Evaluation of the Contributing Area for Recovery Wells at the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota

By J. Hal Davis

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Contents

Figures

Tables

Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)

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

$$°F=(1.8\times°C)+32$$

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

$$°C=(°F-32)/1.8$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 1929).

Altitude, as used in this report, refers to distance above the vertical datum.

Acronyms and Abbreviations

ft/d	Feet per day
gal/min	Gallons per minute
NIROP	Naval Industrial Reserve Ordnance Plant
TCE	Tetrachloroethene

Evaluation of the Contributing Area for Recovery Wells at the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota

By J. Hal Davis

Abstract

The Naval Industrial Reserve Ordnance Plant is located on the southernmost tip of Anoka County, Minnesota, within the City of Fridley, and about one-quarter mile east of the Mississippi River. Industrial production at the plant began in 1941 and has continued since that time. Contamination spills and poor disposal practices in the past have led to significant ground-water contamination beneath the facility. A ground-water recovery (and containment) system began operation in 1992 to prevent contaminated ground-water from migrating off site. In an effort to determine the effectiveness of the recovery system, pressure transducers were installed in 23 monitoring wells, multiple hand water-level measurements were taken in an additional 56 wells, and two extensive rounds of water-level measurements were taken in all wells (one during pumping and one during non-pumping conditions).

The cones of depression of the shallow flow zone wells AT-8 (17 gallons per minute (gal/min) and AT-9 (142 gal/min) overlap to form one broad cone, while the cone of depression of well AT-7 (42 gal/min) was more isolated. Shallow flow zone well AT-5A (156 gal/min) had a large, broad cone of depression which was the result of the relatively high pumping rate and the relatively high permeability of 200 feet per day (ft/d). Intermediate flow zone well AT-3A (182 gal/min) had a broad cone of depression that extended to the intermediate clays; well AT-10 (23 gal/min) had a relatively steep cone because it was screened in a relatively low-permeability zone. Deep flow zone well AT-5B (86 gal/min) had a broad cone of depression. Intermediate well AT-3A appears to be drawing water up vertically out of the deep flow zone.

The combined contributing areas of recovery wells AT-7, AT-8, and AT-9 capture the high levels of trichloroethene (TCE) contamination (greater than 100 parts per billion (ppb) along their combined axis. Well AT-5A has a broad contributing area that reaches approximately halfway to the Mississippi River and captures the eastern flank of the highest levels of contamination in the shallow zone; but it does not capture the highest levels that will still discharge to the Mississippi River. The combined contributing areas of wells AT-3A and AT-10 should capture the TCE contamination in the intermediate zone that is moving off site. Well AT-5B captures about a third of the TCE contamination in the deep flow zone where the concentration exceeds 100 ppb.

Introduction

The Naval Industrial Reserve Ordnance Plant (NIROP) is located on the southernmost tip of Anoka County, Minnesota, within the City of Fridley. The plant is located approximately one-quarter mile east of the Mississippi River (fig. 1). Parts of Minneapolis, St. Paul, New Brighton, Saint Anthony, most of Fridley and Brooklyn Center are located within a 3-mile radius of the NIROP facility (TtNUS, 2002a). This facility is currently active and consists of 82.6 acres of government-owned land, of which approximately 50 acres are paved or covered with buildings (TtNUS, 2002a).

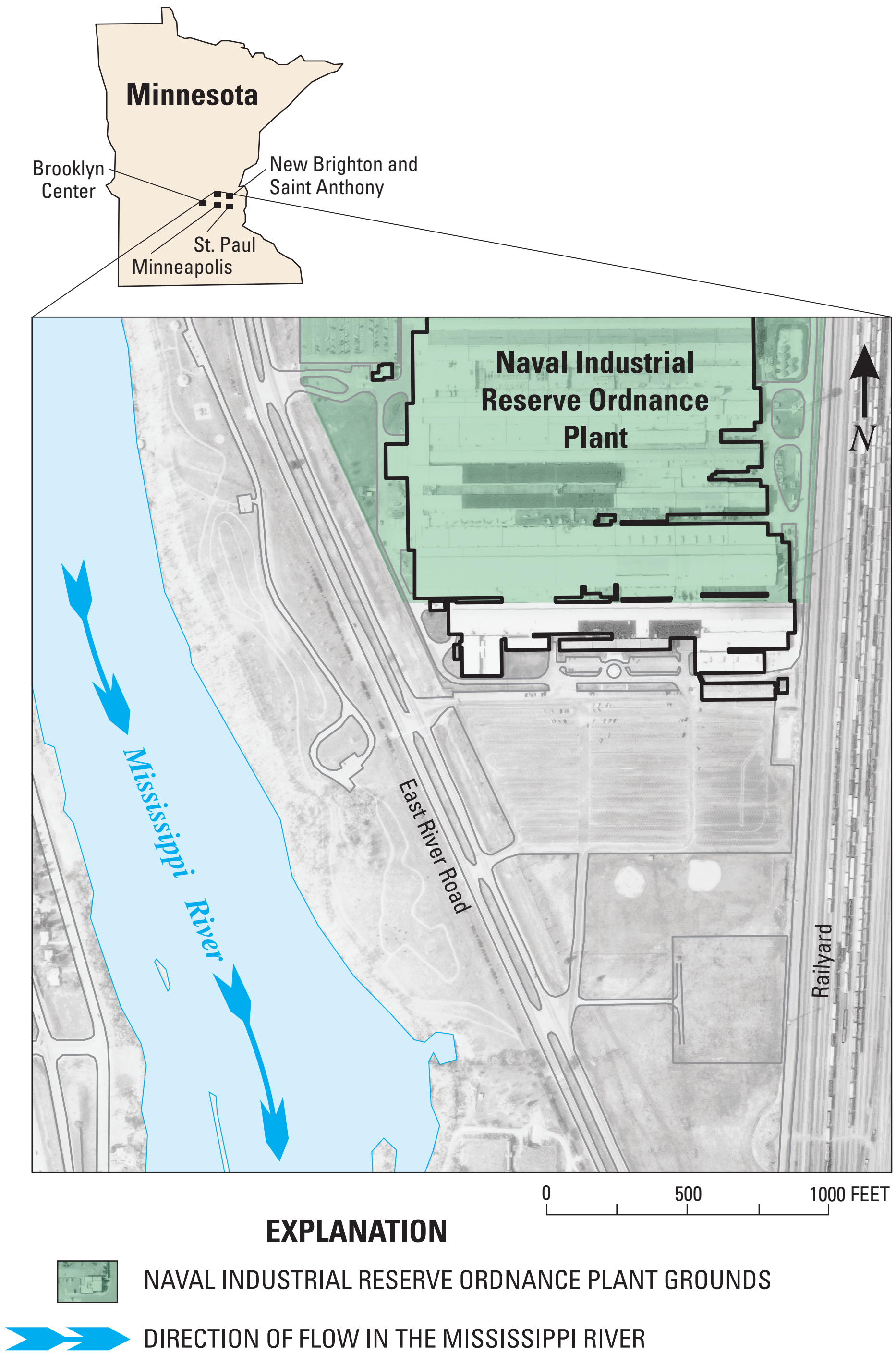


Figure 1. Location of the Naval Industrial Reserve Ordnance Plant.

Industrial production began at the site in 1941 when Northern Pump, in association with the U.S. Navy, established a manufacturing facility to produce 5-inch gun mounts. The facility has been in continuous operation since then and has continued to produce weapon systems. There have been no major functional changes in the industrial operations at NIROP since the plant was constructed in 1941, except that operations have been modernized (TtNUS, 2002a). The processing, assembly, and manufacturing operations conducted at the facility include plating, welding, heat treating, machining, and foundry. Testing facilities include an electronics laboratory, a metallurgical laboratory, hydraulic test bays, and shock/vibration test equipment. In support of these operations, NIROP had previously stored and disposed of industrial wastes, scrap material, drummed wastes, and chemicals at the facility. Spills and disposal practices in the past have led to significant ground-water contamination beneath the facility (TtNUS, 2002a). More specifically, the disposal practices included: (1) trenches in which drums containing liquid wastes were buried, (2) barrow pits used for disposal of drummed wastes, and (3) leaks from storm and sanitary sewers in which liquid wastes were disposed. The liquid wastes that resulted in the currently high levels of ground-water contamination were solvents used to clean and service machinery (TtNUS, 2002a). The U.S. Navy, through its environmental contractors, has conducted studies to locate and remediate ground-water contamination.

A ground-water recovery (and containment) system began operation in 1992 (TtNUS, 2002a.) The purpose of the system was to prevent contaminated ground water from migrating off site by using pump and treat technology. The system has been modified with additional wells being added and low-performance wells being removed to improve the effectiveness. Figure 2 shows the location of the ground-water recovery and monitoring wells. Prior to and during a recent (2001) scheduled shutdown, extensive ground-water level measurements were made to better understand ground-water flow at the site, and more specifically, to determine the contributing areas for the recovery system wells. This work is the subject of this report.

Purpose and Scope

The purpose of this report is to present the ground-water contributing areas for the seven recovery wells at NIROP (fig. 2). Study methods consisted of installing and monitoring pressure transducers in 23 wells, taking multiple discrete water-level measurements in an additional 56 wells, and using these data taken during pumping and non-pumping conditions to determine the ground-water contributing areas for all the recovery wells. Additionally, the report presents the measurements taken during the study, the insights these data provide regarding the ground-water flow system, and the location and size of the contributing area for each of the recovery system wells.

Description of Study Area

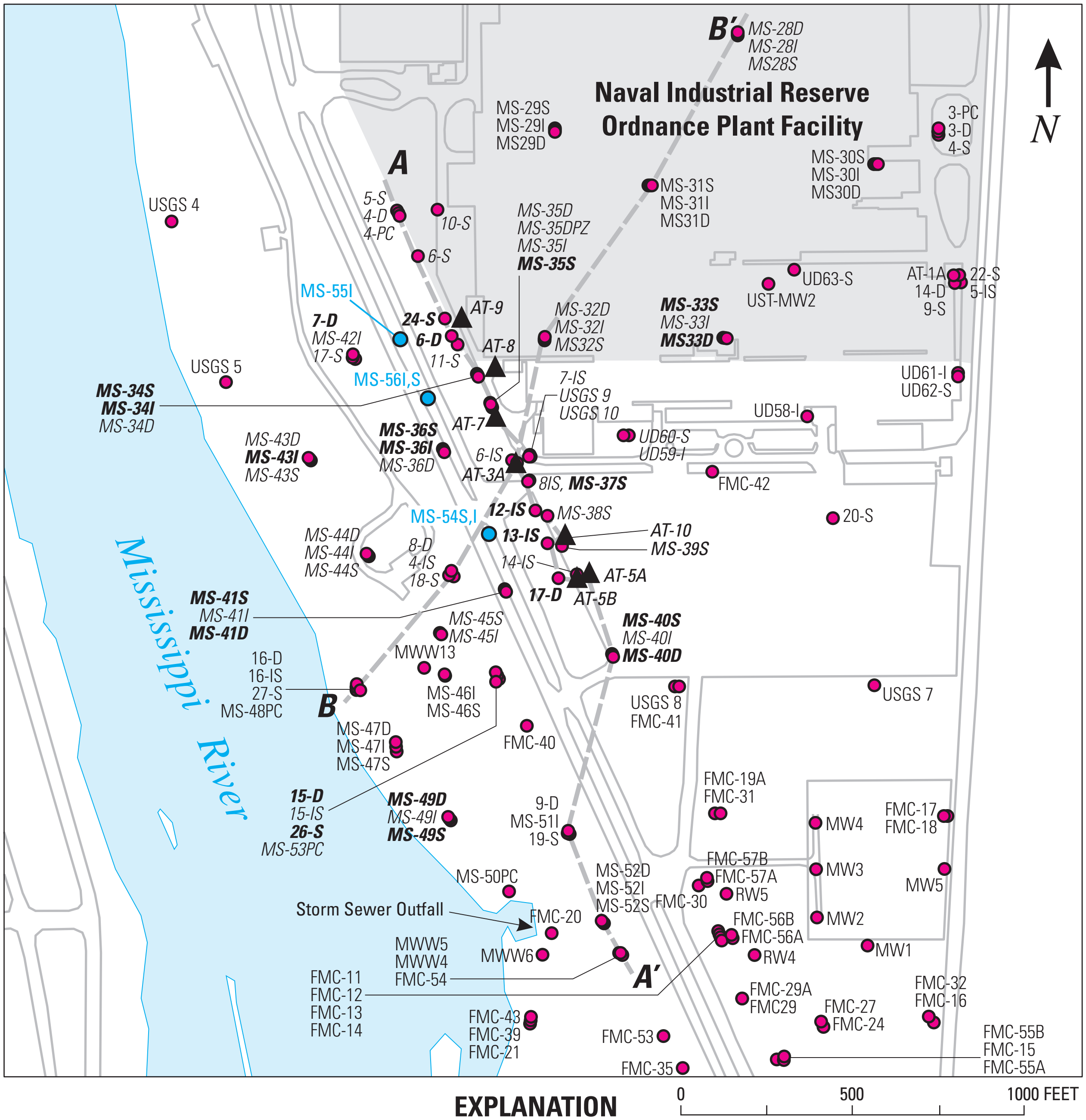
The site lies in the broad, flat alluvial terrace deposits of the Mississippi River valley flood plain. The terrain in the region surrounding the facility is generally flat or gently rolling and ground surface altitude ranges from about 825 to 850 feet above NGVD 1929.

The NIROP is situated on an alluvial terrace east of the Mississippi River. Much of this flat surface is covered by buildings and pavement. Runoff from these hard surfaces is collected by a series of storm sewers that drain to the Mississippi River, which is located aproximately 800 ft west of NIROP.

Surface soils are very sandy and highly permeable. There are no significant water courses, either perennial or intermittent, present on the site (TtNUS, 2002a).

Data Collection and Fieldwork

The goal of the fieldwork was to collect data that would be used to characterize ground-water flow in the vicinity of the recovery wells during pumping and non-pumping conditions. Prior to a planned shutdown of the recovery wells in 2001, pressure transducers were installed in 23 monitoring wells for this study so that water levels could be continuously monitored in the vicinity of the recovery system wells. On August 20, 2001 water-level measurements were taken in all the wells at the facility to determine ground-water levels during pumping. On August 21, 2001, at 11:08 a.m., all of the recovery wells were turned off and remained off until 3:15 p.m. on October 12, 2001. On September 26, 2001, measurements were again taken to determine non-pumping ground-water levels. Table 1 lists all the wells used and the water-level measurement method; table 2 lists the wells with pressure transducers and the data collection start and end dates. Table 3 lists the pumping and non-pumping water levels and the amount of recovery measured.



EXPLANATION

A – – A′ CROSS-SECTION LOCATION

MONITORING WELL LOCATION AND NAME

USGS 4 Regular font indicates that only two water-level measurements were taken: one during pumping and one during non-pumping conditions

MS-33I *Italic font indicates that multiple hand water-level measurements were taken before, during, and after pumping*

MS-33S ***Bold italic font indicates that a pressure transducer was used to measure water levels before, during, and after pumping***

MS-54S,I WELL LOCATION AND NAME – Drilled after test was completed.

AT-10 RECOVERY SYSTEM PUMPING WELL LOCATION AND NAME – All pumping wells had multiple hand water-level measurements taken before, during, and after pumping

Figure 2. Location of ground-water recovery and monitoring wells.

Table 1. Description of pumping and monitoring wells.

Well name	Depth (in feet)	Diameter (in inches)	Top of casing (in feet)	Screen length (in feet)	Glacial-drift aquifer zone	Type of water-level measurement
10-S	29.5	2	835.73	10.1	Shallow	Multiple Hand
11-S	29.3	2	835.75	10.0	Intermediate	Multiple Hand
12-IS	74.8	2	834.94	20.0	Intermediate	Solinist Pressure Transducer
13-IS	73.5	2	834.96	10.0	Intermediate	Solinist Pressure Transducer
14-D	90.0	3	837.75	10.0	Deep	Pumping/Non-Pumping
14-IS	66.8	unk	835.21	10.0	Shallow	Multiple Hand
15-D	133.8	unk	834.01	20.0	Deep	Non-Solinist Pressure Transducer
15-IS	75.0	2	833.67	10.0	Intermediate	Multiple Hand
16-D	114.0	2	833.08	20.0	Deep	Pumping/Non-Pumping
16-IS	85.2	2	832.77	10.0	Intermediate	Pumping/Non-Pumping
17-D	104.4	unk	835.24	unk	Deep	Solinist Pressure Transducer
17-S	36.0	2	835.48	10.0	Shallow	Multiple Hand
18-S	37.8	3	833.86	10.0	Shallow	Multiple Hand
19-S	42.5	2	834.18	10.0	Shallow	Multiple Hand
20-S	32.6	2	837.51	10.0	Shallow	Pumping/Non-Pumping
22-S	35.0	2	837.60	15.0	Shallow	Pumping/Non-Pumping
24-S	35.0	2	836.19	15.0	Shallow	Solinist Pressure Transducer
26-S	40.0	2	834.06	10.0	Shallow	Non-Solinist Pressure Transducer
27-S	50.3	2	832.74	10.0	Shallow	Pumping/Non-Pumping
3-D	79.2	2	837.35	10.2	Deep	Pumping/Non-Pumping
3-PC	156.7	4	838.53	unk	Bedrock	Pumping/Non-Pumping
4-D	119.3	2	834.65	10.0	Deep	Multiple Hand
4-IS	75.0	2	833.34	10.0	Intermediate	Multiple Hand
4-PC	181.0	4	834.63	unk	Bedrock	Multiple Hand
4-S	33.2	2	837.33	15.0	Shallow	Pumping/Non-Pumping
5-IS	60.0	2	837.86	10.0	Intermediate	Pumping/Non-Pumping
5-S	33.0	2	834.92	15.0	Shallow	Multiple Hand
6-D	128.6	2	835.54	10.0	Deep	Solinist Pressure Transducer
6-IS	unk	unk	836.53	unk	Intermediate	Multiple Hand
6-S	33.0	2	835.60	15.2	Shallow	Multiple Hand
7-D	115.0	4	835.61	10.0	Deep	Solinist Pressure Transducer
7-IS	unk	unk	837.02	unk	Intermediate	Multiple Hand
8-D	125.0	4	833.92	10.0	Deep	Multiple Hand
8-IS	unk	unk	836.65	unk	Intermediate	Multiple Hand
9-D	121.3	4	834.22	10.0	Deep	Multiple Hand
9-S	27.8	2	836.53	10.0	Shallow	Pumping/Non-Pumping
AT-10	84	8	837.11	16	Intermediate	Multiple Hand
AT-3A	105.0	8	836.10	35.6	Intermediate	Multiple Hand
AT-5A	66.0	8	835.57	30.0	Shallow	Multiple Hand
AT-5B	136.0	8	835.62	35.0	Deep	Multiple Hand
AT-7	39	8	836.30	10	Shallow	Multiple Hand
AT-8	38	8	835.18	10	Shallow	Multiple Hand
AT-9	52	8	836.82	17	Shallow	Multiple Hand
FMC-11	95.0	4	835.50	10.0	Intermediate	Pumping/Non-Pumping
FMC-12	70.0	4	835.37	5.0	Intermediate	Pumping/Non-Pumping
FMC-13	46.0	4	835.32	5.0	Shallow	Pumping/Non-Pumping
FMC-14	30.0	4	835.26	5.0	Shallow	Pumping/Non-Pumping
FMC-15	32.0	4	836.16	5.0	Shallow	Pumping/Non-Pumping
FMC-16	31.0	4	837.16	5.0	Shallow	Pumping/Non-Pumping
FMC-17	35.0	4	837.59	4.0	Shallow	Pumping/Non-Pumping
FMC-18	65.0	4	837.54	5.0	Intermediate	Pumping/Non-Pumping
FMC-19A	38.0	4	835.24	5.0	Shallow	Pumping/Non-Pumping
FMC-20	38.0	4	833.48	5.0	Shallow	Pumping/Non-Pumping
FMC-21	42.0	2	833.00	4.0	Shallow	Pumping/Non-Pumping

Table 1. Description of pumping and monitoring wells.—Continued

Well name	Depth (in feet)	Diameter (in inches)	Top of casing (in feet)	Screen length (in feet)	Glacial-drift aquifer zone	Type of water-level measurement
FMC-24	32.0	2	837.46	4.0	Shallow	Pumping/Non-Pumping
FMC-27	61.0	4	837.30	4.0	Intermediate	Pumping/Non-Pumping
FMC-29	93.0	6	836.32	55.0	Intermediate	Pumping/Non-Pumping
FMC-29A	64.7	2	834.85	20.7	Intermediate	Pumping/Non-Pumping
FMC-30	112.0	4	835.07	72.0	Deep	Pumping/Non-Pumping
FMC-31	160.0	4	834.64	unk	Bedrock	Pumping/Non-Pumping
FMC-32	160.0	4	837.41	unk	Bedrock	Pumping/Non-Pumping
FMC-35	60.0	4	832.15	35.0	Intermediate	Pumping/Non-Pumping
FMC-39	134.0	4	832.08	89.0	Deep	Pumping/Non-Pumping
FMC-40	137.0	4	833.93	91.0	Deep	Pumping/Non-Pumping
FMC-41	143.0	4	835.67	62.0	Deep	Pumping/Non-Pumping
FMC-42	137.5	8	835.61	unk	Bedrock	Pumping/Non-Pumping
FMC-43	178.0	4	831.89	unk	Bedrock	Pumping/Non-Pumping
FMC-53	135.0	4	831.10	99.5	Deep	Pumping/Non-Pumping
FMC-54	140.0	4	832.50	75.5	Deep	Pumping/Non-Pumping
FMC-55A	93.0	2	834.22	5.0	Deep	Pumping/Non-Pumping
FMC-55B	65.0	2	834.24	5.0	Intermediate	Pumping/Non-Pumping
FMC-56A	95.0	2	834.53	5.0	Deep	Pumping/Non-Pumping
FMC-56B	60.0	2	834.41	5.0	Intermediate	Pumping/Non-Pumping
FMC-57A	100.0	2	834.28	5.0	Deep	Pumping/Non-Pumping
FMC-57B	68.0	2	834.42	5.0	Intermediate	Pumping/Non-Pumping
MS-28D	114.7	2	834.80	5.1	Deep	Multiple Hand
MS-28I	85.5	2	834.83	5.1	Intermediate	Multiple Hand
MS-28S	27.3	2	834.81	10.1	Shallow	Multiple Hand
MS-29D	136.7	2	834.69	5.1	Deep	Pumping/Non-Pumping
MS-29I	81.2	2	834.67	5.1	Intermediate	Pumping/Non-Pumping
MS-29S	27.3	2	834.68	10.1	Shallow	Pumping/Non-Pumping
MS-30D	99.4	2	834.81	4.8	Deep	Pumping/Non-Pumping
MS-30I	67.8	2	834.85	5.0	Deep	Pumping/Non-Pumping
MS-30S	27.5	2	834.83	9.9	Shallow	Pumping/Non-Pumping
MS-31D	127.2	2	834.81	5.0	Deep	Pumping/Non-Pumping
MS-31I	96.6	2	834.81	5.1	Intermediate	Pumping/Non-Pumping
MS-31S	27.5	2	834.81	10.1	Shallow	Pumping/Non-Pumping
MS-32D	126.2	2	834.75	5.0	Deep	Multiple Hand
MS-32I	84.8	2	834.69	5.1	Intermediate	Multiple Hand
MS-32S	26.1	2	834.76	10.1	Shallow	Multiple Hand
MS-33D	120.3	2	834.76	5.1	Deep	Solinist Pressure Transducer
MS-33I	75.9	2	834.74	5.1	Intermediate	Multiple Hand
MS-33S	27.1	2	834.72	10.1	Shallow	Solinist Pressure Transducer
MS-34D	135.5	2	834.35	10.0	Deep	Multiple Hand
MS-34I	79.5	2	834.35	10.0	Intermediate	Solinist Pressure Transducer
MS-34S	27.0	2	834.31	10.0	Shallow	Solinist Pressure Transducer
MS-35D	132.6	2	834.45	10.0	Deep	Multiple Hand
MS-35DPZ	132.0	2	834.26	10.0	Deep	Multiple Hand
MS-35I	82.0	2	834.21	10.0	Intermediate	Multiple Hand
MS-35S	27.0	2	834.22	10.0	Shallow	Solinist Pressure Transducer
MS-36D	131.5	2	834.79	10.0	Deep	Multiple Hand
MS-36I	80.5	2	834.70	10.0	Intermediate	Solinist Pressure Transducer
MS-36S	42.0	2	834.80	10.0	Shallow	Solinist Pressure Transducer
MS-37S	48.0	2	834.21	10.0	Intermediate	Solinist Pressure Transducer
MS-38S	42.0	2	834.64	10.0	Shallow	Multiple Hand
MS-39S	41.5	2	834.76	10.0	Shallow	Multiple Hand
MS-40D	135.5	2	834.70	10.0	Deep	Solinist Pressure Transducer
MS-40I	60.7	2	834.64	10.0	Shallow	Multiple Hand
MS-40S	41.0	2	834.61	10.0	Shallow	Solinist Pressure Transducer

Table 1. Description of pumping and monitoring wells.—Continued

Well name	Depth (in feet)	Diameter (in inches)	Top of casing (in feet)	Screen length (in feet)	Glacial-drift aquifer zone	Type of water-level measurement
MS-41D	132.0	2	834.89	10.0	Deep	Solinist Pressure Transducer
MS-41I	90.0	2	834.82	15.0	Intermediate	Multiple Hand
MS-41S	41.0	2	834.82	10.0	Shallow	Non-Solinist Pressure Transducer
MS-42I	52.5	2	835.33	10.0	Shallow	Multiple Hand
MS-43D	111.4	2	834.27	10.0	Deep	Multiple Hand
MS-43I	80.3	2	834.32	15.0	Intermediate	Solinist Pressure Transducer
MS-43S	37.0	2	834.42	10.0	Shallow	Multiple Hand
MS-44D	118.0	2	833.58	10.0	Deep	Multiple Hand
MS-44I	80.0	2	833.62	10.0	Intermediate	Multiple Hand
MS-44S	34.0	2	833.53	10.0	Shallow	Multiple Hand
MS-45I	90.0	2	832.07	10.0	Intermediate	Multiple Hand
MS-45S	33.0	2	832.13	10.0	Shallow	Multiple Hand
MS-46I	85.1	2	831.61	10.0	Intermediate	Pumping/Non-Pumping
MS-46S	34.0	2	831.67	10.0	Shallow	Pumping/Non-Pumping
MS-47D	130.4	2	834.51	10.0	Deep	Pumping/Non-Pumping
MS-47I	79.2	2	834.55	10.0	Intermediate	Pumping/Non-Pumping
MS-47S	38.0	2	834.83	10.0	Shallow	Pumping/Non-Pumping
MS-48PC	165.3	2	831.50	15.0	Bedrock	Pumping/Non-Pumping
MS-49D	127.4	2	833.87	10.0	Deep	Non-Solinist Pressure Transducer
MS-49I	84.9	2	834.02	15.0	Intermediate	Multiple Hand
MS-49S	38.0	2	834.16	10.0	Shallow	Solinist Pressure Transducer
MS-50PC	170.0	2	833.88	15.0	Bedrock	Pumping/Non-Pumping
MS-51I	75.0	2	833.66	10.0	Intermediate	Multiple Hand
MS-52D	138.0	2	833.27	15.0	Deep	Pumping/Non-Pumping
MS-52I	79.0	2	833.25	10.0	Intermediate	Pumping/Non-Pumping
MS-52S	38.0	2	833.14	10.0	Shallow	Pumping/Non-Pumping
MS-53PC	166.9	2	832.64	15.0	Bedrock	Multiple Hand
MW1	47.7	4	838.51	20.0	Intermediate	Pumping/Non-Pumping
MW2	46.0	4	839.59	20.0	Intermediate	Pumping/Non-Pumping
MW3	45.5	4	840.22	20.0	Intermediate	Pumping/Non-Pumping
MW4	46.0	4	839.52	20.0	Intermediate	Pumping/Non-Pumping
MW5	45.0	4	838.36	20.3	Intermediate	Pumping/Non-Pumping
MWW13	30.0	2	833.33	3.0	Shallow	Pumping/Non-Pumping
MWW4	55.0	2	832.01	4.0	Intermediate	Pumping/Non-Pumping
MWW5	29.0	unk	831.39	3.0	Shallow	Pumping/Non-Pumping
MWW6	27.0	2	831.05	3.0	Shallow	Pumping/Non-Pumping
RW4	50.5	6	835.00	27.7	Shallow	Pumping/Non-Pumping
RW5	59.5	6	833.84	27.9	Intermediate	Pumping/Non-Pumping
UD58-I	80.1	2	837.60	10.0	Intermediate	Pumping/Non-Pumping
UD59-I	70.8	2	836.68	10.0	Intermediate	Multiple Hand
UD60-S	30.2	2	837.60	10.0	Shallow	Multiple Hand
UD61-I	73.5	2	835.16	10.0	Intermediate	Pumping/Non-Pumping
UD62-S	29.7	2	835.26	10.0	Shallow	Pumping/Non-Pumping
UD63-S	30.1	2	837.00	10.0	Shallow	Pumping/Non-Pumping
USGS 10	128.0	2	836.85	10.0	Deep	Multiple Hand
USGS 4	43.0	2	831.84	10.0	Shallow	Pumping/Non-Pumping
USGS 5	42.5	2	832.86	10.0	Shallow	Pumping/Non-Pumping
USGS 7	43.0	2	835.47	10.0	Shallow	Pumping/Non-Pumping
USGS 8	42.5	2	836.10	10.0	Shallow	Multiple Hand
USGS 9	43.0	2	836.50	10.0	Shallow	Multiple Hand
UST-MW2	29.5	2	837.35	10.0	Shallow	Pumping/Non-Pumping

Table 2. Wells equipped with pressure transducers and data collection dates.

Well name	Depth (in feet)	Data collection start	Data collection end	Type of pressure transducer
6-D	128.6	8/20/2001	10/30/2001	Solinist Pressure Transducer
7-D	115.0	8/17/2001	11/8/2001	Solinist Pressure Transducer
12-IS	74.8	8/17/2001	2/7/2002	Solinist Pressure Transducer
13-IS	73.5	8/17/2001	11/8/2001	Solinist Pressure Transducer
15-D	133.8	6/13/2001	2/7/2002	Non-Solinist Pressure Transducer
17-D	104.4	8/17/2001	2/7/2002	Solinist Pressure Transducer
24-S	35.0	8/20/2001	10/30/2001	Solinist Pressure Transducer
26-S	40.0	7/17/2001	2/7/2002	Non-Solinist Pressure Transducer
MS-33D	120.3	8/17/2001	11/8/2001	Solinist Pressure Transducer
MS-33S	27.1	8/17/2001	2/7/2002	Solinist Pressure Transducer
MS-34I	79.5	8/20/2001	10/30/2001	Solinist Pressure Transducer
MS-34S	27.0	8/20/2001	10/30/2001	Solinist Pressure Transducer
MS-35S	27.0	8/17/2001	2/7/2002	Solinist Pressure Transducer
MS-36I	80.5	8/17/2001	2/5/2002	Solinist Pressure Transducer
MS-36S	42.0	8/17/2001	2/5/2002	Solinist Pressure Transducer
MS-37S	48.0	8/17/2001	2/7/2002	Solinist Pressure Transducer
MS-40D	135.5	8/17/2001	2/5/2002	Solinist Pressure Transducer
MS-40S	41.0	8/20/2001	10/30/2001	Solinist Pressure Transducer
MS-41D	132.0	8/17/2001	2/5/2002	Solinist Pressure Transducer
MS-41S	41.0	7/17/2001	2/7/2002	Non-Solinist Pressure Transducer
MS-43I	80.3	8/17/2001	11/8/2001	Solinist Pressure Transducer
MS-49D	127.4	8/14/2001	2/7/2002	Non-Solinist Pressure Transducer
MS-49S	38.0	8/17/2001	2/5/2002	Solinist Pressure Transducer

Multiple hand water-level measurements, using electric measuring tapes, were taken in an additional 56 wells (fig. 2 and table 1). The measurements were taken at the following times: (1) immediately before the pumps were shut off at 11:08 a.m. on August 21, 2001; (2) six additional times at approximately 1-hour intervals on August 21, 2001, after the pumps were shut off; (3) twice on August 22 and 23, 2001; and (4) once on August 25 and 28, September 4, 10, and 26, 2001. Other measurements were made periodically in some wells to check the accuracy of the pressure transducers.

Two well nests (of three wells each) were monitored to determine the magnitude of water-level changes in the glacial-drift aquifer not associated with the recovery test. These background wells were MS-28S, MS-28I, and MS-28D located directly upgradient from the recovery system and wells MS-49S, MS-49I, and MS-49D located downgradient from the recovery system and close to the Mississippi River (fig. 2.) In addition, the stage of the Mississippi River was monitored.

Hydrogeologic Setting

The facility is underlain by sedimentary rocks of Cambrian through Quaternary age (fig. 3). The lithology consists of limestone, dolostone, clay, and sand of varying degrees of lithification (Lindgren, 1990). The geologic units from oldest to youngest are: the Jordan Sandstone of Cambrian age, the Prairie du Chien and St. Peter Sandstone of Ordovician age, and the glacial-drift deposits of Quaternary age.

Table 3. Water levels and water-level recovery.

Well name	Pumping water level (in feet)	Non-pumping water level (in feet)	Recovery (in feet)	Well name	Pumping water level (in feet)	Non-pumping water level (in feet)	Recovery (in feet)
10-S	814.07	815.07	1.00	MS-33D	814.46	815.02	0.56
11-S	804.94	807.85	2.91	MS-33I	814.74	815.26	0.52
12-IS	810.54	813.06	2.52	MS-33S	815.00	815.46	0.46
13-IS	808.94	814.07	5.13	MS-34D	806.31	809.58	3.27
14-D	815.29	815.65	0.36	MS-34I	804.88	807.82	2.94
14-IS	796.85	802.93	6.08	MS-34S	812.49	814.85	2.36
15-D	804.40	806.03	1.63	MS-35D	809.75	809.52	-0.23
15-IS	803.90	805.53	1.63	MS-35DPZ	805.53	809.35	3.82
16-D	801.55	801.96	0.41	MS-35I	804.67	807.76	3.09
16-IS	801.98	802.43	0.45	MS-35S	812.17	814.70	2.53
17-D	805.92	811.52	5.60	MS-36D	804.87	809.05	4.18
17-S	810.38	811.67	1.29	MS-36I	804.52	807.38	2.86
18-S	804.08	806.13	2.05	MS-36S	806.36	808.13	1.77
19-S	799.89	800.40	0.51	MS-37S	804.50	807.99	3.49
20-S	816.69	816.65	-0.04	MS-38S	797.86	802.61	4.75
22-S	816.30	816.30	0.00	MS-39S	797.29	802.01	4.72
24-S	812.45	814.72	2.27	MS-40D	806.14	807.66	1.52
26-S	803.94	805.60	1.66	MS-40I	798.23	801.22	2.99
27-S	801.89	802.33	0.44	MS-40S	798.32	801.21	2.89
3-D	815.31	815.66	0.35	MS-41D	804.14	806.27	2.13
3-PC	815.73	816.05	0.32	MS-41I	804.14	806.29	2.15
4-D	805.70	806.70	1.00	MS-41S	798.78	802.49	3.71
4-IS	804.16	806.21	2.05	MS-42I	810.39	811.68	1.29
4-PC	815.63	815.93	0.30	MS-43D	802.97	803.83	0.86
4-S	816.68	816.42	-0.26	MS-43I	801.64	801.73	0.09
5-IS	815.71	815.91	0.20	MS-43S	801.87	801.84	-0.03
5-S	813.68	814.90	1.22	MS-44D	804.14	806.11	1.97
6-D	804.96	807.83	2.87	MS-44I	804.13	806.15	2.02
6-IS	803.73	807.72	3.99	MS-44S	803.61	804.98	1.37
6-S	813.14	814.74	1.60	MS-45I	803.94	805.73	1.79
7-D	803.18	804.23	1.05	MS-45S	803.87	805.65	1.78
7-IS	803.92	807.73	3.81	MS-46I	801.85	805.31	3.46
8-D	804.16	806.24	2.08	MS-46S	803.66	805.26	1.60
8-IS	806.30	809.80	3.50	MS-47D	803.16	804.45	1.29
9-D	799.78	800.30	0.52	MS-47I	800.69	801.19	0.50
9-S	816.29	816.26	-0.03	MS-47S	796.63	801.12	4.49
AT-10	791.91	814.01	22.10	MS-48PC	813.46	813.92	0.46
AT-3A	765.98	808.70	42.72	MS-49D	800.07	800.59	0.52
AT-5A	793.85	801.56	7.71	MS-49I	800.17	800.44	0.27
AT-5B	791.80	807.67	15.87	MS-49S	799.95	800.22	0.27
AT-7	809.29	814.89	5.60	MS-50PC	813.55	813.98	0.43
AT-8	804.61	814.93	10.32	MS-51I	799.91	800.42	0.51
AT-9	805.85	814.87	9.02	MS-52D	809.03	809.65	0.62
MS-28D	815.69	816.02	0.33	MS-52I	799.75	799.80	0.05

Table 3. Water levels and water-level recovery.—Continued

Well name	Pumping water level (in feet)	Non-pumping water level (in feet)	Recovery (in feet)	Well name	Pumping water level (in feet)	Non-pumping water level (in feet)	Recovery (in feet)
MS-28I	815.82	815.92	0.10	MS-52S	799.74	799.79	0.05
MS-28S	815.74	815.89	0.15	MS-53PC	813.62	814.05	0.43
MS-29D	816.08	816.49	0.41	MWW13	801.49	802.06	0.57
MS-29I	814.78	815.50	0.72	MWW5	799.43	799.44	0.01
MS-29S	814.72	815.48	0.76	MWW6	805.44	805.66	0.22
MS-30D	814.93	815.34	0.41	UD59-I	813.01	814.66	1.65
MS-30I	814.85	815.33	0.48	UD60-S	814.94	815.61	0.67
MS-30S	816.17	816.02	-0.15	USGS 10	808.08	809.31	1.23
MS-31I	815.29	815.59	0.30	USGS 4	800.07	799.76	-0.31
MS-31S	814.70	815.47	0.77	USGS 5	800.03	799.74	-0.29
MS-32D	807.30	810.29	2.99	USGS 7	813.72	814.32	0.60
MS-32I	806.44	809.11	2.67	USGS 8	798.86	801.02	2.16
MS-32S	815.14	815.13	-0.01	USGS 9	810.66	813.32	2.66

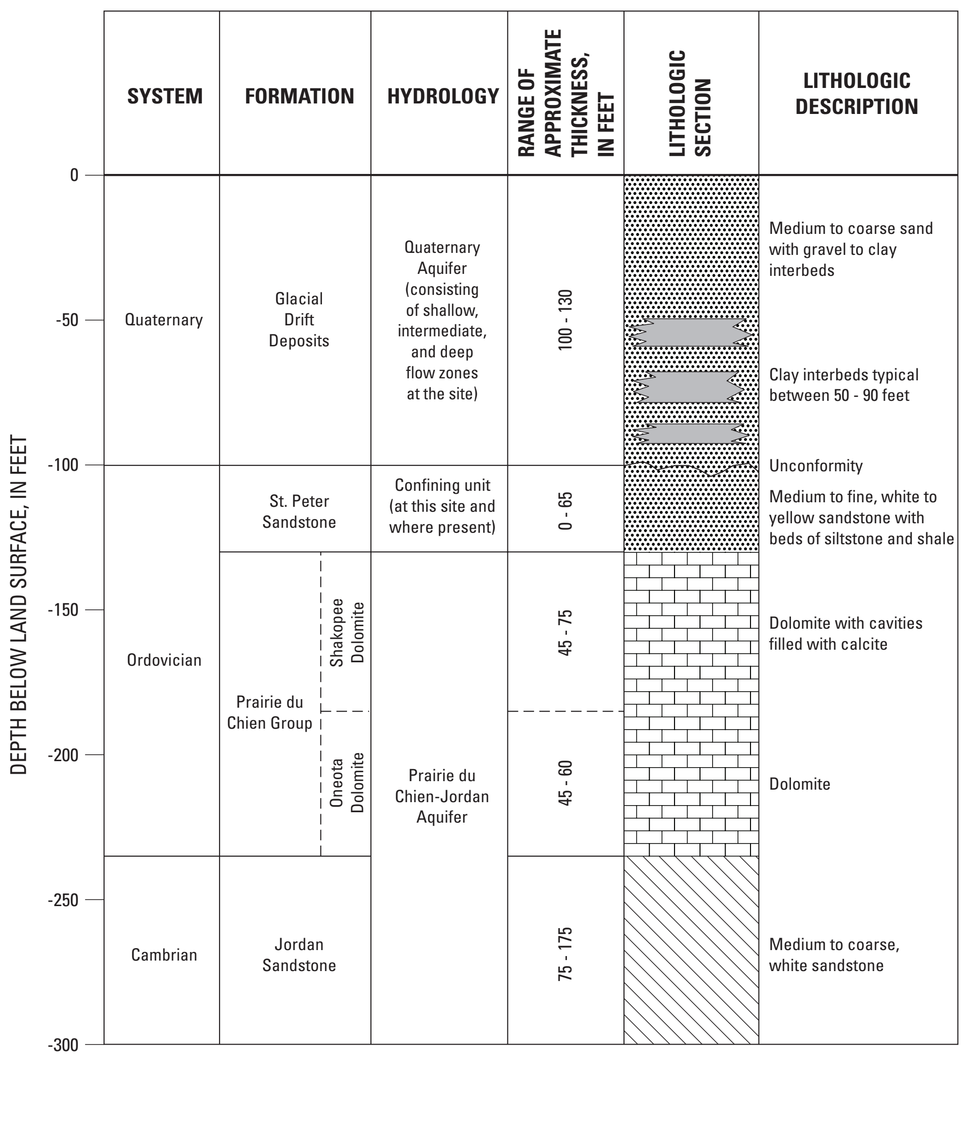


Figure 3. Hydrogeologic units (after Lindgren, 1990, and TtNUS, 2002a.)

The glacial-drift deposits form the uppermost permeable unit at the facility and contain the water table (figs. 4 and 5). These deposits range in thickness up to about 130 ft and consist of medium to coarse sand, fine sand, gravel, and discontinuous very fine grained (clay, silty clay, sandy clay, and silt) interbeds. The clay and silt interbeds range up to 46 ft in thickness (TtNUS, 2002a). Most of the ground-water contamination at the site is located within the glacial-drift deposits (TtNUS, 2002a) where most of the monitoring wells have been installed.

The St. Peter Sandstone unconformably underlies the glacial-drift deposits. The upper part of the formation is sandstone and is used in some areas for domestic water supply; hydraulic conductivities range from 24-50 ft/d. The lower part of the St. Peter is siltstone and shale, known as the Basal St. Peter Confining Unit, and is considered a potential confining unit. The St. Peter unconformably overlies the Prairie du Chein. The St. Peter Sandstone is present under most of the facility but is absent in the southwest corner. The St. Peter consists of a fine- to medium-grained, friable, well-sorted, white to yellow sandstone, with beds of siltstone and shale in the lower part of the formation (TtNUS, 2002a.) The St. Peter Sandstone is not highly permeable (Theil, 1944) especially when compared to the overlying glacial drift deposits and the underlying Prairie du Chien Group (TtNUS, 2002a). Therefore, it is considered a confining unit at the site where present.

The Prairie du Chien Group underlies the St. Peter Sandstone and consists of the Shakopee Dolomite and the Oneota Dolomite. The Shakopee Dolomite is mostly a massive, drab, dolomitic limestone with cavities filled with crystalline calcite (Theil, 1944.) The Oneota Dolomite is thick bedded, drab to buff and may contain interbeds of sandstone and shale. The Jordan Sandstone underlies the Prairie du Chien Group (not shown on hydrologic sections A and B, figs. 4 and 5 respectively), and is a loosely cemented, medium- to coarse-grained, white sandstone. Together, the Prairie du Chien Group and Jordan Sandstone form the Prairie du Chien Group-Jordan aquifer. This aquifer supplies about 80 percent of the ground water produced in the region (TtNUS, 2002a.) Schoenberg (1990) presented the expected range of conductivities for the Prairie du Chein to be 20 to 106 ft/d.

Recovery System Test Results and Discussion

This section describes the data collected during the water-level measurement period from August 20 to September 26, 2001, although some data were collected before and after this period. A discussion on the importance of the data to understanding the ground-water flow system is also included. Specifically, the items discussed are: (1) the response of the background upgradient and downgradient monitoring wells; (2) the water-level response in representative well nests that illustrate general trends; and (3) the potentiometric surfaces in the shallow, intermediate, and deep flow zones for non-pumping and pumping conditions.

Numerous monitoring wells have been installed at the site over the last several years. The primary naming convention that has evolved based on well depth is: wells designated with an “S” in the name are shallow depth wells; wells designated with an “I” or “IS” are intermediate depth wells; wells designated with a “D” are deep wells; and wells with a “PC” are bedrock wells. One well has been designated “DPZ” and is approximately the same depth as a ‘D’ well a few feet away (fig. 4 and table 1.) Historically, there have been three flow zones designated at the facility, which are shallow, intermediate, and deep; all the shallow wells were used to make the shallow flow zone map, all the intermediate wells were used to make the intermediate flow zone map, and all the deep wells were used to make the deep flow zone map. This method was also used in this report with a few important exceptions. Where the intermediate clay is present (figs. 4 and 5), it was assumed that the intermediate flow zone was replaced by the low-permeability intermediate clay and that no flow was occurring in the intermediate zone. Some intermediate wells in this area were screened above the intermediate clay and some were screened below the intermediate clay. If a well was screened above the clay and responded identically to the adjacent shallow well, then that well was considered to be a shallow well. Conversely, if a well was screened below the clay and responded identically to the adjacent deep well, then that well was considered to be a deep well.

The water-level hydrographs in this report have a vertical axis range of 12 ft. This allows the graphs to be quickly compared without having to visually adjust for various scales.

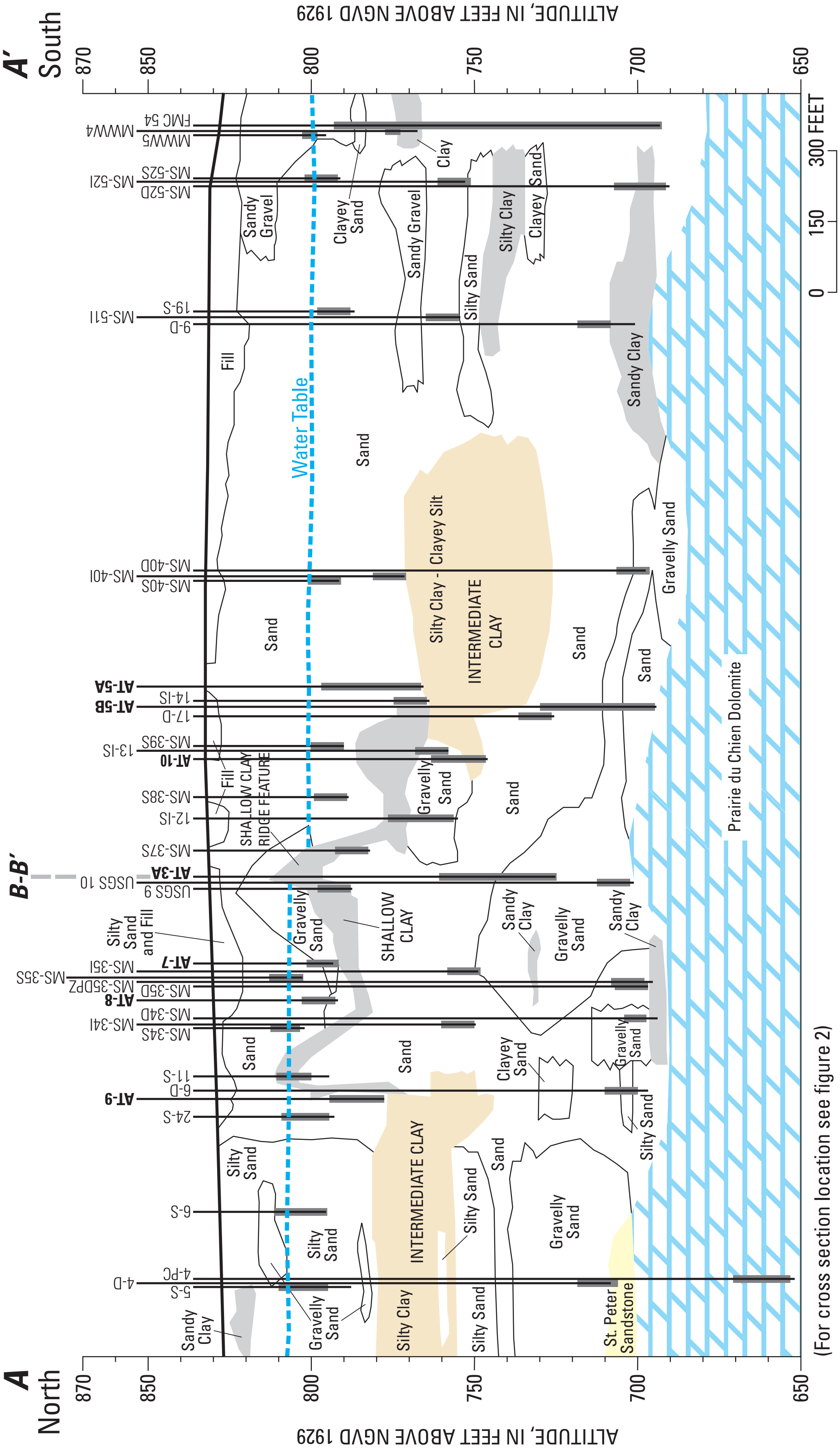


Figure 4. Hydrogeologic section A-A′ (modified from TtNUS, 2002a).

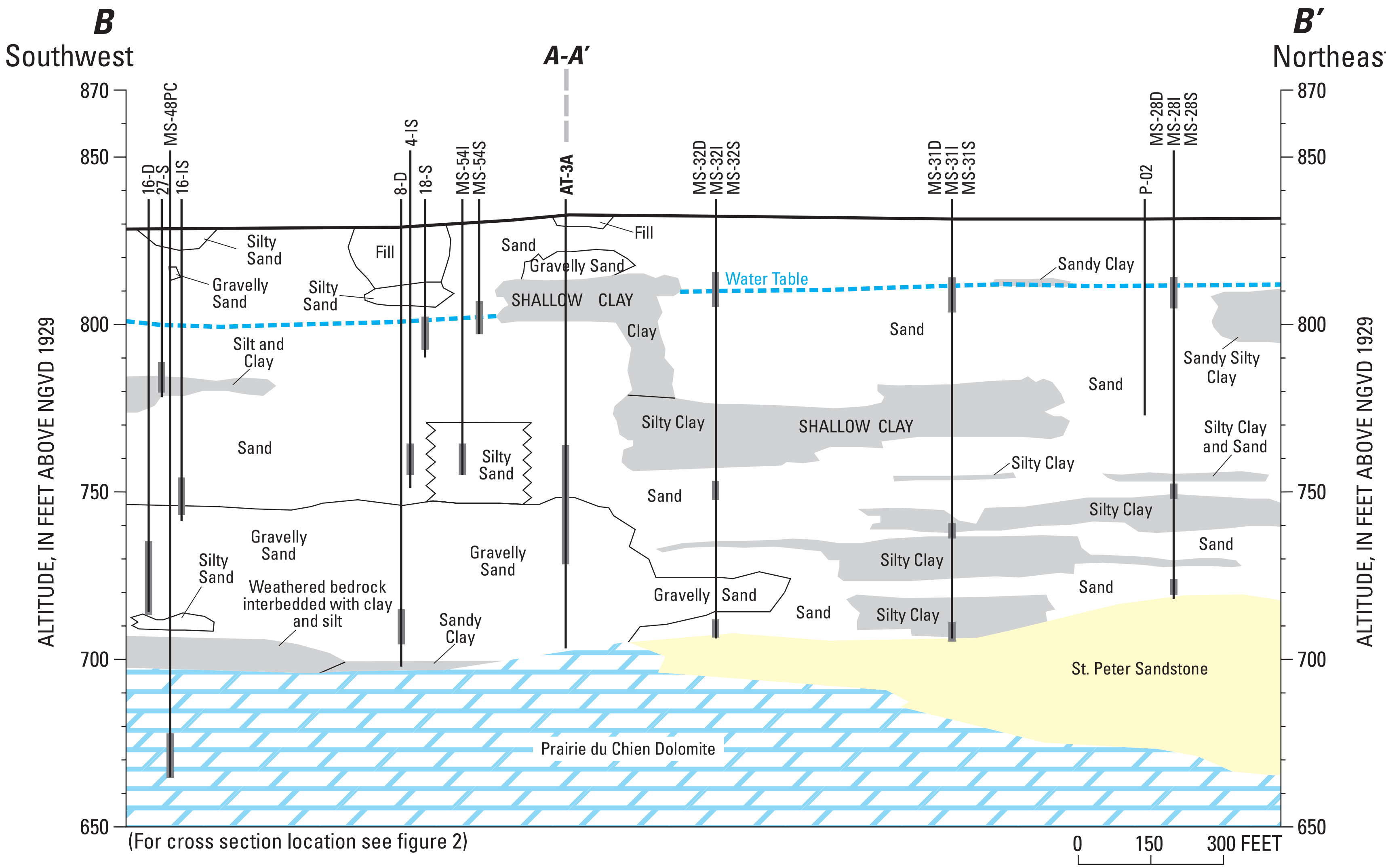


Figure 5. Hydrogeologic section B-B′ (modified from TtNUS, 2002a).

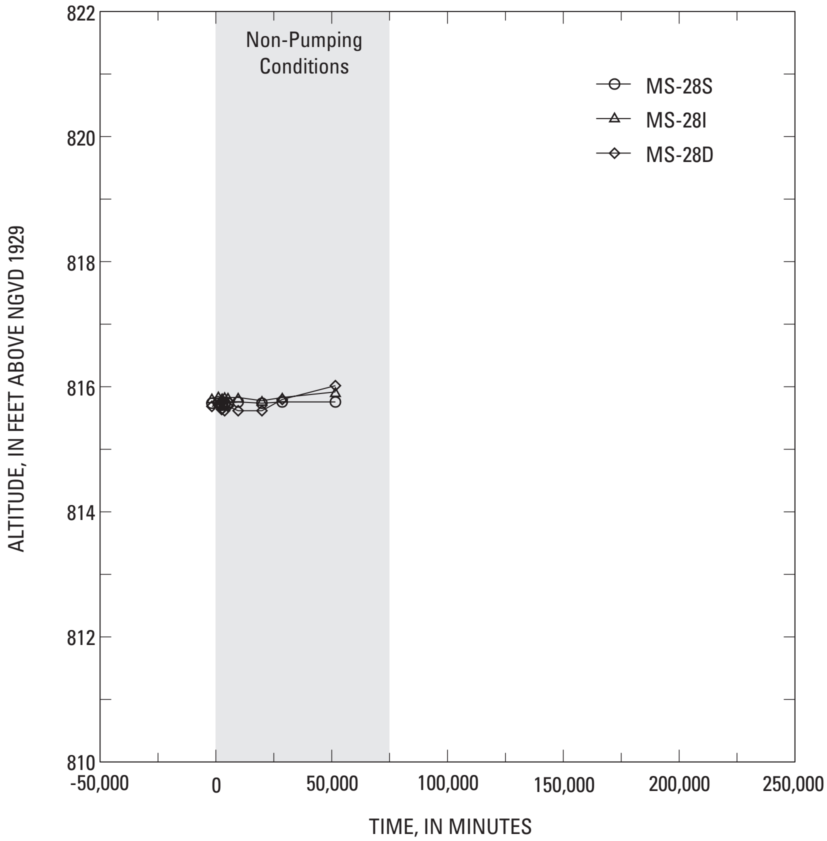


Figure 6. Water-level changes in upgradient background wells MS-28S, MS-28I, and MS-28D.

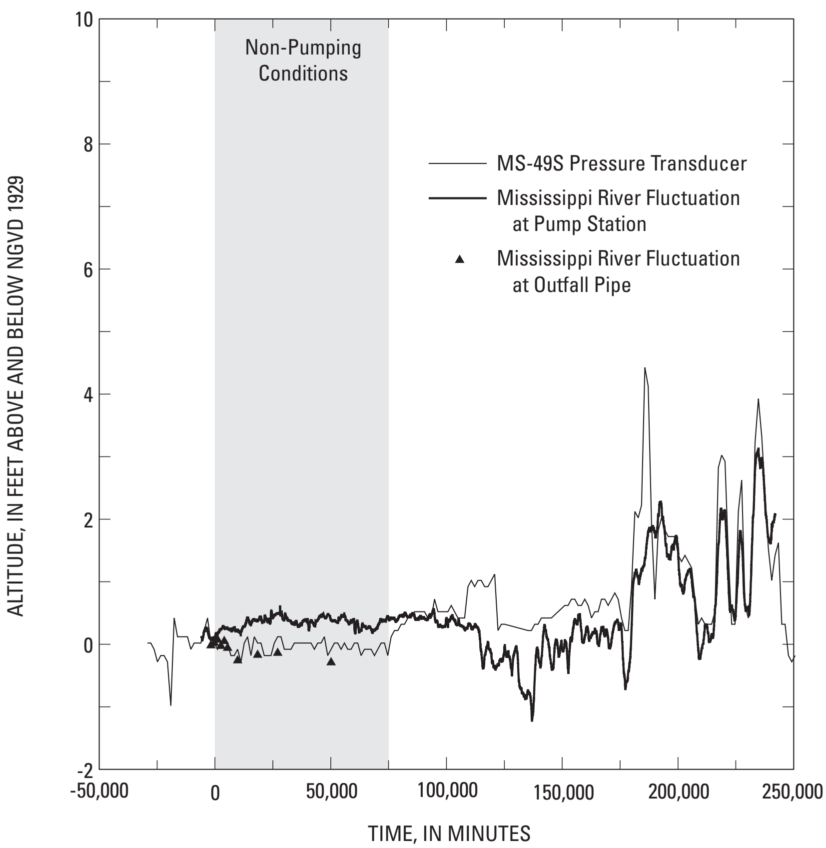


Figure 7. Water-level changes in background well MS-49S and Mississippi River.

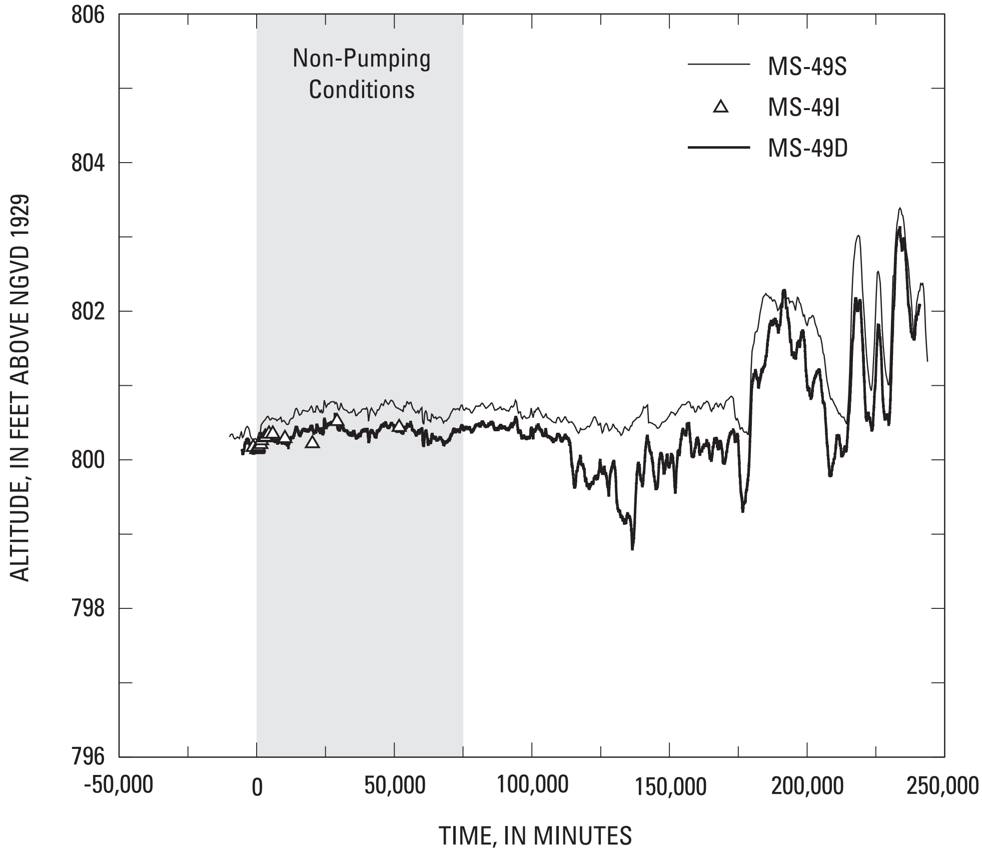


Figure 8. Water-level changes in background wells MS-49S, MS-49I, and MS-49D.

Water-Level Trends in the Upgradient and Downgradient Wells

Water levels in the upgradient and downgradient background wells were monitored to determine trends associated with climate or river stage. Water levels in the upgradient wells MS-28S, MS-28I, and MS-28D are shown in figure 6. In wells MS-28S and MS-28I, there was little water-level change during the entire measurement period. From August 20 (the day before the pumps were turned off) until September 26, 2001, the water levels rose only 0.02 ft and 0.01 ft in wells MS-28S and MS-28I, respectively. The water-level in well MS-28D rose 0.33 ft during the course of measurement. Most of this rise occurred between September 10 and September 26, 2001; the measurement on September 10, 2001, indicated water levels had risen only 0.11 ft.

The water levels in the downgradient well MS-49S and the Mississippi River are shown in figure 7. The water level in the river was measured at two locations: (1) discrete measurements were taken at the storm-sewer outfall pipe (location is shown on figure 2); and (2) at a pumping station located directly down-river from the storm-sewer outfall pipe. In this report, discrete measurements refer to measurements taken by hand at irregular intervals. As seen in figure 7, the river showed little fluctuation immediately before, during, and immediately after the non-pumping period. The water level in well MS-49S rose about 0.20 ft immediately after the pumps were turned off; this may have been water-level recovery due to the cessation of pumping. After this initial recovery, the water level remained fairly constant. The water levels in wells MS-49I and MS-49D also rose about 0.20 ft immediately after the pumps were turned off; water levels remained fairly constant for the remainder of the period (fig. 8). There were no significant trends in the either the upgradient or downgradient wells, therefore, no correction was applied to any of the water-level data collected.

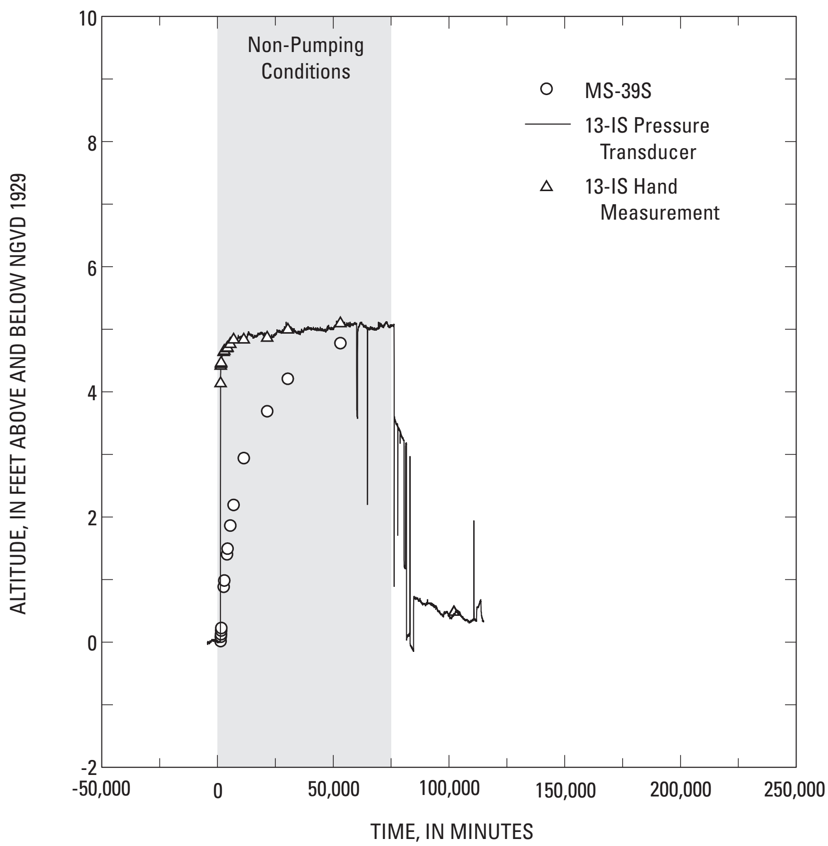


Figure 9. Water-level response of monitoring wells MS-39S and 13-IS, showing the response difference of an unconfined (water table) well and a well completed in a confined aquifer.

Ground-Water Level Responses in Representative Wells and Well Nests

The ground-water level responses in individual wells and especially in well nests to the cessation of pumping revealed how permeable zones within the glacial-drift aquifer are connected. In the aquifer at NIROP, the permeable zones seem to be hydrologically connected in some areas and are discrete hydrologic units in others. Understanding the connections between permeable zones is important in determining the contributing areas of the pumping wells.

The confined and unconfined parts of the glacial-drift aquifer responded differently when the pumps were turned off. The upper part of the glacial-drift aquifer is unconfined (contains the water table) and recovered relatively slowly compared to the deeper confined parts (fig. 9). The confined well 13-IS recovered 4.5 ft almost instantaneously (the full recovery was slightly greater that 5 ft) whereas the adjacent well MS-39S took the full 36 days from pump shutdown until the last round of measurements to recover and still may have been recovering. This difference in recovery was used to determine confined or unconfined conditions in some wells.

In some well nests the water levels in all wells responded identically. An example of this is the nest with wells 18-S, 4-IS, and 8-D (fig. 10.) Both the shape and magnitude of the recovery was identical in all three wells. These wells are installed in a vertically extensive sand (fig. 5) and the identical response indicates that there is a good vertical connection between these wells in the glacial-drift aquifer. Thus, pumping in one zone could draw water from deeper or shallower zones if the pumping rate was sufficiently high. The well nests in which all the wells had similar responses indicating good vertical connection are highlighted with large dots on figure 11.

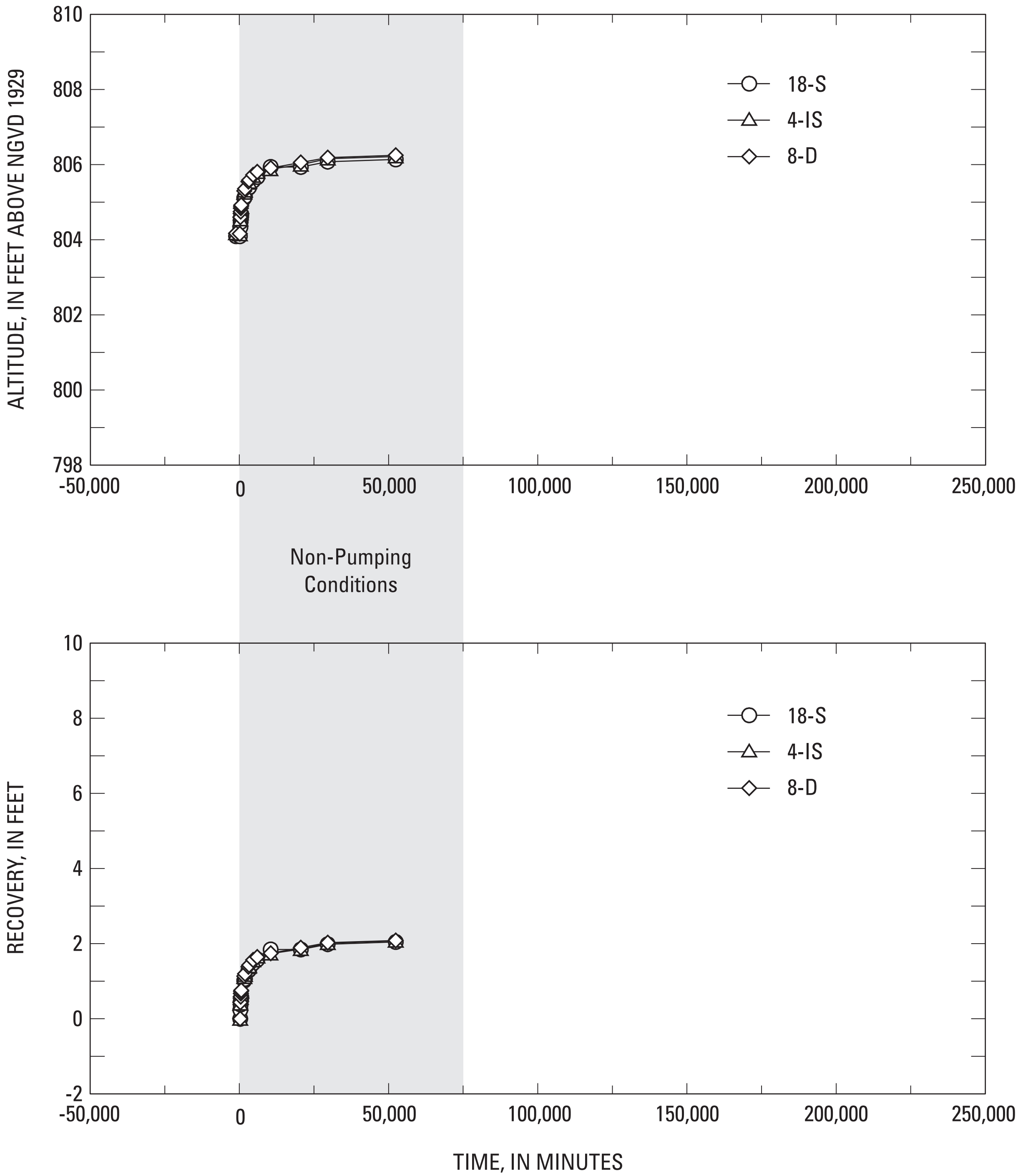


Figure 10. Water-level altitude and recovery in wells 18-S, 4-IS, and 8-D indicating a good vertical connection between the shallow, intermediate, and deep zones of the glacial-drift aquifer.

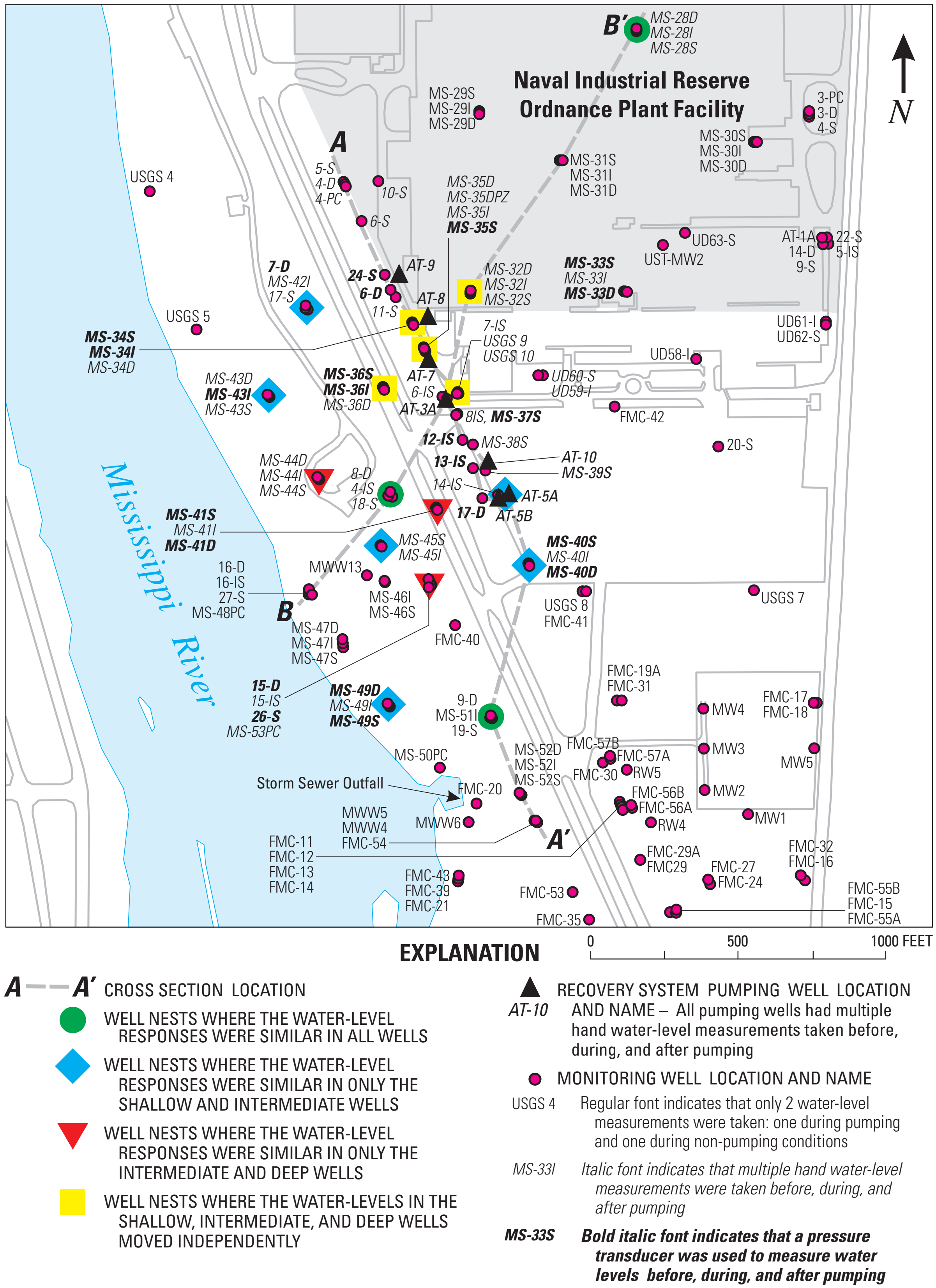


Figure 11. Water-level response in well nests during recovery.

In some well nests, both the ground-water altitudes and water-level responses were different for each of the wells. The well nest with wells MS-34S, MS-34I, and MS-34D (fig. 12) showed this response. The difference in water-level response between shallow and intermediate wells is explained by the shallow clay (fig. 4). The reason for different responses between the intermediate and deep wells is not fully understood, but is presumedly due to permeability differences in the heterogeneous sediments. Also, the different responses could be partially due to the gravelly sand at the base of the glacial-drift aquifer being connected (fig. 4). All the well nests that showed a different response in each well are highlighted with a large square on figure 11. The independent response of each well could be due to a number of causes including a poor vertical connection in the glacial-drift aquifer or horizontal permeability contrasts.

In some well nests, the water-level altitudes and water-level responses were the same for the shallow and intermediate wells but different for the deep well. The well nest with wells MS-43S, MS-43I, and MS-43D (fig. 13) showed this response, which indicates a good vertical connection between the shallow and intermediate wells and a poor connection with the deep well. This response further indicates that the shallow and intermediate zones are vertically well connected and that the deep well is part of a different flow zone. All the well nests that showed this response are highlighted with a large diamond on figure 11.

In some well nests, the water altitudes and water-level responses were the same for the intermediate and deep wells but different for the shallow well. The well nest with wells MS-44S, MS-44I, and MS-44D (fig. 14) showed this response, which indicates a good vertical connection between the intermediate and deep wells and a poorer vertical connection with the shallow well. This response also indicates that the intermediate and deep zones are well connected vertically and that the shallow zone is not well connected vertically. All the well nests that showed this response are highlighted with a large inverted triangle on figure 11.

Water-Level Differences Between the Shallow and Deep Wells During Non-Pumping Conditions

The difference in ground-water levels between the shallow and deep wells during non-pumping conditions (fig. 15) due to the effect of two clay layers (the shallow clay and the intermediate clay) show a downward gradient across the northern part of the site and an upward gradient across the southern part. The extent of the shallow clay is shown in figs. 4, 5, and 15 (the ridge feature is part of the shallow clay and is discussed in the following paragraphs). The intermediate clay is also shown in figs. 4, 5, and 15 (but is partly covered by the shallow clay in fig. 15); the full extent of the intermediate clay is shown in later figures. The intermediate clay grades into a silt of limited areal extent near the center of the study area. Although the shallow and intermediate clays are treated as separate clay layers, they are connected and seem to form one locally extensive confining unit. In the northern half of the study area, the head differences range from -9.6 ft (negative values indicate a downward gradient) near the center of the clays to +1.0 ft near the eastern edge. In the southern half of the study area, the head differences during the recovery period range from +10.7 ft near the center of the clays to near 0 at the edge of the clays. Whereas the clays affect ground-water flow, the intermediate silt seems to have little effect on flow.

The ridge feature is part of the shallow clay and affects ground-water flow. The ridge feature is shown in cross section in figure 4 and in plain view in figure 15. As seen in figure 4, both north and south of the ridge the water table is relatively flat, while across the ridge the water table abruptly drops about 10 ft. The rapid drop of water levels is caused by the ridge retarding horizontal ground-water flow. It is unknown if the ridge is nearly impermeable (composed of dense clay) and allows almost no flow across it, or, if it is low permeability (consisting of silts and clays) and thus allows some small amount of flow. The rapid drop of water levels across the ridge in combination with the shallow and intermediate clays (which prevent vertical ground-water flow between the shallow and deep zones) causes the unusual distribution of head differences observed. The rapid change in water-level differences due to the ridge extends to the southernmost part of the study area. The head difference in the well nest just west of the ridge is +9.2 ft; the head difference in the well nest just to the east of the ridge is +0.5 ft (fig. 15).

The low-permeability nature of the ridge feature was observed in a glacial-drift aquifer test performed in January 2000 (Davis, 2000b.) Well AT-5A was pumped at 167 gal/min for approximately 3 days and drawdown occurred in all the nearby shallow wells except MS-37S (fig. 16). Using the Theis equation (which was used to analyze the test), well MS-37S should have had a drawdown of 0.72 ft if it were part of the shallow flow zone (well AT-5A is screened in the shallow zone). However, the cone of depression did not cross the ridge and no drawdown was observed in this well.

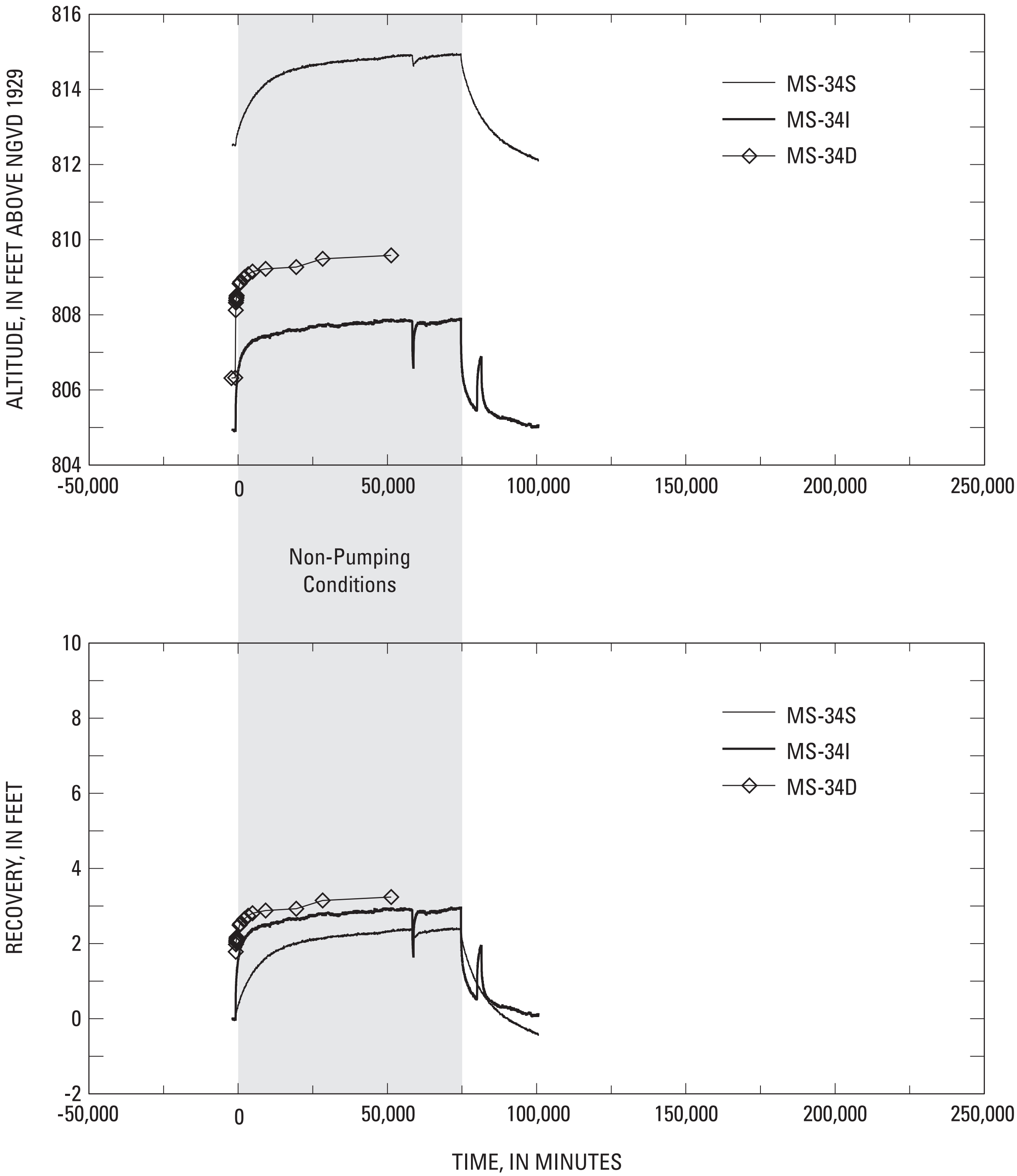


Figure 12. Water-level altitude and recovery in wells MS-34S, MS-34I, and MS-34D showing different water-levels and response in the shallow, intermediate, and deep wells.

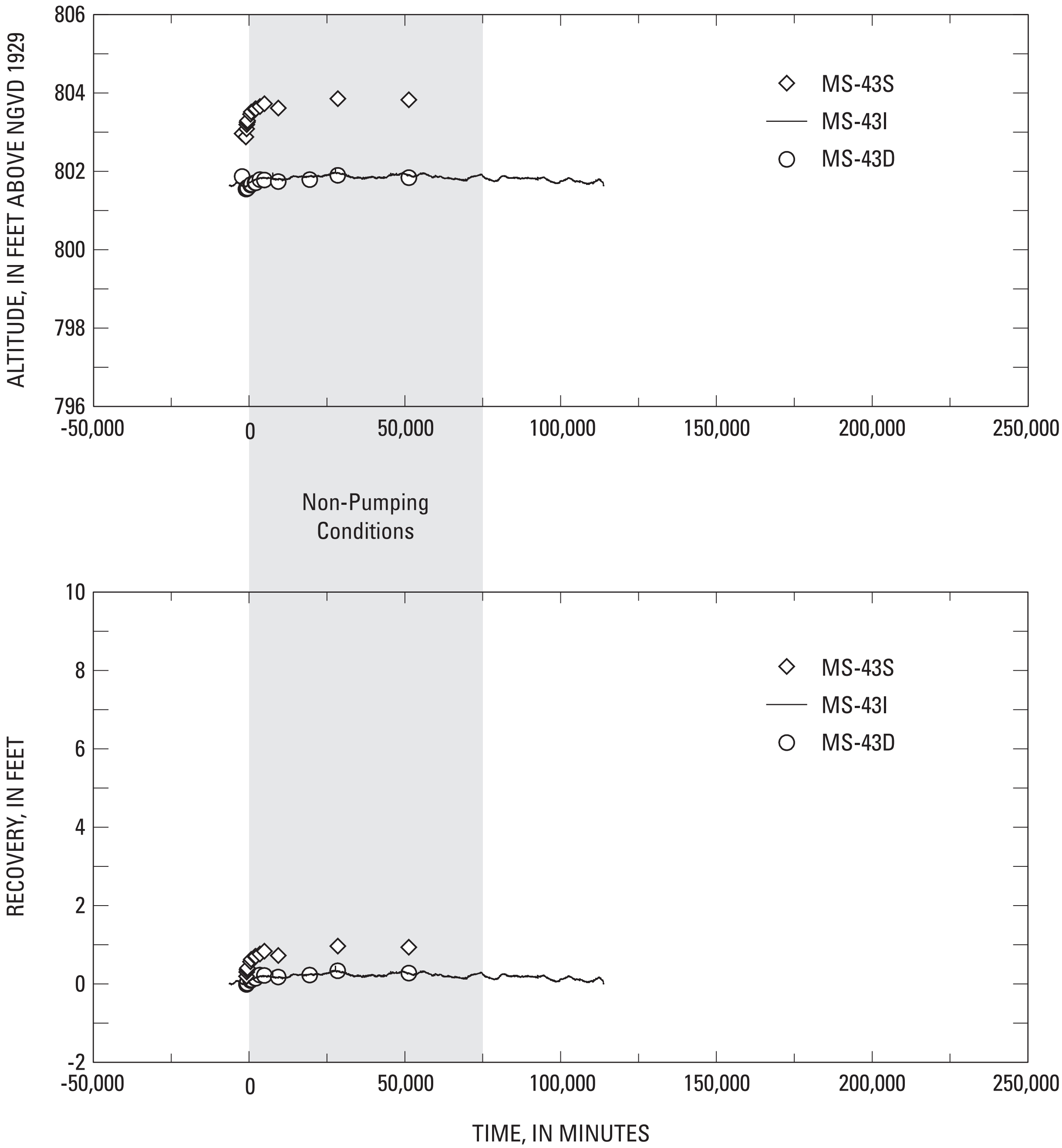


Figure 13. Water-level altitude and recovery in wells MS-43S, MS-43I, and MS-43D showing a similar water-level response in the shallow and intermediate wells, but a different water-level response in the deep well.

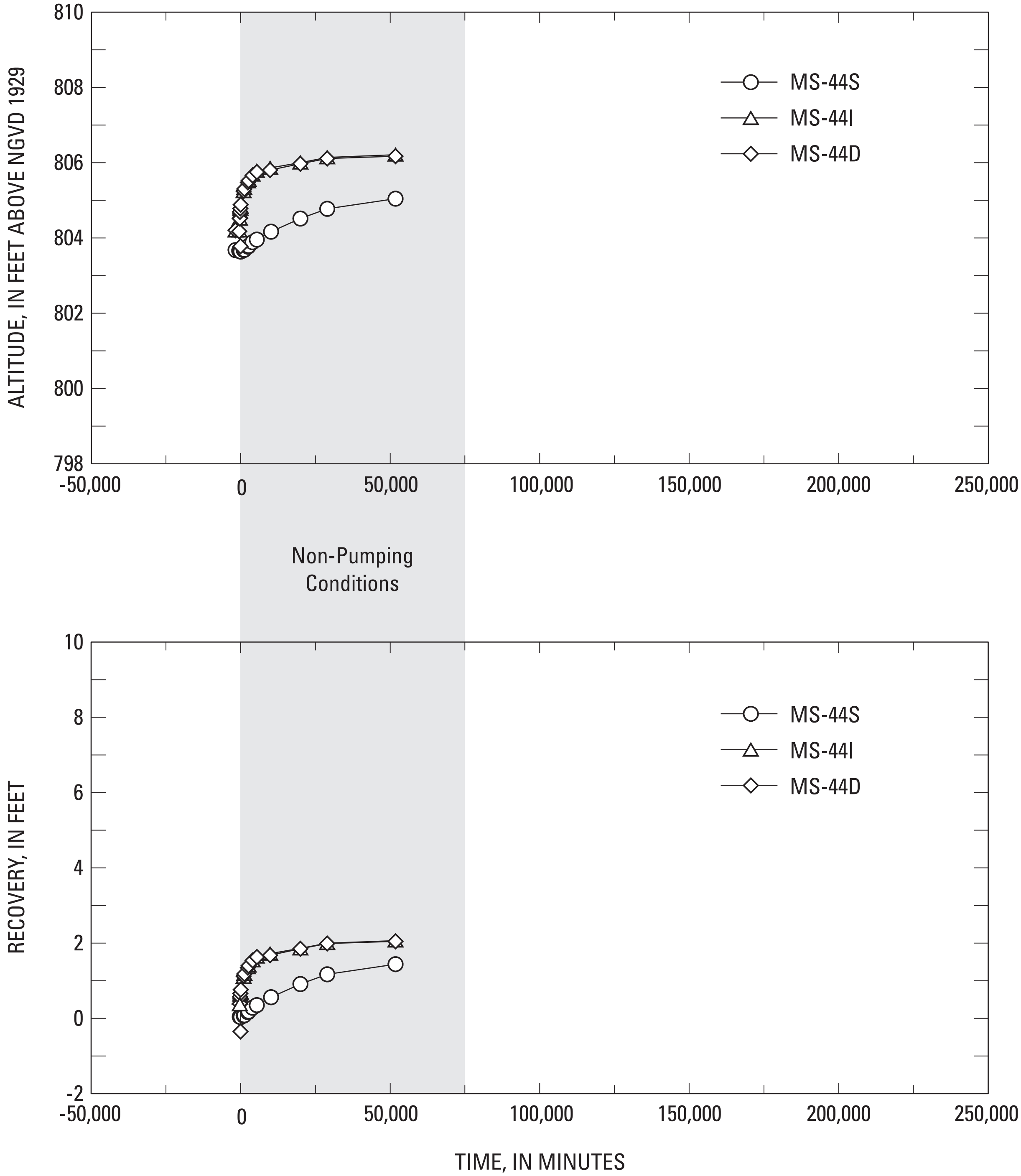
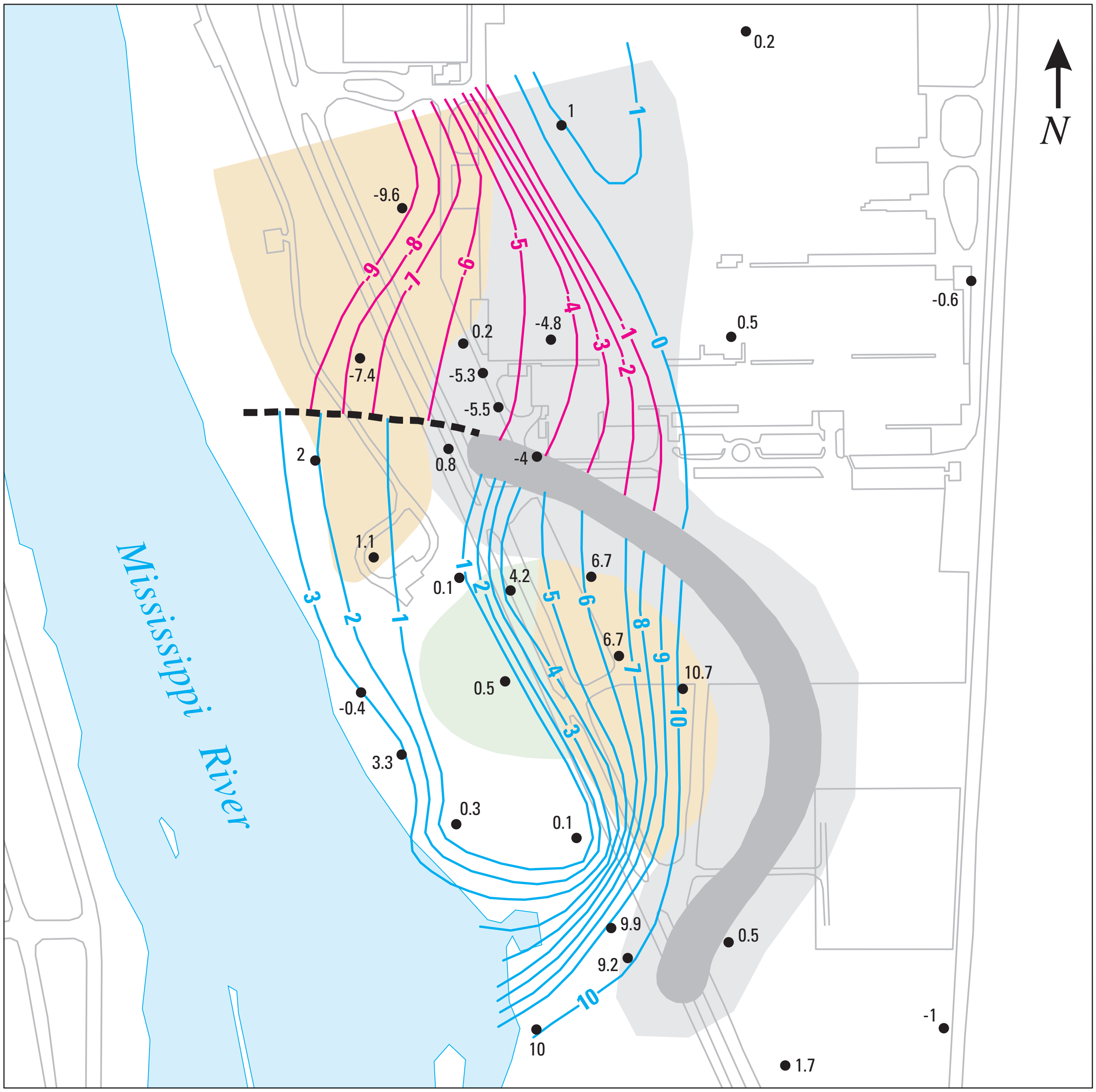


Figure 14. Water-level altitude and recovery in wells MS-44S, MS-44I, and MS-44D showing a similar water-level response in the intermediate and deep wells, but a different water-level response in the shallow well.



EXPLANATION

RIDGE FEATURE	POSSIBLE EXTENTION OF THE RIDGE FEATURE
SHALLOW CLAY	-7- DOWNWARD GRADIENT – Contour interval is 1 foot
INTERMEDIATE CLAY	10 ZERO OR UPWARD GRADIENT – Contour interval is 1 foot
INTERMEDIATE SILT	1.7 ● WELL LOCATION – Value is the water-level difference between the shallow and deep zones. Positive numbers indicate an upward gradient, negative numbers indicate a downward gradient

Figure 15. Water-level difference between the shallow and deep wells during non-pumping conditions.

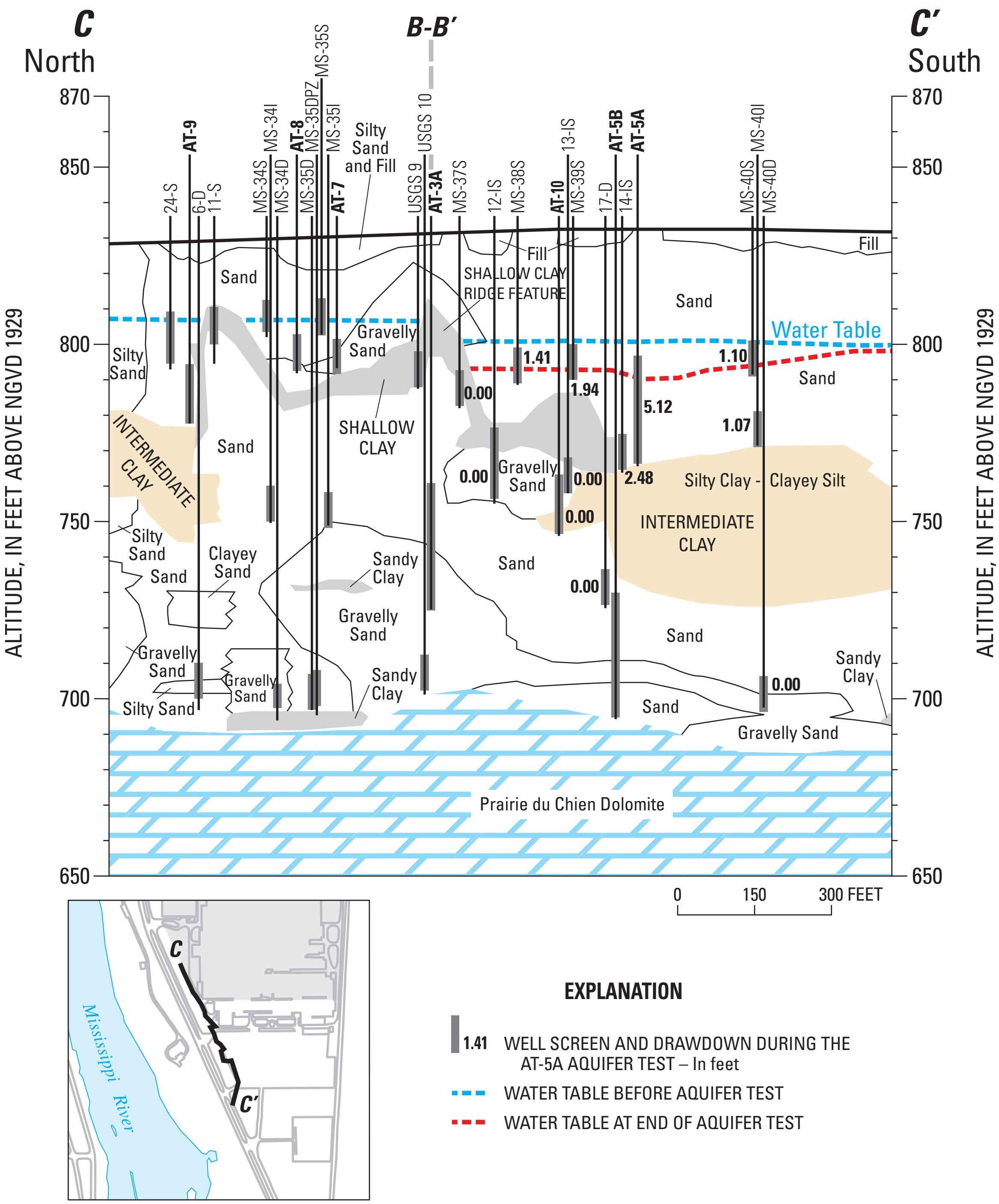


Figure 16. Drawdown during the AT-5A aquifer test conducted in January, 2000.

The lack of drawdown indicates that this well is hydrologically separated by the ridge from well AT-5A. Because well MS-37S is separated from the shallow flow zone by the ridge part of the shallow clay, this well is considered to be in the intermediate flow zone.

Between the ridge and river is a large area where the head difference is low (the area within the +1-ft contour on fig. 15) and values are as low as 0.1 ft. The lithology in this area is largely sand with some silt but little clay to prevent the vertical movement of ground water. The reason the head difference almost disappears is probably because ground water is moving up from the intermediate and deeper flow zones into the shallow flow zone to equalize the pressure head. The intermediate silt does not appear to be of sufficiently low permeability to prevent the heads from equalizing between the deep and shallow zones.

Data for two wells, 11-S and 17-D, did not fit the trends associated with nearby wells. Well 11-S is discussed here and well 17-D is discussed later. The head difference between wells 11-S and 6-D was only 0.2 ft (this head difference is directly north of the north end of the ridge feature on fig. 15) whereas the surrounding values are in the range of -5.0. The ground-water altitudes and water-level responses for wells 11-S, 24-S, MS-34I, and 6-D are shown in figure 17. The shallow well 11-S water level was similar to levels in the intermediate well MS-32I and the deep well 6-D but different than the nearby shallow well 24-S. For this reason, it appears that well 11-S is not part of the shallow flow system. During the period from September 2005 through December 2005, a pressure transducer was installed in well 11-S. During this period, the intermediate pumping well AT3-A was turned off for a 12-day period. The water level in well 11-S rose approximately 1 ft in response to the pump being shut off and drew down approximately 1 ft in response to the pump being turned back on. This further indicates that well 11-S is an intermediate well. Also during this period, shallow pumping well AT-8 was turned off for a 3-week period. There was no response in well 11-S, indicating that it was not connected to the shallow flow system.

Ground-Water Flow During Non-Pumping Conditions

The water-table surface during non-pumping conditions is shown in figure 18. The most prominent feature of the water table is the closely spaced contours caused by the ridge feature of the shallow clay. The contours are extended through the clay. However, as discussed earlier, it is unknown if the ridge is a low-permeability clay allowing essentially no flow across it, or if the ridge is a slightly more permeable silt and clay allowing some flow. Because of the uncertainty, the contours were extended through the ridge feature. The intermediate and shallow clays are shown on the figure because, where present, they form the base of the shallow flow zone. Where the clays are absent, the glacial-drift aquifer probably has a good vertical connection and the shallow, intermediate, and deep flow zones are connected.

A localized ground-water high is present above and north of the intermediate silt. Based on the contours, ground water is moving east, south, and west from the high. This high is probably the result of ground water moving up from the intermediate and deep flow zones and into the shallow flow zone. This upward movement is possible because there is a vertically extensive sand (see well nest 18-S, 4-IS, and 8-D, on fig. 5) and a good vertical connection within the sand as illustrated by wells 18-S, 4-IS, and 8-D, all essentially having the same water level and recovery (fig. 10). The ground-water high is centered in the general area where the vertical gradients are near zero (fig. 15), again indicating that ground water can readily move vertically upward to equalize the heads. As previously discussed, the intermediate silt does not appear to be of sufficiently low permeability to prevent the upward movement of ground water.

Interestingly, shallow ground-water flow west of the ridge feature is generally to the south and not westward toward the river as expected, although the ground-water contours do bend toward the river in the southern part of the study area. A localized ground-water high is present adjacent to the river in the extreme southern part of the study area. Although this high is based on one well, it is believed to be accurate because: (1) the water levels in this well move similarly to nearby wells, indicating that this well is connected to the aquifer; (2) the ground-water high is persistent over time; and (3) most importantly, a seepage face several feet high has been observed in the sidewall of the river directly adjacent to the well.

The potentiometric surface of the intermediate flow zone during non-pumping conditions is shown in figure 19. The intermediate flow zone is banked by the two clays that make up the intermediate clay as shown in figures 4 and 19 and not present where the intermediate clay exists. Flow under the intermediate clay is considered part of the deep flow zone and flow above these clays is considered part of the shallow flow zone.

The potentiometric surface of the deep flow zone is shown in figure 20. Given the complex hydrology of the shallow and intermediate flow zones the most striking feature of the deep flow zone is its relative

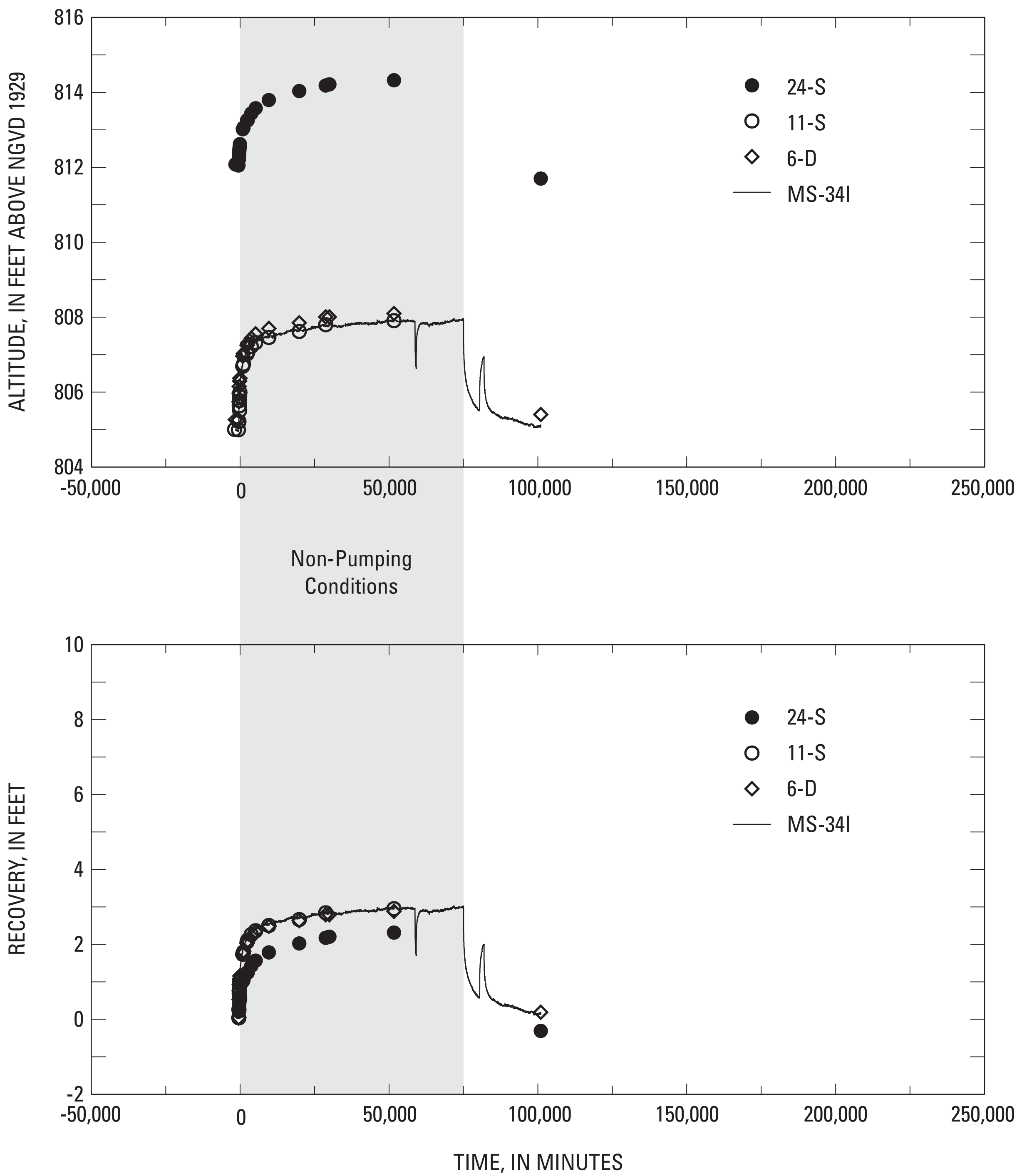


Figure 17. Water-level altitude and recovery in wells 24-S, 11-S, 6-D, and MS-34I.

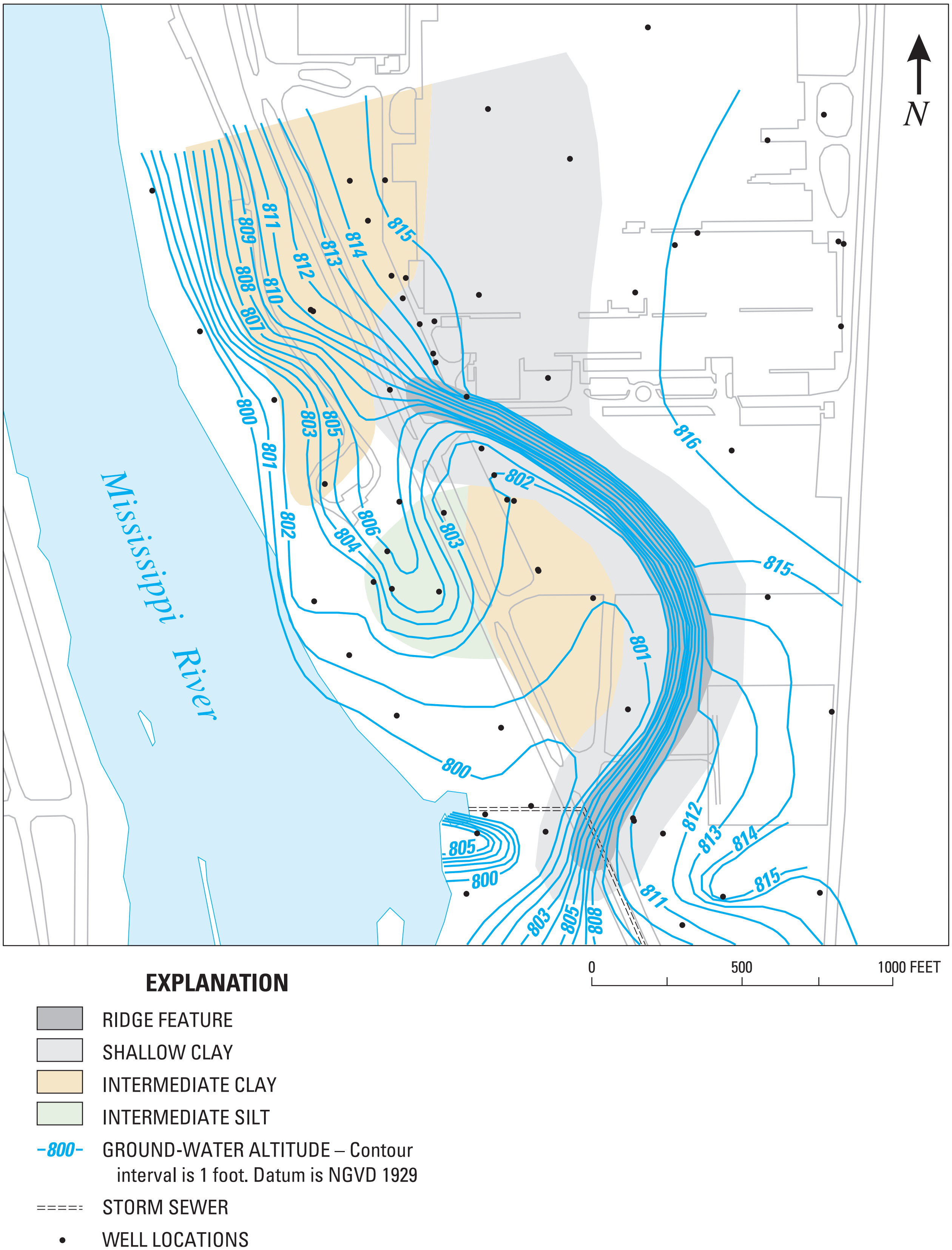


Figure 18. Water-table surface of the shallow flow zone during non-pumping conditions on September 26, 2001.

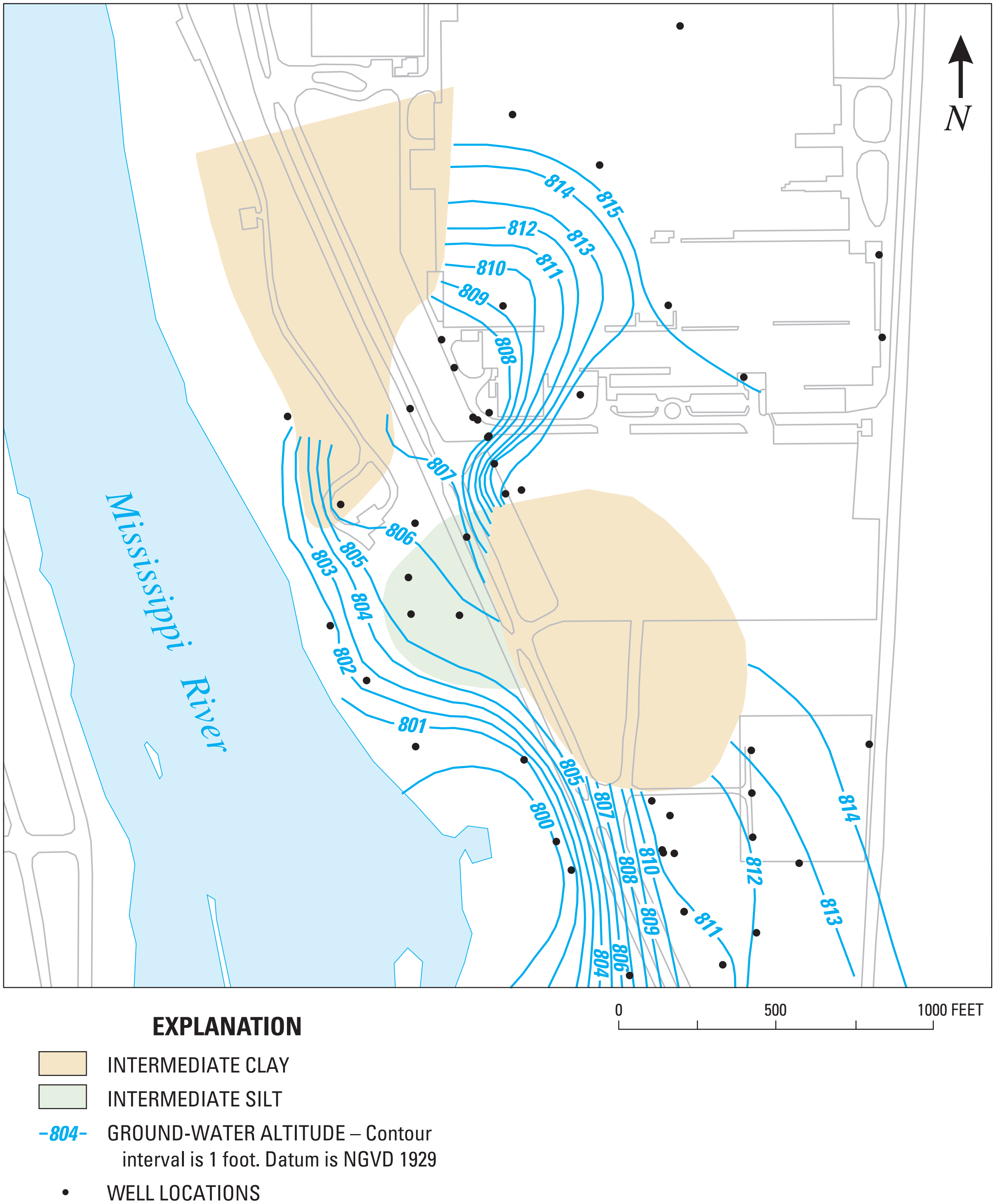


Figure 19. Potentiometric surface of the intermediate flow zone during non-pumping conditions on September 26, 2001.

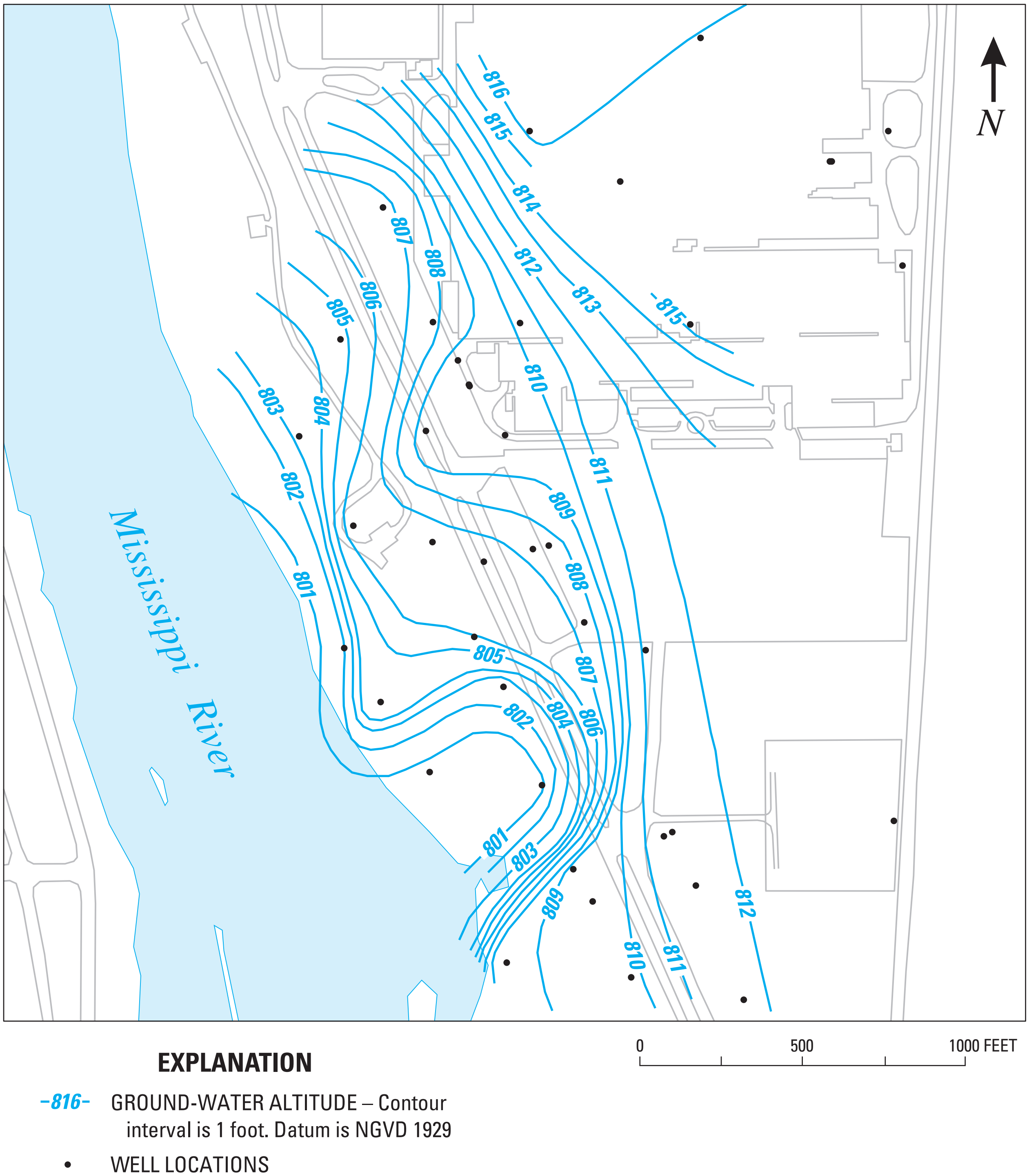


Figure 20. Potentiometric surface of the deep flow zone during non-pumping conditions on September 26, 2001.

Table 4. Recovery well characteristics.

[Note: The water levels may have still been recovering in the shallow wells and, thus, the long-term recovery may have been slightly greater. NGVD, National Geodetic Vertical Datum]

Well name	Aquifer zone	Depth (in feet)	Diameter (in inches)	Screen length (in feet)	Pumpig rate, (in gallons per minute)	Recovery (in feet)	Specific capacity (in gallons per minute per foot)	Pre-pumping saturated thickness (in feet)	Ground-water altitude during pumping on 8/20/2001 (in feet above NGVD 29)
AT-3A	Intermediate	105.0	8	35.6	182	42.72	4.2	103	765.98
AT-5A	Shallow	66.0	8	30.0	156	7.71	20.2	32	793.85
AT-5B	Deep	136.0	8	35.0	86	15.87	5.4	108	791.80
AT-7	Shallow	38.8	8	10.0	42	5.6	7.5	17	809.29
AT-8	Shallow	37.5	8	10.0	17	10.32	1.7	17	804.61
AT-9	Shallow	51.5	8	17.0	142	9.02	15.7	30	805.85
AT-10	Intermediate	83.8	8	16.0	23	22.1	1.0	61	791.91

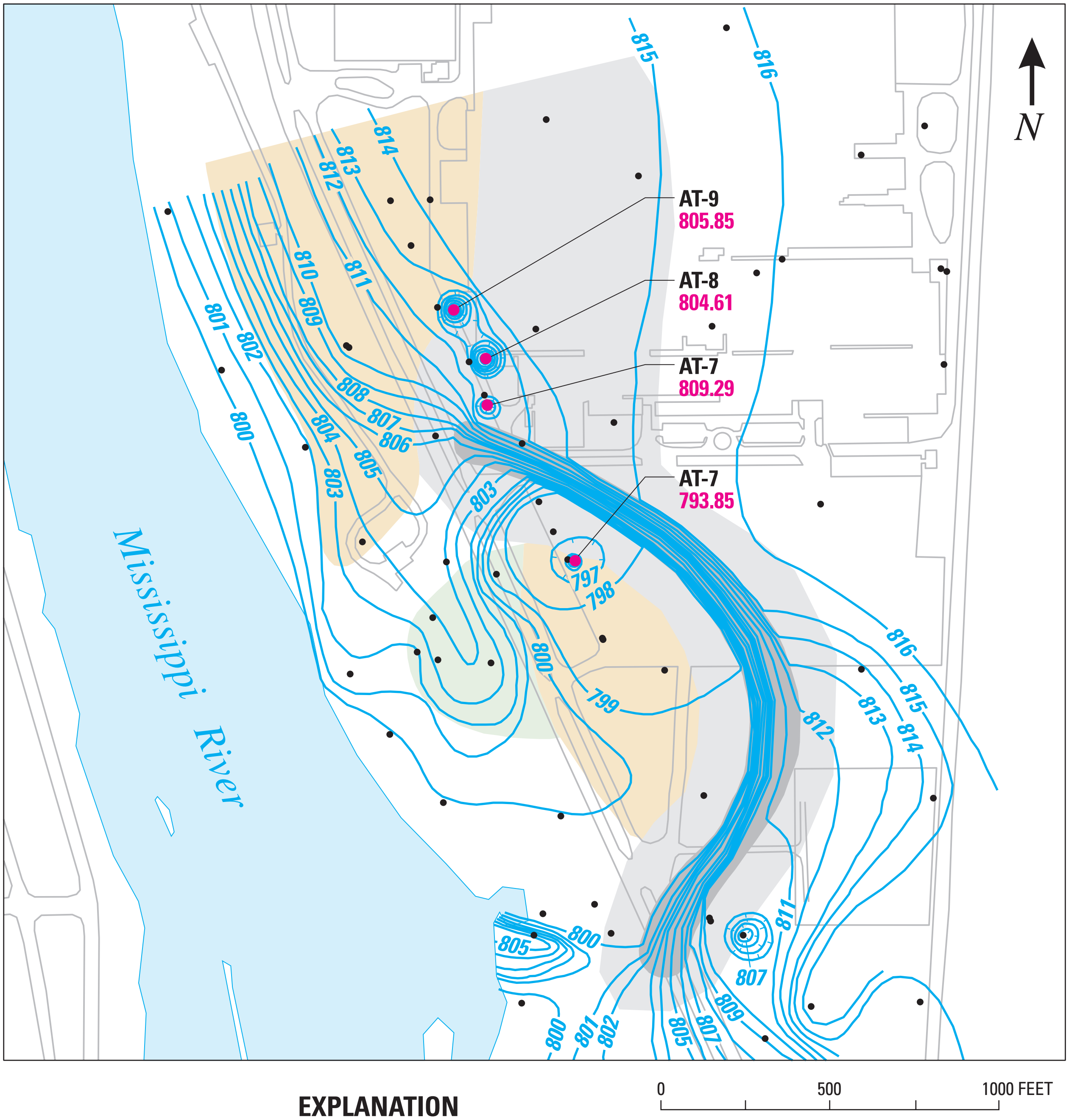
simplicity. Generally, the surface has a gentle slope towards the Mississippi River with two exceptions: (1) the nose near the center of the map, and (2) the embayment near the southern end of the study area. The nose (or more exactly the flattening of the potentiometric surface) occurs directly below a similar flattening in the intermediate flow zone. This feature may be the result of several factors: (1) increased permeabilities in both zones that independently cause the flattening, (2) increased permeabilities in both zones that are vertically connected (between the intermediate and deep zones there are no significant clay layers to prevent upward flow), or (3) upward flow from below into the deep flow zone.

Similar to well 11-S, well 17-D also had unexplained heads, and was not used in the contouring of the deep flow zone because the water-level value of 811.52 ft did not reflect the water levels of the nearby wells. The water level was measured several times on different days to confirm measurement accuracy. On March 27, 2006, deep pumping well AT-3A was turned off and hand measurements were taken in well 17-D; the water level recovered 0.4 ft in approximately 6 hours. On March 28, 2006, deep pumping well AT-5B was turned off and well 17-D recovered 1.8 ft in 6 hours. On March 29, 2006, intermediate pumping well AT-10 was turned off and well 17-D recovered 0.7 ft. Thus, well 17-D appears to have some connection to both the intermediate and deep zones; however, since the water level during non-pumping conditions was most reflective of the intermediate water levels, well 17-D is considered to be an intermediate well.

Ground-Water Flow During Pumping Conditions

The cones of depression in the water-table surface caused by the pumping wells are clearly seen in figure 21 (a description of the pumping wells is given in table 4). As expected, a relatively steep cone of depression developed in the immediate vicinity of the pumping wells, with a flattening and broadening of the cones further away. The cones of depression from wells AT-8 (17 gal/min), and AT-9 (142 gal/min) overlap to form one broad cone around both wells, with the cone of depression from well AT-7 (42 gal/min) being more isolated. Well AT-8 and AT-9 had different pumping rates but about the same drawdown, this is presumably due to a greater permeability at AT-9. Well AT-5A (156 gal/min) had a large broad cone of depression, which was the result of the relatively high pumping rate and the relatively high permeability of 200 ft/d (Davis, 2000b.) The recovery of water levels after pumping stopped is shown in figure 22.

The potentiometric surface of the intermediate flow zone during pumping conditions is shown in figure 23 and the recovery after pumping stopped is shown in figure 24. Well AT-3A was pumped at 182 gal/min and had a recovery (thus an approximate drawdown) of 42.72 ft. Wells 6-IS, located 17 ft northwest of AT-3A, had a recovery of only 3.99 ft, so the large recovery in well AT-3A may be due to well losses at the relatively high pumping rate. This well has a broad cone of depression that extends to the intermediate clays.



EXPLANATION

RIDGE FEATURE

SHALLOW CLAY

INTERMEDIATE CLAY

INTERMEDIATE SILT

-800- GROUND-WATER ALTITUDE – Contour interval is 1 foot. Datum is NGVD 1929

• AT-7 793.85 NIROP RECOVERY WELL – Black number is well number, red number is ground-water altitude, in feet above NGVD 1929

• WELL LOCATIONS

Figure 21. Water-table surface of the shallow flow zone during pumping conditions on August 20, 2001.

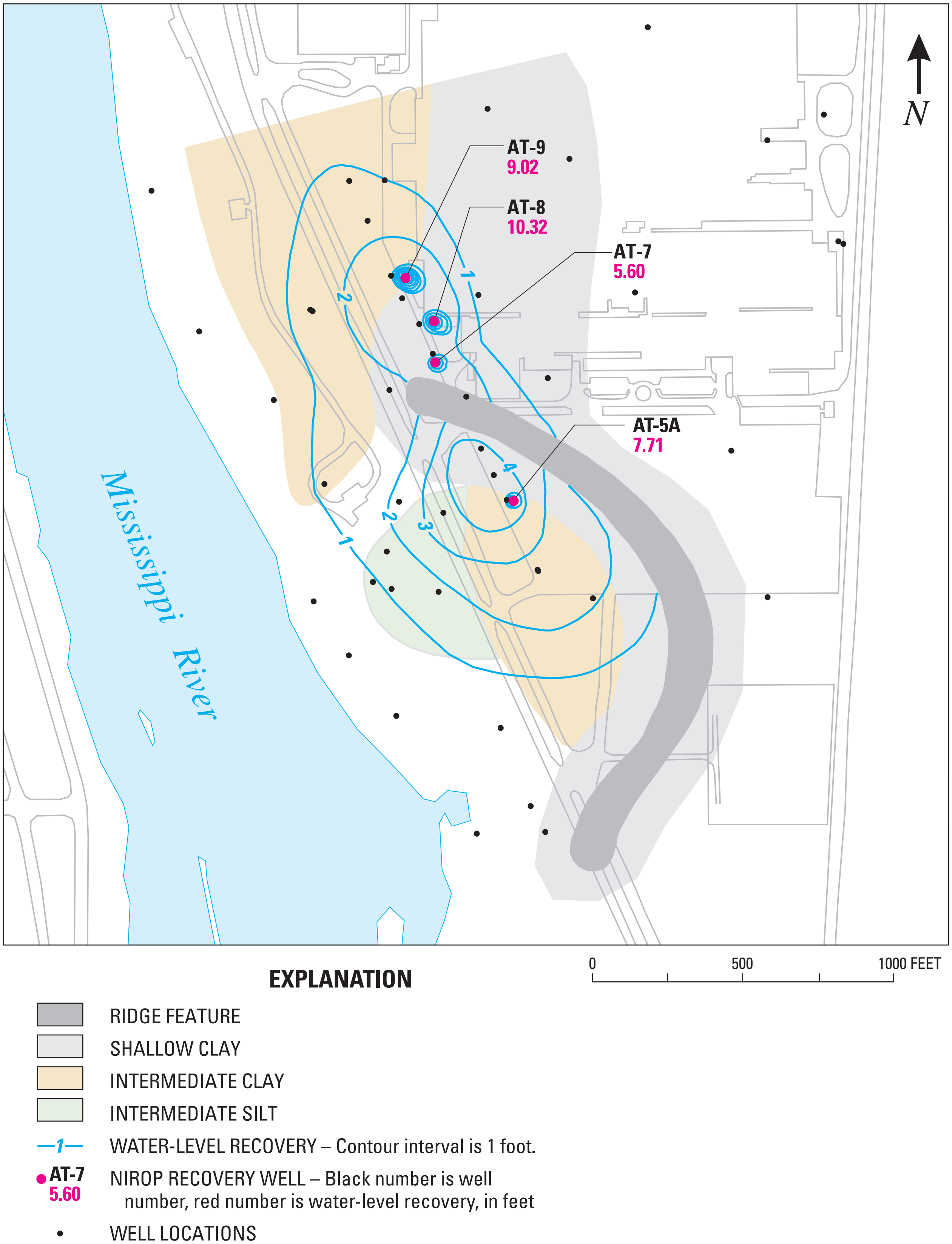
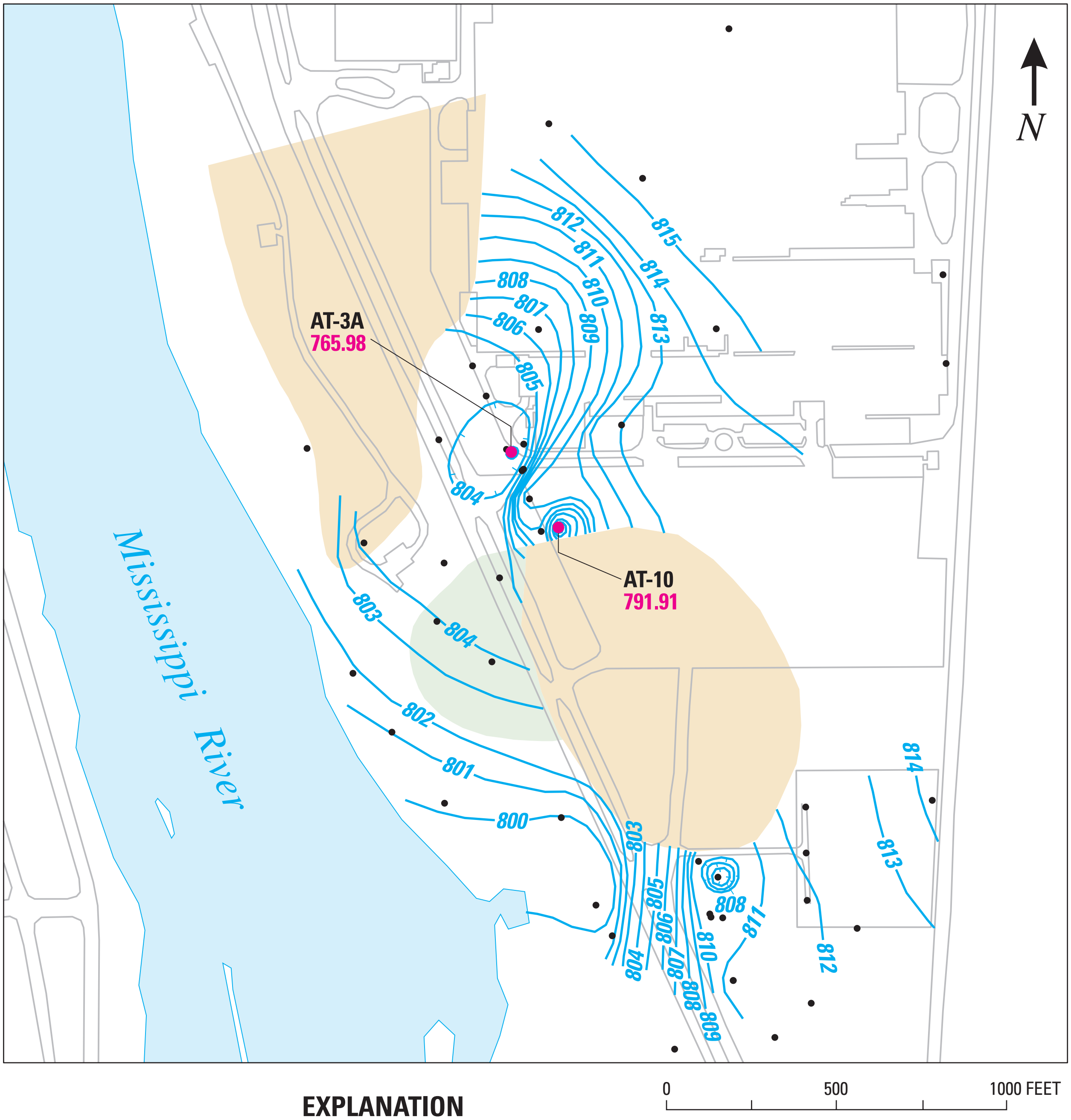


Figure 22. Water-level recovery in the shallow flow zone after pumping stopped as measured on September 26, 2001.



EXPLANATION

INTERMEDIATE CLAY

INTERMEDIATE SILT

–800– GROUND-WATER ALTITUDE – Contour interval is 1 foot. Datum is NGVD 1929

● AT-10 791.91 NIROP RECOVERY WELL – Black number is well number, red number is ground-water altitude, in feet above NGVD 1929

• WELL LOCATIONS

Figure 23. Potentiometric surface of the intermediate flow zone during pumping conditions on August 20, 2001.

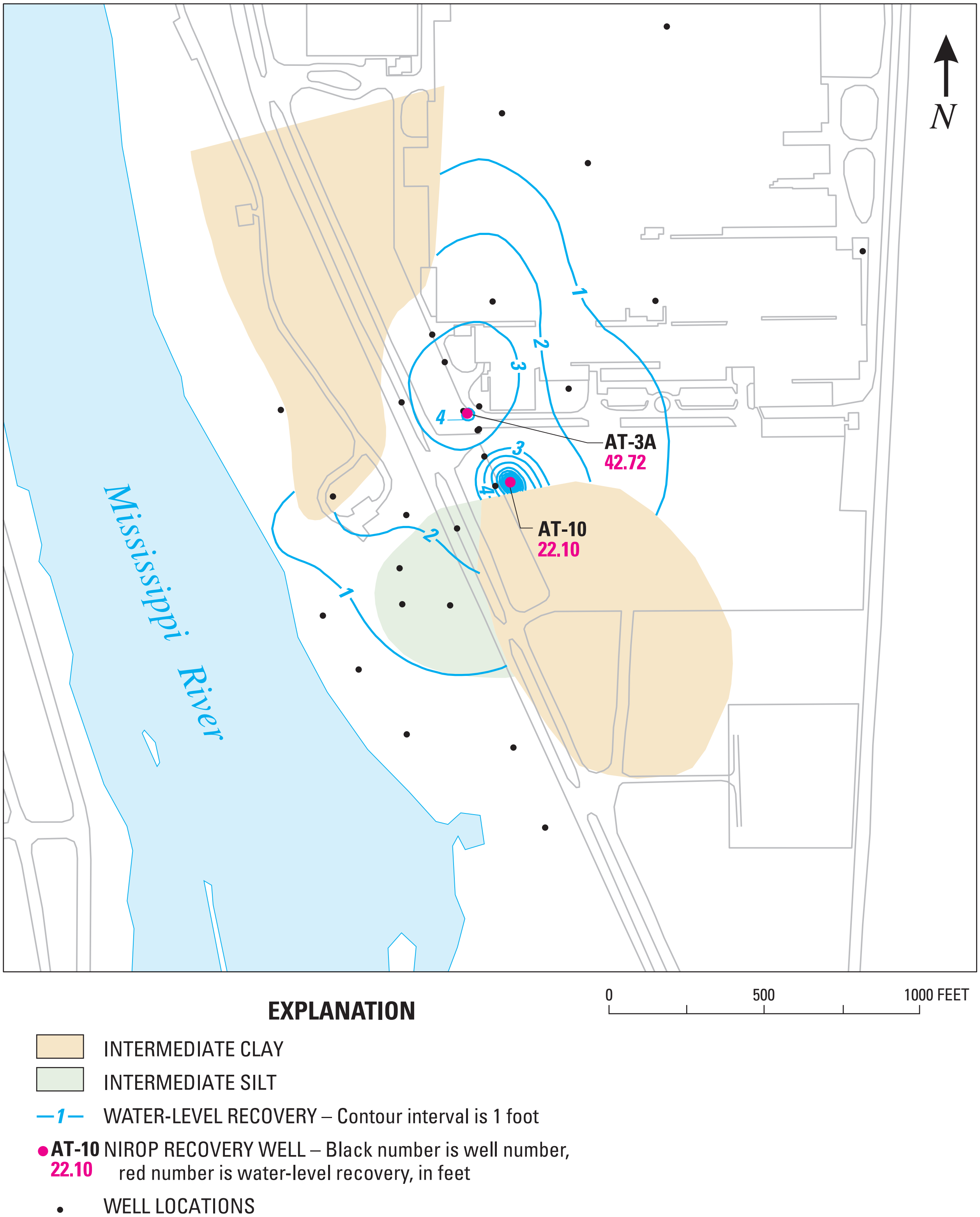


Figure 24. Water-level recovery in the intermediate flow zone after pumping stopped as measured on September 26, 2001.

The broad cone of depression was probably due to a combination of factors: the relatively long screen length of 35.6 ft, the moderately high permeability of 70 ft/d (Davis, 2000a), and the relatively thick sand layer in which the well is screened.

Well AT-10 was pumped at 23 gal/min and had a recovery of 22.10 ft. This well had a relatively steep cone of depression because it is screened in a relatively low-permeability zone (it had the lowest specific capacity of 1.0 gallon per minute per foot of any of the recovery wells as seen in table 4).

The potentiometric surface of the deep flow zone during pumping conditions is shown in figure 25 and the recovery after pumping stopped is shown in figure 26. Well AT-5B was pumped at 86 gal/min and had a recovery of 15.87 ft. The cone of depression associated with well AT-5B is readily apparent on figures 25 and 26; however, a second cone has formed beneath the intermediate well AT-3A. This cone is probably caused either by water moving up vertically to well AT-3A and out of the deep flow zone, or, the relatively long screen length may extend into the deep flow zone.

Occurrence of Trichloroethene

The distribution of trichloroethene (TCE) in the shallow, intermediate, and deep flow zones is shown in figures 27, 28, and 29, respectively, and can be used to help explain ground-water flow in this complex flow system. The highest levels of TCE occur in the intermediate flow zone where concentrations exceed 40,000 ppb (fig. 28). The level of TCE in ground water is regulated and is not to exceed 5 ppb according to the U.S. Environmental Protection Agency (USEPA) and 30 ppb by the Minnesota Pollution Control Agency (TtNUS, 2002b). Based on the potentiometric surface, the TCE will move with ground-water flow through the permeable area (between the intermediate clays) and generally to the southwest. The second highest TCE concentrations were measured in the shallow zone and were as high as 17,000 ppb and exceed 1,000 ppb in a broad area (fig. 27). These high levels in the shallow zone occur directly over the area where ground water may be moving upward from the intermediate flow zone. Regardless of how the TCE arrived in the shallow flow zone in this area, the ground water is dispersing TCE in all directions except northward. One lobe of the TCE contaminant plume is moving toward the river whereas an adjacent lobe is moving southeast with the southeastward moving ground water. The TCE concentrations are significantly lower in the deep flow zone with the highest level measured as 760 ppb and all other concentrations substantially below this level.

Determination of Recovery Well Contributing Areas

The contributing areas for all of the pumping wells were determined by drawing ground-water flow lines perpendicular to the ground-water potentiometric contours; the downgradient limit of each contributing area was positioned at the point where potentiometric contours reverse from the regional gradient to sloping back toward the pumping well. Drawing the contributing areas in this way is appropriate only if ground-water flow is primarily horizontal. This is made more difficult by the complex geology at the site, which consists of a mix of materials with widely varying conductivities in close proximity. This variability can cause deflections in the contours not associated with capture. Drawing the contributing areas is especially difficult where the density of wells is sparse and the cones of depression are relatively steep; contributing areas will change in size if the pumping rates change substantially. The appropriateness of the method is discussed as the contributing areas are discussed.

The contributing areas of shallow wells AT-7 (42 gal/min), AT-8 (17 gal/min), and AT-9 (142 gal/min) are shown in figure 30. Well AT-9 had the largest contributing area of these three wells, which would be expected based on the pumping rates. Well AT-7 had the second largest contributing area and AT-8 had the smallest contributing area. The shallow flow zone in the vicinity of these wells is bounded at the base by the shallow and intermediate clays, thus preventing vertical ground-water movement. Therefore, this method of determining contributing areas should be appropriate.

The contributing area of well AT-5A (156 gal/min) is shown in figure 31. This contributing area has an unusual shape because the eastern boundary is formed by the low-permeability ridge feature and the western boundary is formed by a ground-water divide located along the axis of the ground-water high discussed earlier. In the immediate vicinity of well AT-5A and extending to the south, the shallow flow zone is bounded at the base by the shallow and intermediate clays and, thus, the contributing area should be accurate in these areas. West of the well, the contributing area extends to the ground-water divide where ground water will be moving more vertically and the contributing area would extend downward into the intermediate flow zone.

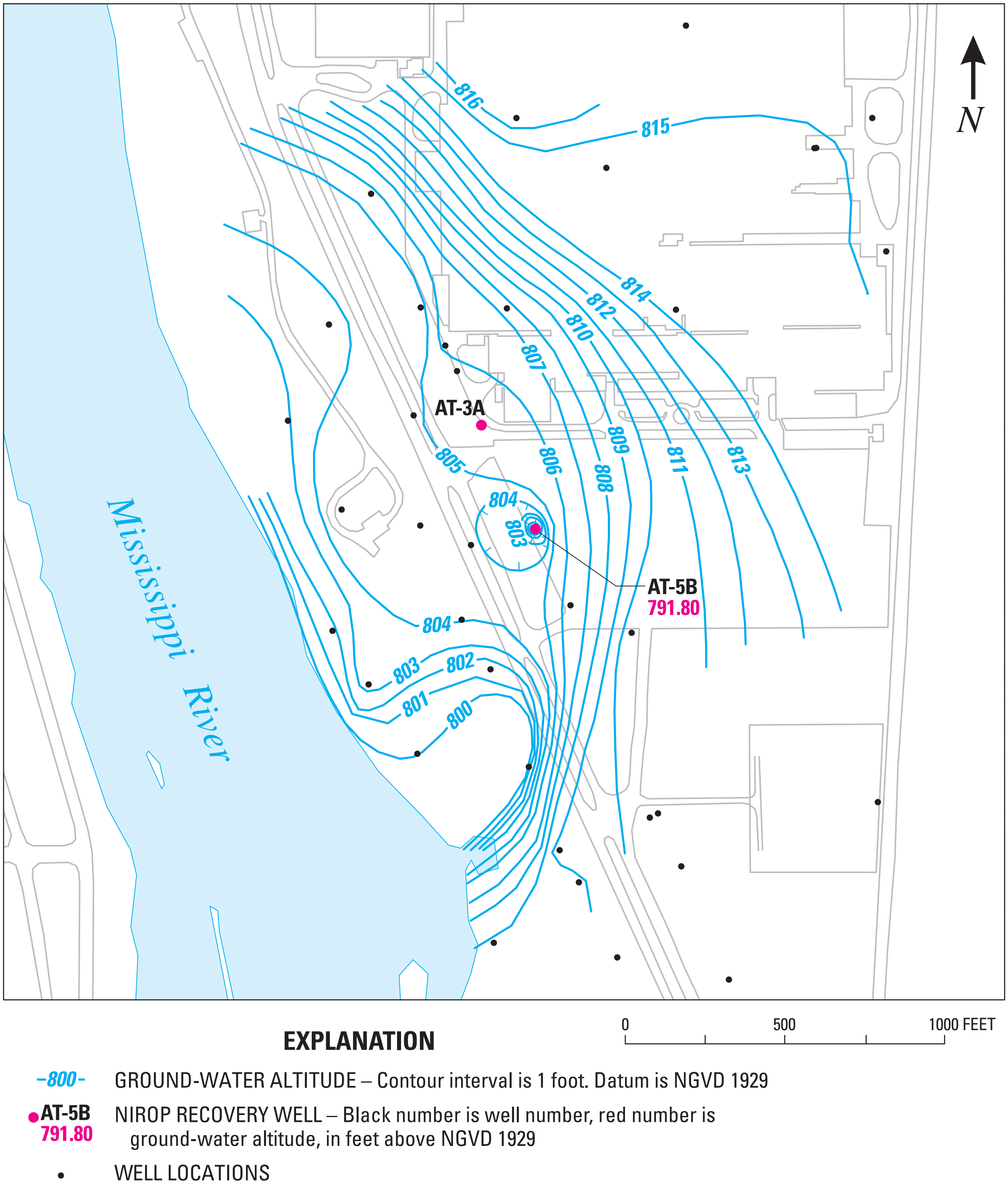


Figure 25. Potentiometric surface of the deep flow zone during pumping conditions on August 20, 2001.

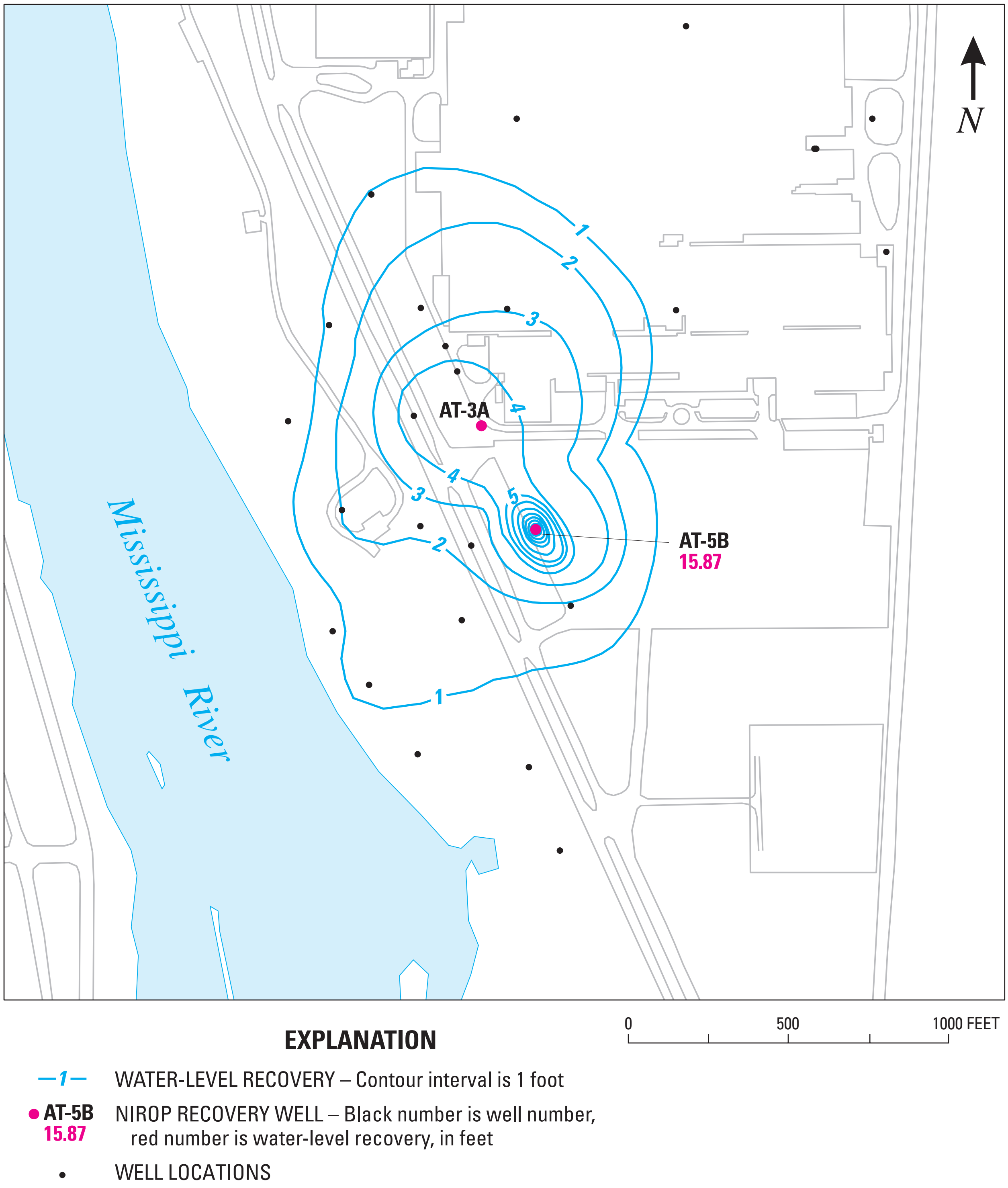


Figure 26. Water-level recovery in the deep flow zone after pumping stopped as measured on September 26, 2001.

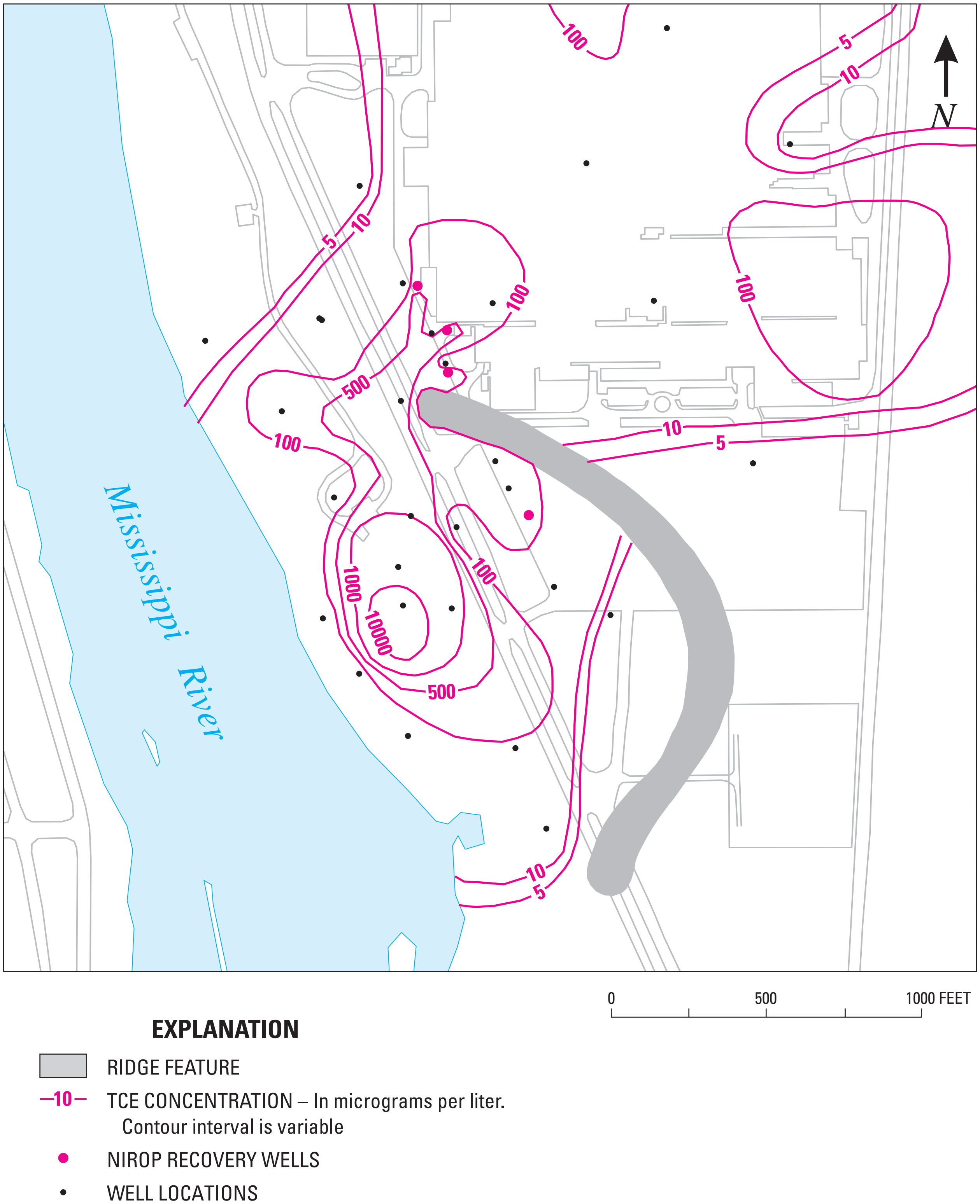


Figure 27. Distribution of trichloroethene (TCE) contamination in the shallow aquifer (modified from TtNUS, 2002a).

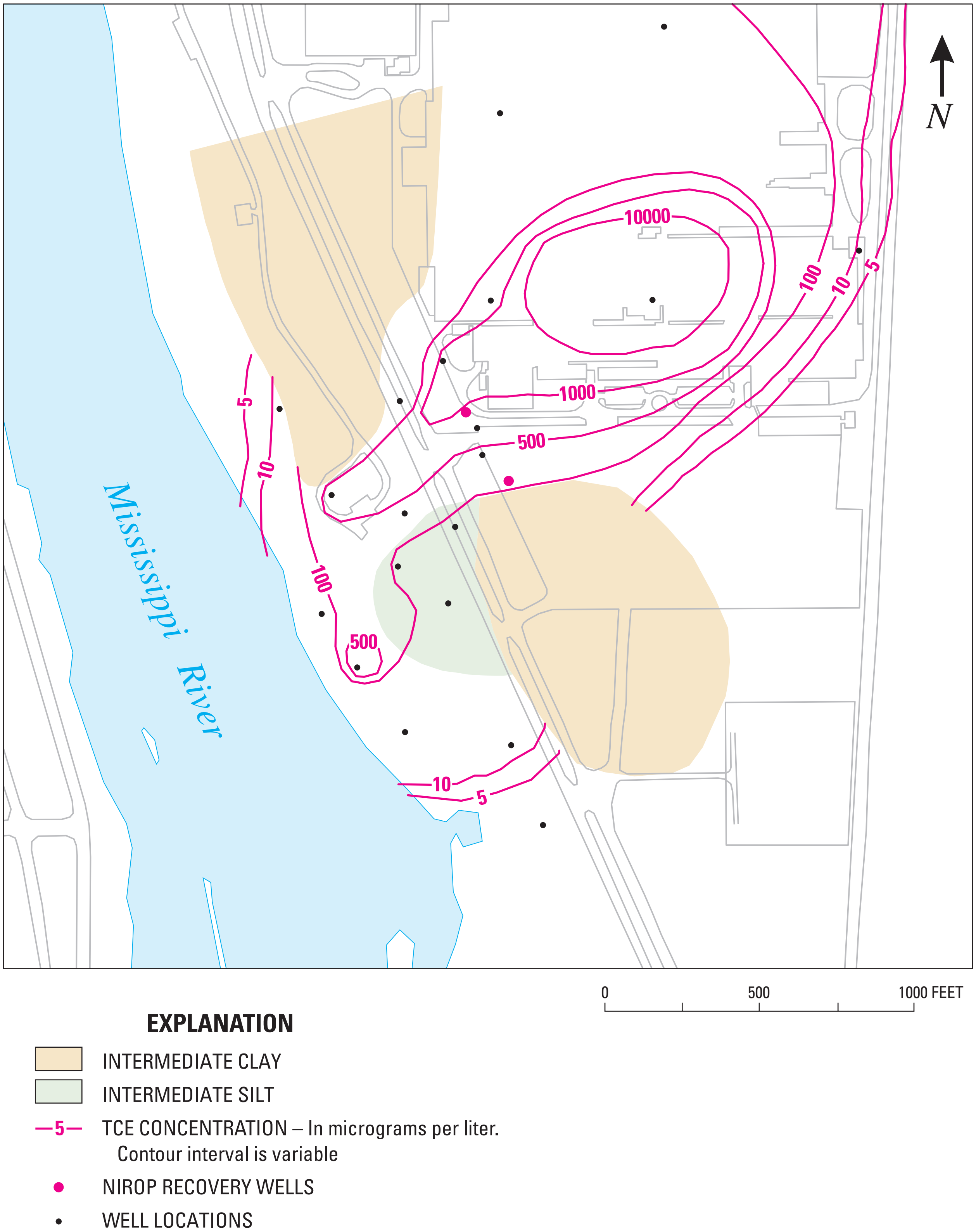


Figure 28. Distribution of trichloroethene (TCE) contamination in the intermediate aquifer (modified from TtNUS, 2002a).

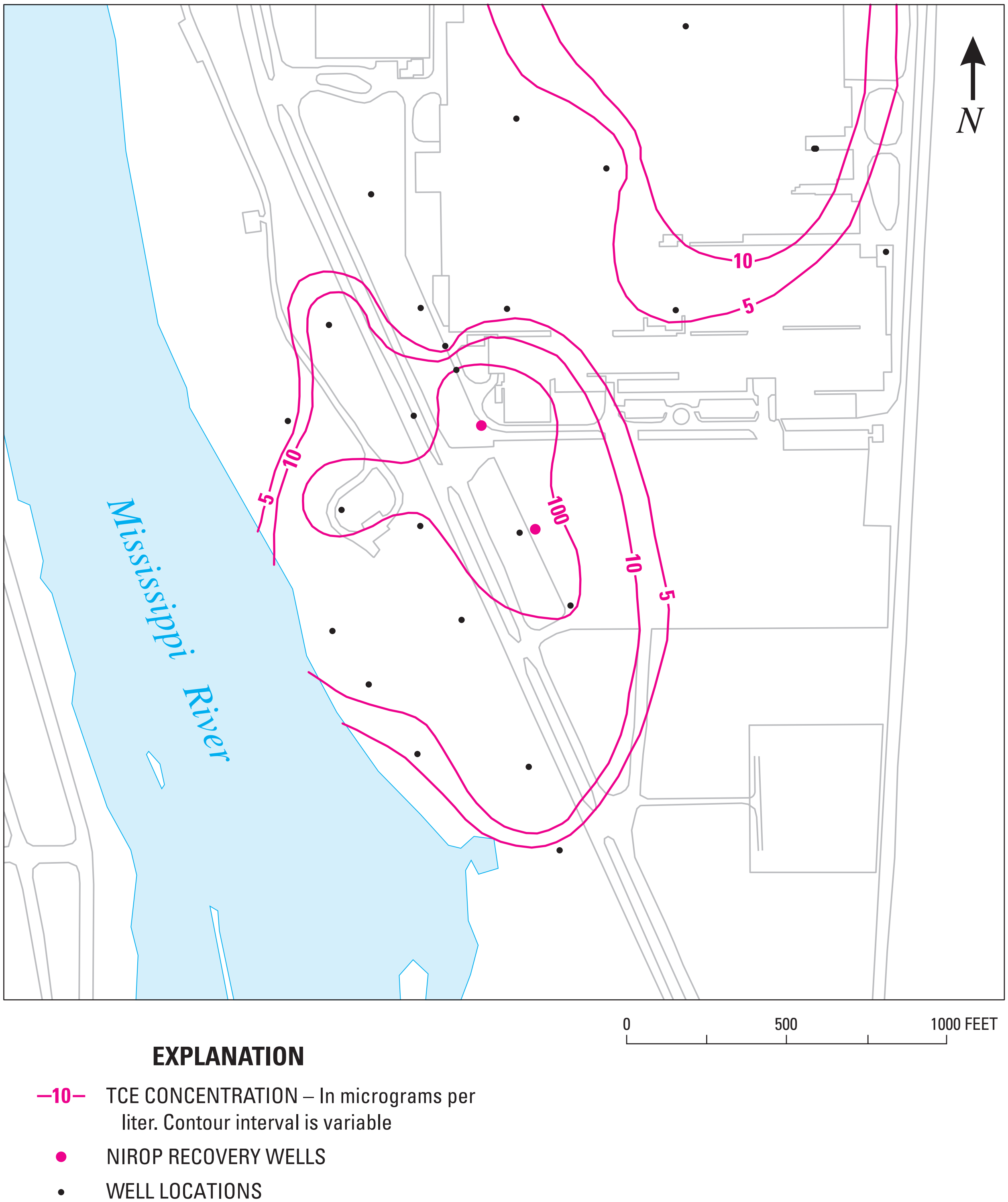


Figure 29. Distribution of trichloroethene (TCE) contamination in the deep aquifer (modified from TtNUS, 2002a).

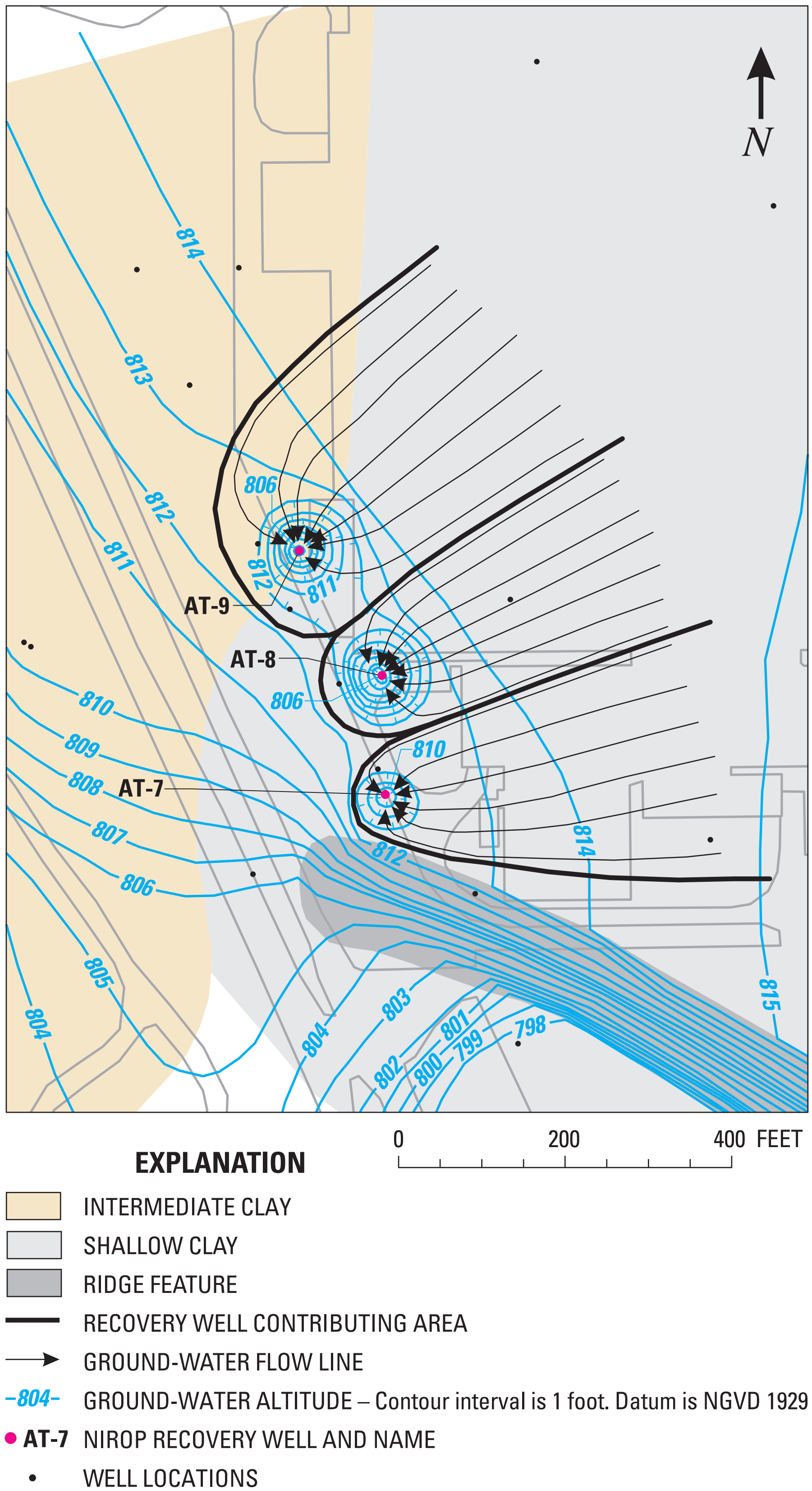


Figure 30. Ground-water flow lines and contributing areas associated with shallow pumping wells AT-7, AT-8, and AT-9.

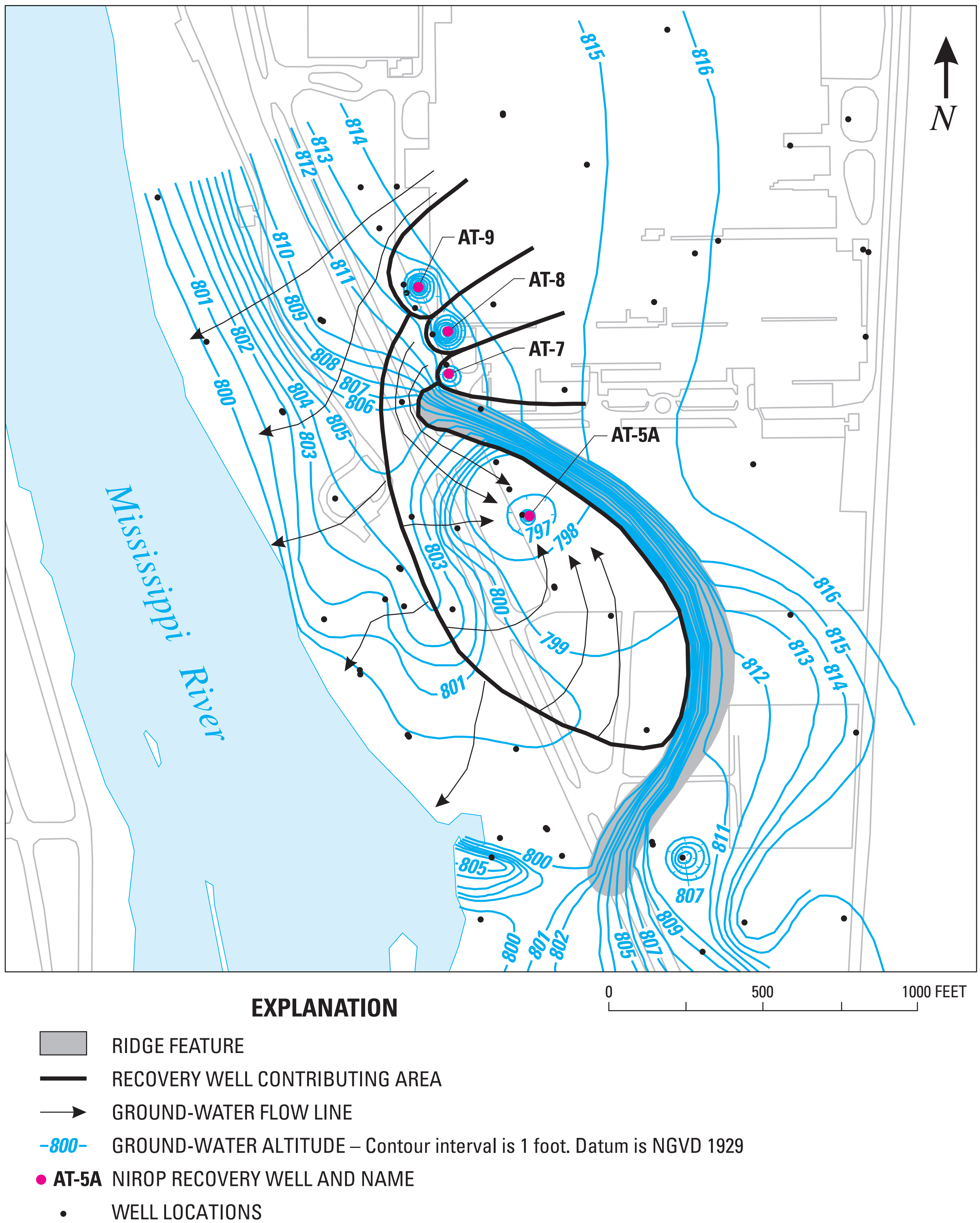


Figure 31. Ground-water flow lines and contributing areas associated with shallow pumping wells AT-5A, AT-7, AT-8, and AT-9.

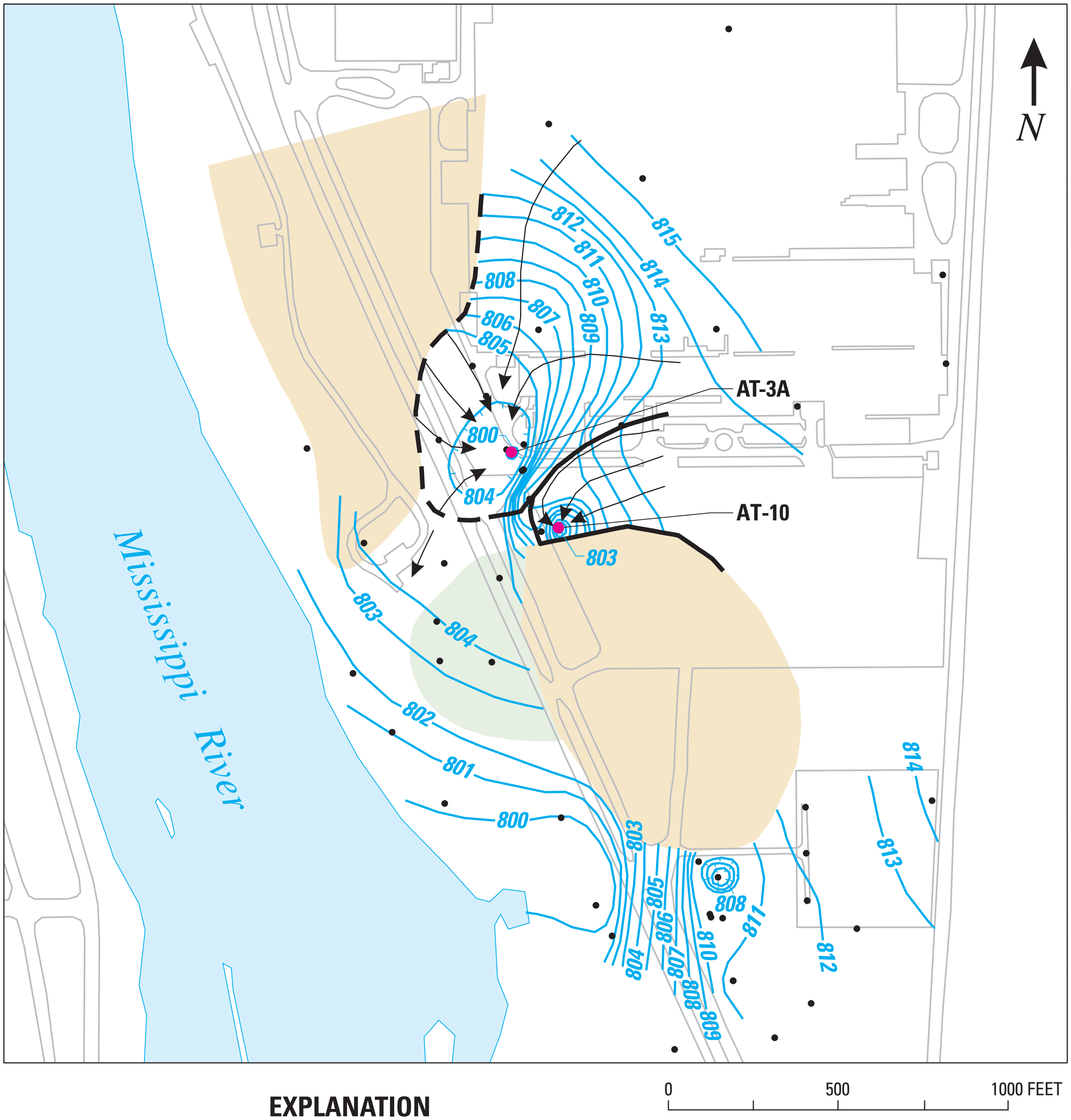
The contributing areas of intermediate wells AT-3A and AT-10 are shown in figure 32. The contributing area of AT-3A (182 gal/min) is larger than that of AT-10 (23 gal/min), mostly because of the larger pumping rate and because AT-3A is screened in higher permeability materials. The contributing area for well AT-3A is dashed because the potentiometric surface downgradient from the well has small relief making it more difficult to determine exactly where the ground-water divide occurs, and because the exact position of the intermediate clay to the north is unknown. The top of the intermediate flow zone is bounded by the shallow clay in this area. The lateral extent of the contributing areas are bounded by the two clays that make up the intermediate clay. There is no clay layer separating the permeable intermediate zone and the deep flow zone, so these wells probably capture some flow from the deep zone. This would be true of well AT-3A because of the higher pumping rate. Well AT-3A may extend into the deep flow zone.

The contributing area of deep well AT-5B (86 gal/min) is shown in figure 33. In this area, the intermediate clay forms the top of the deep flow zone and the bottom is formed by the Prairie du Chien Dolomite (fig. 4.) The Prairie du Chien Dolomite is generally permeable and well AT-5B may be drawing water from it. However, at this site the permeability of the Prairie du Chein is unknown and, more importantly, the exact distribution of the low-permeability St. Peter Sandstone is also unknown. Therefore, it is not possible to know with certainty if water is being captured from the Prairie du Chein. As discussed earlier, the intermediate well AT-3A is probably drawing water from the deep flow zone as evident from the potentiometric and recovery maps. However, there were not sufficient data to draw a deep contributing area due to pumping from intermediate well AT-3A, although it is probably occurring.

The combined contributing areas of recovery wells AT-7, AT-8, and AT-9 capture the higher levels of TCE contamination (greater than 100 ppb) along their combined axis (fig 34.) Well AT-5A has a broad contributing area that reaches approximately halfway to the river and captures the eastern flank of the highest levels of contamination in the shallow zone, but well AT-5A does not capture all of the highest levels of TCE. The high levels of TCE beyond the contributing area will move toward and eventually discharge to the Mississippi River.

The contributing areas of wells AT-3A and AT-10 are shown in figure 35. As discussed earlier, the contributing areas are dashed for these wells because they are less certain than for the other wells. However, as delineated, the wells should capture the higher levels of TCE contamination in the intermediate zone, which is important because these wells are directly downgradient from the highest levels of contamination at the facility. This is also assuming that the flow is predominately horizontal at the in the intermediate zone.

Well AT-5B captures about a third of the TCE contamination in the deep flow zone that exceeds 100 ppb (fig. 36). Therefore, about two thirds of the contamination untouched, including the highest levels found near the river, which can continue to migrate toward the Mississippi River.



EXPLANATION

INTERMEDIATE CLAY

INTERMEDIATE SILT

RECOVERY WELL CONTRIBUTING AREA – Dashed where approximate

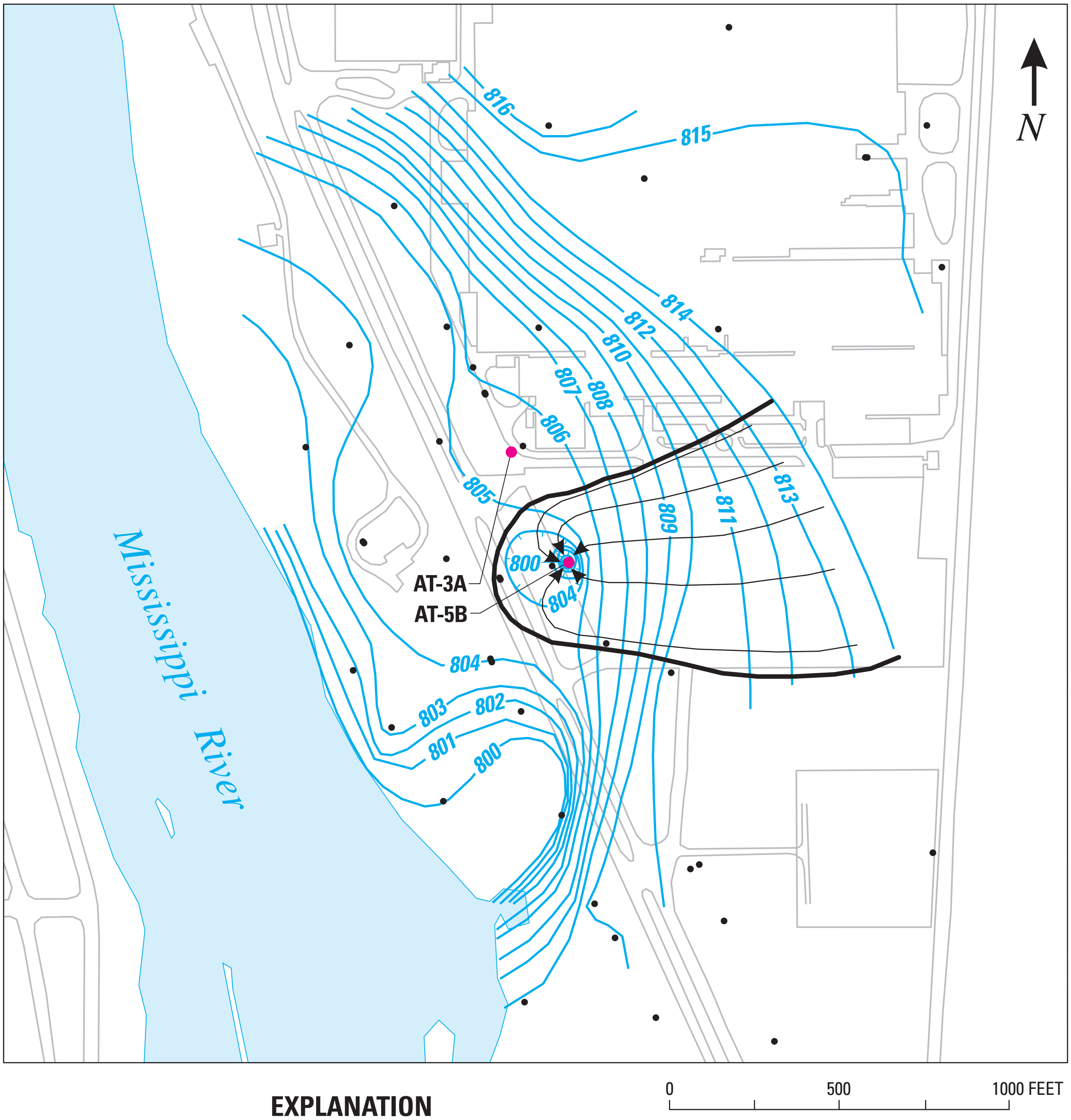
GROUND-WATER FLOW LINE

-800- GROUND-WATER ALTITUDE – Contour interval is 1 foot. Datum is NGVD 1929

● AT-10 NIROP RECOVERY WELL AND NAME

• WELL LOCATIONS

Figure 32. Ground-water flow lines and contributing areas associated with intermediate pumping wells AT-3A and AT-10.



EXPLANATION

- RECOVERY WELL CONTRIBUTING AREA
- GROUND-WATER FLOW LINE
- -800- GROUND-WATER ALTITUDE – Contour interval is 1 foot. Datum is NGVD 1929
- AT-5B NIROP RECOVERY WELL AND NAME
- WELL LOCATIONS

Figure 33. Ground-water flow lines and contributing areas associated with deep pumping well AT-5B.

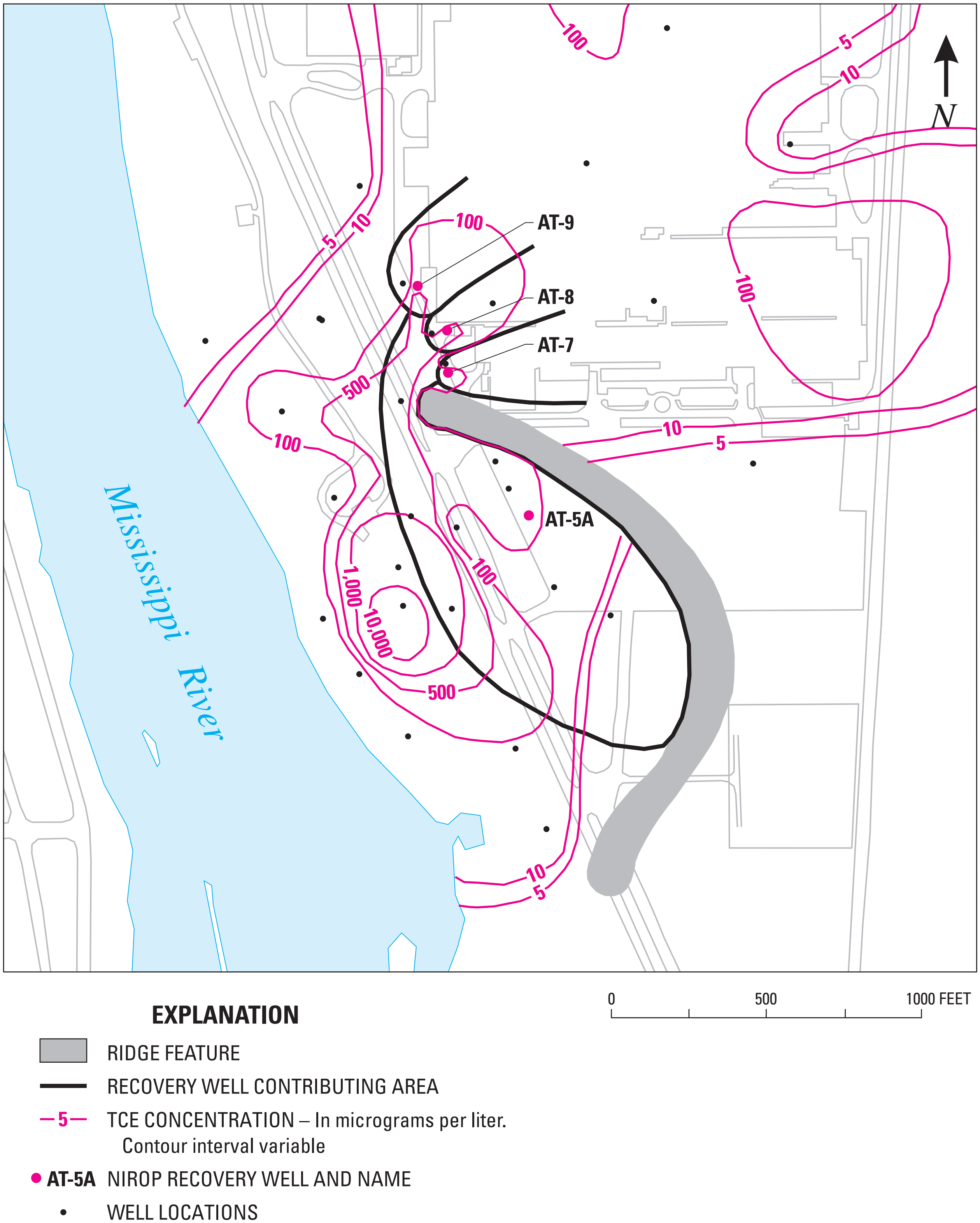


Figure 34. Contributing areas of pumping wells AT-5A, AT-7, AT-8, and AT-9 and the distribution of TCE in the shallow zone.

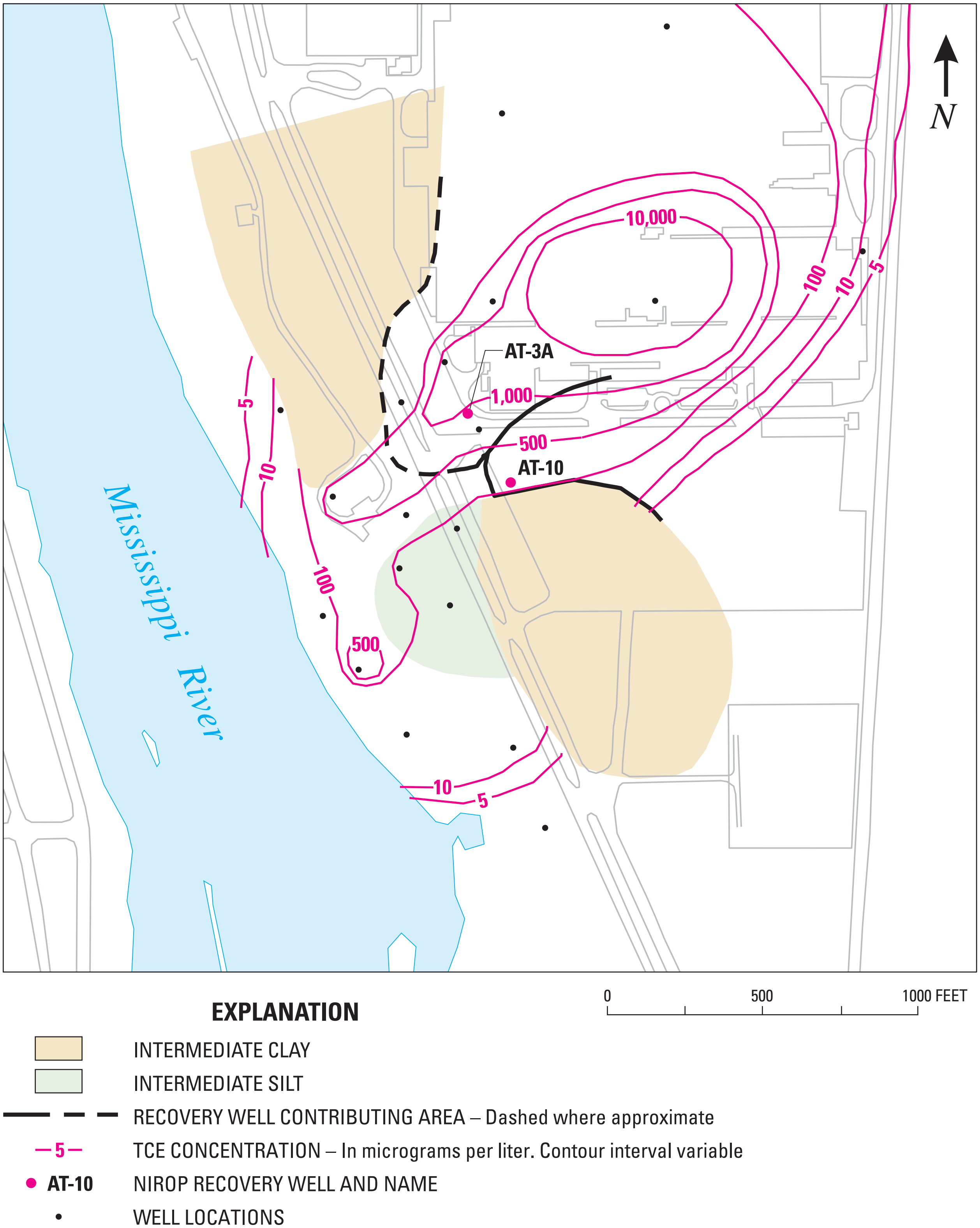


Figure 35. Contributing areas of pumping wells AT-3A and AT-10 and the distribution of TCE in the intermediate zone.

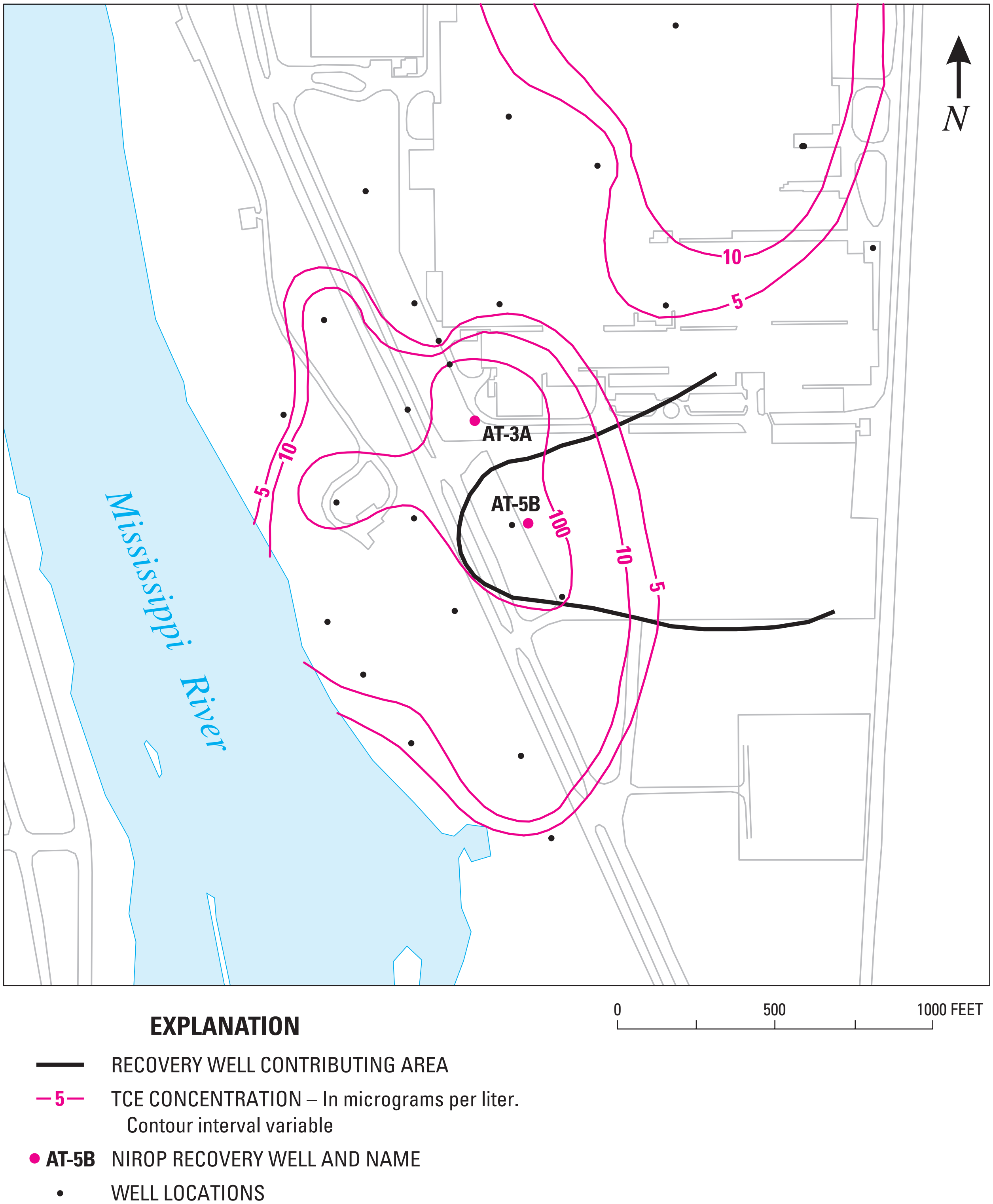


Figure 36. Contributing area of pumping well AT-5B and the distribution of TCE in the deep zone.

Summary and Conclusions

The Naval Industrial Reserve Ordnance Plant is located on the southernmost tip of Anoka County, Minnesota, within the city of Fridley. The plant is located approximately one-quarter mile east of the Mississippi River. Industrial production began in 1941 with a manufacturing facility and it has been in continuous operation since then producing weapon systems of increasing complexity. Contamination spills and disposal practices in the past led to significant ground-water contamination beneath the facility. A ground water recovery (and containment) system began operation in 1992 to prevent contaminated ground-water from migrating off site. This study was undertaken to determine if the ground-water recovery system was preventing off-site migration of contamination. Field-work consisted of installing pressure transducers in 23 wells, taking multiple discrete water-level measurements in an additional 56 wells, and taking two extensive rounds of water-level measurements in all wells (one during pumping and one during non-pumping conditions).

The glacial-drift deposits form the uppermost permeable unit, which contains the water table and lower confined layers. These deposits range in thickness up to 130 ft and consist of medium to coarse sand, fine sand, gravel, and discontinuous very fine-grained (clay, silty clay, sandy clay, and silt) interbeds. The clay and silt interbeds range up to 46 ft in thickness. Most of the ground-water contamination at the site is located within the glacial drift deposits and is where most of the monitoring wells have been installed. Ground-water level responses in individual wells, especially in well nests during the measurement period, revealed that shallow, intermediate, and deep flow zones are present in the glacial-drift aquifer.

The difference in ground-water levels between the shallow and deep wells show a downward gradient across the northern part of the site and an upward gradient across the southern part due to the combined effect of the shallow and intermediate clays. In the northern half of the study area, the head difference ranges from -9.6 ft (negative values indicate a downward gradient) to +1.0 ft; in the southern half the head difference ranges from +10.7 ft to near 0. Where the clays are absent, the glacial-drift aquifer has a good vertical connection and the shallow, intermediate, and deep flow zones are connected.

The most prominent feature of the shallow flow zone (water table) is the closely spaced contours associated with a ridge feature of the shallow clay, which affects ground-water flow. North and south of the ridge the water table is relatively flat, whereas across the ridge the water level abruptly drops about 10 ft. The intermediate flow zone is not present where the intermediate clays exists. Generally, the deep flow zone has a gentle slope toward the Mississippi River.

The cones of depression of the shallow flow zone wells AT-8 (17 gal/min) and AT-9 (142 gal/min) overlapped to form one broad cone while the cone of depression of well AT-7 (42 gal/min) was more isolated. Well AT-5A (156 gal/min) had a large broad cone of depression, which was the result of the relatively high pumping rate and the relatively high permeability of 200 ft/day. Intermediate flow zone well AT-3A (182 gal/min) had a broad cone of depression that extended to the intermediate clays; well AT-10 (23 gal/min) had relatively steep cone because it is screen in a relatively low-permeability zone. Deep flow zone well AT-5B (86 gal/min) and had a broad cone of depression. Intermediate well AT-3A appears to be drawing water up vertically out of the deep flow zone.

The contributing areas for all the pumping wells were determined by drawing ground-water flow lines perpendicular to the ground-water potentiometric contours; the downgradient limit of each contributing area was positioned at the point where potentiometric contours reverse from the regional gradient to sloping back toward the pumping well. The combined contributing areas of recovery wells AT-7, AT-8, and AT-9 capture the higher levels of TCE contamination (greater than 100 ppb) along their combined axis. Well AT-5A has a broad contributing area that reaches approximately halfway to the river and captures the eastern flank of the highest levels of contamination in the shallow zone, but the contributing area does not capture all of the highest levels. The combined contributing areas of wells AT-3A and AT-10 should capture the TCE contamination in the intermediate zone that is moving off site. Well AT-5B captures about a third of TCE contamination in the deep flow zone that exceeds 100 ppb.

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