U.S. DEPARTMENT OF THE INTERIOR
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Geology, Hydrology, and Results of Tracer Testing in the Galena-Platteville Aquifer at a Waste-Disposal Site Near Byron, Illinois

By Robert T. Kay, Douglas J. Yeskis, Scott T. Prinos, William S. Morrow, and Mark Vendl

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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

District Chief
U.S. Geological Survey
221 North Broadway Avenue
Urbana, Illinois 61801

Copies of this report can be purchased from:

U.S. Geological Survey
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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
	Length	
inch (in)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	0.4047	hectare
	Volume	
gallon (gal)	3.785	liter
	Flow rate	
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
gallon per minute (gal/min)	3.785	liter per minute
foot per day (ft/d)	0.3048	meter per day
foot per minute (ft/min)	0.3048	meter per minute
	Hydraulic conductivity*	
foot per day (ft/d)	0.3048	meter per day
	Hydraulic gradient	
foot per foot (ft/ft)	0.3048	meter per meter
	Transmissivity**	
foot squared per day (ft^2/d)	0.09290	meter squared per day
	Pressure	
pound per square inch (lb/in^2)	6.895	kilopascal
	Leakance	
foot per day per foot [ft/d]/ft	0.3048	meter per day per meter

* **Hydraulic conductivity:** Foot per day is the mathematically reduced term of cubic foot per day per square foot of aquifer cross-sectional area.

****Transmissivity:** The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/(ft^2)ft$]. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

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

$$°F = (1.8 \times °C) + 32$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the 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 sea level.

Abbreviated water-quality units: Chemical concentration is given in metric units. Chemical concentration is given in milligrams per liter (mg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water.

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By Robert T. Kay[1], Douglas J. Yeskis[2], Scott T. Prinos[1], William S. Morrow[1], *and* Mark Vendl[2]

Abstract

A study was conducted by the U.S. Geological Survey and the U.S. Environmental Protection Agency of the geohydrology of the dolomite bedrock at a waste-disposal site near Byron, Illinois. The study was designed to identify and characterize the flow pathways through the bedrock aquifer beneath the site. The geologic units of concern at the site are the Glenwood Formation of the Ancell Group, and the Platteville and Galena Groups. These deposits compose the Galena-Platteville aquifer and the underlying Harmony Hill Shale semiconfining unit. The Galena-Platteville aquifer is an unconfined aquifer.

Geophysical logging, water levels, and aquifer-test data indicate the presence of interconnected, hydraulically active fractures in the middle of the Galena-Platteville aquifer (the upper flow pathway), and a second set of hydraulically active fractures (the lower flow pathway). The lower flow pathway may be present through much of the site. Few hydraulically active fractures are present in the upper part of the aquifer near the center of the site, but appear to be more numerous in the upper part of the aquifer in the western and northeastern parts of the site.

Water-level data obtained during the tracer test indicate that pumping effects were present near the pumped wells. Pumping effects may have been present at several wells located along directions of identified fracture orientation from the pumped well. The upper part of the aquifer did not appear to be hydraulically well connected to the flow pathways supplying water to the pumped well. Large background changes in water levels obscured the effects of pumping and prevented calculation of aquifer properties.

The velocity of the bromide tracer through the lower flow pathway under the hydraulic gradient resulting from the pumping was about 152 feet per day. Solution of the Darcy velocity equation results in a calculated effective porosity for this interval of 3.5 percent, indicating hydraulic interconnection between the fractures and the aquifer matrix. Ground-water velocity through the lower flow pathway was calculated to be 15.4 feet per day under hydrostatic conditions.

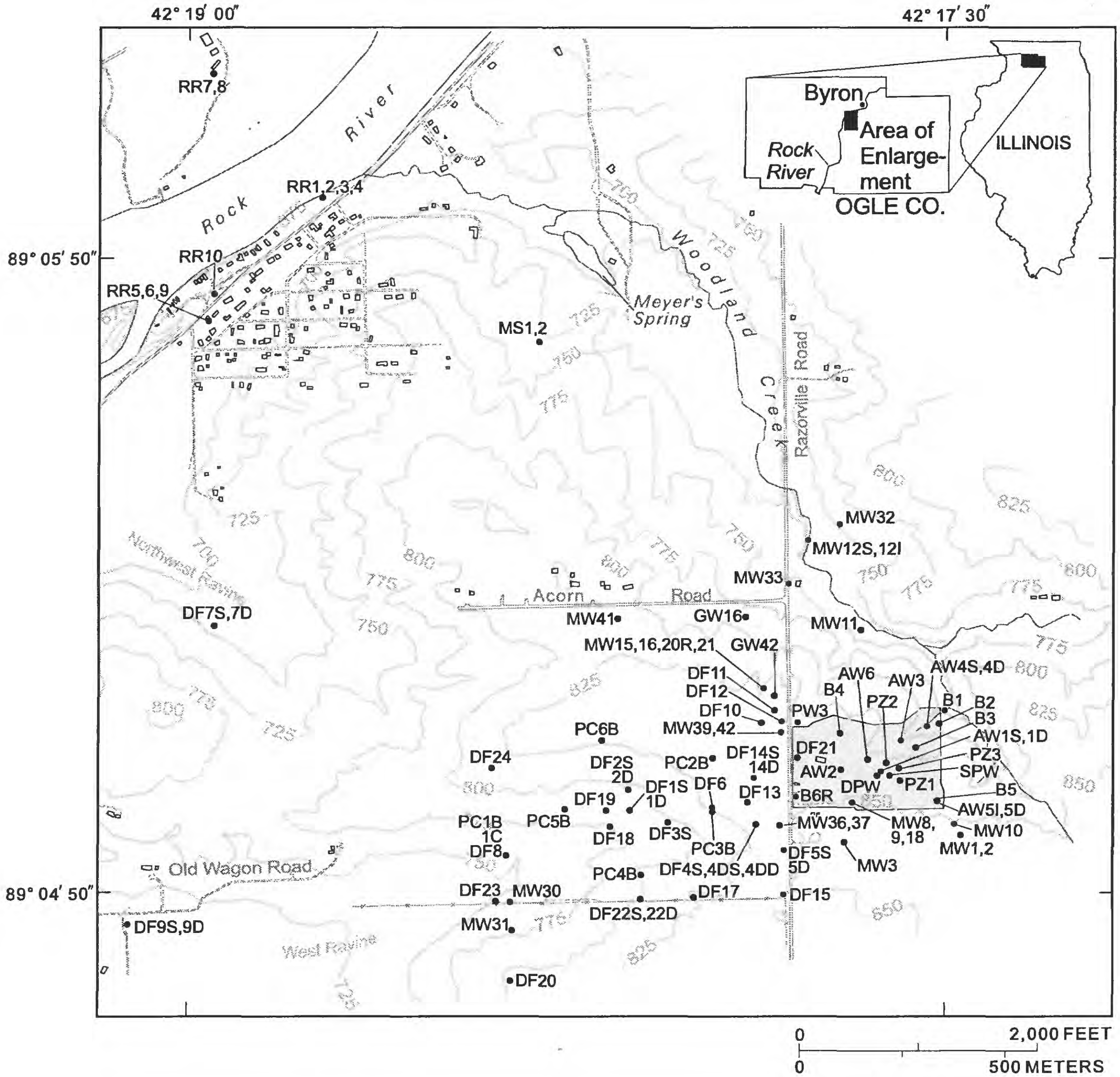
INTRODUCTION

The U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency (USEPA), conducted a study of the geohydrology of the dolomite bedrock at a waste-disposal site in rural Ogle County, northern Illinois. The site is about 3 mi southwest of the town of Byron (fig. 1). The study area corresponds to a 20-acre fenced area east of Razorville Road, formerly used as an automobile and junk salvage yard (fig. 1). A variety of industrial and liquid wastes were deposited in the study area in the 1960's and early 1970's.

The objectives of the study were to locate the pathways of ground-water flow and contaminant migration in the study area and to characterize the hydraulic properties of these pathways. This information is required to assess options for ground-water remediation.

The study was divided into four major components: (1) geophysical logging using conventional logging techniques, (2) geophysical logging using cross-hole

[1] U.S. Geological Survey
[2] U.S. Environmental Protection Agency



EXPLANATION

APPROXIMATE STUDY AREA BOUNDARY

775 — TOPOGRAPHIC CONTOUR--Shows altitude of land surface in feet. Contour interval is 25 feet. Datum is sea level

•DF20 — MONITORING WELL LOCATION AND NAME

Figure 1. Location of the study area and monitoring wells, near Byron, Illinois.

ground-penetrating radar tomography and single-hole reflection, (3) collection of static water-level measurements, and (4) tracer testing. Conventional geophysical logging techniques (natural gamma, acoustic televiewer, heat-pulse flowmeter) were used to determine stratigraphy, fracture orientation, and the depth of the fractures through which ground water is flowing at the wells. Single-hole reflection logs and cross-hole radar tomography were used to identify the location, extent, and orientation of lithologic changes and secondary-permeability features in the bedrock between monitoring wells at the site. Static water-level measurements were collected to identify the vertical and horizontal directions of ground-water flow in the study area and to provide insight as to the spatial distribution of aquifer permeability. Tracer testing was used to determine the effective porosity and rate of ground-water flow through one of the flow pathways.

Purpose and Scope

This report describes the results of a study designed to characterize the geology and hydrology of the uppermost bedrock aquifer underlying a waste-disposal site near Byron, Ill. In addition to a discussion of the geology and hydrology of the study area, the results of geophysical logging and tracer testing are presented. The pathways of ground-water flow in the center of the study area are identified and the effective porosity of one of the flow pathways, as well as the rate of ground-water flow under ambient and pumped conditions is calculated.

Acknowledgments

The authors thank William Bolen, Project Manager, U.S. Environmental Protection Agency for his assistance securing access to the study area so that this investigation could be done. Frederick Paillet, Richard Hodges, James Nicholas, John Lane, and Charles Avery of the U.S. Geological Survey, and James Ursic of the U.S. Environmental Protection Agency are thanked for their assistance in the planning and execution of this study.

GEOLOGY

The bedrock geologic units of concern to this investigation are sandstone, shale, and dolomite of Ordovician age. From oldest to youngest, these units are the Glenwood Formation of the Ancell Group, and the Platteville and Galena Groups (fig. 2). These bedrock deposits are unconformably overlain in the study area by glacial deposits of Quaternary age. The deposits of the Platteville and Galena Groups and the Glenwood Formation are thickest beneath the study area and have been partially or completely removed by erosion near Woodland Creek and the Rock River (fig. 1). The stratigraphic nomenclature used in this report is that of the Illinois State Geological Survey (Willman and others, 1975, p. 61–80 and 218–230).

The Glenwood Formation is a highly heterogeneous unit of sandstone, dolomite, and shale that overlies the St. Peter Sandstone. The base of the Glenwood Formation consists of a poorly sorted, well-rounded, dolomitic quartz sandstone, known as the Kingdom Sandstone Member (fig. 2). The Kingdom Sandstone Member typically is about 16 ft thick beneath the study area (Michael Sargent, Illinois State Geological Survey, written commun., 1993).

The Kingdom Sandstone Member grades upward into a massive argillaceous dolomite known as the Daysville Member of the Glenwood Formation. The Daysville Member is about 16 ft thick beneath the study area (Michael Sargent, Illinois State Geological Survey, written commun., 1993). The uppermost unit of the Glenwood Formation is a gray-green shale known as the Harmony Hill Shale Member. The Harmony Hill Shale Member is about 5 ft thick beneath the study area.

The Platteville and Galena Groups are the uppermost bedrock deposits in the study area and consist of fractured, partly cherty, partly argillaceous dolomite. Shale partings and argillaceous intervals are common throughout these deposits. The two groups are subdivided into formations primarily based on variations in clay and silt content (Willman and Kolata, 1978, p. 7). The primary porosity of the dolomite deposits that compose the Platteville and Galena Groups in and around the study area was calculated to range from about 4 to 22 percent with a median value of about 10 percent (fig. 2) (Patrick Mills, U.S. Geological Survey, written commun., 1993; Kay and others, 1997).

Natural-gamma logging measures the amount of natural-gamma radiation emitted by the surrounding rock. The amount of natural-gamma radiation emitted by the rock is generally a function of the clay content of the rock. Because the formations in the Galena and Platteville Groups are differentiated based partially on variations in clay content, natural-gamma logging is an

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
				Loess, windblown silt, leached	0-15		
				Sand and silt, windblown, leached	0-15		
				Outwash, sand and gravel	0-180		
				Till, brown silty clay to clayey silt with few boulders, stiff	0-26		
				Silt, brown to gray, calcareous, stiff	0-10		
				Till, brown silty sand with few boulders, very stiff to hard	0-25		
ORDOVICIAN	GALENA	DUNLEITH		Dolomite, buff, finely crystalline, thin to medium bedded with white and gray chert nodules, green shale partings in lower portion	0-70	Galena-Platteville aquifer	10.3
		GUTTENBERG		Dolomite, vuggy, with red shale partings	0-7		6.4
	PLATTEVILLE	QUIMBYS MILL		Dolomite, buff and gray, occasional white chert, mottled with numerous shale partings	0-20		10.2
		NACHUSA		Dolomite, pure to slighty argillaceous, vuggy, thickly bedded to massive, occasional white chert	0-25		9.5
		GRAND DETOUR		Dolomite, mottled buff and dark gray, finely crystalline, medium to massive bedded, thin gray and reddish-brown shale partings	0-45		11.3
		MIFFLIN		Dolomite, mottled, thinly bedded, thin gray or green shale partings	0-15		9.4
		PECATONICA		Dolomite, mottled, medium bedded	0-33		9
	ANCELL	GLENWOOD	HARMONY HILL	Shale, green, gray, and brown, thinly laminated	0-5	Harmony Hill Shale semiconfining unit	Unknown
			DAYSVILLE	Shale, brown and gray, sandy Dolomite, greenish-gray, fine-grained	0-16		18
			KINGDOM SANDSTONE	Dolomitic sandstone, greenish-gray	0-16	St. Peter aquifer	16
		ST. PETER SANDSTONE		Sandstone, white, coarse- to medium-grained, quartzose, friable	approximately 420		14

Figure 2. Generalized geologic column showing stratigraphy, geohydrologic units, and median primary porosity of Ordovician and Quaternary deposits, near Byron, Illinois (modified from Gilkeson and others, 1977).

effective method for differentiating the formations in the study area. The stratigraphy of the Galena and Platteville Groups in the study area was obtained by comparing stratigraphic descriptions obtained from cores collected from the borings at wells MW2 and AW1D (Michael Sargent, Illinois State Geological Survey, written commun., 1992) with the natural-gamma response of the formations at these wells. Natural-gamma logs from wells MW2 (fig. 3) and AW1D were compared with natural-gamma logs from wells SPW, PZ1, PZ2, PZ3, and AW1S to determine the stratigraphy at these locations (figs. 4–9). Elevated counts per second readings at about 709 and 736 ft above sea level in well SPW (fig. 4) are caused by partial infilling of fractures by clay deposits. The natural-gamma signal at these depths does not reflect the original bedrock stratigraphy at well SPW. Stratigraphy was correlated between wells to determine the stratigraphy in the center of the study area (figs. 9, 10).

The Pecatonica Formation is the basal unit of the Platteville Group (figs. 2, 10) and is composed of brown, finely vuggy, medium bedded, mottled dolomite. This deposit unconformably overlies the Harmony Hill Shale Member of the Glenwood Formation. The Pecatonica Formation is about 33 ft thick in the study area.

The Mifflin Formation is composed of thinly bedded, mottled dolomite with numerous shale partings. The Mifflin Formation unconformably overlies the Pecatonica Formation and is about 15 ft thick in the study area (figs. 2, 10). The unconformity between the Pecatonica and Mifflin Formations is distinguished by a layer of iron-stained pyrite.

The Grand Detour Formation conformably overlies the Mifflin Formation. The Grand Detour Formation is composed of a lower, medium-grained, medium-bedded, mottled dolomite with little clay and an upper, thinly bedded, argillaceous dolomite with some fossils. The argillaceous deposits in the upper part of the formation are prominent features on the natural-gamma logs corresponding to intervals of elevated counts per second (figs. 3–8). The thickness of the Grand Detour Formation is about 45 ft beneath the study area (figs. 2, 10).

The Nachusa Formation conformably overlies the Grand Detour Formation and is composed of a thickly bedded to massive, fine-to-medium grained, vuggy dolomite (fig. 10). The middle part of the Nachusa Formation is slightly argillaceous. The upper and lower parts of the formation are composed of pure dolomite. This formation is about 25 ft thick in the study area.

The Quimbys Mill Formation is the uppermost deposit of the Platteville Group. This formation unconformably overlies the Nachusa Formation. The Quimbys Mill Formation is composed of mottled dolomite with numerous shale partings and is about 20 ft thick in most of the study area (figs. 2, 10).

The Guttenberg Formation is the basal unit of the Galena Group and is composed of vuggy dolomite with thin beds of red or brown shale. These shale beds are prominent features on the natural gamma logs corresponding to elevated counts per second readings (figs. 3–8). The Guttenberg Formation typically is about 7 ft thick beneath the center and southeastern parts of the study area near the AW1, MW1/MW2, and B5/AW5 well clusters and at wells AW2, PZ1, PZ2, PZ3, SPW, B3, and AW6 (fig. 9). The Guttenberg Formation may have been substantially or completely eroded during the Ordovician System in the western part of the study area near the MW18 well cluster and wells B6R, DF21, PW3, and possibly well B4 (U.S. Environmental Protection Agency, 1994, appendix A; Kay and others, 1997, p. 23). Increased development of fractures and solution openings in the Galena and Platteville deposits may be present in areas where there is substantial erosion of the Guttenberg Formation (Kay and others, 1997, p. 23).

The surficial bedrock deposit in most of the study area is the Dunleith Formation of the Galena Group (figs. 2, 10). The Dunleith Formation is composed of 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. The base of the Dunleith Formation unconformably overlies the Guttenberg Formation where the Guttenberg Formation is present and unconformably overlies the Quimbys Mill Formation where the Guttenberg Formation is absent. The Dunleith Formation is about 70 ft thick in most of the study area, but is thinner or absent in the northeastern part of the study area where it has been partially or completely removed by post-Ordovician System erosion (fig. 1).

Quaternary silt and clay deposits unconformably overlie the Dunleith Formation throughout the study area (figs. 2, 10). Quaternary deposits generally are less than 15 ft thick in the study area.

Acoustic-televiewer logs were run in wells SPW, PZ1, PZ2, PZ3, and AW1S to obtain a more complete characterization of the fractures in the dolomite at the wells (Frederick Paillet, U.S. Geological Survey, written commun., 1993) (figs. 4–8). A series of nearly ver-

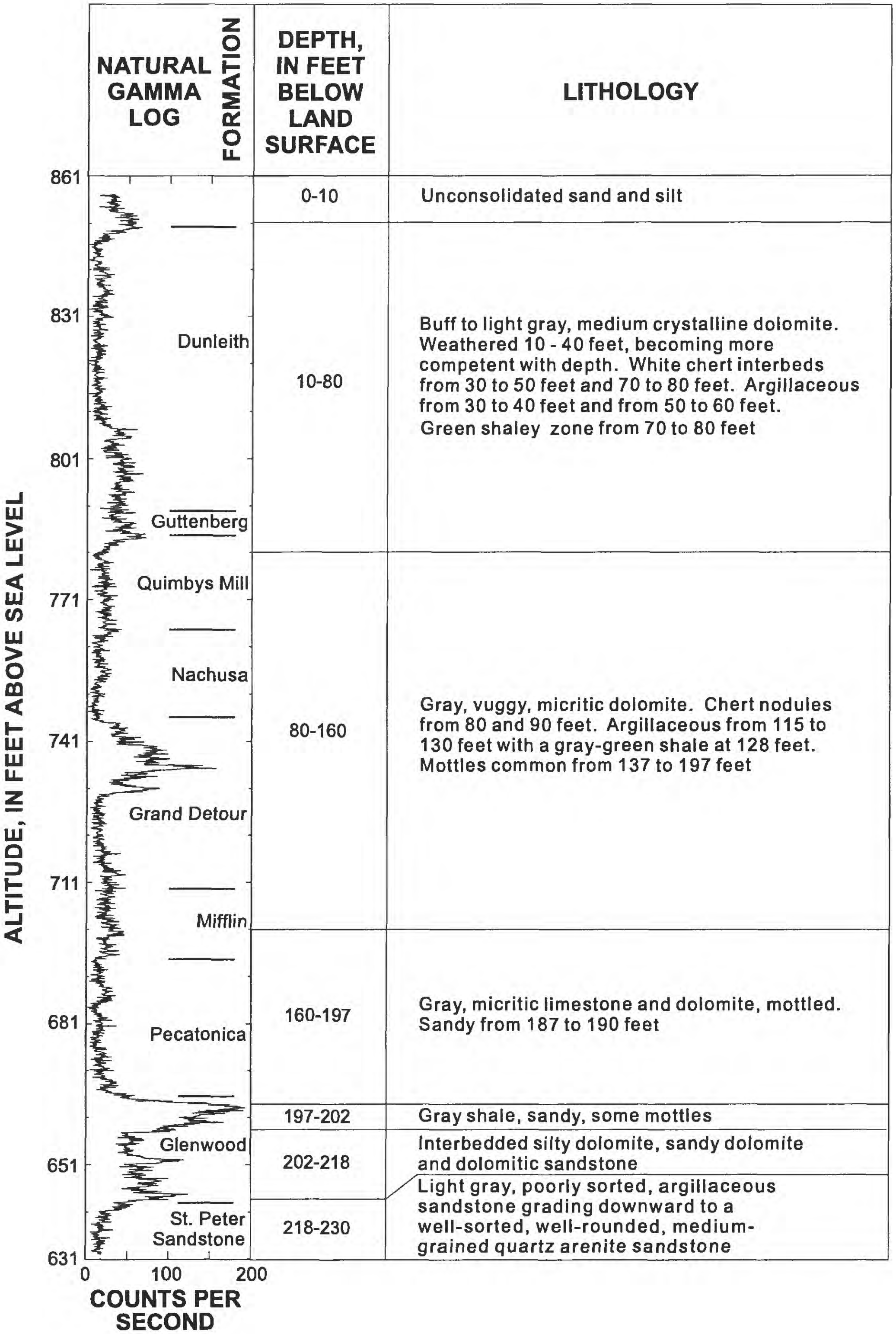


Figure 3. Natural-gamma log, lithologic log, and generalized stratigraphic section for well MW2, near Byron, Illinois.

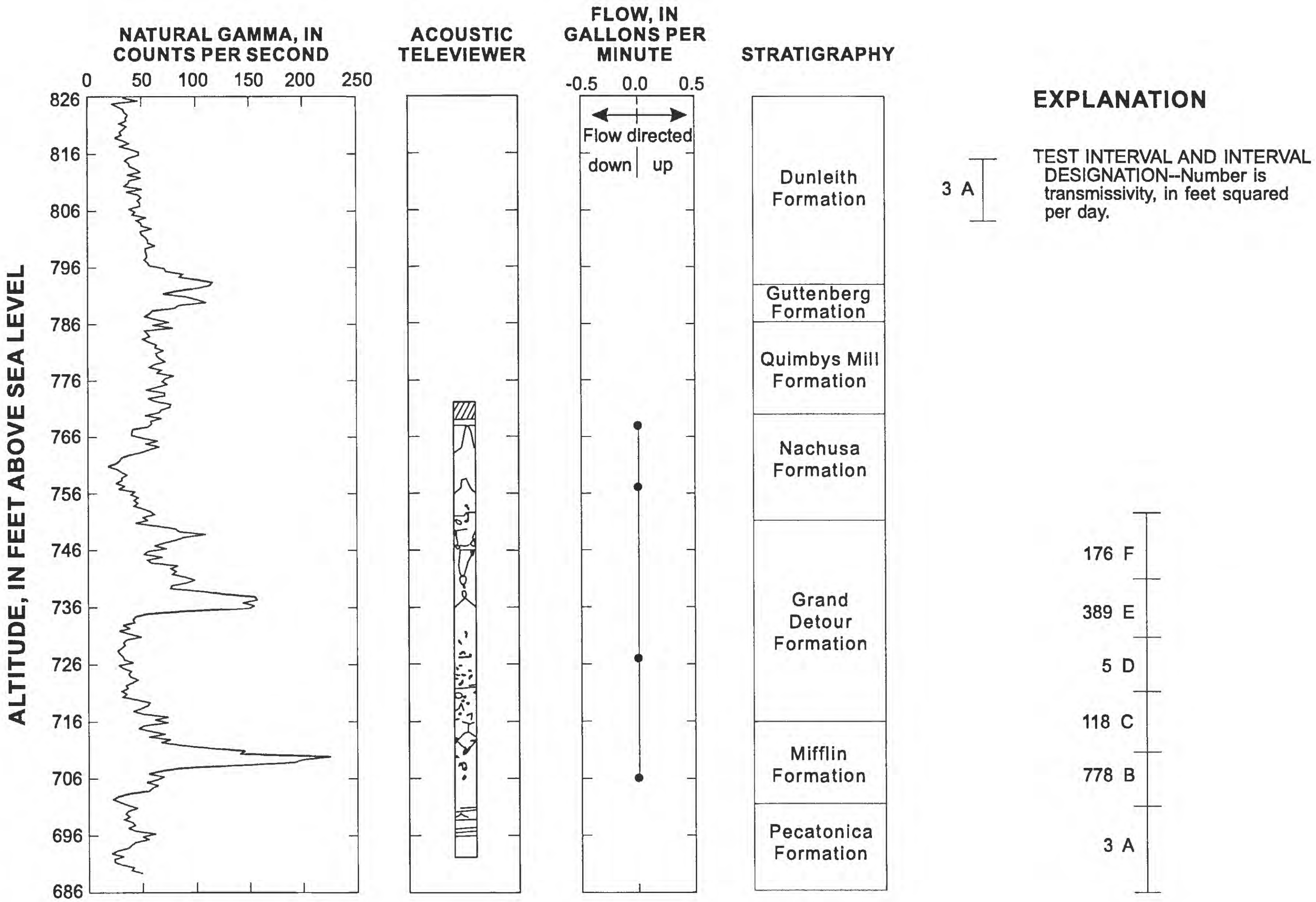


Figure 4. Natural-gamma, acoustic-televiewer, and flowmeter logs; stratigraphy; and transmissivity in the test intervals isolated with a packer assembly for well SPW, near Byron, Illinois.

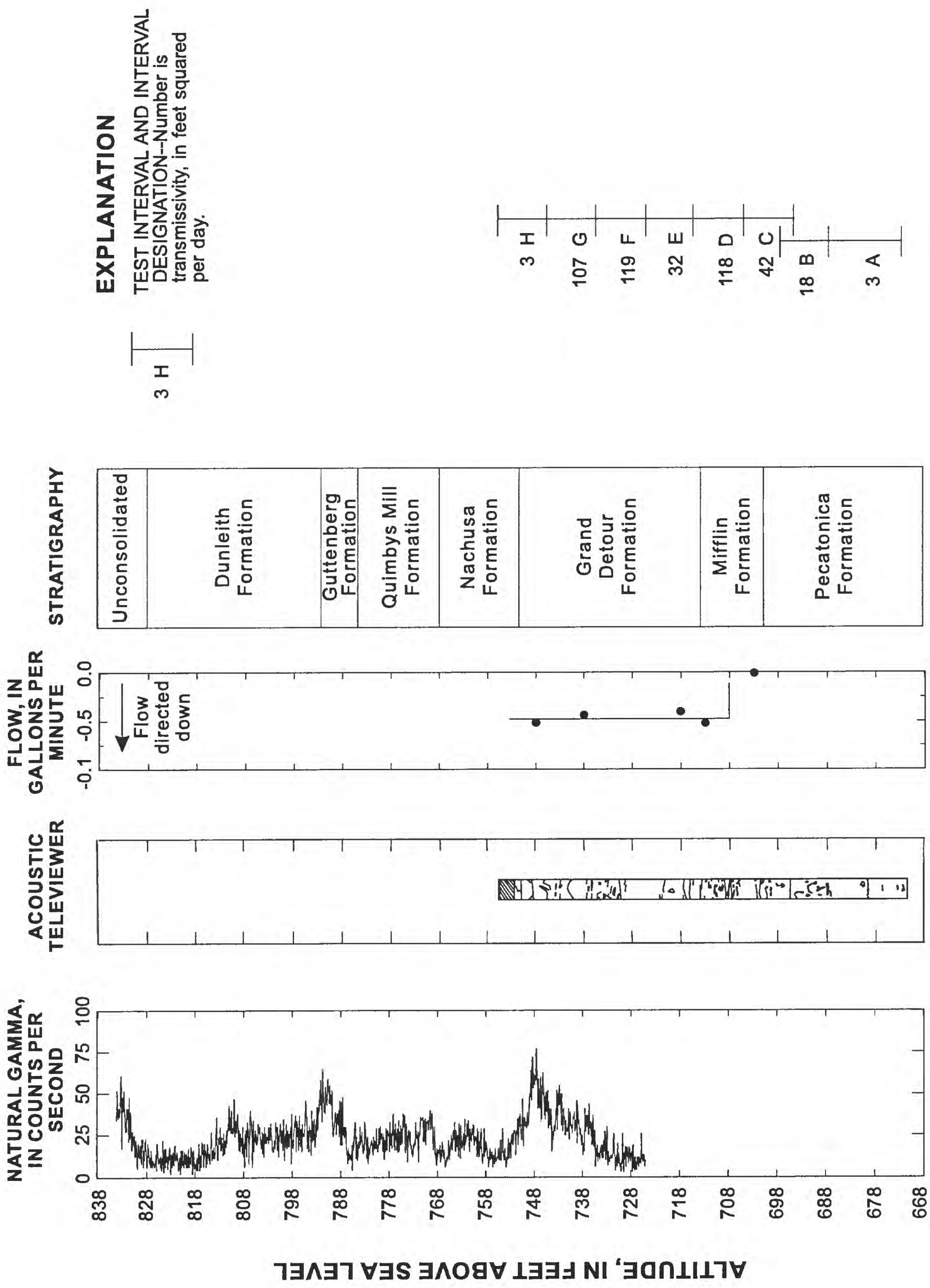


Figure 5. Natural-gamma, acoustic-televiewer, and flowmeter logs; stratigraphy; and transmissivity in the test intervals isolated with a packer assembly for well PZ1, near Byron, Illinois.

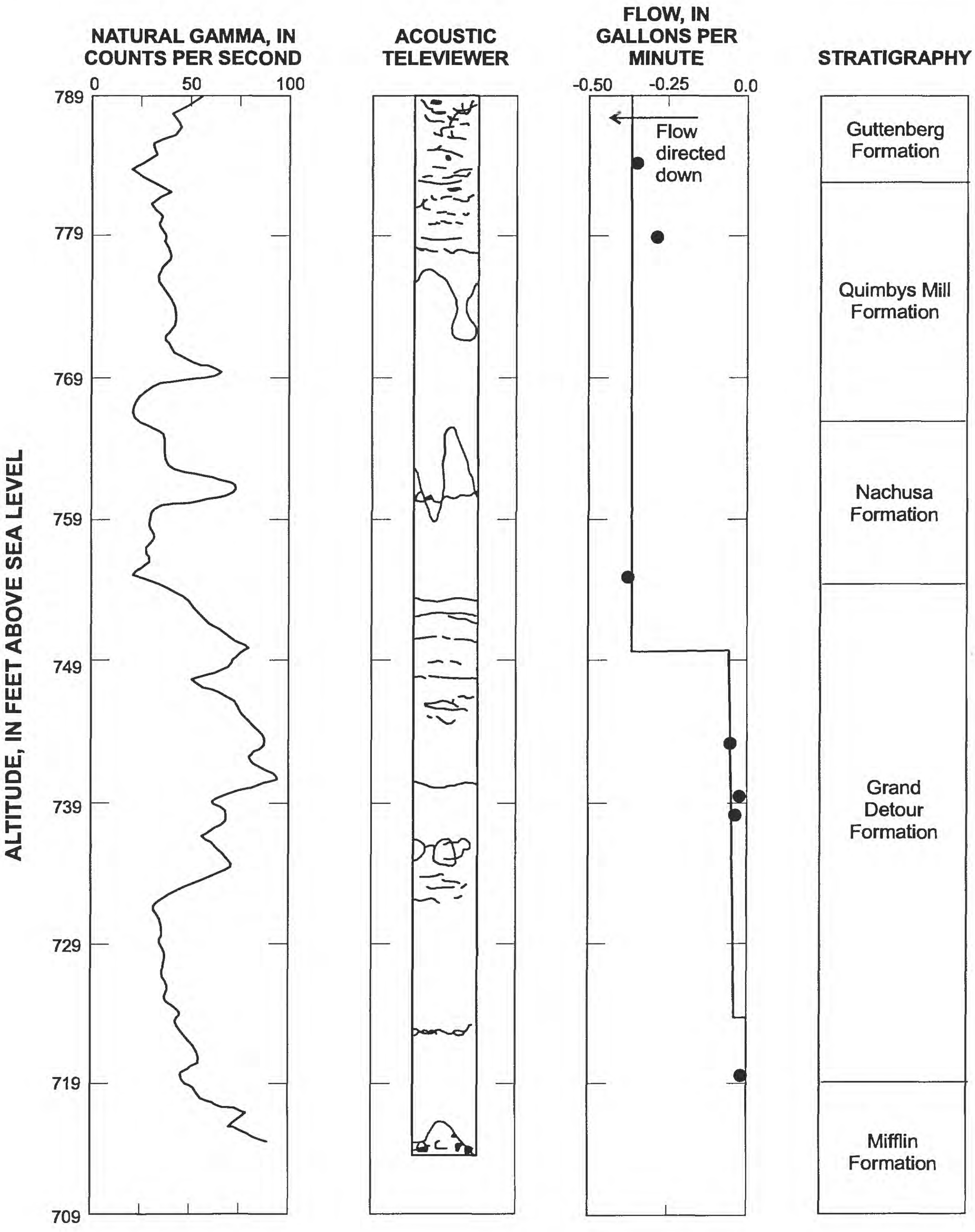


Figure 6. Natural-gamma, acoustic-televiewer, and flowmeter logs, and stratigraphy for well PZ2, near Byron, Illinois (log starts at approximately 40 feet below land surface).

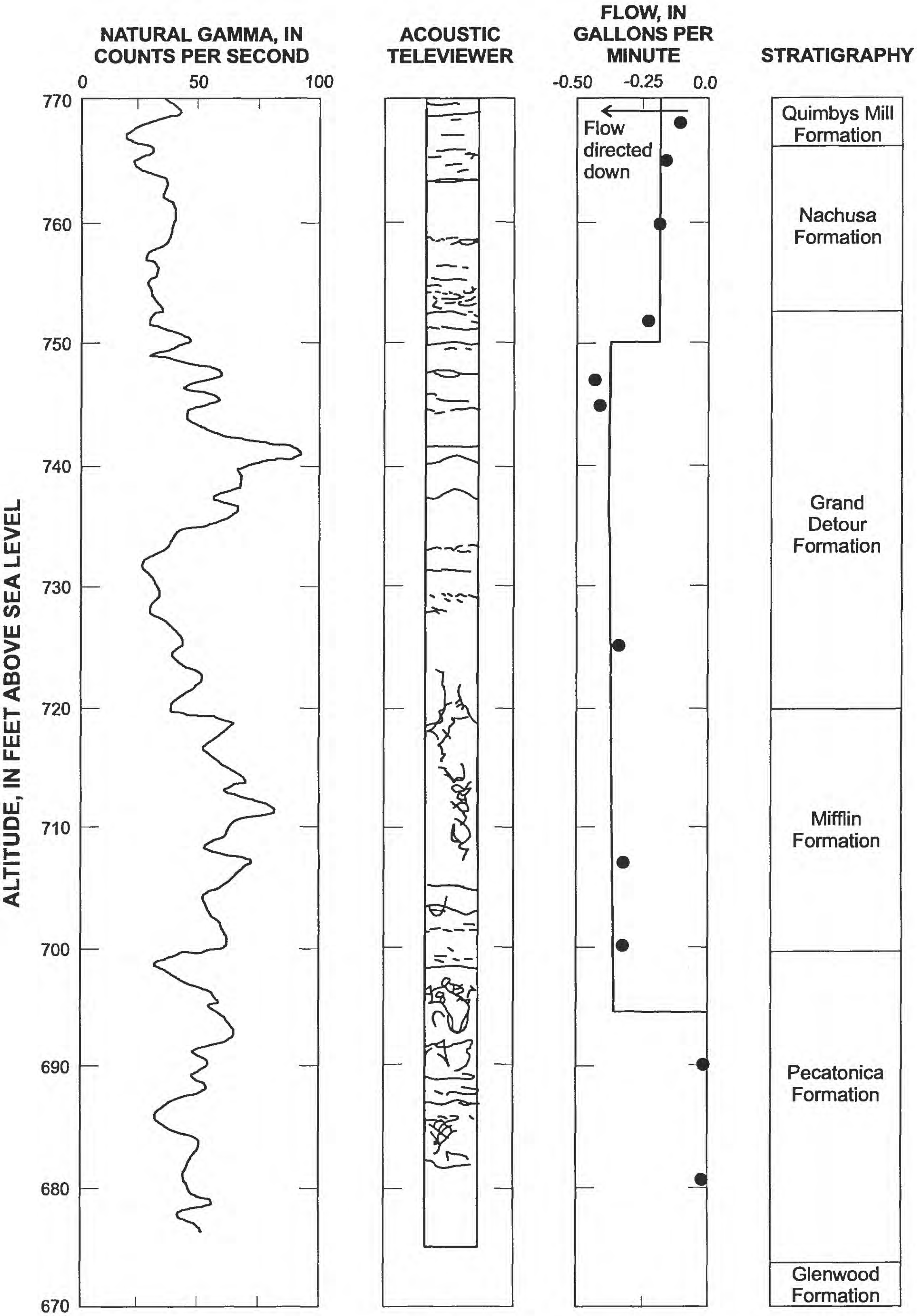


Figure 7. Natural-gamma, acoustic-televiewer, and flowmeter logs, and stratigraphy for well PZ3, near Byron, Illinois (log starts at approximately 60 feet below land surface).

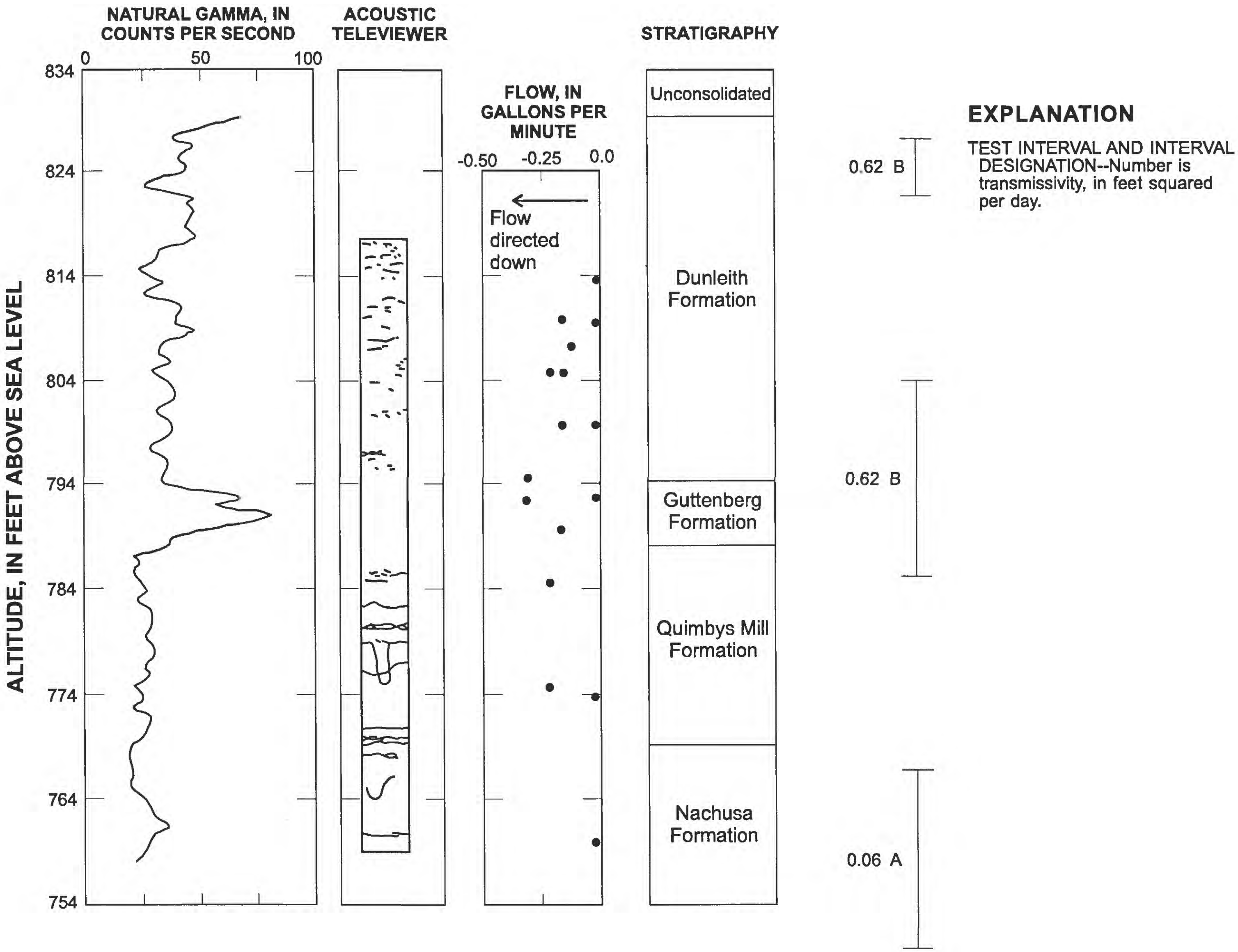


Figure 8. Natural-gamma, acoustic-televiewer, and flowmeter logs; stratigraphy; and transmissivity in the test intervals isolated with a packer assembly for well AW1S, near Byron, Illinois.

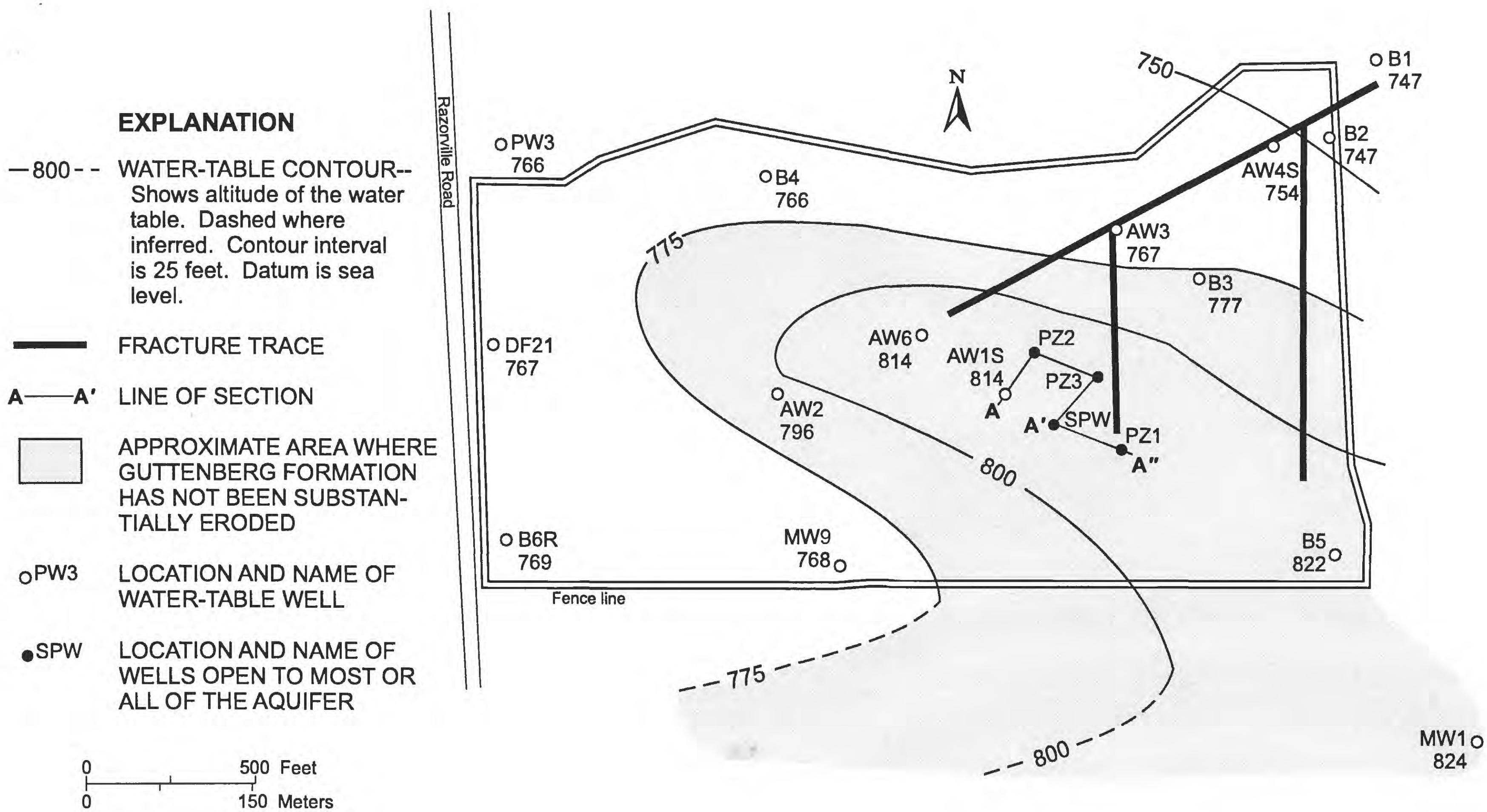


Figure 9. Water-table altitude, fracture traces, and lines of geologic section, near Byron, Illinois, July 8, 1993.

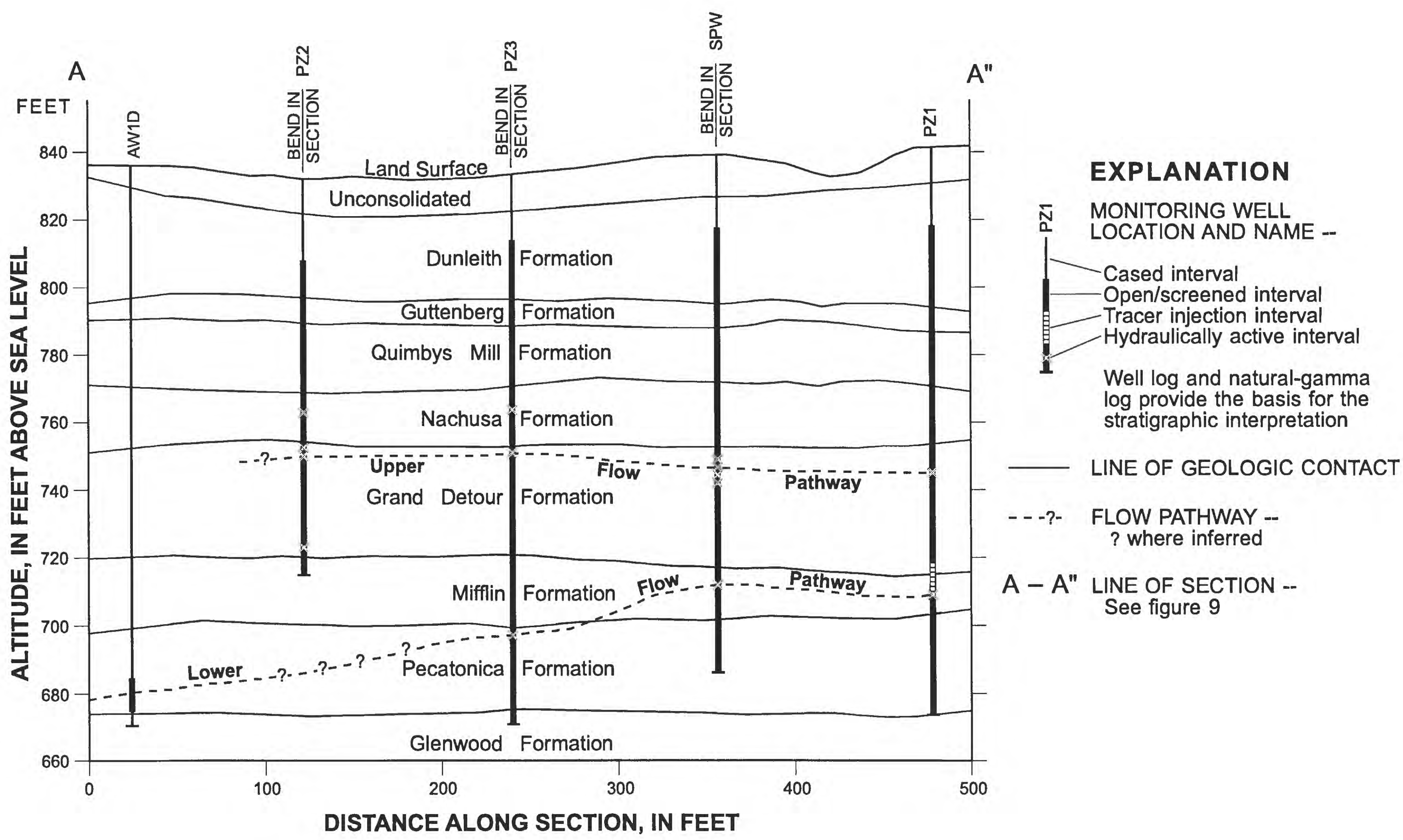


Figure 10. Geologic section A-A" near Byron, Illinois.

tical fractures were detected at well SPW and several inclined fractures were identified at the other wells (table 1). The dip of these inclined fractures varied between 11° and 87° below horizontal. Most of these inclined fractures are oriented between N 45° W and N 70° W and N 0° E and N 30° E (Frederick Paillet, U.S. Geological Survey, written commun., 1993). The inclined fractures generally are oriented parallel to the dominant orientation of the inclined fractures in the dolomite in this area (N 60° W) (Sargent and Lundy, Inc., and Dames and Moore, Inc., 1975) or the north-south trending fracture trace (a surface topographic depression outlining the location of an underlying vertical fracture) present near wells AW3 and PZ3 (fig. 9).

Single-hole directional radar reflection surveys were done in wells SPW, PZ1, PZ2, PZ3, and AW1S to detect the presence and orientation of reflectors potentially associated with lithologic changes, individual fractures, or fracture zones in the bedrock. The single-hole directional reflection surveys were capable of identifying reflectors up to 45 ft away from the wells (Lane and others, 1994, p. 8). Between three and five reflectors were identified from the processed data in the vicinity of wells AW1S, PZ1, PZ2, PZ3, and SPW (table 2) (Niva, 1993). All reflectors identified at well AW1S are very weak and may not be present (John Lane, U.S. Geological Survey, written commun., 1994).

The depths of 14 of the reflectors identified from the single-hole directional radar surveys corresponded to depths of stratigraphic contacts or fractures identified from the natural-gamma or acoustic-televiewer logs, indicating that at least some of the reflectors represent fractures or lithologic changes (tables 1, 2) (figs. 4–8, 10). However, the absence of an identified fracture or lithologic change at the depth predicted by interpretation of the reflector data does not necessarily indicate that the reflector is not associated with a fracture or some variation in lithology. The fracture or variation in lithology associated with the reflector may terminate before it intersects the well, its orientation may change, or the intersection may be above or below the bottom of the well.

The dip of the reflectors ranges from about 25° to 66° below horizontal (tables 1, 2). The strike of the reflectors tends to be randomly oriented. The orientation of the reflectors shows poor agreement with the orientation of the associated fractures determined from the acoustic-televiewer logs. Dip values determined from the reflection surveys tend to be substantially less than the values determined from televiewer logging (tables 1, 2). Strike values determined from the reflection surveys typically vary by more than 40° from the strike values identified from the acoustic-televiewer logging.

Cross-hole radar surveys were done between the AW1S–PZ2, PZ2–PZ3, and PZ3–SPW well pairs (Niva, 1993) (fig. 9). Cross-hole surveys measure the velocity (fig. 11) and attenuation (fig. 12) of the radar pulse between the two surveyed wells. The velocity of the radar pulse through the dolomite primarily is affected by the presence of water-bearing fractures in the dolomite. The attenuation of the pulse is primarily affected by variations in the resistivity of the dolomite. Areas of low signal velocity and high signal attenuation identified from the cross-hole surveys can be interpreted as lithologic boundaries or water-saturated fracture zones. Processing of the velocity and attenuation data allows determination of the location and areal extent of the features between the well pairs.

The cross-hole radar data indicate an upper zone of low velocity and high attenuation along all three profiles at about 740 ft above sea level (figs. 11, 12). A lower zone of low velocity and high attenuation is present at about 710 ft above sea level at well SPW decreasing to about 690 ft above sea level near well PZ3 (Lane and others, 1994). The other cross-hole surveys do not extend deep enough into the dolomite to determine the full extent of the lower zone. The upper zone approximately corresponds to the argillaceous deposits in the upper part of the Grand Detour Formation that are present throughout the study area. The lower zone approximately corresponds to a clay-filled fractured interval at an altitude of about 709 ft above sea level at well SPW and a fractured interval in the Pecatonica Formation at well PZ3, indicating that the lower zone is a fractured interval that is continuous between these wells.

HYDROLOGY

The geohydrologic units of concern to this investigation are the Galena-Platteville aquifer and the Harmony Hill Shale semiconfining unit (fig. 2). The Galena-Platteville aquifer is composed of the dolomite of the Platteville and Galena Groups. The Harmony Hill Shale semiconfining unit is composed of the argillaceous dolomite of the Daysville and Harmony Hill Shale Members of the Glenwood Formation.

The Galena-Platteville aquifer is an unconfined, double-porosity aquifer characterized by a primary

Table 1. Summary of data for inclined fractures identified during acoustic-televiewer logging, near Byron, Illinois (Frederick Paillet, U.S. Geological Survey, wriiten commun., 1993)

	Fracture data		
Well name	**Strike of fracture (degrees from magnetic north)**	**Dip of fracture (degrees from horizontal)**	**Altitude of intersection with borehole (feet above sea level)**
SPW	324	87	765
	270	83	756
	315	39	752
	120	87	745
	288	77	737
	126	77	711
	135	87	703
PZ1	108	39	750
	108	22	749
	126	31	746
	270	45	740
	171	72	735
	198	31	688
PZ2	216	85	775
	315	86	763
	288	73	715
PZ3	0	11	768
	0	31	744
	315	54	741
	315	58	737
	306	77	719
	153	84	716
	333	67	709
	153	78	702
	153	80	694
AW1S	18	63	777
	117	76	776
	27	80	766

Table 2. Summary of reflector data identified during single-hole directional reflection surveys, and fracture data obtained during acoustic-televiewer surveys, near Byron, Illinois (from Niva, 1993; Lane, 1994)
[N/A, not analyzed]

	Reflector data			
Well name	Strike of reflector (degrees from magnetic north)	Dip of reflector (degrees from horizontal)	Projected altitude of intersection with well bore (feet above sea level)	Potential cause of reflection
SPW	320	24	765	Fracture
	100	37	736	Fracture
	N/A	53	720	Unknown
	250	44	709	Fracture
PZ1	120	61	764	Unknown
	210	32	736	Fracture
	70	51	718	Fracture
	190	27	708	Fracture
PZ2	10	37	787	Guttenberg/Quimbys Mill contact or fracture
	260	44	778	Fracture
	40	46	719	Grand Detour/Mifflin contact
PZ3	200	46	784	Unknown
	90	44	746	Fracture?
	250	58	681	Unknown
	280	33	677	Pecatonica/Glenwood contact
	170	65	643	
AW1S	N/A	27	787	Guttenberg/Quimbys Mill contact
	N/A	34	770	Quimbys Mill/Nachusa contact or fracture
	80	42	762	Fracture
	270	89	N/A	Unknown

porosity associated with the porous rock matrix, and a secondary porosity associated with the fractures in the dolomite (Kay and others, 1989). The elements of primary and secondary porosity are hydraulically connected. Most ground-water flow is through the fractures, vugs, and solution openings in the dolomite, whereas most ground-water storage is in the porous matrix.

Slug tests and constant-discharge aquifer tests were done during previous investigations in and near the study area to quantify the hydraulic properties of the Galena-Platteville aquifer and to help identify the fracture pathways through which ground water was flowing (Kay and others, 1989; Kay and others, 1997). Transmissivity values were determined from horizontal hydraulic conductivities obtained from slug tests done in test intervals isolated with a packer assembly in wells AW1S, SPW, and PZ1 (Kay and others, 1997, table 5). Horizontal hydraulic conductivities from test intervals open to the Galena deposits were multiplied by 21 ft, the saturated thickness of the Galena deposits at well AW1S. Horizontal hydraulic conductivities from test intervals open to the Platteville deposits were multiplied by 118 ft, the saturated thickness of the Platteville deposits at wells AW1S, SPW, and PZ1. Transmissivity values ranged from 5.3×10^{-1} to 7.8×10^{2} ft^2/d (figs. 4, 5, and 8). Transmissivity values from test intervals B, C, E, and F in well SPW (altitude 700–720 and about 730–755 ft above sea level) and test intervals D, F, and G in well PZ1 (altitude 703–713 and 723–743 ft above sea level) were greater than 1.0×10^{2} ft^2/d (figs. 4, 5). Transmissivity values from test intervals A and D in well SPW (altitude 686–700 and 720–730 ft above sea level); A, B, C, E, and H in well PZ1 (altitude 673–703, 713–723, and 743–753 ft); and A and B at well AW1S (altitude 751–

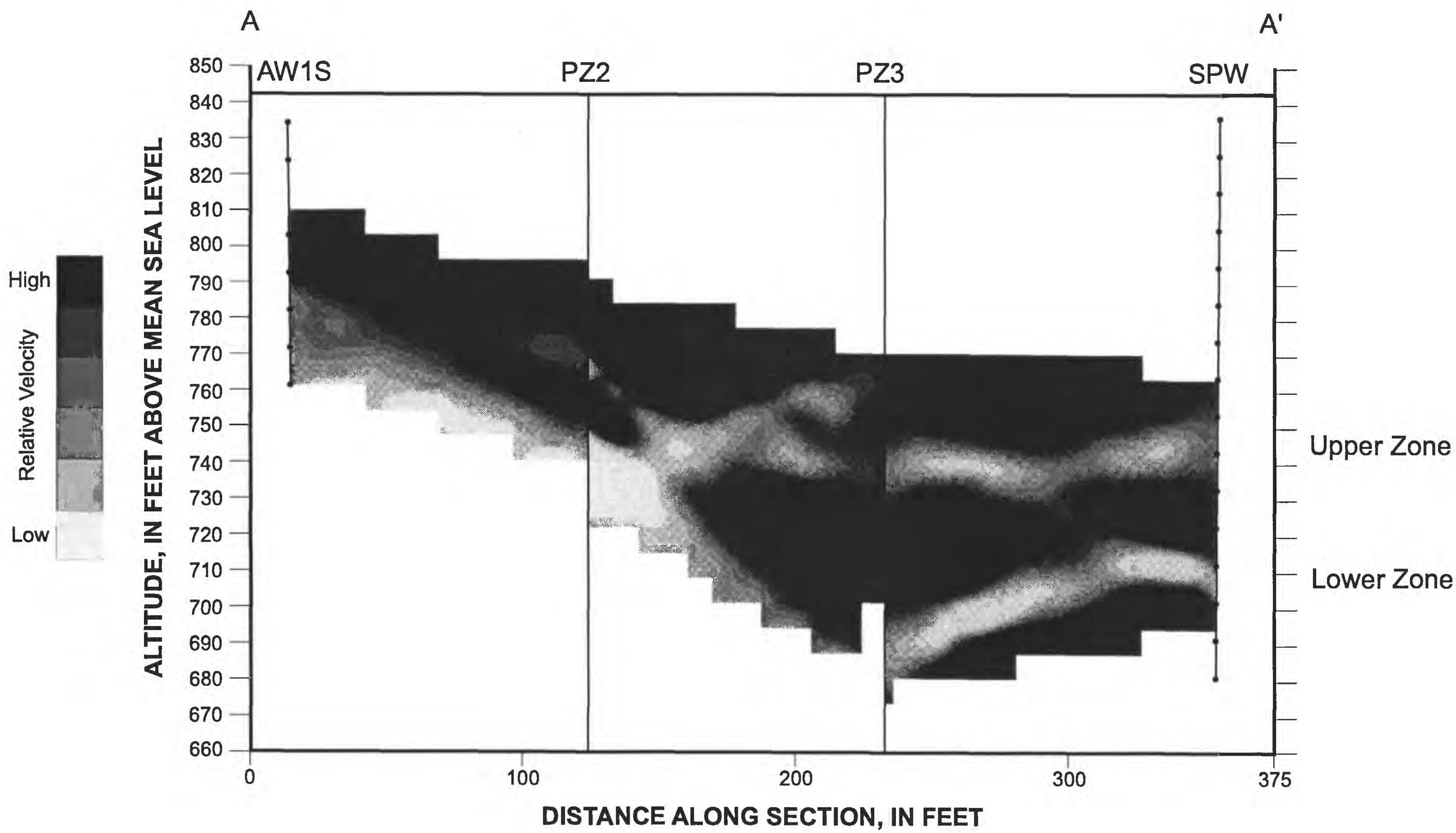


Figure 11. Velocity tomograms between wells AW1S–PZ2, PZ2–PZ3, and PZ3–SPW, near Byron, Illinois (modified from Lane and others, 1994). (Upper and lower zones of low velocity indicate lithologic changes that may correspond to permeable zones.)

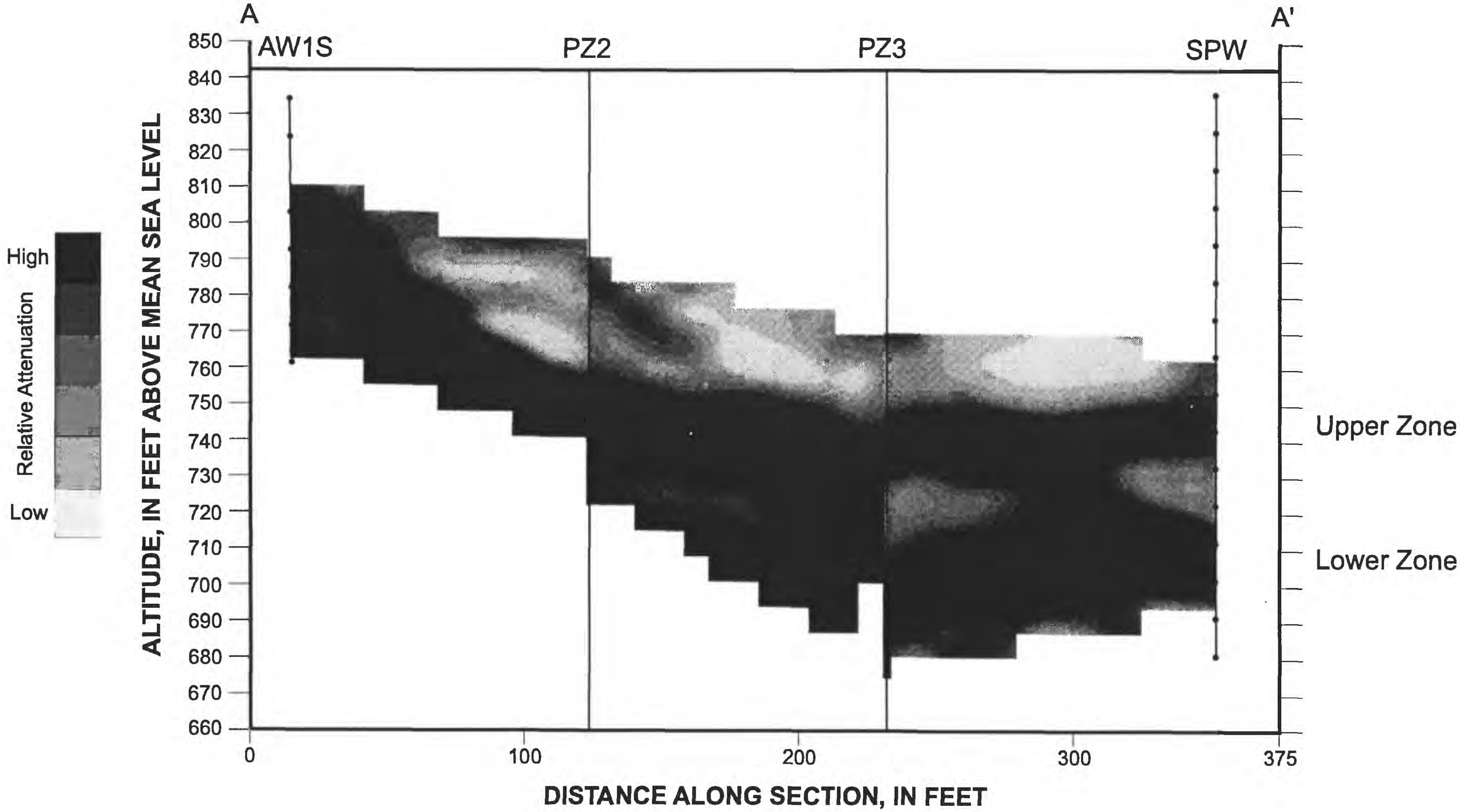


Figure 12. Attenuation tomograms between wells AW1S–PZ2, PZ2–PZ3, and PZ3–SPW, near Byron, Illinois (modified from Lane and others, 1994). (Upper and lower zones of low velocity indicate lithologic changes that may correspond to permeable zones.)

766 and 785–804 ft above sea level) were less than 5.0×10^1 ft^2/d (figs. 4, 5, 8).

A constant-discharge aquifer test was done at well SPW during a previous investigation. Well PZ1 was 115 ft deep when this test was done. Well PZ3 and the AW series of wells were not present when this test was done. The data from this previous test indicate the Galena-Platteville aquifer is anisotropic, and the direction of anisotropy is affected by the dominant orientation of the inclined fractures near the pumped well (Kay and others, 1989, p. 31–41). The calculated transmissivity of the aquifer in the study area was a maximum of 670 ft^2/d directed N 60° W from well SPW. Transmissivity was calculated to be 490 ft^2/d perpendicular to the N 60° W direction. Water levels rose at wells B3, B5, and PZ2 about 1,000 minutes into the aquifer test, indicating that the upper parts of the aquifer became hydraulically isolated from the fractures supplying water to well SPW during the test.

The Galena-Platteville aquifer is underlain by the Harmony Hill Shale semiconfining unit. The Harmony Hill Shale semiconfining unit has a leakance of 4.65×10^{-3} (ft/d)/ft beneath the study area (Kay and others, 1989, p. 47) and restricts downward flow from the Galena-Platteville aquifer.

Water Levels

Ground-water-level measurements made on July 8, 1993, were used to prepare a map of the altitude and configuration of the water table in the study area (fig. 9). The water-table configuration shown in figure 9 is consistent with that determined during other investigations (Kay and others, 1997, fig. 18). The water-table altitude is elevated in the southeastern part of the study area, decreases to the north, northwest, and southwest, and is elevated south of the study area. Water levels in the wells open to the middle (AW5I) and base of the Galena-Platteville aquifer (AW1D, AW4D, AW5D, MW9) and water levels in the wells open to most or all of the saturated thickness of the aquifer (SPW, PZ1, PZ2, PZ3) are lower than the water table (table 3), indicating the potential for downward flow in the aquifer. Water-level altitudes measured during this study typically were 5 to 15 ft higher than those measured during other investigations (Kay and others, 1989, table 1; U.S. Environmental Protection Agency, 1994, Appendix B; Kay and others, 1997, table 1). The water table is in the Dunleith Formation in most of the study area.

Previous investigations have led to the conclusion that variations in the water-table altitude in and near the study area reflect variations in the permeability distribution in the Galena-Platteville aquifer (Kay and others, 1989, p. 18; Kay and others, 1997, p. 21–22). The area where the water-table altitude is above 800 ft was interpreted to be an area of low permeability with minimal fracture interconnection and appears to correspond to areas where the Guttenberg Formation is thickest and most competent (fig. 9). Permeable zones were identified in the deeper parts of the aquifer (primarily the Pecatonica, Mifflin, and Grand Detour Formations) in this part of the study area, and the aquifer can be divided into a shallow, less-permeable interval, and a deeper, more-permeable interval. The presence of a deeper permeable interval in the aquifer is consistent with the potential presence of a fracture network corresponding to the lower zone identified from the cross-hole tomographic survey. The western part of the study area, where the water-table altitude is between 750 and 775 ft above sea level, has little topographic variation and a well-developed system of permeable, interconnected fractures, and solution openings. The northeastern part of the study area, where the water-table altitude is near or below 750 ft above sea level, has steeply dipping topography and a well-developed fracture network.

Flowmeter Logging

Heat-pulse flowmeter logging was done under conditions of ambient flow in wells SPW, PZ1, PZ2, PZ3, and AW1S (Frederick Paillet, U.S. Geological Survey, written commun., 1993, 1997) (figs. 4–8). If vertical variations in water level are present within the aquifer at a well, vertical flow will occur within the well. Heat-pulse flowmeter logs measure the direction (up or down) and rate of vertical flow at various depths in the well and are used to identify the depths where measurable changes in the rate of flow are present. Inflow (flow into the well from the aquifer) is identified by an increase in flow rate along the direction of flow in the well. Outflow (flow out of the well to the aquifer) is identified by a decrease in flow rate along the direction of flow in the well. The depths where the rate of flow changes commonly are intervals of increased aquifer permeability. Heat-pulse flowmeter logs were compared with acoustic-televiewer and borehole-radar logs to identify the specific features (vugs, fractures) transmitting water.

Table 3. Monitoring well and water-level data, near Byron, Illinois

Aquifer interval well is open to: GP, most or all of the Galena-Platteville aquifer; WTGP, water table in Galena-Platteville aquifer; BGP, base of Galena-Platteville aquifer; MGP, middle of Galena-Platteville aquifer, SS-St. Peter Sandstone aquifer

[Water-level altitude: NT, measurement not taken; ~, approximately]

Well name	Open interval (feet below land surface)	Measuring point altitude (feet above sea level)	Water-level altitude, July 8, 1993 (feet above sea level)	Aquifer interval well is open to
SPW	20–150	836.43	767.41	GP
PZ1	20–165	838.51	NT	GP
PZ2	20–115	829.21	NT	GP
PZ3	15–160	829.81	~767	GP
AW1S	7–83	833.89	814.72	WTGP
AW1D	149–161	833.55	766.88	BGP
AW2	10–71	843.13	796.77	WTGP
AW3	9–45	799.77	767.56	WTGP
AW4S	15–50	783.70	754.39	WTGP
AW4D	96–118	783.94	748.68	BGP
AW5I	93–100	845.79	783.30	MGP
AW5D	159–172	845.81	767.88	BGP
AW6	9–35	828.70	814.38	WTGP
B1	14–35	771.81	747.92	WTGP
B2	31–60	792.76	747.95	WTGP
B3	32–50	819.85	777.51	WTGP
B4	63–90	834.03	766.71	WTGP
B5	21–40	846.82	822.85	WTGP
B6R	15–102	851.69	768.91	WTGP
MW1	13–71	862.15	824.53	WTGP
MW2	219–231	861.38	NT	SS
MW8	170–180	853.40	766.98	BGP
MW9	96–106	852.66	768.08	WTGP
DF12	122–134	834.74	766.91	MGP
DF21	18–100	840.43	767.34	WTGP
PW3	8–91	833.38	766.83	WTGP

No vertical flow was identified in well SPW under conditions of ambient flow (fig. 4). The lack of ambient flow in well SPW probably results from an absence of enough vertical variation in water level within the well to drive flow (Kay and others, 1997, p. 26). The lack of vertical variation in water level at well SPW can probably be attributed to good vertical hydraulic interconnection within the inclined fractures that intercept the wellbore (fig. 4).

Flowmeter logging in well PZ1, under conditions of ambient flow, indicates inflow of water draining down the wellbore to the top of the water column and possibly inflow from the fractures at or near the highest point of flow measurement at 748 ft (Frederick Paillet, U.S. Geological Survey, written commun., 1993, 1997). Outflow was through a vuggy, fractured part of the aquifer in the Mifflin Formation at an altitude of about 708 ft above sea level (figs. 5, 10). The outflow interval has a transmissivity of 1.2 X 10^2 ft^2/d (fig. 5). The altitude of the outflow interval corresponds to one of the reflectors identified from the single-hole radar survey (table 2). The altitude of the outflow interval also is consistent with the altitude of the lower zone identified at well SPW on the cross-hole tomograms (figs. 11, 12).

Flowmeter logging in well PZ2, under conditions of ambient flow, indicates inflow of water draining down the wellbore to the top of the water column and possibly inflow from a series of fractures above the highest point of flow measurement at 784 ft above sea level (fig. 6). Outflow was through the inclined or horizontal fracture in the Nachusa Formation at an altitude of about 761 ft, one or more horizontal fractures in the Grand Detour Formation between 748–754 ft, and the fracture at 723 ft (figs. 6, 10). Single-hole reflection data identified a reflector at about 787 ft in this well (Niva, 1993). No reflectors were identified at the other depths of active flow in this well.

Flowmeter logging in well PZ3, under conditions of ambient flow, indicates inflow of water draining down the wellbore to the top of the water column and perhaps inflow from some of the horizontal fractures above the second point of flow measurement at 764 ft above sea level (fig. 7). Measurable inflow was present from a horizontal fracture in the Grand Detour Formation at 750 ft. Outflow was through horizontal and (or) inclined fractures in the Pecatonica Formation at an altitude of about 694 ft (figs. 7, 10). Single-hole reflection data identified a reflector at 746 ft in this well, but no reflectors were identified that clearly correspond to depths of measurable flow. The outflow interval near 694 ft approximately corresponds to the altitude of the lower zone identified at well PZ3 on the cross-hole tomograms (figs. 11, 12).

Flowmeter logging in well AW1S, under conditions of ambient flow, indicated less than 0.10 gal/min of downflow in the well (fig. 8). The change in the amount of flow was too small to identify specific depths of flow into or out of this well.

Well SPW also was pumped at 1.5 gal/min with the pump intake set near the static water level in the well to induce flow in the well. This enabled identification of the location of the flow intervals that could not be identified during conditions of ambient flow. Flowmeter logging during pumping in well SPW identified measurable flow through the inclined fractures in the Grand Detour Formation above 736 ft above sea level as well as through the inclined fracture in the Mifflin Formation at about 711 ft (Frederick Paillet, U.S. Geological Survey, written commun., 1993) (figs. 4, 10). A small amount of water (about 0.03 gal/min) was flowing through one or more horizontal fractures in the Pecatonica Formation at about 698 ft. Single-hole reflection surveys identified a reflector at about 709 ft in well SPW, but no reflectors were identified near the other flow intervals. The flow interval at 711 ft approximately corresponds to the depth of the lower zone identified at well SPW on the cross-hole tomograms (figs. 11, 12). The intervals of active flow in well SPW also tend to have higher transmissivity values (fig. 4). This indicates the lower zone is a hydraulically active fracture (the fracture transmits substantial amounts of water) and that it may extend from wells PZ3 and SPW to well PZ1.

Flowmeter logging in wells PZ1, PZ2, and AW1S also was done in conjunction with pumping in well SPW at 22 gal/min, and in well PZ3 at 32 gal/min, to determine the changes in flow between ambient and pumping conditions in the surrounding wells (Frederick Paillet, U.S. Geological Survey, written commun., 1993). Both wells were pumped for more than 180 minutes. Analysis of changes in flow rates in the wells during pumping can help identify flow pathways between wells.

Water-level measurements were collected in wells AW1S, AW1D, AW3, SPW, PZ1, PZ2, and B3 during pumping in well PZ3 to provide information on flow direction. It was anticipated that measuring the water-level response in these wells to pumping in well PZ3 would enable further characterization of the flow pathways in the study area. Other than well PZ3, which exhibited water-level changes of about 22 ft, none of the wells monitored exhibited a clear response to pumping in well PZ3. These water-level measurements, therefore, provided no information that defined the flow pathways in the study area.

Analysis of changes in the flow in well PZ1 during pumping in well SPW indicated hydraulic connection between the fractured area at an altitude of 708 ft above sea level in well PZ1 and one or more fractures supplying the water pumped from well SPW. The most likely pathway for flow between wells PZ1 and SPW appears to be the lower zone identified by the cross-hole tomograms, and is further indication that the lower zone is a hydraulically active fractured area that is continuous between wells PZ1 and SPW (figs. 10, 11, 12).

Analysis of flow in well PZ2 during pumping in well SPW indicated hydraulic connection through the fractures between about 748 and 754 ft above sea level at well PZ2 and possibly, the horizontal or inclined fracture at about 761 ft. These fractures would appear to be hydraulically connected to the inclined fractures above 736 ft in well SPW (fig. 10).

Analysis of flow in well PZ3 during pumping in well SPW indicated hydraulic connection between the fractures at altitudes of about 764, 750, and 694 ft above sea level at well PZ3 and one or more fractures supplying water to well SPW. The hydraulically active fractures at 750 and 764 ft above sea level are most likely hydraulically connected to the inclined fractures above 736 ft in well SPW. The hydraulically active fractures at 694 ft at well PZ1 may be connected to the hydraulically active horizontal fractures at 698 ft at well SPW. However, the cross-borehole tomography data indicate the fractured interval at 694 ft at borehole PZ3 is probably connected to the hydraulically active inclined fracture at about 711 ft above sea level at well SPW (figs. 10, 11, 12).

No changes in flow were observed in well AW1S during pumping in well SPW. The lack of change in flow during pumping indicates poor hydraulic connection between the open interval at well AW1S and the fractures and vugs supplying water to well SPW. An absence of permeable fractures at well AW1S is consistent with the low (less than 1 ft^2/d) transmissivity values calculated for the aquifer at the well.

Analysis of changes in the flow in well PZ2 during pumping in well PZ3 indicated hydraulic connection between the horizontal fractures above 784 ft, and at 748–754 ft above sea level in well PZ2 and one or more fractures supplying the water pumped from well PZ3. The most likely pathway for flow between these wells appears to be a hydraulically active fracture at about 750 ft in well PZ3, and perhaps the fractures above 764 ft.

No changes in flow were observed in wells AW1S and SPW during pumping in well PZ3. Water-level data collected from wells PZ1, PZ2, SPW, AW1S, B3, and AW3 also showed no clear response to pumping in well PZ3. The flowmeter and water-level data indicate poor hydraulic connection between the open interval in these wells and the fractures supplying water to well PZ3.

Analysis of the flowmeter, acoustic-televiewer, slug test, and borehole-radar data indicate inclined fractures that intercept the wellbore above 736 ft and at 711 ft above sea level supply most of the water to well SPW. These fractures are hydraulically connected to an upper flow pathway at about 750 ft and a lower flow pathway below 711 ft (fig. 10). 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 well AW1S. The lower flow pathway appears to correspond to a fractured interval that extends between wells SPW and PZ1 at an altitude between 711 and 708 ft and between wells SPW and PZ3 at an altitude between 711 and about 694 ft. The lower flow pathway appears to correspond to the lower zone identified by the cross-hole logging and corresponds to the Mifflin and Pecatonica Formations (figs. 10, 11, 12).

RESULTS OF TRACER TESTING

Once the flow pathways were identified in the Galena-Platteville aquifer, a constant-discharge aquifer test was conducted as part of a larger tracer test done from June 30 to July 16, 1993. The tracer test was done to characterize the hydraulic properties of the lower flow pathway. The tracer test was conducted in four phases: background water-level monitoring, pumping, tracer injection, and recovery from pumping. The background water-level monitoring phase of the test was done from 1025 on June 30 to 1617 on July 10 and corresponds to the period from 0 to 14,752 minutes of the test. The pumping phase of the test was done from 1617 on July 10 to 1701 on July 13 and corresponds to the period from 14,753 to 19,123 minutes of the test. The tracer injection phase of the test was done from 1852 on July 10 to 1701 on July 13 and corresponds to the period from 14,903 to 19,123 minutes of the test. The recovery phase of the test was done from 1702 on July 13 to 1430 on July 16 and corresponds to the period from 19,124 to 24,726 minutes of the test. Graphs of the water-level data collected during the test from selected wells are presented in appendix 1. Because the saturated thickness of the aquifer was abnormally high during the tracer test, hydraulic conditions in the upper flow pathway and the upper part of the aquifer during the test may not be representative of more normal conditions (Rushton and Chan, 1976).

Water levels were monitored during all phases of the tracer test with pressure transducers rated at 0–5 and 0–10 lb/in^2 in observation wells AW1S, AW1D, AW3, AW5I, AW5D, B3, B4, B5, MW8, and MW9. These transducers can accurately detect water-level changes of 0.01 ft. Water levels in well SPW were monitored with a 0–30 lb/in^2 transducer, which is capable of accurately detecting water-level fluctuations of about 0.10 ft. The accuracy of the transducer data was checked periodically with electric-tape measurements. The electric-tape measurements typically were within 0.03 ft of the transducer readings. Water levels in the remaining observation wells and all of the background wells were measured periodically with electric tapes. Observation wells are those monitoring wells where the water level was expected to respond to pumping in well SPW. Background wells are those monitoring wells where the water level was not expected to respond to pumping in well SPW. Barometric pressure and precipitation also were monitored in the area during all phases of the tracer test.

The background water-level-monitoring phase of the tracer test consisted of measuring water levels in the observation wells (B3, B4, B5, AW1S, AW1D, AW5I, AW5D, DF21, PZ2, AW3, AW2, AW4S, AW4D, AW6, MW8, MW9, PW3) and the background wells (B1, B2, B6, DF5S, DF5D, DF11, DF12, GW42, MW1, MW2, MW15, MW16, MW20R, MW21, MW36, MW37, MW42) (fig. 1) from 4 to 10 days before the start of pumping. Water levels were monitored in the background wells to determine the amount of water-level change in the aquifer caused by precipitation and fluctuations in barometric pressure so that the amount of drawdown (water-level change due to pumping) in the observation wells could be quantified.

Wells B1, B2, B3, B4, B5, B6, AW1S, AW2, AW3, AW4S, AW6, MW9, DF5S, DF11, DF21, GW42, MW1, and MW15 are open to the water table at the top of the Galena-Platteville aquifer (Kay and others, 1997, table 1) (table 3). Wells AW5I, MW16, DF5D, and DF12 are open to the middle of the aquifer (Kay and others, 1997, table 1). Wells AW4D, AW5D, MW8, MW10, MW36, and MW42 are open to the base of the Galena-Platteville aquifer (Kay and others, 1997, table 1). Wells MW2, MW20R, MW21, MW37, and MW39 are open to the St. Peter aquifer (Kay and others, 1997, table 1) (table 3). In addition, packer assemblies were installed in wells PZ1 and PZ3 to provide more detailed data on the distribution of water levels and drawdown within the aquifer at these wells. Well PZ1 was separated into zones above the packed interval (PZ1A) from the water surface to 724 ft above sea level, a packed interval from 708 to 718 ft (PZ1P), and below the packed interval from 704 ft above sea level to the bottom of the well (PZ1B). Well PZ3 was separated into zones above the packed interval extending from the water surface to 714 ft above sea level (PZ3A), a packed interval between 710 and 700 ft (PZ3P), and below the packed interval from 696 ft to the bottom of the well (PZ3B). The packers were set so that the intervals of active flow identified during the flowmeter logging done in conjunction with the pumping in well SPW could be isolated from the rest of the borehole.

The pumping phase of the tracer test consisted of pumping water from well SPW at a constant rate of 20 gal/min (3,859 ft^3/d) for 3,068 minutes while monitoring water levels in the observation and background wells. The discharge rate was increased to 28 gal/min after 3,068 minutes of pumping and gradually decreased to about 25 gal/min by 4,365 minutes. Pumping from well SPW stopped after 4,365 minutes. A flowmeter was connected to the discharge line to verify the discharge rate. The pumping rate was checked periodically by timing how long it took to fill a 5-gal bucket with water from the discharge line. The pumped water was discharged to storage tanks, which drained to a water-treatment system before discharge near well B3. Transducers were used to measure water-level changes in wells AW1S, AW1D, AW3, AW5I, AW5D, AW6, PW3, DF21, PZ1A, PZ1B, PZ3A, PZ3P, PZ3B, MW8, MW9, and B5 on a logarithmic time interval during the pumping phase of the tracer test.

The tracer injection phase of the test began 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 well PZ1 (PZ1P) open to the aquifer from 708 to 718 ft above sea level. Well SPW was pumped for 150 minutes before tracer injection. Water-level measurements in the observation wells indicated that the effects of pumping in well SPW on the flow field had stabilized by the time tracer injection began. Tracer injection required approximately 3 minutes. The rate of tracer injection was slow enough to induce minimal change in water level in the injection interval. The bromide concentration in the water pumped from well SPW was monitored every half hour for 3,120 minutes using a bromide ion-specific electrode.

The recovery phase of the tracer test consisted of monitoring water levels in the observation and background wells for approximately 5,608 minutes after pumping stopped. Time and water-level data for the recovery phase were not in good agreement with the data from the pumping phase and were not analyzed quantitatively.

Water levels in the observation and background wells typically declined between 0.25 and 2.0 ft during the background water-level-monitoring phase of the test and declined between 0.11 and 1.79 ft during the pumping and recovery phases of the test (appendix 1). The total change in water level during the 10-day span from the first to last measurements ranged from 0.22 ft at well B3 to 3.22 ft at wells B4 and MW8. Analysis of the water-level data from the background and observation wells indicated no clear correlation between the amount of water-level decline and the permeability of the aquifer at the well, the water-table altitude at the well, or the areal location of the well.

Analysis of the graphs of water level with time shows that water levels declined during most of the test for almost all of the wells (appendix 1). Analysis of the graphs of water level with time from the wells monitored with the pressure transducers shows that the rate of decline in the depth to water in most of these wells increased about 7,800 minutes into the test. This time marks the change from a period of overall decrease in barometric pressure to a period of overall increase (appendix 2). Water levels in some of the wells also appeared to change in response to short-term fluctuations in barometric pressure. In the absence of other factors affecting water levels, decreases in barometric pressure produce a decrease in the depth to water in the well, whereas an increase in barometric pressure produces an increase in the depth to water in the well. Therefore, the change in the rate of water-level decline at about 7,800 minutes into the test appears to be related to the effects of barometric-pressure fluctuations on water levels.

Water-level data for wells B3, MW8, MW9, B5, AW3, AW5I, and AW6 were corrected for fluctuations in barometric pressure using methods outlined by Clark (1967). After correction for fluctuations in barometric pressure, water levels in these wells continued to decline appreciably during the tracer test (appendix 3), indicating that some factor other than barometric pressure also was affecting water levels during the test. Water levels in these wells showed no clear response to pumping after the data were corrected for changes in barometric pressure.

Precipitation measured during June 1993 at the National Oceanic and Atmospheric weather station at the Rockford Airport, about 15 mi northeast of the study area, was more than 7 in. above normal at this station (National Oceanic and Atmospheric Administration, 1993a). A total of 1.23 in. of rain fell at the Rockford Airport from July 1 to July 8, 1993, and 1.16 in. of rain fell at the airport from July 8 to July 16, 1996 (National Oceanic and Atmospheric Administration, 1993b). The abnormally high amounts of precipitation prior to the test resulted in abnormally high ground-water levels in the study area. It is probable that, in addition to fluctuations in the barometric pressure, water levels in the study area were declining following this period of abnormally high precipitation. The existence of declining water levels following a rise in water levels attributed to recharge from precipitation make unambiguous correction of the water-level data for changes in barometric pressure impossible in this aquifer.

The absence of correlation between water-level fluctuations in the observation and background wells, declining water levels after the precipitation events, and uncertainty about the exact relation between the amount of fluctuation in barometric pressure and the resultant amount of change in water levels prevented correction of the tracer-test data to the degree of uncertainty required for analysis of time-drawdown data (less than 0.05 ft). Therefore, transmissivity and storativity values were not calculated. The data were qualitatively analyzed to obtain a general understanding of the flow pathways in the study area.

Comparison of the trends in water levels with pumping changes clearly indicates that the rate of water-level decline in wells PZ2 and AW1D, and in all of the packed zones in wells PZ1 and PZ3, increased when pumping began in well SPW and increased when the pumping rate was increased (appendix 1). Water levels in these wells rose temporarily, typically by more than 0.10 ft, shortly after pumping terminated. Drawdown was clearly observed in these wells. Comparison of the trends in water levels with pumping changes indicates that the rate of water-level decline in wells DF21, PW3, B4, AW2, AW3, AW5D, and AW6 may have increased slightly when pumping began, or water levels may have risen for a brief time after pumping terminated (appendix 1). Drawdown may have resulted in these wells. The amount of drawdown, if present, could not be accurately determined at these wells.

Analyses of flowmeter and borehole-radar data indicate that water will flow to the inclined fracture at well SPW primarily through the upper flow pathway around 750 ft above sea level and the lower flow pathway below 711 ft. Because most of the flow is through these pathways, it can be assumed that observation 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 well SPW. Intervals PZ3P (0.07 ft), PZ3B (0.10 ft), PZ1B (0.32 ft), and wells AW1D (0.08 ft) and PZ2 appear to be in moderately good 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 well SPW.

The maximum amount of drawdown measured in wells PZ1 and PZ3 100 minutes after the start of pumping was above the packed interval, indicating extensive hydraulic interconnection through the upper flow pathway. Drawdown in interval PZ1A was 0.20 ft greater than in interval PZ3A. Drawdown in interval PZ1P was more than 0.80 ft greater than in interval PZ3P. Drawdown in interval PZ1B was about 0.20 ft greater than drawdown in interval PZ3B. Because well PZ3 is about 10 ft closer to the pumped well than well PZ1, the larger amount of drawdown in well PZ1 indicates that there is preferential flow between wells SPW and PZ1. Well PZ1 is located along the dominant orientation of inclined fractures in the dolomite (N 60° W) from well SPW and also is located along the orientation of the inclined fractures detected at well SPW. The conclusion that there is preferential flow through the aquifer in the N 60° W direction is further supported by the fact that most of the other wells that may be responding to pumping (AW1D, AW5D, AW6, PW3, DF21) tend to be oriented along the dominant fracture orientation from well SPW. This is consistent with the results of the previous aquifer test in well SPW (Kay and others, 1989, p. 31).

The presence of measurable drawdown in well PZ3 100 minutes after the start of pumping in well SPW during the tracer test contrasts with the absence of measurable drawdown in well SPW 100 minutes after the start of pumping in well PZ3 during the flowmeter logging. The dissimilarity in the response to pumping in this well pair, even though well PZ3 was pumped at a substantially greater rate, indicates that wells PZ3 and SPW are supplied, at least in part, through different flow pathways. The presence of different flow pathways supplying water to different wells in different parts of the study area indicates that the Galena-Platteville aquifer is heterogeneous in the study area. The most likely pathway for flow to well PZ3 that does not appear to contribute substantial flow to well SPW is the vertical fracture between wells AW3 and PZ1 outlined by the fracture trace in figure 9. However, water levels in wells AW3 and PZ1 showed no clear response to pumping or the cessation of pumping in well PZ3, so the importance of this fracture on flow in the study area could not be determined.

Wells B5 and AW1S are both oriented along the dominant inclined fracture orientation from the pumped well. Drawdown was not detected in these wells. Drawdown was detected in well AW1D open to the deeper part of the aquifer near well AW1S. Water-level declines that might be partially attributable to drawdown were detected in well AW5D open to the deeper part of the aquifer near well B5. The distribution of drawdown at the AW1S/AW1D and B5/AW5I/AW5D well clusters indicates that the lower flow pathway may extend to these areas (fig. 10). The upper part of the aquifer at these wells in the central and southeastern parts of the study area appears to have a low permeability and low hydraulic connection through vertical fractures. If drawdown was present at wells DF21 and PW3, it can be inferred that, the aquifer also has a higher degree of vertical fracture interconnection and a more extensively developed network of interconnected fractures in the northwestern part of the study area. This is consistent with the analysis of the water-level measurements and the geophysical data.

Monitoring of the concentration of bromide ion in the water pumped from well SPW indicated that the leading edge of the tracer migrated the 108 ft from the packed zone in well PZ1 to well SPW in 750 minutes (fig. 13). The bulk of the tracer migrated from well PZ1 to well SPW in 1,020 minutes. The velocity (V) of the tracer movement through the lower flow pathway between wells PZ1 and SPW under the hydraulic gradient imposed by the pumping was about 207 ft/d based on the first arrival of the tracer, and 152 ft/d based on the peak value for the tracer migration. If it is assumed that the tracer velocity is equivalent to the ground-water

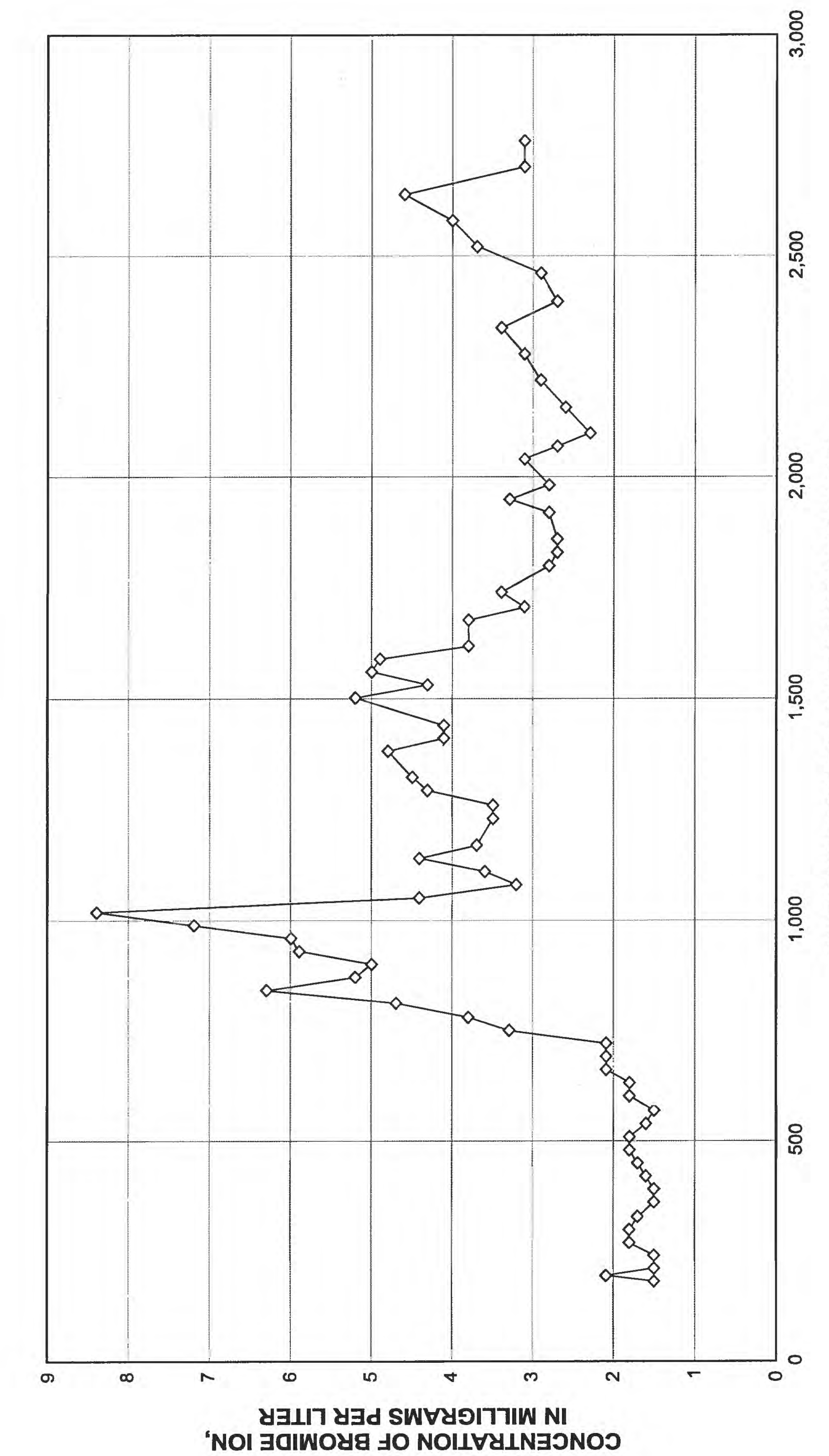


Figure 13. Concentration of bromide ion in water pumped from well SPW during the tracer injection phase of the tracer test, near Byron, Illinois, July 12–14, 1993.

velocity, ground-water velocity can be described by the Darcy velocity equation as

$$V = T/bn(dh/dl), \quad (1)$$

where b is the thickness of the aquifer (fracture) transmitting flow,

n is the effective porosity of the aquifer,

dh is the difference in head in the direction of flow, and

dl is the distance over which dh is measured and is equal to the distance between wells PZ1 and SPW.

The measured difference in head values (*dh*), altitude of about 824 ft above sea level at well SPW and 837 ft in the PZ1P interval, was about 13 ft during the test. If it is assumed that the direction of flow is directly from well PZ1 to well SPW through a fractured interval at a uniform altitude of about 709 ft, *dl* is equal to the nominal distance between the wells (108 ft). The average transmissivity of the lower flow pathway, as determined from slug tests from the packed intervals corresponding to the altitude of the pathway in wells PZ1 (interval B) and SPW (interval B) (figs. 4, 5), is 448 ft^2/d. Substituting these values into equation 1, the sum of the thickness and porosity of the lower flow pathway (*bn*) is 0.26 ft based on the first arrival of the tracer and 0.35 ft based on the arrival of the tracer peak.

The effective porosity of the lower flow pathway is determined by dividing the value of *bn* by the thickness of the flow pathway. Unfortunately, the thickness of flow pathways in a fractured-rock aquifer is often difficult to measure and spatially variable. The thickness of the lower flow pathway, as determined by the cross-borehole radar (fig. 11) is less than 10 ft. If the maximum thickness of the lower flow pathway is about 10 ft, the minimum effective porosity of the lower flow pathway ($n = b/10$) is calculated at 2.6 or 3.5 percent, depending on the tracer velocity used.

An effective porosity of 2.6–3.5 percent is lower than the median primary porosity of the Platteville deposits by about a factor of 2–3 (fig. 2) and exceeds typical effective porosity values for fractures of less than 1 percent (Alan Shapiro, U.S. Geological Survey, oral commun., 1998). An effective porosity value for the lower flow pathway that is higher than those typical of fractures and lower than those typical of the rock matrix indicates that the fractures and matrix in the Galena-Platteville aquifer in this area are hydraulically interconnected. Hydraulic interconnection between fractures and matrix is expected for a double-porosity medium such as the Galena-Platteville aquifer.

Water-level data obtained from discrete intervals in boreholes PZ1 and SPW during previous investigations indicates that the water-level altitude at any point in well SPW, and at the interval from 708 to 718 ft above sea level at well PZ1, is approximated by the water-level altitude in the open wells (Kay and others, 1997, p. 24). The difference in water-level altitude between these wells measured in May 1987 was 1.3 ft (Kay and others, 1989, p. 5). Water levels measured in May 1987 were used because they were more typical than those measured during the current investigation. If a *dh* of 1.3 ft, and a *bn* of 0.35 ft are substituted into equation 1 and the other variables are kept constant, the average ground-water velocity through the lower flow pathway is about 15.4 ft/d under hydrostatic conditions.

SUMMARY AND CONCLUSIONS

The U.S. Geological Survey and the U.S. Environmental Protection Agency conducted a study of the geology and hydrology in the dolomite bedrock at a waste-disposal site near Byron, Illinois in July 1993. The bedrock geologic units of concern in this study are the Glenwood Formation of the Ancell Group, and the Platteville and Galena Groups. These deposits compose the Harmony Hill Shale semiconfining unit and the Galena-Platteville aquifer. The bedrock deposits are unconformably overlain by unsaturated Quaternary glacial deposits.

Flowmeter, acoustic-televiewer, and borehole-radar data indicate the presence of two flow pathways in the Galena-Platteville aquifer. The upper flow pathway is at about 750 ft above sea level and corresponds to the upper part of the Grand Detour Formation of the Platteville Group. The altitude of the lower flow pathway varies in the study area, but is below 711 ft and corresponds to parts of the Mifflin and Pecatonica Formations of the Platteville Group.

Water-level data obtained during the tracer test indicate the upper and lower flow pathways are hydraulically connected to pathways of preferential flow along the dominant vertical-fracture orientation in the dolomite. Vertical hydraulic interconnection appears to be greater in the northwestern part of the study area than in the central and southeastern parts and may be affected by the degree of erosion of the Guttenberg Formation within the Galena Group, which took place during the Ordovician System.

The velocity of the tracer through the lower flow pathway was about 152 ft/d under the hydraulic gradient imposed by the pumping. Solution of the Darcy velocity equation results in a calculated effective porosity for this interval of 3.5 percent, indicating hydraulic connection between the fracture and the aquifer matrix. Ground-water velocity through the lower flow pathway is calculated to be 15.4 ft/d under hydrostatic conditions.

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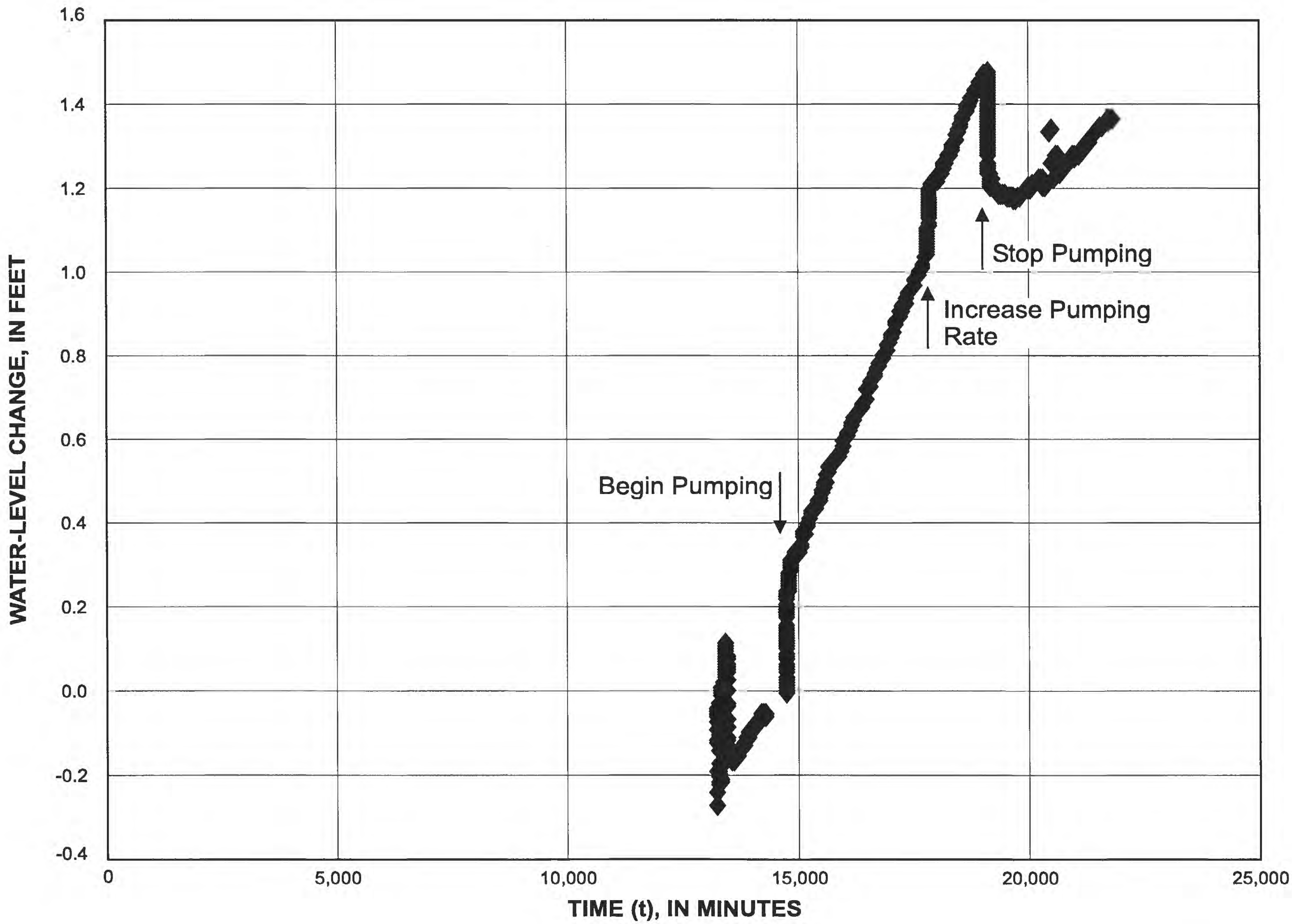
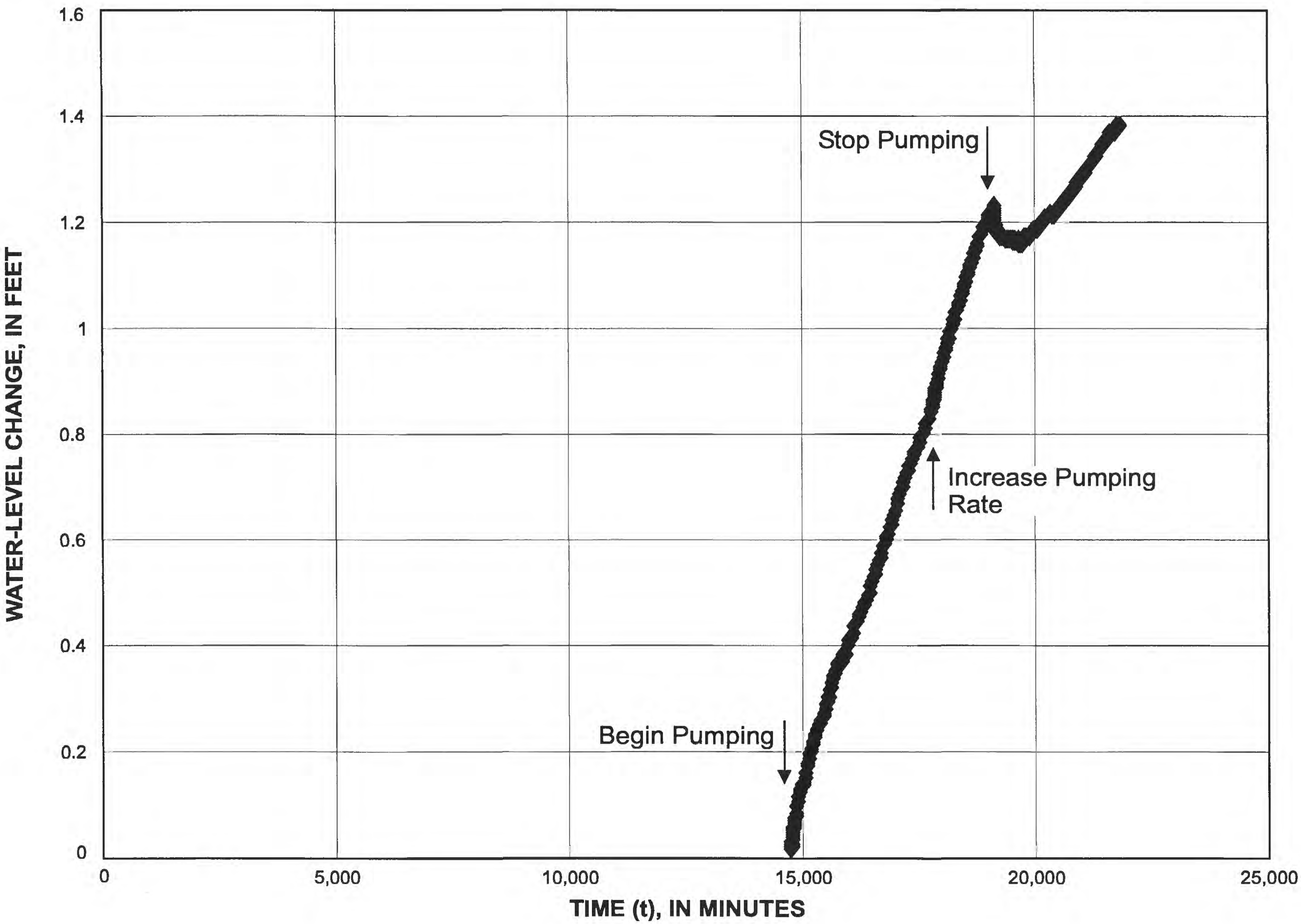
APPENDIXES 1–3

APPENDIX 1.

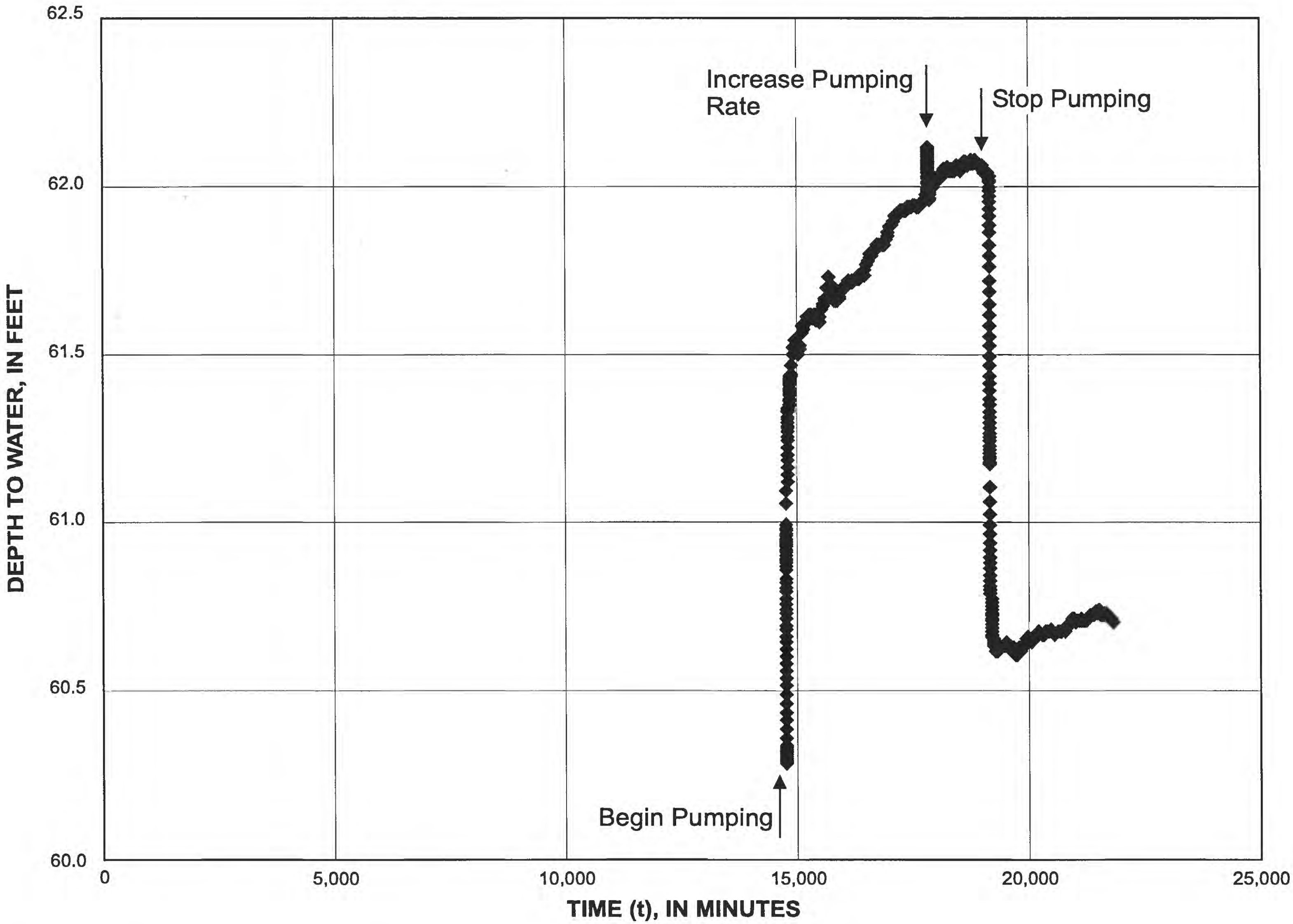
Summary of Data Collected During the Tracer Test—Water-Level Data from Selected Wells



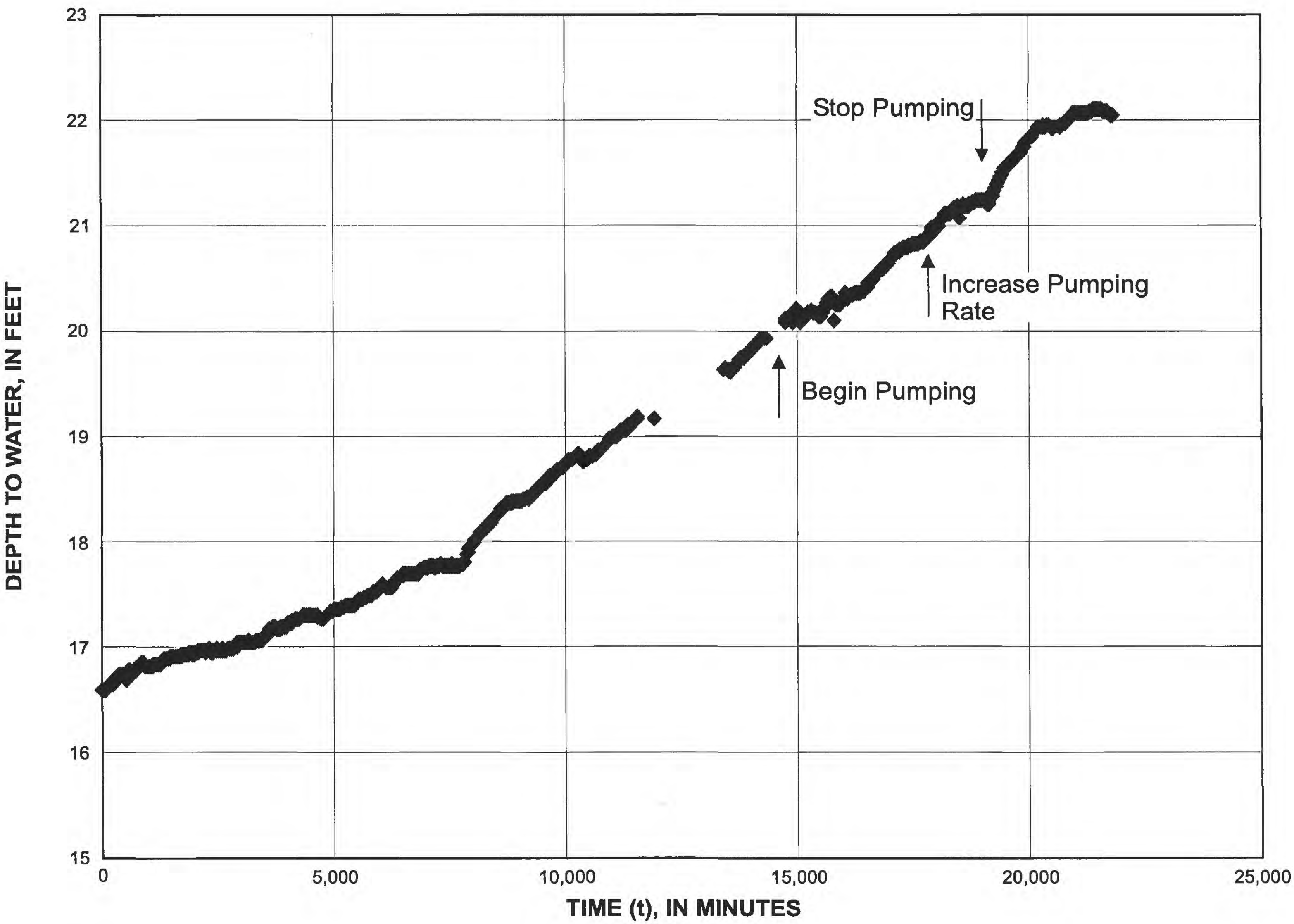
Appendix 1a. Uncorrected data for observation well PZ1, below packed zone during tracer test in well SPW near Byron, Illinois, June 30–July 16, 1993.



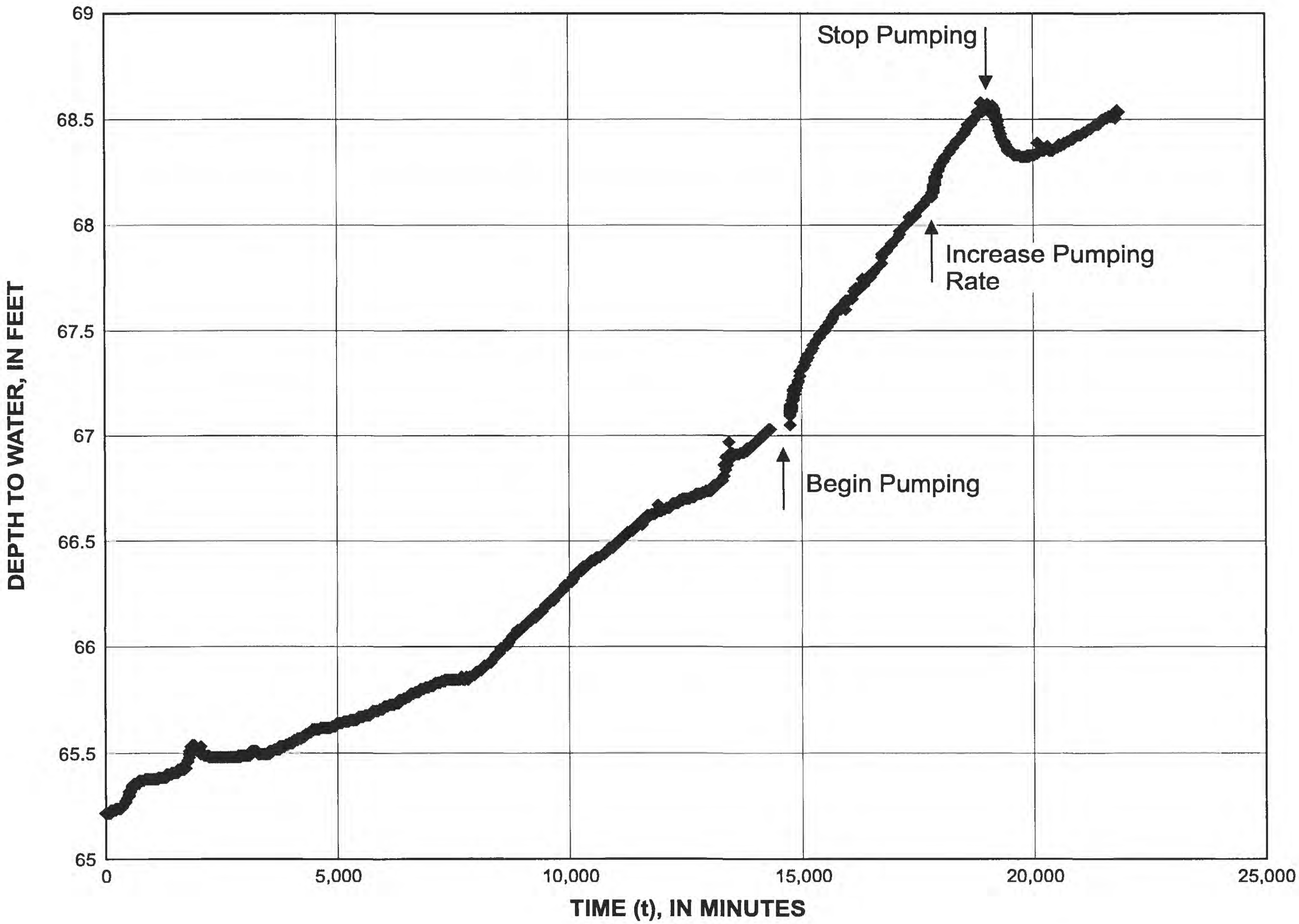
Appendix 1b. Uncorrected data for observation well PZ3, packed zone during tracer test in well SPW near Byron, Illinois, June 30–July 16, 1993.



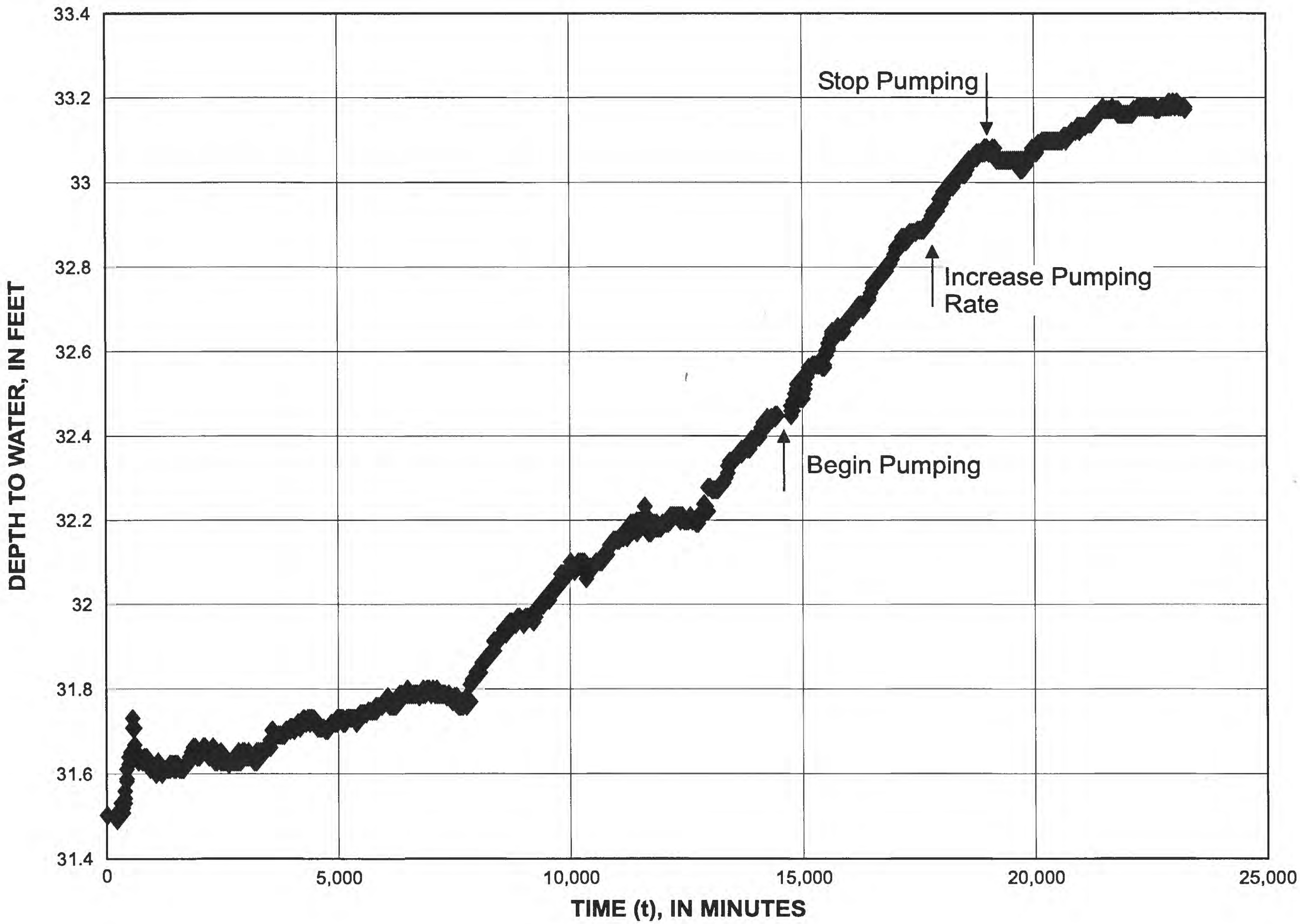
Appendix 1c. Uncorrected data for observation well PZ3, above packed zone during tracer test in well SPW near Byron, Illinois, June 30–July 16, 1993.



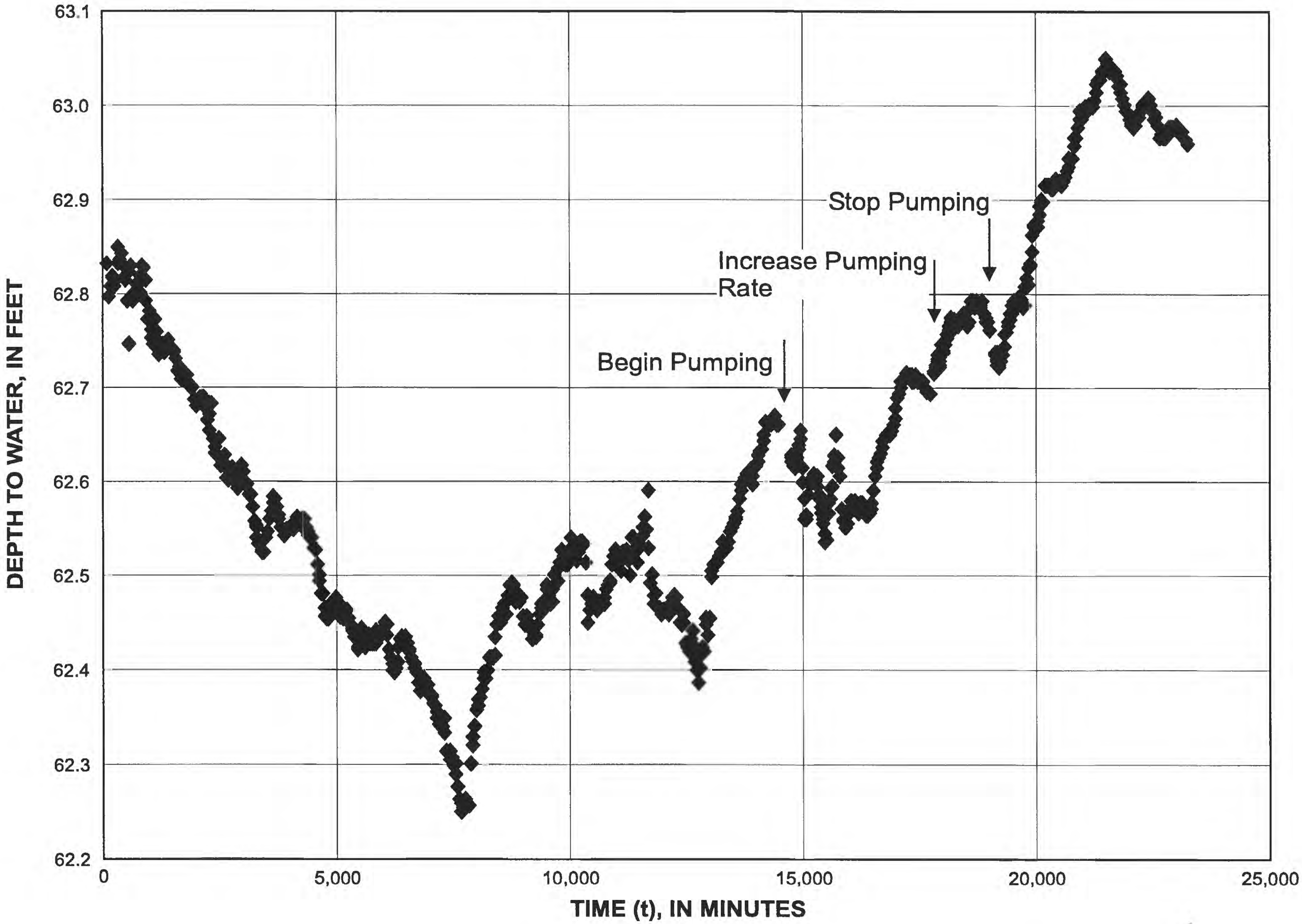
Appendix 1d. Uncorrected data for observation well AW1S during the tracer test in well SPW near Byron, Illinois, June 30–July 16, 1993.



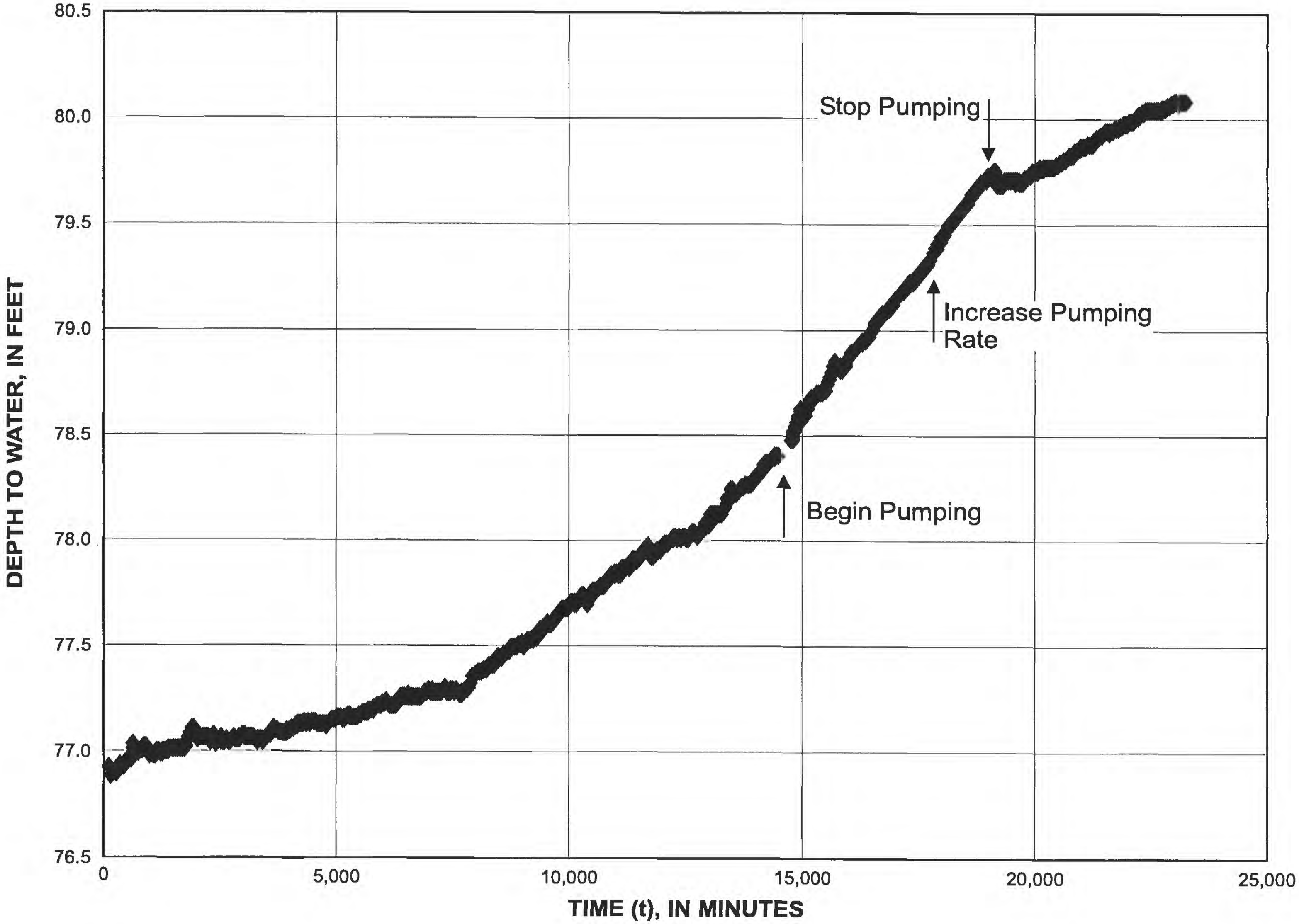
Appendix 1e. Uncorrected data for observation well AW1D during the tracer test in well SPW near Byron, Illinois, June 30–July 16, 1993.



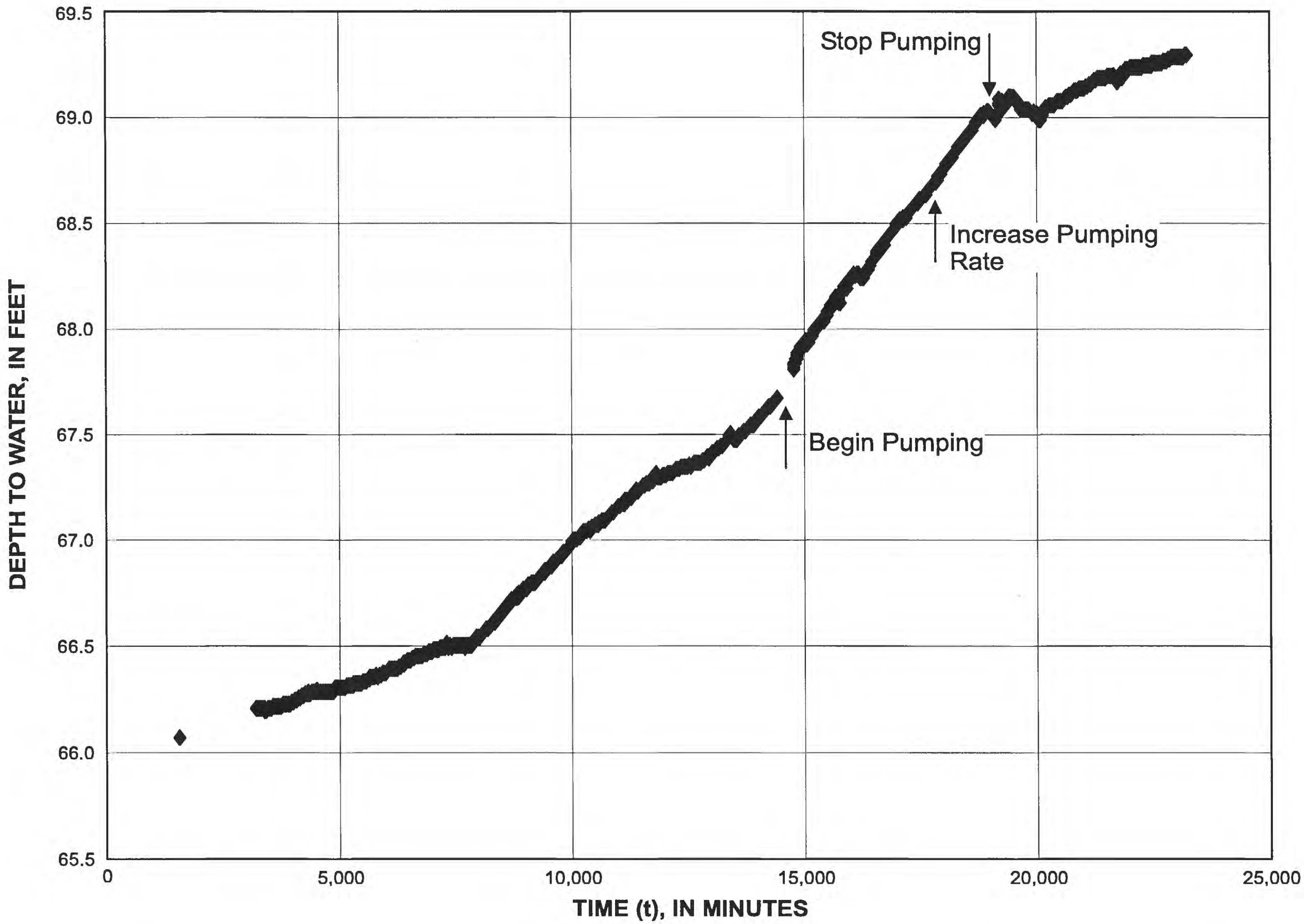
Appendix 1f. Uncorrected data for observation well AW3 during the tracer test in well SPW near Byron, Illinois, June 30–July 16, 1993.



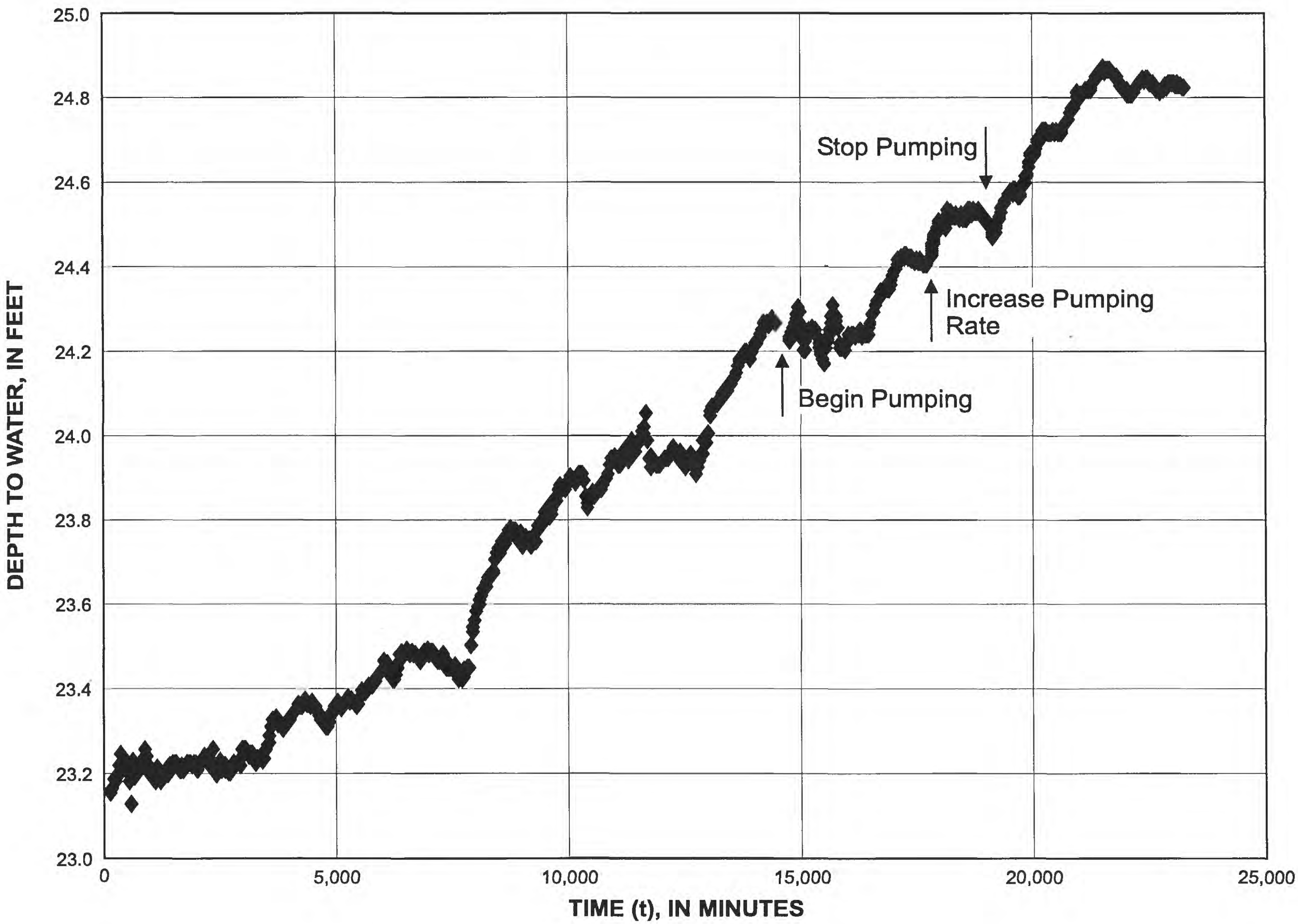
Appendix 1g. Uncorrected data for observation well AW5I during the tracer test in well SPW near Byron, Illinois, June 30–July 16, 1993.



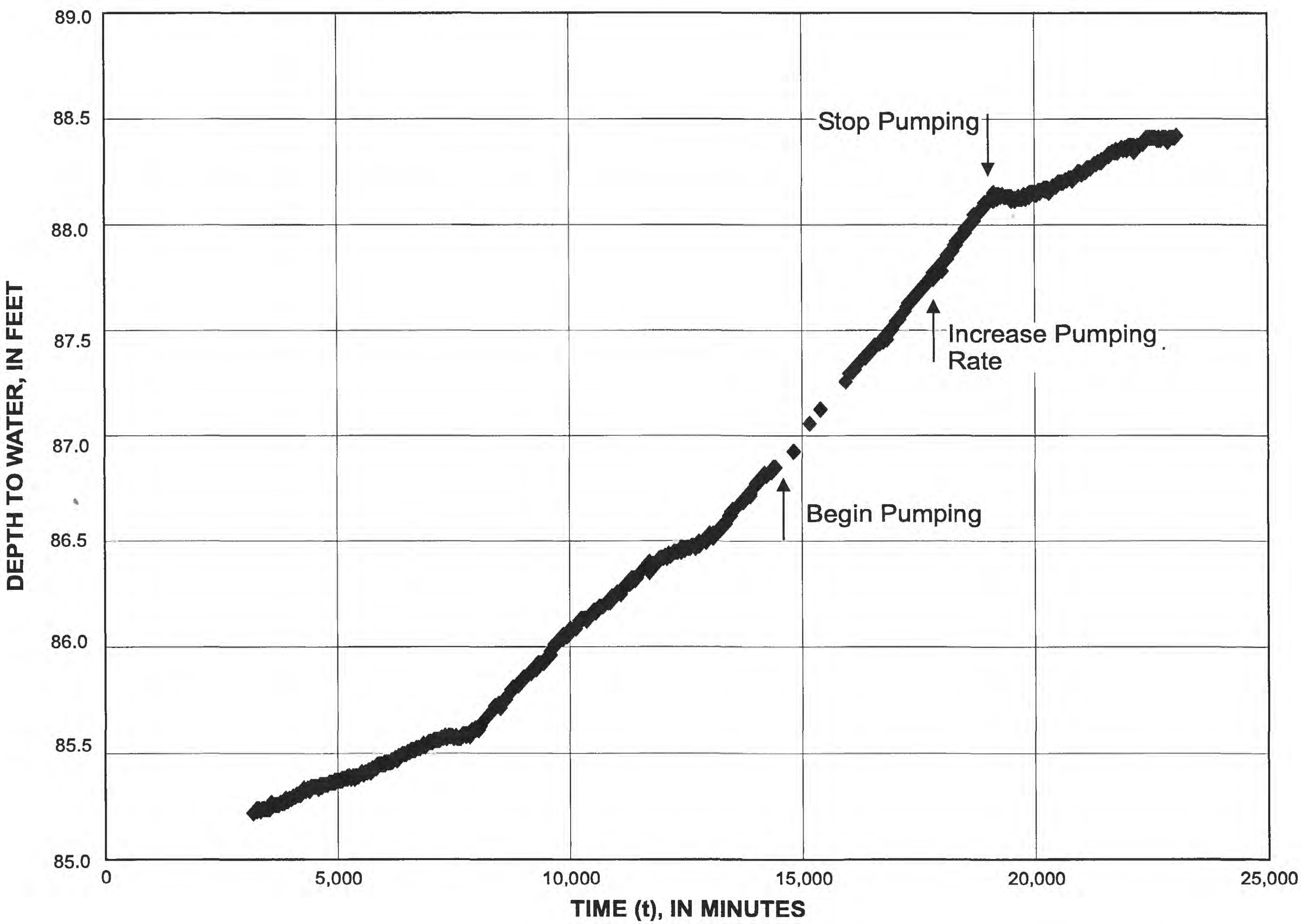
Appendix 1h. Uncorrected data for observation well AW5D during tracer test in well SPW near Byron, Illinois, June 30–July 16, 1993.



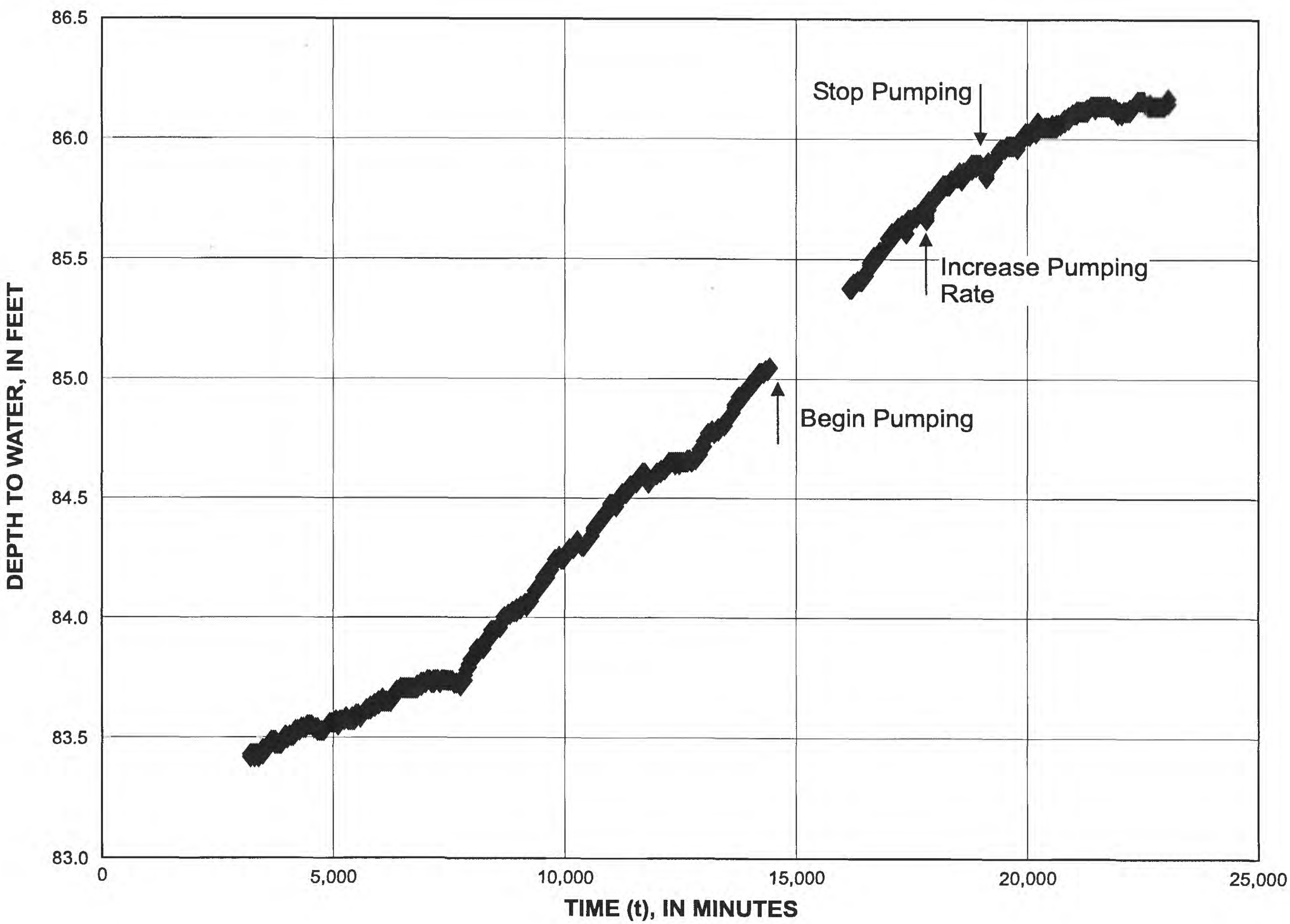
Appendix 1i. Uncorrected data for observation well B4 during the tracer test in well SPW near Byron, Illinois, June 30–July 16, 1993.



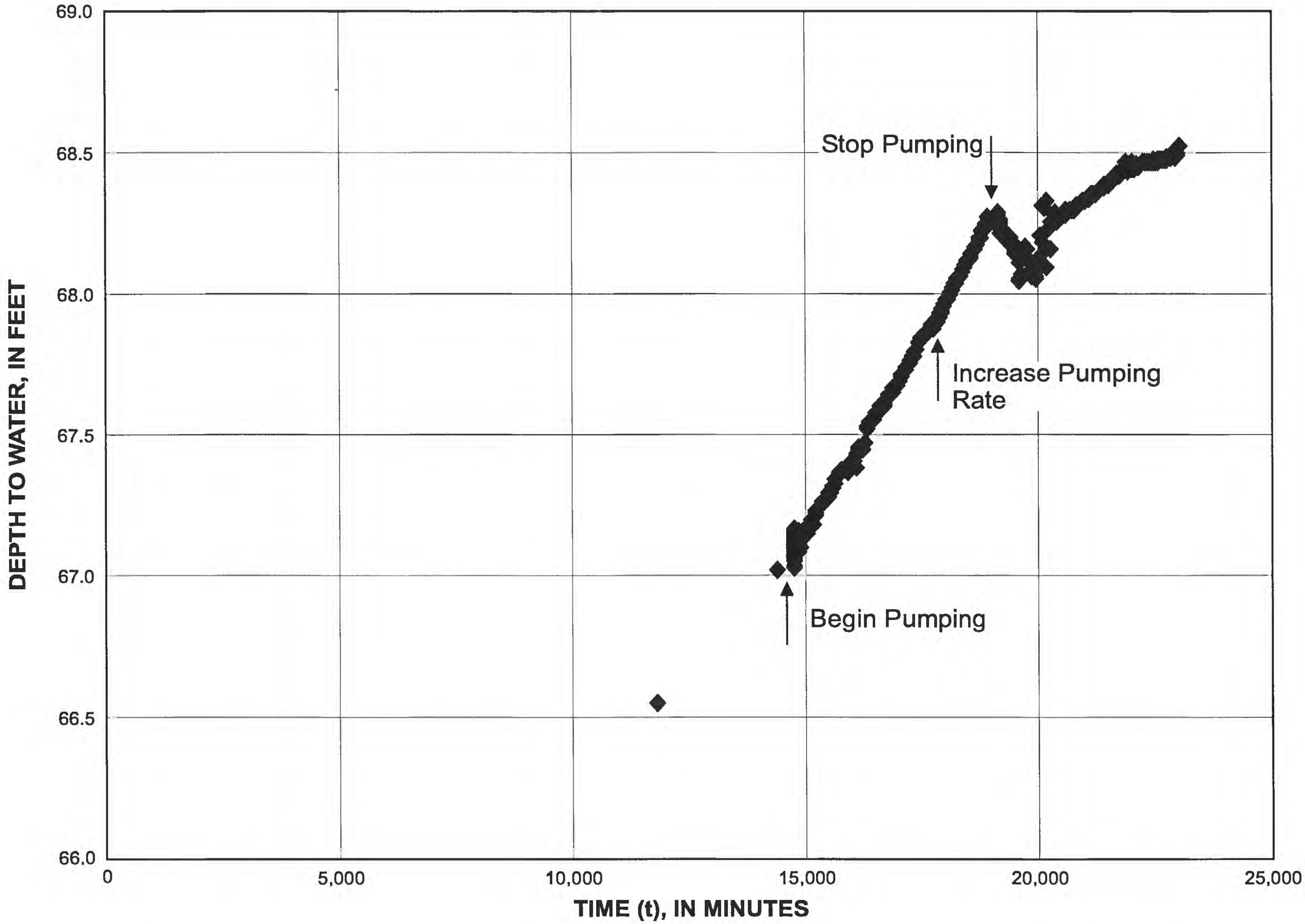
Appendix 1j. Uncorrected data for observation well B5 during the tracer test in well SPW near Byron, Illinois, June 30–July 16, 1993.



Appendix 1k. Uncorrected data for observation well MW8 during the tracer test in well SPW near Byron, Illinois, June 30–July 16, 1993.



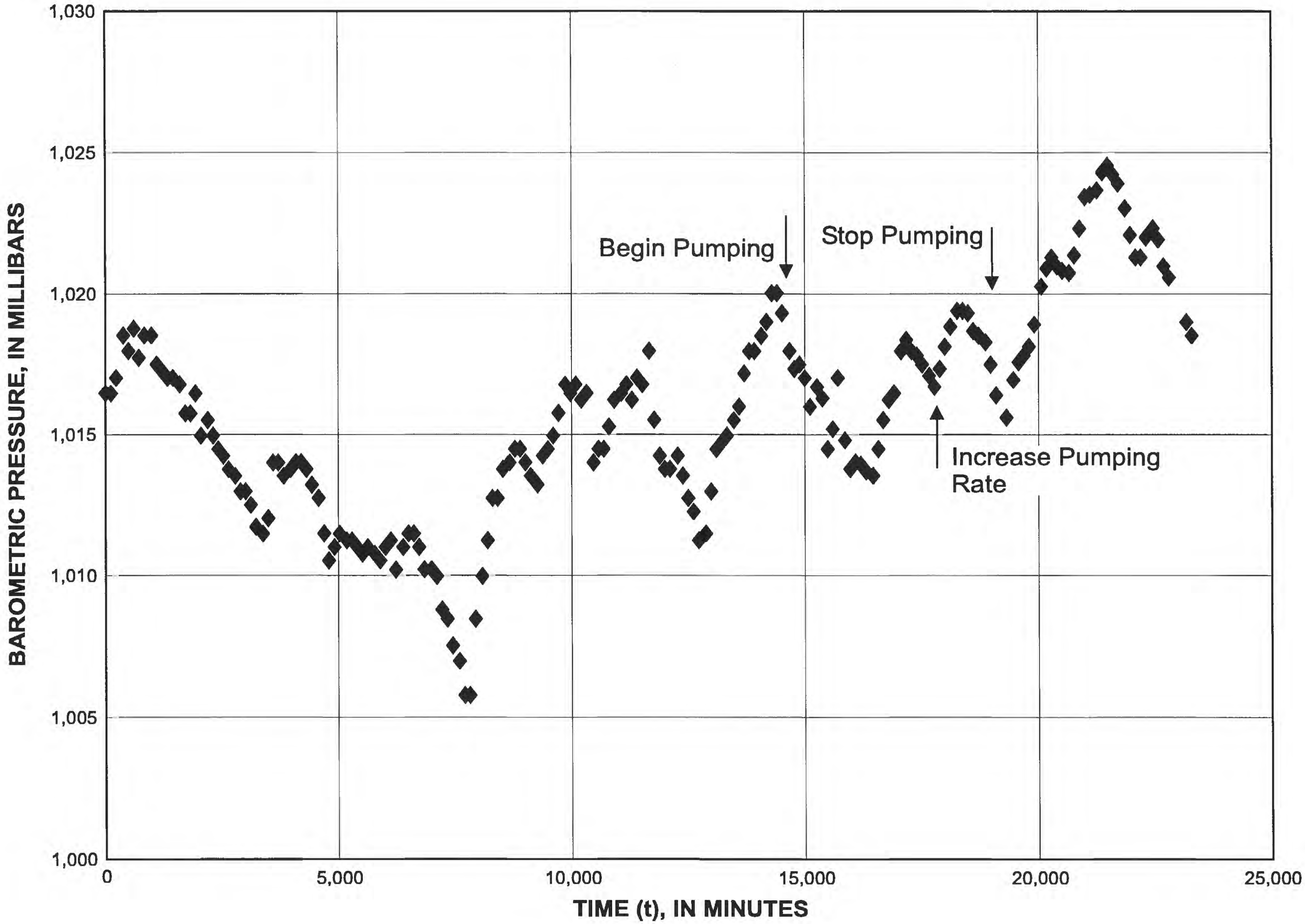
Appendix 1I. Uncorrected data for observation well MW9 during the tracer test in well SPW near Byron, Illinois, June 30–July 16, 1993.



Appendix 1m. Uncorrected data for observation well PW3 during the tracer test in well SPW near Byron, Illinois, June 30–July 16, 1993.

APPENDIX 2.

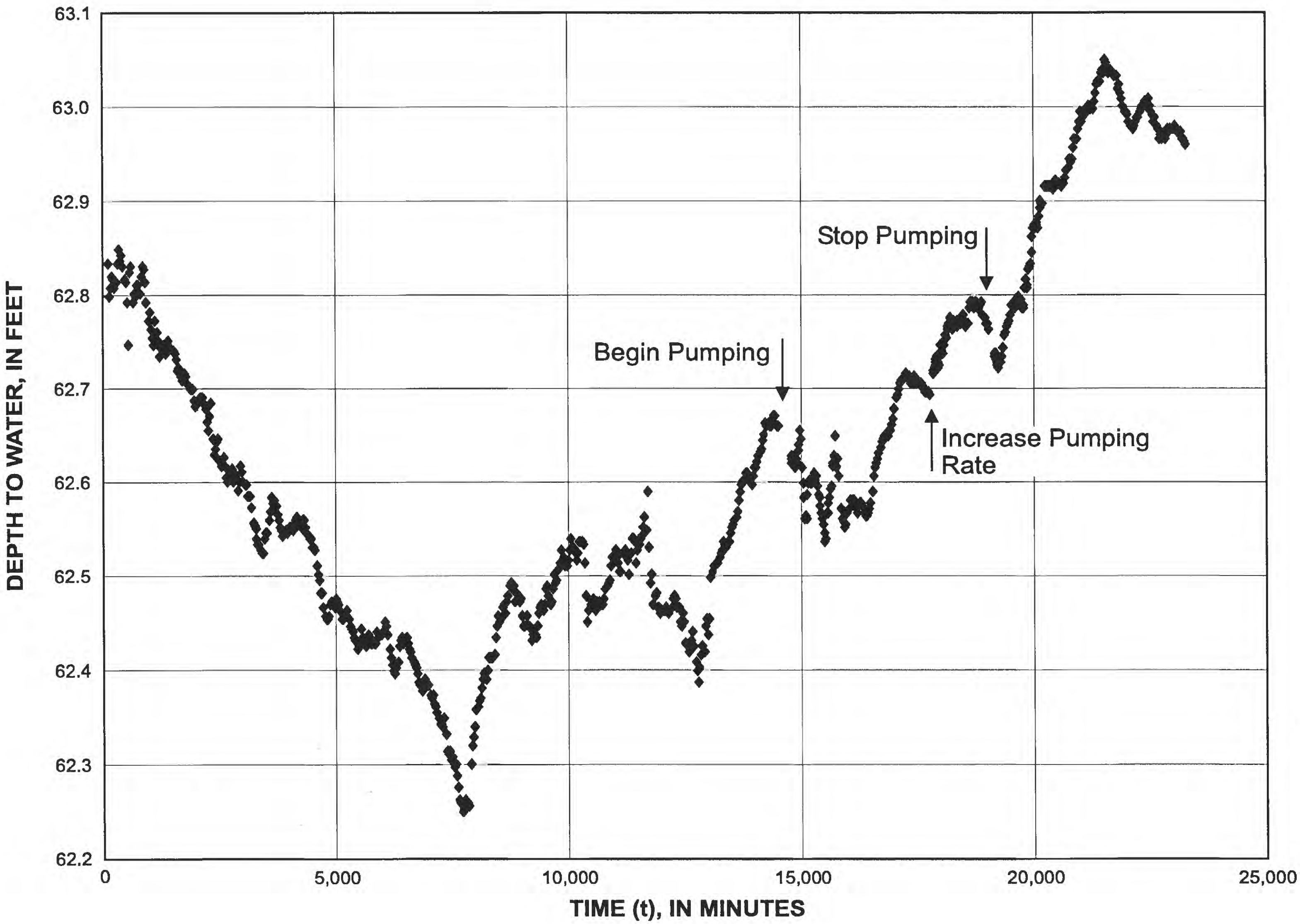
Summary of Data Collected During the Tracer Test—Barometric Pressure Data



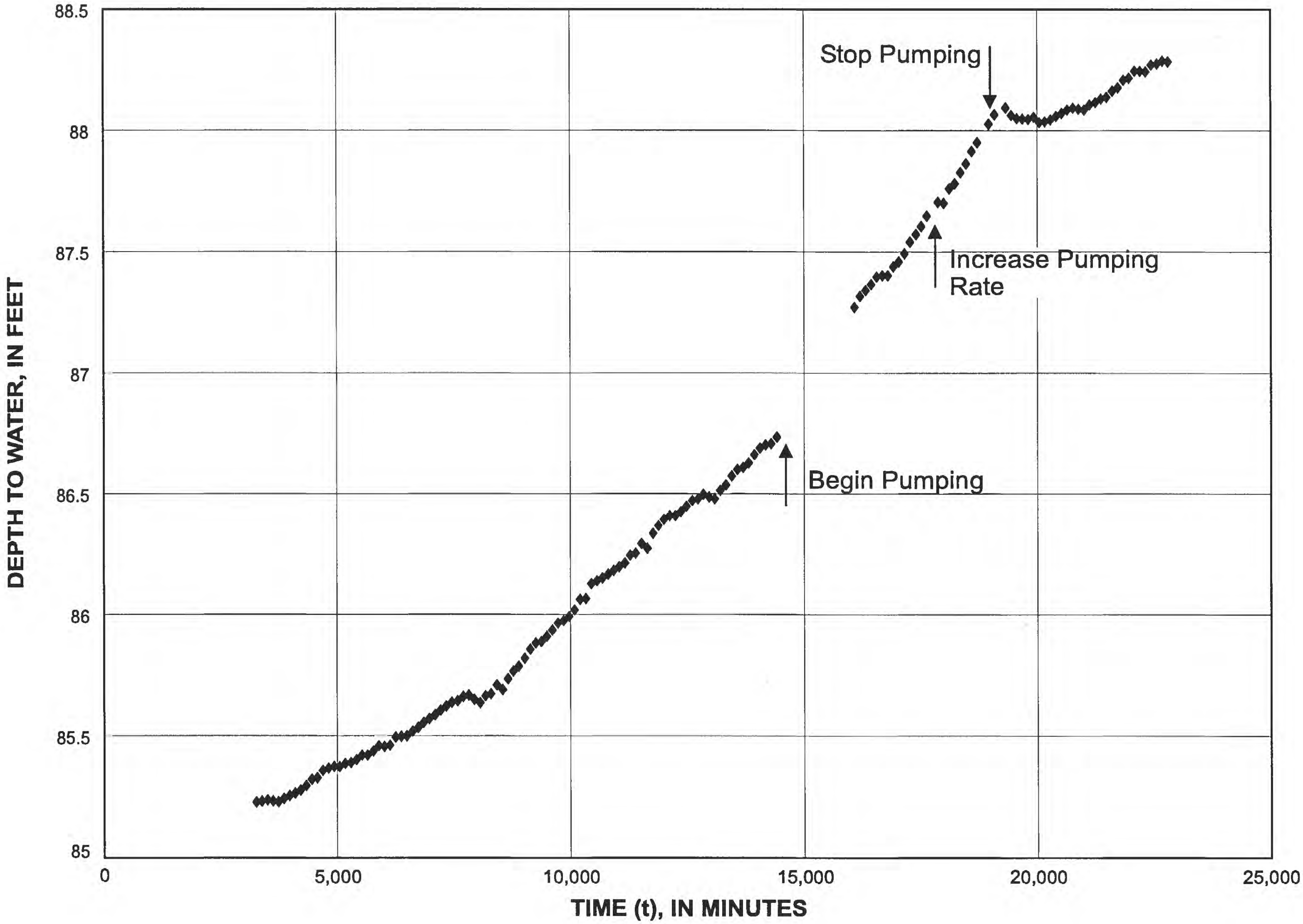
Appendix 2. Barometric pressure readings during the tracer test in well SPW near Byron, Illinois, June 30–July 16, 1993.

APPENDIX 3.

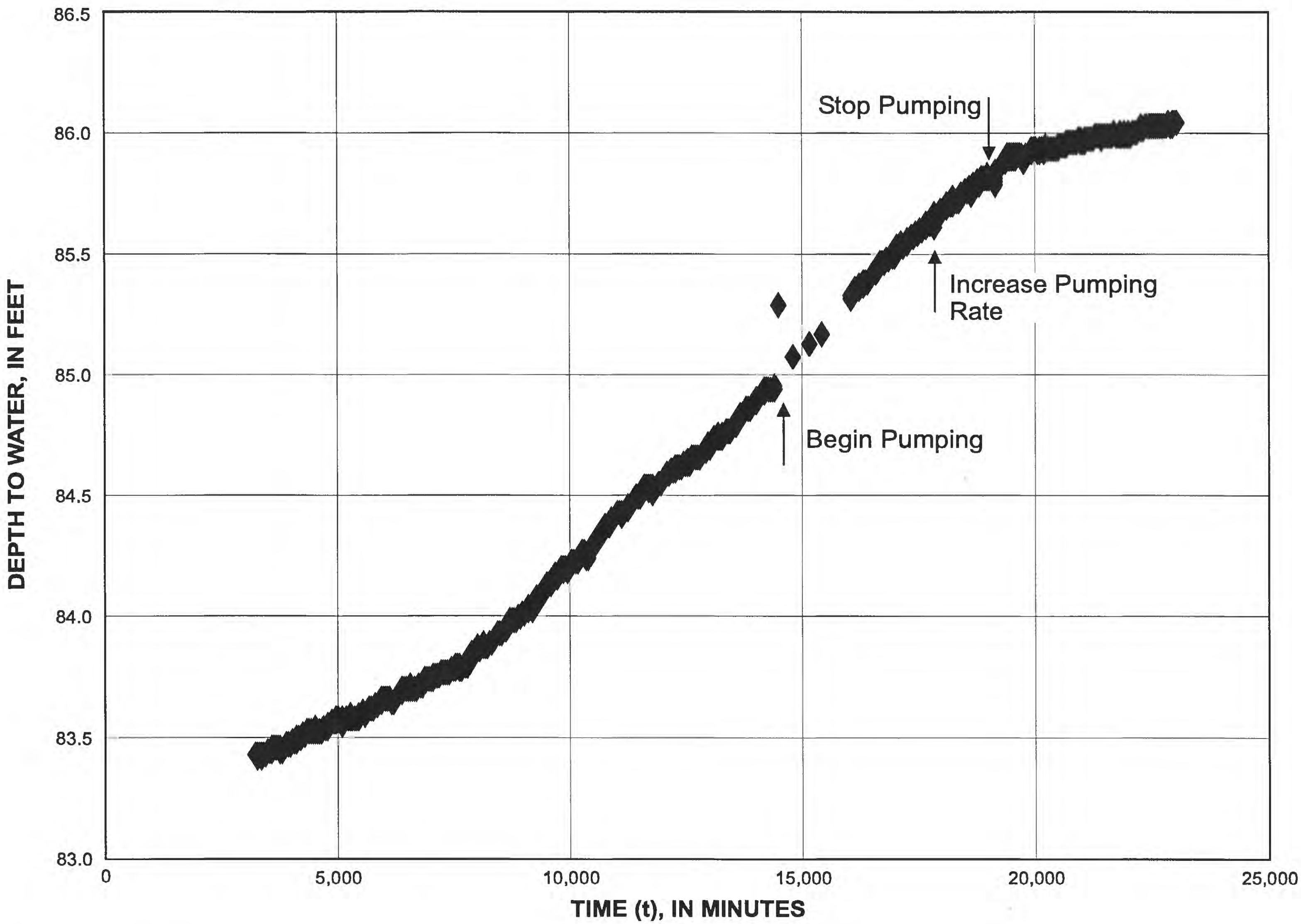
Summary of Data Collected During the Tracer Test—Water-Level Data Corrected for Fluctuations in Barometric Pressure



Appendix 3a. Water-level data adjusted for a barometric efficiency of 50 percent collected from observation well AW5I during the tracer test in well SPW near Byron, Illinois, June 30–July 16, 1993.



Appendix 3b. Water-level data adjusted for a barometric efficiency of 40 percent collected from observation well MW8 during the tracer test in well SPW near Byron, Illinois, June 30–July 16, 1993.



Appendix 3c. Water-level data adjusted for a barometric efficiency of 35 percent collected from observation well MW9 during the tracer test in well SPW near Byron, Illinois, June 30–July 16, 1993.