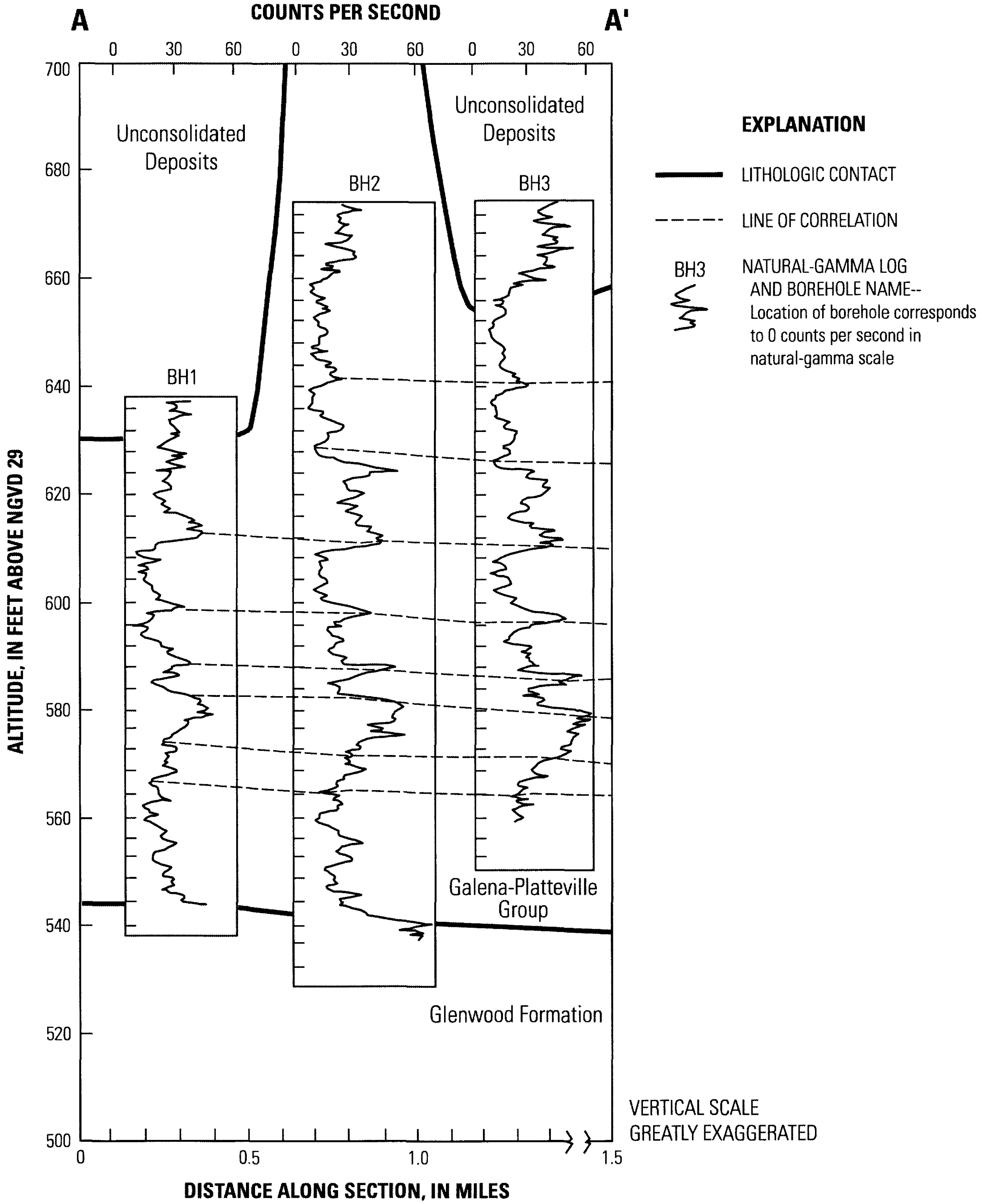

Figure E1. Correlation of natural-gamma logs along line of section A-A′ at the Southeast Rockford site, Ill. (line of section A-A′ shown in figure 26.)

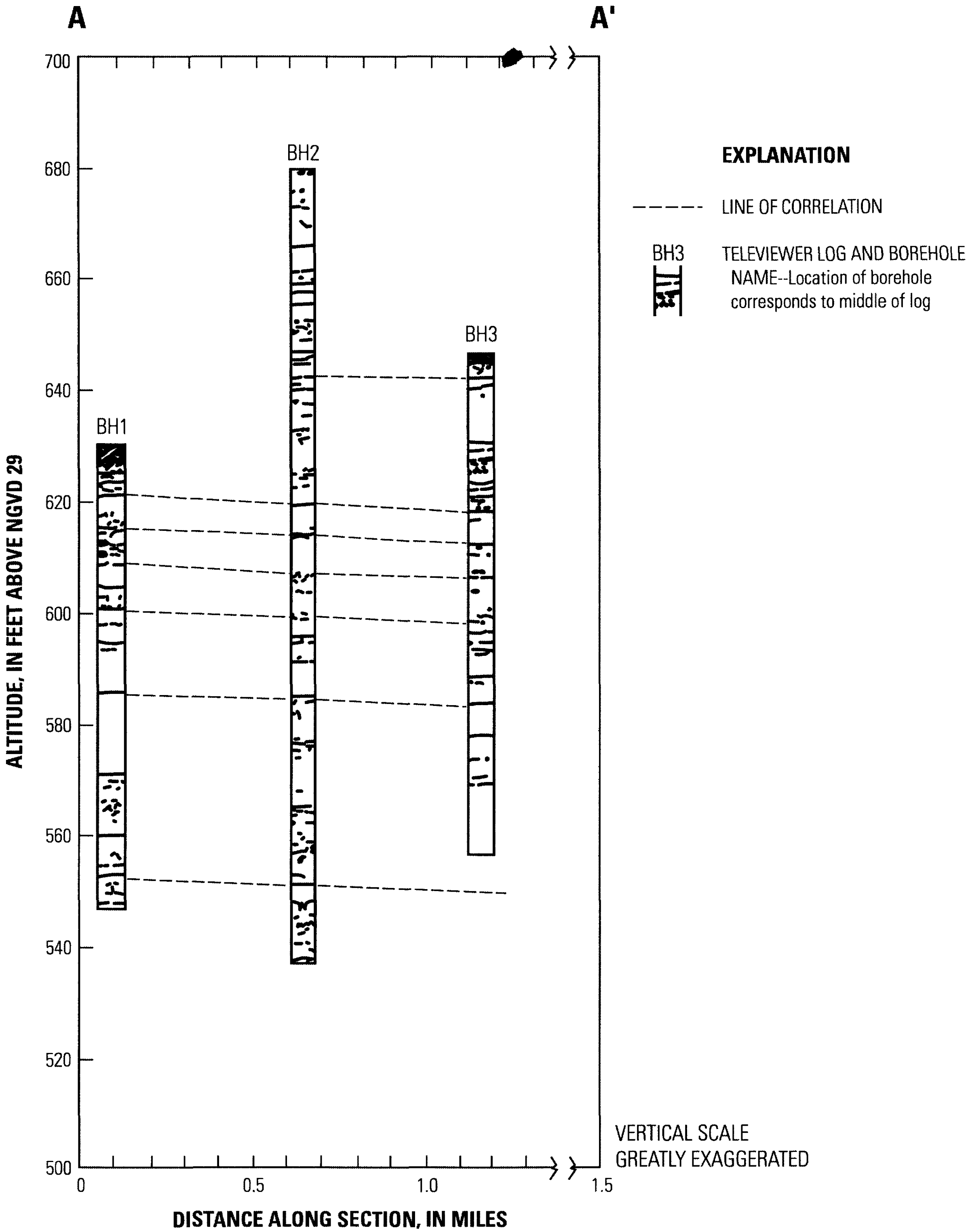

Figure E2. Correlation of acoustic-televiewer logs along line of section A-A′ at the Southeast Rockford site, Ill. (line of section A-A′ shown in figure 26.)

Single Measurements

Water levels measured in test intervals isolated with a packer assembly sampled most of the saturated thickness of the aquifer at boreholes BH1 and BH2 (table E1). With the exception of the test interval B at borehole BH1, water levels in the test intervals isolated with the packer assembly indicate the potential for downward flow within the Galena-Platteville aquifer. The upward hydraulic gradient in test interval B likely is because of inadequate time allowed for the water level in the test interval to decline to its hydrostatic level, which is indicative of low aquifer permeability at this test interval. Water levels above, within, and below the test intervals typically differed by less than 5 ft at borehole BH1, but exceeded 20 ft for all but one of the test intervals in borehole BH2. Borehole BH1 is located near the center of the bedrock valley, whereas borehole BH2 is located along the bedrock ridge near the MW103 well cluster. The differences in water levels above, within, and below the test intervals in borehole BH1 tended to increase with depth, being less than 1 ft in interval F, about 2 ft in intervals A and E, and more than 4 ft in intervals B-D. The differences in water levels above, within, and below the test intervals in borehole BH2 also tended to increase with depth, being about 20 ft in intervals E and F, about 23 ft in interval D, and more than 30 ft in intervals A-C. These patterns indicate that the vertical hydraulic conductivity of the Galena-Platteville aquifer decreases with increasing depth in these areas.

Comparison of water-level measurements in test intervals and the open boreholes in borehole BH1 did not show clear trends, indicating that no one zone is substantially more permeable than any other. Water levels within the test intervals at zones E and F approximate the water level in the open borehole, indicating that the most permeable features in the borehole may be located between 601 and 617 FANGVD29. Water-level measurements from open borehole BH2 were too infrequent to allow comparison with water levels in the test intervals, but the data indicate that if one interval substantially is more permeable than any other, it is located above the top of interval A (557 FANGVD29) and below the bottom of interval F (732 FANGVD29).

Continuous Measurements

Water levels measured hourly in borehole BH3 during a 17-day period in December 1992 showed no clear correlation with pumping from a Rockford Municipal Supply well 16 (RMS16), located at the northeast corner of Alpine and Harrison Roads (fig. 26). RMS16 is cased through the Galena-Platteville aquifer and is open to the underlying Cambrian-Ordovician aquifer. The lack of water-level declines in the Galena-Platteville aquifer during pumping in the underlying aquifer indicates that the Glenwood Formation and the lower part of the Galena-Platteville aquifer has low vertical hydraulic conductivity

Table E1. Water levels in test intervals isolated with a packer assembly, Southeast Rockford site, Ill.

[NA, measurement not applicable]

			Water-level altitude			
Borehole name (fig. 26)	Test interval	Altitude of test interval (feet above National Geodetic Vertical Datum of 1929)	Open borehole (feet above National Geodetic Vertical Datum of 1929)	Above test interval (feet above National Geodetic Vertical Datum of 1929)	Within test interval (feet above National Geodetic Vertical Datum of 1929)	Below test interval (feet above National Geodetic Vertical Datum of 1929)
BH1	A	544-566	715.40	715.50	715.46	NA
	B	574-584	712.20	717.32	718.32	713.52
	C	577-587	715.36	723.84	716.04	713.13
	D	587-597	715.35	717.10	716.65	712.25
	E	601-611	715.47	716.30	715.52	714.28
	F	607-617	715.42	715.54	715.49	715.02
	G	616-626	715.47	NA	713.72	NA
BH2	A	536-557	757.67	759.60	728.85	NA
	C	582-592	NA	760.45	756.93	724.38
	B	592-602	NA	767.14	747.60	726.06
	D	652-662	NA	768.45	763.22	745.20
	E	688-698	NA	768.60	767.67	748.10
	F	732-742	763.2	NA	768.27	752.52

and is composed of competent dolomite with few or no secondary-permeability features.

Geophysical Logs

Flowmeter logs also were run to identify the presence of permeable features in the Galena-Platteville aquifer beneath the Southeast Rockford site.

Flowmeter Logging

Impeller flowmeter logging was done under ambient-flow conditions in boreholes BH1, BH2, and BH3 (fig. E3). Downward flow was detected in each borehole. Flow rates in these boreholes exceeded 5 gal/min, above the range of detection for the heat-pulse flowmeter to be used. Because the volume of flow within the borehole is affected by the both the hydraulic conductivity of the aquifer and the vertical hydraulic gradient within the borehole, the high flow rate measured in these boreholes generally indicates high vertical hydraulic gradient and (or) Kh of the Galena-Platteville aquifer. Analysis of the water-level data indicates the high amount of flow is likely to be related to the high vertical hydraulic gradients, which indicates high vertical hydraulic conductivity, and a poorly developed network of vertically interconnected features in the aquifer.

Flowmeter logging in borehole BH1 indicates inflow from presumed subhorizontal fractures in the weathered bedrock above 620 FANGVD29, and inflow from one or more subhorizontal fractures at 601-606 FANGVD29, a subhorizontal fracture near the transition between the Grand Detour and Mifflin Formations at about 596 FANGVD29, and fractures associated with a shaley interval in the Mifflin Formation at about 587 FANGVD29. Outflow was through a vuggy interval and a subhorizontal fracture in the Pecatonica Formation at about 563-567 FANGVD29 (figs. E1, E2, E3)(table 16).

Flowmeter logging in borehole BH2 indicates inflow from a secondary-permeability feature in the Dunleith Formation at about 720 FANGVD29. Outflow was through a subhorizontal fracture associated with an argillaceous bed near the bottom of the Grand Detour Formation at about 600 FANGVD29, and through a subhorizontal fracture in the Pecatonica Formation at about 548 FANGVD29.

Flowmeter logging in borehole BH3 indicates inflow from subhorizontal fractures in the weathered bedrock above 650 FANGVD29. Outflow was identified through a subhorizontal fracture associated with a shaley bed near the transition between the Mifflin and Grand Detour Formations at about 597 FANGVD29. Variations in the flow near a fractured and vuggy area in the upper part of the Grand Detour Formation at about 628 FANGVD29 appear to be caused by the impeller getting caught on the side of the borehole. It is unclear if this zone is permeable. Flow was not detected below about 595 FANGVD29 in borehole BH3.

Aquifer tests

Slug tests and specific-capacity tests were used to quantify the hydraulic properties of the Galena-Platteville aquifer. Analysis of these tests also provided some insight into variations in the permeability of the aquifer (table 16).

Slug tests

Kh values were obtained from slug tests performed by Camp, Dresser, and McKee (1994) in 22 monitoring wells open to the Galena-Platteville aquifer at the Southeast Rockford site, including monitoring wells installed at permeable intervals in boreholes BH1 and BH2. Kh values ranged from 0.25 to 20 ft/d, with a geometric mean value of 2.6 ft/d (Camp Dresser and McKee, 1994). Kh values from slug tests done in monitoring wells installed at the permeable intervals identified with flowmeter logging in boreholes BH1 and BH2 were between 13 and 20 ft/d and were the highest values determined with the slug tests. These results confirm that the flowmeter logging identified permeable parts of the aquifer. Kh values indicate no apparent trends with areal location or proximity to the bedrock valley or bedrock uplands.

Specific-capacity tests

Specific-capacity tests were done in boreholes BH1, BH2, and BH3 in conjunction with borehole development. Specific-capacity analysis resulted in calculated transmissivity values of 6.8×10^3, 1.0×10^3, and 7.4×10^2 ft^2/d for boreholes BH1, BH2, and BH3, respectively. If the transmissivity value is divided by the length of the open interval at each borehole, the Kh of the Galena-Platteville aquifer is estimated to be 77 ft/d at borehole BH1, 5.3 ft/d and borehole BH2, and 8.0 ft/d at borehole BH3. Specific-capacity test results indicate that the Galena-Platteville aquifer substantially is more permeable at borehole BH1, located near the center of the bedrock valley, than at boreholes BH2 and BH3, which are located in areas where the bedrock surface is higher. However, the availability of only three data points limits the certainty of this conclusion.

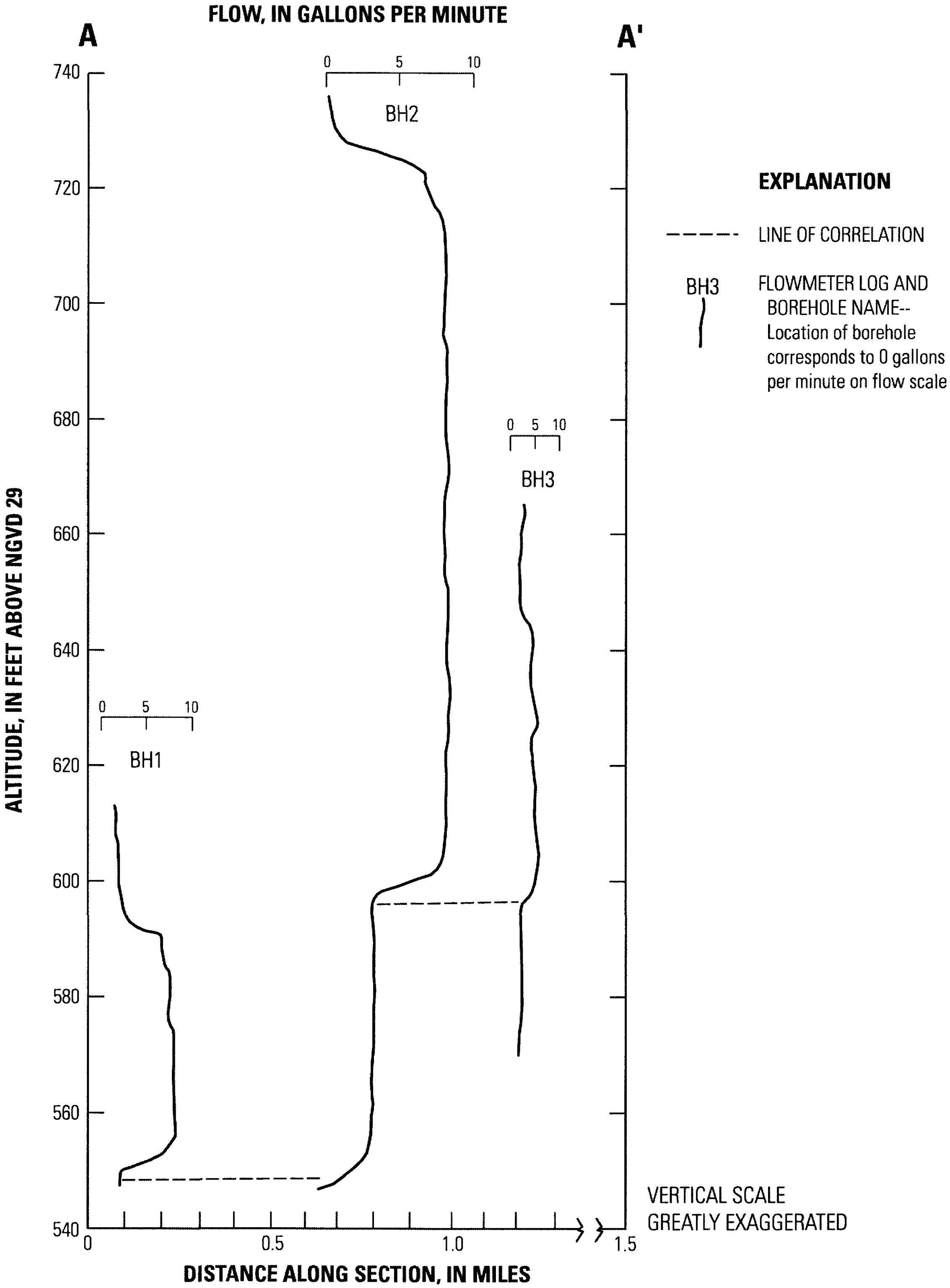

Figure E3. Correlation of flowmeter logs along line of section A-A′ at the Southeast Rockford site, Ill. (line of section A-A′ shown in figure 26.)

Location of Contaminants

The concentration and distribution of VOC's in ground water beneath the Southeast Rockford site was determined by sampling water quality from test intervals isolated with a packer assembly (Kay and others, 1994) and from monitoring wells (Camp Dresser and McKee, 1992, 1994). VOC's were detected in all but one of the test intervals isolated with a packer assembly in boreholes BH1, BH2, and BH3 (table E2), indicating vertical hydraulic connection within the aquifer. This interpretation is contrary to the conclusion, made from analysis of the vertical distribution of water levels, that there is low vertical hydraulic interconnection within the deeper part of the aquifer. It is possible that the presence of VOC's in the deeper parts of the aquifer results from nonaqueous phase liquids in the aquifer or vertical flow within the boreholes transporting VOC's from the top to the bottom of the aquifer.

Ground-water-quality data obtained from monitoring wells indicates two VOC plumes in the Galena-Platteville aquifer emanating from separate areas at the Southeast Rockford site (fig. 29). Both of these plumes appear to move along the primary direction of ground-water flow as identified with the water-level measurements. Water-quality data collected prior to this investigation indicated that these plumes may have been absent in the Galena-Platteville aquifer and the overlying unconsolidated aquifer in the vicinity of the MW105 and MW107 well clusters. Borehole BH3 is located approximately midway between wells open to the Galena-Platteville aquifer at the MW105 and MW107 clusters, and borehole BH3 is located hydraulically downgradient from these wells. The open interval of the monitoring wells was based on their approximate location (top, middle, bottom) within Galena-Platteville aquifer, rather than the locations of identified permeable features. The presence of VOC's in borehole BH3, identified by intensive characterization of the aquifer in this area, indicates that the plumes may be connected west of Alpine Road (fig. 29). Detection of VOC's in permeable parts of the aquifer in an area thought not to contain VOC's based on sampling results from the monitoring wells indicates that ground-water-flow pathways in this area may be complex, with more flow through permeable features and less flow through more impermeable parts of the aquifer. This interpretation appears to be confirmed by the apparent presence of VOC's only in permeable intervals in borehole BH3.

Table E2. Results of water-quality sampling from test intervals isolated with a packer assembly, Southeast Rockford site, Ill.

Borehole name (fig. 26)	Test interval	Altitude of test interval (feet above National Geodetic Vertical Datum of 1929)	Total concentration of volatile organic compounds (micrograms per liter)
BH1	A	571-592	2,185
	B	600-610	2,173
	C	604-614	208
	D	613-623	2,690
	E	627-637	6,510
	F	633-643	2,370
	G	643-653	1,798
BH2	A	536-557	414
	C	582-592	2,840
	B	592-602	1,446
	D	652-662	1,502
	E	688-698	2,780
	F	732-742	3,870
BH3	B	560-577	0
	A	587-597	42
	D	623-633	35
	C	641-651	13

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Appendix F—Belvidere Area Data

The USGS and USEPA began to perform detailed investigations of the Galena-Platteville aquifer in the Belvidere area during 1990 with the first of six investigations at the PCHSS. Prior to the studies by the USGS and USEPA, hydrogeologic data pertaining to the Galena-Platteville aquifer in the Belvidere area were limited to less than 20 lithologic logs and monitoring wells installed in the upper 30 ft of the aquifer. These data were collected as part of IEPA-coordinated studies of three Superfund sites. The investigations performed at the PCHSS indicated the need for an area-wide understanding of ground-water flow and water quality in the bedrock aquifers, particularly the Galena-Platteville aquifer. Therefore, investigations of hydrogeology and water quality in the greater Belvidere area were performed. The various USGS and USEPA investigations in the Belvidere area and at the PCHSSS were completed by 2002.

Data that form the primary basis for this discussion were collected throughout the Belvidere area; however, borehole and monitoring-well data are concentrated within the city of Belvidere, and particularly in the vicinity of the PCHSS (figs. 30, 31; tables 17, 18). Details of the Belvidere area investigations, including investigative methods and results, are presented in Brown and Mills (1995), vanderPool and Yeskis (1991), Mills and others (1998, 1999b, 2002a, b), and Mills and Kay (2003). Details of the USGS and USEPA investigations focusing on the PCHSS are presented in Mills (1993a, b, c), Mills and others (1994, 1998, 1999a), Kay and others (2000), and Kay (2001).

Previous Studies and Database Search

Various hydrogeologic studies of the Galena-Platteville aquifer have been done in the Belvidere area, including studies of three Superfund sites (Roy F. Weston, Inc., 1988; Science Applications International Corporation, 1992, 1996, 1998; Clayton Environmental Consultants, 1996), an industrial facility (GZAGeoEnvironmental, Inc., 1993), one leaking underground-storage-tank site (Total Environmental Services, 1992) and a multi-county study (Berg and others, 1984). With the exception of the study at the industrial facility, hydrologic data from the Galena-Platteville aquifer collected by previous investigators were sparse and limited to the upper 30 ft of the aquifer. The previous studies expanded the distribution of hydrologic data and provided a preliminary hydrogeologic and water-quality framework for the Galena-Platteville aquifer.

A detailed study of the stratigraphy and lithology of the Galena and Platteville Groups throughout their subcrop area by Willman and Kolata (1978) particularly was useful in initial characterization of these units and features of the units that possibly affect ground-water flow and contaminant migration. Detailed studies of the distribution and orientation of orthogonally related fractures in the Galena and Platteville Groups, where exposed in outcrops and quarries in northern Illinois (Foote, 1982; McGarry, 2000), were useful in initial characterization of aquifer anisotropy and possible preferential flow paths. These studies indicated primary and secondary orientations of the fracture sets of about N. 60-75° W. and N. 30° E., with variability in the orientation of fracture sets.

A survey was done to identify existing wells and test borings within the Belvidere area (Brown and Mills, 1995). The survey included retrievals from the well-construction databases maintained by the USGS and the ISGS and data from reports on the environmental studies at the three Superfund sites, leaking underground-storage-tank sites, and other hazardous-waste or industrial sites in the area. From this survey, 725 wells and borings were identified, including 380 open exclusively to the Galena-Platteville aquifer. Lithologic logs available for these wells were used to determine the lithology, distribution, and thickness of the unconsolidated and bedrock deposits in the Belvidere area. These logs rarely were detailed enough to assist in the identification of stratigraphic subunits or permeable intervals associated with fractures or other features.

Quarry and Outcrop Visits

Hydrogeologic features were mapped and ground-water discharges and withdrawals were identified during inspections of the Schlicting, Irene Road, and Belstone Quarries in the Belvidere area (table 17)(fig. 30). Limited solution was observed at fractures and bedding-plane partings and water seepage was observed above low-permeability intervals in the Galena Group at the Irene Road Quarry. One particular interval restricting flow was identified as the Dygerts bentonite bed in the Wise Lake Formation. This bed was not detected in other parts of the Belvidere area, nor was this interval associated with ground-water flow.

Vertical-fracture orientations of a representative fracture set in the dolomite were measured at an unnamed quarry in the northwest part of the study area (fig. 30). The primary and secondary orientations of N. 80° W. and N. 10° E. varied by about 20° from the orientations mapped by Foote (1982) and McGarry (2000) in nearby quarries (N. 60° W. and N. 30° E), but were within their range of measurements.

A unit tentatively identified as belonging to the Dubuque Formation is exposed at a natural outcrop adjacent to the Belstone Quarry (Dennis Kolata, Illinois State

Geological Survey, oral commun., 1995). The Dubuque and Wise Lake Formations both were identified at the Irene Road Quarry.

Quarry inspections enhanced understanding of the stratigraphy and lithology of the Galena-Platteville deposits, orientation of some of the secondary-permeability features in the dolomite, and some of the hydrogeologic features that affect ground-water flow.

Surface geophysics

Azimuthal square-array direct-current resistivity (SAR) surveys were done at the PCHSS and at two sites located along the southernmost of the northeast-trending bedrock highs near the Irene Road Quarry and near Stone Quarry Road (table 17, fig. 30) (Mills and others, 1998). At each site, up to nine surveys were conducted representing increasingly larger squares (from about 14 to 223 ft), and, theoretically, detection and measurement of orientation of increasingly deeper fractures.

The SAR survey done at the PCHSS indicated two or more fracture orientations along each square, which the orientations varying by as much as 60° between squares. The primary orientation of the inclined fractures indicated by the SAR data for the smallest squares (25, 36 and 42 ft) was N. 90° E. The primary orientation of the inclined fractures indicated by the SAR data for the two largest squares (110 and 160 ft), those least likely to be affected by the overburden, was N. 45° E. with a secondary set oriented at about S. 45° E. A secondary porosity of about 15 percent was estimated with the SAR data from the squares less than 110 ft in size, but could not be calculated from larger squares. The SAR survey at the PCHSS was affected by substantial cultural interference including high-power, electrical-transmission lines, and underground metal piping. Because of the interference, survey results were considered unusable.

Deeply penetrating high-angle fractures (interpreted as extending to about 223 ft below land surface) tentatively were identified at the Stone Quarry Road and Irene Road sites. The survey at the Stone Quarry Road site indicated primary and secondary orientations of this deep fracture set of about N. 60° E. and N. 45° W., respectively. The survey at the Irene Road site indicated a primary orientation of the deep fracture set of about N. 30° W. (fig. A2). A secondary porosity of typically less than 1 percent, and decreasing with depth, was calculated at these sites. Variability in the results indicated the possibility of nearby electrical interference (Peter Joesten, U.S. Geological Survey, written commun., 1996); however, the closest identified above-ground power lines were about 700 ft from the sites. Operations at the quarry adjacent to the Irene Road site may account for the difference between fracture orientations at the Irene Road and Stone Quarry Road sites.

The SAR surveys, although providing information on porosity and fracture orientation, are not necessarily considered to be reliable because of the effects of cultural interference. This unreliability is indicated by differences in fracture orientations with depth at each site and between sites, coupled with poor-to-moderate agreement with orientations determined by previous investigations, quarry visits, and borehole-geophysical methods. The surveys appear to verify the presence of orthogonal fracture sets in the Galena and Platteville Groups.

Lithologic Logs

Lithology and substantial changes in water return during drilling were described for all of the boreholes drilled by the USGS for investigations in the Belvidere area, particularly those in the vicinity of the PCHSS (tables 17, 18, 19). For this investigation, a BMW prefix in the location identifier denotes a Belvidere Municipal Well. A B or T prefix in the location identifier denotes that the activity was performed while the location was a borehole. A G prefix in the location identifier denotes that the activity was performed in the monitoring well completed in that borehole. USGS drilling logs provided preliminary information on the location and distribution of secondary-permeability features in the dolomite. This information generally was confirmed and expanded upon during subsequent data collection. Fractures were indicated at borehole T4 at the PCHSS between 734 and 739 FANGVD29 and at about 742-744 FANGVD29 in boreholes T5-T8 at the PCHSS (table 19). With the exception of an apparent fracture at about 709 FANGVD29 in boreholes T1 and T2 (table 19), fractures or solution openings in the deeper part of the aquifer were not identified with lithologic logging.

All boreholes described here returned moderate to large volumes of water during drilling, indicating generally permeable rock, with that part of the boreholes near the bedrock surface tending to be the most permeable. For example, borehole T4 at the PCHSS indicated a loss of circulation during drilling between 734 and 739 FANGVD29, and increases in water return were observed at about 742-744 FANGVD29 in boreholes T5-T8, indicating the presence of a permeable feature at these altitudes (table 20). With the exception of an increase in water return at about 709 FANGVD29 in boreholes T1 and T2, clear indicators of permeable features in the deeper parts of the aquifer were not readily apparent during drilling.

Core Analysis

Cores collected from overlapping altitudes in boreholes B115BD, B125B, B126BD, B127GP, B127SP, and B128GD were described to provide a composite of the stratigraphy in the vicinity of the PCHSS (Michael Sargent, Illinois State Geological Survey, written comun., 1992; Mills and others, 1998)(table 17, fig. 31). These core data are assumed to typify the Belvidere area.

The cores indicate that the Platteville and Galena Groups are composed of the Pecatonica (about 451-478 FANGVD29), Mifflin (about 478-501 FANGVD29), Grand Detour (about 501-547 FANGVD29), Nachusa (about 547-556 FANGVD29), Quimbys Mill (about 556-568 FANGVD29), Dunleith (568-633 FANGVD29), and Wise Lake and Dubuque Formations (633 FANGVD29 to the top of bedrock) (fig. 35). The contact between the Wise Lake and Dubuque Formations could not be differentiated in the cores and the two units are not differentiated. An unconformity is present in the dolomite between the Quimbys Mill and Dunleith Formations at about 568 FANGVD29.

Differentiation of the formations (and to a greater extent, members) that compose the Galena and Platteville Groups from the cores proved difficult, because traditional differentiation is made primarily on the basis of the weathering signature of exposed units. Subsequent use of natural-gamma logs assisted differentiation of the units by allowing identification of variations in clay content. However, stratigraphic delineations made on this basis of natural-gamma signatures can be inconsistent with those made on the basis of weathering signature. Error in the identified depths of stratigraphic transitions between some units that are similar in lithology, particularly within the Galena Group, may be as much +/- 25 ft. The difficulty in delineating the stratigraphy of the Galena Group is compounded by possible erosion or removal of bentonite marker beds during drilling. In particular, what has been identified as the Dygerts bentonite bed (Willman and Kolata, 1978; McGarry, 2000) at the Irene Road Quarry (fig. 30) does not seem to be present where cores were collected.

Core analyses indicate the Galena and Platteville Groups are composed of dolomite; no limestone was identified during inspection. The argillaceous content of each Group varies, with the Platteville Group being more argillaceous than the Galena Group. The highest percentage of clays are indicated in the Mifflin Formation, with as much as 15 percent of the 25-ft section of core consisted of shale interbeds, most less than 2 in. thick.

Vuggy porosity generally is developed in units with low clay content (fig. 35). Core inspection indicated vugs are best developed in the Galena Group and in the Nachusa Formation of the Platteville Group. Vuggy intervals in the cores seem to be best developed at about 550-660 FANGVD29 (at about 125-235 ft below land surface). Visual inspection of the cores provides no indication that the vugs are highly interconnected.

Prominent inclined fractures were not identified in the cores. Weakly developed healed fractures are present at many intervals within the Galena Group, but virtually are absent within the Platteville Group, indicating that the density of the inclined fractures decreases with depth. Numerous horizontal breaks are described in the cores, generally along shale partings. No weathering was identified along the breaks and they are attributed to mechanical breakage during core collection. With one possible exception, no pronounced intervals of solution associated with the partings or other horizontal bedding features were detected in the cores. A gravely mud is described as "sticking" to the core collected from borehole B128GP at an altitude of about 530 ft (depth about 250 ft) (Mills and others, 1998). The origin of the mud is uncertain and is described as possibly (1) a potassium-bentonite clay bed, (2) a mud-filled fracture, or (3) mud from the drill site.

The primary porosity of the Platteville and Galena Groups determined from 57 core samples ranged from about 4 to 25 percent with a geometric mean value of about 9.6 percent (fig. 35)(Mills and others, 1998). The geometric mean value for primary porosity was 5.1 percent for the Mifflin Formation, 6.6 percent for the Grand Detour Formation, 7.4 percent for the Quimbys Mill Formation, 8.3 percent for the Pecatonica Formation, about 12.1 percent for the Dunleith and Dubuque/Wise Lake Formations, and 12.6 percent for the Nachusa Formation. The primary porosity of the core samples from the Dubuque and Wise Lake Formations (the uppermost units in the area) is consistent with the secondary porosity of about 15 percent calculated with the SAR survey at the PCHSS.

Laboratory porosity estimates provided better understanding of the effective primary porosity of individual stratigraphic units than visual core inspection. Intervals of the Galena and Platteville Groups with comparatively high porosities generally coincided with intervals identified as vuggy by acoustic-televiewer logging and, in some cases, with flow, as measured with the flowmeter. The core analyses provided no hydraulic information about bedding-plane partings or fractures.

In general, analysis of cores provided useful information on lithology, stratigraphy, and matrix characteristics such as primary porosity, and, perhaps, trends in density of fractures in the Belvidere area. Core analysis was less useful in identification and description of fractures and solution zones. Possible error in depth identification also may be associated with core analysis, as the result of mechanical breakage and partial core recoveries.

Geophysical Logs

Various geophysical logs were run in boreholes and wells open to the Galena-Platteville aquifer in the Belvidere area (table 17). The boreholes were distributed across an area of about 1.5 mi^2 in Belvidere, concentrated in the vicinity of the PCHSS. Many of the log types were useful in enhancing characterization of the hydrogeologic framework of the Galena-Platteville deposits underlying the Belvidere area.

Borehole Camera

Camera logging was done in seven boreholes and one well (table 17), six with a side-looking, black-and-white camera and two (BMW2, B128GP) with a color camera using down- and side-looking lenses. Logging with the black-and-white camera was limited by cable length to a depth of 120 ft. Logging of borehole B305 was limited to inspection of a well obstruction because the camera could not be adequately focused in the 10-in. diameter well; most boreholes were 6 in. in diameter. Water clarity in the boreholes typically was adequate for camera logging.

Various observations specific to individual boreholes were made during camera logging. Bedding-plane partings were identified at altitudes of about 660 and 525 FANGVD29 (referred to in previous reports as the 125-ft and 260-ft partings on the basis of depth at the PCHSS and referred to as the 660-ft and 525-ft partings in this report) in borehole B128GP (table F1, fig. 35). On the basis of the camera log from this borehole, the aperture of the 525-ft parting is estimated at about 2 in. This altitude is about 5 ft lower than the location of the gravelly mud is described in the core collected from borehole B128GP, indicating either that this is not the same feature or that the core depth was inaccurate because of breakage. Although no fracture was identified at this altitude, material suspended in the water column was observed moving out of borehole B128GP and into the aquifer at about 485 FANGVD29, indicating the presence of a permeable feature.

The 660-ft parting was identified in borehole B436GPD (fig. 30, table F1). The water in this borehole was turbid at about 685 to 675 FANGVD29. The turbidity could not be attributed to any features noted in camera logging, however, water clarity improved at 675 FANGVD29, possibly indicating a permeable fracture at this altitude.

The 660-ft parting and an inclined fracture at an altitude of about 630 FANGVD29 were identified in municipal well BMW2 (fig. 30, table F1). Although vertical offset across the wall of the well was noted, the dip angle was not quantified. The aperture of the fracture is estimated at about 1 in. Camera logging indicated that many of the enlargements in the well that appeared to be fractures or partings in geophysical logs, were the effects of drilling—that is, change in the size of the drill bit or off-center movement of the bit. The distinct transition from dolomite of the Platteville Group to the sand-rich deposits of the underlying Glenwood Formation and St. Peter Sandstone were identified readily in the camera log.

Vugs were identifiable in all of the camera-logged boreholes; vuggy intervals were recorded that generally correlate with intervals identified in rock cores. Bedding-plane partings and inclined fractures with apertures greater than about 0.5 in. generally were identifiable. Many of the smaller partings identified with camera logs were not identified in the borehole-geophysical logs. Bedding-plane partings and fractures were identified readily in the wells logged with the color camera; the depths of most of these features were greater than the cable length of the black-and-white camera. Cavities immediately below the casings of boreholes B115BD and B126BD also were identified readily. The cavities indicate that the boreholes may not have been cased adequately into the competent deposits below the weathered-bedrock surface. Images with the best resolution were obtained using the black-and-white camera. For the color camera, images from

Table F1. Principal bedding-plane partings identified in the units that compose the Galena and Platteville groups underlying Belvidere, Ill.

Approximate altitude of parting (feet above National Geodetic Vertical Datum of 1929)	Formation where parting was identified	Borehole or well where parting was identified
740	Dubuque/Wise Lake	BMW2, B115BD, B124GP, B125BD, B126BD, B128GP, B126GP, T5, T6, T7, T8
660	Dubuque/Wise Lake	T1, T2, T3, T4, T5, T6, T7, T8, B305SP, BMW2, B124GP, B126GP, B128GP, B130GP, B133GP, B134GP, B136GP, B436GBD
590	Dunleith	B305SP, BMW2, B128GP,
560	Quimbys Mill	B124GP, B128GP, B130GP
525	Grand Detour	B305SP, B124GP, B126BD, B127GP, B128GP, B133GP, B136GP, G137GP
485	Mifflin	B128GP, BMW2

the downward-looking lens had better resolution than images from the side-looking lens. Major changes in lithology (such as from dolomite to sandstone), but not particular lithologies, were identified with both cameras. Changes in lithology were indicated by changes in the intensity of light reflected from the borehole wall and changes in rock color. Both cameras provided depth measurements accurate to about +/- 1 ft. Differences in depths measured with the cameras and other geophysical-logging tools had to be accounted for when comparing identified features; in some cases, these differences seemed as large as 5 ft.

Caliper

Three-arm caliper logging was done in 21 boreholes and 1 well (table 17). Caliper logs indicate increases in borehole diameter of more than 1 in. at about 525, 563, 595, and 660 FANGVD29 in borehole B128GP (fig. F1, table 19); 660 FANGVD29 in borehole B436; 742 FANGVD29 in boreholes T6 (fig. F2, table 19) and T8; at about 525 FANGVD29 in borehole B127GP (table 19, fig. F3), and immediately below the casing at about 747, 755, 704 and 747 FANGVD29 in boreholes B115BD, B126BD, B137GP and B130GP, respectively. Three-arm caliper logs also indicate more than 1 in. of enlargement in borehole diameter between about 700 and 709 FANGVD29 in boreholes T1 (fig. A3, table 19) and T2. The caliper log from that part of borehole open to the Galena-Platteville deposits indicated areas of enlargement at about 502, 525, 582, and 664 FANGVD29 in borehole B305 and at about 458, 625 and 660 FANGVD29 in well BMW2 (fig. 35). Caliper logs from the remaining boreholes indicated little variation in borehole diameter.

Altitudes of increased borehole diameter identified with the caliper logs corresponded to the approximate location of possible fractures described by the lithologic logging in boreholes T1, T2, T6, and T8 (table 19). Altitudes of many intervals of increased borehole diameter identified with the caliper logs corresponded to the approximate location of possible fractures identified with camera logging in boreholes B128GP and well BMW2. Enlarged areas associated with the bottom of the casing in boreholes B115BD, B126BD, B130GP, and B137GP likely are artifacts of the drilling process on weathered rock rather than discrete secondary-permeability features.

Natural gamma

Natural-gamma logs run in boreholes B125BD, B115BD, B127GP, B128GP, and B127SP in the vicinity of the PCHSS were compared to the stratigraphic descriptions for these boreholes so the natural-gamma signal of the formations could be identified. Natural-gamma logs from these boreholes then were compared with natural-gamma logs from 22 other boreholes and wells located throughout the Belvidere area (figs. F1-F6, A3, 35, table 17) to provide additional understanding of the stratigraphy in the area and the lithology that may affect ground-water flow within the aquifer. However, as previously indicated, inconsistencies are associated with directly linking natural-gamma signatures with stratigraphic descriptions of the rock cores and the stratigraphic interpretations are subject to some degree of uncertainty. Compounding the designation difficulties are limitations in the resolution of depth measurements. Because the radius of investigation only is about 1 ft and signal sensitivity is affected by borehole diameter, errors in measurement of bedding depth and thickness may occur and the presence of thin beds, such as bentonite layers, may be obscured.

The logs provided a good indication of the relative increase in clay content from the Galena Group to the Platteville Group and readily distinguished the approximate positions of the argillaceous Glenwood Formation and non-argillaceous St. Peter Sandstone. Stratigraphy determined from the natural-gamma logs indicates that the Galena-Platteville deposits have a uniform thickness and are subhorizontal across the Belvidere area. Peaks in natural-gamma activity provided identification of at least two key marker beds at altitudes of about 525 and 660 FANGVD29. The marker bed at 660 FANGVD29 was identified to varying degrees in at least eight boreholes and wells distributed over the 1.5-mi^2 logging area and was present in all of the boreholes near the PCHSS. This marker bed appears to be either a potassium-bentonite deposit in the Wise Lake Formation or clay infilling of a prominent bedding-plane parting. The marker bed at 525 FANGVD29 also could be identified in boreholes distributed over the area, and appears to be the Stillman Member of the Grand Detour Formation. The altitude of the marker beds vary by as little as 5 ft indicating that the beds of the Galena and Platteville Groups essentially are flat-lying in this area. Anomalous features indicative of clay infilling of fractures were not observed.

Single-point resistance

SPR logging was done in eight boreholes and one well (table 17). SPR logs indicated an increase in signal response below the casing at about 742 FANGVD29 in borehole B115BD, indicated variable response in borehole B125BD, indicated essentially no change in borehole B126BD, and increased gradually between 704 and 744 FANGVD29 in borehole B127GP then remained essentially unchanged to the bottom of the borehole (fig. F3). The response of the SPR log for

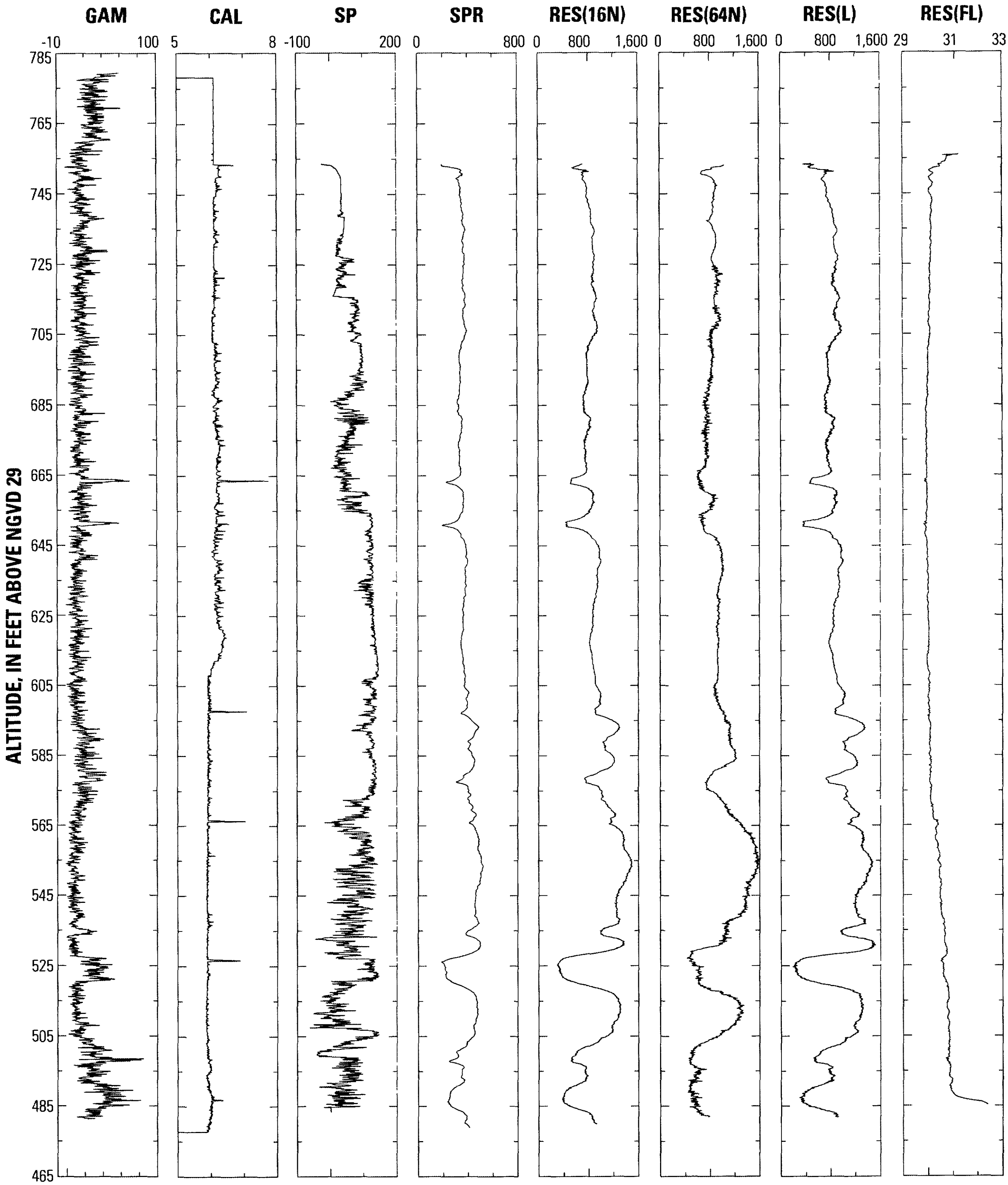
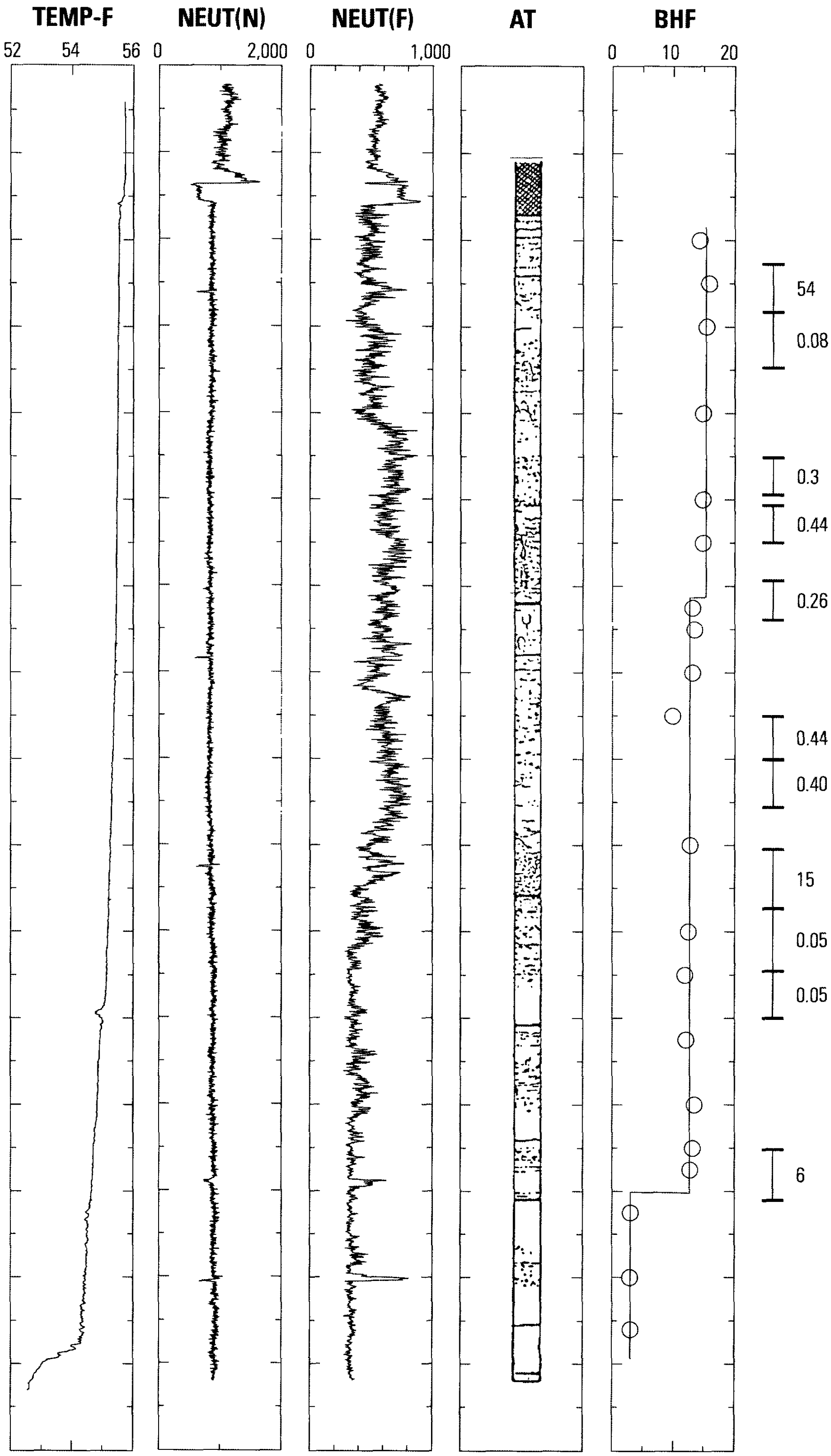


Figure F1. Stratigraphy, selected geophysical logs, and horizontal hydraulic conductivity for borehole G128GP in Belvidere, Ill.



EXPLANATION

GAM NATURAL GAMMA, IN COUNTS PER SECOND

CAL CALIPER, IN INCHES

SP SPONTANEOUS POTENTIAL, IN OHMS

SPR SINGLE-POINT RESISTANCE, IN OHM-METERS

RES(16N) NORMAL RESISTIVITY-- 16 INCHES, IN OHM-METERS

RES(64N) NORMAL RESISITVITY-- 64 INCHES, IN OHM-METERS

RES(L) LATERAL RESISTIVITY, IN OHM-METERS

TEMP-F TEMPERATURE, IN DEGREES FAHRENHEIT

NEUT(N) NEUTRON--NEAR, IN COUNTS PER SECOND

NEUT(F) NEUTRON--FAR, IN COUNTS PER SECOND

AT ACOUSTIC TELEVIEWER

BHF BOREHOLE FLOW, IN GALLONS PER MINUTE (GPM)

54 SLUG-TEST INTERVAL WITH HORIZONTAL HYDRAULIC CONDUCTIVITY, IN FEET PER DAY

○ DOWNFLOW, IN GALLONS PER MINUTE (GPM)

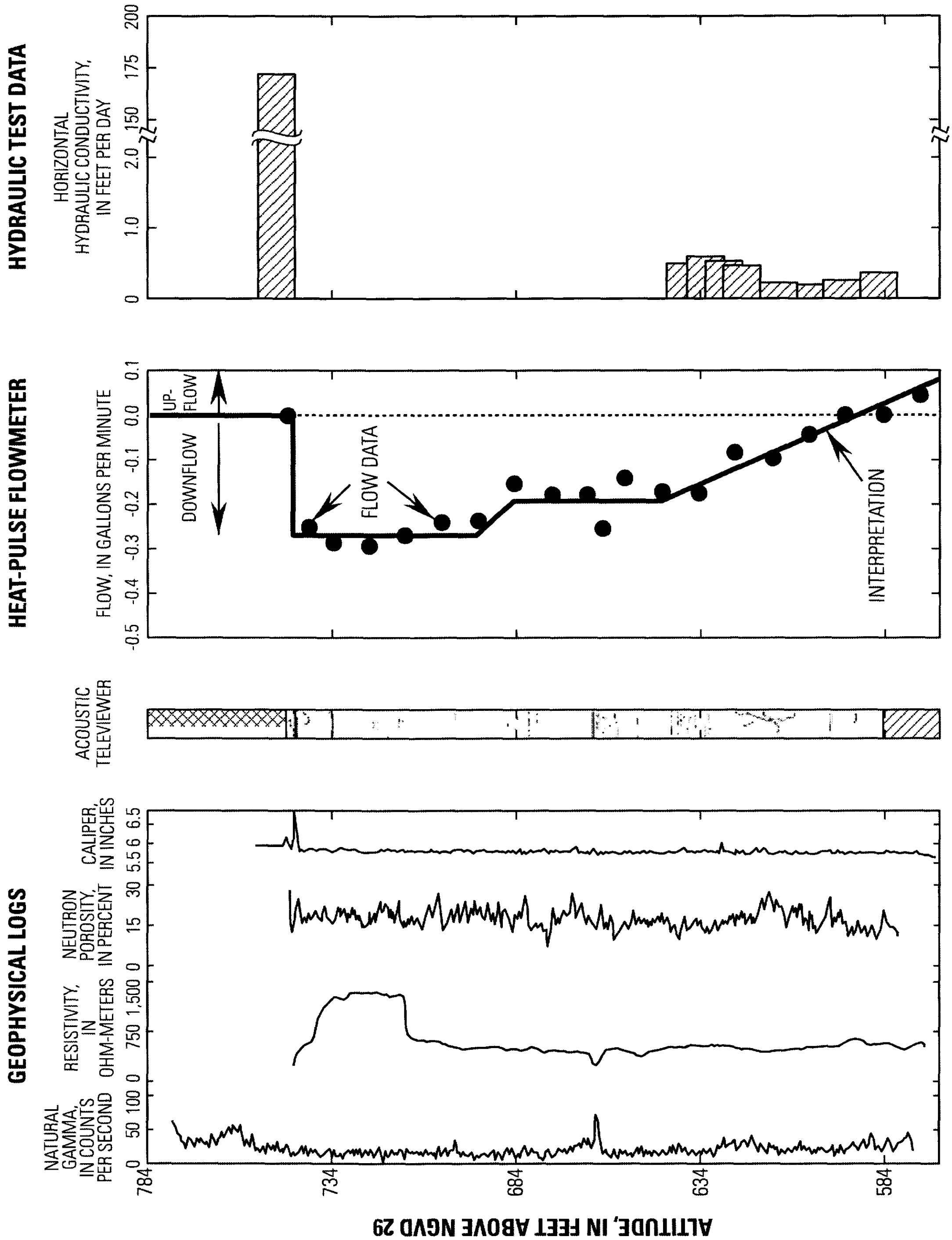


Figure F2. Stratigraphy, selected geophysical logs, and horizontal hydraulic conductivity for borehole T6 in Belvidere, Ill.

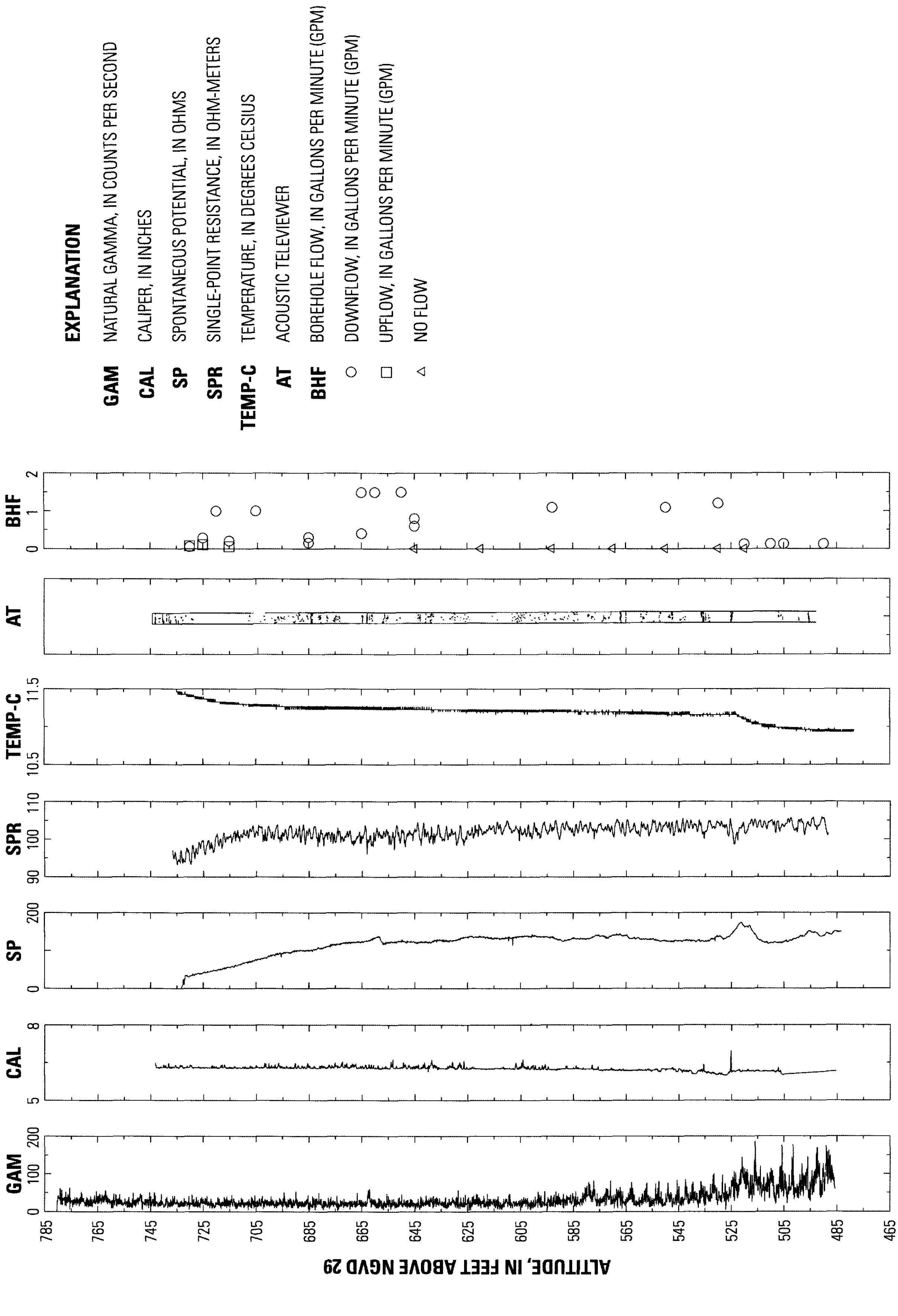
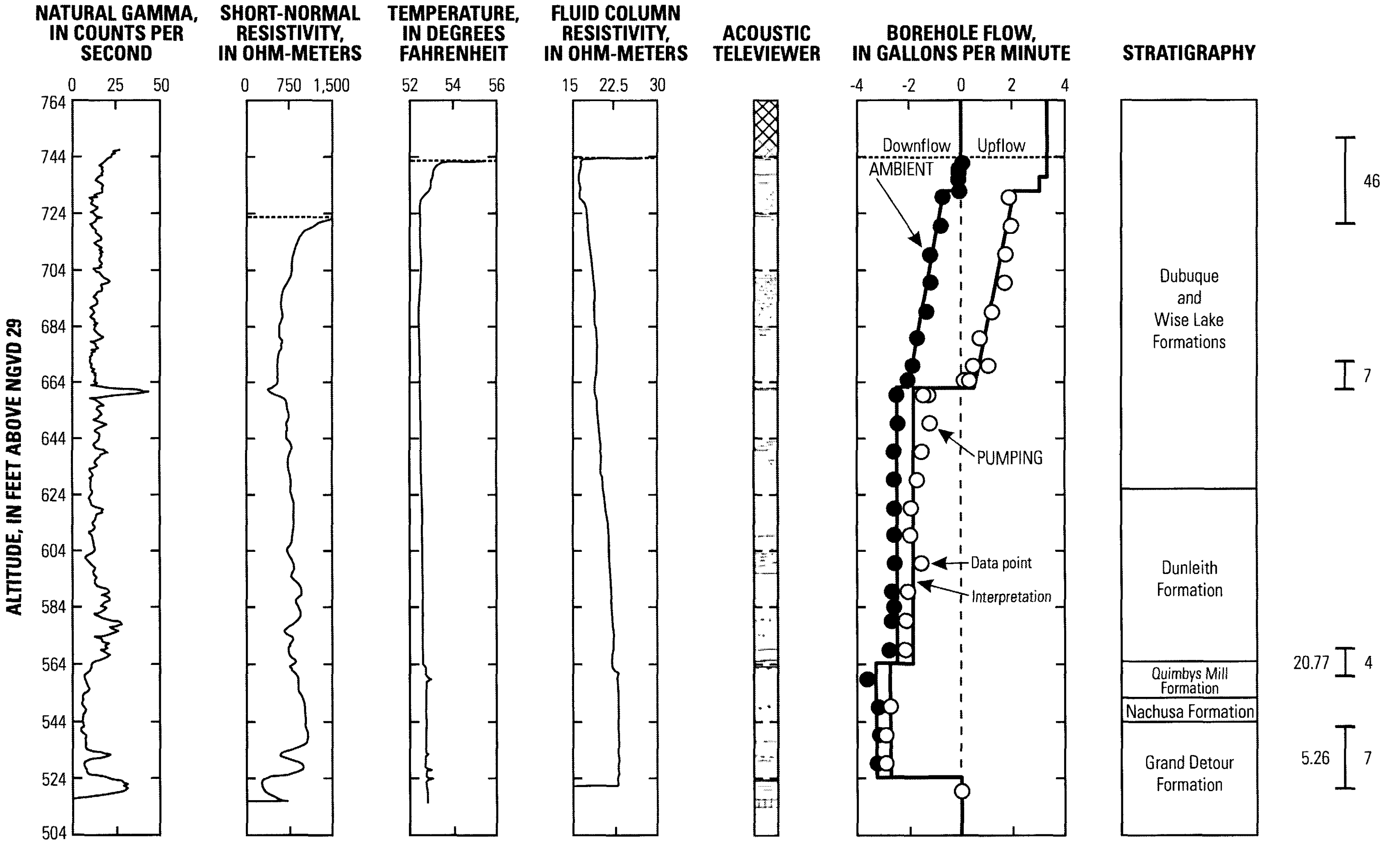


Figure F3. Stratigraphy, selected geophysical logs, and horizontal hydraulic conductivity for borehole G127GP in Belvidere, Ill.

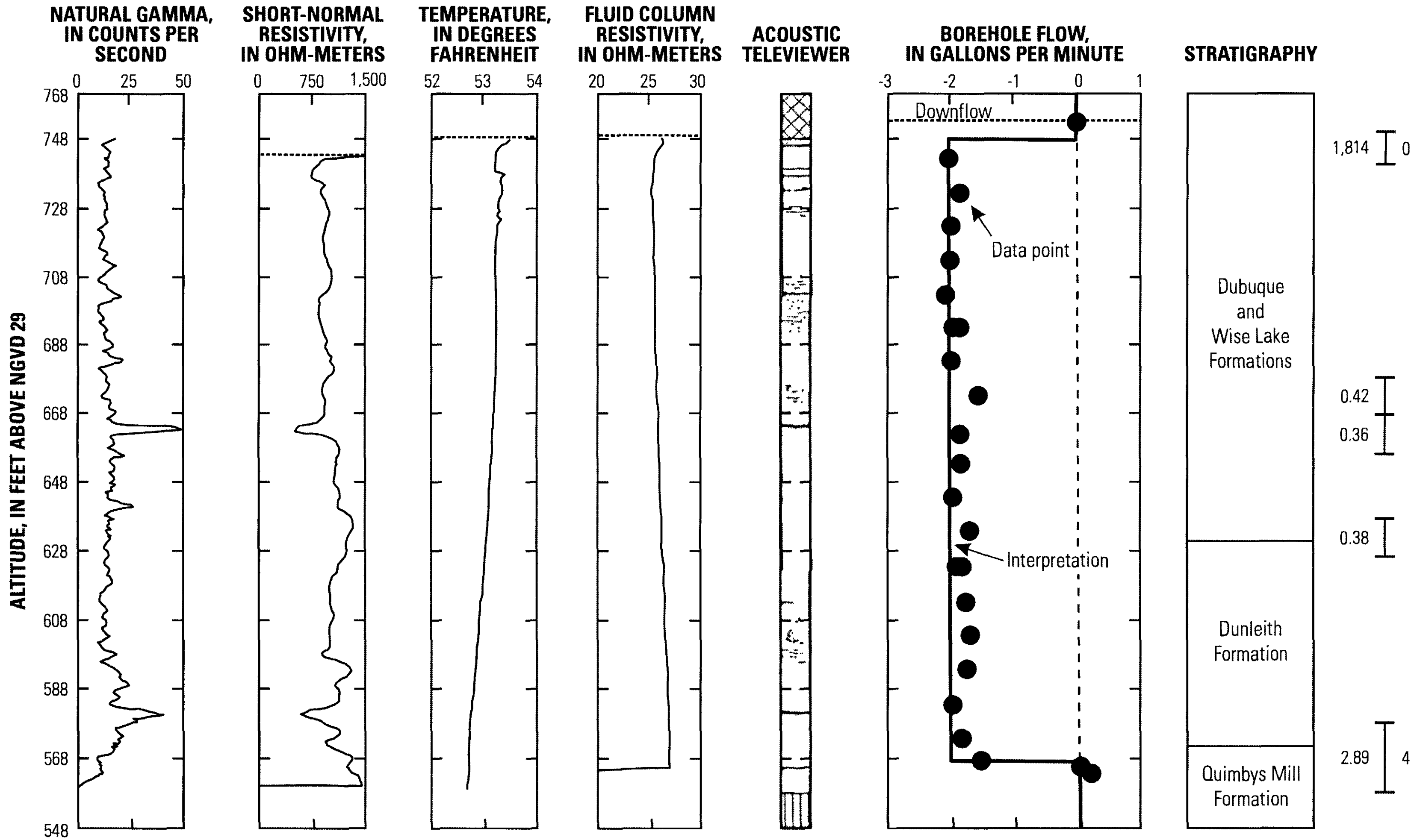


EXPLANATION

5.26 ⌶ 7 TEST INTERVAL--Number on left is horizontal hydraulic conductivity, in feet per day. Number on right is total concentration of volatile organic compounds, in micrograms per liter

------------ WATER LEVEL IN BOREHOLE AT TIME OF LOGGING

Figure F4. Stratigraphy, selected geophysical logs, and horizontal hydraulic conductivity for borehole G124GP in Belvidere, Ill.



EXPLANATION

2.89 ⌶ 4 TEST INTERVAL--Number on left is horizontal hydraulic conductivity, in feet per day. Number on right is total concentration of volatile organic compounds, in micrograms per liter

------------ WATER LEVEL IN BOREHOLE AT TIME OF LOGGING

Figure F5. Stratigraphy, selected geophysical logs, and horizontal hydraulic conductivity for borehole G130GP in Belvidere, Ill.

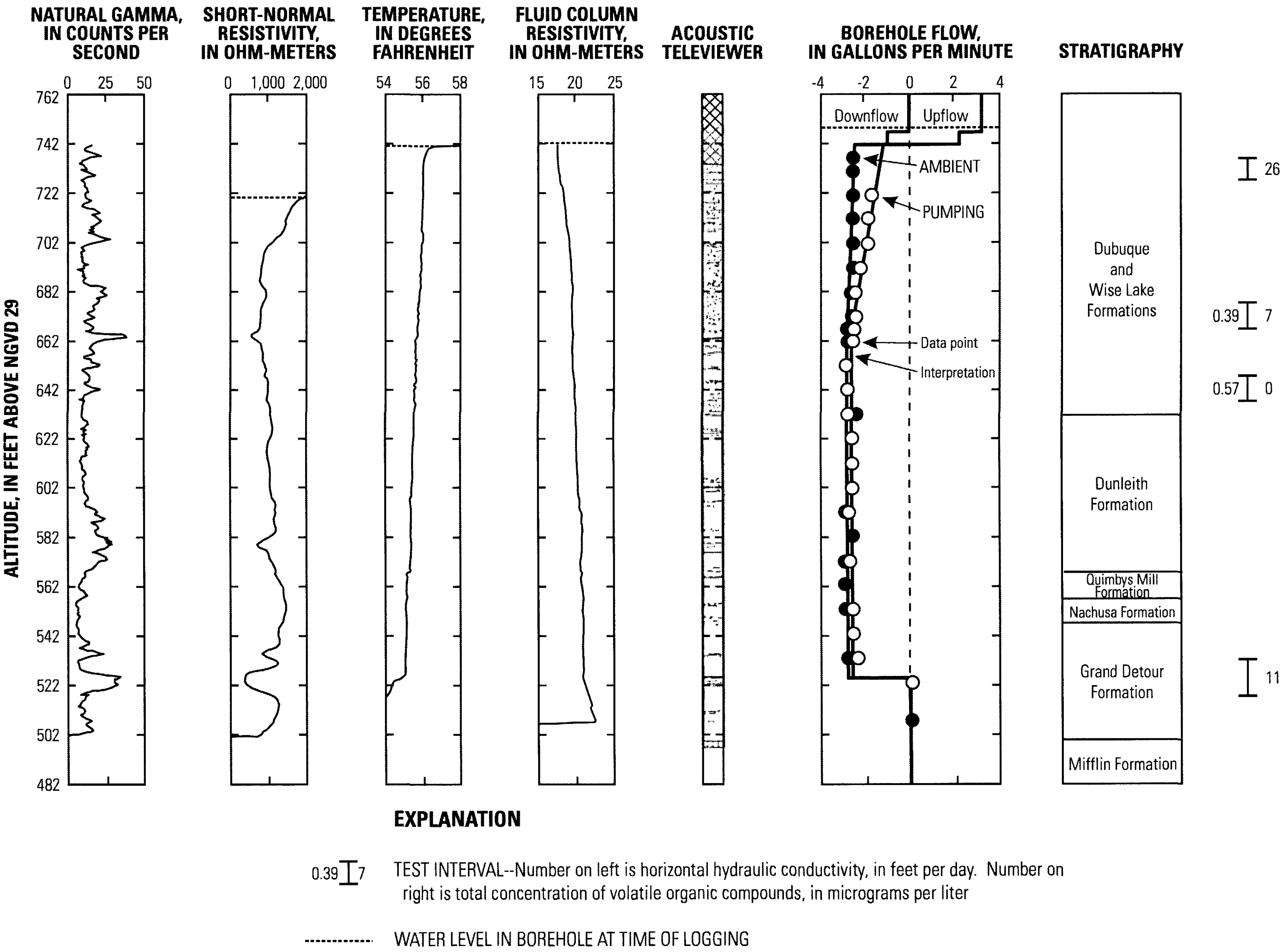


Figure F6. Stratigraphy, selected geophysical logs, and horizontal hydraulic conductivity for borehole G136GP in Belvidere, Ill.

that part of the borehole open to the Galena-Platteville deposits in borehole B127SP was consistent between about 494 and 747 FANGVD29, with the exception of sharp, isolated decreases in response at about 544, 554, and 683 FANGVD29. The response of the SPR log for borehole B128GPD indicated abrupt, isolated decreases in response at about 525, 575, 649, and 660 FANGVD29 (fig. F1, table 19). The response of the SPR log for borehole B436 generally was consistent throughout the borehole with the exception of a sharp decrease in response at about 660 FANGVD29. The SPR signal from that part of well BMW2 open to the Galena-Platteville dolomite indicates an abrupt decrease in signal response at about 485, 490, 525, and 660 FANGVD29. The SPR signal from the Galena-Platteville deposits at borehole B305 indicates abrupt decreases at about 490, 525, 582, and 664 FANGVD29.

SPR logs responded to some of the potential secondary-permeability features identified with other methods. Although never strong, the correlation was most consistent for the prominent 525-ft parting and less consistent for the 660-ft parting. In most cases, the SPR signal response was inversely correlated with natural-gamma activity or well diameter, as indicated by the three-arm caliper logs. As with SP logs, the resolution of the thickness and depth of a feature was less than that of caliper or natural-gamma logs.

Normal resistivity

Normal resistivity logging done in 14 boreholes and 1 well (figs. A3, F1, F2, F4, F5, F6; table 17) typically mirrored the signal responses of the SPR logs (fig. F1) and indicated an approximately inverse relation with natural-gamma response. High normal resistivity readings in the upper part of boreholes T6 and T1 were not detected during subsequent logging in these wells and these readings are assumed to be instrument error. Each of the logs typically responded in a similar manner, but signal responses usually were muted as the radius of investigation of the tool increased, 16-in. normal resistivity logs typically indicated substantially more detail than the 64-in. normal logs in boreholes G128GP, 00350, and B436, as well as well BMW2. SPR logs tended to indicate smaller changes in signal response than 16-in. normal resistivity logs, but more than 64-in. normal resistivity. This result indicates possible lithologic variations beyond the immediate vicinity of the boreholes.

Neutron

Near-well or far-well neutron logging was done at borehole B128GP (fig. F1) at the PCHSS. Near-well logging indicated a near-uniform count rate with small, distinct decreases in signal response at about 502, 525, 597, 646, and 732 FANGVD29 (table 19). Far-well logging, representing a larger radius of investigation than near-well logging, typically indicated about 400 cps from 484 to 580 FANGVD29 with small, distinct increases at about 502 and 525 FANGVD29. Higher count rates (and higher porosity) of about 600 cps were present from about 590 to 700 FANGVD29 with a small, distinct increase at about 597 FANGVD29. Count rates of about 500 cps were detected between about 702 FANGVD29 and the top of the Galena-Platteville dolomite at about 750 FANGVD29.

Neutron logs calibrated against porosity in boreholes T1 (fig. A3), T6 (fig. F2), and T8 at the PCHSS displayed variable response, but indicated lower porosity near the bottom of the boreholes at 569-594 FANGVD29 and near the top of the boreholes 709-760 FANGVD29 (table 19). Intervals of higher porosity were detected at 599-619, 664-674, and 684-709 FANGVD29. These patterns generally are consistent with those identified at borehole B128GP (table 19).

Although the absolute porosity values do not agree, variations in porosity identified from the neutron logs generally are consistent with the porosity variations identified from the analysis of the core samples. In particular, the elevated porosity in the 590-700 FANGVD29 interval at borehole B128GP and in parts of this interval at boreholes T1, T6, and T8 correlates well with the high porosity values (typically about 10-20 percent) determined from cores collected from the Galena Group (fig. 35). The lack of agreement between the two methods partly results because the neutron logs measure a larger volume of rock than the cores.

Neutron logs were more effective identifying variations in matrix porosity than in identifying potential fractures, presumably because the amount of water in the fractures is small in comparison to that in clay minerals and matrix porosity. Neutron logs (particularly the near-neutron logs) run in borehole B128GPD indicated some changes potentially associated with many of the potential secondary-permeability features identified with the caliper, SPR, or resistivity logs (fig. F1; table 19). However, these changes also correlate with areas of increased clay content identified with the natural-gamma logging, indicating the response may be caused more by water in the clays than by water in secondary-permeability features. Porosity values calculated from the neutron logs from borehole T6 indicated an increase associated with the potential secondary-permeability feature identified with the lithologic and caliper logging at 744 FANGVD29 (table 19), as well as at about 610-620 FANGVD29. However, these increases were not substantially different from nearby depths and the degree of response to the features is unclear. Porosity values obtained from the neutron log at borehole T1 did not indicate an increase associated with potential secondary-permeability features identified with lithologic and caliper logging.

Acoustic televiewer

Acoustic-televiewer logs indicate the presence of numerous bedding-plane partings through the entire thickness of all of the boreholes logged. Subhorizontal bedding-plane partings were identified at about 485, 494, 525, 564, and 660 FANGVD29 in every borehole open to those altitudes in the Belvidere area (figs. A3, F1-F6; tables 19, F1, F2) indicating that these are geographically widespread features. The 525-ft parting is associated with the top of the argillaceous part of the Grand Detour Formation and the 660-ft parting is associated with an argillaceous marker bed, indicating that lithologic characteristics (which may affect hydraulic characteristics) affect the location of these features. Numerous other prominent subhorizontal bedding-plane partings were identified within small parts of the Belvidere area, including one at about 744 FANGVD29 in boreholes T5-T8 at the PCHSS.

Acoustic-televiewer logs identified near-vertical fractures between about 699 and 709 FANGVD29 at boreholes T1 and T2 (same fracture) and between about 606 and 622 FANGVD29 in borehole T6 (figs. A3, F2). These fractures are subparallel with a strike of about N. 45° E., which is consistent with the vertical fracture orientation identified with the SAR survey performed at the PCHSS. Near-vertical fractures were identified in borehole B134GP at about 550 and 715 FANGVD29. The fracture at 715 FANGVD29 has a strike of about N. 19° W., whereas the fracture at about 550 FANGVD29 has a strike of about N. 79° W. A near-vertical fracture identified at about 630 FANGVD29 in well BMW2 has a strike of about N. 45° W. These measurements approximate the predominant orientation (about N. 60° W.) of other inclined fractures in the area, as determined at local quarries (Foote, 1982; Mills and others, 2002a), and are consistent with the vertical-fracture orientations identified with the SAR surveys at the Irene (N. 30° W.) and Stone Quarry Road sites (N. 60° E. and N. 45° W.).

Acoustic-televiewer logs also indicate the presence of vuggy intervals throughout the dolomite, with the formations composing the Galena Group being vuggier than most of the formations (except possibly the Nachusa Formation) that compose the Platteville Group (figs. A3, F1-F6). Vugs generally are most evident in the altitude interval at about 550-660 FANGVD29. Vuggy intervals were detected at about 684-704 and 724-734 FANGVD29 in borehole B124GP (fig. F4), at 693-708 FANGVD29 in borehole B130GP (fig. F5), 673-698 FANGVD29 in borehole B133GP, above 662 FANGVD29 in borehole B136GP (fig. F6), above about 574 FANGVD29 in borehole B137GP, at about 600-640 and 682-702 FANGVD29 in boreholes T1-T8 (figs. A3, F2), at about 570-604, 624-654, 672-706 FANGVD29 in borehole B127GP (fig. F3), and at about 500-510, 540-560, 570-600, and 660-720 FANGVD29 in borehole B128GP (fig. F1). Vuggy intervals identified with the televiewer logs generally indicated moderate agreement with intervals of increased porosity identified with the neutron logs in boreholes T1, T6, T8, and B128GPD (table 19). Vuggy intervals identified with the televiewer logs typically are similar to those identified with borehole-camera logging, and visual inspection and porosity measurement of cores. Although vugs were recorded in other intervals, comparison with rock cores indicated that, in some cases, the apparent vugs may be small cavities that are well-drilling artifacts.

Acoustic-televiewer logs confirmed the presence of numerous vugs and bedding-plane partings that were identified with other methods (table 19). For example, in each borehole where a parting was identified in the lithologic and caliper logs, the parting also was identified in the acoustic-televiewer log. This relation particularly is true for the 660- and 525-ft partings. Acoustic-televiewer logs also identified partings that were not apparent based on other methods. For example, a parting at an altitude of about 485 FANGVD29 in borehole B128GP (referred to in previous reports as the 300-ft parting based on depth at the PCHSS and referred to as the 485-ft parting in this report) was identified with the televiewer logs, but was not apparent in the camera log, rock core, or other geophysical logs. Additionally, televiewer logs enabled identification of the type and orientation of secondary-permeability features that could not be identified with other methods except camera logging. However, bedding-plane partings identified in the acoustic-televiewer logs should be verified with caliper and natural-gamma logs, as well as other data, because signal responses on acoustic-televiewer logs can be similar for wash outs of argillaceous material (including shale partings and bentonite beds) and fractures.

Borehole ground-penetrating radar—single hole

A single-hole directional GPR reflection survey done in borehole B127GP at the PCHSS in 1991 (Niva, 1991; J.W. Lane, Jr., U.S. Geological Survey, written commun., 1993; Mills and others, 1998) was capable of signal penetration about 50 ft into the dolomite. Interpretation of the radar data from this survey indicated the presence of 35 reflectors in the vicinity of the borehole (Mills and others, 1998)(table F2). Most of the reflectors are considered to represent bedding-plane partings (including the 525- and 660-ft partings) and isolated cavities. The cavities, if present, are assumed to be small; large cavities (greater than about 1 in^3) have not been detected with other methods.

Dips of the GPR reflectors interpreted as fractures (excluding the bedding-plane fracture assumed to represent the 525-ft parting) range from about 33° to 86°. The

Table F2. Summary of orientation of fractures and reflectors in select boreholes by method of detection, Belvidere Ill.

[Bold denotes reflectors calculated to intercept the borehole above or below the open interval of the borehole. NI, not identified; ND, no data; F, fracture; BPP, bedding-plane parting; P, point feature; NA, not applicable; NC, could not be calculated]

Borehole name	Altitude or projected altitude of intersection with borehole (feet above National Geodetic Vertical Datum of 1929)	Acoustic Televiewer			Single-hole ground-penetrating radar reflectors		
		Strike (degrees from magnetic north)	Dip (degrees from horizontal)	Interpretation of feature	Strike (degrees from magnetic north)	Dip (degrees from horizontal)	Interpretation of reflector
T1	**813.5**	NI	NI	NI	N 50° E	82.0	F
	753.1	NI	NI	NI	S 70° W	43.4	F
	729.5	NI	NI	NI	NC	52.5	F
	700-709	N 43° E	88	F	NI	NI	NI
	664.2	NA	0	BPP	N 50° E	49.9	F
	658.3	NI	NI	NI	N 30° E	.0	BPP
	657.7	NI	NI	NI	NC	16.6	F
	651.0	NA	0	BPP	NI	NI	NI
	640.2	NI	NI	NI	NC	38.9	F
	632.1	NI	NI	NI	NC	52.5	F
	631.1	NA	0	BPP	NC	36.4	F
	601.0	NA	0	BPP	NI	NI	NI
	577.0	NI	NI	NI	NC	57.9	F
	574.0	NI	NI	NI	N 90° E	51.6	F
	515.3	NI	NI	NI	S 60° E	65.4	F
	503.1	NI	NI	NI	S 50° E	72.4	F
T6	**2922.0**	NI	NI	NI	NC	89.1	F
	812.5	NI	NI	NI	NC	74.3	F
	769.2	NI	NI	NI	S 70° W	55.3	F
	745.0	NA	0	F	NI	NI	NI
	734.0	NA	0	F	NI	NI	NI
	689.8	NI	NI	NI	N 40° E	40.1	F
	678.7	NI	NI	NI	S 40° W	41.3	F
	662.0	NA	0	F	NI	NI	NI
	659.0	NI	NI	NI	N 40° E	.0	BPP
	652.1	NI	NI	NI	NC	56.7	F
	629.8	NI	NI	NI	NC	ND	F
	628.2	NI	NI	NI	NC	40.9	F
	604-620	N 50° E	88	F	NI	NI	NI
	568.1	NI	NI	NI	S 10° W	64.6	F
	513.7	NI	NI	NI	S 70° W	74.9	F
T8	744.9	NA	0	F	N 30° E	38.3	F
	732.0	NA	0	BPP	NI	NI	NI
	700.0	NA	0	BPP	NI	NI	NI
	688.2	NI	NI	NI	N 60° E	34.5	F
	675.0	NI	NI	NI	NC	27.8	F
	660.0	NA	0	BPP	NI	NI	NI
	656.3	NI	NI	NI	N 50° E	.0	F
	649.0	NA	0	BPP	NI	NI	NI
	612.7	NI	NI	NI	S 10° W	50.0	F

Table F2. Summary of orientation of fractures and reflectors in select boreholes by method of detection, Belvidere Ill. --Continued.

Borehole name	Altitude or projected altitude of intersection with borehole (feet above National Geodetic Vertical Datum of 1929)	Acoustic Televiewer			Single-hole ground-penetrating radar reflectors		
		Strike (degrees from magnetic north)	Dip (degrees from horizontal)	Interpretation of feature	Strike (degrees from magnetic north)	Dip (degrees from horizontal)	Interpretation of reflector
T8 (cont.)	**551.4**	NI	NI	NI	N 40° E	52.6	F
	526.7	NI	NI	NI	N 10° E	70.3	F
B127GP	**1380.0**	NI	NI	NI	NA	85.6	F
	1027.0	NI	NI	NI	S 40° W	83.7	F
	933.0	NI	NI	NI	N 70° W	78.4	F
	909.0	NI	NI	NI	NC	76.0	F
	834.0	NI	NI	NI	N 90° W	66.5	F
	770.8	NI	NI	NI	NC	51.3	F
	745.0	NA	0	F	NI	NI	NI
	740.0	NA	0	BPP	NI	NI	NI
	738.0	NA	0	BPP	NI	NI	NI
	732.1	NA	0	BPP	NC	52.8	F
	731.8	NA	0	BPP	NA	.0	BPP
	704.6	NI	NI	NI	NA	.0	BPP
	685.6	NA	0	BPP	NA	.0	BPP
	680.3	NA	0	BPP	NA	.0	BPP
	673.8	NI	NI	Vugs?	NA	.0	BPP
	662.0	NA	0	F	NI	NI	NI
	658.3	NI	NI	Vugs?	NA	NA	P
	657.4	NA	0	BPP	NA	.0	BPP
	640.3	NA	0	BPP	NA	NA	P
	639.0	NA	0	BPP	NC	48.9	F
	637.4	NI	NI	NI	NA	.0	BPP
	637.0	NI	NI	NI	NA	NA	P
B127GP	622.3	NI	NI	Vugs?	NA	NA	P
	606.2	NI	NI	Vugs?	N 0° E	69.8	F
	595.0	NI	NI	NI	NA	.0	BPP
	588.8	NI	NI	NI	NA	NA	P
	572.4	NA	0	BPP	NA	.0	BPP
	566.0	NA	0	BPP	NI	NI	NI
	564.0	NA	0	BPP	NI	NI	NI
	538.0	NI	NI	NI	NA	NA	P
	535.0	NA	0	BPP	NI	NI	NI
	525.0	NA	0	BPP	NC	10.2	F
	507.8	NI	NI	NI	NA	.0	BPP
	502.5	NI	NI	NI	NA	NA	P
	499.6	NI	NI	NI	NA	46.3	F
	498.6	NI	NI	NI	ND	NA	P
	497.6	NI	NI	NI	NA	NA	P
	495.7	NA	0	BPP	NC	63.2	F
	479.9	NI	NI	NI	N 50° W	71.0	F
	475.0	NI	NI	NI	N 70° W	32.8	F
	469.1	NI	NI	NI	N 90° W	61.7	F
	111.9	NI	NI	NI	N 80° W	84.2	F

strike of the reflectors tends to be randomly oriented, ranging from N. 0° W. to N. 140° W.; however, orientations at six of the eight fractures with measured strikes range from N. 50° W. to N. 90° W. These orientations are consistent with measurements at quarries and outcrops in the Belvidere area (primary orientation of about N. 60° W.) (Foote, 1982), but indicate poor agreement with the results of the SAR survey performed within 20 ft of this borehole.

Only six of the GPR reflectors interpreted as inclined fractures are calculated to intersect the open interval of the borehole (table F2). However, fractures were not identified with televiewer or other methods at any of these depths (table F2). Four of the possible fractures identified in GPR logging of B127GP have been interpreted as intercepting the borehole trace about 30 ft above or 300 ft below the Glenwood Formation. Such fractures, if extending to these depths, would penetrate the lower part of the Galena-Platteville dolomite to a depth greater than that typically indicated in other carbonate units in northern Illinois (Csallany and Walton, 1963).

Single-hole directional GPR-reflection surveys done in boreholes T1, T3, T6, and T8 at the PCHSS in 1996 were capable of signal penetration about 15-30 ft into the dolomite (Lane and others, 1994). Between 8 and 13 reflectors were identified in the vicinity of these boreholes (table F2). Aside from a horizontal reflector associated with the 660-ft parting, all of the reflectors were interpreted as inclined fractures, with two distinct orientations. The most frequently interpreted direction of reflector strike near boreholes T1, T3, T6, and T8 is N. 30° E. to N. 50° E. and its counterpart from S. 30° W. to S. 50° W. This orientation is consistent with the inclined fracture orientations identified with the acoustic-televiewer logs boreholes T1, T2, and T6 and the SAR survey done near borehole B127GP. The less frequently interpreted direction of reflector strike is roughly north-south from N. 30° E. to N. 10° W. and its counterpart from S. 30° W. to S. 10° E. Most of the reflectors dip between 40 and 60 degrees from horizontal. Dip values determined from the reflection surveys tend to be substantially less than the values determined from televiewer logging.

A reflector that appears to be the near-vertical fracture identified with the televiewer logging in boreholes T1 and T2 was identified with the GPR reflection survey in borehole T3. This fracture was not identified during the reflection survey done in borehole T1. The reflector terminates below about 610 FANGVD29. The fracture probably extends some distance below this altitude, but it is likely that the size of the fracture decreases with depth and does not produce a strong enough response for the reflector to be identified. The inclined fracture identified at 608-622 FANGVD29 with the televiewer log in borehole T6 was not identified with the single-hole GRP survey.

The type, location, and orientation of secondary-permeability features identified with the single-hole direction GPR surveys indicated moderate agreement with those identified using the other methods (tables F2, 19). The 525-ft and 660-ft partings were identified with the GPR surveys and other reflectors interpreted as bedding-plane partings may represent some of the small partings or vuggy intervals indicated with other logs. However, the altitude of the other bedding-plane partings identified with the GPR logs typically vary by 5 ft or more from those identified with other methods. The offsets in depth do not seem consistent, thus, depth differences do not seem accounted for by a difference in reference datums for measurements. Orientations of inclined fractures determined from the GPR logging in the T series of boreholes were consistent with those identified with the televiewer logs and with the SAR survey done within 20 ft of borehole B127GP. However, these orientations varied considerably between boreholes T1, T3, T6, and T8 and borehole B127GP, a distance of less than 150 ft. Fracture orientations determined at borehole B127GP could represent the orthogonal counterpart of the fracture sets in the nearby boreholes. Additionally, many of the inclined fractures identified with the GPR logging were not identified with other logs at the altitude the fracture was calculated to intersect the borehole. The number of inclined fractures identified with televiewer logs intersecting a given borehole also was substantially lower than indicated with the GPR surveys. This discrepancy may result because of termination of the fracture before it intercepts the borehole, which may indicate decreasing fracture size and density with depth in the Galena-Platteville dolomite.

Borehole ground-penetrating radar—cross-hole

Cross-hole GPR surveys done at the PCHSS between the T2-T7, T2-T8, T2-T3, T3-T8, T3-T7, and T7-T8 borehole pairs differentiate the Galena-Platteville dolomite into three units (Lane and others, 1994). The lower unit is present between about 567 (the bottom of these boreholes) and about 602 FANGVD29 and is characterized by low signal attenuation and high velocity consistent with competent dolomite (table F3). The porosity for this unit, based on the calibrated GPR signal, was from 12 to 13 percent. The middle unit is present at 602-700 FANGVD29 and is characterized by low velocity with interspersed beds of high and low attenuation, which is indicative of competent dolomite with intervals of variable porosity. The porosity of most of the middle unit was calculated to be about 13 percent, with porosity of about 13.5-14 percent at about 667 FANGVD29 and between 681 and 693 FANGVD29, porosity of about 13.5-15 percent at about 605-615 FANGVD29, and porosity of about 12-13 percent at about 676 FANGVD29. The upper unit extends from about 700 FANGVD29 to about 5 ft below the bottom of the casings (about 744 FANGVD29), where the signal was lost. The upper unit is characterized by low signal attenuation and high velocity consistent with competent dolomite. The porosity of the upper unit was estimated to be about 11-12.5 percent from the GPR signal. Although the absolute values for porosity from the GPR logs was lower than for the neutron logs from boreholes T1 and T6, the trends in porosity were similar for both logs (table 19). Porosity values measured in the core samples were consistent with the values obtained from the GPR survey.

Water-level measurements

A synoptic measurement of water levels from wells distributed throughout the Belvidere area was done to evaluate horizontal flow directions. Water levels also were measured in selected monitoring and water-supply wells in the Belvidere area for evaluation of (1) vertical flow directions, (2) hydraulic connection within and between aquifers, (3) the location of permeable features, and (4) response to climatological events and withdrawals from water-supply wells.

Synoptic measurements

During July 1993, water levels were measured in about 150 wells in the Belvidere area; about 50 of which were open to the Galena-Platteville aquifer (Mills and others, 1999a, b)(table 17). Water levels were measured in monitoring wells at the PCHSS and the rest of the Belvidere area, but most of the water levels were measured in residential-supply wells. More than half of these wells were located in subdivisions and some water levels likely were affected by nearby withdrawals. About 80 percent of the wells open to the Galena-Platteville aquifer were open only to the upper half of the aquifer and conclusions regarding water-level trends and flow directions may not be representative of the deeper parts of the aquifer. Surface-water levels were measured at the Kishwaukee River to supplement ground-water levels in the glacial drift aquifer above the Galena-Platteville aquifer.

Water levels in the Galena-Platteville aquifer ranged from about 740 to 900 FANGVD29 and were similar to those within the overlying glacial drift aquifer (figs. 34a, 34b). Data from well clusters open to both the glacial drift and Galena-Platteville aquifers indicated that the potentiometric surface of the glacial drift aquifer generally is less than 1 ft higher than that of the upper part of the Galena-Platteville aquifer and about 5-10 ft higher than that of the middle part of the Galena-Platteville aquifer. The potentiometric surface of both aquifers mimics the configuration of land-surface topography, indicating that the aquifers are unconfined. Horizontal flow generally is toward the Kishwaukee River and its principal tributaries. Vertical flow generally seems to be downward. The availability of wells, particularly in and near Belvidere, was insufficient to map possible flow toward the Troy Bedrock Valley, drawdown associated with municipal-well withdrawals, or areas of upward flow associated with discharge. However, there are a number of areas within the Belvidere area, particularly in the city of Belvidere, where the water level in the Galena-Platteville aquifer is substantially lower than in surrounding areas (fig. 34b). These areas of lower water

Table F3. Summary of ground-penetrating radar tomographic anomalies, Belvidere, Ill.

[<, less than altitude of bottom of borehole; 737*, top of signal reading; d, discontinuous feature]

Borehole pair	Altitude of low-velocity intervals (feet above National Geodetic Vertical Datum of 1929)	Altitude of high-velocity intervals (feet above National Geodetic Vertical Datum of 1929)	Altitude of low-attenuation intervals (feet above National Geodetic Vertical Datum of 1929)	Altitude of high-attenuation intervals (feet above National Geodetic Vertical Datum of 1929)
T2-T7	611.5, 648d, 664, 674.5, 690	<567-602, 677, 700-737*	<567-602, 611.5, 700-737*	641, 661, 677-700 by well T2
T2-T8	611.5, 648d, 664, 674.5, 691	<567-602, 701-737*	<567-618, 618-737*	644, 661, 677
T3-T2	611.5, 651-684	<567-602, 701-737*	703-737*	651-667
T3-T8	615, 648d, 667, 690	<567-592, 710-737*	<567-608, 611.5, 700-737*	638, 657.3
T7-T3	611.5, 644d, 667, 690	<567-602, 704-737*	<567-618, 704-737*	Alternating high and low; 628-664
T7-T8	615, 648d, 667, 690	<567-600, 704-737*	<567-615, 700-737*	657.3-661

levels appear to be associated with pumping from quarries, and municipal- and industrial-supply wells.

Continuous measurements

Continuous measurements of water levels were made in boreholes and wells at different times (table 17). Continuous measurements were important for identifying the climatic and anthropogenic factors affecting water levels and the variability of flow direction as well as the locations of permeable features within the Galena-Platteville aquifer underlying the Belvidere area.

Water levels were measured on a 15-minute sampling frequency in wells G115D, G115B, G126BGP, and G127SP at the PCHSS during November and December 1992. Continuous measurements did not indicate a rapid response to precipitation events in the Galena-Platteville aquifer (fig. F7a), but did indicate pronounced short-term (seconds to hours) hydraulic responses to pumping and the termination of pumping in nearby municipal-supply wells (fig. F7c). Water levels in well G127GP, open to the deep part of the Galena-Platteville aquifer at about 490 FANGVD29 (depth of about 295 ft), changed by about 25 ft in almost instantaneous response to initiation or cessation of withdrawals at municipal well BMW6. Well BMW6 is located within 100 ft of well G128GP (fig. 31) and is open, in part, to the Galena-Platteville aquifer, although most of the water is taken from the St. Peter Sandstone and other underlying aquifers. Similar, but more subdued responses to withdrawals are indicated in wells open to shallower parts of the aquifer (fig. F7a). For example, water levels in well G115BD, open at about 630 FANGVD29 (depth about 150 ft), frequently changed by about 3 ft in the span of less than 1 day. Water levels in well G115B, open at about 730 FANGVD29 (depth of about 50 ft), typically changed by less than 0.1 ft during the same period. Water levels in these wells also responded to pumping in well BMW4, although to a lesser degree than to pumping in well BMW6.

Water-level responses similar to those described above also were recorded at well G305GPC in the central part of Belvidere in November and December 1992. Water levels in well G305GPD, open to the 525-ft parting, dropped as much as 7 ft in apparent response to withdrawals at well BMW5 located more than 0.5 mi away. Water-level response in well G305GPS, open to the 660-ft parting, was negligible.

The water-level responses described above are consistent with those observed during subsequent continuous monitoring events done in a variety of monitoring wells and in borehole test intervals isolated with a packer assembly. Water levels in monitoring wells or test intervals open to the 525-ft parting typically fluctuated by 5-30 ft in almost instantaneous response to pumping in the municipal-supply wells. Water levels in wells or test intervals open to progressively shallower parts of the Galena-Platteville aquifer also had almost instantaneous response to pumping but with progressively smaller fluctuations. Subsequent monitoring indicates that pumping stresses from the municipal-supply wells were not transmitted to the upper part of the Galena-Platteville aquifer or the glacial drift aquifer, at least in the vicinity of the PCHSS.

Water levels also were collected at a 15-minute frequency in monitoring wells G124GP, G133GP, G134GP, and G136GP during February 2000 (fig. F8). All of these wells were open to the 525-ft parting, and all responded to pumping in wells BMW4, BMW6, and perhaps nearby industrial-supply wells (fig. 30). Water-level fluctuations in well G124GP, located nearest BMW6, tended to be largest and usually were in excess of about 6 ft daily. Water-level fluctuations in well G136GP tended to be intermediate, and fluctuations in wells G133GP and G134GP tended to be lowest, usually about 4 ft during a day. Changes in water level during pumping usually were substantial enough to alter flow directions in the 525-ft parting from its typical direction south toward the Kishwaukee River to north toward well BMW6. Water levels in wells G124GPS, G134GPS, and G136GPS, open to the upper 15 ft of the Galena-Platteville aquifer, did not respond to pumping.

Analysis of the continuous water-level data indicate that the 525-ft parting located throughout at least the center part of the Belvidere area is permeable, and is connected to the open intervals in BMW4, BMW5, and BMW6, and perhaps other domestic, industrial- and municipal-water-supply wells in Belvidere. Deep, widespread, permeable bedding-plane partings (such as the 485-ft parting) also may be present, but the relative unavailability of monitoring points open to the aquifer below 525 FANGVD29 precluded verification of the presence of such features. Pumping and the termination of pumping in the municipal-supply wells induces large, instantaneous water-level changes in the 525-ft parting, which are transmitted vertically within the aquifer through a hydraulically interconnected network of vugs and inclined fractures. These water-level changes are sufficient to alter flow directions within the deeper part of the aquifer, but are attenuated in the upper part of the aquifer. The dampening of the water-level change with increasing vertical distance above the 525-ft parting indicates an increase in the capacity of the aquifer to respond to the hydraulic stress induced by drawdown in the 525-ft parting by flow from storage and permeable features. This response is consistent with an increasing well developed network of secondary-permeability features with decreasing depth in the Galena-Platteville aquifer.

The effect of nearby ground-water withdrawals on the approach taken for water-level measurement in this

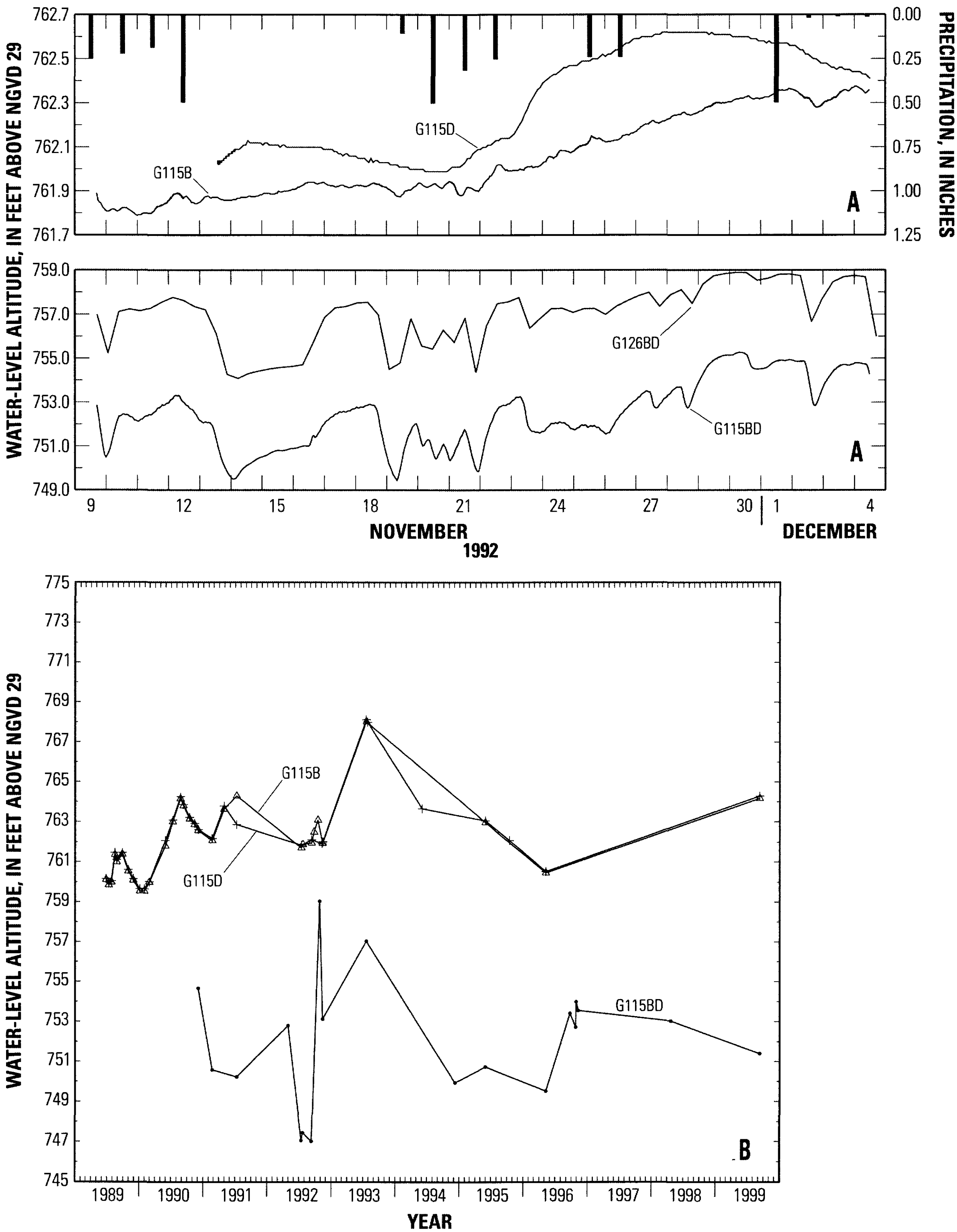


Figure F7. Hydrographs for select wells open to the Galena-Platteville and adjacent aquifers underlying Belvidere, Ill., showing response to (A) precipitation, (B) climatological trends, and (C) withdrawals from high-capacity supply wells.

urban setting should be considered. In some wells, water levels usually changed so rapidly and to such an extent that accurate measurement with a steel tape and chalk was impractical to impossible; use of an electric-sensor tape generally was necessary for water-level measurements. Also, when storing a reference water level in an automatic data logger, setting the reference level immediately following manual measurement was necessary to avoid error in the reference level for subsequent automatic measurements.

Periodic measurements

Water levels were measured periodically in 11 wells located in the city of Belvidere (table 17). Measurements were made during field trips at time intervals that typically ranged from less-than hourly to annually. These data provided information on longer-term water-level trends (up to 12 years) in response to climatalogical trends and (or) ground-water use (fig. F7b). Over the period of measurement, water levels at all depths of the Galena-Platteville aquifer varied by about 5-10 ft, typically in response to long-term variations in recharge. The greatest increase in water levels was in 1993, in response to an unusually large amount of precipitation that year (greater than 150 percent of annual average). During other periods, water levels typically varied by about 5 ft or less. Water levels measured in the deeper parts of the aquifer, such as well G115BD, were affected by ground-water withdrawals as well as long-term trends

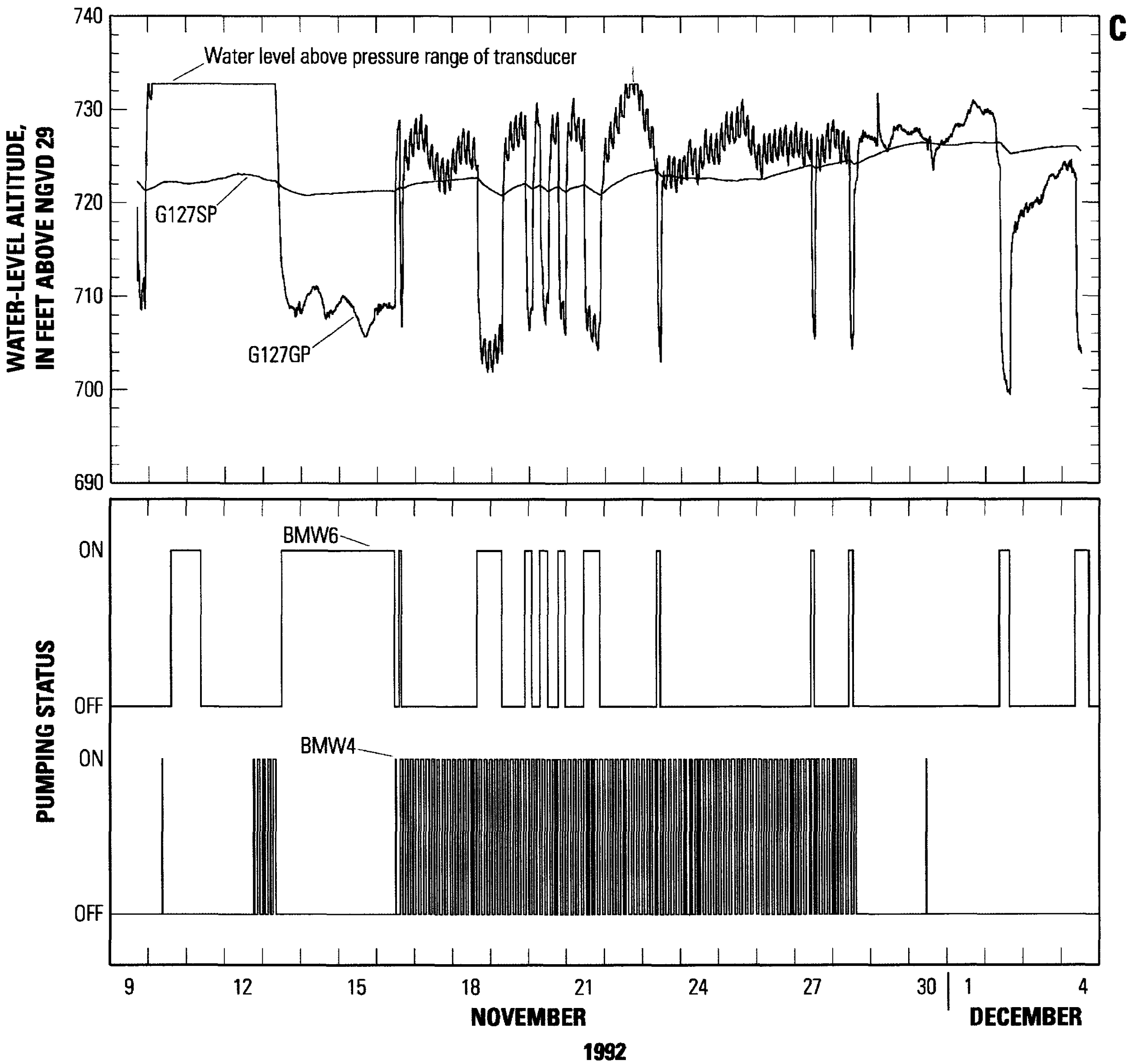


Figure F7. Continued.

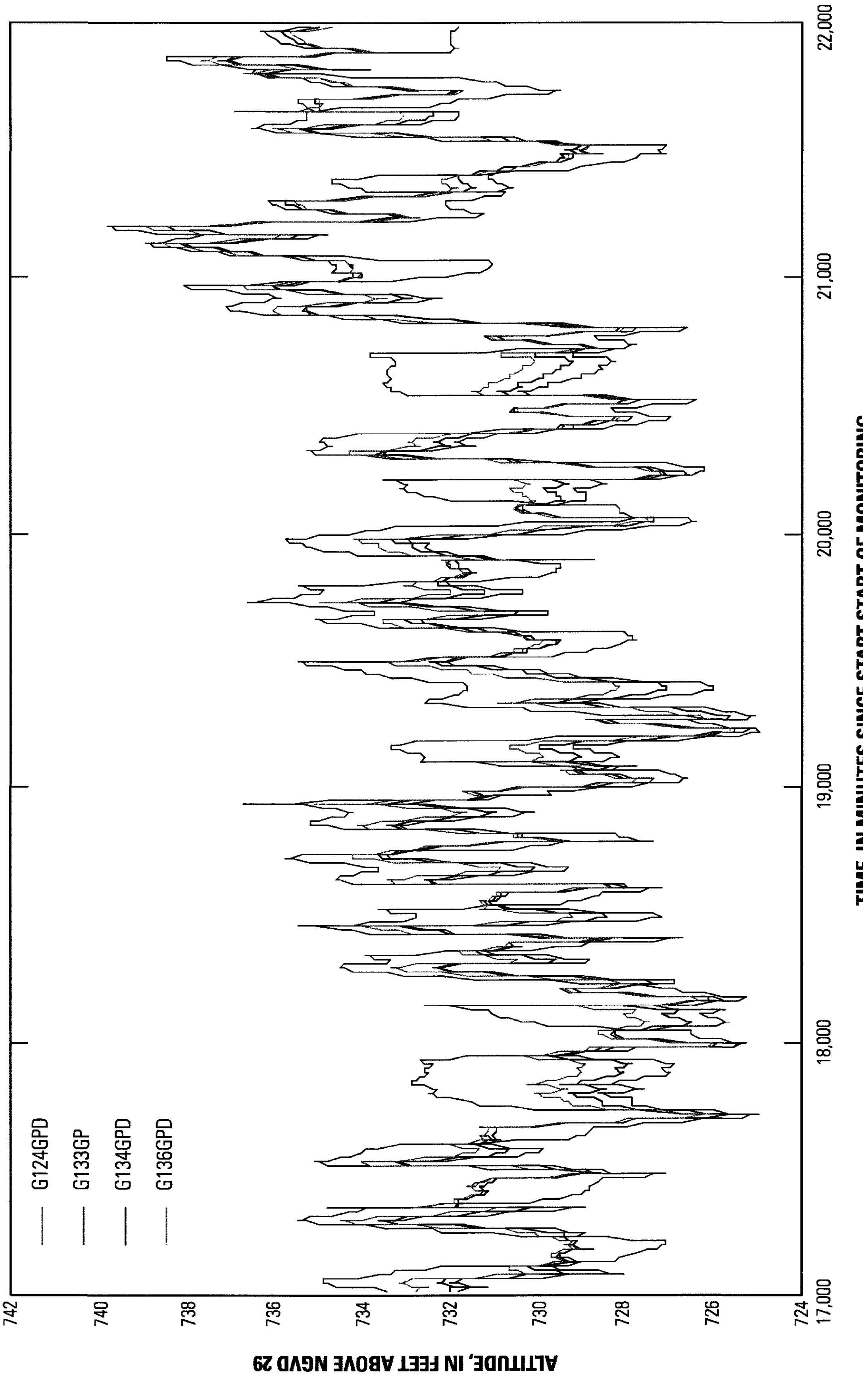


Figure F8. Water-level fluctuations in wells G124GP, G133GP, G134GP, and G136GP open to the 525-ft parting in Belvidere, Ill.

in recharge.

The timing of the water-level changes generally was similar at all depths of the aquifer (fig. F7b). These trends indicate that the Galena-Platteville aquifer has sufficient hydraulic connection to respond to ambient hydraulic effects as a single aquifer. However, as indicated by the continuous measurements, the upper part of the aquifer seemed to be partly hydraulically isolated from the deeper parts of the aquifer. The partial isolation is made apparent when the aquifer is pumped. For example, water-level measurements collected during June and October of 1991 in monitoring wells open to the Galena-Platteville aquifer at the PCHSS indicate that ground-water-flow directions differ between the upper (above 632 FANGVD29) and middle parts of the aquifer. Flow in the upper part of the aquifer is oriented to the southwest, whereas flow in the middle part of the aquifer is to the southeast (fig. F9). Furthermore, the direction of ground-water flow in the middle part of the aquifer at the PCHSS varied by about 15° between June and October, presumably in response to variations in the effects of pumping in the nearby municipal-supply wells. No variation in the direction of ground-water flow was detected in the upper part of the aquifer (Mills, 1993b). The difference in flow directions between the middle and upper parts of the Galena-Platteville aquifer indicate that these two parts of the aquifer have some hydraulic isolation, which indicates the presence of vertical variations in permeability within the aquifer.

Water levels also were measured periodically at clusters of vertically nested monitoring wells. Measurements were made at intervals from once per year to about monthly. These data provided information on vertical gradients within the Galena-Platteville aquifer and between it and the glacial drift and St. Peter aquifers above and below, respectively.

Vertical-hydraulic gradients between the glacial drift aquifer and the upper 30 ft of the Galena-Platte-

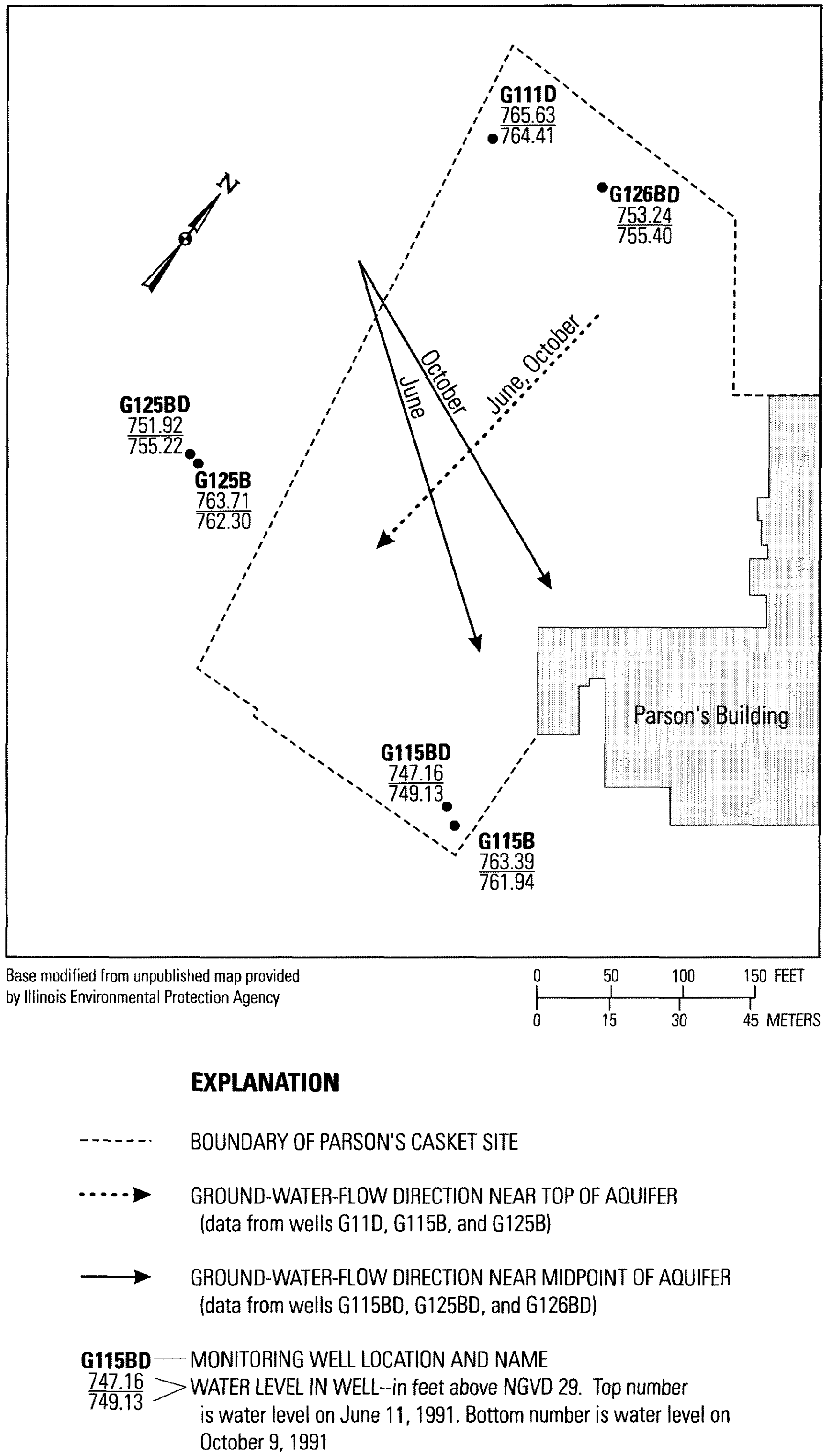


Figure F9. Water-level altitudes and approximate ground-water-flow directions in the Galena-Platteville aquifer, Belvidere, Ill., June and October 1991.

ville aquifer typically are directed downward away from streams. Supplemental data from the Belvidere Landfill No. 1 site (fig. 30) (Roy F. Weston, Inc., 1988) indicate that gradients are upward where flow discharges from the upper part of the aquifer into the Kishwaukee River (and likely to other streams).

In and near the city of Belvidere, vertical hydraulic gradients within the Galena-Platteville aquifer typically are downward away from streams. No data are available from the deeper part of the aquifer immediately adjacent to streams. However, water levels measured at well G436BD and boreholes B134GP and B137GP located within about 350 ft of the Kishwaukee River (fig. 30) indicate a downward gradient of about 0.05-0.1 ft/ft between the river and the deeper part of the aquifer. Flow in the deep part of the aquifer in these areas, particularly in the 525-ft parting, appears to move beneath the river to nearby municipal- and industrial-supply wells. These flow directions are at least partly in response to pumping from water-supply wells and may not represent natural conditions.

In the city of Belvidere and vicinity, vertical-hydraulic gradients between the Galena-Platteville and St. Peter aquifers appear to be directed downward under natural conditions, but flow directions may be reversed in the vicinity of the water-supply wells during pumping periods (fig. F7c). At the G127GP/G127SP well nest at the PCHSS, gradients typically range from about 0.13 ft/ft downward to 0.06 ft/ft upward (Mills and others, 1998).

Single measurements with packers

Single water-level measurements were collected in test intervals isolated with a dual-packer assembly in 18 boreholes in the Belvidere area, primarily in the vicinity of the PCHSS (Mills, 1993a, b, c; Mills and others, 1998; Mills and others, 2002a) (table 17). These water-level data improved understanding of the magnitude of the vertical variations in water level within the Galena-Platteville aquifer and the factors that affect these variations.

Vertical differences in water levels above and below the test intervals isolated with a dual-packer assembly typically varied with the borehole depth. Water levels above and below the test intervals in boreholes T1, T6, (table F4), T2, T3, T5, T7, T8, B125BD, and B126BD typically varied by less than 5 ft. Water levels above and below the test intervals in borehole B115BD typically varied by less than 5 ft and always varied by less than 11 ft, with the largest differences in the test intervals below 656 FANGVD29. These boreholes are drilled to a depth of 215 ft or less (altitude greater than about 570 FANGVD29) (table 18). Water levels above and below the test intervals in boreholes B124GP, B127GP, B128GP, B133GP, B134GP, B136GP, and B137GP varied as much as 30 ft (table F4). These boreholes are drilled to a depth in excess of 265 ft (altitude about 520 FANGVD29). Water levels measured in the test intervals open at or near the marker bed at about 660 FANGVD29 in boreholes B124GP, B133GP, and B136GP were within 2.5 ft of the water levels above the test interval, but were more than 14 ft higher than water levels below the test interval. The increase in differences in water levels with borehole depth is, in part, a response to the effects of pumping in the nearby water-supply wells and indicates that the vertical hydraulic conductivity of the Galena-Platteville aquifer decreases with depth. This decrease in permeability indicates that vertical secondary-permeability features in the Galena-Platteville aquifer are fewer, smaller, and less interconnected with depth at the PCHSS, and presumably the entire Belvidere area. The small difference in water levels within the Galena-Platteville aquifer above the marker bed at 660 FANGVD29 and the large difference in water levels below that altitude indicate that this bed may correspond to a transition from depths of higher to lower vertical hydraulic interconnection in at least some locations. This interpretation is consistent with the analysis of the cores and borehole GPR data.

Single water-level measurements from test intervals isolated with a packer assembly also were useful for identifying permeable intervals in the aquifer at boreholes T1-T8 at the PCHSS. Data from borehole T6 are representative of boreholes T5-T8. Water levels in borehole T6 prior to packer inflation typically were within 0.05 ft of the water level in the zone (either within or above the test interval) that was open to the subhorizontal bedding-plane parting at about 744 FANGVD29 (fig. F2, table F4). Water levels in the zones not open to this bedding-plane parting (within or below the test interval) typically were 0.5-3 ft lower than in the open borehole. The water-level measurements indicate that the subhorizontal bedding-plane parting at about 744 FANGVD29 in boreholes T5-T8 is the most permeable feature at these boreholes. Water-level measurements also indicate that the inclined fracture at about 699-709 FANGVD29 in boreholes T1 and T2 may be the most permeable feature in these boreholes (tables 20, F4).

Geophysical logs

Various geophysical logs were run in boreholes and wells open to the Galena-Platteville aquifer as part of the Belvidere area study (table 17). The boreholes were distributed across an area of about 1.5 mi^2 in Belvidere, but most were near the PCHSS. Many of the logs were useful in enhancing characterization of the hydrologic framework of the area.

Spontaneous potential

SP logging was done in eight boreholes and one well (table 17). SP logs indicated abrupt increases in signal response at about 660 FANGVD29 in borehole B125BD; about 660, 673, 705, and 755 FANGVD29 in borehole B126BD; 525 and 660 FANGVD29 in borehole B127GP (fig. F3); and about 485 and 660 FANGVD29 in borehole B127SP, and, possibly, at about 500 and 525 FANGVD29 in borehole B128GP (fig. F1). These intervals correspond to lithologic contacts, particularly the 525- and 660-ft partings, that may correspond to permeable features in the Galena-Platteville aquifer. Gradual increase in spontaneous potential was detected above about 660 FANGVD29 in boreholes B125GP, B126GP, and B127GP. This interval also may correspond to permeable features in the aquifer. SP logs run in boreholes B115BD, B436, B305, and B137GP did not indicate the presence of permeable features.

Bedding-plane partings associated with argillaceous deposits at about 525 and 660 FANGVD29 may be permeable based on interpretations of the SP logs. SP response also appears to be affected by clay content and changes in borehole diameter, such as the large increase in SP response at 485 FANGVD29 in borehole B127SP, an altitude where there is no apparent fracture or increase in natural-gamma activity, but with a decreased borehole diameter. It is unclear, therefore, if the SP log is responding to geologic or hydraulic conditions. The utility of the SP log is decreased by its poor resolution of the depth of the secondary-permeability feature as defined with other methods. For example, the SP signal response to the feature at 525 FANGVD29 in borehole B127GP (fig. F3) occurs over a range of about 5 ft. Use of the SPR log may assist the interpretation of SP logs. At all depths where partings are indicated in both the SP and SPR logs, the signal responses are opposite (increase in SP log and decrease in SPR signal). At 485

Table F4. Water levels in test intervals isolated with a packer assembly from select boreholes, Belvidere, Ill.

[NA, not available; NT, measurement not taken; < less than]

Borehole name (fig. 31)	Altitude of test interval (feet above National Geodetic Vertical Datum of 1929)	Altitude of water level: Open borehole (feet above National Geodetic Vertical Datum of 1929)	Above test interval (feet above National Geodetic Vertical Datum of 1929)	In test interval (feet above National Geodetic Vertical Datum of 1929)	Below test interval (feet above National Geodetic Vertical Datum of 1929)
T1	567-582	759.50	757.88	755.42	NA
	616-626	760.89	760.95	757.80	757.12
	627-637	760.98	761.00	759.94	759.47
	696-733	760.86	NA	760.97	758.27
T6	579-589	760.67	760.77	757.25	757.40
	589-599	760.74	760.78	757.92	758.01
	606-616	760.68	760.74	759.15	757.66
	616-626	760.73	760.72	759.42	757.98
	627-637	760.81	760.75	756.44	755.25
	682-692	761.47	761.48	760.50	759.17
	742-745	760.66	NA	760.70	758.46
B124GP	518-540	NT	758.95	731.55	NA
	556-566	NT	758.11	752.51	731.49
	658-668	747.25	760.38	758.40	743.87
	716-747	NT	NA	748.68	745.87
	737-747	742.75	NA	757.03	<754
B115BD	631-646	NT	762.96	753.20	NA
	646-656	NT	762.88	757.30	754.58
	656-666	NT	762.95	761.95	754.84
	666-676	NT	762.92	761.44	761.08
	676-686	NT	762.97	761.70	760.96
	686-696	NT	762.93	761.81	760.93
	696-706	NT	762.86	762.23	760.96
	710-720	NT	763.79	763.66	763.00
	724-734	NT	763.62	763.50	792.96
	742-745	NT	NA	763.59	762.76

FANGVD29, the altitude of the increase in SP signal in borehole B127SP, the SPR signal also increases. Where natural-gamma and caliper logs are unavailable, this similarity in response may be useful in distinguishing changes in diameter resulting from drilling or from hydraulic features.

Temperature

Temperature logging was done in 12 boreholes and 1 well (table 17). Temperature logs typically indicated an overall decrease in water temperature with increasing depth, with particularly large changes across the first 5-10 ft of the water column. Temperature changes in the upper part of the water column likely reflect the effect of ambient temperature on the water and the probe, and not the presence of permeable features. Abrupt changes in fluid temperature were observed at about 525, 560, and 728 FANGVD29 in borehole B124GP (fig. F4); at about 525 FANGVD29 in borehole B127GP (fig. F3); at about 483 and 565 FANGVD29 in borehole B128GP (fig. F1); at about 521 FANGVD29 in borehole B133GP; at about 525 FANGVD29 in boreholes B134GP and B136GP (fig. F6); and at about 525, 647, and 703 FANGVD29 in borehole B137GP. Many of these intervals correspond to bedding-plane partings identified with other methods and may be permeable (tables F1, 20). Changes in the rate of change in fluid temperature with depth were observed at about 660 FANGVD29 in borehole B134GP, and about 525 and above 702 FANGVD29 in borehole B127GP. These intervals also may correspond to the locations of permeable features in the aquifer (table 20).

Fluid resistivity

Fluid-resistivity logging was done in 11 boreholes and 1 well (table 17). For the most part, resistivity measurements did not vary except near the top of the water column within the borehole casings. Resistivity logs did indicate moderate to abrupt changes in signal response at about 563 and 728 FANGVD29 in borehole B124GP (fig. F4), at about 525 and 565 FANGVD29 in borehole B128GP, at about 743 FANGVD29 in borehole B130GP (fig. F5), at about 525, 660, and 720 FANGVD29 in borehole B133GP, at about 683 FANGVD29 in borehole B134GP, and at about 525 and 725 FANGVD29 in borehole B136GP (fig. F6), and between about 655 and 665 FANGVD29 in borehole B436. Many of these intervals correspond to bedding-plane partings and appear to be permeable (table 20). Fluid-resistivity logs from the remaining boreholes indicated no changes in resistivity that clearly would be indicative of permeable features.

Heat-pulse flowmeter logs

Flowmeter logs were run under hydraulic conditions of ambient flow in 16 boreholes and well BMW2 (table 17). Flow typically was directed downward in these boreholes, with intermittent measurement of upward flow apparently being related to the pumping effects from nearby water-supply wells.

Flowmeter logging in borehole B124GP indicates inflow from bedding-plane partings and vugs from the bottom of the borehole casing to the top of the 660-ft parting, inflow from a subhorizontal bedding-plane parting at about 564 FANGVD29, and outflow through the 525-ft parting (fig. F4). Flow volumes in borehole B127GP varied during different logging events for that part of the borehole above 525 FANGVD29, indicating possible inflow from bedding-plane partings or vugs at about 705-725 FANGVD29 and through the 660-ft parting (fig. F3). Flowmeter logging clearly indicated outflow through the 525-ft parting in borehole B127GP. Although predominantly downward, upward flow in the borehole also was recorded. The variability in the amount and direction of flow in borehole B127GP is in apparent response to pumping from wells BMW4 and BMW6. Flowmeter logging in borehole B128GP indicates flow through the 485-, 525-, and 660-ft partings (fig. F1). Flowmeter logs run in borehole B130GP indicate inflow from a subhorizontal bedding-plane parting below the bottom of the casing at about 746 FANGVD29 and outflow through a subhorizontal bedding-plane parting at about 567 FANGVD29 (fig. F5). Flowmeter logs in boreholes B133GP, B134GP, and B136GP (fig. F6) indicate inflow through bedding-plane partings and vugs from the bottom of the casing to the 660-ft parting, and outflow through the 525-ft parting. Flowmeter logging in borehole B137GP indicates inflow below the bottom of the casing at about 724 FANGVD29, outflow through subhorizontal bedding-plane partings and vugs between about 648 and 724 FANGVD29, and outflow through subhorizontal bedding-plane partings at about 577 and 525 FANGVD29.

Flowmeter logging done under ambient-flow conditions in boreholes T1-T8 indicated variable flow directions during different logging events. Downward flow was measured above 604 FANGVD29 during all logging events. Between about 584 and 604 FANGVD29, upward and downward flow was measured in boreholes T1 (fig. A3), T2, T3, T6 (fig. F2), and T7 during at least one of the three logging events in these boreholes. The transition between upward and downward flow and the transient nature of the change indicates a permeable feature may be present between 584 and 604 FANGVD29, and that this feature is in better hydraulic connection with the secondary-permeability network affected by pumping in the municipal wells than the rest of the borehole. However, analysis of the lithologic and geophysical logs did not identify a secondary-permeability feature in this interval. Flowmeter logging in boreholes T1 and T2 indicates inflow associated with the high-angle fracture between about 699 and 709 FANGVD29, and outflow through the vugs between about 602 and 642 FANGVD29 (fig. A3). Flowmeter logging in borehole T3 indicates inflow through vugs between about 684 and 694 FANGVD29, and outflow through vugs between 632 and 642 FANGVD29. Flowmeter logging in borehole T5 indicates inflow associated with a subhorizontal bedding-plane parting at about 742 FANGVD29, and outflow through vugs between about 682 and 692 FANGVD29. Flowmeter logging in boreholes T6, T7, and T8 indicates inflow associated with a subhorizontal bedding-plane parting at about 742 FANGVD29, and outflow through vugs between about 682 and 692 and 589 and 647 FANGVD29 (fig. F2).

Flowmeter logging in municipal well BMW2 was limited to one flow measurement (at about 590 FANGVD29) within the interval open to the Galena-Platteville aquifer because of concerns over tool safety. About 5 gal/min of downward flow at this point indicated inflow from bedding-plane partings above 590 FANGVD29, potentially including the 660-ft parting, and (or) a steeply inclined fracture at an altitude of about 625 FANGVD29 (depth of about 135 ft).

Downward flow also was recorded during logging of borehole B436. Inflow occurred from the weathered surface of the Galena-Platteville aquifer, just below the base of the casing at altitude of about 735 FANGVD29 (depth about 30 ft), and from the 660-ft parting. Inflow was recorded at an altitude of about 620 FANGVD29 (depth about 145 ft), however, no partings or fractures are evident in the geophysical logs at this interval. Vugs are identified in the acoustic-televiewer log, however, their size and prevalence appear much greater in other intervals where inflow was not recorded.

Flowmeter Logging During In-Borehole Pumping

Flowmeter logging in conjunction with pumping in boreholes B124GP, B133GP, B134GP, and B136GP identified the same permeable features that were identified during logging under ambient-flow conditions (figs. F4, F6). Logging in conjunction with pumping tended to emphasize the flow contribution from the permeable features above 660 FANGVD29, but the volume of flow below 660 FANGVD29 typically was similar to the volume measured under ambient conditions. Differences between the ambient and in-borehole pumping profiles above 660 FANGVD29 indicate that vertical hydraulic gradients are smaller above than below 660 FANGVD29, and flow rates are affected by drawdown induced by pumping. The small differences between the ambient and pumping profiles below 660 FANGVD29 indicate that pumping had little effect on flow, which indicates that the vertical hydraulic gradients below this interval are high, and that the vertical hydraulic conductivity of this interval is low in comparison to that above 660 FANGVD29. These results are consistent with the analysis of the water-level data collected by use of a packer assembly in these boreholes.

Logging During Cross-Borehole Pumping

While boreholes T1, T3, and T7 were pumped as part of their development, flowmeter logs were run in the other boreholes in the T1-T8 series. Analysis of flowmeter data collected during this logging identified four permeable features in that part of the Galena-Platteville aquifer penetrated by these boreholes: (1) the subhorizontal bedding-plane parting at about 742 FANGVD29 in boreholes T5, T6, T7, and T8; (2) the inclined fracture from 699 to 709 FANGVD29 at boreholes T1 and T2; (3) vugs from about 682 to 692 FANGVD29; and (4) vugs from about 602 to 642 FANGVD29. These features are consistent with those identified with the flowmeter logging under ambient conditions in these boreholes, and to a lesser degree with the lithologic logging. Logging during pumping tended to emphasize the location of the permeable features and to highlight their interconnection.

Based on the flowmeter data collected during both ambient and cross-borehole pumping, Paillet (1997) calculated the transmissivity of the subhorizontal bedding-plane parting at about 742 FANGVD29 to be 216 ft^2/d, with a storage coefficient of less than 1×10^{-3} (table F5). The transmissivity of the inclined fracture from 697 to 707 FANGVD29 was calculated to be 130 ft^2/d, with an undetermined storage coefficient. The transmissivity of the vuggy interval from 682 to 692 FANGVD29 was calculated to be 8.6 ft^2/d, with a storage coefficient of 2×10^{-5}. The transmissivity and storage coefficient of the vuggy interval at about 602-642 FANGVD29 were calculated to be 43 ft^2/d and 2×10^{-5}, respectively.

Aquifer tests

Slug tests, specific-capacity tests, multiple-well aquifer tests, and tracer tests were performed in the Galena-Platteville aquifer in the Belvidere area.

Slug tests

Kh values were obtained from slug tests in monitoring wells and in test intervals isolated with a packer assembly (table 17). All test locations were in the Belvidere area, and about two-thirds of the locations at or near the PCHSS. Tests in wells done as part of other studies (Clayton Environmental Consultants, Inc., 1996; GZA GeoEnvironmental, Inc., 1993; Roy F. Weston, Inc., 1988) also were evaluated. About 90 percent of the aquifer thickness was tested in 51 test intervals isolated with a packer assembly at 5 boreholes. Additional tests were performed in 87 selected test intervals isolated with a packer assembly in 15 boreholes.

Kh values from slug tests in the Galena-Platteville aquifer ranged from about 0.005 to about 2,500 ft/d. This large variation in Kh indicates that the Galena-Platteville aquifer is highly heterogeneous in the Belvidere area. Intervals with elevated Kh (greater than 1 ft/d) were restricted primarily to four parts of the aquifer: the upper 20 ft of the bedrock, the 660-ft parting, the 564-parting, and the 525-ft parting (fig. 35). Elevated Kh values for these intervals were not recorded at all locations and in at least one borehole, B128GP, additional partings with elevated Kh compared to the rest of the aquifer (at altitudes of about 595 and 485 FANGVD29; depths of about 190 and 300 ft) were recorded (fig. F1).

On the basis of vertical variations in Kh, and in conjunction with interpretations based on other methods, the Galena-Platteville aquifer within the Belvidere area can be divided arbitrarily into five units: the upper 20 ft of the bedrock surface, from 21 ft below the bedrock surface to the 660-ft parting, from below the 660-ft parting to just above the 525-ft parting, the 525-ft parting, and from the bottom of the 525-ft parting to the base of the aquifer at about 455 FANGVD29. These units are recognized primarily from data at and near the PCHSS and their presence may differ within the Belvidere area.

Table F5. Aquifer parameters calculated from flowmeter logging, slug testing, and constant-discharge aquifer testing for select boreholes, Belvidere, Ill.

[< less than; na, not applicable; nc, not calculated]

	Cross-borehole flowmeter logging			Slug testing			Constant-discharge aquifer testing		
Permeable feature	Estimated transmissivity (feet squared per day)	Estimated storage coefficient (dimensionless)	Estimated horizontal hydraulic conductivity (feet per day)	Estimated transmissivity (feet squared per day)	Estimated storage coefficient (dimensionless)	Estimated horizontal hydraulic conductivity (feet per day)	Estimated transmissivity (feet squared per day)	Estimated storage coefficient (dimensionless)	Estimated horizontal hydraulic conductivity (feet per day)
Subhorizontal fracture at about 742 feet in boreholes T5, T6, T7, and T8	216	<0.001	na	516	na	71.6	7414	0.02	na
Inclined fracture from about 699 to 709 feet in boreholes T1 and T2	130	na	na	1900	na	na	22.6	.00076	na
Vuggy interval from about 682 to 692 feet in boreholes T1 through T8	8.6	.00002	0.9	5.6	na	.56	nc	nc	nc
Vuggy interval from about 602 to 642 feet in boreholes T1 through T8	42.3	.00002	1.1	18.2	na	.91	18.1	na	1.6

For example, a semiconfining unit was identified above the 660-ft parting near an industrial facility about 2.5 mi southwest of the PCHSS (GZA GeoEnvironmental, Inc., 1993). However, data review indicates that this semiconfining unit may be the clay-rich interval associated with the 660-ft parting.

Kh values obtained from 13 slug tests done in the upper 20 ft of the Galena-Platteville aquifer ranged from 0.054 to 360 ft/d with a geometric mean of 4.3 ft/d. These values indicate that the upper 20 ft of the aquifer generally is permeable and contains a well-developed network of interconnected secondary-permeability features.

Kh values obtained from 29 slug tests done in that part of the aquifer from 21 ft below the bedrock surface to the 660-ft parting ranged from 0.067 to 2,500 ft/d, with the highest values being associated with the 660-ft parting. Excluding the outlier value of 2,500 ft/d, the geometric mean Kh for this part of the aquifer is 0.36 ft/d. Kh values from 31 slug tests done in the Galena-Platteville aquifer between the 660- and 525-ft partings, and excluding an anomalous permeable parting at 564-ft identified in various boreholes, ranged from 0.036 to 20 ft/d, with a geometric mean of 0.37 ft/d. Kh values obtained from analysis of four slug tests done in the 564-ft parting ranged from 0.036 to 21 ft/d with a mean value of 2.4 ft/d. These values indicate that with the exception of the 564- and 660-ft partings, which vary in permeability, this interval is only moderately permeable in the Belvidere area.

Kh values obtained from analysis of six slug tests of the 525-ft parting ranged from 0.13 to 180 ft/d with a geometric mean value of 17.3 ft/d. Typically, this feature is highly permeable in the Belvidere area.

Kh values obtained from analysis of seven slug tests done below the 525-ft parting ranged from 0.005 to 11 ft/d with a geometric mean of 0.21 ft/d. Typically, this part of the aquifer is moderately to poorly permeable in the Belvidere area.

Kh values obtained from analysis of the slug tests also were evaluated in relation to the stratigraphic units to which the wells or borehole-test intervals were open (fig. F10). The highest geometric mean and greatest range of Kh for these units is associated with the Dubuque/Wise Lake Formations of the Galena Group and the Grand Detour Formation of the Platteville Group (excluding the Quimbys Mill Formation, where too few tests were available for evaluation). This distribution results, at least in part, because of the high permeability of the weathered-bedrock surface and the 660-ft parting located in the Dubuque and Wise Lake Formations and the 525-ft parting located in the Grand Detour Formation (figs. 35, F1, F4, F6).

The location of permeable features identified from the slug tests frequently indicated good agreement with the location of permeable features identified with lithologic and geophysical logging, and water-level measurements (table 20). This agreement partly is related in that many of the intervals chosen for slug-testing were selected because flowmeter logging indicated the presence of permeable features. Areas of elevated permeability identified with multiple methods include the shallow subhorizontal bedding-plane parting at about 742 FANGVD29 in boreholes T5-T8, the high-angle fracture at about 699-709 FANGVD29 in boreholes T1 and T2, and the 525-ft and 660-ft parting in many boreholes (figs. 35, A3, F1, F2, F4-F6; table 20). However, areas of active flow identified in the vuggy intervals at 602-642 and 682-692 in boreholes T1-T8 and above 662 FANGVD29 in boreholes B124GP, B126GP, B127GP, B133GP, B134GP, and B136GP frequently had Kh values of less than 0.50 ft/d, whereas the 658-668 FANGVD29 interval in borehole B130GP had a Kh value of about 1.0 ft/d, but was not identified as being permeable with any other method. In borehole B128GP, slug tests indicated Kh values of 17 and 48 ft/d at about 564 and 595 FANGVD29 (depths about 190 and 220 ft), respectively, yet flowmeter logging indicated no flow at these altitudes. These occasional differences between slug testing and flow profiling appear to be caused by the distribution of variations in vertical hydraulic gradient and Kh within the individual boreholes. At boreholes T1 and T6, highly permeable features are present only near the top of the boreholes (figs. A3, F2). Under these conditions, water coming in through the fractures in the upper part of the boreholes only can move out through the less permeable features in the deeper part of the borehole, which can be identified with the flowmeter logging. At borehole B128GP (fig. F1), permeable features are distributed over the length of the borehole, with the largest differences in water level being between the top and bottom of the borehole. Under these conditions, most inflow is from the permeable features at the top of the borehole, most outflow is through the 525-ft parting near the bottom of the borehole, and less permeable features in the middle of the borehole (such as the parting at about 565 FANGVD29 with Kh of 17 ft/d) may not affect the water movement. Such permeable features may not be identified with flowmeter logging, but they can be identified with slug tests.

Differences in the location of permeable features identified with slug tests and some of the other study methods also may be the result of nearby pumping. During tests in the deeper part of the Galena-Platteville aquifer, water levels usually fluctuated and the data could not be analyzed. The effect was most evident in test intervals open to the permeable 660-ft and 525-ft partings. For example, analysis of slug testing done on the 660-ft parting at borehole B115BD yielded Kh values that varied by two orders of magnitude potentially because of pumping effects. Pumping affected the calculated of Kh in borehole B127GP, resulting in the lowest value reported for the 525-ft parting (0.13 ft/d). However, flowmeter logging indicated that the 525-ft parting was permeable at this borehole.

The vertical distribution of permeability within the Galena-Platteville aquifer identified from the slug tests indicated moderate agreement with the distribution identified with the continuous water-level measurements (table 20). Results from application of both methods indicated that the 525-ft parting was permeable. However, water-level measurements, core analysis, and single-hole GPR surveys indicated a decrease in aquifer permeability with depth, whereas slug tests did not indicate substantial changes in the Kh of the aquifer, which were not associated with bedding-plane partings and the weathered bedrock. These differences likely are related to the importance of the vertical secondary-permeability features on flow in the aquifer. These features were underrepresented by the small amount of aquifer stressed by slug testing in the vertical boreholes, but were well represented in the large volume of aquifer (thousands of cubic feet) stressed by the municipal-well pumping.

Specific-Capacity Tests

Spatial variability in transmissivity and Kh of the Galena-Platteville aquifer was computed from specific-capacity data recorded on the driller's logs of about 250 residential-supply wells open to the aquifer (table 17).

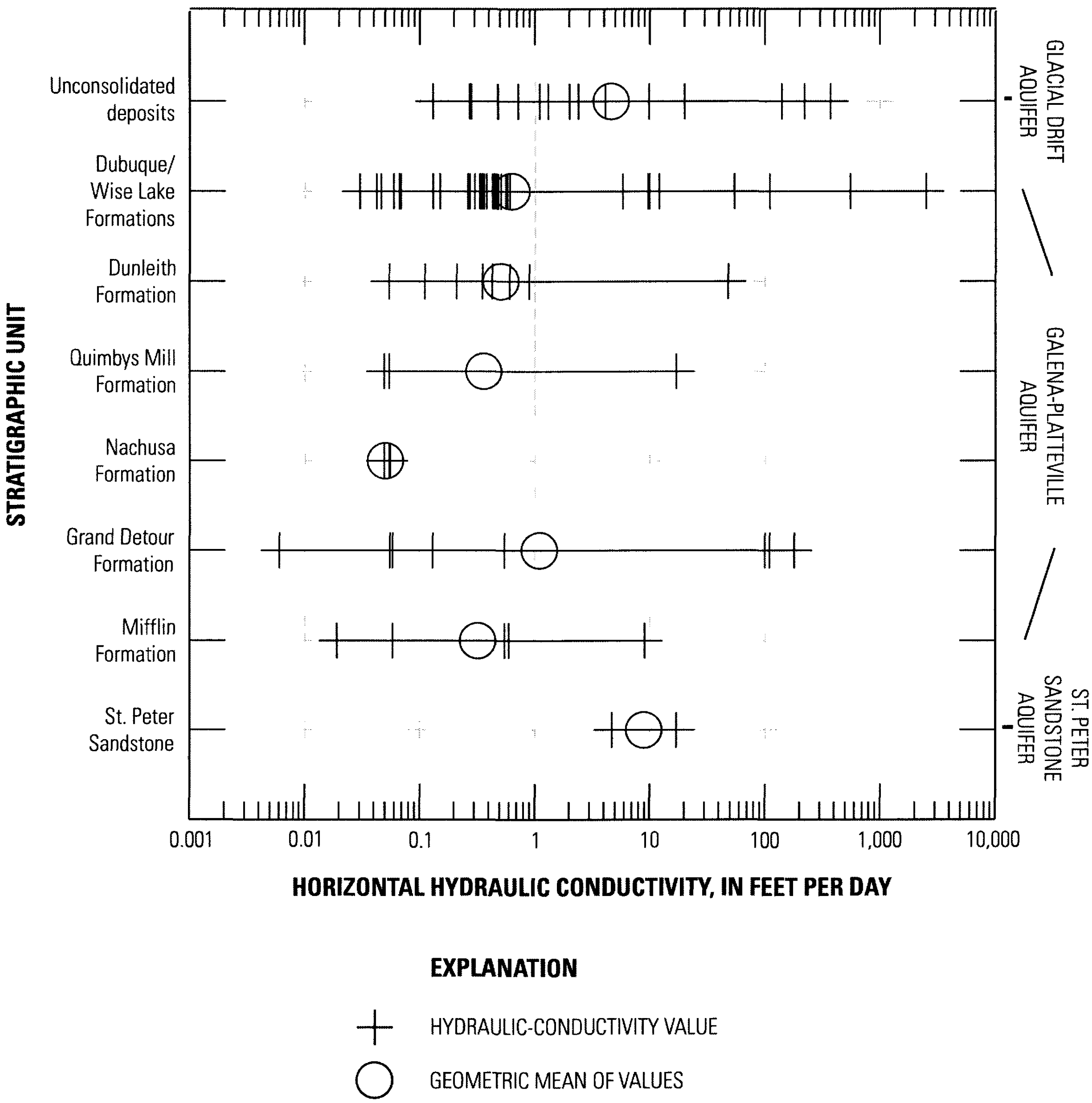


Figure F10. Distribution of horizontal hydraulic conductivity within units that compose the Glacial Drift, Galena-Platteville, and St. Peter aquifers underlying Belvidere, Ill.

The wells were distributed throughout the Belvidere area, but about 90 percent of the wells tested were from four rural subdivisions. About 75 percent of the wells were open only to the upper part of the aquifer. Specific-capacity data collected during development of boreholes B130GP, B133GP, B134GP, and B136GP near the PCHSS also were analyzed. These boreholes penetrated more than 75 percent of the aquifer.

Estimated transmissivity and Kh values indicated no clear variations with location or amount of aquifer penetrated. Transmissivity estimates from the residential-supply wells ranged from about 30 to 7,700 ft^2/d; with about 90 percent of the wells being less than 1,000 ft^2/d. Estimated Kh from these wells ranged from about 0.2 to 450 ft/d; in 98 percent of the wells, Kh was less than 50 ft/d. Transmissivity estimates from boreholes B130GP, B133GP, B134GP, and B136GP were 5,400 ft^2/d, 430 ft^2/d, 270 ft^2/d, and 1,100 ft^2/d, respectively. Kh estimates from these boreholes ranged from 1.3 to 29 ft/d.

Multiple-Well, Constant-Discharge Tests

A multiple-well, constant-discharge aquifer test was done in June 1991 by pumping 29 gal/min from borehole B127GP over a period of 1,020 minutes (Mills, 1993b). Borehole B127GP penetrated about 90 percent of the thickness of the Galena-Platteville aquifer during this test. Drawdown was measured in monitoring wells G115B, G125B, and G111D open to the upper 10-20 ft of the aquifer and monitoring wells G115BD, G125BD, and G126BD open to the aquifer above about 635 FANGVD29 (fig. F11). Interpretation of the aquifer-test data are complicated by changes in water levels because of pumping from wells BMW4 and BMW6, the proximity of the shallow wells to the overlying glacial drift aquifer, and a lack of observation wells (only three observation wells each in the middle and shallow parts of the aquifer).

Drawdown in wells G115B, G125B, and G111D ranged from 0.01 to 0.37 ft and the cone of depression was oriented approximately N. 45° W./S. 45° E. (fig. F11). Drawdown in wells G115BD, G125BD, and G126BD ranged from 0.76 to 4.29 ft, and was oriented approximately east-west. These orientations are based on only three data points in each part of the aquifer and should be considered as approximate. The drawdown orientation in both the shallow and deep parts of the aquifer is consistent with either the primary or secondary orientation of inclined fractures identified with the SAR survey in this area as well as the predominate fracture orientation identified with the single-hole GPR tomography in borehole B127GP. The difference in the orientation of drawdown indicates that there may be a change in the dominant orientation of the inclined fractures with depth in the aquifer, which is consistent with the SAR survey.

Transmissivity estimates ranged from about 150 to 300 ft^2/d for the deep (100-200 ft) part of the aquifer and from about 1,500 to 7,000 ft^2/d for the shallow (40-100 ft) part of the aquifer using the method of Boulton and Streltsova-Adams (1978). Kh estimates for these respective parts of the aquifer ranged from 0.6 to 1.0 ft/d and from about 5 to 30 ft/d. Specific yield based on data from well G125BD was about 0.2. Kh values estimated from the constant-discharge test for the deeper part of the aquifer at borehole B127GP were higher, but generally consistent with those obtained from slug tests done in seven test intervals isolated with a packer assembly in the deeper part of this borehole (average value of 0.22 ft/d). Slug tests were not performed in the upper part of this borehole, so comparisons between the shallower and deeper parts of the aquifer cannot be made.

A series of constant-discharge aquifer tests was done to test the hydraulic properties of the permeable intervals in the Galena-Platteville aquifer identified at boreholes T1-T8. Packers were used to isolate selected parts of boreholes T1, T2, T3, T5, T6, T7, and T8 in addition to monitoring well G115BD (table F6) so that the distribution of drawdown in the various parts of the aquifer could be measured. Borehole T1 was pumped to test the hydraulic properties of the upper and lower parts of the permeable vuggy interval identified with cross-borehole flowmeter logging at 618-638 FANGVD29 in boreholes T1-T8 and the inclined fracture identified at about 699-709 FANGVD29 in boreholes T1 and T2. Borehole T6 was pumped to test the hydraulic properties of the permeable subhorizontal bedding-plane parting identified at about 742 FANGVD29.

Analysis of the constant-discharge aquifer test done in the vuggy interval at 618-628 FANGVD29 indicated a transmissivity from about 8 to 22 ft^2/d and a Kh from 0.8 to 2.2 ft/d (table F5). Drawdown in the aquifer below 618 FANGVD29 typically was about 10 ft (table F6), indicating high vertical hydraulic connection between the vuggy interval and that part of the aquifer below 618 FANGVD29. Drawdown in the aquifer above 628 FANGVD29 was highest at borehole T3, which does not intercept permeable fractures, medium in boreholes T1 and T2, which are open to the permeable inclined fracture at about 699-709 FANGVD29, and lowest in boreholes T6-T8, which are open to the permeable subhorizontal bedding-plane parting at about 742 FANGVD29. The distribution of drawdown in these boreholes indicates vertical hydraulic connection between aquifer materials at 618-628 and above 628 FANGVD29, at least partly through inclined fractures.

Analysis of the constant-discharge aquifer test done in the vuggy interval at 628-638 FANGVD29 indicated a transmissivity from about 9 to 18 ft^2/d and a Kh from 0.9 to 1.8 ft/d (table F5). Drawdown in the aquifer below

628 FANGVD29 typically was about 10 ft, indicating high vertical hydraulic connection between the 628-638 interval and that part of the aquifer from about 567 to 624 FANGVD29 (table F6). Drawdown patterns in those parts of the aquifer open above 638 FANGVD29 were similar to those observed during the test of the interval at 618-628 FANGVD29.

Analysis of the constant-discharge aquifer test done in the inclined fracture at about 699-709 FANGVD29 in boreholes T1 and T2 indicated a transmissivity of 22 ft^2/d and a storage coefficient of 7.6 X 10^{-4} (table F5). A Kh was not calculated for this interval because of the uncertainty of the fracture aperture. About 1-1.5 ft of drawdown was detected in the aquifer below 699 FANGVD29 (table F6), indicating that this inclined fracture extends into the deeper part of the aquifer.

Analysis of the constant-discharge aquifer test done in the subhorizontal bedding-plane parting at about 742 FANGVD29 at borehole T6 indicated a transmissivity of more than 7,400 ft^2/d and a storage coefficient of 2.0 X 10^{-2} (table F5). A Kh was not calculated for this interval because of the uncertainty of the aperture of the bedding-plane parting. Little or no drawdown was measured in the aquifer below the bedding-plane parting. However, because drawdown in the subhorizontal bedding-plane parting was less than 0.30 ft, it is unclear if the absence of substantial drawdown in the deeper test intervals indicates minimal hydraulic interconnection between the bedding-plane parting and the aquifer below the parting, or that this part of the aquifer is permeable enough to respond easily to the small stress induced by pumping with minimal drawdown.

The hydraulic properties calculated from the constant-discharge aquifer tests in the T series of boreholes are similar to those calculated from the slug testing and analysis of flowmeter data collected during cross-hole pumping for the vuggy interval at 618-638 FANGVD29 (table F5). The

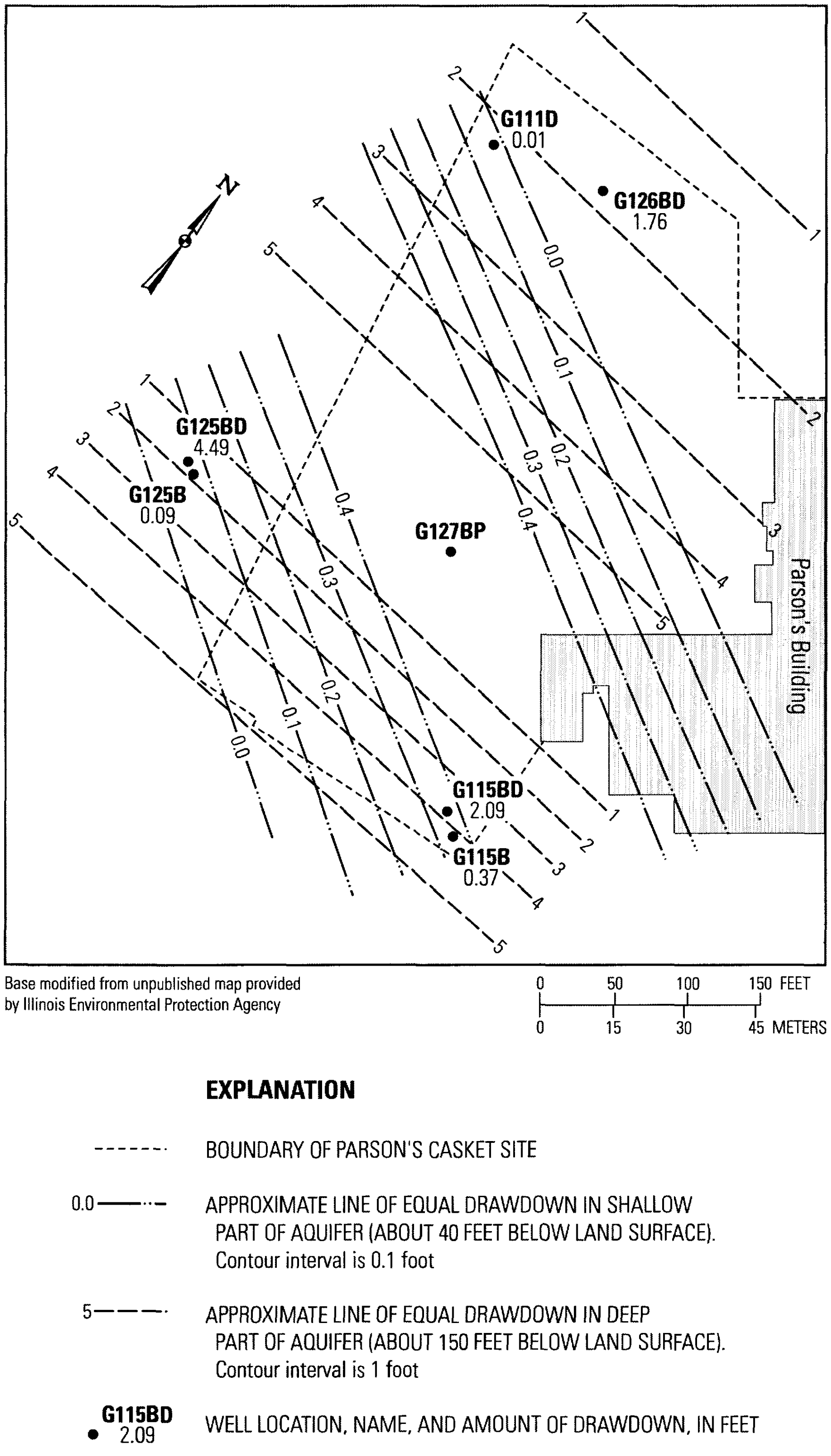


Figure F11. Differential drawdown in the upper and lower parts of the Galena-Platteville aquifer in response to a constant-discharge aquifer test, Belvidere, Ill., June 1991.

transmissivity calculated from the constant-discharge aquifer test in the T series of boreholes also is similar to that calculated from the flowmeter data collected during cross-hole pumping for the inclined fracture at 699-709 FANGVD29 at boreholes T1 and T2, but substantially is lower than the transmissivity value calculated with the slug testing. The hydraulic properties of the permeable intervals calculated from the constant-discharge aquifer tests in the T series of boreholes differ substantially from the hydraulic properties identified with the slug testing and flowmeter-data analysis for the subhorizontal bedding-plane parting at 742 FANGVD29 (table F5). This difference may partly result because of the volume of aquifer tested with the different methods. The inclined fracture appears to decrease in size and permeability with depth. Slug tests only stress the shallow, most permeable part of the fracture. The other methods involve pumping and also stress the deeper, less permeable parts of the fracture. The difference in the results of the test methods also may be because of the methods used in the

Table F6. Configuration of packers and distribution of drawdown during constant-discharge aquifer testing in boreholes T1-T8, Belvidere, Ill.

[>, greater than; na, not applicable]

			Packer configuration			Drawdown at end of test		
Pumped borehole	Altitude of pumped interval (feet above National Geodetic Vertical Datum of 1929)	Observation borehole	Altitude above packed interval (feet above National Geodetic Vertical Datum of 1929)	Altitude of packed interval (feet above National Geodetic Vertical Datum of 1929)	Altitude below packed interval (feet above National Geodetic Vertical Datum of 1929)	Above packed interval (feet)	In packed interval (feet)	Below packed interval (feet)
T1	616-626		630-732	616-626	567-612	0.57	63.51	11.62
		T2	630-734	616-626	567-612	.57	36.64	12.67
		T3	630-732	616-626	567-612	1.63	18.88	11.93
		T5	670-744	656-666	638-652	.06	.45	2.85
		T6	630-745	616-626	567-612	.05	11.87	8.85
		T7	630-744	616-626	567-612	.05	12.69	10.09
		T8	630-746	616-626	567-612	.06	16.68	12.24
T1	626-636		640-732	626-636	567-622	.32	>55.5	11.66
		T2	640-734	626-636	567-622	.32	39.45	12.78
		T3	640-732	626-636	567-622	1.12	18.35	12.24
		T5	670-744	656-666	638-652	.02	.48	9.93
		T6	640-745	626-636	567-622	.04	13.67	9.98
		T7	640-744	626-636	567-622	.04	13.88	10.82
		T8	640-746	626-636	567-622	.07	17.41	12.59
T1	696-732		na	696-732	567-692	9.25	na	1.54
		T2	696-734	682-696	567-678	9.15	2.84	1.43
		T3	696-732	682-692	567-678	.84	2.27	1.12
		T5	na	736-744	638-731	na	.80	.62
		T6	na	736-745	567-732	na	na	1.06
		T7	na	736-744	567-732	na	.07	1.03
		T8	na	736-746	567-732	na	.07	1.19
T6	736-745		na	736-745	567-692	na	.22	.04
		T1	na	696-732	567-692	na	.09	.01
		T2	696-734	682-696	567-732	.09	.19	.00
		T3	696-732	682-692	567-678	.09	.04	.00
		T5	na	736-744	638-731	na	.10	.02
		T7	na	736-744	567-732	na	.16	.03
		T8	na	736-746	567-732	na	.14	.00

data analysis. The bedding-plane parting at about 742 FANGVD29 terminates against permeable sand-and-gravel deposits between boreholes T5 and T3. It is likely that the sand-and-gravel deposits recharge the bedding-plane parting during the aquifer testing, lowering the amount of drawdown. However, data analysis involved techniques where a homogenous and isotropic aquifer of infinite extent was assumed. These assumptions likely resulted in an overestimation of the transmissivity of the bedding-plane parting.

A series of single-well, constant discharge aquifer tests was performed in 18 test intervals isolated by use of a packer assembly in boreholes B125GP, B126GP, and B127GP by monitoring drawdown during pre-sample purging. Kh estimates based on analyses using the method of Cooper and Jacob (1946) ranged from 0.035 to 37 ft/d. The highest Kh values typically were associated with tests done in the upper part of the aquifer, at the 660-ft parting, and at the 525-ft parting. These estimates of Kh typically were higher than those produced with slug testing and indicated no systematic correlation with the results of the slug testing. However, these tests were useful for identifying intervals of comparatively high and low permeability.

Tracer testing

A tracer test was conducted in conjunction with cross-hole GPR tomography at boreholes T1-T8 to determine flow pathways and hydraulic properties of the permeable vuggy interval between about 618 and 638 FANGVD29. The test consisted of pumping from the 628-638 FANGVD29 interval in borehole T6 while continuously injecting a 10,000 mg/L sodium-chloride tracer into this interval at borehole T2. GPR surveys were done between the T2-T8, T2-T7, and T3-T8 borehole pairs to monitor the tracer movement. Comparison of GPR tomograms performed before and at various times during the tracer test (fig. A11) indicates predominately horizontal tracer movement through the 628-638 FANGVD29 interval with a component of downward movement because of either tracer-density effects or in response to pumping in wells BMW4 and BMW6. Tracer movement through the inclined fracture at 699-709 FANGVD29 also is indicated by the tomography.

Although the tracer did not migrate the entire distance from the injection to the extraction borehole, the tomograph data allowed analysis of the rate of tracer movement that would not have been possible otherwise, including calculation of an effective porosity of 8.8 percent for the interval at 628-638 FANGVD29. This value is substantially lower than the mean porosity of 15 percent measured from a core sample collected at this altitude in well G115BD. The difference in the calculated porosity may be the result of differences in the scale of investigation (inches for the cores and tens of feet of the tracer test), and the differences between total and effective porosity.

Flow modeling

The USGS modular computer code MODFLOW (McDonald and Harbaugh, 1988) was used to simulate steady-state, ground-water flow in the 80-mi^2 Belvidere study area (Mills and others, 2002a) (fig. F12). The objective of numerical model simulation was, in part, to determine ground-water-flow direction and locations of discharge and pathways of contaminant movement. Principal locations of ground-water discharge within the study area include the Kishwaukee River, its tributaries, and local water-supply wells. Most discharge to wells is to the eight municipal wells in Belvidere (BMW2-BMW9); six of which are open, in part, to the Galena-Platteville aquifer (BMW2-BMW7).

The flow model consists of four layers that represent the glacial drift aquifer (layer 1), the Galena-Platteville aquifer (layer 2), the Glenwood semiconfining unit (layer 3), and the sandstone aquifers of the Cambrian-Ordovician aquifer system, including the St. Peter aquifer (layer 4). Four zones, representing hydrologically different parts of the glacial drift aquifer, were assigned to model layer 1. Uniform properties were assigned to the individual model layers (2-4) representing bedrock aquifers. Although the Galena-Platteville aquifer is known to be heterogeneous and anisotropic, data were not available for reliable zonation of hydraulic properties of the unit; the persistence of lateral or vertical trends in properties that have been identified is uncertain. Lateral flow boundaries in the glacial drift and bedrock aquifers were placed at distances where flow is expected to be unaffected by pumping from the Belvidere municipal wells. Water levels in the glacial drift aquifer (layer 1) and along the western boundary of the Cambrian-Ordovician aquifer system (layer 4) were specified on the basis of available data. Water levels along the eastern boundary of the Cambrian-Ordovician aquifer system (layer 4) were located along a regional ground-water divide (Visocky, 1993, 1997).

The model was calibrated to ground-water levels measured in July 1993. Ground-water discharge estimated from streamflows measured in the Kishwaukee River and adjusted to account for inflow from its tributaries and wastewater discharge, in September 2000, also was used for model calibration. Ground-water-withdrawal rates were applied for all wells reportedly producing more than 1 Mgal during 1993, including the seven operational municipal wells (BMW3-BMW9). About 80 percent of these supply wells are located in the city of Belvidere (fig. 30).

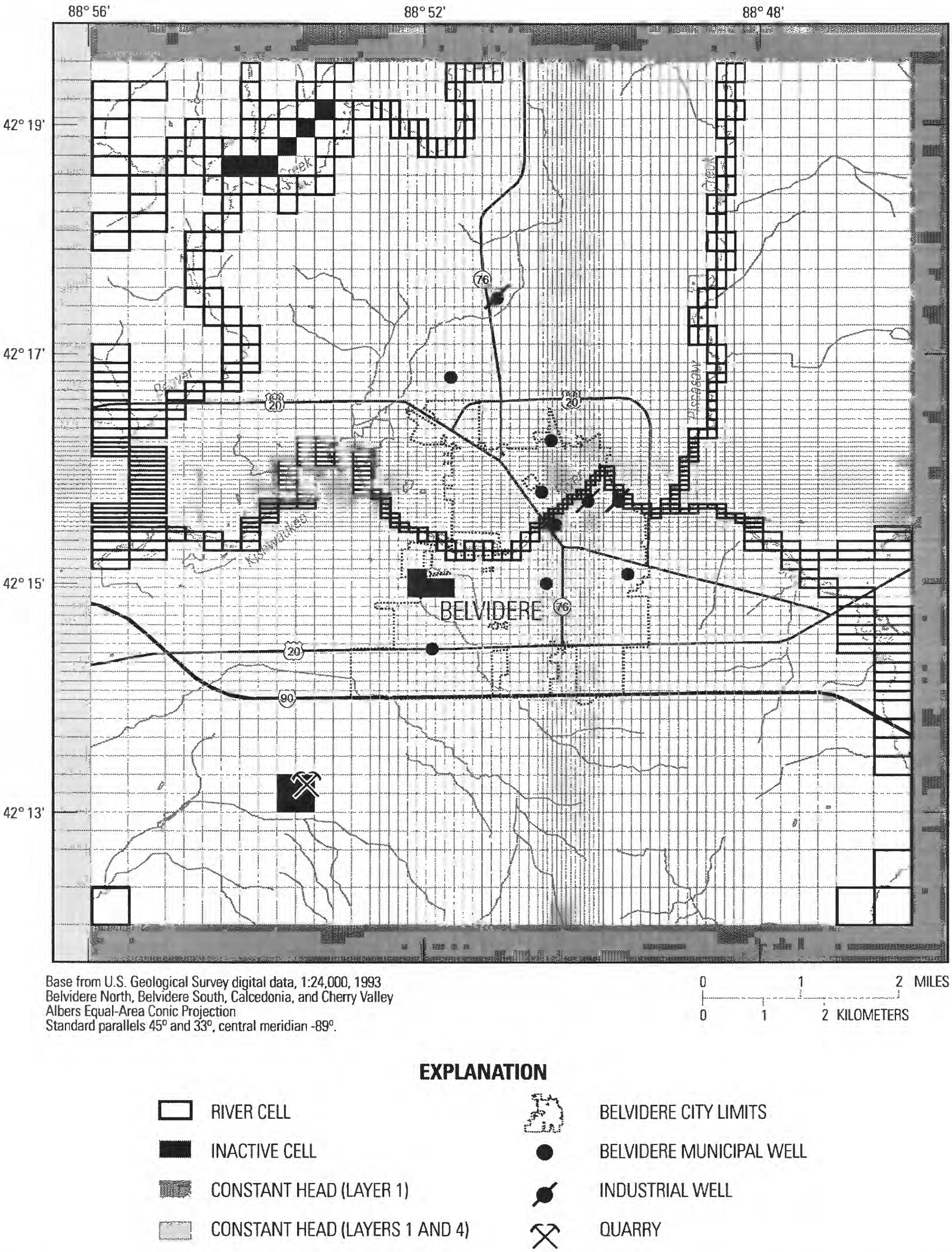


Figure F12. Model grid, boundary conditions, river cells, and wells used in the simulation of ground-water flow in the aquifers and confining unit underlying Belvidere, Ill.

A fundamental assumption made during MODFLOW simulation is that the hydrogeologic units represented by model layers are composed of continuous porous media. Although porosity that affects flow in the Galena-Platteville aquifer is represented predominantly by fractures and bedding-plane partings, these openings are connected; flow also occurs through vuggy intervals in the aquifer. Additionally, the smallest cell size, 250 ft by 250 ft, is substantially larger than the approximate 80 ft or less spacing between fractures (McGarry, 2000). Because of the cell size and the fracture spacing, the assumption of a continuous porous media is considered reasonable at the regional scale of flow simulation. Additionally, because of the higher permeability of the overlying and underlying aquifers, the model generally was insensitive to the hydraulic properties assigned to the Galena-Platteville aquifer.

Ground-water-flow paths simulated in a flow model can be delineated using particle tracking. By use of the USGS code MODPATH (Pollock, 1989) with output from MODFLOW, particle pathlines were computed in each model cell. Using the calibrated hydraulic conductivity and the computed three-dimensional hydraulic gradients, hypothetical water particles were tracked along the hydraulic gradient within the computed flow field (Mills and others, 2002b).

The particle-tracking scheme used in MODPATH is valid only for computing and interpolating advective velocities from intercellular flows. Accordingly, the particle pathlines are based on advective particle movement and travel times—no diffusion, dispersion, or chemical or microbiological retardation is incorporated into particle movement. The particle-tracking analysis was based on a model in which steady-state conditions are assumed and, thus, the analysis is insensitive to and does not represent short-term variations in natural (such as seasonal recharge) and anthropogenic (such as well withdrawals) stresses.

There is uncertainty in the simulated delineation of flow patterns and estimation of travel times by particle tracking. The calibrated model is a numerical representation of the ground-water-flow system; simulated water levels do not precisely match measured water levels, and actual ground-water-flow paths are more complex than the simulated flow paths. Numerical approximations, scale limitations, grid design, boundary conditions, and calibration data each can affect the accuracy of model simulation and, therefore, the particle-tracking analysis. Heterogeneity of the hydraulic properties of the aquifers underlying the study area, particularly hydraulic conductivity, is considered to have the greatest effect on the accuracy of this and other simulations of ground-water flow. Scale limitations of the numerical model also are considered to affect the simulation accuracy. Estimates of hydraulic conductivity can vary over as much as five orders of magnitude in the fractured dolomite of the Galena-Platteville aquifer. The initial model was designed to investigate regional ground-water flow. Local flow, such as flow to small streams and flow adjacent to sources and sinks, may not be represented accurately in the regional model. The model does not account accurately for the local effects of secondary porosity in the Galena-Platteville aquifer. Bedding-plane partings and inclined fractures are known to provide preferential pathways for water movement and seem to provide pathways for contaminant movement (Mills and others, 2002a).

For the model analysis, particles were forward tracked from the top and bottom center of all cells representing the glacial drift aquifer (layer 1) to determine where water discharges from the Galena-Platteville aquifer to the overlying glacial drift aquifer and from selected cells to determine flow paths from known or possible contaminant source areas to discharge locations. Because of the limitations associated with the scale of the regional model, including the inability to accurately define local hydrogeologic conditions, results of this analysis are considered most appropriate for general illustration of possible flow paths and discharge locations.

As part of the flow analysis, areas contributing recharge (ACR) to the Belvidere municipal wells and selected industrial wells also were delineated. ACR's to the wells open to the Cambrian-Ordovician aquifer system (model layers 2-4) were delineated by back-tracking particles from the full length of the interval of each well open to the Galena-Platteville aquifer (model layer 2) to the base of the glacial drift aquifer.

Given the hydrogeology and water quality in the vicinity of the supply wells, the approach used to delineate ACR's and ground-water travel times for the wells open, in part, to the Galena-Platteville aquifer is considered appropriate. In much of the area where the municipal wells are located, permeable deposits of sand and gravel (Kh up to 370 ft/d) that generally are less than 40 ft thick overlie the less permeable (Kh about 0.05 ft/d) Galena-Platteville aquifer (Mills and others, 2002a). These permeability contrasts contribute to rapid vertical movement of DNAPL's through the glacial drift aquifer and pooling on the surface of the dolomite aquifer; high concentrations of TCE (1,300 μg/L), indicative of nearby DNAPL's, have been detected within 5 ft of the top of the aquifer at the PCHSS (Mills, 1993b). DNAPL's, such as TCE and PCE detected in the aquifers underlying Belvidere, can move independently of the prevailing direction of ground-water flow in the aquifers because of the density contrast between the DNAPL's and ground water. As the DNAPL's dissolve in ground water, they can move from pool locations to area wells through a network of inclined fractures and subhorizontal bedding-plane partings, such as the network within the Galena-Platteville aquifer (Mills and others, 2002a). ACR's to wells for which such flow conditions are present cannot be simulated by conventional methods based solely on prevailing directions of ground-water flow.

In delineation of ACR's, errors in estimation of Kh result in substantial uncertainty in the representation of hydraulic gradients upgradient of a well (Varljen and Shafer, 1991) and, thus, errors in estimation of area-related ground-water travel times. Travel times also are affected by uncertainties associated with estimation of the aquifer porosity. Porosity has a linear effect on the travel time of a particle, but has no effect on the particle pathlines. An increase in the porosity decreases the area associated with each travel time. Porosities for the Belvidere model were estimated on the basis of literature values (Freeze and Cherry, 1979), laboratory measurements (Mills and others, 1998), and geophysical methods (Mills and others, 1998, appendix 6). Porosities of 20, 1, 1, and 25 percent were assigned to the glacial drift aquifer (model layer 1), the Galena-Platteville aquifer (model layer 2), the Glenwood confining unit (model layer 3), and the sandstone aquifers of the Cambrian-Ordovician aquifer system (model layer 4), respectively. With possible under-estimation of porosity of up to one order of magnitude, travel times in the Galena-Platteville similarly may be under-estimated.

As indicated by the general simulation of flow (Mills and others, 2002a), about 90 percent of recharge is to the aquifers overlying the Glenwood confining unit, with most of the flow discharging through the glacial drift aquifer to the Kishwaukee River and its tributaries. Simulated potentiometric levels and flow directions approximate the levels and directions determined by synoptic measurements in 1993. The root-mean-square error between simulated and measured water levels was about 10 ft, with the majority of the error associated with levels in the deep sandstone aquifer system (model layer 4). Most of the discharge from the Galena-Platteville to the glacial drift aquifer occurs in the southern part of the Troy Bedrock Valley (fig. F13). About 65 percent of the flow entering the valley through the Galena-Platteville aquifer discharges to the Kishwaukee River and about 35 percent flows westward out of the study area. Only about 10 percent of recharge from precipitation (about 0.95 in/yr) flows from overlying aquifers to the St. Peter and deeper sandstone aquifers, also presumably within the southern part of the Troy Bedrock Valley, where the Glenwood confining unit seems to be partly to completely absent. About 7 percent of outflow from the ground-water system is discharge to the municipal and industrial wells in the area, less than 2 percent of this outflow is from the Galena-Platteville aquifer.

The Kh of the Galena-Platteville aquifer estimated from flow simulation was about one order of magnitude less than the Kh estimated based from the geometric mean of all available aquifer tests (0.05 ft/d and 0.59 ft/d, respectively). The difference indicates that the hydraulic conductivity of the aquifer may be substantially less in parts of the study area other than the city of Belvidere (where all of the aquifer tests were done). This difference may be attributed to a reduction in matrix and (or) fracture permeability.

The following characteristics of steady-state, ground-water flow in the Belvidere area are indicated from the simulated pathlines from possible contaminant source areas (fig. F14):

- Ground water moves from the glacial drift aquifer into the Galena-Platteville and underlying sandstone aquifers, particularly where flow is affected by withdrawals from the Belvidere municipal wells.

- Ground water discharges to three municipal wells (BMW3, BMW4, and BMW6; fig. F14), in part, through the Galena-Platteville aquifer.

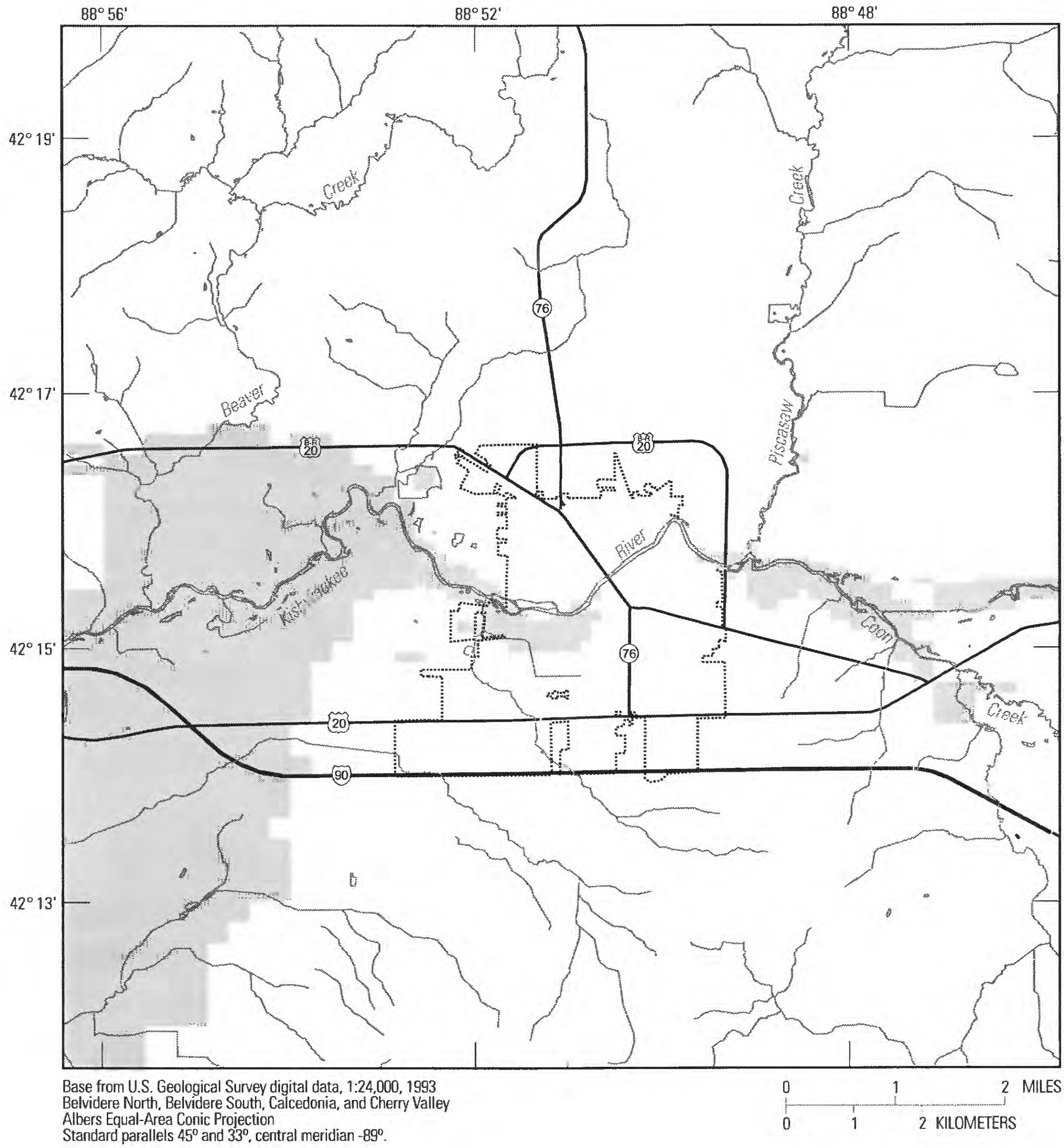
- Ground-water flow from one source area is northward beneath the Kishwaukee River in the Galena-Platteville and sandstone aquifers, with discharge to a municipal well (BMW4). Flow southward from the PCHSS and nearby source areas does not underflow the Kishwaukee River in the underlying bedrock aquifers. Apparently, flow into the bedrock aquifers near these source areas is affected more by pumping from nearby municipal wells (BMW4, BMW6) than by pumping from wells south of the river.

Ground-water flow that originates in the glacial drift aquifer may discharge to municipal well BMW8, a well open exclusively to the St. Peter and deeper sandstone aquifers underlying the Glenwood confining unit. On the basis of tritium data, near-well geology, and historical water-quality data, the St. Peter aquifer is considered to be confined and, thus, less vulnerable to contamination from overlying aquifers (Mills and others, 2002a, b). Flow simulation indicates that leakage through the confining unit represents only a fraction of total flow within the ground-water system simulated by the model. Thus, substantial contaminant transport to the St. Peter and deeper aquifers is considered unlikely.

During the 1993 model-calibration period, well BMW2 was not operating and well BMW3 was used sparingly. Total withdrawals for the municipal system were greater after 1996, when these wells were returned to full operation (J.A. Grimes, Belvidere Water Department, written commun., 2001).

The following characteristics of steady-state, ground-water flow in the Belvidere area, under ground-water-withdrawal rates of 2000 are indicated from the simulated pathlines from possible contaminant source areas:

- Underflow beneath the Kishwaukee River is restricted to the sandstone aquifers that underlie



EXPLANATION

DOWNWARD DISCHARGE FROM THE GLACIAL DRIFT AQUIFER (MODEL LAYER 1) TO THE GALENA-PLATTEVILLE AQUIFER (MODEL LAYER 2)

UPWARD DISCHARGE FROM THE GALENA-PLATTEVILLE AQUIFER (MODEL LAYER 2) TO THE GLACIAL DRIFT AQUIFER (MODEL LAYER 1)

BELVIDERE CITY LIMITS

Figure F13. Simulated distribution of leakage from the Galena-Platteville to the glacial drift aquifer in the vicinity of Belvidere, Ill., 1993.

the Galena-Platteville aquifer.

- Some of the flow that discharged into the Kishwaukee River from source areas east and west of Belvidere in 1993 is diverted through the Galena-Platteville aquifer into the underlying sandstone aquifers. This flow discharges to municipal wells located almost 2 mi from the two contaminant-source areas.

Ground-water-flow patterns, as simulated by particle tracking, generally are substantiated by available water-quality data. Contaminant plumes have been mapped from many of the identified source areas, including the Parson's, MIG/DeWane, and Belvidere Landfill No. 1 Superfund sites (fig. 30). VOC's, particularly TCE and PCE, have been detected consistently in samples from wells BMW2 and BMW3, and intermittently in samples from wells BMW4 and BMW6 (Mills and others 1999, 2002a, b; Mills and Kay, 2003). However, flow paths

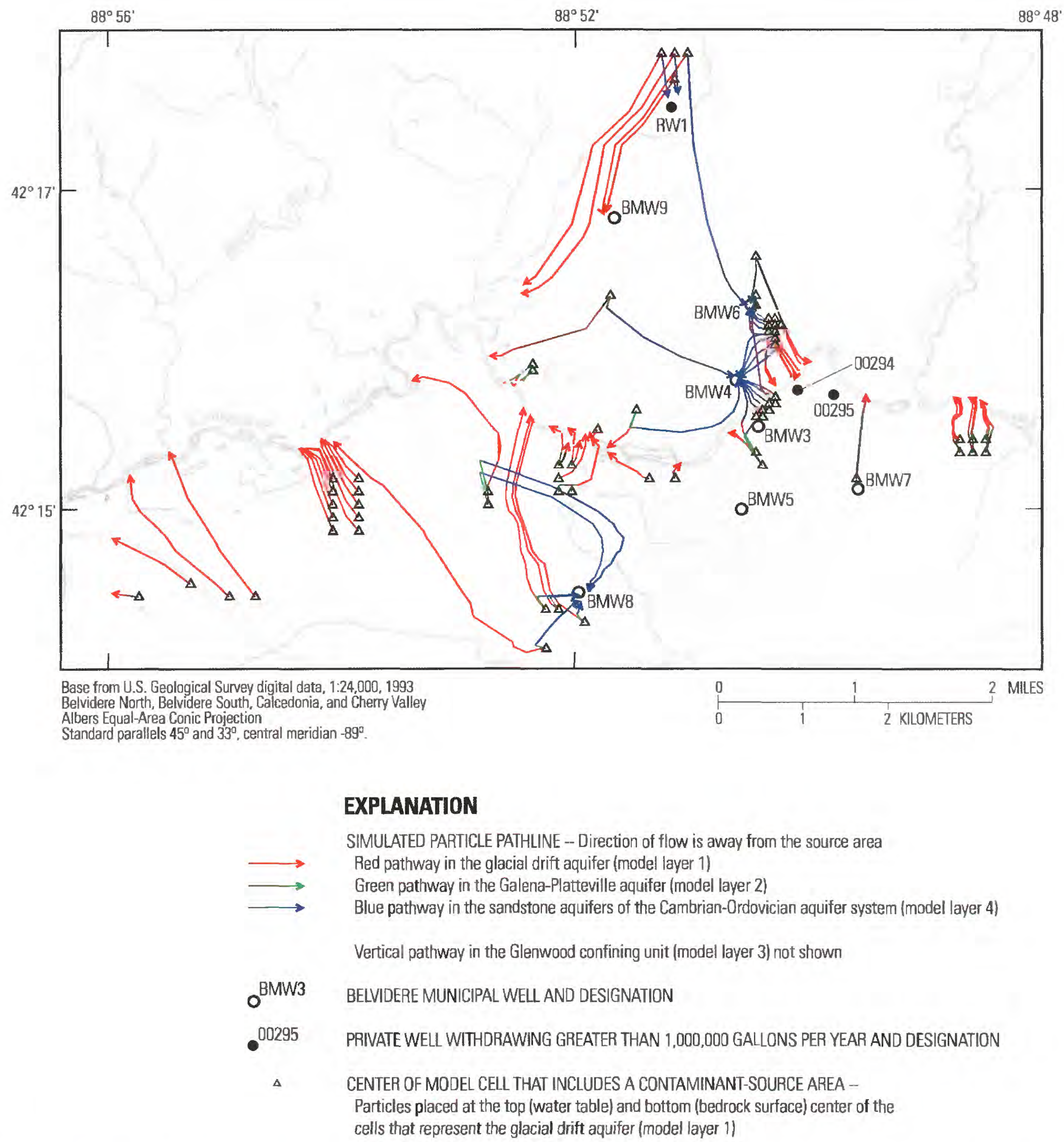


Figure F14. Simulated particle pathlines from possible contaminant source areas to discharge locations in the vicinity of Belvidere, Ill., 1993.

from some source areas may not be well delineated with the particle-tracking analysis because of insufficient representation of preferential flow paths. For example, the simulated pathlines for ground-water-withdrawal rates in 2000 indicate that ground-water flow in bedrock aquifers beneath the Kishwaukee River is restricted to the St. Peter and deeper sandstone aquifers. Sampling of isolated bedding-plane partings in the Galena-Platteville aquifer at borehole B137GP (fig. 30) in 2002 indicated VOC's that seem to be moving beneath the river from the PCHSS in the 525-ft parting and, possibly, other partings.

Areas contributing recharge to Belvidere municipal wells BMW3-BMW7 and industrial wells open to the Galena-Platteville aquifer are indicated in figure F15; areas indicated are not limited by travel time. The areas were simulated using the 1993 ground-water-withdrawal rates used for model calibration.

Ground water withdrawn from the Galena-Platteville aquifer is a mixture of waters with a range of residence times in the aquifer (fig. F16). Residence time in the aquifer is a surrogate for contaminant travel time because the simulation represents dissolved DNAPL's introduced to ground water near the top of the aquifer. The residence time for water that enters near the top of the aquifer is less than a year; the longest residence times are for water that enters a well near the base of the aquifer. For example, on the basis of an effective porosity of 1 percent, simulated residence times for water that is withdrawn from the Galena-Platteville aquifer by municipal well BMW3 range from about 0 to about 85 years with an average residence time of about 40 years.

Simulated residence times increase as porosity increases. Residence times for 50 percent of the water withdrawn from the Galena-Platteville aquifer, using porosity estimates of 1 and 20 percent, are contrasted in figure F16b. This porosity contrast is important, because of the uncertainty associated with estimating the effective porosity of the aquifer. Using the conservative estimate of 1 percent porosity, average residence times range from about 2 to 70 years. The shortest residence time is associated with a well that is open to only 22.5 ft of the aquifer and is located at the edge of the Troy Bedrock Valley, where the aquifer is only about 40 ft thick. The longest residence time is associated with a well with one of the lowest withdrawals rates included in the simulation and one of the longest open intervals in the Galena-Platteville aquifer (257 ft).

If the movement of ground water (and possibly contaminants) from near land surface to the top of the Galena-Platteville aquifer is rapid then the simulation-based estimates of residence times of water within the Galena-Platteville aquifer (model layer 2) can be compared reasonably to water-quality-based estimates of travel times of water from near land surface to various depths within the aquifer. Detection of methyl tertiary-butyl ether (MTBE) in water samples from municipal well BMW4 (Richard Cobb, Illinois Environmental Protection Agency, written commun., 2001), open to the deeper half of the Galena-Platteville aquifer, indicates that in this part of the study area, travel times between near land surface and the mid-part of the Galena-Platteville aquifer may be less than about 16 years (MTBE was first used as a gasoline additive in the United States in 1979). Tritium levels in samples from area wells open to the Galena-Platteville aquifer indicate that water withdrawn from almost all parts of the aquifer is less than 50 years old. These ages compare favorably with the residence times simulated for 50 percent of water pumped from the Galena-Platteville aquifer by the municipal and private wells, based on a porosity estimate of 1 percent (fig. F16B).

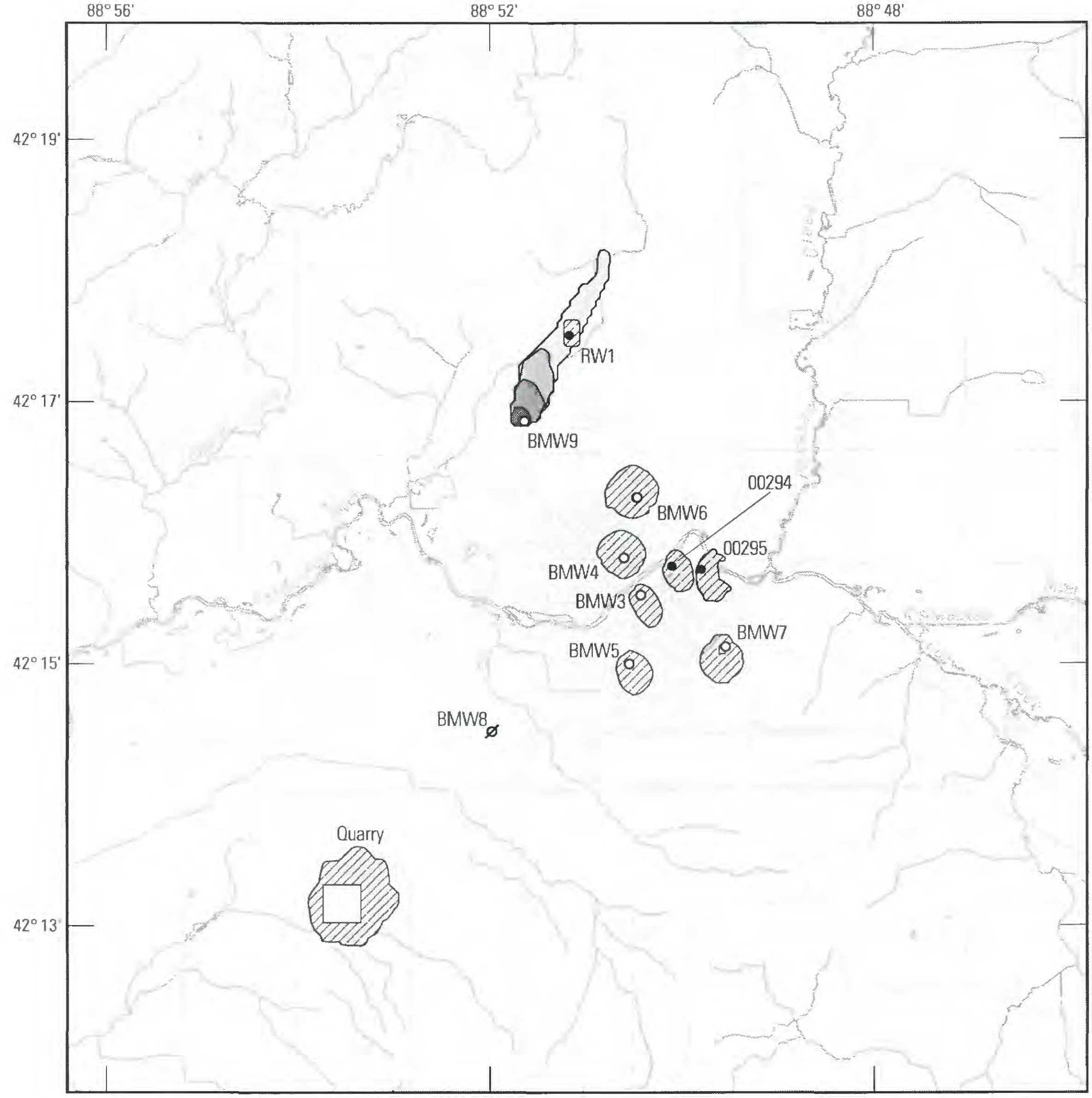
The effects of hydraulic-property heterogeneity and scale limitations on the accuracy of the model simulation of ground-water flow underlying the Belvidere area are mitigated to a large extent in that most of the hydraulic conductivity and porosity data were collected in the same part of the study area (in Belvidere) where water-level data were concentrated for model calibration, model-cell sizes were smallest, and particle-tracking analysis was focused. Although the uncertainties and limitations associated with this and other numerical models should not be ignored, such models provide unique and important understanding of ground-water-flow systems.

Locations of contaminants and other water-quality indicators

Water-quality data were collected from residential-supply wells, industrial- and municipal-supply wells, monitoring wells, and from test intervals in boreholes isolated with a packer assembly at various times from a variety of locations in the Belvidere area. Samples were analyzed for a variety of constituents, including VOC's, tritium, field parameters, and metals.

Synoptic and Periodic Sampling for VOCs in Water-Supply Wells

The concentration and distribution of VOC's in ground water beneath the Belvidere area was determined from samples collected from monitoring and water-supply wells, including the eight municipal wells in Belvidere (table 17) during a synoptic assessment of water quality performed during July 1993. Samples were collected from 60 wells open to the glacial drift aquifer, 30 wells (80 percent of available wells) open to the Galena-Platteville aquifer, and 4 wells open to the St. Peter aquifer (Mills and others, 1999). Samples also were collected from 15 wells open, in part, to the Galena-



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°.

EXPLANATION

AREA CONTRIBUTING RECHARGE TO OPEN INTERVAL OF WELL IN GLACIAL DRIFT AQUIFER --
- 0-1 year
- Greater than 1-5 years
- Greater than 5-10 years
- Greater than 10-25 years

AREA CONTRIBUTING RECHARGE TO OPEN INTERVAL OF WELL IN GALENA-PLATTEVILLE AQUIFER FROM BASE OF GLACIAL DRIFT AQUIFER -- Maximum estimated travel times range from 2 to 67 years

BMW3 BELVIDERE MUNICIPAL WELL AND DESIGNATION

00295 PRIVATE WATER-SUPPLY WELL WITHDRAWING GREATER THAN 1,000,000 GALLONS PER YEAR AND DESIGNATION

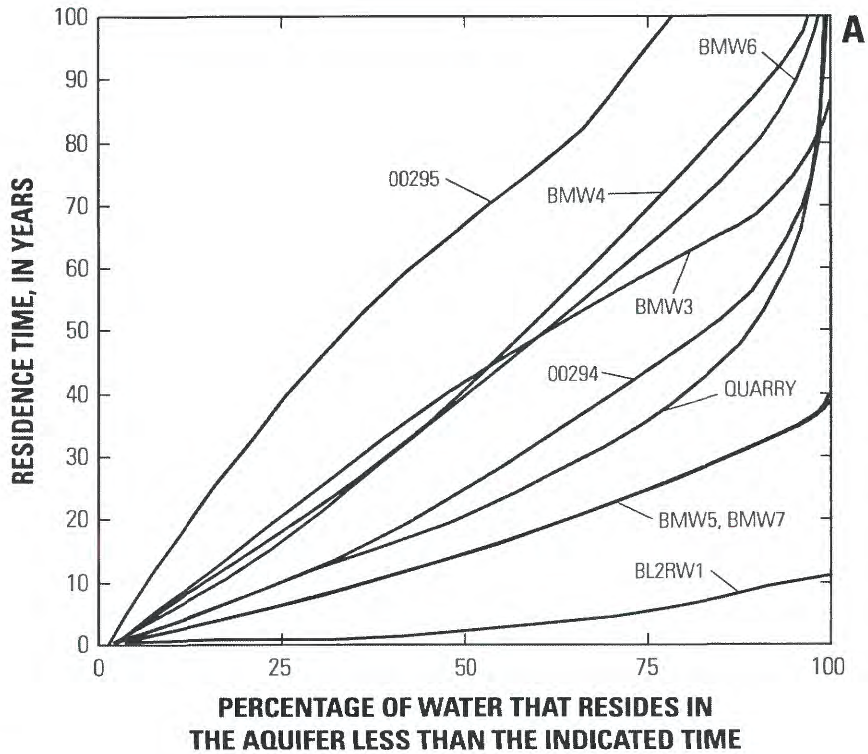
BMW8 BELVIDERE MUNICIPAL WELL OPEN TO CONFINED SANDSTONE AQUIFERS OF THE CAMBRIAN-ORDOVICIAN AQUIFER SYSTEM AND DESIGNATION

Figure F15. Simulated travel-time-related areas contributing recharge to municipal and private wells withdrawing greater than 1,000,000 gallons per year in the vicinity of Belvidere, Ill., 1993.

Platteville aquifer, including 6 of the municipal-supply wells. During 1994-2002, samples were collected from about 25 wells open to the Galena-Platteville aquifer and 10 wells open to the adjacent aquifers; these data provided information on temporal trends in water quality in the Belvidere area (Mills and others, 1998, 2002a, b; Mills and Kay, 2003).

Sampling results indicate that VOC's are present in all aquifers underlying Belvidere, including the Galena-Platteville aquifer. Fine-grained sediments in the glacial drift seem to restrict distribution of metals and other inorganic contaminants to the immediate vicinity of the source areas. TCE and PCE are the principal VOC's detected at concentrations above regulatory levels (5 µg/L for these compounds), with the largest number of detections and highest concentrations in the glacial drift aquifer. Generally, VOC concentrations in the Galena-Platteville aquifer seem to exceed regulatory levels only at locations within about 0.25 mi of contaminant source areas, including the PCHSS. Across most of the study area, the Glenwood confining unit restricts downward movement of VOC's into the underlying St. Peter aquifer. In the vicinity of the Belvidere municipal-supply wells, downward movement also seems restricted by lateral movement of flow toward the municipal wells through permeable intervals (fractures, partings, and vugs) in the Galena-Platteville aquifer. Fractures and (or) unused wells that may penetrate the confining unit seem to provide local pathways to the sandstone aquifers. VOC concentrations in most wells varied little over the 9-year study period indicating a near steady-state, ground-water-flow system. However, near wells BMW2 and BMW3 (fig. 30), VOC concentrations in the Cambrian-Ordovician aquifer system, which includes the Galena-Platteville aquifer, and the overlying glacial drift aquifer, seem to be fluctuating in response to changes in the use of these municipal wells, which were not operating during about 1992-96.

The distribution of VOCs in the Galena-Platteville aquifer in the vicinity of the PCHSS indicates that the bulk of the VOC plume is migrating from the site, through the area of borehole B134GP, and toward the Kishwaukee River. Although this interpretation is complicated by the potential presence of source areas other than the PCHSS, the presence of VOCs in municipal wells BMW4 and BMW6 (Mills and others, 1999; 2002) as well as boreholes B124GP, B130GP, B133GP, B136GP, and B137GP, indicates flow components in the aquifer to the north, east, and west, and beneath the river to the south. The bedding-plane parting at about 525 FANGVD29 appears to be a primary conduit for flow in the aquifer. This interpretation is consistent with the analysis of the



B

Well	Porosity, in percent: 1	Porosity, in percent: 20
	Residence time of 50 percent of the water, in years	
RW1	2	50
BMW6	40	800
BMW4	40	800
00294	20	500
00295	70	1,000
BMW3	40	800
BMW7	10	300
BMW5	10	300
QUARRY	20	400

Figure F16. Simulated residence time of water in the Galena-Platteville aquifer (model layer 2) withdrawn by selected wells in the vicinity of Belvidere, Ill., (A) distribution of residence times using a porosity of 1 percent and (B) residence times of 50 percent of the water using porosities of 1 and 20 percent.

continuous water-level measurements from the deeper parts of the aquifer, but was not apparent readily from the single water-level measurements.

Tritium Sampling

Tritium samples were collected from six wells open exclusively to the Galena-Platteville aquifer and eight wells open exclusively to the adjacent aquifers (Mills and others, 2002a, b). Tritium levels above 1 TU in all samples indicate water throughout the Galena-Platteville aquifer was derived from recharge that occurred within the past 50 years (fig. F17). The aquifer is considered unconfined (Illinois Environmental Protection Agency, 2003; Szabo and others, 1996), with at least moderate vertical hydraulic connection. Tritium concentrations indicated no clear trends with depth, reducing the utility of this method for identifying flow rates or providing a narrower range of ground-water ages within the aquifer.

Sampling from Test Intervals Isolated with a Packer Assembly

The distribution and concentration of VOC's in ground water beneath the Belvidere area also was determined by sampling specific depth intervals at 14 monitoring wells and 8 boreholes at test intervals isolated with a packer assembly; sample locations were within the limits of the city of Belvidere, primarily in the vicinity of the PCHSS (Mills and others, 1998, 2002a, b; Mills and Kay, 2003). Vertical profiling was used to identify pathways for preferential flow through the aquifer.

VOC's are present throughout the aquifer, indicating ground-water flow and contaminant migration through a hydraulically connected network of inclined fractures, bedding-plane partings, and vugs. The generally widespread distribution of VOC's within the aquifer precludes identification of specific flow pathways in most of the aquifer. However, VOC's were detected only in the test interval open to the 525-ft parting in borehole B137GP, indicating that this parting is a flow pathway.

Sampling of specific depth intervals in wells and boreholes provided useful information on vertical directions of flow and distribution of contaminants in the Galena-Platteville aquifer, particularly in an area affected by pumping from municipal wells. Movement of water was indicated to be downward, with VOC's distributed through most of the 300-ft thickness of the aquifer beneath the PCHSS. Concentrations of VOC's in the test intervals isolated with a packer assembly displayed no clear and direct correlation with aquifer permeability (fig. F18). However, VOC concentrations typically tended to be highest in the upper 10-20 ft of the aquifer, decrease in the intermediate intervals, and increase in the deepest intervals. The higher concentrations in the upper part of the aquifer appear to be related to the proximity of the contaminant source area(s) near the land surface.

The effects of vertical flow within the borehole on sampling results complicate analysis of water-quality data from test intervals isolated with a packer assembly. Common practices of purging the water from packer-test intervals using borehole-volume and field-characteristic stabilization criteria (Mills and others, 1998) may not adequately remove the artificially introduced water and, thus, may not provide representative samples from the aquifer. This possibility is supported by results of a field test conducted at borehole T5, in which water samples were collected for VOC analysis from four packer-isolated permeable intervals during drilling, immediately following drilling, and about 1 month after drilling.

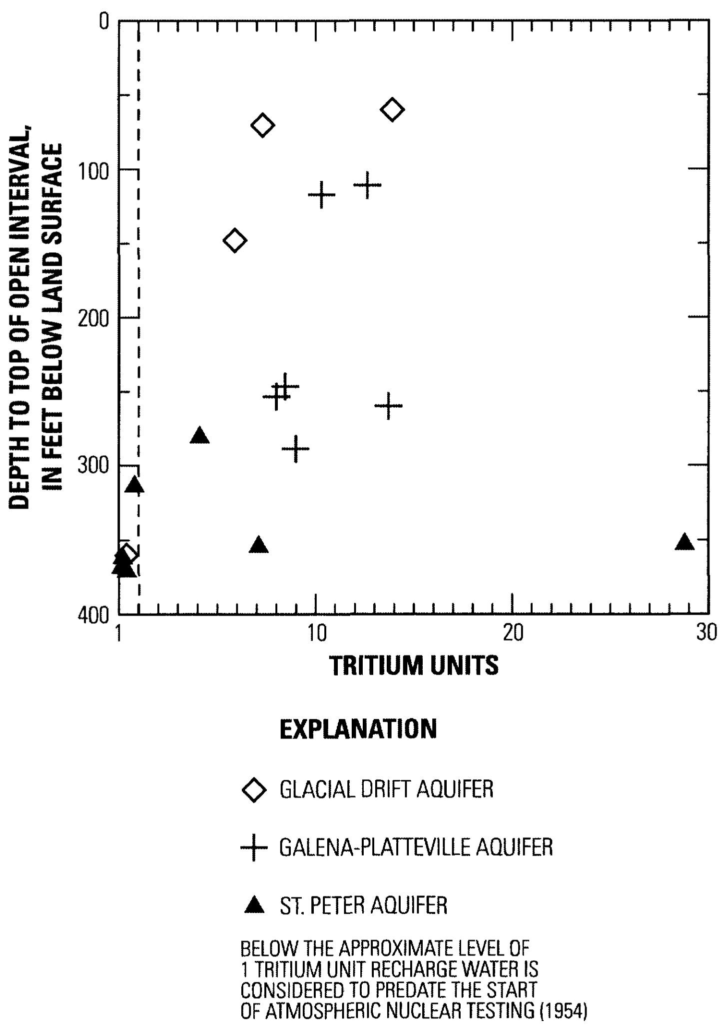


Figure F17. Tritium levels in aquifers underlying Belvidere, Ill., 1999-2000.

VOC concentrations in the samples near the bottom of the borehole increased by about one order of magnitude in 36 hours, indicating that the most representative packer-test results are obtained as soon as possible after drilling and adequate borehole development.

Analysis of the concentrations of naturally occurring water-quality constituents in the Galena-Platteville aquifer provided limited additional insight into the hydrogeologic characteristics of the aquifer. Notable exceptions were the analyses of arsenic, chromium, cobalt, and fluoride concentrations with depth in borehole B127GP (Mills, 1993b). Arsenic, chromium, and cobalt were present at detectable concentrations only in the test intervals open to the permeable subhorizontal bedding-plane partings at about 485 and 525 FANGVD29. Also, concentrations of fluoride that generally were less than 0.3 mg/L increased to 1.8 mg/L in the test interval that included the 525-ft parting. These patterns indicate that water quality in these intervals differs from that in the rest of the aquifer, either because of proximity to a naturally occurring source of these constituents, or because of preferential flow from a surficial source of these constituents into these bedding-plane partings.

Near-Continuous Vertical Profiling of Field Parameters

Field parameters were monitored in well BMW2 by in-situ, near-continuous vertical profiling with a multiparameter, water-quality monitor (Mills and others, 1998) (fig. F19). In well BMW2, values of dissolved oxygen (DO), oxidation-reduction potential (ORP), pH,

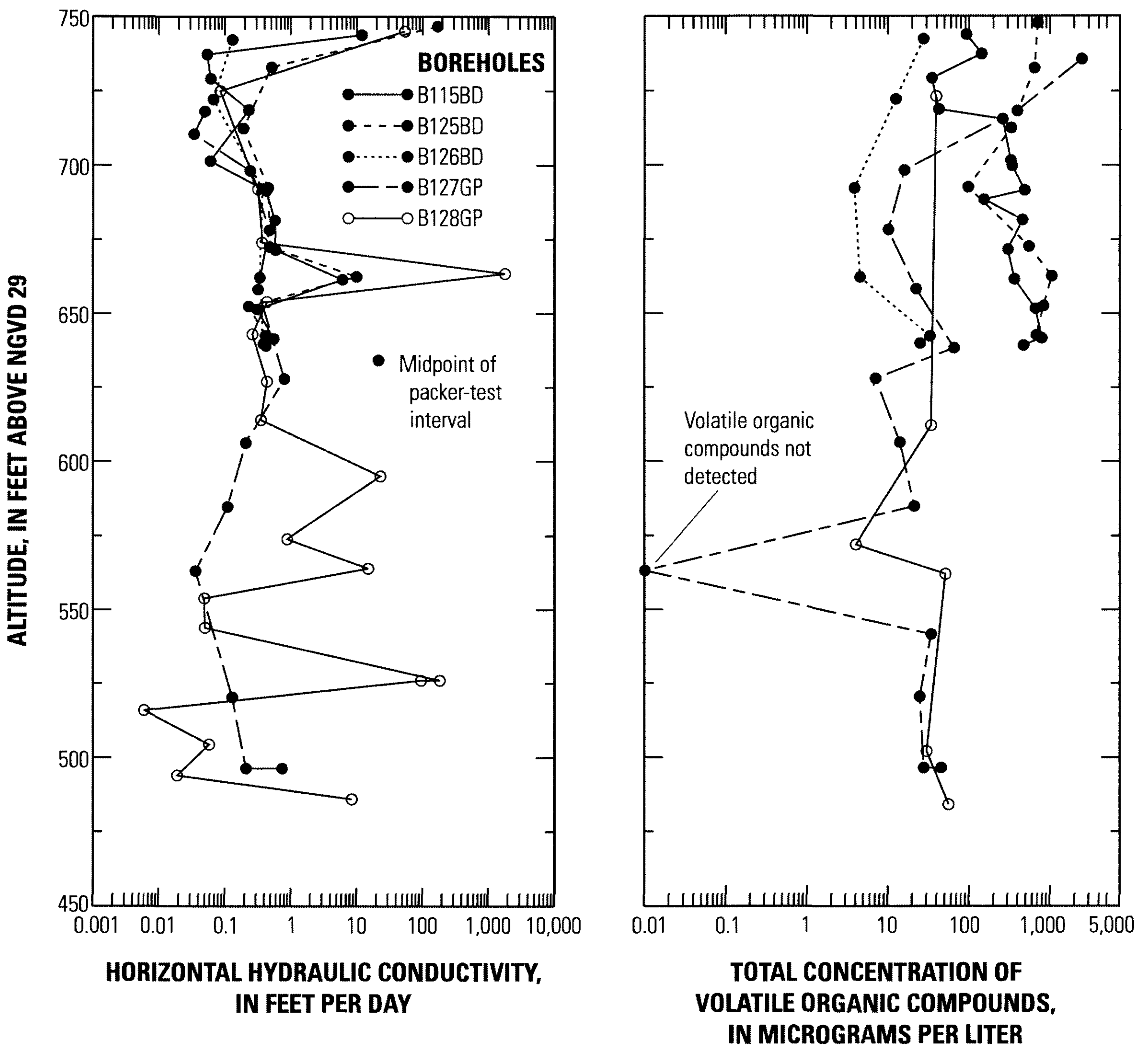


Figure F18. Vertical distribution of horizontal hydraulic conductivity and total concentration of volatile organic compounds at select boreholes open to the Galena-Platteville aquifer underlying Belvidere, Ill.

specific conductance, and temperature generally were more variable (either increasing or decreasing) above 675 FANGVD29 than below. The vertical trends in concentrations of DO and ORP generally mirrored each other. With the exception of temperature, all other parameters fluctuated (increased or decreased) between the altitudes of about 680 and 635 FANGVD29. The fluctuations may be indicative of inflow of water from the 660-parting and the inclined fracture identified at about 625 FANGVD29 in the caliper and acoustic-televiewer logs. In-situ profiling of water quality was not done at depths below 200 ft because of instrument limitations. The observed trends seem to represent (1) flow-induced mixing of waters of the glacial drift aquifer and the shallower part of Galena-Platteville aquifer, (2) atmospheric effects on water characteristics near (within about 60 ft) the water surface, and (or) (3) mechanical mixing of water in the well with movement of the profiling monitor.

Profiles of DO, ORP, pH, specific conductance, and temperature by use of the multi-parameter water-quality monitor in borehole B127GP (fig. F19) generally were more variable (either increasing or decreasing) above than below 682 FANGVD29. These data indicate mixing of different waters above 682 FANGVD29, and the presence of more variable flow above 682 FANGVD29 than below this altitude. An increase in ORP and decreases in temperature and pH at and below about 524 FANGVD29 indicate possible inflow of water from the bedding-plane parting at this altitude.

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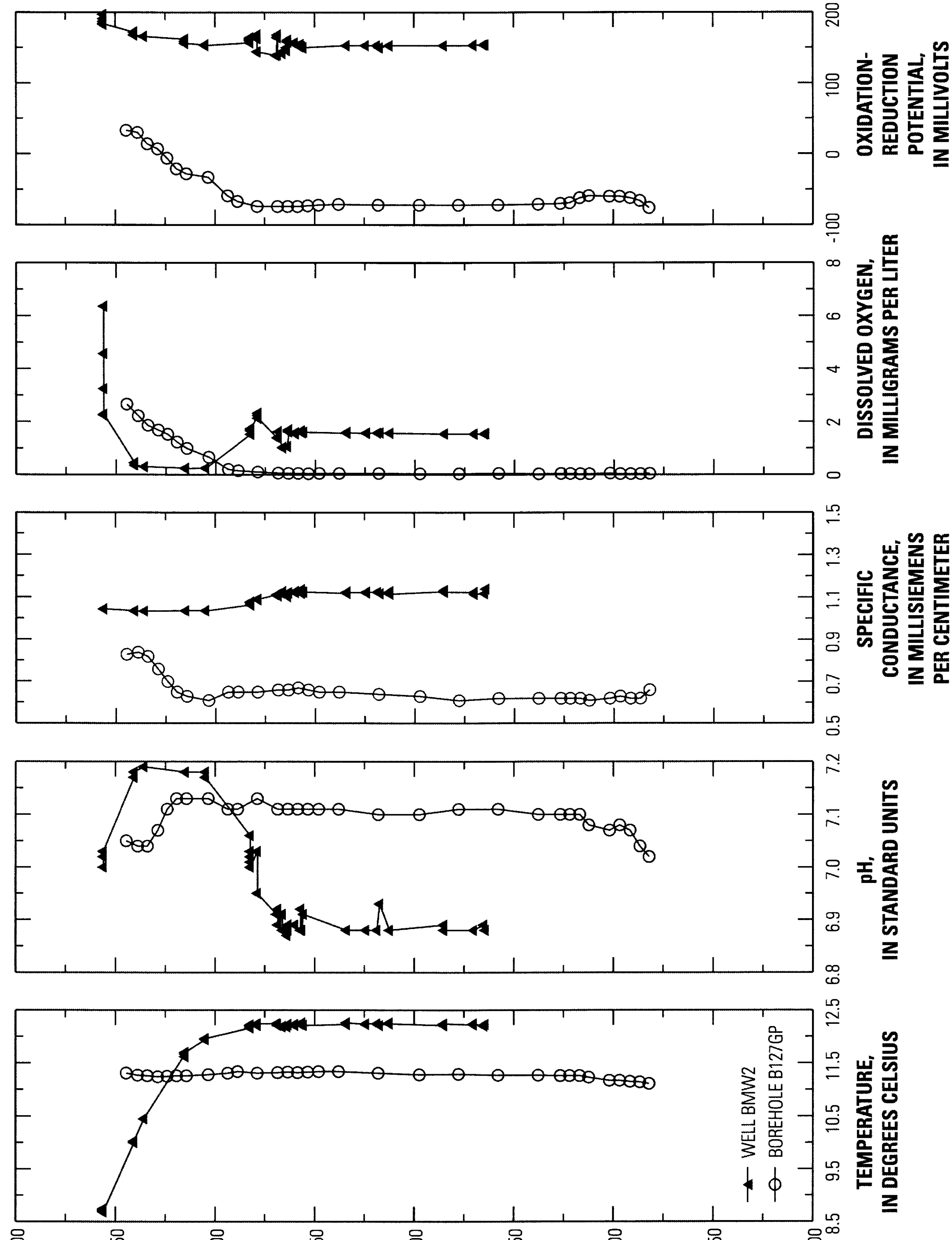

Figure F19. Vertical profile of field parameters in municipal well BMW2 (March 24, 1993) and borehole G127GP (December 5, 1991), Belvidere, Ill.

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Appendix G—Waupun Site Data

The hydrogeologic characterization of the Waupun site is based on data collected and interpreted by the USGS and USEPA. A total of 14 investigative methods were used at borehole FL-800, FL-801, and FL-802 (fig. 37) to develop the hydrogeologic framework for the Waupun site (table 1). Most of these methods contributed to the characterization.

Previous investigations

A comprehensive geologic and hydrologic study was performed in Fon du Lac County (Newport, 1962) in which the thickness, character, and areal extent of the various aquifers and confining units were determined. The Ordovician Sinnipee Group dolomites form the subcrop in the county, west of the Niagaran Escarpment, including the area beneath the Waupun site (fig. 36). In the eastern part of the county the Sinnipee Group is overlain by the younger rocks (Newport, 1962). Unconsolidated deposits overlie the Sinnipee Group wherever the Sinnipee is the subcrop. Where it constitutes the subcrop, the Sinnipee Group aquifer is unconfined and recharged primarily by the direct downward percolation of precipitation through unconsolidated deposits to the water table. As a result, the Sinnipee Group aquifer likely has been exposed to greater dissolution and infiltration at the Waupun site than in areas where overlying bedrock units are present. The general direction of ground-water flow in this area is to the southeast.

Core analysis

Bedrock core was cut in borehole FL-800 from 19.5 ft below ground surface (3-5 ft into competent bedrock) to a depth of 206 ft. Recovered bedrock core was described in detail (Mike Sargent, Illinois State Geological Survey, written commun., 1998)(table 21). The Glenwood Sandstone of the Ancell Group (fig. 11), the deepest unit encountered by the core, is a medium-grained, gray to brown sandstone. The Sinnipee Group at the site is about 185 ft thick and consists of light-gray to medium-bluish-gray dolomite. The unconsolidated deposits largely are of glacial origin. These deposits are about 16 ft thick, and consist of stratified till, clay, and sand and gravel.

The Sinnipee Group contains the Platteville Formation (Pecatonica, McGregor, and Quimbys Mill members), the Decorah Formation (Spechts Ferry Shale), and the Galena Dolomite (Dunleith and Wise Lake members) (table 21). The Platteville Formation is 51 ft thick and is composed of massive, crystalline dolomite. An unconformity appears to separate the Platteville Formation from the overlying Decorah Formation. The Decorah Formation is about 14 ft thick and composed of dolomite and shale. The dolomite:shale ratio of the Decorah Formation grades upward from 60:40 at the base to 95:5 at the top. The Galena Dolomite overlies the Decorah Formation and is about 119 ft thick in this area. The Galena Dolomite generally is an argillaceous dolomite. Shale partings and upward-fining sequences are common.

Physical analysis of the dolomite matrix was conducted on seven core samples of the Galena Dolomite, two samples of the Decorah Formation, and six samples of the Platteville Formation (table G1). Two samples of the Glenwood Formation also were analyzed. Among the Sinnipee Group samples, porosity values ranged from a low value of 1.6 percent at the top of the Galena Dolomite to a high value of 9.7 percent in the Decorah Formation. The mean porosity of the Decorah Formation samples is 8.3 percent, the mean porosity of the Galena Dolomite samples is about 2.4 percent, and the mean porosity of the Platteville Formation samples is 3.6 percent. The low porosity of the Galena Dolomite and Platteville Formation is consistent with the overall massive, crystalline nature of the dolomites in these units. There appears to be no appreciable difference in either the bulk or grain densities in samples of the three Sinnipee Group units. Grain density ranges from 2.5 to 2.9 g/cm^3 (table G1); the higher value is typical of pure dolomite (Hurlbut and Klein, 1977, p. 308).

Geophysical logs

Geophysical logs for boreholes FL-800, FL-801, and FL-802 indicate that the nature of the Sinnipee Group does not change appreciably over the relatively short distance (about 100 ft) between them (figs. G1, G2, G3).

Caliper

The caliper logs in all three boreholes indicate the borehole diameter is greater than its nominal value of 6 in. at about 810, 870, 881, 890, and 913 FANGVD29 (figs. G1, G2, G3). None of these features is greater than 1 in. in diameter, but they may correspond to secondary-permeability features and appear to correlate between each of the boreholes.

Natural Gamma

The high shale content of the Decorah Formation is reflected on the natural-gamma logs (figs. G1, G2, G3)

Table G1. Physical properties of selected rock core intervals from borehole FL-800 at the Waupun site, Fond du Lac County, Wis.

[NGVD of 1929, National Geodetic Vertical Datum of 1929]

Stratigraphy	Core interval, in feet above NGVD of 1929	Porosity, in percent	Bulk density, in grams per cubic centimeters	Grain density, in grams per cubic centimeters
Galena Dolomite	928.9 - 928.7	1.6	2.8	2.9
	906.7 - 907.3	1.9	2.4	2.5
	869.8 - 869.4	2.1	2.8	2.9
	852.3 - 852.0	3.2	2.8	2.9
	830.3 - 830.0	1.7	2.7	2.7
	825.7 - 825.4	3.8	2.7	2.8
	814.1 - 813.8	2.3	2.8	2.8
Decorah Formation	807.4 - 807.0	6.9	2.6	2.7
	799.4 - 799.0	9.7	2.5	2.8
Platteville Formation	794.6 - 794.3	1.8	2.8	2.8
	786.0 - 785.7	3.7	2.7	2.8
	774.8 - 771.5	4.0	2.7	2.8
	765.8 - 765.0	4.3	2.7	2.8
	755.1 - 754.8	4.1	2.7	2.8
	747.8 - 747.5	3.7	2.7	2.8
Glenwood Formation	747.2 - 746.7	3.0	2.7	2.8
	744.9 - 744.6	14.6	2.3	2.6

as a zone of higher gamma counts per second between about 796 and 810 FANGVD29 (geophysical log altitudes appear to be about 2 ft lower than correlative core altitudes). The more massive, less argillaceous, Galena Dolomite and Platteville Formation both have lower gamma cps than the Decorah Formation.

Normal Resistivity

Normal resisitivity logs were run to aid stratigraphic correlation at the Waupun site. The shaley nature of the Decorah Formation is reflected in lower resistance on the short-normal resistivity log (figs. G1, G2, G3). Short-normal resistivity logs indicated no clear response to areas of potential secondary-permeability features identified with the caliper logs.

Neutron

Neutron logging was performed only in borehole FL-800. The following discussion is a summary of logging results provided by Fred Paillet (U.S. Geological Survey, written commun., 1997). The neutron log (calibrated for limestone porosity) shows values of –4 to –2 percent over all of borehole FL-800 except for the Decorah Formation at 796-810 FANGVD29, with an apparent porosity of 10-20 percent. The higher porosity of the Decorah Formation in comparison to the rest of the Sinnipee Group (table G1) is reflected in the neutron porosity log (fig. G1). Neutron-porosity logs calibrated in limestone need to be corrected to account for the effects of quartz lithology in a sandstone. The difference in mineral grain lithology causes a limestone-calibrated, neutron-porosity log to read –5 percent in a 100 percent quartz environment, whereas all neutron-porosity calibrations should tend toward the same value in 100-percent water. Thus, a +5 percent porosity calibration correction is required to convert limestone-calibrated porosity to quartz-calibrated porosity in the vicinity of the zero-porosity limit on the neutron log. The correlation decreases linearly with increasing porosity. The small negative values for porosity, from –4 to 0 percent, probably indicate the substantial portion of quartz (possible chert) in the dolomite. The highest apparent porosity measured with the neutron log at borehole FL-800 is associated with an increase in borehole diameter at the top of the Decorah Formation at about 810 FANGVD29. It is unclear if this increased porosity is associated with the shale layer or the possible fracture.

Acoustic Televiewer

The following discussion is a summary of logging results provided by Fred Paillet (U.S Geological

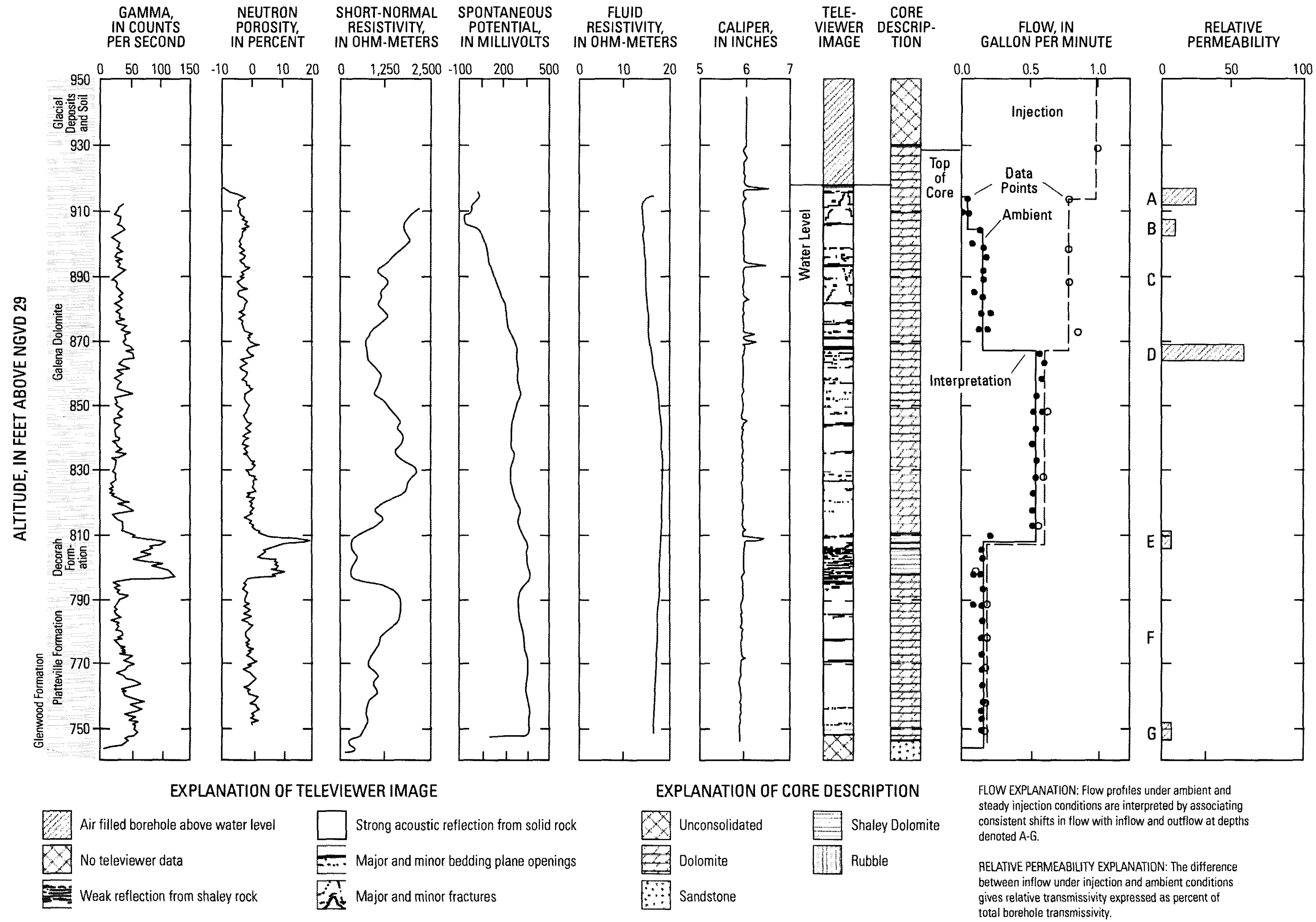

Figure G1. Geophysical logs, televiewer image, generalized core description, heat-pulse flowmeter data and relative permeability plot for borehole FL-800 at the Waupun site, Fond du Lac County, Wis.

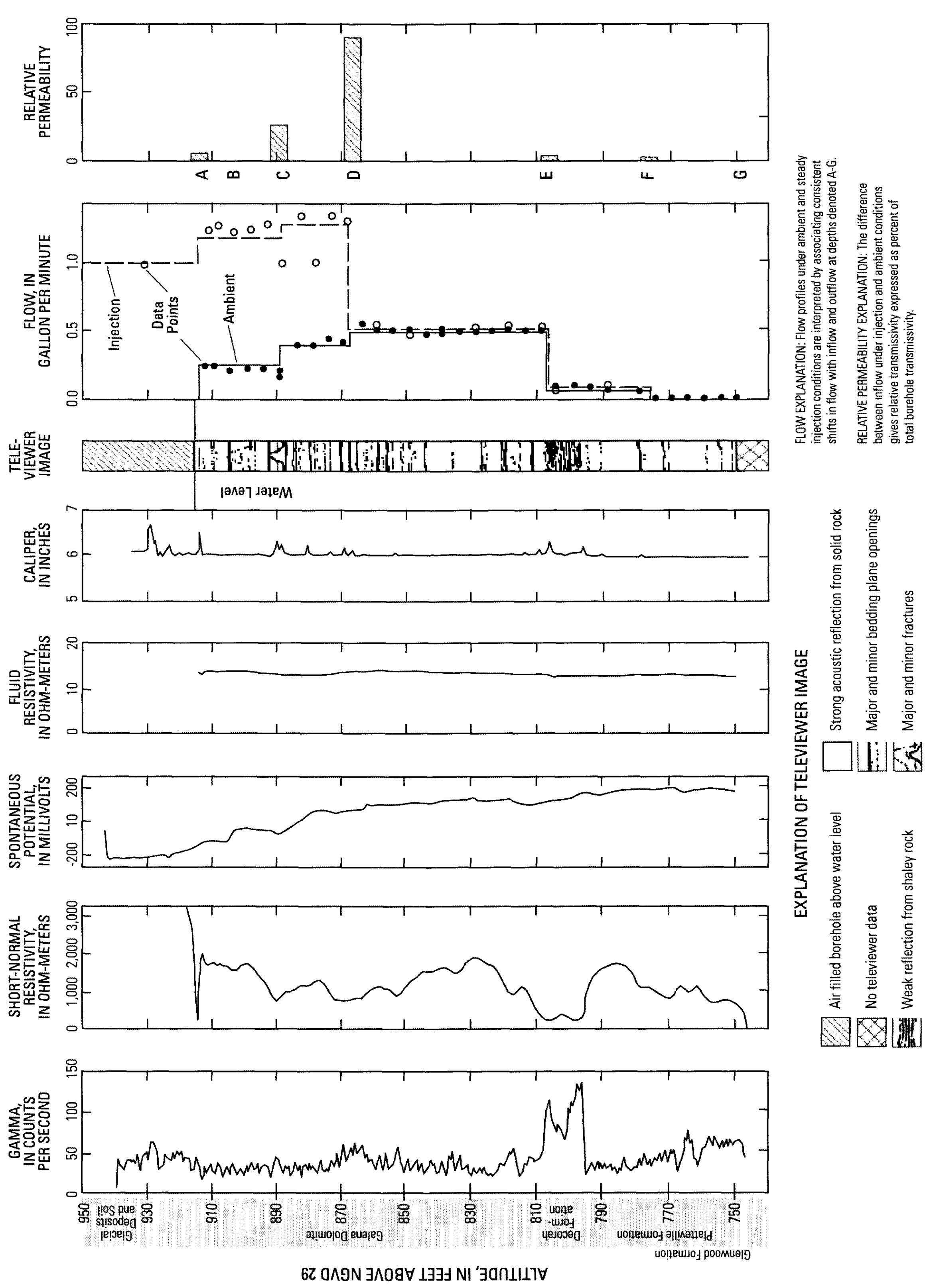

Figure G2. Geophysical logs, televiewer image, heat-pulse flowmeter data and relative permeability plot for borehole FL-801 at the Waupun site, Fond du Lac County, Wis.

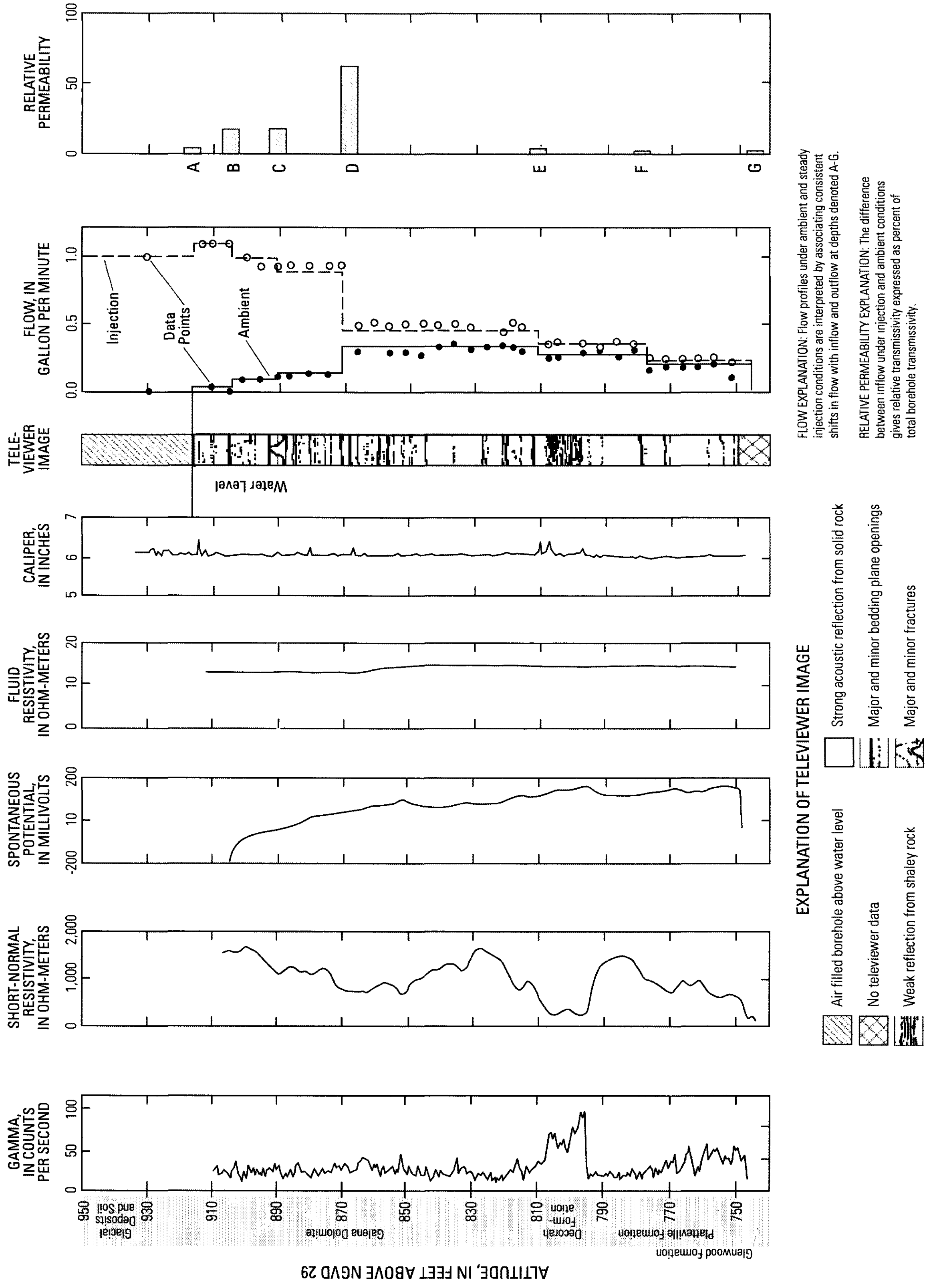

Figure G3. Geophysical logs, televiewer image, heat-pulse flowmeter data and relative permeability plot for borehole FL-802 at the Waupun site, Fond du Lac County, Wis.

Survey, written commun., 1997). The televiewer logs indicate many horizontal bedding-plane partings at each of the boreholes, most of which correspond to areas of increased borehole diameter identified with the caliper logs. The water level at about 915 FANGVD29 coincides with a prominent bedding-plane parting identified with the caliper logs that could not be imaged with the televiewer because the televiewer only transmits a signal in a fluid filled borehole. The distribution of bedding-plane partings on the televiewer logs does not correlate with the distribution of bedding-plane partings described in the core, probably because the listing of bedding-plane partings in the core description does not indicate that some partings apparently are much bigger or more extensively weathered than others. The televiewer log shows a massive interval at 900-907 FANGVD29, which correlates with a massive interval in the core. However, there is a conspicuous bedding plane at 913 FANGVD29 on the televiewer log that is not referred to in the core description.

Two inclined fractures (at 910 and 888 FANGVD29) are indicated on the televiewer log for borehole FL-800 and detected on the core (fig. G1). A third fracture indicated by the core near 874 FANGVD29 was not indicated in the televiewer log. A large inclined fracture was detected with the televiewer log at 890 and 900 FANGVD29 in borehole FL-801. All of these fractures dip to the ENE and strike to the WNW.

Borehole GPR

A single-hole directional borehole GPR survey was conducted in FL-800 using a 60-MHz transmitter and a 60-MHz directional receiver. The results of the analysis of the single-hole directional reflection survey in FL-800 indicate that a group of reflectors at the site have strikes from magnetic north of 40 degrees to 60 degrees, with a conjugate set of 130 to 150 degrees (table G2) (John Lane, U.S. Geological Survey, written commun., 1997). Other strikes are interpreted from the data at 190 and 300 degrees. Reflector dip data are presented as angles with respect to the borehole. These data must be subtracted from 90 degrees to obtain dip. Some reflectors correlate well with other borehole-geophysical logs, and others do not correlate. A partial explanation for any lack of correlation may be that the borehole radar can obtain reflections from structures that are present beyond the borehole but do not extend to the borehole wall. The interpretations include a "depth of intersection" for each reflector; this value is the depth at which the reflector would intersect the borehole if it were large or areally extensive enough to do so. In some cases, the intersection depth can be negative, or it can project to depths deeper than the drilled borehole depth. These depths are "tie-points" that allow one to reconstruct the geometry and location of the reflectors with respect to the borehole (John Lane, U.S. Geological Survey, written commun., 1997).

A cross-hole radar tomography survey was conducted between boreholes FL-800 and FL-802 using a 22-MHz transmitter and receiver. The cross-hole tomography data were interpreted to produce velocity and attenuation tomograms between FL-802 (left-side tomogram) and FL-800 (John Lane, U.S. Geological Survey, written commun., 1997) (figs. G4, G5). The velocity tomograms show the lowest velocities between 817 and 785 FANGVD29. The attenuation tomograms indicate the highest attenuation centered at about 802 FANGVD29. The decrease in radar-propagation velocity and the increase in radar-wave attenuation have been associated with increased water content and EM-wave attenuation associated with high-porosity, electrically conductive rocks. The low velocity/high-attenuation zone correlates well with a zone of decreased resistivity and increased porosity and gamma counts from about 795 to 810 FANGVD29, as indicated on the short-normal resistivity, neutron porosity, and natural-gamma logs. This zone has been interpreted as a shaley dolomite (Decorah Dolomite). The low-velocity/high-attenuation zone, extending between FL-802 and FL-800 in the velocity and attenuation tomograms at about 810 FANGVD29, is consistent with the interpretation of a fracture at this depth made with the other borehole-geo-

Table G2. Results of analysis of the single-hole directional reflection survey in borehole FL-800, Waupun site, Fond du Lac County, Wis.

[NGVD of 1929, National Geodetic Vertical Datum of 1929; na, not applicable]

Altitude (feet above NGVD of 1929)	Angle (degrees)	Strike (degrees from magnetic north)	Dip (degrees from horizontal)
3,696	1.1	40	88.9
1,019	5.6	130	84.4
970	14.5	na	75.5
933	61.7	na	28.3
925	61.6	60	28.4
922	29.2	10	60.8
916	90.0	na	.0
907	90.0	na	.0
870	Subhorizontal	150	Subhorizontal
853	88.4	na	1.6
848	90.0	300	.0
816	75.5	na	14.5
805	90.0	na	.0
797	90.0	na	.0
745	66.5	na	23.5

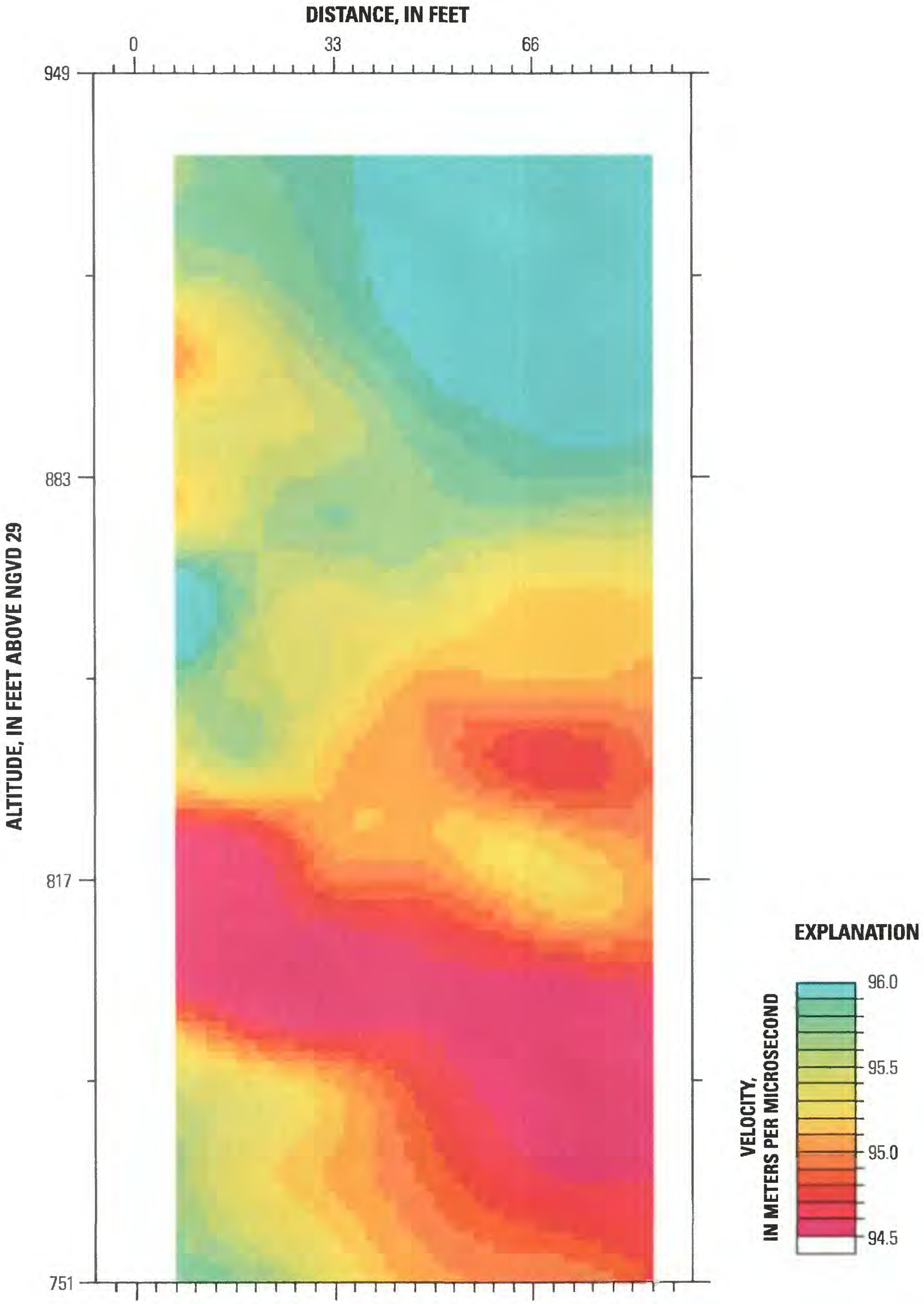

Figure G4. Cross-hole velocity tomogram between boreholes FL-800 and FL-802, Waupun site, Wis.

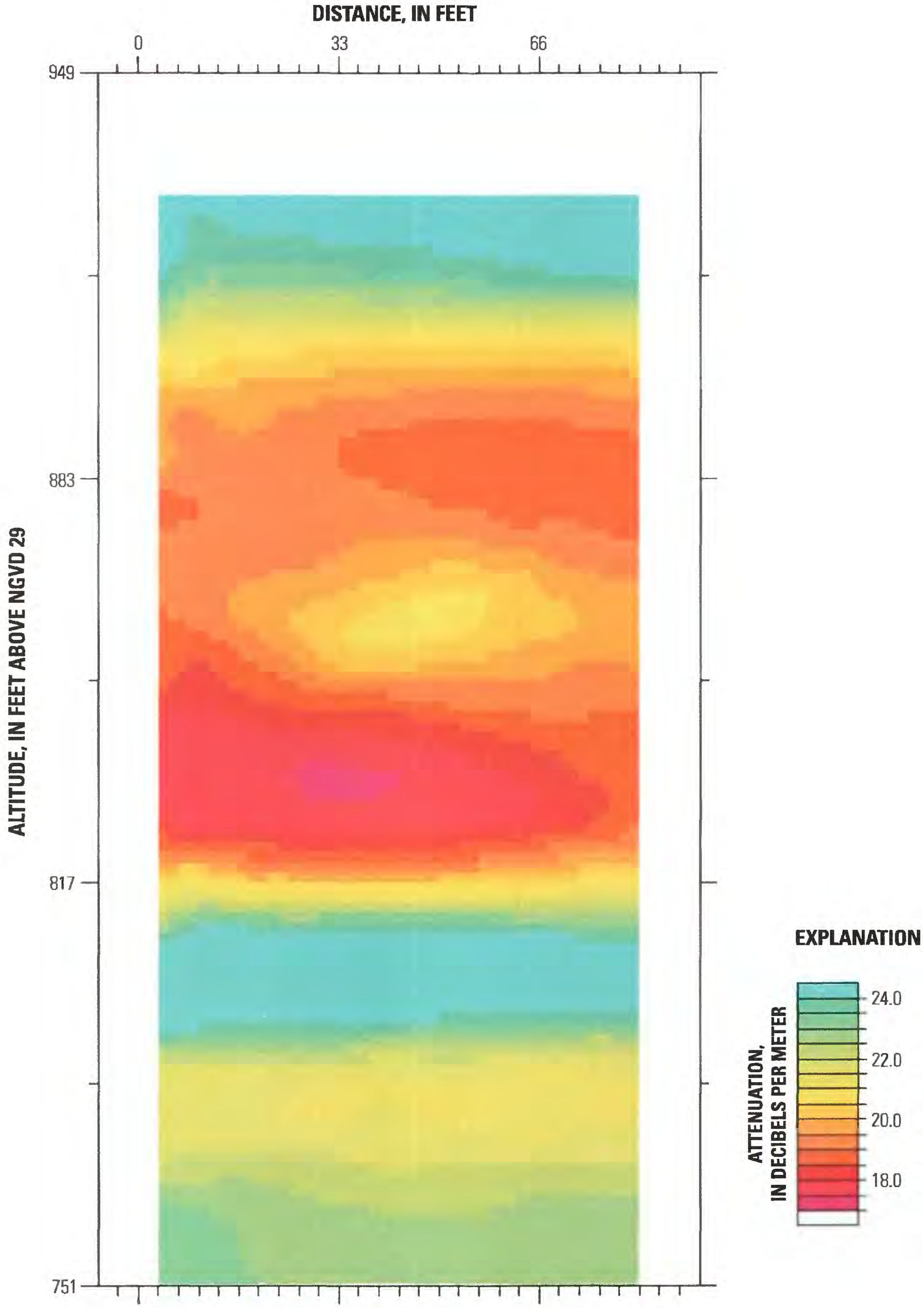

Figure G5. Cross-hole attenuation tomogram between boreholes FL-800 and FL-802, Waupun site, Wis.

physical logs in boreholes FL-800 and FL-802. This zone is near the upper contact of the shaley dolomite and the "cleaner" dolomite.

Hydrology

Water-level measurements, geophysical logging, and aquifer testing were used to assess the hydrology of the Sinnepee Group aquifer at the Waupun site.

Water-level measurements

Water levels were measured once in nine test intervals isolated by use of a packer assembly in borehole FL-800 and two intervals in each of boreholes FL-801 and FL-802 (fig. G6). Static water levels were measured in the selected intervals (table G3), and vertical hydraulic gradients were estimated by comparing levels in adjacent intervals (table G4). Vertical hydraulic gradients were found to be almost uniformly down, with values ranging from 0.040 to 0.863 ft/ft. The few upward gradients were found to range from 0.006 to 0.797 ft/ft. The gradients measured in intervals K and J are 0.062 ft/ft down in borehole FL-800, 0.058 ft/ft down in borehole FL-801 and 0.057 ft/ft down in borehole FL-802 (table G4).

Geophysical logs

Fluid Resistivity

Fluid resistivity indicates a slight but consistent increase at about 870 FANGVD29 in all three boreholes (figs. G1, G2, G3). Fluid resistivity also shows a slight decrease at about 807 FANGVD29 in borehole FL-801 and a slight decrease beginning between about 810 and 820 FANGVD29 in borehole FL-800. These intervals may correspond to the location of permeable features in the Galena-Platteville aquifer.

Flowmeter Logging

The following discussion is from a summary of logging results provided by Fred Paillet (U.S. Geological Survey, written commun., 1997). Flowmeter logging under ambient conditions identified 0.2-0.8 gal/min of downward flow in each of the boreholes. The flowmeter profiles indicate that the flow enters and exits at bedding-plane partings at about 810 and 870 FANGVD29 in each of the boreholes, with flow at about 890 FANGVD29 in boreholes FL-801 and FL-802, and about 905 FANGVD29 in boreholes FL-800 and FL-802. There also is inflow from one or more features above or near the water level (about 915 FANGVD29) in each of the boreholes, possibly the fracture identified with the caliper log at about 915 FANGVD29. Each of these features appears to be permeable. Although the same general set of bedding planes seems to be active in all three boreholes, including one associated with the top of the Decorah Formation at about 810 FANGVD29, the amount contributed from each parting varies between boreholes.

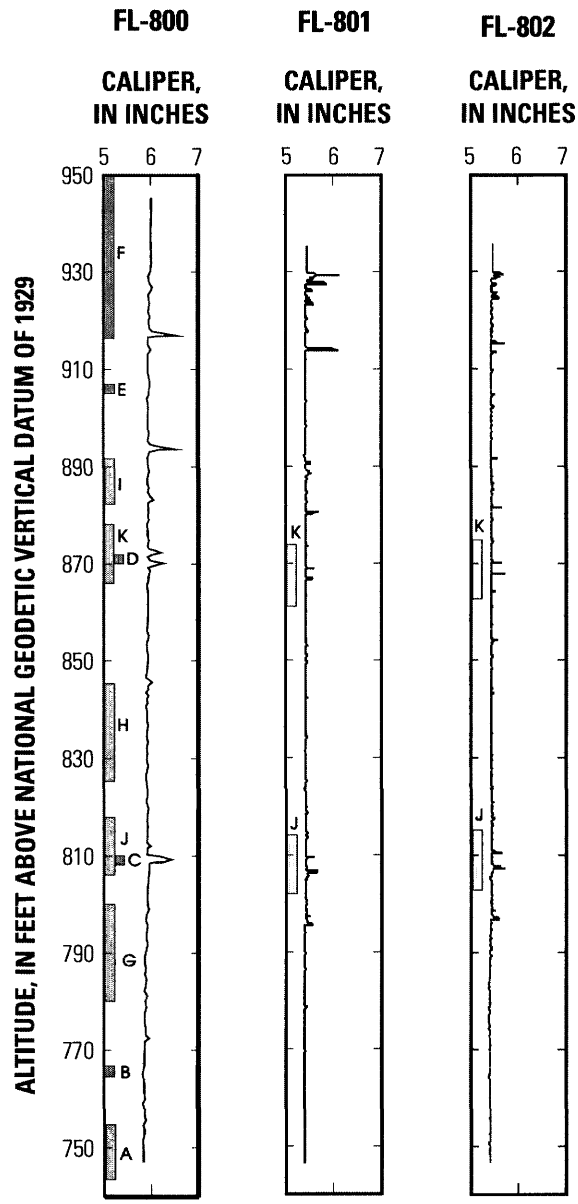

Figure G6. Caliper logs, packed intervals and test-interval designation for boreholes FL-800, FL-801, and FL-802, Waupun site, Wis.

Table G3. Measured static water levels in test intervals isolated with a packer assembly in boreholes FL-800, FL-801, and FL-802 at the Waupun site, Fond du Lac County, Wis.

[NGVD of 1929, National Geodetic Vertical Datum of 1929]

Borehole name	Test interval	Altitude of test interval, in feet above NGVD of 1929	Stratigraphy	Water level altitude in test interval, in feet above NGVD of 1929
FL-800	F	917 - 930.5	Galena Dolomite-Wise Lake and Dunleith Dolomite members	922.45
	E	907 - 905	Galena Dolomite-Wise Lake and Dunleith Dolomite members	915.47
	I	892 - 882.1	Galena Dolomite-Wise Lake and Dunleith Dolomite members	914.71
	D	872 - 870	Galena Dolomite-Wise Lake and Dunleith Dolomite members	914.80
	K	877.4 - 865.9	Galena Dolomite-Wise Lake and Dunleith Dolomite members	911.34
	H	844 – 824.1	Galena Dolomite-Wise Lake and Dunleith Dolomite members	912.15
	C	810 - 808	Decorah Formation-Spechts Ferry Shale	912.70
	J	817.4 – 805.9	Galena Dolomite-Wise Lake and Dunleith Dolomite members, and Decorah Formation-Spechts Ferry Shale	907.63
	G	800 – 780.1	Platteville Formation-Quimbys Mill member	889.00
	B	768 - 765	Platteville Formation-McGregor member	908.16
	A	755 - 744	Platteville Formation-Pecatonica member and Ancell Group-Glenwood Formation	896.22
FL-801	K	873.5 - 861.8	Galena Dolomite-Wise Lake and Dunleith Dolomite members	909.32
	J	813.5 – 801.8	Galena Dolomite-Wise Lake and Dunleith Dolomite members, and Decorah Formation-Spechts Ferry Shale	905.84
FL-802	K	874.5 - 863	Galena Dolomite-Wise Lake and Dunleith Dolomite members	911.22
	J	814.5 - 803	Galena Dolomite-Wise Lake and Dunleith Dolomite members, and Decorah Formation-Spechts Ferry Shale	907.80

The relative amounts of water entering and exiting a borehole depends on the product of fracture permeability and the head difference driving the flow. A true relative permeability profile can be obtained by subtracting inflows obtained under two different hydraulic conditions. Ambient and steady injection conditions are described here. The data are plotted as discrete flowmeter measurements (data) and as "step profiles" (the interpretation) (figs. G1, G2, G3). The differences profiles show that the pair of bedding-plane fractures at about 870 FANGVD29 may be much more permeable than any of the other bedding planes intersecting the borehole. The bedding plane at about 915 FANGVD29 is not fully saturated, so these data may not be a fair representation of the relative permeability of that bedding plane.

The data do not allow comparison of the relative permeability of the fractures between boreholes. In order to do this comparison, the relative flows must be normalized. Normalization is done by measuring the drawdown (here build-up) produced by the pumping (here injection) (figs. G1, G2, G3). The boreholes were so productive that no change in water levels was measured during injection and the data could not be normalized to compare relative permeability across the boreholes.

The logs from all three boreholes correlate closely. The bedding planes conducting flow are similar for all three boreholes. However, there is some difference in the relative amounts of flow in each borehole, which indicates the variability of the bedding-plane permeability. The results indicate that the bedding-plane partings at about 868-870 FANGVD29 are the main conduit. The bedding-plane parting at about 915 FANGVD29 also clearly is important as it appreciably affects water levels.

Aquifer tests

Slug tests and constant-discharge aquifer tests were performed at the Waupun site. Both types of aquifer tests improved the understanding of the hydrology of the secondary-permeability network at the site.

Slug tests

Based on inspection of the core and results of the geophysical logging, slug tests were conducted on nine selected test intervals isolated with a packer assembly in borehole FL-800 and two intervals in each of boreholes FL-801 and FL-802 (fig. G6). These intervals were chosen to evaluate the range of Kh present in both fractured and unfractured parts of the boreholes. Estimated Kh values ranged from 0.002 to 117 ft/d (table G5). Test intervals that included bedding-plane partings had estimated Kh values ranging from 0.2 to 177 ft/d. Test intervals that did not contain bedding-plane partings had estimated Kh values ranging from 0.002 to 1 ft/d. Perme-

Table G4. Vertical hydraulic gradients calculated between selected test intervals isolated with a packer assembly in boreholes FL-800, FL-801, FL-802 at the Waupun site, Fond du Lac County, Wis.

[-, denotes downward flow]

Borehole name	Test intervals being compared	Vertical hydraulic gradient, in foot per foot
FL-800	F/E	-0.393
	E/I	-.040
	I/D	.006
	I/K	-.219
	D/H	-.073
	K/H	.020
	K/J	-.062
	H/C	.024
	H/J	-.200
	C/G	-1.251
	J/G	-.863
	G/B	.797
	B/A	-.724
FL-801	K/J	-.058
FL-802	K/J	-.057

Table G5. Horizontal hydraulic conductivity of test intervals isolated with a packer assembly in boreholes FL-800, FL-801, and, FL-802 estimated from slug tests at the Waupun site, Fond du Lac County, Wis.

[NGVD of 1929, National Geodetic Vertical Datum of 1929]

Borehole name	Test interval	Altitude of test interval, (feet above NGVD of 1929)	Horizontal hydraulic conductivity, (feet per day)
FL-800	F	917 - 930.5	0.2
	E	907 - 905	1
	I	892 - 882.1	8
	D	872 - 870	55
	K	877.4 - 865.9	117
	H	844 - 824.1	.4
	C	810 - 808	7
	J	817.4 - 805.9	.7
	G	800 - 780.1	.01
	B	768 - 765	.008
	A	755 - 744	.002
FL-801	K	873.5 - 861.8	19
	J	813.5 - 801.8	2
FL-802	K	874.5 - 863	55
	J	814.5 - 803	.7

able features indicated with the caliper and flowmeter logs were consistent with those intervals having high Kh from the slug tests.

Constant-discharge aquifer tests

The hydraulic connection among the three boreholes through specific intervals was evaluated by cross-borehole testing, where water was pumped from test intervals isolated with a packer assembly in one borehole and changes in water level were observed in the other two boreholes. Intervals J (the permeable bedding-plane parting at about 810 FANGVD29) and K (the permeable bedding-plane parting at about 870 FANGVD29) (fig. G6) were selected for cross-borehole testing based on evaluation of the cores, geophysical logs, and slug tests. Cross-borehole tests were conducted in intervals J and K independently. Interval J was pumped at about 4 gal/min in each borehole, while drawdown in the pumped borehole and both observation boreholes was monitored. Following the evaluation of interval J, the packers were moved to isolate interval K, which was evaluated in the same manner.

The results of the cross-hole aquifer test in interval J are presented in figures G7a, b, and c. Drawdown in the pumped borehole was greatest in borehole FL-800 at about 33 ft, and least in FL-801 at about 4.5 ft. These data indicate that test interval J is most permeable at borehole FL-801 and least permeable in borehole FL-800. During pumping from any of the three boreholes, drawdown began immediately in the others. Regardless of the magnitude of the drawdown in the pumped borehole, drawdown in interval J in the observation boreholes was about 1 ft at the end of the pumping phase of the test (100 minutes), indicating that the test interval is isotropic in the vicinity of the boreholes. The pumped borehole recovered more quickly than the observation boreholes during pumping in boreholes FL-800 and FL-801 (figs. G7a and b). Initially, the rate of recovery after the termination of pumping in borehole FL-802 was faster than in the other boreholes. Once the water level in borehole FL-802 equaled that of the other boreholes, the recovery data were similar for all three boreholes (fig. G7a).

The results of the cross-hole aquifer test in packed interval K are presented in figures G8a, b, and c. Drawdown in the pumped borehole was much less in interval K than observed in interval J, indicating that interval K is more permeable. The drawdown was greatest in borehole FL-801 (about 1.3 ft), and least in borehole FL-800 (about 0.9 ft). The drawdown values are similar, but the specific-capacity data indicate that test interval K may be most permeable at borehole FL-800 and least permeable in borehole FL-801. Pumping from any of the three boreholes results in immediate drawdown in the others. Regardless of the magnitude of the drawdown in the

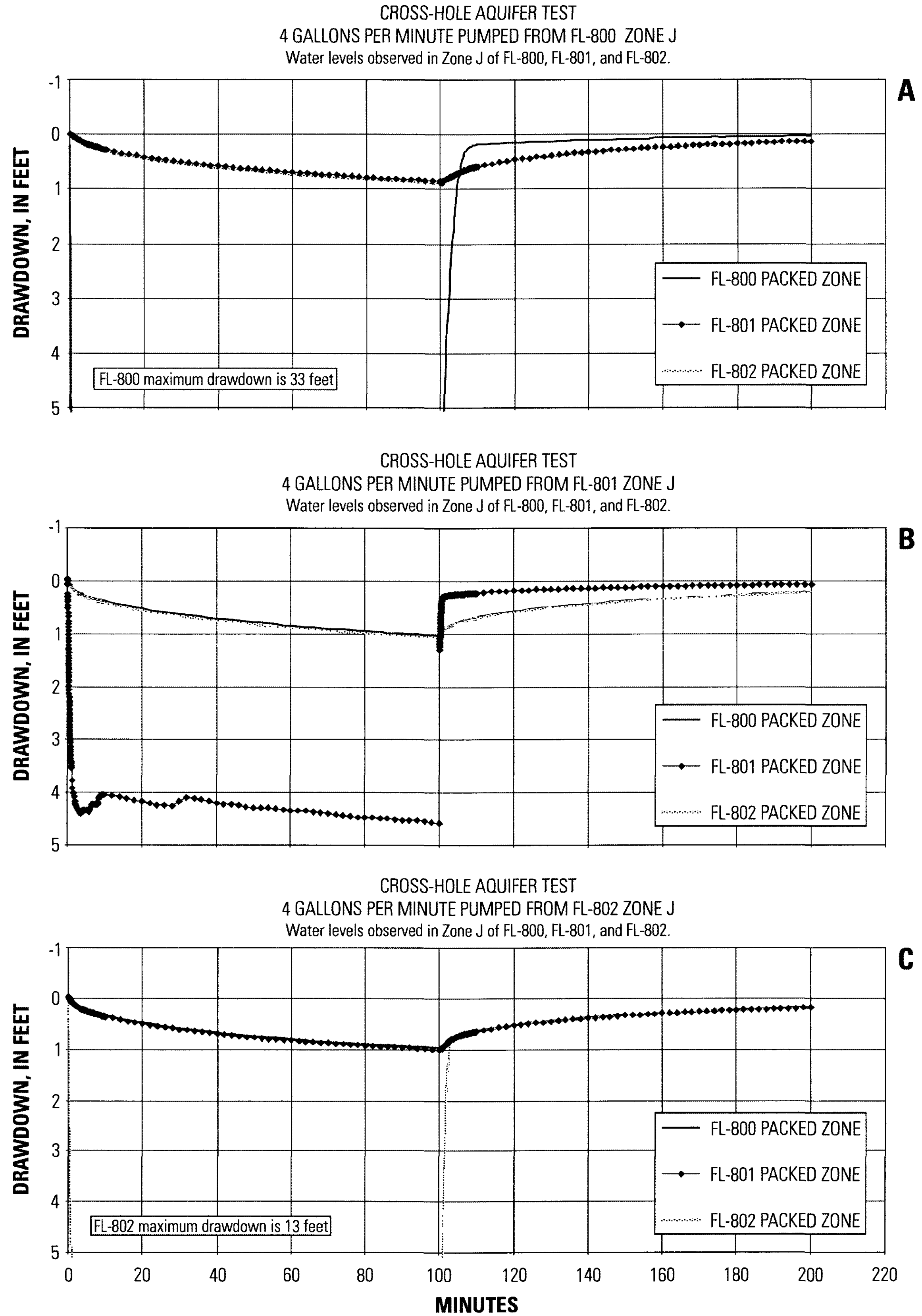

Figure G7. Changes in water levels observed in packed interval J during cross-borehole aquifer tests at the Waupun site, Wis. A) pumped borehole is FL-800, B) pumped borehole is FL-801, C) pumped borehole is FL-802.

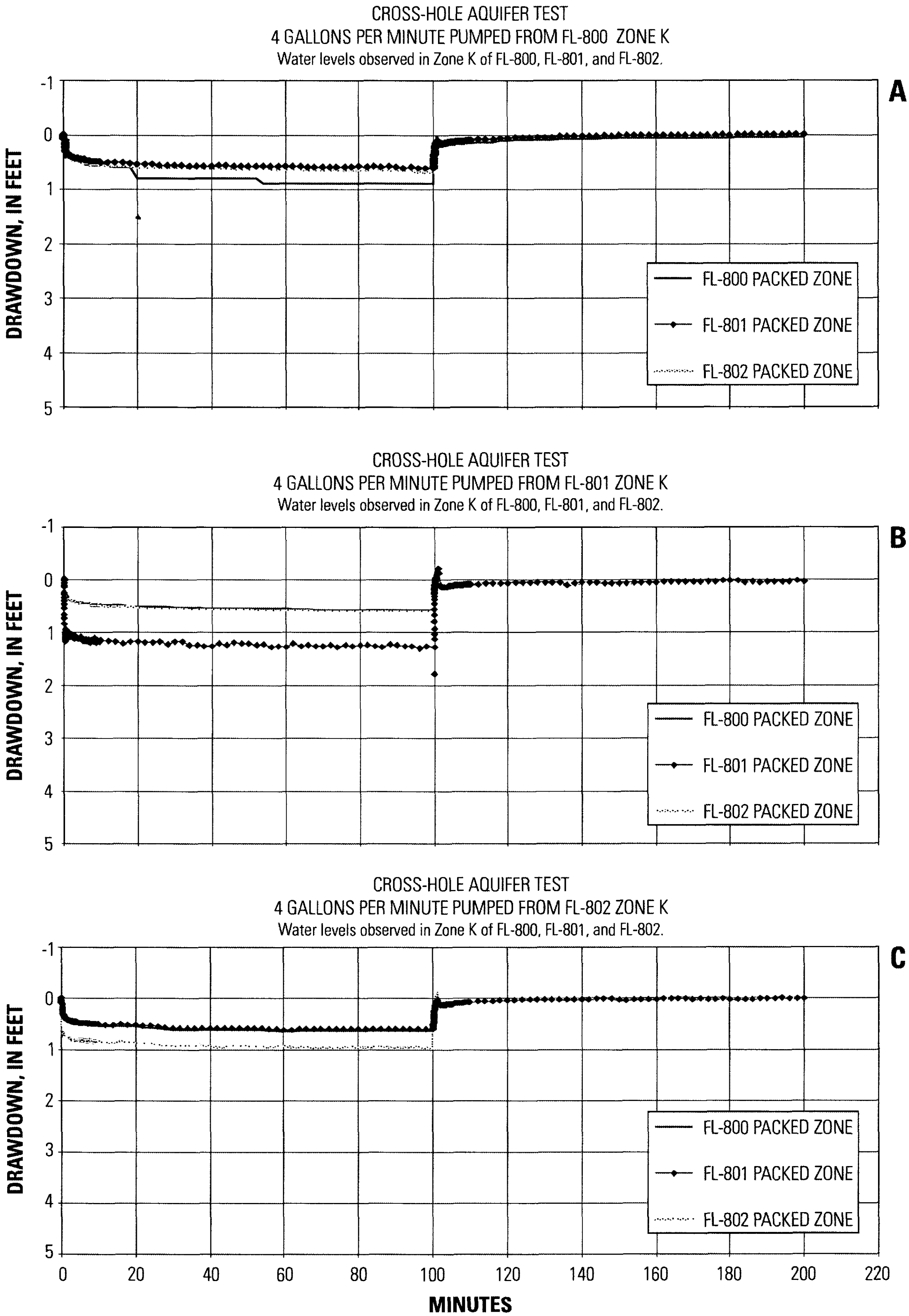

Figure G8. Changes in water levels observed in packed interval K during cross-borehole aquifer tests at the Waupun site, Wis. A) pumped borehole is FL-800, B) pumped borehole is FL-801, C) pumped borehole is FL-802.

pumped borehole, the drawdown in the other boreholes was between 0.6 and 0.7 ft at the end of the pumping phase of the test (100 minutes). Initially, the rate of recovery after the termination of pumping in the pumped boreholes was faster than in the observation boreholes. Once the water level in the pumped borehole equaled that of the observation boreholes, the recovery data were similar for all three boreholes (figs. G8a, b, c). All of the recovery profiles for test interval K showed water-level oscillation, which is indicative of a highly permeable aquifer.

Location of contaminants

Water-quality analyses were conducted only for samples from borehole FL-800. Samples were collected on April 8 and 9, 1996, during borehole development, and on April 24 and 25, 1996, from four test intervals isolated by use of a packer assembly. Test interval F was defined by a single packer set at 917 FANGVD29 with the tested interval extending to the water table at 930.5 FANGVD29 (fig. G6). Test intervals C, D, and E were isolated by two packers on either side of a 2-ft screen. Intervals C and D are shorter packed intervals that fall within intervals J and K, respectively (fig. G7). Analytical data for inorganic constituents and major ions are presented in tables G6 and G7.

In the samples taken during borehole development, acetone, trichloroethene, tetrachlorethene, 1,1,2-trichloroethane, and diethylphthalate were detected and considered representative of in-situ water quality. In the samples taken from the test intervals isolated by use of a packer assembly, 3-Heptone was detected in zone F. Acetone and toluene were detected in zone E. Trichloroethene was detected in zone D, and toluene was detected in zone C. Detections of VOC's are too sparse to assist in characterization of the secondary-permeability network at the Waupun site.

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Table G6. Inorganic and major ion analytical data for water from test intervals F, E, D, and C in borehole FL-800 sampled April 24 and 25, 1996, at the Waupun site, Fond du Lac County, Wis.

[MCL, maximum contaminant level; -, no established MCL; mg/L, milligrams per liter; µg/L, micrograms per liter; µSiemens/cm, microSiemens per centimeter; na, not analyzed; test interval reported as feet above National Geodetic Vertical Datum of 1929]

Constituent	MCL[a]	Units	Test interval F, from 917 to 930.5 feet	Test interval E, from 905 to 907 feet	Test interval D, from 870 to 872 feet	Test interval C, from 808 to 810 feet
pH	-	Standard units	7.67	7.4	7.4	7.2
Hardness Total	-	mg/L as $CaCo_3$	na	610	570	640
Calcium dissolved	-	mg/L as Ca	na	130	120	130
Magnesium dissolved	-	mg/L as Mg	na	70	66	76
Sodium dissolved	-	mg/L as Na	na	10	15	17
Sodium adsorption ratio	-	ratio	na	.2	.3	.3
Sodium percent	-	percent	na	4	6	6
Potassium dissolved	-	mg/L as K	na	5.5	15	31
Chloride dissolved	-	mg/L as Cl	190	81	95	130
Sulfate dissolved	-	mg/L as SO_4	110	120	140	150
Fluoride dissolved	-	mg/L as F	.1	.2	.2	.2
Silica dissolved	-	mg/L as SiO_2	19	15	13	14
Iron dissolved	300	µg/L as Fe	25	190	330	250
Manganese dissolved	50	µg/L as Mn	140	34	74	93
Residue dissolved 180C	-	mg/L	1080	700	692	884
Dissolved solids sum	-	mg/L	na	665	672	796
Bromide dissolved	-	mg/L as Br	.06	.1	.09	.11
Specific conductance	-	µSiemens/cm	1490	1110	1130	1400
Alkalinity as CaCO3	-	mg/L as $CaCo_3$	317	388	345	412

[a] Secondary Drinking Water Standard (U.S. Environmental Protection Agency, 2000)

Table G7. Trace element and major ion analytical data for water from test intervals F, E, D, and C in borehole FL-800 sampled April 24 and 25, 1996, at the Waupun site, Fond du Lac County, Wis.

[All values reported in micrograms per liter; MCL, maximum contaminant level; -, no established MCL; <, less than the indicated detection limit; (B), detected in laboratory blank; --, not analyzed; zone interval reported as feet above National Geodetic Vertical Datum of 1929]

Constituent	MCL	Test interval F, from 917 to 930.5 feet	Test interval E, from 905 to 907 feet	Test interval D, from 870 to 872 feet	Test interval C, from 808 to 810 feet
Aluminum	50-200 [b]	272	< 80	< 80	< 80
Antimony	6 [a]	1	2	21	9
Arsenic	50 [a]	< 2	4.1	5.1	< 2
Barium	2,000 [a]	208	175	209	216
Beryllium	4 [a]	< 1	< 1	< 1	< 1
Cadmium	5 [a]	< 0.2	< 0.2	< 0.2	< 0.2
Calcium	-	145,000	129,000	122,000	140,000
Chromium	100 [a]	< 8	< 8	< 8	< 8
Cobalt	-	< 6	< 6	< 6	< 6
Copper	1,000 [b]	48.7	43.2	< 6	< 6
Iron	300 [b]	778	456	775	432
Lead	15 [a]	5	< 2	2	< 4
Magnesium	-	87,900	68,000	65,200	77,100
Manganese	50 [b]	149	40.9	88.2	108
Nickel	100 [a]	33.8	74.4	37.4	35.2
Potassium	-	99,200	8780	18,700	36,900
Selenium	50 [a]	< 2	< 2	< 2	< 2
Silver	100 [b]	< 6	< 6	< 6	< 6
Sodium	20,000 [c]	25,400	10,700	15,500	18,000
Thallium	2 [a]	< 2	< 2	< 2	< 2
Vanadium	-	< 5	< 5	< 5	< 5
Zinc	5,000 [b]	43.6	< 40	56.4	307

[a] Primary Drinking Water Standard (U.S. Environmental Protection Agency, 2000)

[b] Secondary Drinking Water Standard (U.S. Environmental Protection Agency, 2000)

[c] Drinking Water Equivalent Level (U.S. Environmental Protection Agency, 2000)

Newport, T. G., 1962, Geology and ground-water resources of Fond du Lac County, Wisconsin: U.S. Geological Survey Water-Supply Paper 1604, 52 p.

U.S. Environmental Protection Agency, 2000, Drinking water standards and health advisories: U.S. Environmental Protection Agency, Washington, D.C., EPA 822-B-00-001, Summer 2000, 12 p.

Appendix H—Better Brite Site Data

The hydrogeologic characterization of the Better Brite site is based on data collected and interpreted by the USGS and USEPA. A total of 16 investigative methods were used at borehole BN-483 (fig. 38) to develop the hydrogeologic framework for the Better Brite site. Detailed discussion of the investigation is presented in Batten and others (1999).

Previous investigations

Most of the previous geologic characterizations on the Galena-Platteville dolomite were completed as a result of other projects in the area. Hydrologic characterization of Brown County by Krohelski (1986) and Walker and others (1998) were used as the basis for describing the geologic and hydrologic frameworks. The site investigations were limited to the surficial deposits overlying the Galena-Platteville aquifer (Simon Hydro-Search, Inc., 1992).

Lithologic logs

Fractured dolomite was observed during lithologic logging of borehole BN-483 in the upper part of the bedrock deposits from about 566 to 576.5 FANGVD29 (depth of 24.5 to 35 ft) (table H1). Fractures were infilled with silt and clay material. Lithologic logging was not done below 566 FANGVD29, where core was available from this interval.

Core analysis

Continuous 3-in core was cut from the bottom of the casing at 566 FANGVD29 to the end of the borehole at 432 FANGVD29 (depth of 169 ft). A total of 126 ft of core was recovered from the 134-ft cored interval. Approximately 6 ft of core was not recovered from the fractured dolomite between 557 and 576 FANGVD29 (depth of 35-44 ft) and 2 ft of soft sandstone was not recovered from the interval between 432 and 436 FANGVD29 (depth of 165-169 ft).

A lithologic description and stratigraphic interpretation of the rock core from borehole BN-483 was completed by Michael Sargent and Zakaria Lasemi (Illinois State Geological Survey, written commun., 1994)(table H1). The ISGS found the units encountered in borehole BN-483 to be difficult to correlate with those collected from other locations in southern Wisconsin and Illinois. However, on the basis of their lithologic description, ISGS identifies the Galena Dolomite from about 545 to 576.5 FANGVD29 (depth of 24.5-55.8 ft), the Decorah Formation from about 488 to 545 FANGVD29 (depth of 55.8-112.8 ft), and the Platteville Formation from about 441 to 448 FANGVD29 (depth of 113-160 ft). Sandstone of the Glenwood Formation is present below the Platteville Formation to about 433 FANGVD29 (depth of about 169 ft). Choi (1998) completed a study correlating approximately 60 rock cores and outcrops in east-central and southern Wisconsin including the core from borehole BN-483. Choi interprets the Decorah Formation as being absent in borehole BN-483, with the Galena Dolomite unconformably overlying the Platteville Dolomite at about 488 FANGVD29 (depth of about 113 ft).

Among the samples from the Sinnipee Group, porosity values in samples collected from the core ranged from 1.8 percent near the base of the Galena Dolomite to 7.7 percent in a sample from the Platteville Formation. The mean porosity of two Decorah Formation samples is about 6.8 percent compared to a mean of 3.5 percent for seven Galena Dolomite and Platteville Formation samples. The low porosity of the Galena Dolomite and Platteville Formation likely is explained by the massive, crystalline nature of the dolomites in these units at this borehole.

There appears to be no appreciable difference in either the bulk or grain densities in samples of the Sinnipee Group. Grain density ranges from 2.67 to 2.87 g/cm^3, the higher of which are typical values for pure dolomite (Hurlbut and Klein, 1977, p 308).

Geophysical logs

Borehole Camera

A borehole-camera log was completed December 20, 1993, with a 2-in., black-and-white camera. A wash out of the dolomite below the surface casing from 556 to 565 FANGVD29 (depth of 36 to 45 ft) was identified. This interval also is where no core was recovered, indicating that the dolomite is weathered. Borehole-camera logging also identified the presence of layering within the Galena-Platteville dolomite.

Caliper

The three-arm caliper log indicated an enlarged borehole from the bottom of the surface casing to approximately 557 FANGVD29 (depth of 44 ft). This result is consistent with the core and camera logs, which indicated removal of weathered and fractured dolomite from this interval (fig. 39). The caliper log indicated competent bedrock through the rest of the borehole.

Natural Gamma

A sharp decrease in signal response on the natural-gamma log occurs below about 485 FANGVD29 (depth of about 116 ft). This transition is within 2 ft of the altitude of the contact between the Decorah Formation and Platteville Dolomite identified from the core analysis. The sharp decrease in signal response on the natural-gamma log represents the less argillaceous nature of the Platteville Dolomite compared to the Decorah Formation and the Galena Dolomite.

Single-Point Resistivity and Resistivity

A sharp increase in resistance values (SPR) and resistivity (normal resistivity) values occurs at 485 FANGVD29 (fig. 39). This increase is in response to the lower clay content in the dolomite of the Platteville Formation relative to the Galena Dolomite and the Decorah Formation.

Neutron

The neutron log indicates lower and less variable porosity in the Platteville Formation than in the overlying Decorah Formation and perhaps the Galena Dolomite (fig. 39). These patterns generally are consistent with the results of the porosity determined from the core analysis, which indicate increased porosity associated with the Decorah Formation, but may be inconsistent with the porosity data indicating similar values in the Galena Dolomite and the Platteville Formation. The lower part of the wash out from about 556 to 565 FANGVD29 corresponds to an interval of elevated log response and appears to be a response to the enlarged borehole at this interval.

Acoustic Televiewer

The major feature identified with the televiewer log is the wash out from the bottom of the casing to about 557 FANGVD29 (fig. 39). This interval corresponds to an area of weathered and fractured dolomite identified with the caliper and camera logs. The acoustic-televiewer log also shows some thin horizontal features from

Table H1. Lithologic description and stratigraphic interpretation by the Illinois State Geological Survey of core and drill cuttings from borehole BN-483 near the Better Brite Superfund Site, De Pere, Wis. (modified from Michael L. Sargent and Zakaria Lasemi, Illinois State Geological Survey, written commun., 1994)

Depth below land surface (feet)	Lithologic description of core and drill cuttings
0 - 24.4	Undifferentiated glacial deposits and soil, mostly red-brown sandy clay with trace of gravel.
24.5 - 41.5	Galena Dolomite; gray, very weathered, fractured (24.5-35 based on drill cuttings, 35-41.5 no return in core barrel)
41.6 - 55.8	Galena Dolomite; light olive gray to light brownish gray to pale yellow brown, occassional argillaceous shale or calcarenite interbeds, slightly fossiliferous becoming more fossiliferous in lower 7 feet, fossils include echinoderm and trilobite fragments and possibly bryozoans and brachiopods, predominant shale zone from 51.2 to 51.4 feet, quite fractured from 41.8 to 43.5 feet.
55.9 - 112.8	Decorah Formation; Interbedded dolomite and shale; section can be broken up into seven (possibly eight) cycles in which basal rock is pure dolomite that becomes progressively more argillaceous upward. Each cycle terminates at a hardground. Cycle thicknesses range from about 3 to 24 feet. Dolomites are mostly pinkish gray or very light brownish to medium dark gray and are finely crystalline. Some paper-thin shaley partings are present in the purer dolomite zones. A few small pin-head to about 0.5-inch size vugs are present throughout. Shale rocks are mostly dark grayish olive green. Entire formation is slightly fossiliferous but generally more fossiliferous in shaley zones. Bryozoans are most common recognizable fossil, but some zones contain abundant trilobite and brachiopod debris. Hardground surfaces are dark gray to dusky brown and are pyritic. Some of this dark colorization is probably phosphatization.
112.9 - 142.5	Platteville Formation (upper unit); very dense, fine-grained, mottled pinkish-gray to light gray; occassional paper-thin wavy dark shaley partings and olive-gray argillaceous streaks. Slightly cherty with several 0.5 to 1.5 inch thick chert beds and occassional scattered chert nodules; occasional small vugs throughout this zone; sublithographic calcarenitic beds (somewhat fossiliferous) from 116.8 to 118.9 feet. Upper unit includes rocks of the Quimbys Mill, Nachusa, and Grand Detour Formations in Illinois, but cannot be readily subdivided here using either Illinois or Wisconsin nomenclature.
142.6 - 159.8	Platteville Formation (lower unit); very fine-grained to lithographic; light brownish-gray matrix speckled with medium-gray to dark olive-gray, paper-thin wavy shale partings. This lower unit shows six sedimentation cycles ranging from about 2- to 5-feet thick; each cycle has a burrowed pure dolomite at it's base and becomes more argillaceous dolomite with wavy shale and argillaceous beds up to about 1-inch thick toward the top; very few pin-head to 0.5 inch vugs throughout this lower unit. The lower unit resembles only the Pecatonica Formation of Illinois and southern Wisconsin and cannot be subdivided. The contact with the underlying Glenwood Formation is sharp and at a hardground.
159.9 - 166.8	Ancell Group - Glenwood Formation; quartz sandstone; pale-brown, medium-grained, dolomite cemented; 0.1-inch thick hematite accumulation at 159.9 to 160 feet; pale-red to grayish-red sandstone at 160.0 to 161.8 feet.; mostly medium-dark gray to very light gray medium-grained sandstone from 161.8 to 166.8 feet; poorly cemented to friable below 162.6 feet.

about 459 to 551 FANGVD29. Review of the geophysical logs and inspection of the core indicates that these are thin (less than 1 in) partings of soft shale or clay that separate massive dolomite units above and below.

Hydrology

Ground-water flow at the Better Brite site was characterized by use of water-level measurements, geophysical logs, slug tests, and the location of contaminants.

Water-level measurements

Single water-level measurements were collected in test intervals isolated with a packer assembly and in two monitoring wells installed in borehole BH-483. Because borehole BN-483 is the only data point in the Galena-Platteville aquifer at the Better Brite site, vertical differences in water levels in this borehole are the only water-level data available for analysis.

Single Water-Level Measurements—Packers

Water levels were measured in test intervals isolated with a packer assembly in borehole BN-483 (table H2). Some of the test intervals were not fully saturated, indicating that equilibrium water levels had not been reached because of unsaturated conditions or the slow recovery rates resulting from the low permeability in the Galena-Platteville aquifer.

The static water level measured in the wash-out zone below the bottom of the casing (packed interval A) was about 585.3 FANGVD29. The static water level measured in the interval from about 441 FANGVD29 (depth of 160 ft) to the bottom of the borehole (packed interval H) was 452.0 FANGVD29 or possibly lower. The lower static water level in the St. Peter aquifer (indicated by packed interval H) relative to the Galena-Platteville aquifer is the result of municipal pumpage from the St. Peter aquifer (Krohelski, 1986). Comparison of static water levels in packed intervals A and H translates into a total drop in water levels of more than 130 ft across the Galena-Platteville aquifer at the Better Brite site, indicating that the aquifer has a low vertical hydraulic conductivity and may be partly unsaturated.

Single Water-Level Measurements—Monitoring Wells

Water levels were measured from monitoring wells installed in borehole BN-483 on October 17, 1994, by Simon Hydro-Search, the contractor to USEPA working on the site remediation. Because the elevation of the measuring point for the constructed monitoring wells is unknown, water levels are presented in feet below land surface (bls). The deep bedrock well had a depth to water of 119.65 ft bls and a measured water column of less than 0.5 ft, indicating that the deeper part of the Galena-Platteville may be unsaturated at the Better Brite site. The shallow bedrock well, screened approximately 81 ft bls, had a depth to water of 55.97 ft bls. The water table was about 9.70 ft bls in this area. All of these water levels indicate large downward vertical gradients. However, with only one round of water levels collected, the temporal/seasonal variations in water levels remain unknown.

Table H2. Measured static water levels (hydraulic heads) in borehole BN-483 near the Better Brite Superfund Site, De Pere, Wis.

Packed interval	Packed interval (feet below land surface)	Stratigraphic unit	Date of test (month-day-year)	Static water level(feet above National Geodetic Vertical Datum of 1929)
A	[1]35-52	Galena Dolomite	11-18-93	585.28
B	50-70	Galena Dolomite and Decorah Formation	11-17-93	583.56
C	66-86	Decorah Formation	11-23-93	583.68
D	72-92	Decorah Formation	11-18-93	[2] 587.03
E	86-106	Decorah Formation	11-23-93	586.67
F	112-132	Platteville Formation	11-19-93	[2] 586.56
G	131-151	Platteville Formation	11-22-93	[2] 501.19
H	[3]160-169	Glenwood Formation	11-17-93	[2] 452.02

[1] Packed interval is less than 20 feet, extending from the bottom of the casing to 52 feet.

[2] Water level had not reached equilibrium and reported level probably is higher than the actual level.

[3] Packed interval is less than 20 feet, extending from 160 feet to total depth of the test well.

Geophysical logs

Fluid temperature, resistivity, and SP logs were run in borehole BN-483.

Fluid temperature

Temperature measurements (fig. 39) show a slight increase consistent with ground water entering the borehole from the wash out between the bottom of the casing and about 555 FANGVD29 (depth of 46 ft). The temperature log also shows changes that are consistent with flow into the St. Peter aquifer below about 451 FANGVD29 (depth of 150 ft) (Fred Paillet, U.S. Geological Survey, written commun., 1999).

Fluid resistivity

Fluid-resistivity measurements (fig. 39) also indicate that ground water is entering the borehole from the wash out between the bottom of the casing and about 555 FANGVD29 (depth of 46 ft). The fluid-resistivity log indicated no change over the remainder of the borehole.

Spontaneous potential

The slight decrease in SP readings at about 485 FANGVD29 is indicative of the major lithologic and stratigraphic change at this depth (fig. 39). The log appears to be responding to the lithologic change at this altitude, rather than to a permeable feature. The change in SP within the cased interval of the borehole at about 565-570 FANGVD29 may be related to the effects of flow from the underlying wash out.

Aquifer tests

Slug tests were completed at this site to estimate the Kh of the aquifer.

Slug tests

Slug tests were attempted at eight test intervals isolated with a packer assembly within borehole BN-483 (table H3). The test intervals generally were 20 ft in length. Four of the eight intervals were slug tested successfully, the remaining four intervals could not be slug tested because water levels did not reach hydrostatic equilibrium within 2-12 hours. The values determined for the three intervals of the unweathered dolomite range from about 0.0005 to 0.0034 ft/d. These low values are

Table H3. Horizontal hydraulic conductivity of selected depth intervals in borehole BN-483 near the Better Brite Site, De Pere, Wis., estimated from displacement/recovery (slug) tests

[--, no data]

Test interval (feet below land surface)	Horizontal hydraulic conductivity (feet per day)	Comments
35-52 [1]	2.0×10^{-1}	Fractured and weathered dolomite from 35 to 44 feet. Hydraulic conductivity of this zone probably considerably higher than 0.2 feet per day.
50-70	--	No measurable response to slug injection. Water level recovered only 0.19 ft over a period of about 14 hours after pumping this borehole interval dry.
66-86	5.0×10^{-4}	Low-quality data in first 20 seconds of slug test.
72-92	--	No slug test. Water level recovered about 3 feet over a period of about 14 hours after pumping this borehole interval dry.
86-106	3.4×10^{-3}	Low-quality data in first 30 seconds of slug test.
112-132	--	No slug test. Water level showed no measurable recovery for about 40 minutes after pumping this borehole interval dry.
131-151	1.9×10^{-3}	Low-quality data in first 30 seconds of slug test. Actual hydraulic conductivity value may be lower because static water level in tested interval still was dropping prior to the slug test.
160-169 [2]	--	No slug test. Water level showed no measurable recovery over a period of 4 hours after pumping this borehole interval dry.

[1] Packed interval is less than 20 feet, extending from the bottom of the casing to 52 feet.

[2] Packed interval is less than 20 feet, extending from 160 feet to total depth of the test well.

more indicative of a confining unit than and aquifer (Freeze and Cherry, 1979, p. 29). The Kh of the four intervals that could not be tested are believed to be less than 0.0005 ft/d. The presence of shaley zones and partings in the core indicates that the vertical hydraulic conductivity of the unweathered dolomite probably is less than the Kh.

The estimated Kh of the test interval that includes the weathered dolomite just below the bottom of the casing is about 0.2 ft/d (table H3). Because less than half of the 20-ft test interval is the weathered section, its conductivity probably is appreciably greater than the 0.2 ft/d estimated for the entire interval.

Location of contaminants

Water samples were collected only from the uppermost test interval isolated with a packer assembly at 549-566 FANGVD29 (depth of 35-52 ft). The low permeability of the unweathered dolomite in the remaining test intervals prevented the collection of water-quality samples because the test intervals were pumped dry during purging and did not recover within 2-12 hours. No inorganic constituents of environmental concern were detected in the sample. Toluene was the only VOC detected, and was found in estimated concentrations of 1 and 2 μg/L in duplicate samples (Batten and others, 1997). However, toluene at low concentrations may be present because of field or laboratory contamination, and this detection may not be representative of in-situ water quality.

Water-quality samples from the monitoring wells completed in borehole BN-483 were taken by Simon Hydro-Search, Inc. in October 1994. The deep bedrock well could not be sampled because an insufficient volume of water was available, even after the well was allowed to recover for 1 week. Samples from the shallow bedrock well had higher concentrations of chromium, lead, manganese and zinc relative to the concentrations in the samples obtained by use of the packer assembly. However, this difference could be related to sampling method (bailers were used that could artificially increase turbidity) indicated by the color and clarity of the water, as well as the elevated concentrations of aluminum and potassium. No VOC's were detected in these samples (Simon Hydro-Search, Inc., 1995).

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