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Open-File Report 2016–1066

U.S. Department of the Interior
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SALLY JEWELL, Secretary

U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2016

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Conversion Factors

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)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Mass	
kilogram (kg)	2.205	pound avoirdupois (lb)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as
°F = (1.8 × °C) + 32.

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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

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.

Concentrations of chemical constituents in water are given in micrograms per liter (µg/L).

Abbreviations

1,1-DCA	1,1-dichloroethane
1,1-DCE	1,1-dichloroethene
1,1,2-TCE	1,1,2-trichloroethane
1,2-DCE	1,2-dichloroethene
cis-1,2-DCE	cis-1,2-dichloroethene
DCA	1,2-dichloroethane
DNAPL	dense nonaqueous phase liquid
EPA	U.S. Environmental Protection Agency
NIROP	Naval Industrial Reserve Ordnance Plant
PCE	tetrachloroethene
TCA	1,1,1-trichloroethane
TCE	trichloroethene
trans-1,2-DCE	trans-1,2-dichloroethene
USGS	U.S. Geological Survey

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An early draft of this report was also reviewed by B.G Campbell, U.S. Geological Survey (USGS); and J.R. Stark, USGS. J.H. Davis, USGS, was principal investigator from project inception to September 2012. Davis built numerical model simulations, applied these simulators, generated figures, and authored the early draft. J.N. King, USGS, revised the manuscript to address comments from reviews of the early draft.

Preliminary Investigation of Groundwater Flow and Trichloroethene Transport in the Surficial Aquifer System, Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota

By Jeffrey N. King and J. Hal Davis

Abstract

Industrial practices at the Naval Industrial Reserve Ordnance Plant, in Fridley, Minnesota, caused soil and groundwater contamination. Some volatile organic compounds from the plant might have discharged to the Mississippi River forced by the natural hydraulic gradient in the surficial aquifer system. The U.S. Environmental Protection Agency included the Naval Industrial Reserve Ordnance Plant on the Superfund National Priorities List in 1989.

This report describes a preliminary characterization of trichloroethene transport in the surficial and Cambrian-Ordovician aquifer systems at the Naval Industrial Reserve Ordnance Plant. The characterization first involved simulation of 2001 conditions using a model, followed by an application of this 2001 simulator to 2011 conditions.

The U.S. Geological Survey, in cooperation with the U.S. Department of the Navy, used a steady-state, uniform-density groundwater flow model to simulate measured potentiometric heads in aquifer systems on August 20, 2001, and a single-phase, conservative, non-reactive, miscible transport model to simulate trichloroethene concentrations in aquifer systems measured in 2001. The U.S. Department of the Navy furnished trichloroethene source areas and trichloroethene source area concentrations to the U.S. Geological Survey for this model simulation. Furnished delineations were postulated and informed by data collected from 1995 to 2011. The groundwater flow simulation of August 20, 2001, was superior to the trichloroethene transport simulation at replicating measurements; simulated potentiometric heads matched 90 percent of measured potentiometric heads on August 20, within 2 feet at selected locations whereas simulated trichloroethene concentration contours of 3, 10, 100, 1000, and 10,000 micrograms per liter (µg/L) correctly bounded 52 percent of measured concentrations in 2001 at selected locations. The degree to which the simulated trichloroethene plume does not match trichloroethene measurements in the surficial aquifer system during the 2001 simulation may suggest that furnished trichloroethene source areas and trichloroethene source area concentrations did not accurately represent all trichloroethene sources in the hydrogeologic system.

During the model simulation of 2001, trichloroethene discharged to the Mississippi River. A simulated 900-foot-long zone of benthic trichloroethene discharge flux existed in the shallow flow zone, across which simulated trichloroethene discharged from the surficial aquifer system to the Mississippi River at simulated trichloroethene concentrations that ranged from 3 µg/L to more than 100 µg/L. The Mississippi River was not sampled for volatile organic compounds in Fridley, Minn., from 1999 to 2016 (the publication of this report). Trichloroethene concentrations were measured in wells close to the Mississippi River in the surficial aquifer system on the downgradient side of the Naval Industrial Reserve Ordnance Plant groundwater flow field; for example, at well MS–43 in the shallow flow zone of the surficial aquifer system 280 feet east of the Mississippi River between December 1999 and August 2012, trichloroethene concentrations ranged from 130 to 220 µg/L. The 220-µg/L maximum concentration was reached in March 2003 and October 2006. The August 2012 concentration was 140 µg/L.

The August 20, 2001, groundwater flow model simulator and the 2001 trichloroethene transport simulator were applied to a groundwater extraction and treatment system that existed in 2011. Furnished trichloroethene source areas and concentrations in the 2001 simulator were replaced with different, furnished, hypothetical source areas and concentrations. Forcing in 2001 was replaced with forcing in 2011. No trichloroethene concentrations greater than 3 µg/L were simulated as discharging to the Mississippi River during applications of the 2001 simulator to the 2011 groundwater extraction and treatment system. These applications were not intended to represent historical conditions. Differences between furnished and actual trichloroethene sources may explain differences between measurements and simulation results for the 2001 trichloroethene transport simulator. Causes of differences between furnished and actual trichloroethene sources may cause differences between hypothetical application results and the performance of the actual U.S. Department of the Navy groundwater extraction and treatment system at the Naval Industrial Reserve Ordnance Plant. Other limitations may also cause differences between application results and performance.

Introduction

Industrial practices at the Naval Industrial Reserve Ordnance Plant (NIROP) in Fridley, Minnesota (fig. 1), caused soil and groundwater contamination (U.S. Environmental Protection Agency, 1987, 1990, 2003 [records of decision]; Lane and others, 2007). Soil and groundwater were contaminated under the main NIROP building, NIROP property, and Anoka County Riverfront Regional Park (fig. 2) along the Mississippi River (fig. 1). The U.S. Geological Survey (USGS), in cooperation with the U.S. Department of the Navy (herein referred to as "the Navy"), investigated this contaminated groundwater.

The U.S. Environmental Protection Agency (1987, 1990, 2003 [records of decision]; and 2014, 2012b), Tetra Tech (2002) and Davis (2007) described industrial practices at NIROP. Industrial production began at NIROP in 1940. Chemicals, scrap material, and industrial waste were stored, burned, and disposed of at NIROP. Drums that contained liquid waste were buried in trenches and borrow pits. Liquid waste was discharged to storm and sanitary sewers.

The U.S. Environmental Protection Agency (EPA) added NIROP to the Superfund National Priorities List on November 21, 1989 (U.S. Environmental Protection Agency, 1990 [record of decision]; Minnesota Pollution Control Agency, 2015). The EPA issued records of decision for NIROP groundwater on September 28, 1990, and for NIROP soils on September 17, 2003. The EPA identified volatile organic compounds at NIROP. Trichloroethene (TCE) was the most common volatile organic compound measured at NIROP. Trichloroethene has moderate solubility and high mobility in groundwater.

The main NIROP building is divided into two parts (fig. 2): the northern part covers 37.5 acres, and the southern part covers 7.3 acres (U.S. Environmental Protection Agency, 2003 [record of decision]; Minnesota Pollution Control Agency, 2015). The 56.2-acre NIROP EPA Superfund site, as delineated in the U.S. Environmental Protection Agency (2003) record of decision covers the 37.5-acre northern part of the main building; and land north, east, and west of the northern part of the main building (fig. 2). The 7.3-acre southern part of the main building is not part of NIROP EPA Superfund site.

The following four Fridley, Minn., sites (fig. 2) within 2,000 feet (ft) of NIROP are also subject to EPA or State of Minnesota action for contamination of groundwater or soils with volatile organic compounds:

- The FMC Corp., (Fridley Plant) EPA Superfund site (fig. 2) was added to the Superfund National Priorities List in September 1983 (Minnesota Pollution Control Agency, 2014c). The site was ranked first on the National Priorities List when listed, principally owing to an assessment of the site as a potential threat to human health or the environment (U.S. Environmental Protection Agency, 1987 [record of decision]). The EPA issued a record of decision for this site on September 30, 1987. The U.S. Environmental Protection Agency (1987) record of decision identified volatile organic compounds at the site, including TCE. The FMC Corp., (Fridley Plant) EPA Superfund site is about 1,000 ft south of the main NIROP building and about 700 ft east of the Mississippi River.
- The Kurt Manufacturing Co., EPA Superfund site (fig. 2) was added to the Superfund National Priorities List in June 1986 (U.S. Environmental Protection Agency, 2012a). Both soil and groundwater are contaminated at the site (Minnesota Pollution Control Agency, 2013b). The U.S. Environmental Protection Agency (2014) identified volatile organic compounds at the site, including TCE. The Kurt Manufacturing Co., EPA Superfund site is about 2,000 ft northeast of the main NIROP building and about 3,000 ft east of the Mississippi River.
- The Dealers Manufacturing State of Minnesota Superfund site (fig. 2) was added to the State of Minnesota Permanent List of Priorities in 1990 (Minnesota Pollution Control Agency, 2013a). The Minnesota Pollution Control Agency (2013a) identified volatile organic compounds at the site, including TCE. The site is about 1,000 ft northeast of the main NIROP building and about 3,000 ft east of the Mississippi River.
- The BAE Resource Conservation and Recovery Act site (fig. 2) was identified as contaminated in 1981 with volatile organic compounds, including TCE (Minnesota Pollution Control Agency, 2014a). The BAE Resource Conservation and Recovery Act site is in the main NIROP building, in the 7.3-acre southern part, south of NIROP EPA Superfund site.

Site names used in this report, which describe these four Fridley, Minn., sites near NIROP, conform to EPA or State of Minnesota records. Site names used in this report do not imply current property ownership.

Groundwater extraction and treatment systems exist to mitigate contamination at NIROP and on other Fridley, Minn., sites (fig. 2) (Tetra Tech, 2013b). On December 7, 1987, a groundwater extraction system began operating on the FMC Corp., (Fridley Plant) EPA Superfund site (Minnesota Pollution Control Agency, 2004). The Navy began operating a groundwater extraction system at NIROP in September 1992, and modified the system in 1995, 1998, 2001, and 2011; for example, the Navy replaced extraction well AT–3A (fig. 3) with extraction wells AT–11, AT–12, and AT–13 in 2011 (fig. 3). These systems extract groundwater contaminants by altering—with extraction wells—the native potentiometric-head gradient. Extracted groundwater was treated to remove volatile organic compounds, and treated water was returned to the natural hydrologic system. Tetra Tech (2013b) reported that since September 1992, the Navy treated more than 4.3 billion gallons (gal) of groundwater at NIROP and extracted more than 34,000 pounds of TCE.

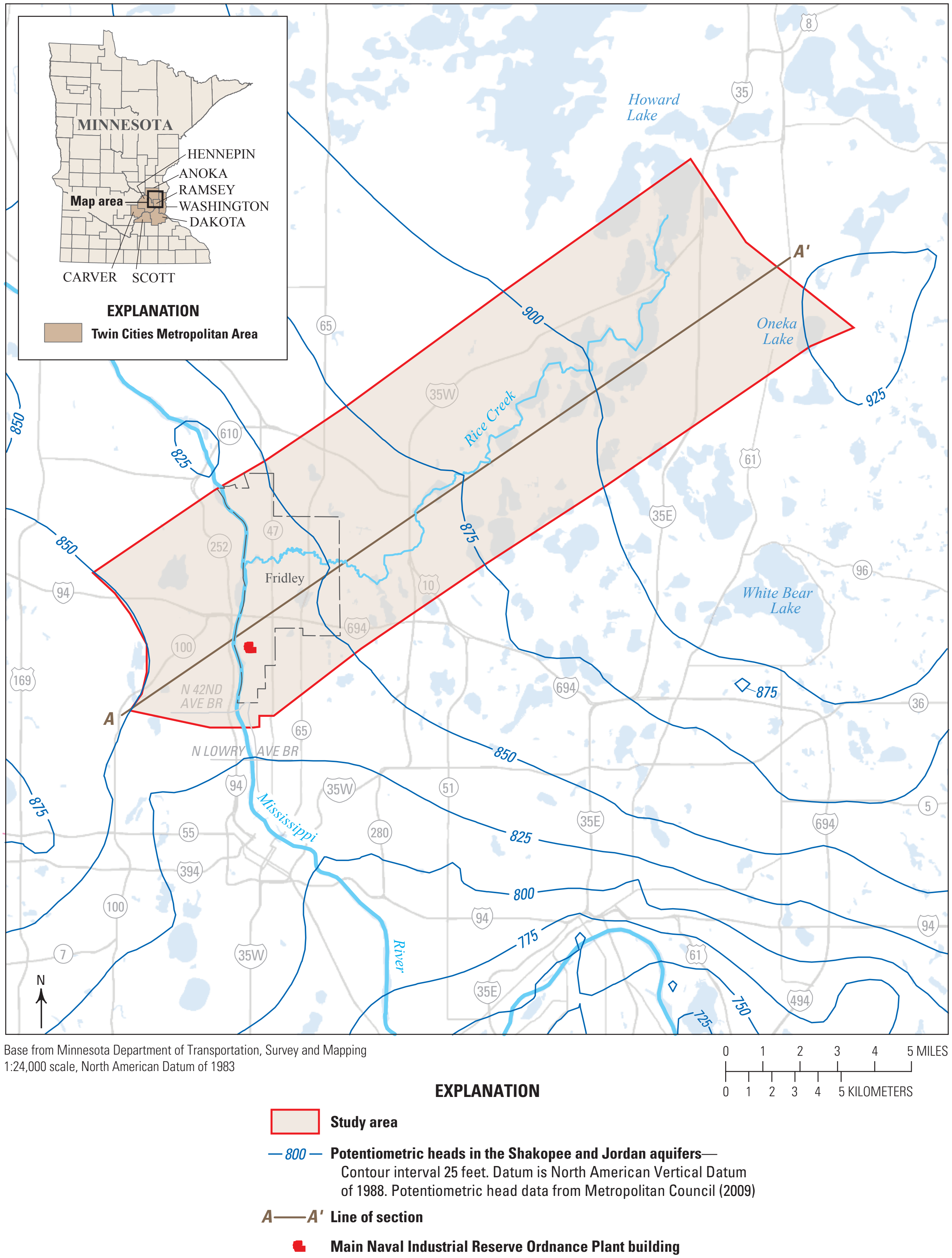


Figure 1. Study area in and near Fridley, Minnesota; and potentiometric heads in the Shakopee and Jordan aquifers, and line of section *A–A′*.

Figure 2. Location of the Naval Industrial Reserve Ordnance Plant and four other sites with volatile organic compound contamination in the subsurface in Fridley, Minnesota: Kurt Manufacturing Co., U.S. Environmental Protection Agency (EPA) Superfund site; Dealers Manufacturing State of Minnesota Superfund site; FMC Corp., (Fridley Plant) EPA Superfund site (FMC); and BAE Resource Conservation and Recovery Act site (BAE RCRA).

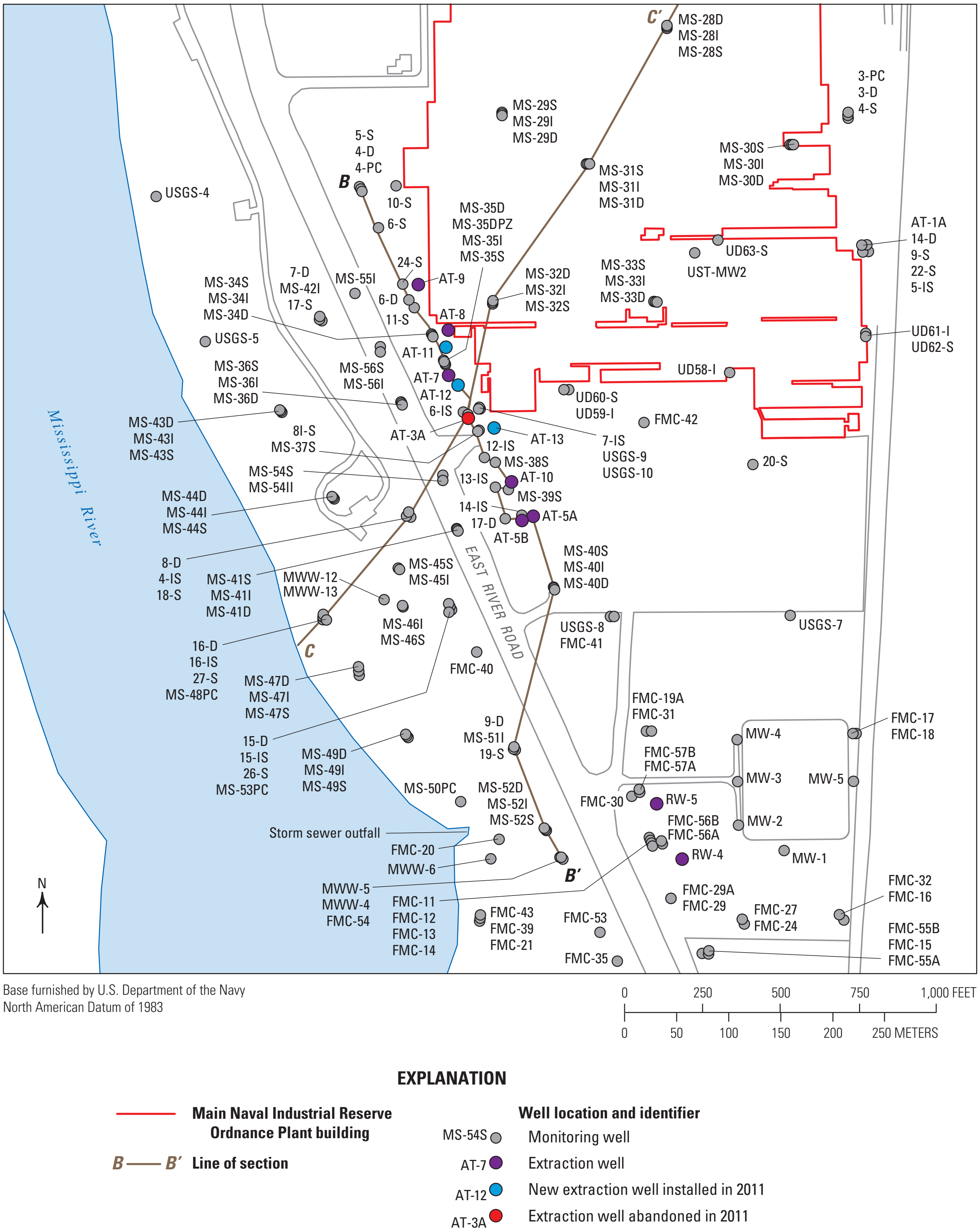


Figure 3. Locations of monitoring wells, extraction wells, and lines of section at and near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.

Contaminated groundwater in the surficial and underlying Cambrian-Ordovician aquifer systems might affect water resources; for example, some volatile organic compounds from NIROP and other Fridley, Minn., sites might have discharged to the Mississippi River forced by natural hydraulic gradients in the surficial aquifer system and underlying Cambrian-Ordovician aquifer system. The city of Minneapolis, Minn. (not shown), drinking water treatment plant obtains source water from an intake pipe in the Mississippi River. The Mississippi River, at the location of this intake, is the drinking water source for 500,000 people (U.S. Environmental Protection Agency, 1990 [record of decision], 2012b). Volatile organic compounds in the surficial and underlying Cambrian-Ordovician aquifer systems may affect other water resources; for example, during high demand periods, the city of Fridley, Minn., satisfies water source needs of 29,000 people using a well near NIROP.

Purpose and Scope

The primary purpose of this report is to describe a preliminary characterization of TCE transport at NIROP (fig. 2). This report describes preliminary simulations that use models of uniform-density groundwater flow and TCE transport in the surficial aquifer system and underlying Cambrian-Ordovician aquifer system. These preliminary simulations accounted for the effects of groundwater extraction and treatment systems at NIROP and at the FMC Corp., (Fridley Plant) EPA Superfund site.

This report includes a brief review of selected previous investigations. The hydrogeologic setting and estimates of hydrogeologic parameters are described. A brief summary of groundwater contamination at NIROP and on other Fridley, Minn., sites, and results of groundwater flow and TCE transport model simulations are presented.

Description of Study Area

The study area (fig. 1) was roughly rectangular and measured 20 miles (mi) by 6 mi. The area was oriented with the long axis in a northeasterly-southwesterly direction, which was generally aligned with Rice Creek (fig. 1). The Mississippi River is about 700 ft west of NIROP (fig. 2) in the western part of the study area. The Naval Industrial Reserve Ordnance Plant is on glacial and fluvial deposits on the Mississippi River alluvial terrace. The geographic domain of interest was NIROP, other contaminated Fridley, Minn., sites, and part of Anoka County Riverfront Regional Park. The geologic domain of interest was the surficial aquifer system.

Approach

The preliminary characterization of TCE transport in the surficial and Cambrian-Ordovician aquifer systems at NIROP first involved a simulation of 2001 conditions using groundwater flow and TCE transport models, followed by an application of the 2001 simulator to 2011 conditions. First, a groundwater flow simulation of August 20, 2001, was compared with potentiometric head measurements made on August 20, 2001. The groundwater flow simulation was forced by conditions that were representative of August 20, 2001. A TCE transport simulation of 2001 was compared with TCE concentration measurements in 2001. The Navy furnished TCE source area geometries and concentrations for the TCE transport simulation of 2001. Second, the 2001 flow and transport simulators were applied to 2011. The application of the groundwater flow simulator was forced by conditions that were representative of 2011. The Navy furnished hypothetical TCE source area geometries and concentrations for the application of the TCE transport simulator to 2011. These preliminary applications did not represent historical conditions. Several postulations were made, including but not limited to the following: groundwater flow and potentiometric head on August 20, 2001, were postulated as representative of 2001 in the TCE transport simulation; and it is possible to draw meaningful, preliminary science findings using steady-state groundwater flow and constituent transport simulations. The terms “potentiometric head” and “hydraulic head” are equivalent.

The groundwater flow model MODFLOW 2000 (Harbaugh and others, 2000) and uniform-density, single phase, miscible transport model MT3DMS (Zheng and Wang, 1998) were applied to the study area. Models were applied to a variably-spaced grid to provide the resolution necessary to simulate TCE transport at NIROP. The local groundwater flow system was primarily forced by the regional groundwater flow system. The hydrogeologic system was represented using higher resolution in the area of concern for TCE transport and lower resolution beyond this area; for example, potentiometric head was simulated in the surficial aquifer system on a regional scale to simulate the effect of the regional flow system on potentiometric head at the local NIROP scale. Similarly, potentiometric head was simulated in the Shakopee aquifer to simulate the effect of subjacent leakage on potentiometric head in the surficial aquifer system.

Previous Investigations

Guswa and others (1982), Stark and Hult (1985), Lindgren (1990), Schoenberg (1990, 1994), and Metropolitan Council (2009, 2014) used models to simulate groundwater flow in the Twin Cities Metropolitan Area (fig. 1). These studies used different representations of the system to meet the needs of specific problems (fig. 4). Guswa and others (1982), Schoenberg (1990), and Metropolitan Council (2009, 2014) simulated the surficial and Cambrian-Ordovician aquifer systems (fig. 4) from glacial and fluvial deposits at the surface to the base of underlying bedrock. Stark and Hult (1985) simulated a part of the Cambrian-Ordovician aquifer system. Lindgren (1990) and Schoenberg (1994) simulated the surficial aquifer system and part of the Cambrian-Ordovician aquifer system.

Metropolitan Council (2009, 2014) simulated steady-state, regional, groundwater flow in the surficial and Cambrian-Ordovician aquifer systems to incorporate land use into water supply plans, assess current and future groundwater withdrawals, assess future groundwater availability, and identify water supply alternatives. The 4,913-square-mile (mi^2) Metropolitan Council (2009) study area (fig. 5) included all or parts of several counties (not shown) in Minnesota and Wisconsin (fig. 5). Metropolitan Council (2009) used MODFLOW–96 (Harbaugh and McDonald, 1996) to provide the best available water demand, land use, and hydrogeologic data to promulgate a consensus, regional, calibrated, predictive planning tool for use by multiple governmental entities. The model simulation described in Metropolitan Council (2009) was updated by the simulation described in Metropolitan Council (2014) to incorporate transience, update the stratigraphic framework, implement a new recharge calculation, and use MODFLOW–NWT (Niswonger and others, 2011).

Schoenberg (1994) characterized groundwater discharge from the Cambrian-Ordovician aquifer system to the following three river segments in Minnesota: the Mississippi River near Fridley, Minn., and Brooklyn Center, Minn. (not shown); the Minnesota River (not shown) near Eagan, Minn. (not shown), and Bloomington, Minn. (not shown); and the Mississippi River at Minneapolis, Minn. Upstream of NIROP, a surficial aquifer system; a rubble zone between the St. Peter and Prairie du Chien aquifers; and the St. Peter, Prairie du Chien, and Jordan aquifers were identified as discharging to the Mississippi River. Runkel and others (2003) and Tipping and others (2006) divided the Prairie du Chien aquifer into the Shakopee aquifer and Oneota confining unit. Schoenberg (1994) stated that groundwater flows from these hydrogeologic units through alluvial deposits to the Mississippi River. Schoenberg (1994) described a steady-state, vertically oriented, two-dimensional groundwater flow model simulation of the Fridley, Minn., and Brooklyn Center, Minn., study area for November 17, 1989. Numerical simulations of the Eagan, Minn., and Bloomington, Minn., study area; and the Minneapolis, Minn., study area were not developed. Permeameter and slug tests were used to estimate hydraulic conductivity from 4×10^{-5} foot per day (ft/d) for an olive-black till to 80 ft/d for alluvium. A strong, qualitative correlation existed between potentiometric-head measurements in a well cluster about 100 ft east of the Mississippi River and the water-surface elevation in the Mississippi River. This well cluster bored through alluvium, sand and gravel outwash, glacial outwash, and the St. Peter Sandstone. A strong hydraulic connection existed between the river and hydrogeologic units in the surficial aquifer system, St. Peter and Prairie du Chien aquifers, and a rubble zone between the St. Peter aquifer and Prairie du Chien aquifer. Between 1970 and 1979, Schoenberg (1994, 1990) reported a simulated groundwater discharge with an average of 44 cubic feet per day (ft^3/d), per foot along each river, for the Mississippi River from the streamflow-gaging station in St. Paul, Minn. (not shown), to the station in Anoka, Minn. (not shown), and for the Minnesota River from the confluence with the Mississippi River to the streamflow-gaging station in Jordan, Minn. (not shown).

Schoenberg (1990) characterized the effects of contemporary and planned groundwater withdrawals on the surficial and Cambrian-Ordovician aquifer systems near Minneapolis, Minn. Geologic and hydrologic information that described the system were consolidated. Simulated potentiometric head was most sensitive to variation in recharge rate, vertical hydraulic conductivity in the surficial aquifer system, and vertical hydraulic conductivity in a single, combined confining unit in the St. Lawrence and Franconia Formations. Using a revised Paleozoic stratigraphic nomenclature for Minnesota, Mossler (2008) renamed the Franconia Formation as the Tunnel City Group; the Tunnel City Group includes rock units between the Wonewoc Sandstone and St. Lawrence Formation. Schoenberg (1990) quantified groundwater use and groundwater flux among primary units of the Cambrian-Ordovician aquifer system. Schoenberg (1990) stressed the importance of buried-bedrock valleys—filled with glacial and fluvial deposits—and river valleys in controlling near-surface groundwater flow. Glacial and fluvial deposits control inter-aquifer flux where bedrock aquifers interface through buried bedrock valleys.

Schoenberg (1990) contoured predevelopment and 1980-era potentiometric heads in the Prairie du Chien and Jordan aquifers, and showed that near NIROP, predevelopment potentiometric heads ranged from 800 to 850 ft above the North American Vertical Datum of 1988 (NAVD 88). Schoenberg (1990) determined that potentiometric heads in the Prairie du Chien and Jordan aquifers dropped between 20 and 40 ft at NIROP from predevelopment to 1965, and between 5 and 25 ft from predevelopment to 1980. Reeder (1966) described 90-ft declines in 1980-era potentiometric heads in the Prairie du Chien and Jordan aquifers relative to predevelopment, and 240-ft declines in 1980-era potentiometric heads in the Mount Simon and Hinckley aquifers, relative to predevelopment.

Lindgren (1990) simulated groundwater flow in the Prairie du Chien and Jordan aquifers, and in overlying aquifers, to characterize the hydrogeologic system and response of the system to hypothetical groundwater withdrawals near the City of Minneapolis, Minn., drinking water treatment plant. Lindgren (1990) determined that leakage to a confined aquifer in the surficial aquifer system, and to the St. Peter aquifer, ranged from 1.0 to 2.3 inches per year (in/yr) using a steady-state model simulation that represented the period from 1885 to 1930. Leakage—forced by groundwater extraction from 1970 to 1979—increased above this estimate by as much as 3.0 in/yr. Lindgren (1990) described a transient simulation of calendar year 1987, and determined that leakage to these units varied seasonally during five stress periods of irregular duration and spatially across the study area from 0.4 to 2.1 in/yr.

Lindgren (1990) determined that hypothetical, late summer groundwater extraction of the Prairie du Chien and Jordan aquifers at the rate of 27.5×10^6 gallons per day (gal/d) caused potentiometric head to decrease 80 ft in these aquifers, and caused a 60-ft drawdown in a confined aquifer in the surficial aquifer system and St. Peter aquifer. Hypothetical groundwater extraction forced recharge to these units in about equal parts from the following reservoirs: storage, the Mississippi River, and distant regions across study boundaries. Lindgren (1990) noted that discontinuities in the confining

Aquifer system	Series	Geologic unit	Simulation layer number and simulated unit						
			Guswa and others (1982)	Stark and Hult (1985)	Lindgren (1990)	Schoenberg (1990)	Schoenberg (1994)	Metropolitan Council (2009)	This study
Surficial	Quaternary	Glacial and fluvial deposits	(1) Aquifer within glacial and fluvial deposits	Not simulated	(1) Unconfined aquifer within glacial and fluvial deposits (2) Upper confining unit within glacial and fluvial deposits (3) Confined aquifer within glacial and fluvial deposits	(1) Aquifer within glacial and fluvial deposits	(1–2) Grey till (1–3) Terrace deposits (2–6) Upper red till (3–9) Sand and gravel outwash (7–8) Lower red till (5–11) Alluvium	(1) Glacial and fluvial deposits, Decorah Shale, Platteville Formation, Glenwood Formation	(1) Shallow flow zone (upper part) (2) Shallow flow zone (lower part) (3) Intermediate flow zone (4) Deep flow zone
Cambrian-Ordovician	Ordovician	Decorah Shale Platteville Limestone Glenwood Shale	(2) Decorah-Platteville-Glenwood confining unit	Not simulated	Decorah Shale, Platteville Limestone, and Glenwood Shale not present within the study area	(2) Drift and Decorah-Platteville-Glenwood confining unit	Decorah Shale, Platteville Limestone, and Glenwood Shale not present within the study area		Decorah Shale, Platteville Limestone, and Glenwood Shale not present within the study area
		St. Peter Sandstone	(3) St. Peter aquifer (4) Basal St. Peter confining unit	(1) St. Peter aquifer (2) Basal St. Peter confining unit	(3) Confined drift and St. Peter aquifer (4) Basal St. Peter confining unit	(3) St. Peter aquifer (4) Lower St. Peter confining unit	(7–11) St. Peter aquifer (12–13) Rubble zone	(2) St. Peter Sandstone	(5) St. Peter aquifer and Lower St. Peter confining unit
		Shakopee Formation, Oneota Dolomite (Prairie du Chien Group)	(5) Prairie du Chien-Jordan aquifer	(3) Prairie du Chien Group	(5) Prairie du Chien-Jordan aquifer	(5) Prairie du Chien-Jordan aquifer	(14–16) Prairie du Chien aquifer	(3) Prairie du Chien Group	(6) Shakopee aquifer & Oneota confining unit
	Cambrian	Jordan Sandstone		(4) Jordan Sandstone			(17–20) Jordan aquifer	(4) Jordan Sandstone	(7) Jordan aquifer
		St. Lawrence Formation	(6) St. Lawrence-Franconia confining unit	Not simulated	Not simulated	(6) St. Lawrence-Franconia confining unit	Not simulated	(5) St. Lawrence formation	(8) St. Lawrence confining unit
		Franconia Formation/Tunnel City Group[1]						(6) Franconia formation	(9) Upper Tunnel City aquifer and Lower Tunnel City confining unit
		Ironton Sandstone, Galesvile Sandstone (Wonewoc Sandstone[2])	(7) Ironton-Galesville aquifer			(7) Ironton-Galesville aquifer		(7) Ironton-Galesville sandstones	(10) Wonewoc aquifer
		Eau Claire Sandstone	(8) Eau Claire confining unit			(8–18) Eau Claire confining unit		(8) Eau Claire formation	Not simulated
		Mount Simon Sandstone	(9) Mount Simon-Hinckley aquifer			(19) Mount Simon-Hinckley aquifer		(9) Mount Simon-Hinckley sandstones	
	Pre-Cambrian	Hinckley Sandstone/Solor Church Formation		Not simulated	Not simulated				Not simulated
		Objective	Water-supply planning	Coal-tar derivative transport in the Prairie du Chien-Jordan aquifer, St. Louis Park, Minnesota	Withdrawals from the Prairie du Chien-Jordan aquifer, City of Minneapolis drinking-water treatment plant	Water-supply planning	Characterization of groundwater discharge	Land use and water-supply planning, groundwater withdrawals and availability, and water-supply alternatives	Trichloroethene transport in glacial sediments, Naval Industrial Reserve Ordnance Plant
		Scale	Regional	Local	Local	Regional	Local	Regional	Local
		Domain area	3,000 mi²	380 mi²	870 mi²	4,137 mi²	2,000 ft²	4,913 mi²	120 mi²
		Grid type	Telescoping	Telescoping	Telescoping	Telescoping	Uniform	Uniform	Telescoping
		Domain resolution (rows×columns×layers)	34×37×9	40×42×4	54×41×5	59×69×19	1×50×20	280×264×9	282×268×10
		Plan view cell resolution	4,000 ft–20,000 ft×4,000 ft–20,000 ft	400 ft–14,000 ft×400 ft –14,000 ft	200 ft–20,000 ft×200 ft–20,000 ft	2,000 ft–20,000 ft×2,000 ft–24,000 ft	1 ft×40 ft	1,640 ft×1,640 ft	25 ft–1,000 ft×25 ft–1,000 ft

[1]Mossler (2008) renamed the Franconia Formation as the Tunnel City Group.
[2]Mossler (2008) renamed the Ironton and Galesville Sandstones as the Wonewoc Sandstone.

EXPLANATION

- [shaded box] **Simulation information**
- ft **Foot**
- ft² **Foot squared**
- mi² **Square mile**
- (1) **Simulation layer for each simulated hydrogeologic unit**

Figure 4. Chart detailing the study described in this report and selected regional studies in the Twin Cities Metropolitan Area (fig. 1) that used numerical simulation.

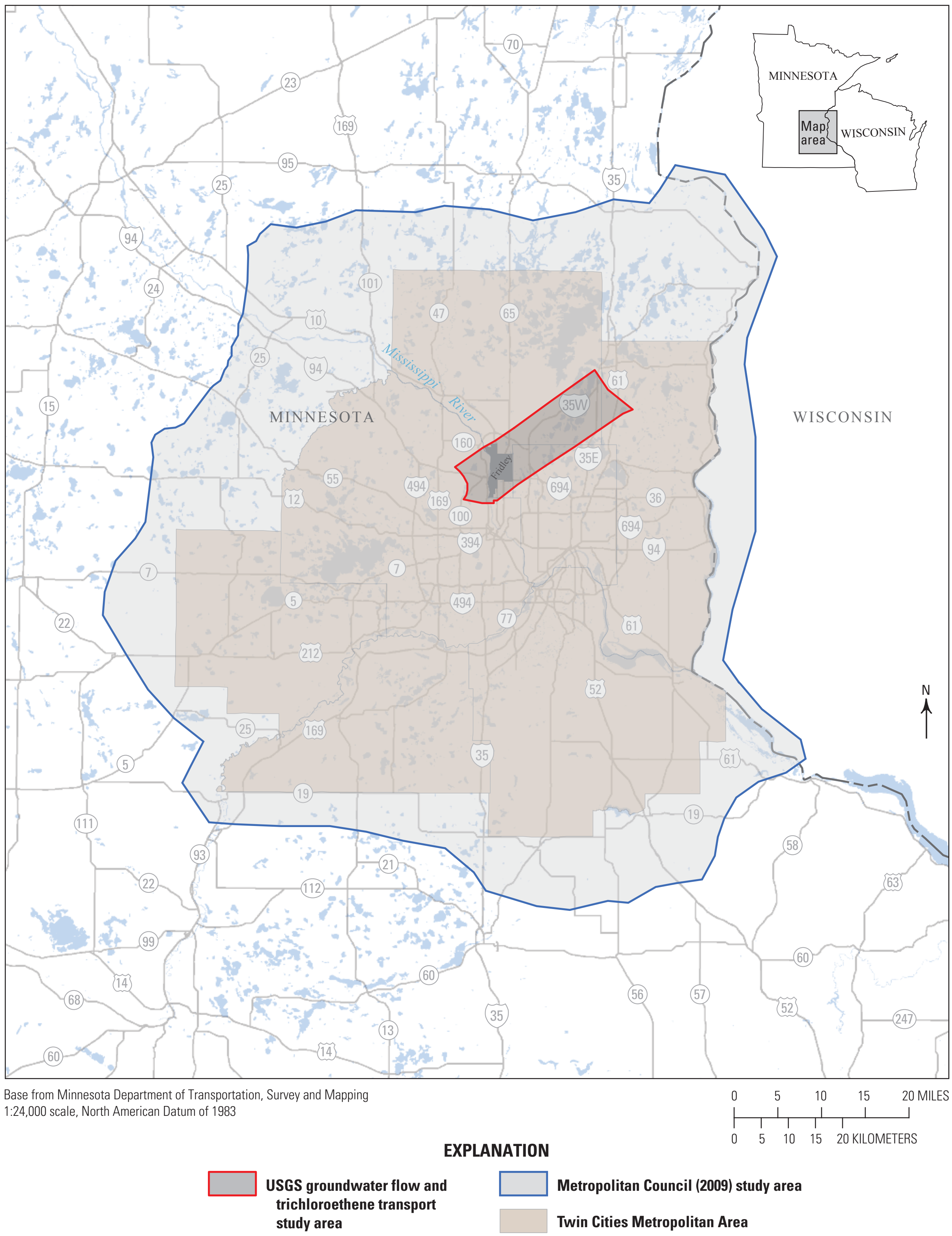


Figure 5. U.S. Geological Survey (USGS) study area, and Metropolitan Council (2009) study area, Minnesota and Wisconsin.

unit at the base of the surficial aquifer system might permit contaminant transport into underlying bedrock aquifers. In particular, Lindgren (1990) stated that near NIROP, unconfined and confined aquifers in the surficial aquifer system, Prairie du Chien aquifer, and Jordan aquifer were hydraulically connected.

Stark and Hult (1985) simulated groundwater flow in the Prairie du Chien and Jordan aquifers, and the transport of coal-tar derivatives from a coal-tar distillation and wood preserving plant in St. Louis Park, Minn. (not shown). The plant, which operated from 1918 to 1972, discharged coal tar into deep aquifers. Stark and Hult (1985) determined that wells open to more than one aquifer altered the potentiometric-head gradient in the Prairie du Chien and Jordan aquifers such that the direction of constituent transport might reverse with respect to constituent transport forced by unstressed potentiometric-head gradients.

Hydrogeologic Setting

Hydrogeologic features of the surficial aquifer system govern groundwater flow and TCE transport at NIROP. The surficial aquifer system at NIROP is underlain by the Cambrian-Ordovician aquifer system (Olcott, 1992) (fig. 6). The surficial and Cambrian-Ordovician aquifer systems are hydraulically connected at some locations.

A regional hydrogeologic system, or aquifer system, is a heterogeneous body composed of hydrogeologic units with a wide areal distribution (Poland and others, 1972; Renken, 1996). Aquifer systems include a minimum of two aquifers and bounding confining units. An aquifer contains saturated, permeable, geologic material that yields a useful quantity of water to a well or spring. Confining units are relatively less permeable than aquifers and impede the movement of water. Bear (1988) defined a confined aquifer as bound above and below by confining units; a confined aquifer is confined by a superjacent and a subjacent confining unit. Leaky aquifers exchange groundwater through semipervious confining units. Individual aquifers in an aquifer system are hydraulically connected, to some degree, by semipervious confining units; for example, in the Twin Cities Metropolitan Area, several aquifers discharge to and are connected by Quaternary glacial sediments that were deposited in glacial and fluvial valleys incised into Paleozoic bedrock (Runkel and others, 2003). The interconnected nature of aquifers within an aquifer system allows the aquifer system to be treated on a regional scale as a single flow system. Confining units can locally impede groundwater flow among aquifers in the aquifer system but do not undermine the regional, interconnected nature of the aquifer system.

In the Twin Cities Metropolitan Area, Schoenberg (1990) referred to the surficial and Cambrian-Ordovician aquifer systems together as the Twin Cities aquifer system (not shown); Schoenberg (1990) did not formally delineate a lateral extent of the Twin Cities aquifer system. Also in the Twin Cities Metropolitan Area, Metropolitan Council (2009) referred to the surficial and Cambrian-Ordovician aquifer systems together as the Twin Cities Metropolitan Area groundwater flow system. Metropolitan Council (2009) did not identify all hydrogeologic boundaries for the Twin Cities Metropolitan Area groundwater flow system.

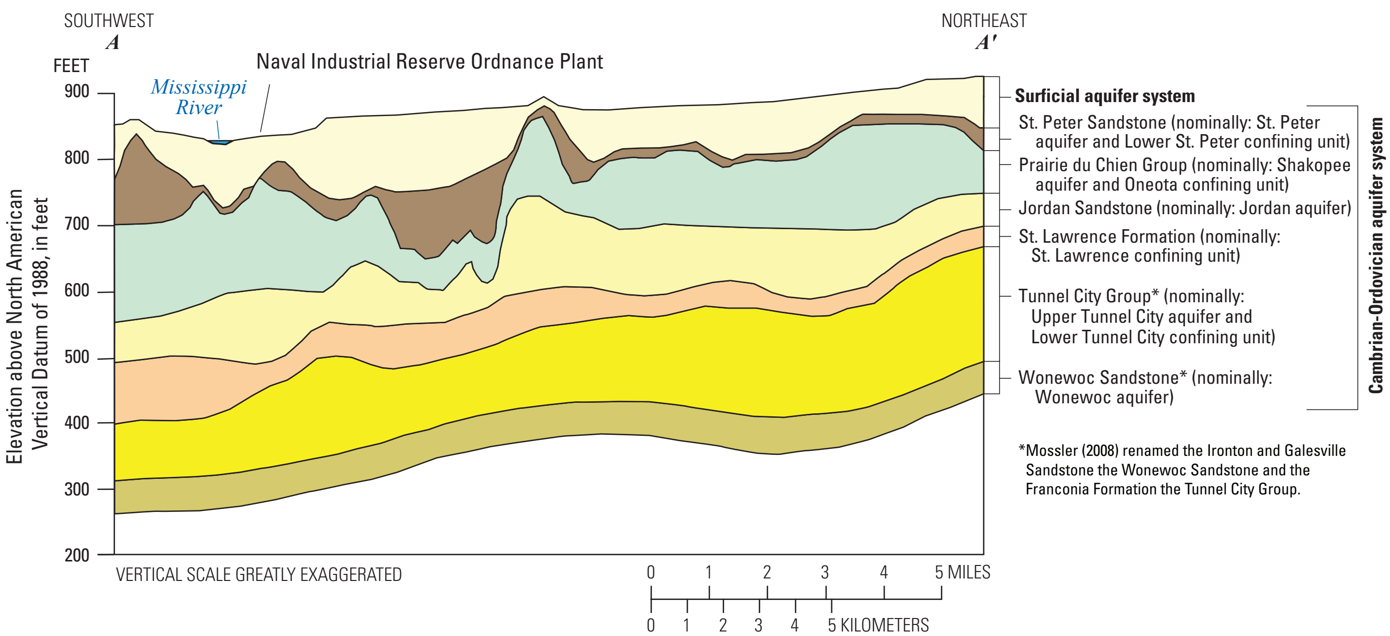


Figure 6. Hydrogeologic cross section *A–A′* near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota. Figure modified from digital elevation models in Metropolitan Council (2009) and Tipping and Mossler (1996). Line of section shown on figure 1.

Surficial Aquifer System

The surficial aquifer system is glacial and fluvial in origin (Schoenberg, 1994) and exists throughout the study area (Lindgren, 1990; Olcott, 1992). The surficial aquifer system consists of Quaternary glacial sediments: an unconsolidated, unsorted, unstratified mixture of fine-grained material, such as clay and silt, to coarser material, such as sand, gravel, and boulders. The surficial aquifer system ranges from 100 to 300 ft in thickness near NIROP (Schoenberg, 1990) and sits on a bedrock-surface elevation that ranges from 450 to 900 ft above the NAVD 88 (Metropolitan Council, 2009). Aquifer units consist of outwash and alluvium composed of sand and gravel, whereas confining units consist of glacial material and alluvium composed of silt and clay (Schoenberg, 1990). Clay and silt interbeds range to as much as 50 ft in thickness.

Near NIROP, Hobbs and Goebel (1982) mapped Des Moines lobe glacial deposits above Superior lobe glacial deposits on a pre-Wisconsin surface. Quaternary units were deposited in glacial and fluvial valleys incised into Paleozoic bedrock. The surficial aquifer system unconformably overlies the Cambrian-Ordovician aquifer system everywhere, except where the surficial aquifer system is completely incised by a fluvial system such as the St. Croix River valley (not shown).

The surficial aquifer system is unconfined to semiconfined. Near NIROP, the surficial aquifer system is underlain by either a lower confining unit of the surficial aquifer system or hydrogeologic units of the Cambrian-Ordovician aquifer system: the lower St. Peter confining unit or Shakopee aquifer (Lindgren, 1990; Runkel and others, 2003).

The surficial aquifer system is heterogeneous. Deposits of gravel, medium- to coarse-grained sand, and fine-grained sand form permeable flow zones that transmit groundwater. Interbedded, discontinuous deposits of clay, sandy clay, silty clay, and silt form confining units that impede the flow of groundwater. Horizontal hydraulic conductivity of transmissive surficial aquifer system media ranges from 10 to 650 ft/d; vertical hydraulic conductivity of these media ranges from 4×10^{-5} to 88 ft/d (table 1). Lindgren (1990) reported a value of 2.5×10^{-2} ft/d for vertical hydraulic conductivity for confining media at the base of the surficial aquifer system. Papadopulos and others (1984) and RMT (1987) estimated 0.5 to 320 ft/d surficial aquifer system hydraulic conductivity near NIROP.

The surficial aquifer system is recharged from land surface by the difference between infiltration and evapotranspiration. Delin and others (2007) stated that recharge from land surface varies seasonally in Minnesota based on climate, antecedent soil moisture, soil hydraulic properties, and depth to the potentiometric surface. Delin and others (2007) presented a statistical summary of total monthly recharge for Elk River near Big Lake, Minn. (not shown), about 30 mi northwest of NIROP, for 1940–79. Recharge was greatest in April and least in December, January, and February for Elk River. August was a less than average recharge month for Elk River. Delin and others (2007) stated that Elk River near Big Lake, Minn., is typical of monthly recharge variability throughout Minnesota.

The surficial aquifer system generally drains to the Mississippi, Minnesota (not shown), and St. Croix (not shown) Rivers. Where and when river stage is greater than aquifer potentiometric head, rivers recharge the surficial aquifer system. Potentiometric head fluctuations exist in the surficial aquifer system. Unstressed potentiometric head in the unconfined part of the surficial aquifer system is lowest in the winter when recharge waters are stored as snow at land surface and highest in the spring when snowmelt and spring rainfall recharge the aquifer (Delin and others, 2007). Potentiometric head declines during the summer when evapotranspiration exceeds precipitation (Lindgren, 1990).

Cambrian-Ordovician Aquifer System

The Cambrian-Ordovician aquifer system consists of a sequence of folded and faulted, mostly Paleozoic sandstones, dolomites, siltstones, shales, and conglomerates (figs. 4 and 6) deposited largely during marine transgression. The Cambrian-Ordovician aquifer system overlies the Hollandale embayment (not shown), which is the lowland of the Proterozoic crystalline basement that flanks the Wisconsin dome to the northeast (Olcott, 1992). Marine sediments were deposited on the Precambrian crystalline basement, forming stratiform geologic units that were subsequently deformed, reflecting the shape of the Hollandale embayment.

Olcott (1992) defined the Cambrian-Ordovician aquifer system in Minnesota using the following hydrogeologic units at NIROP: the St. Peter-Prairie du Chien-Jordan aquifer, St. Lawrence-Franconia confining unit, Ironton-Galesville aquifer, Eau Claire confining unit, and Mount Simon-Hinckley aquifer. Olcott's (1992) framework was regional, and relevant at a multistate scale that included Iowa (not shown), Michigan (not shown), Minnesota (fig. 5), and Wisconsin (fig. 5). Olcott (1992) combined hydrogeologic units that might be considered separate units at smaller scales.

In the Twin Cities Metropolitan Area, other investigators used frameworks of higher geologic and hydrogeologic resolution; for example, Runkel and others (2003) built a hydrogeologic framework for Paleozoic bedrock of southeastern Minnesota—including the Twin Cities Metropolitan Area—using the following units at or near NIROP: the St. Peter aquifer, lower St. Peter confining unit, Shakopee aquifer, Oneota confining unit, Jordan aquifer, St. Lawrence confining unit, upper Franconia aquifer, lower Franconia confining unit, Ironton-Galesville aquifer, Eau Claire confining unit, upper Mount Simon aquifer, middle Mount Simon confining unit, and lower Mount Simon aquifer. Olcott (1992) described the Cambrian-Ordovician aquifer system using three aquifers and two confining units; Runkel and others (2003) used seven aquifers and six confining units to define the same hydrogeologic section. The Shakopee aquifer and Oneota confining unit are components of the Prairie du Chien aquifer from Olcott's (1992) St. Peter-Prairie du Chien-Jordan aquifer.

Table 1. Hydraulic, well yield, and recharge properties of the surficial aquifer system and its lower confining unit, in the Twin Cities Metropolitan Area, Minnesota (fig. 1).

[ft/d, feet per day; ft²/d, square feet per day; anisotropy is a dimensionless ratio of horizontal (K_h) to vertical (K_v) hydraulic conductivity; specific yield and storage coefficient are dimensionless quantities; gal/min, gallons per minute; in/yr, inches per year; —, not provided in reference]

Hydrogeologic unit	Hydraulic properties: Hydraulic conductivity, Horizontal (ft/d)		Vertical (ft/d)		Transmissivity (ft²/d)	Anisotropy (K_h/K_v)	Specific yield
Mississippi River bed sediments	—	—	—	1.0×10^{0}	—	—	—
Unconfined aquifer	5.0×10^{1} –	2.0×10^{2}	—	—	—	—	2.5×10^{-1}
	5.0×10^{1} –	3.0×10^{2}	—	—	—	—	2.5×10^{-1}
	1.0×10^{1} –	2.0×10^{2}	4.0×10^{-4} –	2.0×10^{-2}	—	1.0×10^{5}	—
	2.3×10^{1} –	2.4×10^{2}	2.1×10^{1} –	8.8×10^{1}	—	—	—
Unconfined aquifer (unsorted glacial sediment)	—	—	6.7×10^{-4} –	1.8×10^{-1}	—	—	—
Unconfined aquifer (sand and gravel)	—	—	—	2.1×10^{0}	—	—	—
Undifferentiated aquifer	6.5×10^{1} –	1.4×10^{2}	—	—	—	—	—
Confining units	—	—	4.0×10^{-5} –	2.0×10^{-1}	—	—	—
	—	—	2.0×10^{-4} –	1.0×10^{-3}	—	—	—
Confined aquifer	6.0×10^{1} –	1.2×10^{2}	—	—	—	—	—
	—	4.0×10^{1}	—	—	—	—	—
Confined aquifer (intermediate flow zones)	—	—	—	—	9.0×10^{3}	—	—
Aquifer and basal confining unit	2.0×10^{-3} –	6.5×10^{2}	—	—	—	—	—
Lower confining unit	—	—	—	2.5×10^{-2}	—	—	—

Hydrogeologic unit	Hydraulic properties: Storage coefficient		Other properties: Well yield (gal/min)		Recharge (in/yr)		Source	Method
Mississippi River bed sediments	—	—	—	—	—	—	Lindgren (1990)	—
Unconfined aquifer	—	—	—	—	—	—	Helgesen and others (1973)	—
	—	—	—	—	5.3 –	7.0	Lindgren (1990)	—
	—	—	2.4×10^{2} –	2.4×10^{3}	—	—	Schoenberg (1990)	Numerical model
	—	—	—	—	—	—	Metropolitan Council (2009)	Numerical model
Unconfined aquifer (unsorted glacial sediment)	—	—	—	—	—	—	Larson-Higdem and others (1975) and Norvitch and others (1973)	—
Unconfined aquifer (sand and gravel)	—	—	—	—	—	—	Larson-Higdem and others (1975) and Norvitch and others (1973)	—
Undifferentiated aquifer	3.7×10^{-4} –	1.3×10^{-3}	—	—	—	—	Ranny Company (1978)	—
Confining units	—	—	—	—	—	—	Norris (1962) and Walton (1965)	—
	—	—	—	—	—	—	Lindgren (1990)	—
Confined aquifer	—	—	—	—	—	—	Ranny Compnay (1978)	—
	—	3.7×10^{-4}	—	—	2.6 –	5.7	Lindgren (1990)	—
Confined aquifer (intermediate flow zones)	—	—	—	—	—	—	Stark and Hult (1985)	—
Aquifer and basal confining unit	—	—	—	—	—	—	Helgesen (1977), Helgesen and Lindholm (1977), and Lindholm (1980)	—
Lower confining unit	—	—	—	—	—	—	Lindgren (1990)	—

Subsequent to Runkel and others (2003), Mossler (2008) renamed the Ironton and Galesville Sandstone as the Wonewoc Sandstone; Mossler (2008) also renamed the Franconia Formation as the Tunnel City Group. In conformance with Mossler's (2008) Paleozoic stratigraphic nomenclature for Minnesota, Runkel and others' (2003) Upper Franconia aquifer and Lower Franconia confining unit are referred to in this report as the upper Tunnel City aquifer and lower Tunnel City confining unit; and Runkel and others' (2003) Ironton-Galesville aquifer is referred to as the Wonewoc aquifer.

The principal hydrogeologic units of interest for this report, in the Cambrian-Ordovician aquifer system, included the Wonewoc aquifer and superjacent units of Runkel and others' (2003) framework, revised in conformance with Mossler (2008). Five aquifers (St. Peter, Shakopee, Jordan, upper Tunnel City, and Wonewoc) and four confining units (lower St. Peter, Oneota, St. Lawrence, and lower Tunnel City) between the surficial aquifer system and the Eau Claire confining unit were postulated to be a sufficient buffer to minimize the role of potentiometric-head gradients—between the surficial aquifer system and hydrogeologic units subjacent to the Eau Claire confining unit—on TCE transport at NIROP.

At some locations in the Twin Cities Metropolitan Area, the Ordovician-age St. Peter Sandstone is overlain by the Ordovician-age Glenwood Formation, Platteville Limestone, and Decorah Shale. Runkel and others (2003) designated a Decorah-Glenwood confining unit southwest of NIROP. The Glenwood Formation, Platteville Limestone, and Decorah Shale are not present in the NIROP study area where the St. Peter Sandstone is directly overlain by the surficial aquifer system.

St. Peter Aquifer and Lower St. Peter Confining Unit

The St. Peter aquifer and lower St. Peter confining unit are subjacent to the surficial aquifer system in parts of the NIROP study area. At locations in the NIROP study area where the St. Peter aquifer is absent and the lower St. Peter confining unit is present, the lower St. Peter confining unit impedes the exchange of groundwater between the underlying Shakopee aquifer and the overlying surficial aquifer system. The surficial aquifer system exchanges groundwater directly with the Shakopee aquifer where the St. Peter aquifer and lower St. Peter confining unit are not present (Lindgren, 1990).

The St. Peter aquifer is composed of the upper half of the Ordovician-age St. Peter Sandstone in the Twin Cities Metropolitan Area. The upper half of the St. Peter Sandstone is a well-sorted, friable, texturally homogeneous, coarse clastic rock with nonsystematic and systematic fractures, some dissolution enlargement, cavities, and enlarged bedding-plane fractures (Runkel and others, 2003). Systematic fractures are present in a shallow bedrock setting at depths less than 200 ft below land surface. Preferential-flow fractures in the St. Peter aquifer transmit groundwater and constituents at a faster rate than predicted using intergranular flow theory.

The lower St. Peter confining unit is generally composed of the lower half of the St. Peter Sandstone in the Twin Cities Metropolitan Area. The lower half of the St. Peter Sandstone contains laterally extensive fine clastic rock beds. Mossler (2008) identified the Pigs Eye Member of the St. Peter Sandstone as a marine sedimentary rock at the base of the St. Peter Sandstone in southeastern Minnesota, consisting of interbedded and poorly sorted siltstone, shale, and quartzose sandstone; and identified the St. Peter Sandstone contact with the subjacent Shakopee Formation as unconformable. The lower St. Peter confining unit includes the Pigs Eye Member. Runkel and others (2007) characterized fractured bedrock at a perfluorochemical contamination site near the Lake Elmo area (not shown) of Washington County, Minn. (fig. 1). Matrix properties and secondary pores of wells open to the lower St. Peter confining unit and the underlying Shakopee aquifer were described. The lower St. Peter confining unit and Shakopee aquifer were characterized as exhibiting strong vertical anisotropy with high hydraulic conductivity along bedding plane fracture networks separated by fine clastic or carbonate rock with low hydraulic conductivity perpendicular to bounding fracture networks.

In the study area, the St. Peter Sandstone is about 0 to 50 ft thick; the interface between the St. Peter Sandstone and the overlying surficial aquifer system is about 110 to 130 ft below land surface (figs. 7 and 8; appendix 1) (Tipping and Mossler, 1996; Runkel and Tipping, 2006; Davis, 2007; Minnesota Department of Health, 2008; Metropolitan Council, 2009). Along cross-section *A–A'* (figs. 1 and 6), the St. Peter Sandstone is about 0 to 140 ft thick; the interface between the St. Peter Sandstone and the overlying surficial aquifer system is about 10 to 130 ft below land surface (figs. 6–8). In the Twin Cities Metropolitan Area, the average thickness of the St. Peter Sandstone is about 150 ft and has a maximum thickness of about 190 ft to the north. The St. Peter Sandstone thins to the south. In a study area about 7,000 ft north of NIROP, Schoenberg (1994) described the lowermost part of the St. Peter Sandstone as a unit about 10 to 30 ft thick that consists of sand from the overlying St. Peter Sandstone, and gravel and cobble clasts from the underlying Shakopee Formation.

Horizontal hydraulic conductivity of the St. Peter Sandstone ranges from 1 to 50 ft/d (Norvitch and other, 1973; Barr Engineering, 1976, 1986; Norvitch and Walton, 1979; Woodward, 1986; Kempton and others, 1987; Nicholas and others, 1987; Curry and others, 1988; Graese and others, 1988; Lindgren, 1990; Schoenberg, 1990; Young, 1992; Runkel and others, 2003); vertical hydraulic conductivity ranges from 2×10^{-3} to 17 ft/d (Metropolitan Council, 2009). Runkel and others (2003) reported 38.7 ft/d average hydraulic conductivity; hydraulic conductivity ranged from less than 10 to greater than 250 ft/d for 853 specific capacity tests at depths less than 200 ft below land surface. Tests were documented in the Minnesota County Well Index (Minnesota Department of Health, 2008) for St. Peter Sandstone in southeastern Minnesota. Runkel and others (2003) did not explicitly differentiate specific capacity tests of the St. Peter aquifer from tests that also sampled all or parts of the lower St. Peter confining unit.

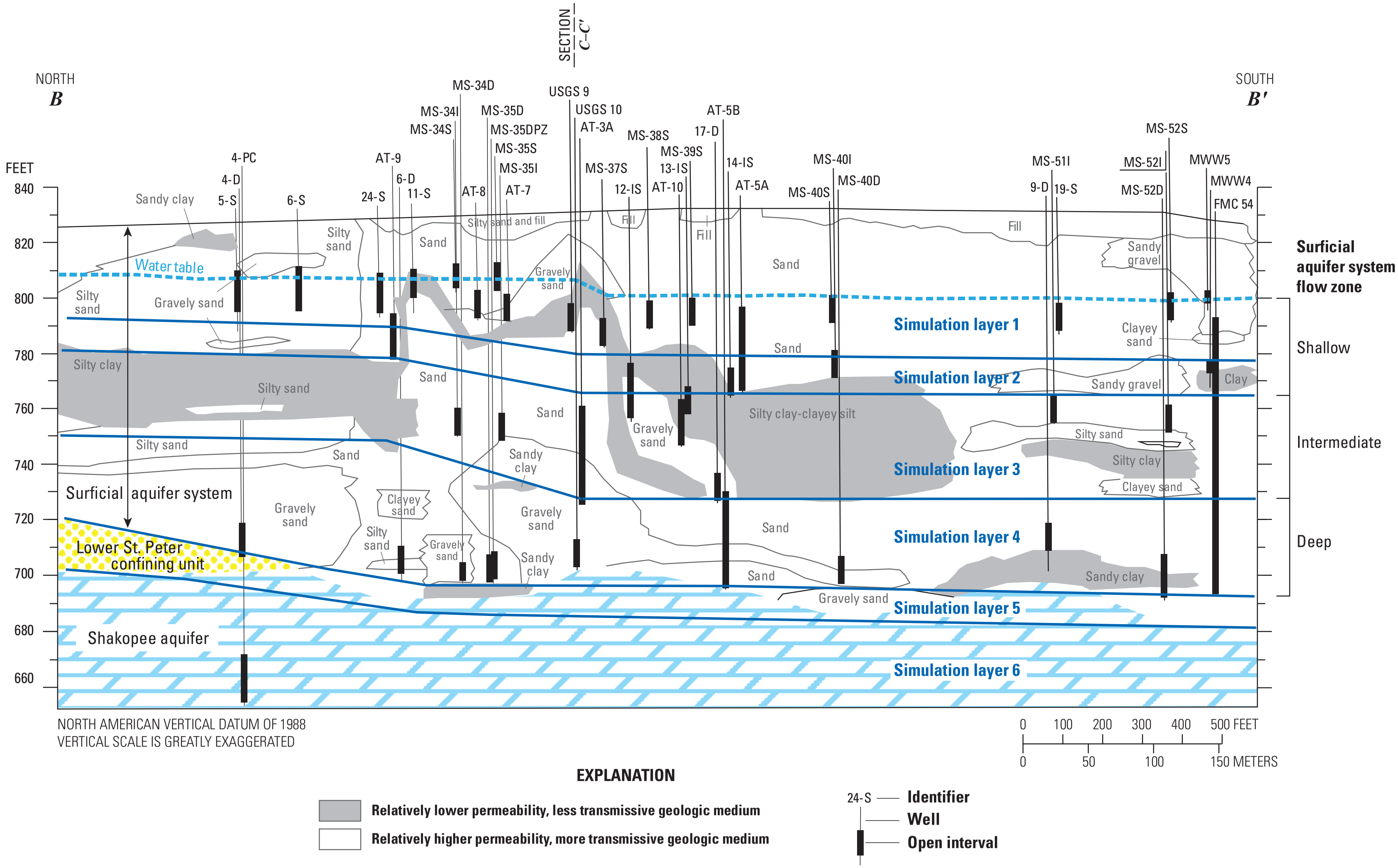


Figure 7. Hydrogeologic cross section *B–B′*, model simulation layers, flow zones, and wells, near the Naval Industrial Ordnance Plant, Fridley, Minnesota. Line of section shown on figure 3.

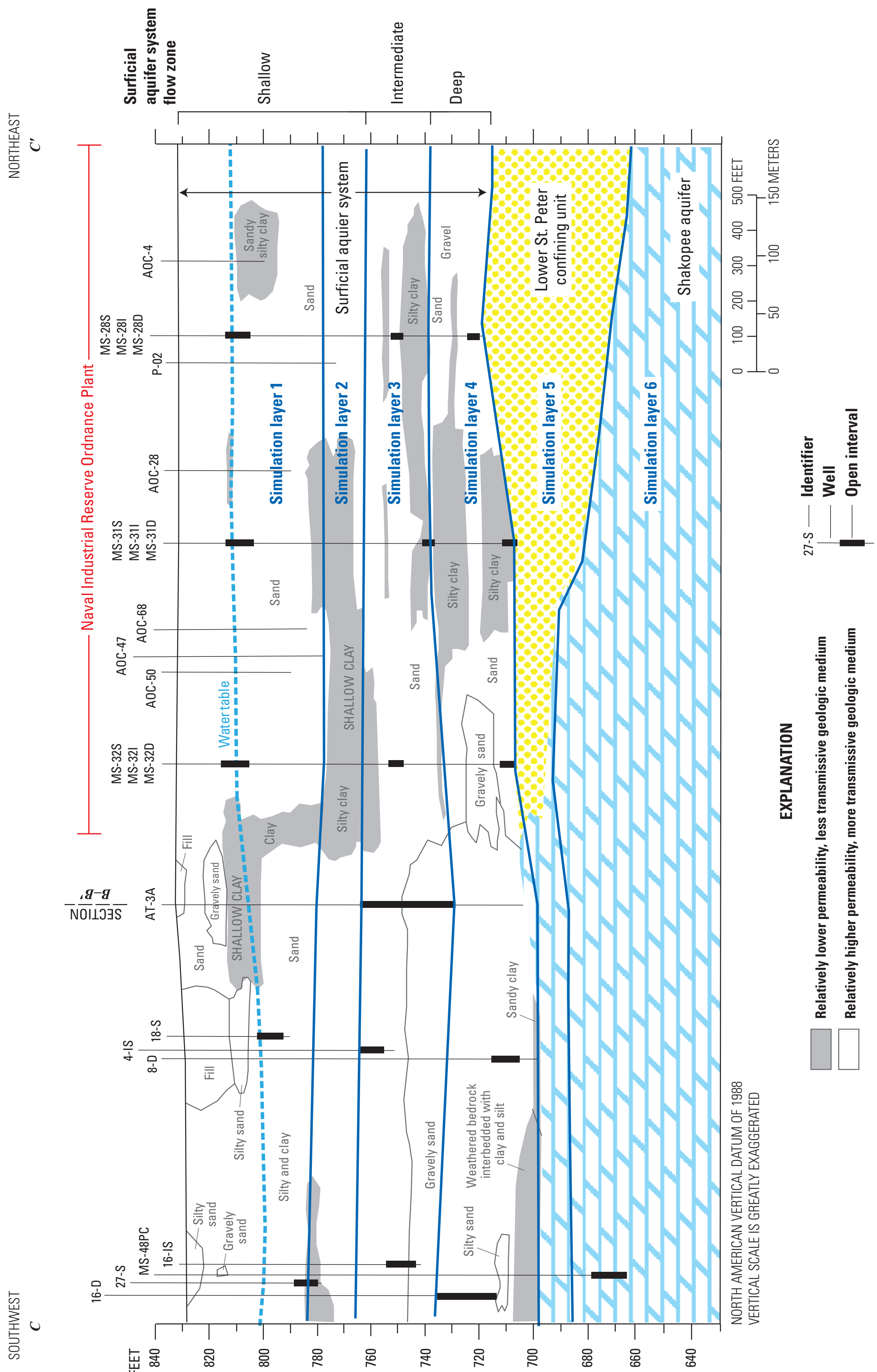


Figure 8. Hydrogeologic cross section *C–C′*, model simulation layers, flow zones, and wells, through the Naval Industrial Ordnance Plant, Fridley, Minnesota. Line of section shown on figure 3.

Vertical hydraulic conductivity of the lower St. Peter confining unit ranges from 10^{-5} to 10^{-3} ft/d (Norvitch and others, 1973; Larson-Higdem and others, 1975; Lindgren, 1990; Schoenberg, 1990, 1994). Some investigators referred to the lower St. Peter confining unit as the Basal St. Peter confining unit (Lindgren, 1990). The lower St. Peter confining unit, where present, is less permeable and less conductive to groundwater flow than the overlying surficial aquifer system and underlying Shakopee aquifer.

Shakopee Aquifer, Oneota Confining Unit, and Jordan Aquifer

The Shakopee aquifer is subjacent to the lower St. Peter confining unit where the lower St. Peter confining unit is present. Where the lower St. Peter confining unit is absent, the Shakopee aquifer is subjacent to either the St. Peter aquifer or the surficial aquifer system. The Shakopee aquifer is roughly composed of the Ordovician-age Shakopee Formation and the upper one-third of the Ordovician-age Oneota Dolomite (Runkel and others, 2003). The Shakopee Formation consists of dolostone, sandy dolostone, and sandstone (Mossler, 2008). The Shakopee aquifer is a karstic, carbonate, rock aquifer with a relatively low matrix porosity of less than 10 percent; and a network of dissolution cavities, dissolution-enlarged horizontal and vertical fractures, conduits, fractures, open joints, and solution channels (Stark and Hult, 1985; Schoenberg, 1990; Runkel and others, 2003; Tipping and others, 2006). The Shakopee aquifer is more conductive to groundwater flow than the underlying Oneota confining unit. The Shakopee Formation is about 80 to 100 ft thick in the Twin Cities Metropolitan Area (Mossler, 2008).

The Shakopee aquifer is recharged primarily by groundwater leakage from overlying units. Larson-Higdem and others (1975) estimated 5.6 in/yr leakage to an unstressed Shakopee aquifer. The Shakopee aquifer discharges at some locations to the Mississippi, Minnesota, and St. Croix Rivers, commonly through direct connections to the surficial aquifer system. The Shakopee aquifer feathers out to the north and west; the aquifer thins to a narrow edge under Rice Creek, which is to the north and northeast of NIROP (Schoenberg, 1990). Where the Shakopee aquifer is intersected by rivers in the east, the aquifer is directly overlain by glacial and fluvial deposits of the surficial aquifer system. The highest potentiometric head in the Shakopee aquifer generally coincides with the highest topographic elevation. Groundwater flow divides in the Shakopee aquifer generally coincide with surface drainage divides.

The Oneota confining unit is subjacent to the Shakopee aquifer. The Oneota confining unit is roughly composed of the bottom two-thirds of the Oneota Dolomite (Runkel and others, 2003). The Oneota Dolomite is about 50 ft thick in the Twin Cities Metropolitan Area; disconformably underlies the Shakopee Formation; unconformably overlies the Jordan Sandstone; and contains dolostone, sandstone, and shale (Mossler, 2008). The subjacent Jordan Sandstone is divided into coarse clastic rock and fine clastic rock components. The Jordan aquifer is composed of a coarse clastic rock component. Where a fine clastic rock component is present at the top of the Jordan Sandstone, this component is a lower part of the Oneota confining unit (Runkel and others, 2003).

The Oneota confining unit is less conductive to groundwater flow than the overlying Shakopee aquifer and the underlying Jordan aquifer (Tipping and others, 2006). Discrete beds with a relatively high secondary porosity and horizontal hydraulic conductivity are present at some locations in the Oneota confining unit; however, vertical hydraulic conductivity is sufficient at these locations to maintain confinement. A regional system of dissolution features and fractures that transmit groundwater vertically is not present in the Oneota confining unit.

In defining a Paleozoic stratigraphic nomenclature for Minnesota, Mossler (2008) separated the Ordovician-age Prairie du Chien Group into two separate geologic units: the Oneota Dolomite and the overlying Shakopee Formation. Previous investigators published extensive geologic and hydrogeologic studies of the Prairie du Chien Group and Prairie du Chien aquifer; for example, to address water supply issues in the Twin City Metropolitan Area, the Metropolitan Council (2009) designated the Prairie du Chien aquifer in place of Runkel and others' (2003) designation of the Shakopee aquifer and Oneota confining unit.

In the study area, the Prairie du Chien Group is about 140 ft thick; the interface between the Prairie du Chien Group and either the overlying St. Peter Sandstone or surficial aquifer system is about 120 to 150 ft below land surface (figs. 6–8; appendix 1) (Tipping and Mossler, 1996; Runkel and Tipping, 2006; Davis, 2007; Minnesota Department of Health, 2008; Metropolitan Council, 2009). Along cross-section *A–A'* (figs. 1, 6), the Prairie du Chien Group is about 40 to 150 ft thick; the interface between the Prairie du Chien Group and the overlying St. Peter Sandstone is about 20 to 200 ft below land surface (fig. 6).

Although Runkel and others (2003) divided the Prairie du Chien aquifer into the Shakopee aquifer and Oneota confining unit, hydraulic conductivity for each unit was not reported: a combined, hydraulic conductivity for the Prairie du Chien aquifer was reported that ranged from an order-of-magnitude 10^0 to greater than an order-of-magnitude 10^3 ft/d and had an average of 60.8 ft/d based on 2,195 specific capacity tests completed at depths less than 200 ft below land surface. At depths greater than 200 ft below land surface, the order of magnitude of hydraulic conductivity ranged from 10^0 to greater than 10^3 ft/d and had an average of 33.5 ft/d based on 448 specific capacity tests. Capacity tests were documented in the Minnesota County Well Index for the Prairie du Chien Group in southeastern Minnesota. Other investigators reported that horizontal hydraulic conductivity in the Shakopee aquifer ranged from 0.1 to 164 ft/d (Norvitch and others, 1973; Larson-Higdem and others, 1975; Camp, Dresser, and McKee, 1991; Runkel, 1999; Runkel and others, 2003; Metropolitan Council, 2009). Camp, Dresser, and McKee (1991) estimated 1.75 ft/d vertical hydraulic conductivity in the Shakopee aquifer and an upper part of the Oneota confining unit. Hydraulic conductivity is larger in shallow bedrock than in deep bedrock because more fractures generally exist in shallow bedrock than in deep bedrock, and fractures commonly transmit groundwater.

The Jordan aquifer is subjacent to the Oneota confining unit. The Jordan aquifer is composed of a coarse clastic rock component of the Cambrian-age Jordan Sandstone. In the study area, the Jordan Sandstone is about 100 ft thick; the interface between the Jordan Sandstone and the overlying Oneota Dolomite is about 230 ft below land surface (fig. 6; appendix 1) (Tipping and Mossler, 1996; Runkel and Tipping, 2006; Minnesota Department of Health, 2008; Metropolitan Council, 2009). Along cross-section *A–A'* (figs. 1, 6), the Jordan Sandstone is about 30 to 140 ft thick; the interface between the Jordan Sandstone and the overlying Oneota Dolomite is about 150 to 290 ft below land surface (fig. 6).

A fine clastic rock component in the Jordan Sandstone is not considered part of the Jordan aquifer where the component abuts the superjacent Oneota confining unit or subjacent St. Lawrence confining unit (Runkel and others, 2003). The coarse clastic rock component is primarily moderately sorted to well-sorted quartzose sandstone (Mossler, 2008). Vertically oriented, systematic fractures are present in the Jordan aquifer in deep bedrock greater than 200 ft below land surface. In shallow bedrock, less than 200 ft below land surface, fractures range from small, irregular, and closed, to vertically oriented joints. A large percentage of groundwater yields to wells in the Jordan aquifer are through fractures. Runkel and others (2003) reported a combined hydraulic conductivity in the Jordan Sandstone that ranged from less than 1 to greater than 250 ft/d and had an average of 43.2 ft/d for 851 specific capacity tests completed at depths less than 200 ft below land surface. At depths greater than 200 ft below land surface, hydraulic conductivity ranged from less than 1 to greater than 250 ft/d and had an average of 17.4 ft/d for 702 specific capacity tests. Tests were documented in the Minnesota County Well Index for Jordan Sandstone in southeastern Minnesota. Other investigators quantified horizontal hydraulic conductivity in the Jordan aquifer as ranging from 0.1 to greater than 500 ft/d (Meyer, 1933; Norvitch and others, 1973; Larson-Higdem and others, 1975; Woodward, 1986; Young, 1992; Runkel, 1999; and Runkel and others, 2003).

Permeability in the loosely cemented, medium- to coarse-grained Jordan aquifer is due to intergranular porosity (Stark and Hult, 1985; Schoenberg, 1990). Schoenberg (1990) added that Jordan aquifer permeability might also be due to joint partings in cemented areas. Porous media of the Jordan aquifer provides more surface area for contaminant adsorption than the Shakopee aquifer, and therefore causes contaminants to be transported less rapidly in the Jordan aquifer than in the Shakopee aquifer (Stark and Hult, 1985).

The Jordan aquifer discharges at some locations to the Mississippi, Minnesota, and St. Croix Rivers, commonly through direct connections to the surficial aquifer system. The Jordan aquifer feathers out to the north and west (Schoenberg, 1990). Generally, the local low in the potentiometric surface of the Jordan aquifer is aligned with the Mississippi River.

The Shakopee and Jordan aquifers are regionally distinct aquifers (Runkel and others, 2003). Previous investigators combined the Shakopee aquifer and Oneota confining unit into the Prairie du Chien aquifer (Setterholm and others, 1991; Wall and Regan, 1994; Runkel and others, 2003; Runkel, 1999; Metropolitan Council, 2009); combined the Prairie du Chien aquifer with the Jordan aquifer to form the Prairie du Chien-Jordan aquifer (Guswa and others, 1982; Stark and Hult, 1985; Lindgren, 1990; Schoenberg, 1990, 1994); and combined the Prairie du Chien-Jordan aquifer with the St. Peter aquifer and lower St. Peter confining unit to form the St. Peter-Prairie du Chien-Jordan aquifer (Olcott, 1992; Delin and Almendinger, 1993).

An efficient hydraulic connection exists at some locations between the Shakopee and Jordan aquifers (Lindgren, 1990). The Shakopee and Jordan aquifers were the most extensively used aquifers in the Cambrian-Ordovician aquifer system (Metropolitan Council, 2009). Production wells were generally open to both aquifers. Stark and Hult (1985) reported that high capacity wells open to the Shakopee aquifer, Oneota confining unit, and Jordan aquifer yield more than 1,000 gallons per minute (gal/min); Schoenberg (1990) reported well yields of 80 to 2,765 gal/min. The Shakopee and Jordan aquifers together supplied about 80 percent of the produced groundwater in the Twin Cities Metropolitan Area from 1961 to 1979 (Horn, 1983). Groundwater withdrawal is seasonal, and summer withdrawal rates are about twice the withdrawal rates in other seasons.

St. Lawrence Confining Unit, Upper Tunnel City Aquifer, Lower Tunnel City Confining Unit, and Wonewoc Aquifer

The St. Lawrence confining unit is subjacent to the Jordan aquifer. The St. Lawrence confining unit is composed of the Cambrian-age St. Lawrence Formation and lower parts of the Jordan Sandstone (Runkel and others, 2003). The Jordan Sandstone is divided into coarse clastic rock and fine clastic rock components; the Jordan aquifer is composed of a coarse clastic rock component, therefore, the fine clastic rock component of the Jordan Sandstone is not considered part of the Jordan aquifer. Where a fine clastic rock component is present at the base of the Jordan Sandstone, this component forms the upper part of the St. Lawrence confining unit. The St. Lawrence Formation conformably underlines the Jordan Sandstone (Mossler, 2008).

The St. Lawrence Formation consists of interbedded carbonate and fine clastic rock components. The carbonate component is more common and tends to be present in the lower part of the St. Lawrence Formation. In deep bedrock at depths greater than 200 ft below land surface, the St. Lawrence Formation includes secondary pores in discrete intervals (Runkel and others, 2006a, 2006b) and dissolution cavities in the direction parallel to bedding. Vertical conductivities are orders of magnitude less than horizontal conductivities in parts of individual shale beds of the St. Lawrence Formation. Discrete intervals of the St. Lawrence confining unit can yield economic quantities of water and locally act as an aquifer, particularly along contact strata between the St. Lawrence confining unit and the underlying upper Tunnel City aquifer. Differential static potentiometric-head measurements at the University of Minnesota Aquifer Thermal Energy Storage field-test facility (not shown) in St. Paul, Minn., confirmed that the St. Lawrence confining unit effectively confines subjacent permeable units (Runkel and others, 2003).

In the study area, the St. Lawrence Formation is about 40 ft thick; the interface between the St. Lawrence Formation and the overlying Jordan Sandstone is about 340 ft below land surface (fig. 6; appendix 1) (Tipping and Mossler, 1996; Runkel and Tipping, 2006; Minnesota Department of Health, 2008; Metropolitan Council, 2009). Along cross-section *A–A'* (figs. 1, 6), the St. Lawrence Formation is about 30 to 90 ft thick; the interface between the St. Lawrence Formation and the overlying Jordan Sandstone is about 220 to 350 ft below land surface (fig. 6).

Runkel and others (2003) reported 10^{-5} to 10^{-4} ft/d bulk vertical hydraulic conductivity in the St. Lawrence Formation in deep bedrock at depths greater than 200 ft below land surface where an average of 14 ft/d hydraulic conductivity was reported for 25 specific capacity tests. Tests were documented in the Minnesota County Well Index for the St. Lawrence Formation in southeastern Minnesota. Miller and Delin (1993) estimated 10^{-2} ft/d horizontal and 10^{-4} ft/d vertical hydraulic conductivity in a fine clastic component of a lower part of the Jordan Sandstone using discrete interval packer tests at the Aquifer Thermal Energy Storage field-test facility about 6 mi southeast of NIROP. Young (1992) estimated from 9.3 to 20 ft/d horizontal hydraulic conductivity using packer tests in the St. Lawrence Formation in Wisconsin. Miller and Delin (1993) also estimated horizontal hydraulic conductivity that ranged from 10^{-2} to 6.7 ft/d in the St. Lawrence Formation using discrete interval packer tests at the field-test facility. Runkel and others (2003) reported 10^{-4} ft/d vertical hydraulic conductivity from an unpublished test in Ramsey County, Minn. (fig. 1).

The upper Tunnel City aquifer and lower Tunnel City confining unit are subjacent to the St. Lawrence confining unit. The upper Tunnel City aquifer and lower Tunnel City confining unit are composed of the Cambrian-age Tunnel City Group, which consists of sandstone and shale. Locally, an upper part of the upper Tunnel City aquifer can also include lower, fractured parts of the St. Lawrence Formation (Runkel and others, 2003). Mossler (2008) renamed the Franconia Formation as the Tunnel City Group. The Mazomanie Member of the Tunnel City Group is a coarse, clastic component of the Tunnel City Group and highly conductive to groundwater flow. Bedding-plane fractures in the upper Tunnel City aquifer are hydraulically active. Walton and others (1991) confirmed using differential static potentiometric-head measurements that the lower Tunnel City confining unit separates the Mazomanie Member from subjacent transmissive units at the Aquifer Thermal Energy Storage field-test facility (Miller and Delin, 1993).

Runkel and others (2006c) characterized intergranular and secondary porosity in the Tunnel City Group and Wonewoc Sandstone. According to Runkel and others (2006c), lithostratigraphic and hydrogeologic interfaces are not coincident everywhere, and intergranular groundwater flow does not contribute more to total groundwater flow than fracture flow.

In the study area, the Tunnel City Group is about 110 ft thick, and the interface between the Tunnel City Group and the overlying St. Lawrence Formation is about 380 ft below land surface (fig. 6; appendix 1) (Runkel and Tipping, 2006; Minnesota Department of Health, 2008; Metropolitan Council, 2009). Along cross-section *A–A'* (figs. 1, 6), the Tunnel City Group is about 90 to 170 ft thick, and the interface between the Tunnel City Group and the overlying St. Lawrence Formation is about 250 to 450 ft below land surface (fig. 6).

Runkel and others (2003) reported 27.8 ft/d average hydraulic conductivity with a range from less than 10 to 180 ft/d for 68 specific capacity tests completed at depths greater than 200 ft below land surface. Tests were documented in the Minnesota County Well Index for the Tunnel City Group in southeastern Minnesota. Runkel and others (2003) did not distinguish between the upper Tunnel City aquifer and the lower Tunnel City confining unit. Miller and Delin (1993) estimated horizontal hydraulic conductivity that ranged from 1.4 to 7.5 ft/d and vertical hydraulic conductivity that ranged from 0.14 to 0.75 ft/d in the upper Tunnel City aquifer using discrete interval packer tests at the Aquifer Thermal Energy Storage field-test facility. Miller and Delin (1993) also estimated horizontal hydraulic conductivity less than 10^{-2} ft/d and vertical hydraulic conductivity less than 10^{-4} ft/d in the lower Tunnel City confining unit.

The Wonewoc aquifer is subjacent to the lower Tunnel City confining unit. The Wonewoc aquifer is composed of the Cambrian-age Wonewoc Sandstone. Mossler (2008) renamed the Ironton and Galesville Sandstones as the Wonewoc Sandstone. Runkel and others (2003) divided the Wonewoc Sandstone into two parts: an upper part composed of a shaly, fine- to coarse-grained, poorly sorted sandstone; and a lower part composed of a clean, fine- to medium-grained sandstone.

In the study area, the Wonewoc Sandstone is about 50 ft thick, and the interface between the Wonewoc Sandstone and the overlying Tunnel City Group is about 490 ft below land surface (fig. 6; appendix 1) (Runkel and others, 2003; Runkel and Tipping, 2006; Minnesota Department of Health, 2008; Metropolitan Council, 2009). Along cross-section *A–A'* (figs. 1, 6), the Wonewoc Sandstone is about 50 ft thick, and the interface between the Wonewoc Sandstone and the overlying Tunnel City Group is about 420 to 520 ft below land surface (fig. 6).

Runkel and others (2003) reported 10.8 ft/d average hydraulic conductivity in the Wonewoc Sandstone, with a range from less than 1.5 to 28 ft/d for 26 specific capacity tests completed at depths greater than 200 ft below land surface. Tests were documented in the Minnesota County Well Index for the Wonewoc Sandstone in southeastern Minnesota. The Minnesota County Well Index did not distinguish between the upper and lower parts of the Wonewoc Sandstone. Other investigators estimated horizontal hydraulic conductivity that ranged from 3 to 31 ft/d in the Wonewoc Sandstone (Eder and Associates, 1997; Young, 1992; Runkel and others, 2003); these investigators also did not distinguish between the upper and lower parts of the Wonewoc Sandstone. Miller and Delin (1993) estimated 5 ft/d horizontal and 0.5 ft/d vertical hydraulic conductivities in the upper part of the Wonewoc Sandstone using discrete interval packer tests at the Aquifer Thermal Energy Storage field-test facility. Miller and Delin (1993) also estimated horizontal hydraulic conductivity that ranged from 1.6 to 7.9 ft/d and vertical hydraulic conductivity that ranged from 0.16 to 0.79 ft/d in the lower part using discrete interval packer tests at the field-test facility.

Subjacent Units

The Eau Claire confining unit, upper Mount Simon aquifer, middle Mount Simon confining unit, and lower Mount Simon aquifer are subjacent to the Wonewoc aquifer. The Eau Claire confining unit and units between the surficial aquifer system and Eau Claire Sandstone were postulated to buffer TCE transport in the surficial aquifer system at NIROP from forcing in the upper Mount Simon aquifer.

The Eau Claire confining unit is subjacent to the Wonewoc aquifer. The Eau Claire confining unit is composed of the Cambrian-age Eau Claire Sandstone. Runkel and others (2003) reported that 335 wells in the Minnesota County Well Index withdraw groundwater from fracture networks in the Eau Claire Sandstone in a northern part of the Twin Cities Metropolitan Area, and they concluded that the effectiveness of the Eau Claire Sandstone as a confining unit in such a setting requires further investigation. Miller and Delin (1993) estimated 10^{-2} ft/d horizontal and 10^{-4} ft/d vertical hydraulic conductivities in the Eau Claire Sandstone using discrete interval packer tests at the Aquifer Thermal Energy Storage field-test facility. Bradbury (2001) estimated horizontal hydraulic conductivity in the Eau Claire Sandstone that ranged from 10^{-3} to 10^{-2} ft/d using discrete interval slug tests in Wisconsin.

In the study area, the Eau Clair Sandstone is about 90 ft thick, and the interface between the Eau Clair Sandstone and the overlying Wonewoc Sandstone is about 540 ft below land surface (fig. 6; appendix 1) (Runkel and others, 2003; Runkel and Tipping, 2006; Minnesota Department of Health, 2008; Metropolitan Council, 2009). Along cross-section *A–A'* (figs. 1, 6), the Eau Clair Sandstone is about 50 to 90 ft thick, and the interface between the Wonewoc Sandstone and the overlying Tunnel City Group is about 470 to 490 ft below land surface (fig. 6).

In a hydrogeologic framework for Paleozoic bedrock of southeastern Minnesota, Runkel and others (2003) divided the Cambrian-age Mount Simon Sandstone into the upper Mount Simon aquifer, middle Mount Simon confining unit, and lower Mount Simon aquifer. The upper Mount Simon aquifer is subjacent to the Eau Claire confining unit. The Mount Simon Sandstone is fine- to coarse-grained, quartzose sandstone with thin beds of siltstone, shale, and very-fine-grained sandstone. In the Mount Simon Sandstone, coarse and fine clastic components transmit and vertically confine groundwater, respectively. The Mount Simon Sandstone is a primary aquifer in the Twin Cities Metropolitan Area with an effective porosity of about 0.2.

In the study area, the Mount Simon Sandstone is about 150 ft thick, and the interface between the Mount Simon Sandstone and the overlying Eau Clair Sandstone is about 620 ft below land surface (fig. 6; appendix 1) (Runkel and others, 2003; Runkel and Tipping, 2006; Minnesota Department of Health, 2008; Metropolitan Council, 2009). Along cross-section *A–A'* (figs. 1, 6), the Mount Simon Sandstone is about 110 to 180 ft thick, and the interface between the Mount Simon Sandstone and the overlying Eau Clair Sandstone is about 550 to 660 ft below land surface (fig. 6).

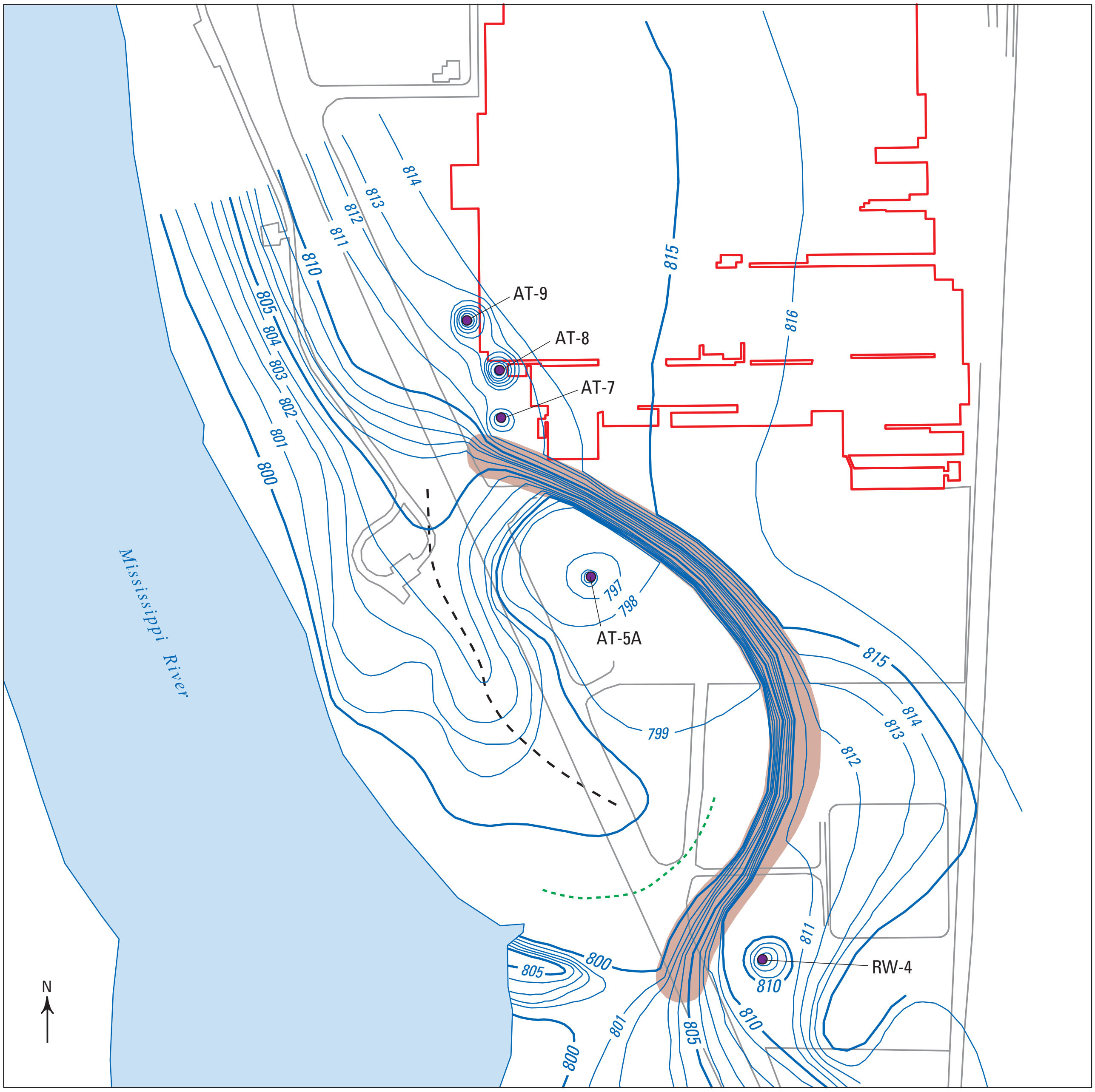
Combined horizontal hydraulic conductivity ranged from 0.38 to 21 ft/d where hydrogeologic components of the Mount Simon Sandstone were treated as one unit (Young, 1992; Carlson and Taylor, 1999; Runkel and others, 2003). Runkel and others (2003) reported 39.5 ft/d average hydraulic conductivity, with a range from about 10 to greater than 200 ft/d for 25 specific capacity tests completed at depths greater than 200 ft below land surface. Tests were documented in the Minnesota County Well Index for the Mount Simon Sandstone in southeastern Minnesota. Runkel and others (2003) did not distinguish among the upper Mount Simon aquifer, middle Mount Simon confining unit, and lower Mount Simon aquifer with this combined hydraulic conductivity estimate. Using discrete interval packer tests in Illinois, Nicholas and others (1987) estimated 1.3 ft/d horizontal hydraulic conductivity in the equivalent of the upper Mount Simon aquifer and 1.5 ft/d in the equivalent of the lower Mount Simon aquifer. Miller and Delin (1993) estimated 10^{-2} ft/d horizontal and 10^{-4} ft/d vertical hydraulic conductivities in parts of the Paleozoic region similar to the middle Mount Simon confining unit based on discrete interval packer tests completed at the Aquifer Thermal Energy Storage field-test facility.

The Precambrian-age (Middle Proterozoic) Hinckley Sandstone of the Keweenawan Supergroup and Solor Church Formation of the Keweenawan Supergroup are at the base of the Cambrian-Ordovician aquifer system (Jones and others, 2013). The Hinckley Sandstone is quartz arenite of aeolian and lacustrine origin. The Solor Church Formation is shale, interbedded with feldspathic sandstone.

Hydrogeology of the Surficial Aquifer System at the Naval Industrial Reserve Ordnance Plant

The surficial aquifer system was the primary aquifer of interest with respect to TCE contamination and transport at NIROP (figs. 7 and 8). Most NIROP monitoring wells are screened in the surficial aquifer system. The Navy furnished Davis (2007) with a geologic conceptual model that divided the surficial aquifer system at NIROP into shallow, intermediate, and deep flow zones. In general, where the surficial aquifer system is not stressed by groundwater extraction, then potentiometric heads in all zones decrease toward the Mississippi River.

A crescent-shaped, clay ridge (fig. 9) governs groundwater flow and constituent transport for part of the shallow flow zone of the surficial aquifer system between



Base furnished by U.S. Department of the Navy
North American Datum of 1983

0 250 500 750 1,000 FEET
0 50 100 150 200 250 METERS

EXPLANATION

Clay ridge

800 **Potentiometric head**—Contoured from measured data. Contour interval 1 foot. Datum is North American Vertical Datum of 1988

Ridge of higher potentiometric head along central axis of lobe of higher potentiometric head

Centerline of saddle feature

Main Naval Industrial Reserve Ordnance Plant building

AT-9 **Extraction well and identifier**

Figure 9. Extraction wells, clay ridge, and potentiometric head in the shallow flow zone of the surficial aquifer system on August 20, 2001, at and near the Naval Industrial Ordnance Plant, Fridley, Minnesota.

NIROP and Mississippi River (AGVIQ-CH2MHill, 2013; Davis, 2007; Tetra Tech, 1999, 2002, 2013b). Davis (2007) measured potentiometric heads in 56 wells, and estimated that northeast of the ridge, the potentiometric-head gradient in the shallow flow zone was constant or gently decreased toward the ridge; southwest of the ridge, the potentiometric-head gradient in the shallow flow zone gently decreased toward the Mississippi River; and across the ridge, the potentiometric-head gradient in the shallow flow zone decreased steeply toward the west with potentiometric heads decreasing about 10 ft across the width of the ridge. Interpreted geologic cross sections built from information collected at soil borings ST–14, ST–15, and ST–16 (not shown), and at test trench TT–18 (not shown) indicate near-surface clays in the general vicinity of part of the crescent-shaped clay ridge through a depth that describes the upper flow zone of the surficial aquifer system (Braun Intertec, 2013a, 2013b, 2013c). Davis (2007, p. 19) stated that "[i]t 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." Potentiometric-head measurements indicated connectivity of the clay unit between logged wells (Davis, 2007).

A high-permeability paleo-channel in the intermediate flow zone of the surficial aquifer system at NIROP consists of sands and gravels (fig. 10) (Davis, 2007). The paleo-channel is a conduit for groundwater flow and contaminant transport from NIROP toward the Mississippi River. Abandoned extraction well AT–3A was open to the paleo-channel; new extraction wells AT–11, AT–12, and AT–13 (fig. 3) are also open to the paleo-channel.

Groundwater on the eastern side of the clay ridge in the shallow zone flows downward into deeper flow zones (figs. 7–11). Davis (2007) determined that shallow and intermediate clays forced a downward potentiometric-head gradient across the northern part of that study area where shallow, intermediate, and deep flow zones of the surficial aquifer system were not hydraulically connected; and that an upward gradient existed across the southern part of that study area where clays were not evident, and shallow, intermediate, and deep flow zones were hydraulically connected. Tetra Tech (2013b) suggested that the ridge was "likely an abandoned river channel filled with fine-grained sediments."

Groundwater also flows upward at NIROP. Lindgren (1990) reported that potentiometric head in well MWW–13 (fig. 3), screened 27 to 30 ft below land surface, was 2.5 to 3 ft lower than the potentiometric head in collocated well MWW–12 (fig. 3), screened 56 to 60 ft below land surface. This finding suggests that groundwater at 56 to 60 ft below land surface flows upward to 27 to 30 ft below land surface. The Mississippi River is a regional surface-water outfall for the Cambrian-Ordovician aquifer system. Groundwater flows from deeper zones toward the Mississippi River. Lindgren (1990) stated that vertical groundwater flow to the Mississippi River at NIROP was enhanced because "the present channel of the Mississippi River coincides with a buried pre-glacial valley."

A groundwater extraction and treatment system exists at NIROP. Groundwater extraction and treatment systems also exist on some other Fridley, Minn., properties (fig. 2) subject to EPA or State of Minnesota action for subsurface contamination with volatile organic compounds. Davis (2007) determined that (1) the NIROP groundwater extraction and treatment system removed TCE mass from the plume, and (2) the system did not prevent offsite migration of contaminated groundwater in 2001. Davis (2007) delineated contributing area for extraction wells AT–3A, AT–5A, AT–5B, AT–7, AT–8, AT–9, and AT–10 (fig. 3); and contoured TCE concentrations in shallow, intermediate, and deep flow zones of the surficial aquifer system.

Groundwater extraction and treatment systems in Fridley, Minn., induce recharge and alter the groundwater flow field in the surficial aquifer system east of the Mississippi River. Lindgren (1990) stated that "induced recharge caused by [groundwater] withdrawals results in the capture by wells of (1) surface water that would ordinarily flow out of the area during seasons of low pumpage, and (2) groundwater that, under unstressed conditions, would discharge to [surface water]."

Brief History of Subsurface Contamination at the Naval Industrial Reserve Ordnance Plant and Selected Reference to Other Subsurface Contamination in Fridley, Minnesota

In 1940, a private company began construction of a facility on the NIROP site, to produce industrial pump equipment (Minnesota Pollution Control Agency, 2015). The U.S. Government purchased the facility at the beginning of World War II, to produce naval guns. In 2004, the Navy sold the facility to a private company. Volatile organic compounds have been used in the facility, primarily as a degreaser for metal parts. Solvents and paint sludge were disposed in pits and trenches at NIROP, in the early 1970s. In December 1980, the Minnesota Pollution Control Agency received information concerning waste disposal practices at NIROP (U.S. Environmental Protection Agency, 1990 [record of decision]). Between March and April 1981, TCE concentrations in groundwater from wells 2 (fig. 2) and 3 (fig. 3) near NIROP were 35 and 200 micrograms per liter (µg/L), respectively. These concentrations were greater than the 5-µg/L EPA maximum contaminant level for TCE (U.S. Environmental Protection Agency, 2013). No known or anticipated adverse effects on human health exist below the maximum contaminant level (Toccalino and others, 2006). The maximum contaminant level is the greatest permissible level of a contaminant in water delivered to any user of a public water system. Maximum contaminant levels are legally enforceable standards (U.S. Environmental Protection Agency, 2015).

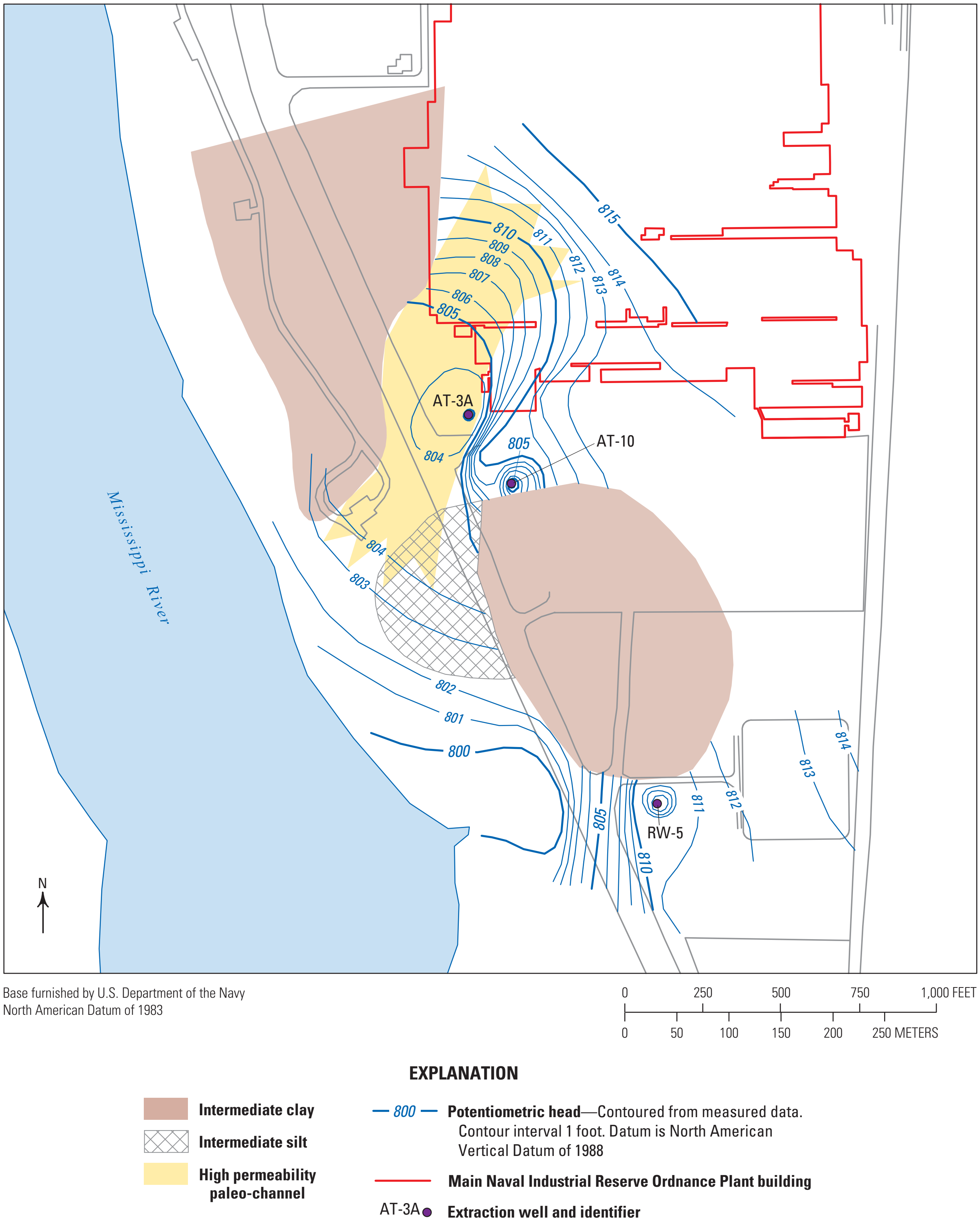
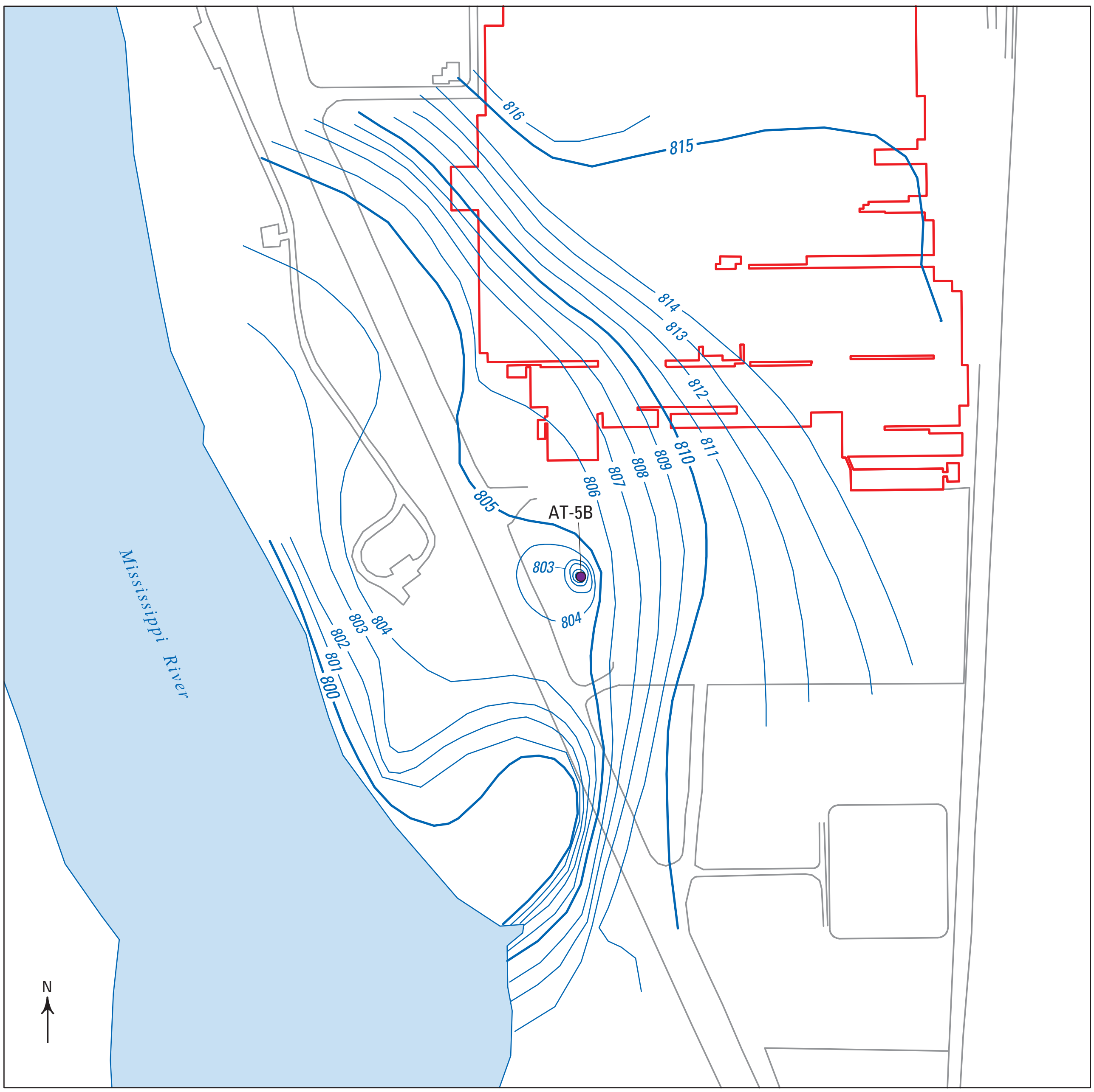


Figure 10. Extraction wells, intermediate clay and silt, a high permeability paleo-channel, and potentiometric head in the intermediate flow zone of the surficial aquifer system on August 20, 2001, at and near the Naval Industrial Ordnance Plant, Fridley, Minnesota.



Base furnished by U.S. Department of the Navy
North American Datum of 1983

0 250 500 750 1,000 FEET
0 50 100 150 200 250 METERS

EXPLANATION

800 — **Potentiometric head**—Contoured from measured data. Contour interval 1 foot. Datum is North American Vertical Datum of 1988

Main Naval Industrial Reserve Ordnance Plant building

AT-5B ● **Extraction well and identifier**

Figure 11. Extraction wells and potentiometric head in the deep flow zone of the surficial aquifer system on August 20, 2001, at and near the Naval Industrial Ordnance Plant, Fridley, Minnesota.

On December 31, 1981, the TCE concentration was 1.2 µg/L inside an intake pipe that supplies source water to the City of Minneapolis, Minn., drinking water treatment plant (U.S. Environmental Protection Agency, 1990 [record of decision], 2012b). The intake pipe withdraws water from the Mississippi River downstream from NIROP. Between 1981 and 1983, the Minnesota Pollution Control Agency detected TCE in 26 of 40 water samples collected from the intake pipe at concentrations that ranged from 0.2 to 1.7 µg/L (U.S. Environmental Protection Agency, 1987 [record of decision]). None of the intake-pipe samples exceeded the EPA maximum contaminant level for TCE.

Studies were completed to locate and remediate contaminated groundwater at NIROP; for example, in 1983 and 1984, the Navy excavated 43 drums and 1,200 cubic yards of soil at NIROP. Soil contained volatile organic compounds, polychlorinated biphenyls, oil and grease, pesticides, and metal-bearing wastes (U.S. Environmental Protection Agency, 2003 [record of decision]). Trichloroethene use was discontinued at NIROP by April 1, 1987 (U.S. Environmental Protection Agency, 1990 [record of decision]). A remedial investigation (RMT, 1987, 1988a) and feasibility study (RMT, 1988b, 1988c) indicated that groundwater and groundwater constituents at NIROP were transported to the Mississippi River. Lindgren (1990, p. 3) stated that the Mississippi River at the City of Minneapolis, Minn., drinking water treatment plant was “vulnerable to adverse changes in water quality caused by dissolved contaminants from upstream agricultural practices, industrial chemical spills, urban runoff, or a combination of these sources.”

The U.S. Environmental Protection Agency (2012b) divided NIROP into three operable units “for ease of addressing contaminant issues.” Operable unit 1 is “groundwater at the site.” Operable unit 2 is “contaminated soil beyond the 57-acre NIROP site building,” and operable unit 3 is “contaminated soil beneath the site building.” The U.S. Environmental Protection Agency (1990) record of decision described operable unit 1. The U.S. Environmental Protection Agency (2003) record of decision described operable units 2 and 3.

The U.S. Environmental Protection Agency (1987 [record of decision], 2014) described contamination at the FMC Corp. (Fridley Plant) EPA Superfund site. The record of decision reported the presence of the following volatile organic compounds in groundwater from wells at the site: TCE, 1,1,1-trichloroethane (TCA), tetrachloroethene (PCE), 1,1-dichloroethane (1,1-DCA), 1,2-dichloroethane (DCA), 1,1-dichloroethene (1,1-DCE), 1,2-dichloroethene (1,2-DCE), 1,1,2-trichloroethane (1,1,2-TCE), benzene, toluene, and xylene. The EPA reported that 98 percent of volatile organic compounds at the FMC Corp. (Fridley Plant) EPA Superfund site were TCE. Maximum TCE concentrations of 47,000 µg/L and 15,000 µg/L were measured in unconfined and confined parts of the surficial aquifer system, respectively.

The U.S. Environmental Protection Agency (1990) record of decision reported the presence of the following volatile organic compounds in groundwater from NIROP wells open to the surficial aquifer system: TCE, TCA, 1,2-DCE, PCE, 1,1-DCA, toluene, xylene, and ethylbenzene. The EPA reported that more than 90 percent of volatile organic compounds at NIROP were TCE. The maximum TCE concentration in groundwater from shallow and deep NIROP wells was 26,000 and 37,000 µg/L, respectively. The maximum TCE concentration in groundwater from shallow and deep upgradient wells was 170 and 4 µg/L, respectively. The maximum TCE concentration in groundwater from shallow and deep downgradient wells was 12,700 and 10,800 µg/L, respectively. Some TCE concentrations exceeded the 5-µg/L maximum contaminant level for TCE. Observed TCA and PCE concentrations also exceeded maximum contaminant levels. U.S. Environmental Protection Agency (1990) record of decision estimated a TCE concentration in benthic groundwater discharge flux to the Mississippi River as much as 10,000 µg/L.

The U.S. Environmental Protection Agency (2003) record of decision reported the presence of the following volatile organic compounds in NIROP soils: TCE, TCA, 1,2-DCE, 1,1-DCA, bromomethane, carbon disulfide, ethylbenzene, styrene, PCE, toluene, and xylenes. The record of decision also reported the presence in NIROP soils of cyanide; semivolatile organic compounds such as polyaromatic hydrocarbons; and inorganics such as aluminum, arsenic, chromium, copper, iron, manganese, and mercury.

Lindgren (1990) mapped July and August 1988 TCE concentrations in the surficial aquifer system at 17 locations near NIROP. Locations were divided into three groups: a northern area near Interstate 694 (fig. 1), a central area near the main NIROP building, and a southern area south of the corporate limit that separates Anoka County, Minn. (fig. 1), and Hennepin County, Minn. (fig. 1). The maximum TCE concentration reported by Lindgren (1990) in the northern area was 1.3 µg/L; the groundwater TCE concentration was measured on the east bank of the Mississippi River, upstream from the main building, and 54 ft below land surface. The remaining four TCE measurements in the northern area were below the 0.2-µg/L TCE detection limit. The maximum TCE concentration in the central area, just downstream from the main NIROP building, was 7,200 µg/L. Other relatively higher-magnitude TCE concentrations existed in the central area. Lindgren (1990) reported that TCE concentration increased with depth in the surficial aquifer system in July and August 1988; and that trace TCE concentrations were measured in the central area, Prairie du Chien aquifer, and well MWW–13. The three TCE concentrations in the southern area were below the 0.2-µg/L detection limit.

Tetra Tech (2013b) documented 2012 operations, maintenance, and monitoring of the groundwater extraction and treatment system at NIROP; evaluated system performance from 1992 to 2012; summarized potential source areas for volatile organic compounds; and delineated groundwater capture zones for extraction wells open to the surficial aquifer system. Tetra Tech (2013b) represented geologic features in the surficial aquifer system on five cross sections; and potentiometric head in shallow, intermediate, and deep flow zones of the surficial aquifer system. Features were verified against high resolution seismic reflection surveys from 1997, gamma logs, and geologist logs; and conform to features described by Davis (2007). Tetra Tech (2013b) plotted groundwater extraction rate time series for groundwater extraction wells, and reported that the Navy treated more than 10^6 cubic meters of groundwater and removed more than 250 kilograms of TCE in 2012. Tetra Tech (2013b) suggested that biological degradation existed in the surficial aquifer system because 1,2-DCE concentrations increased at some locations where TCE concentrations had decreased.

Tetra Tech (2013b) analyzed groundwater quality data collected in February, May, August, September, and November 2012 at about 120 wells within 3,000 ft of the main NIROP building. During 2012, the maximum measured TCE concentration in the shallow flow zone of the surficial aquifer system was 1,000 μg/L. The observation was made in February, at well MS–54S (fig. 3), under East River Road (fig. 3) and southwest of NIROP. In the shallow flow zone of the surficial aquifer system, 29 of 75 TCE concentration samples during 2012 exceeded 100 μg/L. During 2012, the maximum TCE concentration in the intermediate flow zone of the surficial aquifer system was 4,600 μg/L in September at well MS–33I (fig. 3) in the central part of the southern one-third of NIROP. In the intermediate flow zone of the surficial aquifer system, 10 of 101 TCE concentration samples during 2012 exceeded 1,000 μg/L. During 2012, the maximum TCE concentration in the deep flow zone of the surficial aquifer system was 160 μg/L in May at extraction well AT–5B south of NIROP. In the deep flow zone of the surficial aquifer system, 3 of 39 TCE concentration samples during 2012 exceeded 100 μg/L.

Tetra Tech (2013b) reported TCA, 1,1-DCA, 1,1-DCE, *cis*-1,2-dichloroethene (*cis*-1,2-DCE), *trans*-1,2-dichloroethene (*trans*-1,2-DCE), PCE, total 1,2-DCE, TCE, and vinyl chloride concentration measurements in the surficial aquifer system at or near NIROP between October 1, 1983, and November 16, 2012. Using a Mann-Kendall trend analysis of TCE concentration time series, Tetra Tech (2013b) determined that downward TCE concentration trends existed at 29 of 52 wells in the shallow flow zone of the surficial aquifer system, upward TCE concentration trends existed at 3 of 52 wells, and either no trend existed or the time series contained insufficient data to draw a conclusion about TCE concentration trends at 20 of 52 wells. Results were similar in the intermediate flow zone of the surficial aquifer system where Tetra Tech (2013b) reported downward trends, upward trends, and no trend or insufficient data existed at 24, 5, and 8 of 37 wells, respectively; and in the deep flow zone of the surficial aquifer system, where Tetra Tech (2013b) also reported downward trends, upward trends, and no trend or insufficient data existed at 16, 4, and 11 of 31 wells, respectively.

Tetra Tech (2013b) reported that in July, August, and October 1999, the Minnesota Pollution Control Agency did not detect volatile organic compounds in surface-water samples from the Mississippi River. The Mississippi River was not sampled for volatile organic compounds near NIROP between 1999 and the publication of this report. In lieu of volatile organic compound samples from the Mississippi River, Tetra Tech (2013b) measured TCE concentrations during 2012 in wells closest to the Mississippi River. These wells were in the surficial aquifer system on the downgradient side of the NIROP groundwater flow field and in bedrock in Anoka County Riverfront Regional Park. Tetra Tech (2013b) determined that 6 of 7 wells in the shallow flow zone of the surficial aquifer system, 5 of 5 wells in the intermediate flow zone, and 3 of 5 wells in the deep flow zone exceeded State of Minnesota surface-water criteria for TCE concentration. At well MS–43 (fig. 3), in the shallow flow zone of the surficial aquifer system 280 ft east of the Mississippi River between December 1999 and August 2012, TCE concentrations ranged from 130 to 220 μg/L (Tetra Tech, 2013b). The 220-μg/L maximum concentration was reached in March 2003 and October 2006. The August 2012 concentration was 140 μg/L. At well MS–44 (fig. 3), in the shallow flow zone 300 ft east of the Mississippi River between November 1999 and August 2012, TCE concentrations ranged from 6.9 to 120 μg/L (Tetra Tech, 2013b). The 120-μg/L maximum concentration was reached in June 2003 and March 2004. The August 2012 concentration was 6.9 μg/L. At well MS–44, in the intermediate flow zone between November 1999 and November 2012, TCE concentrations ranged from 300 to 900 μg/L (Tetra Tech, 2013b). The 900-μg/L maximum concentration was reached in November 1999. The August and November 2012 concentrations were 540 and 380 μg/L, respectively. At well 27–S (fig. 3), in the shallow flow zone 130 ft east of the Mississippi River between October 1992 and August 2012, TCE concentrations ranged from 18 to 16,000 μg/L (Tetra Tech, 2013b). The 16,000-μg/L maximum concentration was reached in December 1992 and November 1994. The August 2012 concentration was 27 μg/L. At well MS–47 (fig. 3), in the shallow flow zone 130 ft east of the Mississippi River between December 1999 and August 2012, TCE concentrations ranged from 17 to 370 μg/L (Tetra Tech, 2013b). The 370-μg/L maximum concentration was reached in October 2000. The August 2012 concentration was 17 μg/L. At well MS–49 (fig. 3), in the shallow flow zone 160 ft east of the Mississippi River between December 1999 and August 2012, TCE concentrations ranged from 43 to 160 μg/L (Tetra Tech, 2013b). The 160-μg/L maximum concentration was reached in November 2011. The August 2012 concentration was 110 μg/L. Using maps, Tetra Tech (2013a, 2013b) suggested that concentrations of TCE greater than 100 μg/L discharged to the Mississippi River in 2011 and 2012, from the shallow flow zone of the surficial aquifer system.

Volatile organic compounds exist in the Cambrian-Ordovician aquifer system. Tetra Tech (2013b) reported PCE, DCE, and TCE concentration measurements in the Shakopee aquifer or Oneota confining unit at or near NIROP between October 1, 1983, and August 28, 2012 (figs. 12 and 13). Tetra Tech (2013b) did not differentiate between 1,2-DCE; 1,1-DCE; *cis*-1,2-DCE; and *trans*-1,2-DCE in concentration tabulations used to develop figures 12 and 13. Monitoring wells 1–PC, 2–PC, 3–PC, and 4–PC (figs. 1 and 2), are completed in the Shakopee aquifer and Oneota confining unit on the EPA NIROP Superfund site. Fridley well 13 (fig. 2) and well 5–PC (fig. 2), are completed in the Shakopee aquifer and Oneota confining unit, north of the EPA NIROP Superfund site. Wells MS–48PC, MS–50PC, MS–53PC, and FMC–43 (fig. 3), are completed in the Shakopee aquifer and Oneota confining unit, in Anoka County Riverfront Regional Park southwest of the EPA NIROP Superfund site. The maximum concentration of volatile organic compounds measured in the Cambrian-Ordovician aquifer system was 560 µg/L PCE on November 2, 1999, at well 5–PC. The maximum concentration of volatile organic compounds measured in the Cambrian-Ordovician aquifer system on the EPA NIROP Superfund site was 150 µg/L PCE on September 22, 2004, at well 2–PC. The maximum TCE concentration measured in the Cambrian-Ordovician aquifer system was 81 µg/L on October 1, 1983, and April 1, 1984, at well 3–PC.

A dense, nonaqueous-phase liquid (DNAPL) is immiscible and denser than water. Chlorinated solvents such as TCE and PCE may be DNAPLs under certain conditions. The (U.S. Environmental Protection Agency (1992a) defined conditions that may indicate the potential for DNAPLs in groundwater. One of the conditions specified that a DNAPL may be present where the DNAPL concentration in groundwater is greater than 1 percent of either the effective solubility or the pure-phase solubility of the DNAPL. The pure-phase solubility of TCE is 1.472×10^6 µg/L at 25 degrees Celsius (°C) (U.S. Environmental Protection Agency, 2004). As a DNAPL, TCE may be present where the TCE concentration in groundwater is greater than 14,720 µg/L at 25 °C. Tetra Tech (2013b) tabulated 3,323 TCE measurements at and near NIROP. These measurements were collected between October 1, 1983, and November 16, 2012. Of the 3,323 TCE concentration measurements, 39 exceeded 14,720 µg/L. These 39 measurements were collected between October 1, 1983, and December 6, 2001, from four wells in the shallow flow zone of the surficial aquifer system, three wells in the intermediate flow zone, and one well in the deep flow zone. Restated, 1.2 percent of TCE measurements show that TCE may have been present as a DNAPL on or near NIROP between October 1, 1983, and December 6, 2001. As a DNAPL, TCE may be transported faster, deeper, and farther than TCE in a less dense, aqueous phase. The maximum measured TCE concentration was 59,000 µg/L on

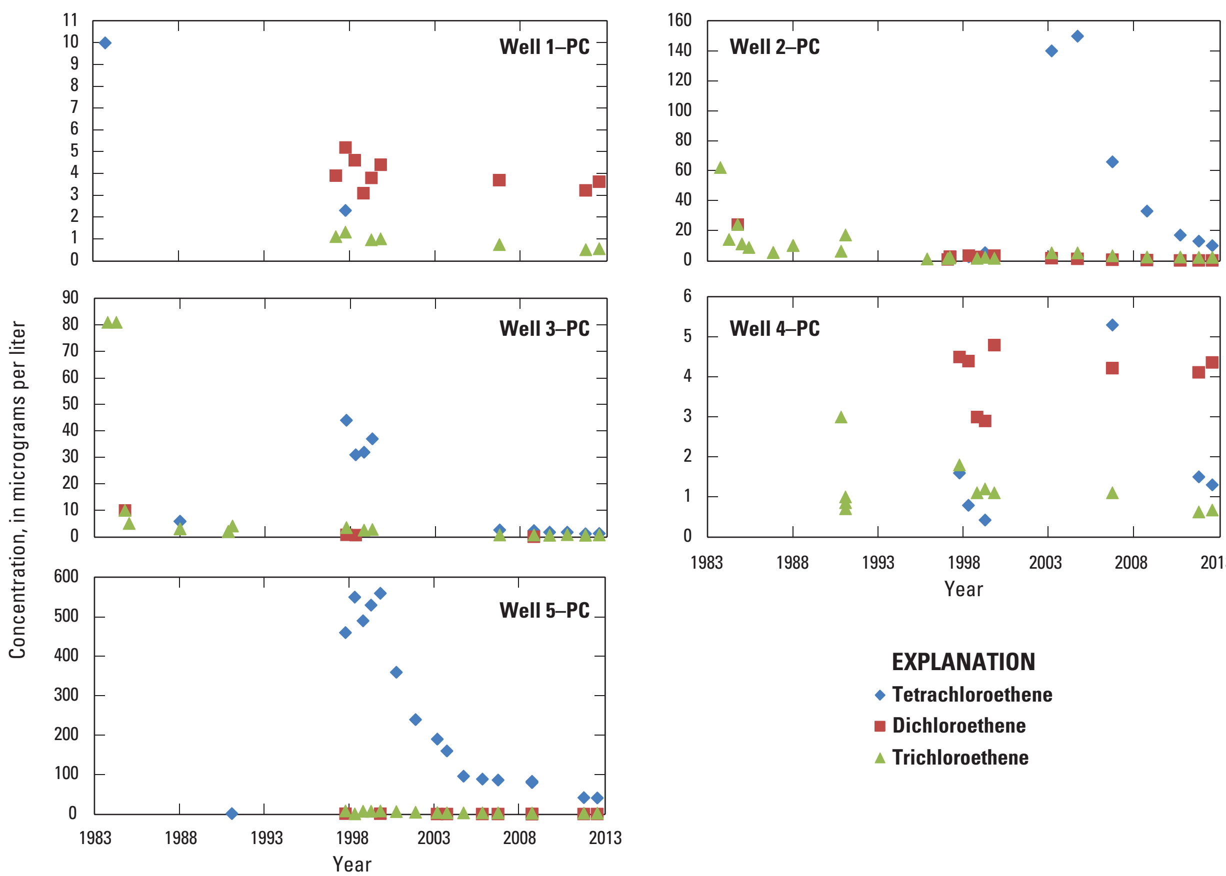


Figure 12. Tetrachloroethene, dichloroethene, and trichloroethene concentrations in groundwater from wells 1–PC, 2–PC, 3–PC, 4–PC, and 5–PC (figs. 2 and 3) that monitor the Shakopee aquifer and Oneota confining unit at and near the Naval Industrial Ordnance Plant, Fridley, Minnesota.

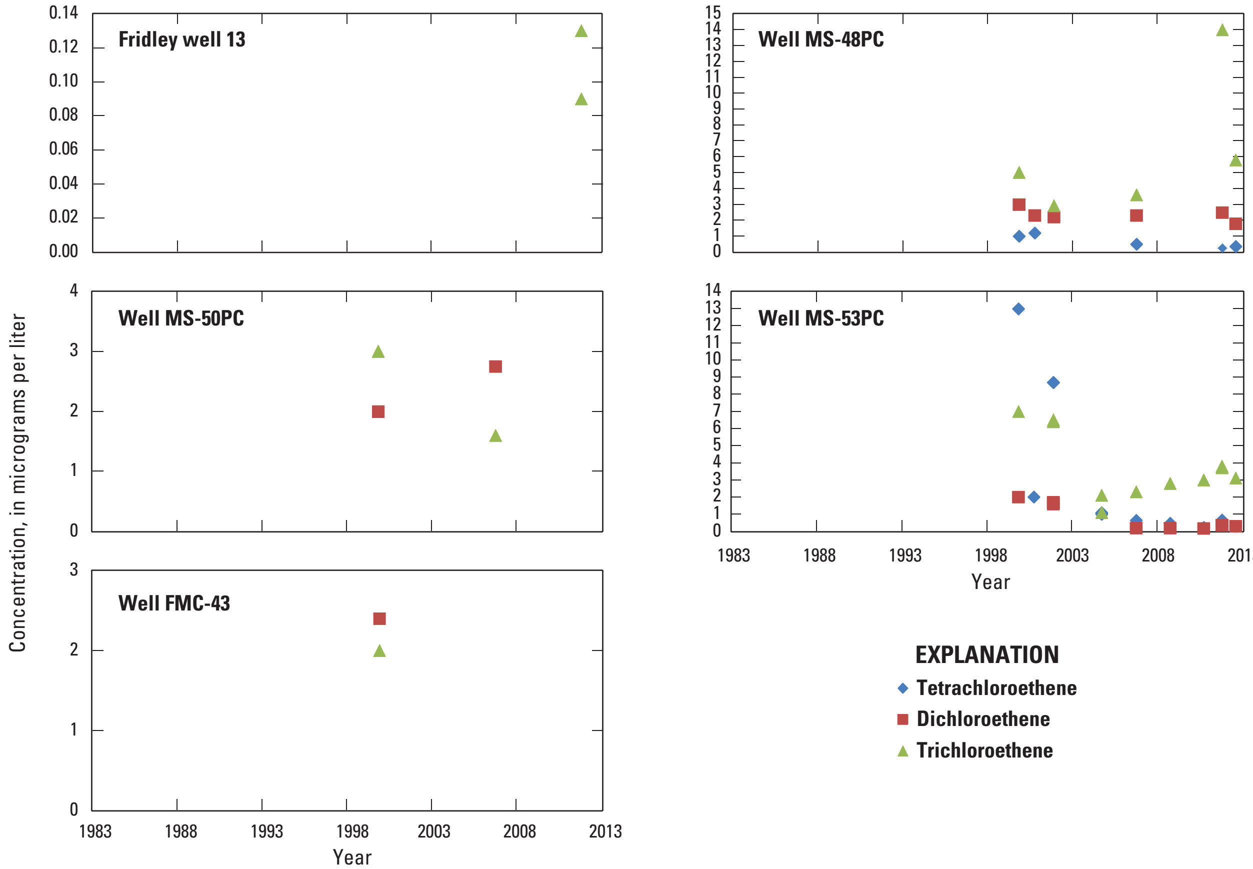


Figure 13. Tetrachloroethene, dichloroethene, and trichloroethene concentrations in groundwater from Fridley well 13 (fig. 2), and wells MS–48PC, MS–50PC, MS–53PC, and FMC–43 (fig. 3) that monitor the Shakopee aquifer and Oneota confining unit at and near the Naval Industrial Ordnance Plant, Fridley, Minnesota.

February 25, 1998, at well MS–32I (fig. 3) in the intermediate flow zone of the surficial aquifer system. Tetra Tech (2013b) did not report TCE concentration measurements that exceeded 14,720 µg/L on or near NIROP between December 7, 2001, and November 16, 2012.

The U.S. Environmental Protection Agency (1998) and Tetra Tech (2003, 2008, 2013b) described 5-year reviews of the EPA NIROP Superfund site. The U.S. Environmental Protection Agency (1992b) and Minnesota Pollution Control Agency (1999, 2004, 2009, 2014b) described 5-year reviews of the FMC Corp. (Fridley Plant) EPA Superfund site.

Preliminary Simulation of Groundwater Flow

The objective of the preliminary groundwater flow simulation (Davis and King, 2016) was to generate a steady-state groundwater flow field to force a general TCE transport simulation for 2001. Groundwater flow was simulated using the numerical model MODFLOW 2000 (Harbaugh and others, 2000). Davis (2007) described potentiometric head measurements at NIROP in late 2001. Potentiometric heads (table 2) were measured at 158 locations on August 20, 2001, forced by groundwater extraction wells (tables 3 and 4). Davis (2007) contoured potentiometric head data for August 20, 2001, in shallow, intermediate, and deep flow zones of the surficial aquifer system (figs. 9–11). Delin and others (2007) showed that August is a below-average month for recharge in Minnesota (see “Surficial Aquifer System” section). Steady-state groundwater flow was simulated for August 20, 2001. It is postulated that forcing in aquifer systems was constant for a sufficient duration on August 20 such that measured potentiometric heads on August 20 had reached a steady state; thus, the steady-state groundwater flow field is postulated to represent an average flow field, such that transient, seasonal forces that act together on the surficial and Cambrian-Ordovician aquifer systems in August represent a composite average force. Actual hydraulic conditions in these aquifer systems are seasonal and transient. The steady-state postulation was necessary due to the limited scope of this preliminary study.

Although the regional groundwater flow model simulation described in Metropolitan Council (2014) updated the simulation described in Metropolitan Council (2009),

Table 2. Well name, well depth below ground surface, well diameter, top-of-casing elevation, screen length, screened flow zone, and potentiometric head on August 20, 2001, at and near the Naval Industrial Ordnance Plant, Fridley, Minnesota.

[Well locations are shown in figures 2 and 3. Elevation is given in feet above the North American Vertical Datum of 1988. The U.S. Department of the Navy furnished potentiometric-head measurements to the U.S. Geological Survey. —, data not available]

Well name	Depth below ground surface (feet)	Well diameter (inches)	Top-of-casing elevation (feet)	Screen length (feet)	Screened flow zone	Potentiometric head on August 20, 2001 (feet)
3–D	79.2	2	837.35	10.2	Deep	815.31
3–PC	156.7	4	838.53	—	Bedrock	815.73
4–D	119.3	2	834.65	10	Deep	805.70
4–IS	75	2	833.34	10	Intermediate	804.16
4–PC	181	4	834.63	—	Bedrock	815.63
4–S	33.2	2	837.33	15	Shallow	816.68
5–IS	60	2	837.86	10	Intermediate	815.71
5–S	33	2	834.92	15	Shallow	813.68
6–D	128.6	2	835.54	10	Deep	804.96
6–IS	—	—	836.53	—	Intermediate	803.73
6–S	33	2	835.60	15.2	Shallow	813.14
7–D	115	4	835.61	10	Deep	803.18
7–IS	—	—	837.02	—	Intermediate	803.92
8–D	125	4	833.92	10	Deep	804.16
8–IS	—	—	836.65	—	Intermediate	806.30
9–D	121.3	4	834.22	10	Deep	799.78
9–S	27.8	2	836.53	10	Shallow	816.29
10–S	29.5	2	835.73	10.1	Shallow	814.07
11–S	29.3	2	835.75	10	Intermediate	804.94
12–IS	74.8	2	834.94	20	Intermediate	810.54
13–IS	73.5	2	834.96	10	Intermediate	808.94
14–D	90	3	837.75	10	Deep	815.29
14–IS	66.8	—	835.21	10	Shallow	796.85
15–D	133.8	—	834.01	20	Deep	804.40
15–IS	75	2	833.67	10	Intermediate	803.90
16–D	114	2	833.08	20	Deep	801.55
16–IS	85.2	2	832.77	10	Intermediate	801.98
17–D	104.4	—	835.24	—	Deep	805.92
17–S	36	2	835.48	10	Shallow	810.38
18–S	37.8	3	833.86	10	Shallow	804.08
19–S	42.5	2	834.18	10	Shallow	799.89
20–S	32.6	2	837.51	10	Shallow	816.69
22–S	35	2	837.60	15	Shallow	816.30
24–S	35	2	836.19	15	Shallow	812.45
26–S	40	2	834.06	10	Shallow	803.94
27–S	50.3	2	832.74	10	Shallow	801.89
AT–10	84	8	837.11	16	Intermediate	791.91
AT–3A	105	8	836.10	35.6	Intermediate	765.98
AT–5A	66	8	835.57	30	Shallow	793.85
AT–5B	136	8	835.62	35	Deep	791.80

Table 2. Well name, well depth below ground surface, well diameter, top-of-casing elevation, screen length, screened flow zone, and potentiometric head on August 20, 2001, at and near the Naval Industrial Ordnance Plant, Fridley, Minnesota.—Continued

[Well locations are shown in figures 2 and 3. Elevation is given in feet above the North American Vertical Datum of 1988. The U.S. Department of the Navy furnished potentiometric-head measurements to the U.S. Geological Survey. —, data not available]

Well name	Depth below ground surface (feet)	Well diameter (inches)	Top-of-casing elevation (feet)	Screen length (feet)	Screened flow zone	Potentiometric head on August 20, 2001 (feet)
AT–7	39	8	836.30	10	Shallow	809.29
AT–8	38	8	835.18	10	Shallow	804.61
AT–9	52	8	836.82	17	Shallow	805.85
FMC–11	95	4	835.50	10	Intermediate	810.48
FMC–12	70	4	835.37	5	Intermediate	810.22
FMC–13	46	4	835.32	5	Shallow	810.16
FMC–14	30	4	835.26	5	Shallow	810.04
FMC–15	32	4	836.16	5	Shallow	809.40
FMC–16	31	4	837.16	5	Shallow	813.67
FMC–17	35	4	837.59	4	Shallow	814.38
FMC–18	65	4	837.54	5	Intermediate	814.12
FMC–19A	38	4	835.24	5	Shallow	799.90
FMC–20	38	4	833.48	5	Shallow	799.69
FMC–21	42	2	833.00	4	Shallow	798.46
FMC–24	32	2	837.46	4	Shallow	815.55
FMC–27	61	4	837.30	4	Intermediate	812.22
FMC–29	93	6	836.32	55	Intermediate	811.52
FMC–29A	64.7	2	834.85	20.7	Intermediate	809.87
FMC–30	112	4	835.07	72	Deep	810.27
FMC–31	160	4	834.64	—	Bedrock	811.45
FMC–32	160	4	837.41	—	Bedrock	813.99
FMC–35	60	4	832.15	35	Intermediate	806.81
FMC–39	134	4	832.08	89	Deep	808.08
FMC–40	137	4	833.93	91	Deep	801.98
FMC–41	143	4	835.67	62	Deep	810.72
FMC–42	137.5	8	835.61	—	Bedrock	—
FMC–43	178	4	831.89	—	Bedrock	813.39
FMC–53	135	4	831.10	99.5	Deep	808.97
FMC–54	140	4	832.50	75.5	Deep	808.66
FMC–55A	93	2	834.22	5	Deep	811.30
FMC–55B	65	2	834.24	5	Intermediate	809.34
FMC–56A	95	2	834.53	5	Deep	810.56
FMC–56B	60	2	834.41	5	Intermediate	810.02
FMC–57A	100	2	834.28	5	Deep	810.46
FMC–57B	68	2	834.42	5	Intermediate	810.21
MS–28D	114.7	2	834.80	5.1	Deep	815.69
MS–28I	85.5	2	834.83	5.1	Intermediate	815.82
MS–28S	27.3	2	834.81	10.1	Shallow	815.74
MS–29D	136.7	2	834.69	5.1	Deep	816.08
MS–29I	81.2	2	834.67	5.1	Intermediate	814.78

Table 2. Well name, well depth below ground surface, well diameter, top-of-casing elevation, screen length, screened flow zone, and potentiometric head on August 20, 2001, at and near the Naval Industrial Ordnance Plant, Fridley, Minnesota.—Continued

[Well locations are shown in figures 2 and 3. Elevation is given in feet above the North American Vertical Datum of 1988. The U.S. Department of the Navy furnished potentiometric-head measurements to the U.S. Geological Survey. —, data not available]

Well name	Depth below ground surface (feet)	Well diameter (inches)	Top-of-casing elevation (feet)	Screen length (feet)	Screened flow zone	Potentiometric head on August 20, 2001 (feet)
MS–29S	27.3	2	834.68	10.1	Shallow	814.72
MS–30D	99.4	2	834.81	4.8	Deep	814.93
MS–30I	67.8	2	834.85	5	Deep	814.85
MS–30S	27.5	2	834.83	9.9	Shallow	816.17
MS–31D	127.2	2	834.81	5	Deep	—
MS–31I	96.6	2	834.81	5.1	Intermediate	815.29
MS–31S	27.5	2	834.81	10.1	Shallow	814.70
MS–32D	126.2	2	834.75	5	Deep	807.30
MS–32I	84.8	2	834.69	5.1	Intermediate	806.44
MS–32S	26.1	2	834.76	10.1	Shallow	815.14
MS–33D	120.3	2	834.76	5.1	Deep	814.46
MS–33I	75.9	2	834.74	5.1	Intermediate	814.74
MS–33S	27.1	2	834.72	10.1	Shallow	815.00
MS–34D	135.5	2	834.35	10	Deep	806.31
MS–34I	79.5	2	834.35	10	Intermediate	804.88
MS–34S	27	2	834.31	10	Shallow	812.49
MS–35D	132.6	2	834.45	10	Deep	809.75
MS–35DPZ	132	2	834.26	10	Deep	805.53
MS–35I	82	2	834.21	10	Intermediate	804.67
MS–35S	27	2	834.22	10	Shallow	812.17
MS–36D	131.5	2	834.79	10	Deep	804.87
MS–36I	80.5	2	834.70	10	Intermediate	804.52
MS–36S	42	2	834.80	10	Shallow	806.36
MS–37S	48	2	834.21	10	Intermediate	804.50
MS–38S	42	2	834.64	10	Shallow	797.86
MS–39S	41.5	2	834.76	10	Shallow	797.29
MS–40D	135.5	2	834.70	10	Deep	806.14
MS–40I	60.7	2	834.64	10	Shallow	798.23
MS–40S	41	2	834.61	10	Shallow	798.32
MS–41D	132	2	834.89	10	Deep	804.14
MS–41I	90	2	834.82	15	Intermediate	804.14
MS–41S	41	2	834.82	10	Shallow	798.78
MS–42I	52.5	2	835.33	10	Shallow	810.39
MS–43D	111.4	2	834.27	10	Deep	802.97
MS–43I	80.3	2	834.32	15	Intermediate	801.64
MS–43S	37	2	834.42	10	Shallow	801.87
MS–44D	118	2	833.58	10	Deep	804.14
MS–44I	80	2	833.62	10	Intermediate	804.13
MS–44S	34	2	833.53	10	Shallow	803.61
MS–45I	90	2	832.07	10	Intermediate	803.94

Table 2. Well name, well depth below ground surface, well diameter, top-of-casing elevation, screen length, screened flow zone, and potentiometric head on August 20, 2001, at and near the Naval Industrial Ordnance Plant, Fridley, Minnesota.—Continued

[Well locations are shown in figures 2 and 3. Elevation is given in feet above the North American Vertical Datum of 1988. The U.S. Department of the Navy furnished potentiometric-head measurements to the U.S. Geological Survey. —, data not available]

Well name	Depth below ground surface (feet)	Well diameter (inches)	Top-of-casing elevation (feet)	Screen length (feet)	Screened flow zone	Potentiometric head on August 20, 2001 (feet)
MS–45S	33	2	832.13	10	Shallow	803.87
MS–46I	85.1	2	831.61	10	Intermediate	801.85
MS–46S	34	2	831.67	10	Shallow	803.66
MS–47D	130.4	2	834.51	10	Deep	803.16
MS–47I	79.2	2	834.55	10	Intermediate	800.69
MS–47S	38	2	834.83	10	Shallow	796.63
MS–48PC	165.3	2	831.50	15	Bedrock	813.46
MS–49D	127.4	2	833.87	10	Deep	800.07
MS–49I	84.9	2	834.02	15	Intermediate	800.17
MS–49S	38	2	834.16	10	Shallow	799.95
MS–50PC	170	2	833.88	15	Bedrock	813.55
MS–51I	75	2	833.66	10	Intermediate	799.91
MS–52D	138	2	833.27	15	Deep	809.03
MS–52I	79	2	833.25	10	Intermediate	799.75
MS–52S	38	2	833.14	10	Shallow	799.74
MS–53PC	166.9	2	832.64	15	Bedrock	813.62
MW–1	47.7	4	838.51	20	Intermediate	812.23
MW–2	46	4	839.59	20	Intermediate	811.91
MW–3	45.5	4	840.22	20	Intermediate	812.36
MW–4	46	4	839.52	20	Intermediate	812.61
MW–5	45	4	838.36	20.3	Intermediate	814.03
MWW–13	30	2	833.33	3	Shallow	801.49
MWW–4	55	2	832.01	4	Intermediate	800.78
MWW–5	29	—	831.39	3	Shallow	799.43
MWW–6	27	2	831.05	3	Shallow	805.44
RW–4	50.5	6	835.00	27.7	Shallow	806.93
RW–5	59.5	6	833.84	27.9	Intermediate	807.33
UD–58I	80.1	2	837.60	10	Intermediate	837.60
UD–59I	70.8	2	836.68	10	Intermediate	813.01
UD–60S	30.2	2	837.60	10	Shallow	814.94
UD–61I	73.5	2	835.16	10	Intermediate	815.99
UD–62S	29.7	2	835.26	10	Shallow	816.28
UD–63S	30.1	2	837.00	10	Shallow	816.13
USGS–10	128	2	836.85	10	Deep	808.08
USGS–4	43	2	831.84	10	Shallow	800.07
USGS–5	42.5	2	832.86	10	Shallow	800.03
USGS–7	43	2	835.47	10	Shallow	813.72
USGS–8	42.5	2	836.10	10	Shallow	798.86
USGS–9	43	2	836.50	10	Shallow	810.66
UST-MW–2	29.5	2	837.35	10	Shallow	816.08

Table 3. Groundwater extraction rates of wells on August 20, 2001 at the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.

[Well locations are shown in figure 3. gal/min, gallon per minute]

Well name	Surficial aquifer system flow zone	Groundwater extraction rate (gal/min)
AT–3A	Intermediate	182
AT–5A	Shallow, lower part	156
AT–5B	Deep	86
AT–7	Shallow, upper part	42
AT–8	Shallow, upper part	17
AT–9	Shallow, upper part	142
AT–10	Intermediate	23

because the August 20, 2001, groundwater flow simulation at NIROP was built before publication of Metropolitan Council (2014), the August 20 simulation was primarily built from the simulation described in Metropolitan Council (2009) using selected refinements (appendix 1) necessary to characterize TCE transport at NIROP. The following groundwater flow simulation components are detailed in appendix 1: geographic extent of the study area, boundary conditions, vertical spatial discretization, vertical datum postulation, sources and sinks, horizontal spatial discretization, initial potentiometric heads, flow parameters, temporal discretization, and numerical solution for potentiometric head. Hydrogeologic parameters for the August 20 groundwater flow simulation were adjusted to minimize differences between measured and simulated potentiometric head (appendix 1).

Simulated potentiometric heads in the shallow flow zone of the surficial aquifer system ranged from 816 ft on the northeastern side of NIROP to 800 ft under the Mississippi River (fig. 14*A*). The simulated potentiometric-head gradient was steepest across the 120-ft-wide crescent-shaped clay area where potentiometric head decreased from 814 ft to 796 ft. Simulated cones of depression existed at extraction wells AT–5 (fig. 3) and AT–9. A lobe of higher potentiometric head was simulated west of extraction well AT–5 in which a ridge of higher potentiometric head (fig. 9) existed along the central axis of the lobe with respect to lower potentiometric head to the east at extraction well AT–5 and lower potentiometric head to the west under the Mississippi River. A saddle feature (fig. 9) was simulated in the contoured representation of potentiometric head, south of the lobe and north of an area of increasing potentiometric head, near the southern end of the crescent-shaped clay area on the southern side of NIROP. The relatively steep potentiometric-head gradient across the crescent-shaped clay area, cones of depression at extraction wells AT–5 and AT–9, lobe of higher potentiometric head, saddle feature, and area of increasing potentiometric head on the southern side of NIROP were shown on a contour map of potentiometric head measured on August 20, 2001, in the shallow flow zone of the surficial aquifer system (fig. 9). The contour map of measured potentiometric head included the following features that were not apparent in the model simulation results: an area of depressed potentiometric head west of the southern tip of the crescent-shaped clay area under the Mississippi River; and cones of depression near extraction wells AT–7, AT–8 and RW–4 (fig. 3) at the FMC Corp. (Fridley Plant) EPA Superfund site in the area southeast of the crescent-shaped clay area.

Simulated potentiometric heads compared favorably to 49 of 56 potentiometric-head measurements on August 20, 2001, in the shallow flow zone of the surficial aquifer system; the absolute value of simulated potentiometric head minus measured potentiometric head was less than 2 ft at 49 locations and greater than 2 ft at 7 locations (fig. 14*A*). Simulated and measured potentiometric head were not compared at extraction wells AT–7, AT–8, or AT–9. Although stresses from extraction wells at the FMC Corp. (Fridley Plant) EPA Superfund site also were simulated southeast of the crescent-shaped clay area, measured, stressed potentiometric head did not compare favorably with simulated potentiometric head everywhere in this area; for example, measured potentiometric head was 5.47 ft less than simulated potentiometric head near extraction well RW–4.

Simulated potentiometric head decreased in the shallow flow zone of the surficial aquifer system from 920 ft at Oneka Lake (figs. 1 and 14*B*) to less than 800 ft under the Mississippi River. Locally depressed, simulated potentiometric-head contours existed under Rice Creek (fig. 14*B*). Regionally, simulated potentiometric-head contours and simulated potentiometric-head gradients were qualitatively similar in the intermediate (fig. 15*B*) and deep (fig. 16*B*) flow zones of the surficial aquifer system, and in the Shakopee aquifer (fig. 17*B*). Locally, differences in simulated potentiometric-head contours and simulated potentiometric-head gradients existed between these units under the Mississippi River (figs. 15*B*, 16*B*, and 17*B*).

Simulated potentiometric head in the intermediate flow zone of the surficial aquifer system ranged from 816 ft on the northeastern side of NIROP to less than 800 ft near well MS–52 (figs. 3 and 15*A*). Simulated potentiometric head under the Mississippi River ranged from less than 801 ft near the northern side of the main NIROP building to a low of about 800 ft near well MS–52 on the southern side of NIROP. The simulated potentiometric-head gradient was steepest near extraction well AT–5 under the northern tip of the 120-ft-wide crescent-shaped clay area in the shallow flow zone of the surficial aquifer system; simulated potentiometric head decreased from 810 ft to less than 799 ft across this area. Simulated cones of depression existed at extraction wells AT–3 (fig. 3) and AT–5. Two clay areas existed north and south of a paleo-channel composed of sands and gravels (fig. 10) in which hydraulic conductivity was lower in clay areas and higher in the paleo-channel (figs. 14*A* and 14*B*). Simulated potentiometric head conformed to the paleo-channel

Table 4. Simulated groundwater extraction rates of wells on August 20, 2001, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.

[Counties are shown in figure 1. Well locations are not shown in this report, see Metropolitan Council (2009). Data are from Metropolitan Council (2009). gal/min, gallon per minute]

Well number	Well name	Groundwater extraction rate (gal/min)	Hydrogeologic unit	County	Section	Township	Range
462968	No name	0.5	Surficial aquifer system: deep flow zone	Ramsey	21	30	23
447893	01U350 308	3.6	Surficial aquifer system: deep flow zone	Ramsey	9	30	23
426842	03F302	201.2	Surficial aquifer system: deep flow zone	Ramsey	16	30	23
426842	03F302	201.2	St. Peter aquifer and Lower St. Peter confining unit	Ramsey	16	30	23
426843	03F303	69.3	Surficial aquifer system: deep flow zone	Ramsey	16	30	23
426844	03F304	197.8	St. Peter aquifer and Lower St. Peter confining unit	Ramsey	16	30	23
426845	03F305	187.7	St. Peter aquifer and Lower St. Peter confining unit	Ramsey	16	30	23
426846a	03F306	98.8	Surficial aquifer system: deep flow zone	Ramsey	16	30	23
426846b	03F306	98.8	St. Peter aquifer and Lower St. Peter confining unit	Ramsey	16	30	23
426847a	03F307	115.9	Surficial aquifer system: deep flow zone	Ramsey	16	30	23
426847b	03F307	115.9	St. Peter aquifer and Lower St. Peter confining unit	Ramsey	16	30	23
453823a	03F308 308-F B-7	74.5	Surficial aquifer system: deep flow zone	Ramsey	16	30	23
453823b	03F308 308-F B-7	74.5	St. Peter aquifer and Lower St. Peter confining unit	Ramsey	16	30	23
453824a	03F312 312-F B-11	45.8	Surficial aquifer system: deep flow zone	Ramsey	16	30	23
453824b	03F312 312-F B-11	45.8	St. Peter aquifer and Lower St. Peter confining unit	Ramsey	16	30	23
508122	03U314 314-U SC-2	39.2	Surficial aquifer system: deep flow zone	Ramsey	16	30	23
508121	03U315 315-U SC-3	61.0	Surficial aquifer system: deep flow zone	Ramsey	16	30	23
453822	03U316 316-U SC-4	7.8	Surficial aquifer system: deep flow zone	Ramsey	16	30	23
453821	03U317 317-U SC-5	92.8	Surficial aquifer system: deep flow zone	Ramsey	16	30	23
429651	Baldwin Lake T.C. No. 2	5.9	Shakopee aquifer and Oneota confining unit	Anoka	31	31	22
208646a	Blaine 3	2.6	Jordan aquifer	Anoka	32	31	23
208646b	Blaine 3	2.6	St. Lawrence confining unit	Anoka	32	31	23
208646c	Blaine 3	2.6	Upper Tunnel City aquifer and Lower Tunnel City confining unit	Anoka	32	31	23
208646d	Blaine 3	2.6	Wonewoc aquifer	Anoka	32	31	23
208645a	Blaine 4	18.1	Jordan aquifer	Anoka	32	31	23
208645b	Blaine 4	18.1	St. Lawrence confining unit	Anoka	32	31	23
208645c	Blaine 4	18.1	Upper Tunnel City aquifer and Lower Tunnel City confining unit	Anoka	32	31	23
208645d	Blaine 4	18.1	Wonewoc aquifer	Anoka	32	31	23
208634a	Blaine 6	128.9	Upper Tunnel City aquifer and Lower Tunnel City confining unit	Anoka	24	31	23

Table 4. Simulated groundwater extraction rates of wells on August 20, 2001, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.—Continued

[Counties are shown in figure 1. Well locations are not shown in this report, see Metropolitan Council (2009). Data are from Metropolitan Council (2009). gal/min, gallon per minute]

Well number	Well name	Groundwater extraction rate (gal/min)	Hydrogeologic unit	County	Section	Township	Range
208634b	Blaine 6	128.9	Wonewoc aquifer	Anoka	24	31	23
208633a	Blaine 11	160.6	Upper Tunnel City aquifer and Lower Tunnel City confining unit	Anoka	24	31	23
208633b	Blaine 11	160.6	Wonewoc aquifer	Anoka	24	31	23
233109a	Blaine 14	75.0	Wonewoc aquifer	Anoka	35	31	23
203424a	Brookdale Shopping Center	1.3	St. Peter aquifer and Lower St. Peter confining unit	Hennepin	2	118	21
203424b	Brookdale Shopping Center	1.3	Shakopee aquifer and Oneota confining unit	Hennepin	2	118	21
203315	Brooklyn Center 1	1.8	Jordan aquifer	Hennepin	34	119	21
203317	Brooklyn Center 2	63.6	Jordan aquifer	Hennepin	34	119	21
203260	Brooklyn Center 3	20.1	Jordan aquifer	Hennepin	25	119	21
203259	Brooklyn Center 4	426.6	Jordan aquifer	Hennepin	25	119	21
203258	Brooklyn Center 5	435.8	Jordan aquifer	Hennepin	25	119	21
203321a	Brooklyn Center 6	314.8	Shakopee aquifer and Oneota confining unit	Hennepin	36	119	21
203321b	Brooklyn Center 6	314.8	Jordan aquifer	Hennepin	36	119	21
203257	Brooklyn Center 7	298.6	Jordan aquifer	Hennepin	25	119	21
110493	Brooklyn Center 9	202.1	Jordan aquifer	Hennepin	25	119	21
468118	Brooklyn Center 10	311.7	Jordan aquifer	Hennepin	25	119	21
224765a	Brooklyn Center, City of	23.1	Shakopee aquifer and Oneota confining unit	Hennepin	25	119	21
224765b	Brooklyn Center, City of	23.1	Jordan aquifer	Hennepin	25	119	21
203026a	Brooklyn Park 1	20.8	Wonewoc aquifer	Hennepin	23	119	21
138928	Brookside MHP 2	0.2	Shakopee aquifer and Oneota confining unit	Ramsey	4	30	23
184900	Brooklyn Park 12	86.5	Jordan aquifer	Hennepin	25	119	21
109793	Brookside Mobile Home Park	20.9	Shakopee aquifer and Oneota confining unit	Ramsey	4	30	23
110488	Burlington Northern	17.3	Surficial aquifer system: deep flow zone	Anoka	27	30	24
559393a	Burlington Northern Rail	9.4	Surficial aquifer system: deep flow zone	Anoka	34	30	24
559393b	Burlington Northern Rail	9.4	St. Peter aquifer and Lower St. Peter confining unit	Anoka	34	30	24
208648	Centennial MHP	73.4	St. Peter aquifer and Lower St. Peter confining unit	Anoka	34	31	23
562962a	Centennial Middle School	0.7	Upper Tunnel City aquifer and Lower Tunnel City confining unit	Anoka	18	31	22
562962b	Centennial Middle School	0.7	Wonewoc aquifer	Anoka	18	31	22

Table 4. Simulated groundwater extraction rates of wells on August 20, 2001, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.—Continued

[Counties are shown in figure 1. Well locations are not shown in this report, see Metropolitan Council (2009). Data are from Metropolitan Council (2009). gal/min, gallon per minute]

Well number	Well name	Groundwater extraction rate (gal/min)	Hydrogeologic unit	County	Section	Township	Range
209209a	Centennial School	3.1	St. Lawrence confining unit	Anoka	24	31	23
209209b	Centennial School	3.1	Upper Tunnel City aquifer and Lower Tunnel City confining unit	Anoka	24	31	23
209209c	Centennial School	3.1	Wonewoc aquifer	Anoka	24	31	23
511091a	Centerville 1	2.8	Shakopee aquifer and Oneota confining unit	Anoka	14	31	22
511091b	Centerville 1	2.8	Jordan aquifer	Anoka	14	31	22
512748a	Centerville 2	56.8	Shakopee aquifer and Oneota confining unit	Anoka	23	31	22
512748b	Centerville 2	56.8	Jordan aquifer	Anoka	23	31	22
203577	Charles C. Webber Park	4.9	Shakopee aquifer and Oneota confining unit	Hennepin	4	29	24
208569	Chomonix C.C. No.1	1.2	St. Lawrence confining unit	Anoka	21	31	22
208637	Circle Pines 1	142.7	Upper Tunnel City aquifer and Lower Tunnel City confining unit	Anoka	25	31	23
208636a	Circle Pines 3	80.2	Jordan aquifer	Anoka	25	31	23
208636b	Circle Pines 3	80.2	St. Lawrence confining unit	Anoka	25	31	23
206680a	Designware Industries	1.5	Shakopee aquifer and Oneota confining unit	Anoka	15	30	24
206680b	Designware Industries	1.5	Jordan aquifer	Anoka	15	30	24
206685a	Fridley 1	0.5	Upper Tunnel City aquifer and Lower Tunnel City confining unit	Anoka	23	30	24
206685b	Fridley 1	0.5	Wonewoc aquifer	Anoka	23	30	24
206673a	Fridley 6	134.1	Shakopee aquifer and Oneota confining unit	Anoka	14	30	24
206673b	Fridley 6	134.1	Jordan aquifer	Anoka	14	30	24
206678	Fridley 7	75.0	Shakopee aquifer and Oneota confining unit	Anoka	14	30	24
206669	Fridley 8	147.0	Shakopee aquifer and Oneota confining unit	Anoka	14	30	24
206672a	Fridley 9	12.2	Shakopee aquifer and Oneota confining unit	Anoka	14	30	24
206672b	Fridley 9	12.2	Jordan aquifer	Anoka	14	30	24
206658	Fridley 10	327.0	St. Peter aquifer and Lower St. Peter confining unit	Anoka	11	30	24
206658b	Fridley 10	82.2	Upper Tunnel City aquifer and Lower Tunnel City confining unit	Anoka	11	30	24
206657a	Fridley 11	82.2	St. Lawrence confining unit	Anoka	11	30	24
209207	Fridley 12	315.4	Jordan aquifer	Anoka	12	30	24
206696a	Fridley 13	2.5	Shakopee aquifer and Oneota confining unit	Anoka	27	30	24

Table 4. Simulated groundwater extraction rates of wells on August 20, 2001, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.—Continued

[Counties are shown in figure 1. Well locations are not shown in this report, see Metropolitan Council (2009). Data are from Metropolitan Council (2009). gal/min, gallon per minute]

Well number	Well name	Groundwater extraction rate (gal/min)	Hydrogeologic unit	County	Section	Township	Range
206696b	Fridley 13	2.5	Jordan aquifer	Anoka	27	30	24
206679	Fridley Junior High School	6.8	Shakopee aquifer and Oneota confining unit	Anoka	14	30	24
206683	Fridley Senior High School	13.0	Shakopee aquifer and Oneota confining unit	Anoka	23	30	24
206659	Fridley Terrace MHP 1	19.3	Surficial aquifer system: deep flow zone	Anoka	12	30	24
206659c	Fridley Terrace MHP 1	82.2	Wonewoc aquifer	Anoka	12	30	24
206660a	Fridley Terrace MHP 2	10.5	Shakopee aquifer and Oneota confining unit	Anoka	12	30	24
206660b	Fridley Terrace MHP 2	10.5	Jordan aquifer	Anoka	12	30	24
206660c	Fridley Terrace MHP 2	10.5	St. Lawrence confining unit	Anoka	12	30	24
206660d	Fridley Terrace MHP 2	10.5	Upper Tunnel City aquifer and Lower Tunnel City confining unit	Anoka	12	30	24
206660e	Fridley Terrace MHP 2	10.5	Wonewoc aquifer	Anoka	12	30	24
236512a	Gordon Rendering Co	0.3	Shakopee aquifer and Oneota confining unit	Ramsey	21	30	23
236512b	Gordon Rendering Co	0.3	Jordan aquifer	Ramsey	21	30	23
566113a	Green Value Nursery	7.2	Shakopee aquifer and Oneota confining unit	Anoka	1	31	22
566113b	Green Value Nursery	7.2	Jordan aquifer	Anoka	1	31	22
476680	Heather Ridge Town House	11.4	Shakopee aquifer and Oneota confining unit	Ramsey	1	30	23
654497	Hugo 3	23.5	Jordan aquifer	Washington	20	31	21
671642	Hugo 4	28.2	Jordan aquifer	Washington	20	31	21
235543	Kurt Manufacturing	1.7	Shakopee aquifer and Oneota confining unit	Anoka	27	30	24
538076	Kurt Manufacturing RW-C	30.5	Surficial aquifer system: deep flow zone	Anoka	27	30	24
208996a	Lexington 1	46.6	Shakopee aquifer and Oneota confining unit	Anoka	35	31	23
208996b	Lexington 1	46.6	Jordan aquifer	Anoka	35	31	23
208996c	Lexington 1	46.6	St. Lawrence confining unit	Anoka	35	31	23
240171a	Lino Lakes 1	73.2	Shakopee aquifer and Oneota confining unit	Anoka	28	31	22
240171b	Lino Lakes 1	73.2	Jordan aquifer	Anoka	28	31	22
110471	Lino Lakes 2	168.6	Jordan aquifer	Anoka	30	31	22
559373a	Lino Lakes 3	101.4	Shakopee aquifer and Oneota confining unit	Anoka	28	31	22
559373b	Lino Lakes 3	101.4	Jordan aquifer	Anoka	28	31	22
554207	Lino Lakes 4	135.2	St. Lawrence confining unit	Anoka	25	31	22

Table 4. Simulated groundwater extraction rates of wells on August 20, 2001, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.—Continued

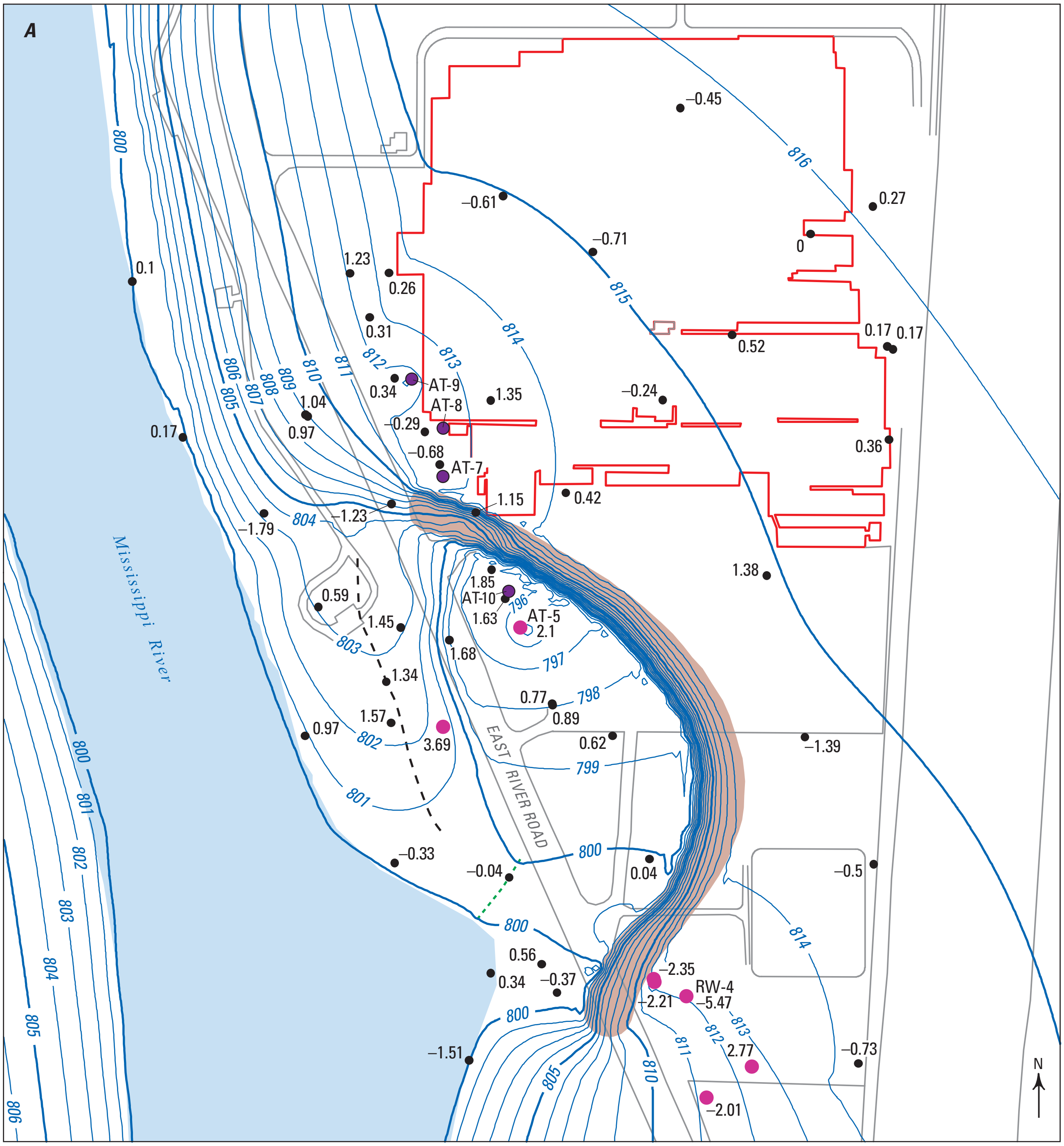
[Counties are shown in figure 1. Well locations are not shown in this report, see Metropolitan Council (2009). Data are from Metropolitan Council (2009). gal/min, gallon per minute]

Well number	Well name	Groundwater extraction rate (gal/min)	Hydrogeologic unit	County	Section	Township	Range
694492a	Lino Lakes Elementary	0.4	Shakopee aquifer and Oneota confining unit	Anoka	29	31	22
694492b	Lino Lakes Elementary	0.4	Jordan aquifer	Anoka	29	31	22
436687a	Meredith, Harvey	4.5	Shakopee aquifer and Oneota confining unit	Anoka	1	31	22
436687b	Meredith, Harvey	4.5	Jordan aquifer	Anoka	1	31	22
480297	Metropolitan Council	4.7	Surficial aquifer system: deep flow zone	Hennepin	35	119	21
208566a	MN CF - Lino Lakes 1	32.9	Upper Tunnel City aquifer and Lower Tunnel City confining unit	Anoka	18	31	22
208566b	MN CF - Lino Lakes 1	32.9	Wonewoc aquifer	Anoka	18	31	22
206721a	Mounds View 1	82.9	Upper Tunnel City aquifer and Lower Tunnel City confining unit	Ramsey	8	30	23
206721b	Mounds View 1	82.9	Wonewoc aquifer	Ramsey	8	30	23
206720	Mounds View 3	130.0	Jordan aquifer	Ramsey	8	30	23
206722a	Mounds View 5	146.4	Shakopee aquifer and Oneota confining unit	Ramsey	8	30	23
206722b	Mounds View 5	146.4	Jordan aquifer	Ramsey	8	30	23
206717a	Mounds View 6	55.1	Jordan aquifer	Ramsey	7	30	23
206717b	Mounds View 6	55.1	St. Lawrence confining unit	Ramsey	7	30	23
206717c	Mounds View 6	55.1	Upper Tunnel City aquifer and Lower Tunnel City confining unit	Ramsey	7	30	23
206717d	Mounds View 6	55.1	Wonewoc aquifer	Ramsey	7	30	23
206793a	New Brighton 3	70.7	Shakopee aquifer and Oneota confining unit	Ramsey	30	30	23
206793b	New Brighton 3	70.7	Jordan aquifer	Ramsey	30	30	23
206793c	New Brighton 3	70.7	St. Lawrence confining unit	Ramsey	30	30	23
206792a	New Brighton 4	217.4	Shakopee aquifer and Oneota confining unit	Ramsey	30	30	23
206792b	New Brighton 4	217.4	Jordan aquifer	Ramsey	30	30	23
206792c	New Brighton 4	217.4	St. Lawrence confining unit	Ramsey	30	30	23
206796	New Brighton 5	80.1	Jordan aquifer	Ramsey	30	30	23
206797	New Brighton 6	70.5	Jordan aquifer	Ramsey	30	30	23
206795a	New Brighton 8	7.9	Shakopee aquifer and Oneota confining unit	Ramsey	30	30	23
206795b	New Brighton 8	7.9	Jordan aquifer	Ramsey	30	30	23
206795b	New Brighton 8	7.9	St. Lawrence confining unit	Ramsey	30	30	23
582628a	New Brighton 15	276.4	Shakopee aquifer and Oneota confining unit	Ramsey	30	30	23
582628b	New Brighton 15	276.4	Jordan aquifer	Ramsey	30	30	23

Table 4. Simulated groundwater extraction rates of wells on August 20, 2001, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.—Continued

[Counties are shown in figure 1. Well locations are not shown in this report, see Metropolitan Council (2009). Data are from Metropolitan Council (2009). gal/min, gallon per minute]

Well number	Well name	Groundwater extraction rate (gal/min)	Hydrogeologic unit	County	Section	Township	Range
453826a	PJ #310 310-# B-9	90.4	Shakopee aquifer and Oneota confining unit	Ramsey	16	30	23
453826b	PJ #310 310-# B-9	90.4	Jordan aquifer	Ramsey	16	30	23
453827a	PJ #311 311-# B-10	83.8	Shakopee aquifer and Oneota confining unit	Ramsey	16	30	23
453827b	PJ #311 311-# B-10	83.8	Jordan aquifer	Ramsey	16	30	23
453825	PJ#309 309-# B-8	127.6	Jordan aquifer	Ramsey	16	30	23
453828a	PJ#313 313-# B-12	15.5	Shakopee aquifer and Oneota confining unit	Ramsey	16	30	23
453828b	PJ#313 313-# B-12	15.5	Jordan aquifer	Ramsey	16	30	23
208651	Restwood Terrace 1	24.6	Shakopee aquifer and Oneota confining unit	Anoka	35	31	23
231862a	Robinson Landscaping	8.4	Jordan aquifer	Anoka	7	31	22
624188a	Robinson, Butch	3.4	Jordan aquifer	Anoka	6	31	22
431653	RW-2	17.0	Surficial aquifer system: deep flow zone	Anoka	34	30	24
431654	RW-3	30.3	Surficial aquifer system: deep flow zone	Anoka	34	30	24
431655a	RW-4	12.3	Surficial aquifer system: deep flow zone	Anoka	27	30	24
431656a	RW-5	10.3	Surficial aquifer system: deep flow zone	Anoka	27	30	24
538605	Silverthorn Estates Assoc.	9.0	Shakopee aquifer and Oneota confining unit	Ramsey	3	30	23
206638a	Spring Lake Park 1	37.9	Upper Tunnel City aquifer and Lower Tunnel City confining unit	Anoka	2	30	24
206638b	Spring Lake Park 1	37.9	Wonewoc aquifer	Anoka	2	30	24
223294a	Spring Lake Park 2	35.5	St. Lawrence confining unit	Anoka	2	30	24
223294b	Spring Lake Park 2	35.5	Upper Tunnel City aquifer and Lower Tunnel City confining unit	Anoka	2	30	24
223294c	Spring Lake Park 2	35.5	Wonewoc aquifer	Anoka	2	30	24
206637a	Spring Lake Park 3	2.2	St. Lawrence confining unit	Anoka	2	30	24
206637b	Spring Lake Park 3	2.2	Upper Tunnel City aquifer and Lower Tunnel City confining unit	Anoka	2	30	24
206637c	Spring Lake Park 3	2.2	Wonewoc aquifer	Anoka	2	30	24
538124a	The Bridges Golf Course	3.3	Shakopee aquifer and Oneota confining unit	Ramsey	5	30	23
538124b	The Bridges Golf Course	3.3	Jordan aquifer	Ramsey	5	30	23
516061	TPI Petroleum Inc	2.0	Surficial aquifer system: deep flow zone	Hennepin	34	119	21
208989a	Trout Aire	30.8	St. Lawrence confining unit	Anoka	25	32	22
208989b	Trout Aire	30.8	Upper Tunnel City aquifer and Lower Tunnel City confining unit	Anoka	25	32	22
208989c	Trout Aire	30.8	Wonewoc aquifer	Anoka	25	32	22



Base furnished by U.S. Department of the Navy
North American Datum of 1983

0 250 500 750 1,000 FEET
0 50 100 150 200 250 METERS

EXPLANATION

- Clay ridge
- 800 — **Simulated potentiometric head, simulation layer 1**—Contour interval 1 foot. Datum is North American Vertical Datum of 1988
- **Ridge of higher potentiometric head along central axis of lobe of higher potentiometric head**
- **Centerline of saddle feature**
- **Main Naval Industrial Reserve Ordnance Plant building**
- 1.34, 2.1 **Potentiometric-head residuals, simulation layer 1, in feet**—Larger magenta symbol is residual that exceeds 2 feet
- AT-7 **Extraction well and identifier**

Figure 14. Simulated potentiometric head in the shallow flow zone of the surficial aquifer system on August 20, 2001. *A*, the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota. *B*, the study area in and near the Naval Industrial Ordnance Plant, Fridley, Minnesota.

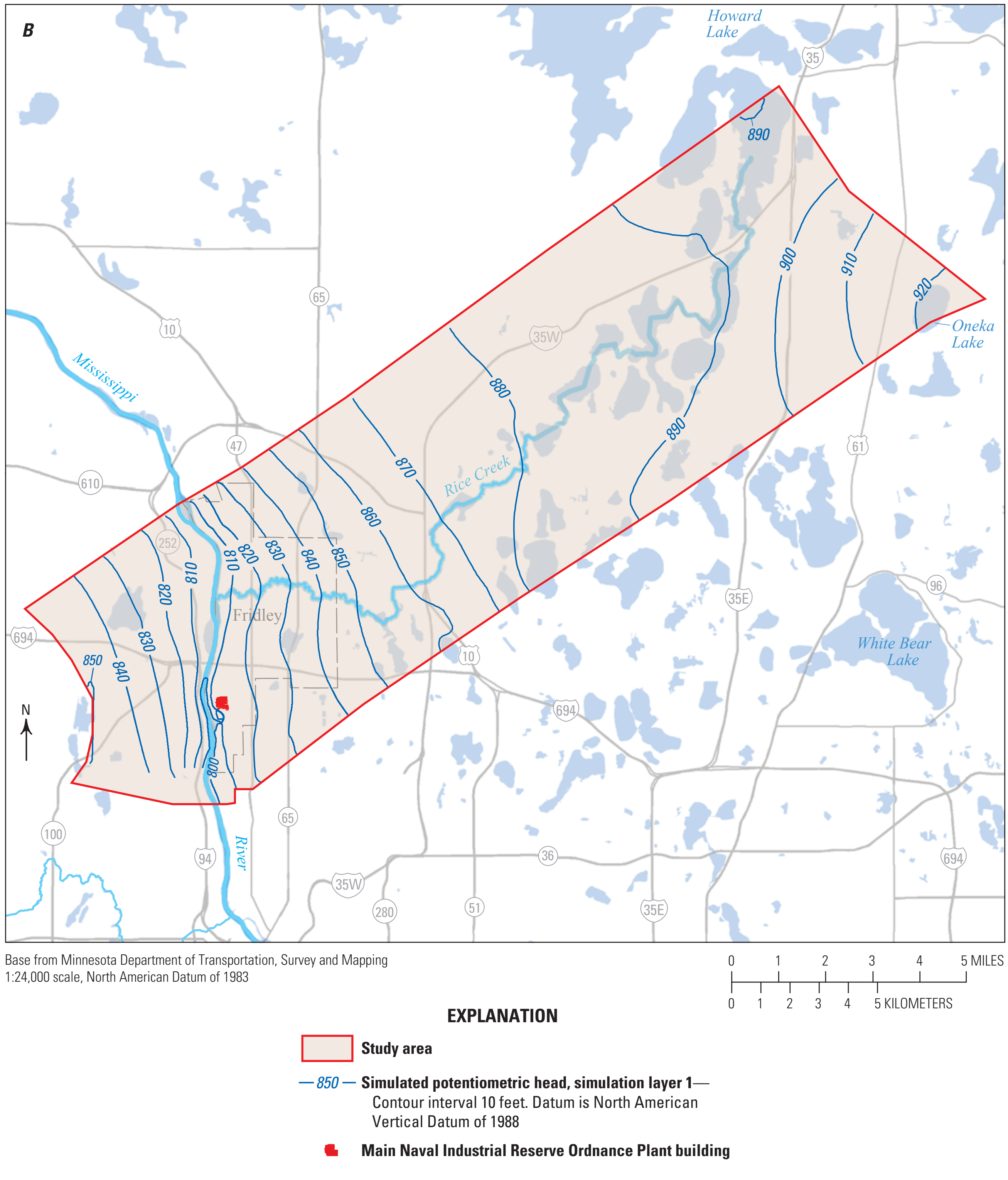
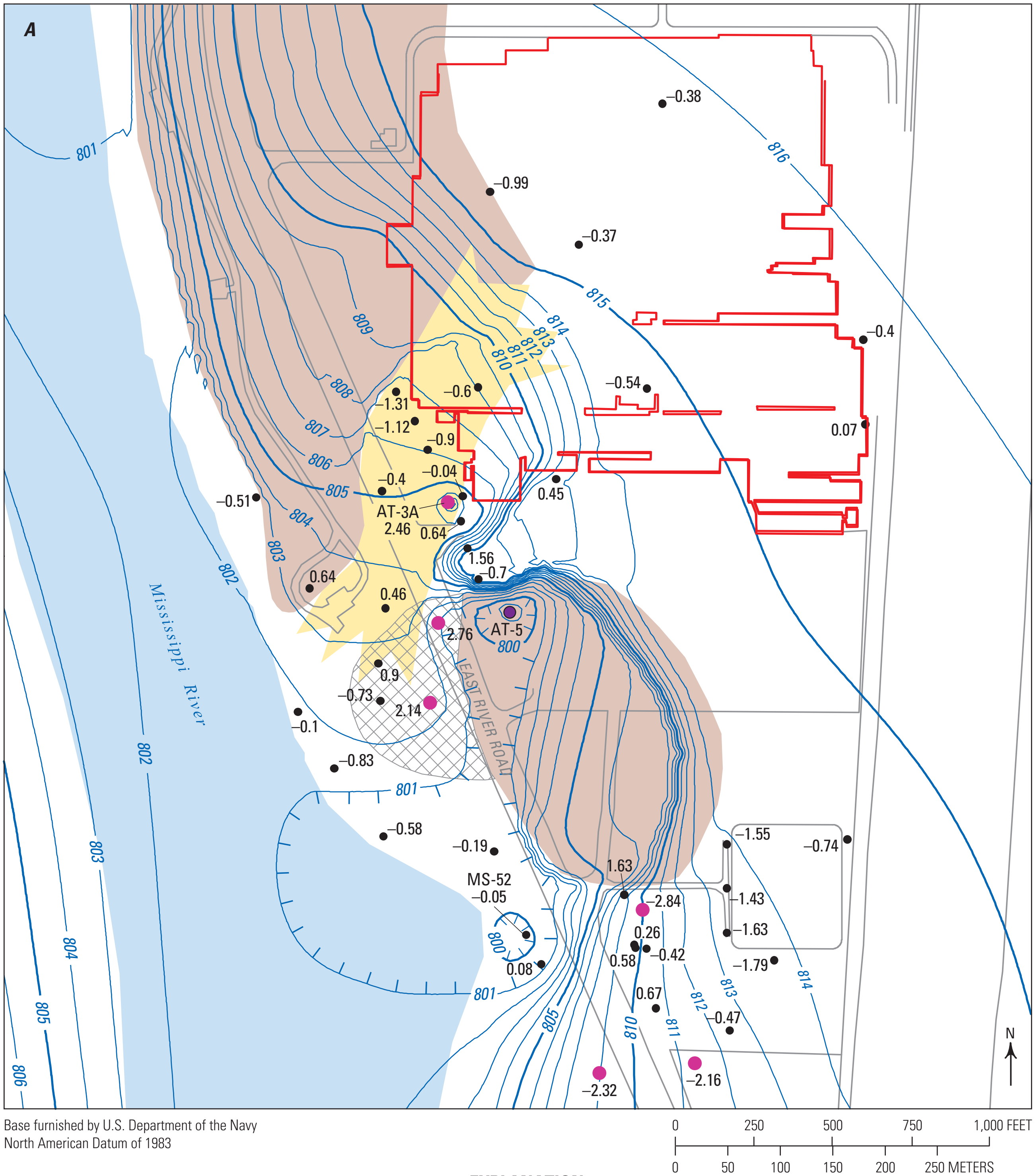


Figure 14. Simulated potentiometric head in the shallow flow zone of the surficial aquifer system on August 20, 2001. *A*, the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota. *B*, the study area in and near the Naval Industrial Ordnance Plant, Fridley, Minnesota.—Continued

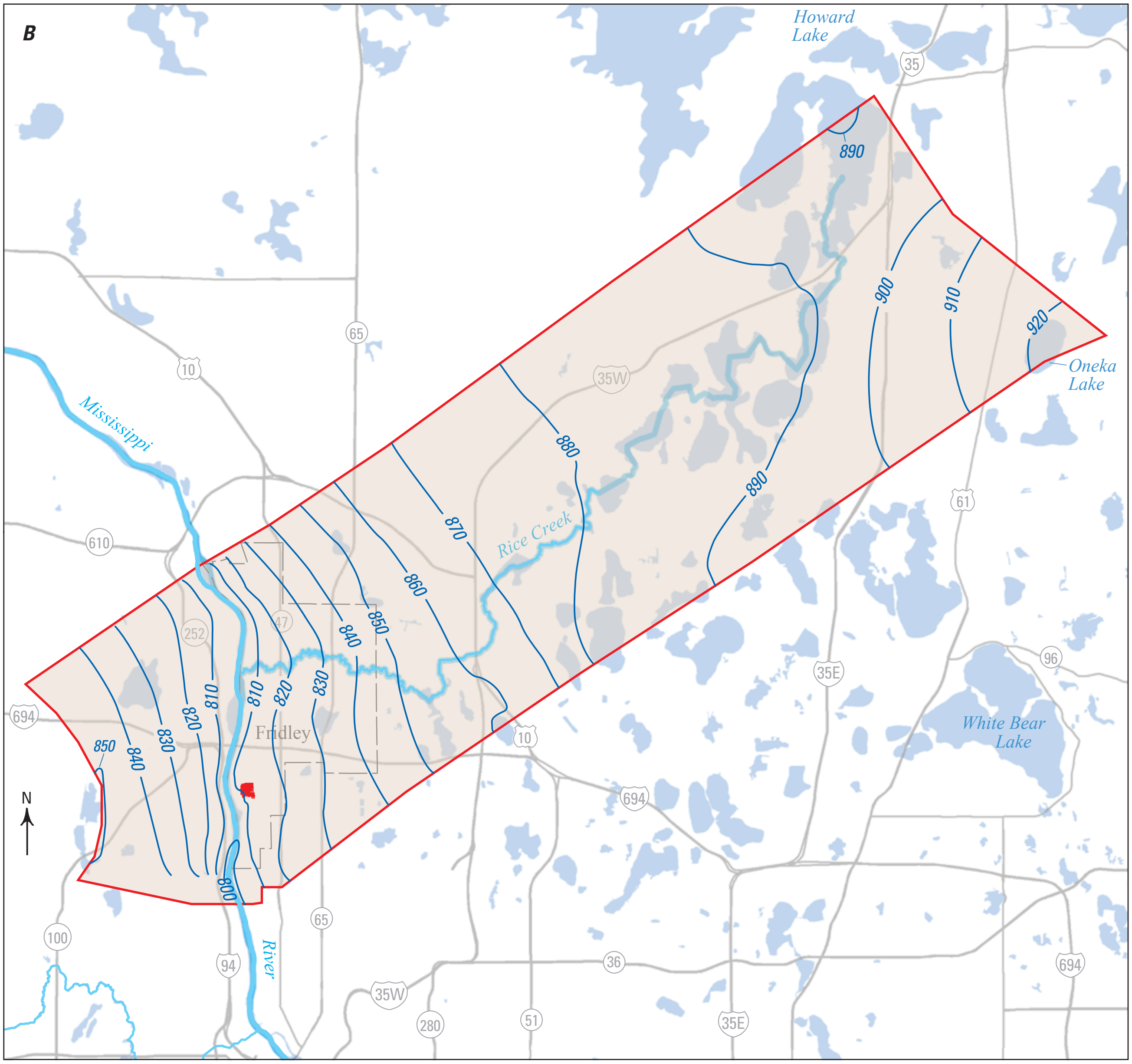


Base furnished by U.S. Department of the Navy
North American Datum of 1983

EXPLANATION

- Intermediate clay
- Intermediate silt
- High permeability Paleo-channel
- 800 — **Simulated potentiometric head, simulation layer 3**—Hachures indicate depression. Contour interval 1 foot. Datum is North American Vertical Datum of 1988
- **Main Naval Industrial Reserve Ordnance Plant building**
- −0.42, −2.16 **Potentiometric-head residuals, simulation layer 3, in feet**—Larger magenta symbol is residual that exceeds 2 feet
- AT-5 **Extraction well and identifier**

Figure 15. Simulated potentiometric head in the intermediate flow zone of the surficial aquifer system on August 20, 2001, Fridley, Minnesota. *A*, the Naval Industrial Reserve Ordnance Plant. *B*, the study area in and near the Naval Industrial Ordnance Plant.



EXPLANATION

Study area

— *850* — **Simulated potentiometric head, simulation layer 3**—Contour interval 10 feet. Datum is North American Vertical Datum of 1988

Main Naval Industrial Reserve Ordnance Plant building

Figure 15. Simulated potentiometric head in the intermediate flow zone of the surficial aquifer system on August 20, 2001, Fridley, Minnesota. *A*, the Naval Industrial Reserve Ordnance Plant. *B*, the study area in and near the Naval Industrial Ordnance Plant.—Continued

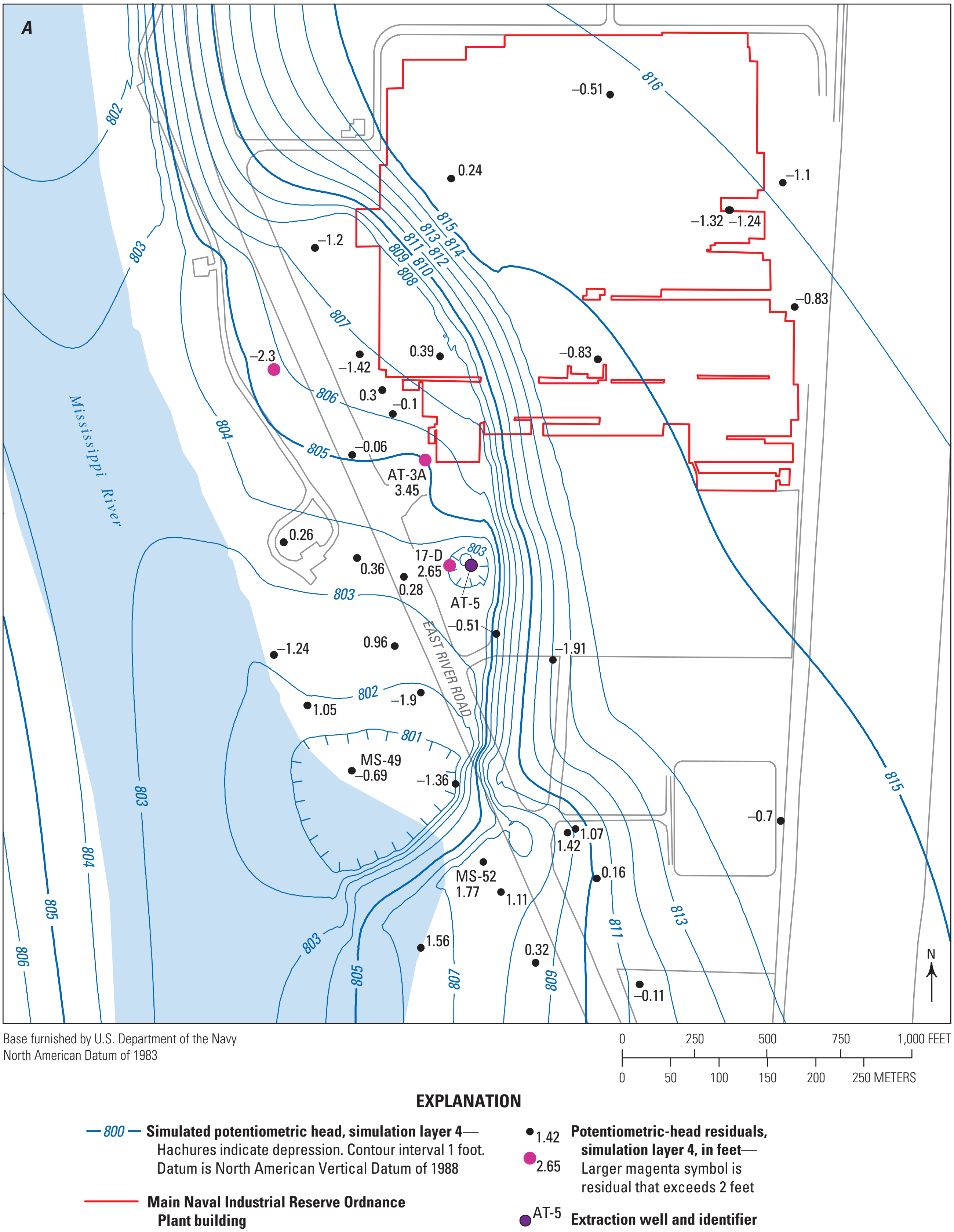


Figure 16. Simulated potentiometric head in the deep flow zone of the surficial aquifer system on August 20, 2001, Fridley, Minnesota. *A*, the Naval Industrial Reserve Ordnance Plant. *B*, the study area in and near the Naval Industrial Ordnance Plant.

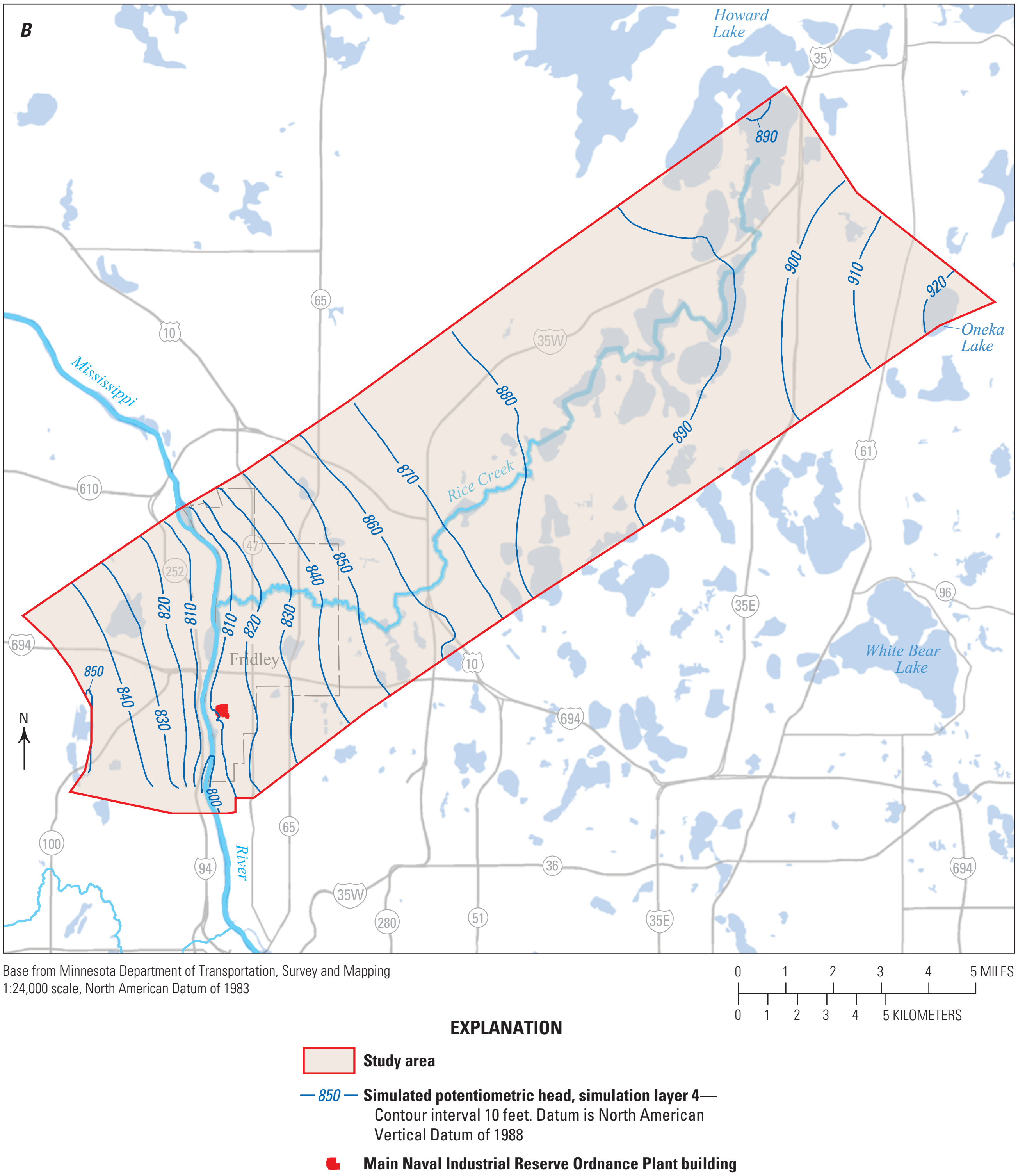


Figure 16. Simulated potentiometric head in the deep flow zone of the surficial aquifer system on August 20, 2001, Fridley, Minnesota. *A*, the Naval Industrial Reserve Ordnance Plant. *B*, the study area in and near the Naval Industrial Ordnance Plant.—Continued

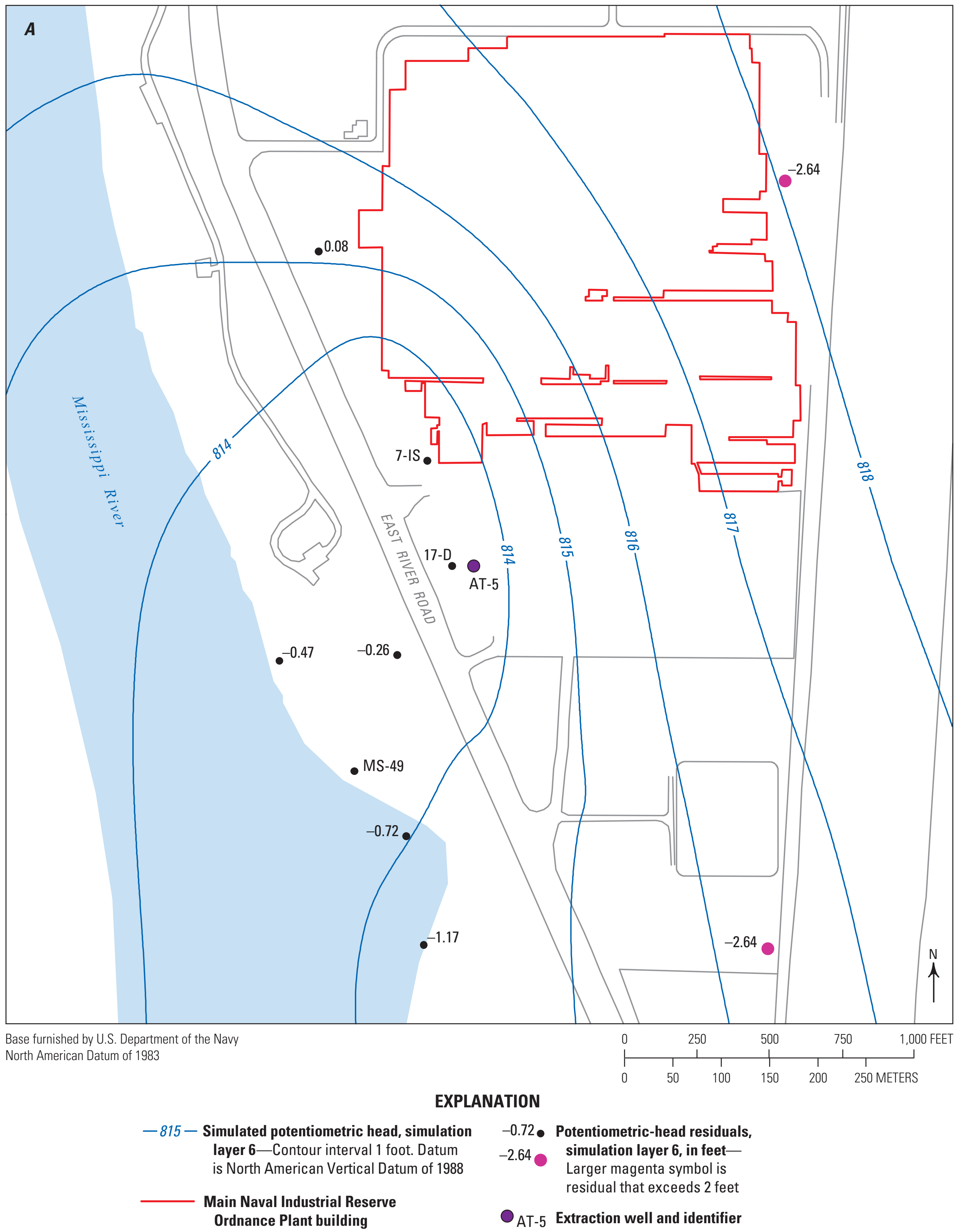
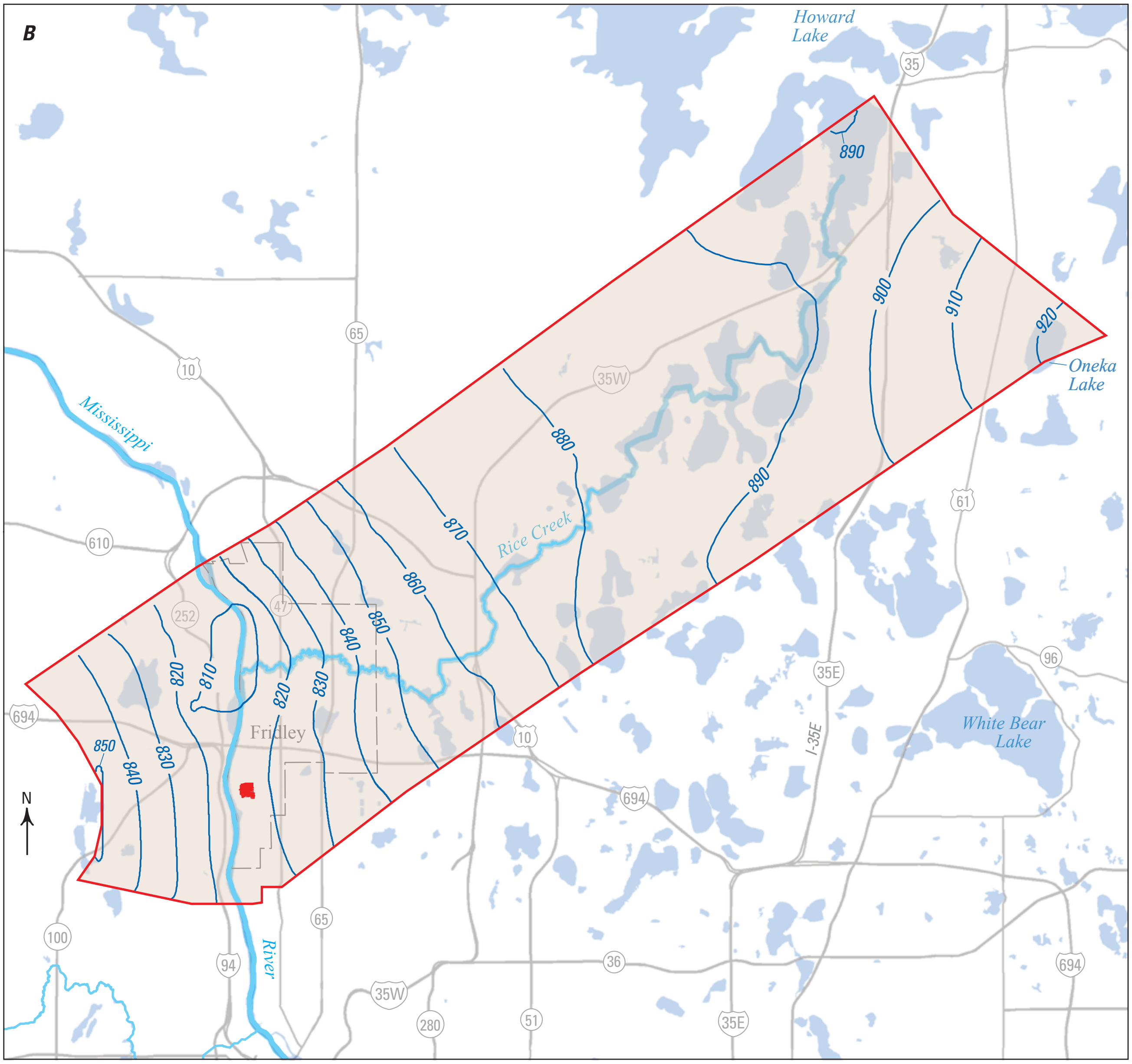


Figure 17. Simulated potentiometric head in the Shakopee aquifer on August 20, 2001, Fridley, Minnesota. *A*, the Naval Industrial Reserve Ordnance Plant. *B*, the study area in and near the Naval Industrial Ordnance Plant.



Base from Minnesota Department of Transportation, Survey and Mapping
1:24,000 scale, North American Datum of 1983

0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

EXPLANATION

Study area

— *850* — **Simulated potentiometric head, simulation layer 6**—Contour interval 10 feet. Datum is North American Vertical Datum of 1988

Main Naval Industrial Reserve Ordnance Plant building

Figure 17. Simulated potentiometric head in the Shakopee aquifer on August 20, 2001, Fridley, Minnesota. *A*, the Naval Industrial Reserve Ordnance Plant. *B*, the study area in and near the Naval Industrial Ordnance Plant.—Continued

such that potentiometric head was higher in clay areas on the edge of a transect perpendicular to the central axis of the paleo-channel and lower in the paleo-channel. A cone of depression at extraction well AT–3 and potentiometric head conformance to the paleo-channel were shown on a contour map of potentiometric head measured on August 20, 2001 (fig. 10). The contour map of measured potentiometric head included cones of depression in the intermediate flow zone of the surficial aquifer system at extraction wells AT–10 and RW–5 (fig. 3), which were not apparent in model simulation results.

Simulated potentiometric heads compared favorably to 38 of 44 potentiometric-head measurements on August 20, 2001, in the intermediate flow zone of the surficial aquifer system; the absolute value of simulated potentiometric head minus measured potentiometric head was less than 2 ft at 38 locations and greater than 2 ft at 6 locations (fig. 15*A*). Simulated and measured potentiometric heads were not compared in the intermediate flow zone near the location of extraction well AT–5. Stresses from extraction wells on the FMC Corp. (Fridley Plant) EPA Superfund site, southeast of the crescent-shaped clay area, were not simulated; measured, stressed potentiometric head was 2.84 ft less than simulated, unstressed potentiometric head near extraction well RW–5 at the FMC Corp. (Fridley Plant) EPA Superfund site.

Simulated potentiometric head in the deep flow zone of the surficial aquifer system ranged from 816 ft on the northeastern side of NIROP to 801 ft under the Mississippi River near well MS–49 (fig. 16*A*). The simulated potentiometric-head gradient was steepest across a band with relatively lower simulated horizontal and vertical hydraulic conductivities that cross the southwestern corner of the main NIROP building (figs. 15*A* and 15*B*). The simulated potentiometric head decreased from 815 to 808 ft across the band with a width of 200 ft. A cone of depression was simulated in the deep flow zone of the surficial aquifer system at extraction well AT–5B (fig. 3). A depression in simulated potentiometric head existed around well MS–49. The depression around well MS–49 conforms to an area of relatively higher simulated vertical hydraulic conductivity in the deep flow zone of the surficial aquifer system (fig. 15*B*). The depression was bounded on the southeast by an area of relatively lower simulated horizontal hydraulic conductivity (fig. 15*A*). The area of higher simulated vertical hydraulic conductivity drains groundwater from the deep flow zone of the surficial aquifer system to the overlying intermediate flow zone. Simulated potentiometric head in the Shakopee aquifer was 814 ft in this area of vertical groundwater flow toward the Mississippi River. The area of relatively lower simulated horizontal hydraulic conductivity directs simulated groundwater flowing from the north and west into the drain defined by the area of higher simulated vertical hydraulic conductivity. The steep potentiometric-head gradient across a narrow band that crossed the southwestern corner of the main building, the cone of depression at extraction well AT–5B, and the depression in potentiometric head around well MS–49 were shown on a contour map of potentiometric head measured on August 20, 2001, in the deep flow zone of the surficial aquifer system (fig. 11). Simulated potentiometric heads compare favorably to 33 of 36 measurements on August 20, 2001, in the deep flow zone of the surficial aquifer system; the absolute value of simulated minus measured potentiometric head was less than 2 ft at 33 locations and greater than 2 ft at 3 locations (fig. 16*A*). Measured potentiometric head was 3.45 ft greater than simulated potentiometric head in the deep flow zone near well 7–IS (fig. 3).

Simulated potentiometric head in the Shakopee aquifer ranged from 818 ft on the northeastern side of NIROP to 814 ft under the Mississippi River (fig. 17*A*). Groundwater in the model simulation flows vertically under the Mississippi River from regions of higher potentiometric head deeper in the Cambrian-Ordovician aquifer system to regions of lower potentiometric head in the surficial aquifer system (figs. 14*B,* 15*B*, 16*B*, and 17*B*). This potentiometric-head gradient forces benthic discharge flux to the Mississippi River where simulated potentiometric head was the lowest in the vertical section under the Mississippi River (appendix 1) (Lindgren, 1990). Simulated potentiometric heads compare favorably to five of seven potentiometric-head measurements on August 20, 2001, in the Shakopee aquifer; the absolute value of simulated potentiometric head minus measured potentiometric head was less than 2 ft at five locations and greater than 2 ft at two locations (fig. 17*A*). Measured potentiometric head was 2.64 ft less than simulated potentiometric head near wells FMC–32 and 3–PC (fig. 3).

The groundwater model simulation was mass conservative. Water entered the study area across constant potentiometric-head boundaries, as recharge at land surface and as benthic recharge flux from surface-water bodies (appendix 1). The recharge calculation conforms to Metropolitan Council (2009) and Dripps and Bradbury's (2007) daily soil water balance method. Specifically, 9 percent of total influx entered the study area across constant potentiometric-head boundaries during the steady-state simulation, 63 percent of total influx recharged the study area across land surface, and 28 percent of total influx entered the study area as benthic recharge flux across beds of rivers and lakes. Water exited the study area across constant potentiometric-head boundaries, as benthic discharge flux to surface-water bodies, and through wells and drains. Specifically, less than 0.1 percent of total efflux exited the study area across constant potentiometric-head boundaries during the steady-state simulation, 25 percent of total efflux exited the study area through wells, less than 1 percent of total efflux exited the study area through drains, and 74 percent of total efflux exited the study area as benthic discharge flux to rivers and lakes.

Simulated potentiometric heads were within 2 ft of measured potentiometric heads at most locations for the August 20, 2001, model simulation (appendix 1, fig. 1–22). Changes to the August 20 simulation to reduce differences between simulated and measured potentiometric head are detailed in appendix 1.

Preliminary Simulation of Trichloroethene Transport

The objective of the preliminary simulation of TCE transport (Davis and King, 2016) was to develop a general characterization of TCE transport at and near NIROP for 2001. The TCE transport simulation was forced by a steady-state groundwater flow simulation for August 20, 2001. Trichloroethene transport was simulated using the numerical model MT3DMS (Zheng and Wang, 1998). This preliminary simulation of TCE transport can be used to plan a more detailed groundwater flow and TCE transport simulation based on transient forcing.

Source areas and concentrations of TCE for this preliminary model simulation were furnished by the Navy to the USGS. The Navy did not describe all TCE sources in Fridley, Minn. (fig. 2), with furnished TCE source areas. Trichloroethene was measured in the surficial aquifer system upgradient of delineated source areas, and in bedrock beneath the surficial aquifer system at or near NIROP and other locations in Fridley, Minn. (Minnesota Pollution Control Agency, 1999, 2004, 2009, 2013a, 2013b, 2014a, 2014b, 2014c, 2015; Papadopulos and others, 1984; RMT, 1987, 1988a, 1988b, 1988c; Tetra Tech, 2003, 2008, 2013a; U.S. Environmental Protection Agency, 1987, 1990, 2003 [records of decision] and 1992b, 1998, 2012a, 2012b, 2014). Furnished TCE source area delineations and concentrations were informed by data collected from 1995 to 2011. Although informed by collected data, furnished source areas were homogeneous postulations that represent more complex, heterogeneous TCE distributions. The following TCE transport simulation components are detailed in appendix 2: spatial and temporal discretization, initial TCE concentrations, transport parameters, numerical solution for TCE concentration, and calibration.

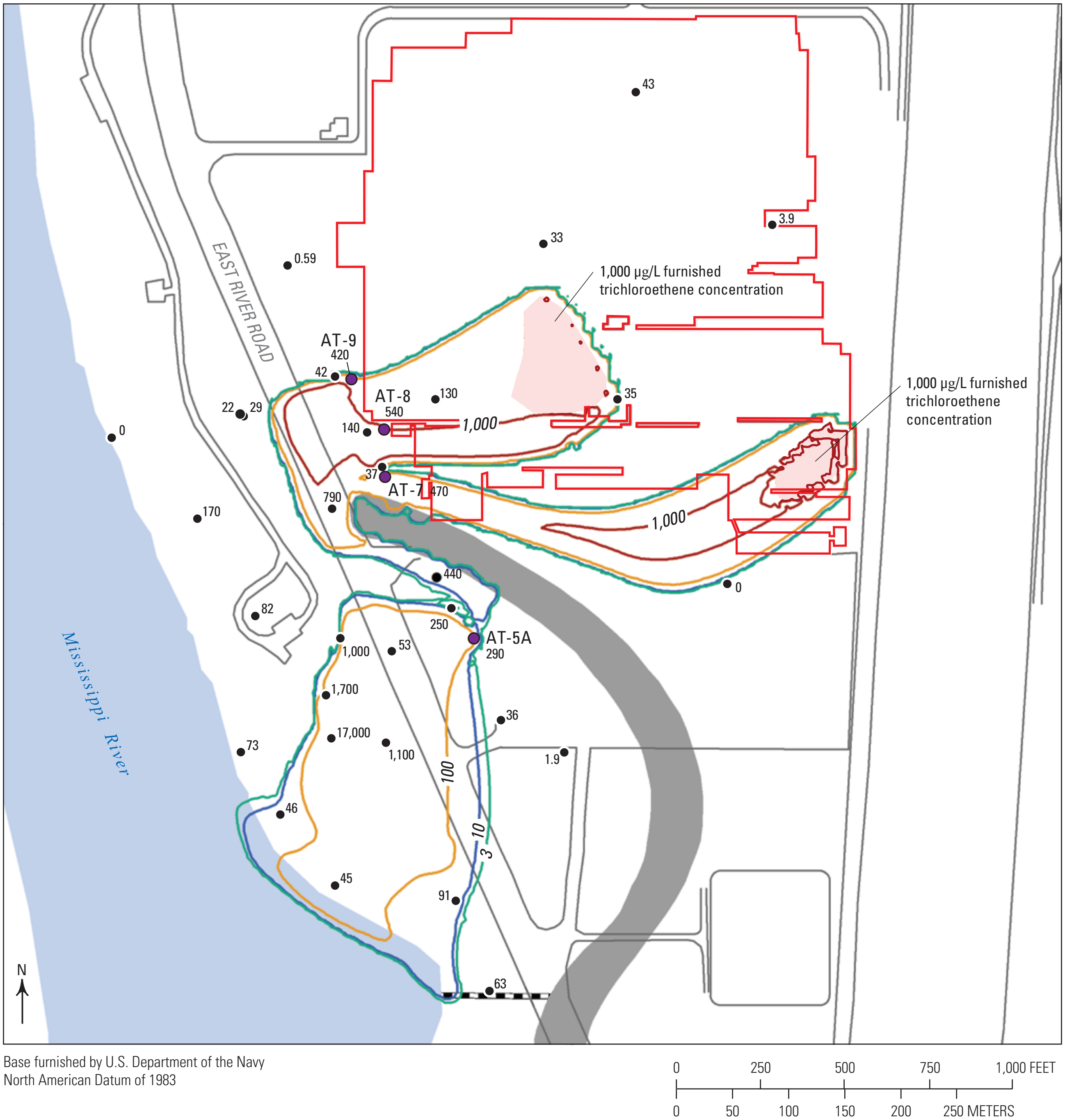
Steady-state groundwater flow is simulated by eliminating products that include the partial differential for time, ∂t, in the governing differential equation. This method cannot be used to simulate steady-state constituent transport. A steady-state transport solution is forced by a steady-state groundwater flow solution applied to a steady-state constituent source area until the transient concentration of the transported constituent does not change.

Transport of TCE was simulated for 2001. The model simulation was forced by the August 20, 2001, steady-state groundwater flow simulation (appendix 1; figs. 14–17) applied to furnished, northern and southern TCE source areas (fig. 18). The northern source area had a constant, 1,000-µg/L TCE concentration in the upper part of the shallow flow zone of the surficial aquifer system (fig. 18) and a constant, 50,000-µg/L TCE concentration in the lower part of the shallow flow zone (not shown). The southern source area had a constant, 1,000-µg/L TCE concentration in the upper part of the shallow flow zone of the surficial aquifer system (fig. 18) and a constant, 12,000-µg/L TCE concentration in the lower part of the shallow flow zone (not shown). The groundwater flow simulation was forced by groundwater extraction at NIROP (table 2) in Fridley, Minn. (table 3), and other parts of the study area (table 3). Transport of TCE was simulated for 3,000 days from June 3, 1993, to August 20, 2001. It was postulated that 3,000 days of transport were sufficient for TCE concentrations to reach a steady state; however, this postulation was not tested.

In the shallow flow zone, TCE was transported to the west from the northern source area to extraction wells AT–7, AT–8, and AT–9 (fig. 18, appendix 2). A simulated 1,000-µg/L maximum TCE concentration contour extended from the northern source area east of the extraction wells to an area west and downgradient of the extraction wells. Simulated TCE was transported to the west from the southern source area to extraction well AT–7 (fig. 3). In the shallow flow zone, a 1,000-µg/L, maximum TCE concentration contour extended from the southern source area to a midpoint between the source area and extraction well. A 100-µg/L, simulated TCE concentration contour connected the southern source area and extraction well AT–7. Simulated TCE from the northern source area joined simulated TCE from the southern source area near extraction well AT–7. The simulated TCE plume in the upper part of the shallow flow zone of the surficial aquifer system near extraction wells AT–7, AT–8, and AT–9 was directed southward by an area of relatively lower hydraulic conductivity between the Mississippi River and extraction wells AT–7, AT–8, and AT–9 (figs. 12*A*, 12*B*, and 18). The simulated TCE plume in this area was a combination of simulated TCE from the northern and southern source areas. The simulated TCE plume was directed southeastward and forced by extraction well AT–5A and simulated hydraulic conductivity in the crescent-shaped clay ridge. Simulated hydraulic conductivity in the crescent-shaped clay ridge is orders of magnitude lower than proximate units. The simulated plume narrows along the southern side of the clay ridge with a maximum, simulated, 10-µg/L TCE concentration contour. Downgradient of extraction well AT–5A, the simulated TCE plume widens, and extends to the south, into the Mississippi River. The maximum, simulated TCE concentration contour was 100 µg/L at the interface between the upper part of the shallow flow zone of the surficial aquifer system and Mississippi River.

In the upper part of the shallow flow zone of the surficial aquifer system, the simulated TCE plume did not conform to measured TCE concentrations at 16 of 34 selected locations (fig. 18); for example, downgradient of extraction well AT–5A, three TCE concentration measurements of 1,100, 1,700, and 17,000 µg/L existed in an area where TCE concentrations greater than 1,000 µg/L were not simulated. Between extraction wells AT–5A and AT–7, measured TCE concentrations of 250 and 440 µg/L existed in an area where TCE concentrations greater than 100 µg/L were not simulated. West of the simulated plume, between the simulated plume and Mississippi River, measured TCE concentrations of 170, 82, 73, 29, and 22 µg/L existed in an area where TCE concentrations greater than 3 µg/L were not simulated.

In the lower part of the shallow flow zone of the surficial aquifer system, the furnished TCE source area concentration was 50,000 µg/L in the northern source area and 12,000 µg/L in the southern source area (fig. 18, appendix 2). As a DNAPL, TCE may be present where TCE concentration in groundwater



EXPLANATION

Trichloroethene source area in shallow flow zone of surficial aquifer system—Delineation and concentration furnished by U.S. Department of the Navy

Clay ridge

Main Naval Industrial Reserve Ordnance Plant building

Simulated trichloroethene concentration, simulation layer 1, in micrograms per liter

3 10 100 1,000

AT-5A **Extraction well and identifier**

63 **Well in shallow flow zone of surficial aquifer system and measured trichloroethene concentration, in micrograms per liter, 2001**—Concentration and location furnished by U.S. Department of the Navy

Figure 18. Simulated and measured trichloroethene concentrations in 2001 in the upper part of the shallow flow zone of the surficial aquifer system, at and near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.

is greater than 14,720 µg/L at 25 °C. In this preliminary model simulation, DNAPL transport processes were not incorporated at the northern source area where the TCE concentration was 50,000 µg/L. Simulated TCE concentration contours in the intermediate flow zone of the surficial aquifer system were a maximum of 10,000 µg/L below the northern source area and 1,000 µg/L below the southern source area (fig. 19). Trichloroethene was transported to the southwest by the groundwater flow simulator (appendix 1, figs. 14–17) from an area in the intermediate flow zone, under the northern source area in the lower part of the shallow flow zone, to extraction well AT–3A. A 10,000-µg/L, maximum, simulated TCE concentration contour extended from this area in the intermediate flow zone, under the northern source area, to within 100 ft of extraction well AT–3A. Simulated TCE was transported to the west from an area under the southern source area to an area west and downgradient of extraction wells AT–3A, AT–5A, AT–5B, and AT–10. A 1,000-µg/L, maximum, simulated TCE concentration contour extended from an area in the intermediate flow zone under the southern source area in the lower part of the shallow flow zone to the west and downgradient of East River Road. Simulated TCE from the northern source area joined simulated TCE from the southern source area between extraction wells AT–3A and AT–10 (fig. 19).

Simulated TCE was transported from the shallow flow zone to the intermediate flow zone of the surficial aquifer system. Simulated TCE was transported in the intermediate flow zone in a paleo-channel composed of sands and gravels (figs. 10 and 19). Simulated hydraulic conductivity was relatively higher in the paleo-channel than in clay areas that bound the paleo-channel (figs. 1–14*A* and 1–14*B*). Simulated TCE in the intermediate flow zone not captured by extraction wells AT–3A, AT–5A, AT–5B, and AT–10 flowed southwest under East River Road toward the Mississippi River. Groundwater flow was directed southwest and south by an area of relatively lower hydraulic conductivity to the northwest of the plume (figs. 1–14*A* and 1–14*B*). Downgradient of East River Road, the plume narrowed to a width of about 100 ft with a maximum simulated TCE concentration contour of 100 µg/L. The intermediate flow zone of the surficial aquifer system is not directly connected to the Mississippi River; TCE in the intermediate flow zone was transported through the shallow flow zone to the Mississippi River by a potentiometric-head gradient that forced vertical groundwater flow from deeper hydrogeologic units in the Cambrian-Ordovician aquifer system to more shallow units in the surficial aquifer system (figs. 14*B*, 15*B*, 16*B*, and 17*B*) (appendix 1) (Lindgren, 1990). The maximum, simulated TCE concentration contour was 100 µg/L in the intermediate flow zone of the surficial aquifer system under the Mississippi River (fig. 19).

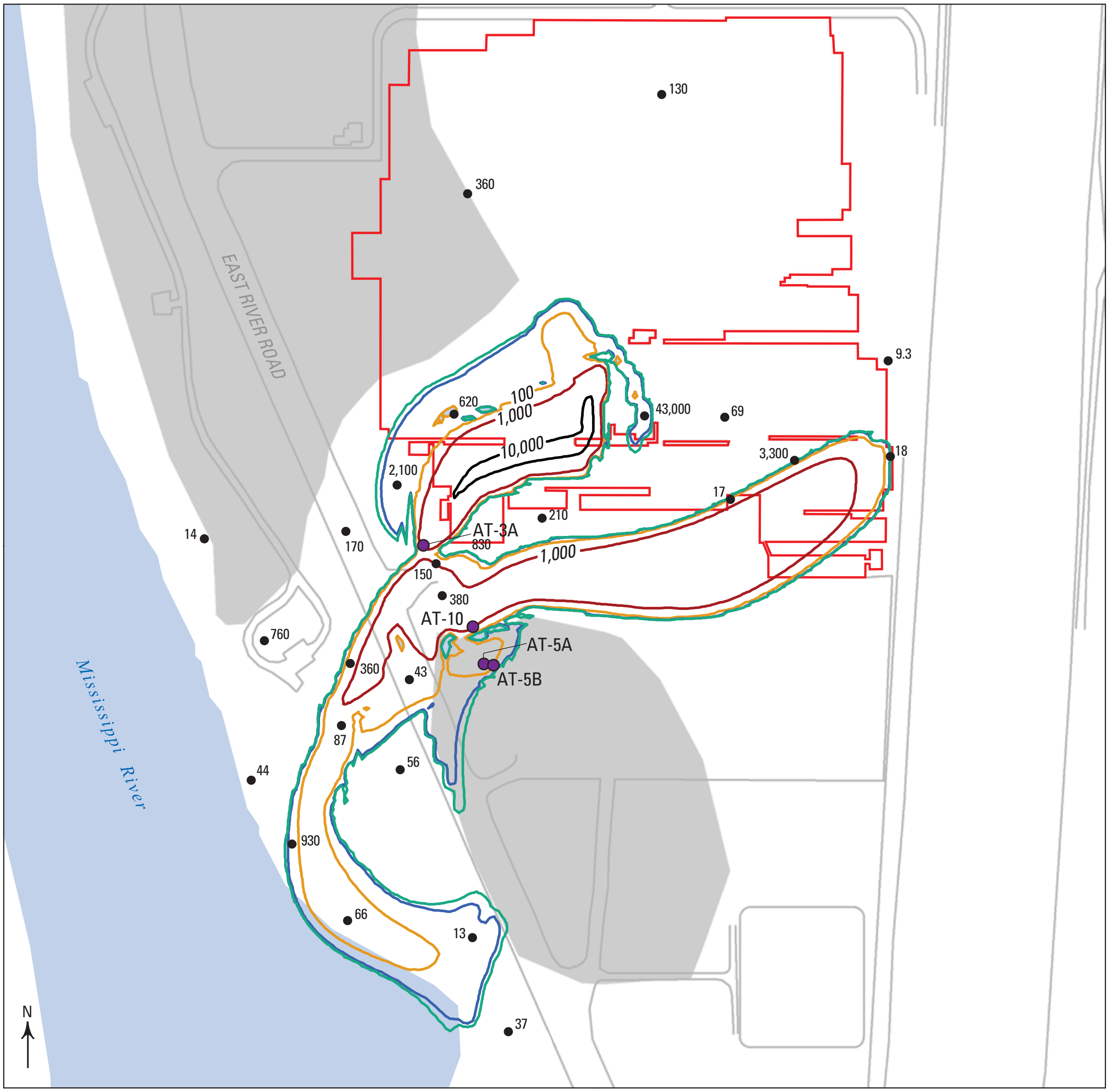
The simulated TCE plume did not conform to measured TCE concentrations at 15 of 26 selected locations in the intermediate flow zone of the surficial aquifer system (fig. 19); for example, neither the furnished northern source area nor the furnished southern source area were the source of measured TCE concentrations of 360, 130, 69, or 9.3 µg/L north and upgradient of the northern source area; other sources of TCE most probably exist at NIROP or in Fridley, Minn., in addition to the two furnished source areas considered in this preliminary TCE transport model simulation of 2001. Near the northern source area, measured TCE concentrations of 43,000, 2,100, 210, and 170 µg/L were not bounded by appropriate simulated TCE concentration contours in the intermediate flow zone; for example, the measured TCE concentration of 2,100 µg/L was between simulated 10- and 100-µg/L TCE concentration contours. Near the southern source area, the measured TCE concentration of 3,300 µg/L was also not bounded by the appropriate simulated TCE concentration contours. Downgradient of East River Road, a measured 930-µg/L TCE concentration was incorrectly bounded by simulated 10- and 100-µg/L TCE concentration contours. Trichloroethene concentrations of 760, 56, 44, and 37 µg/L were measured in areas outside the simulated plume where the simulated TCE concentration was less than 3 µg/L.

Simulated TCE concentration contours in the deep flow zone of the surficial aquifer system were a maximum 1,000 µg/L under the northern source area and 100 µg/L under the southern source area (fig. 20). Simulated TCE from the shallow flow zone of the surficial aquifer system was the source of simulated TCE in the deep flow zone. The maximum, simulated TCE concentration contour was 1,000 µg/L in the deep flow zone under East River Road; the maximum, simulated TCE concentration contour was 10 µg/L (fig. 20) in the deep flow zone under the Mississippi River and downgradient of East River Road.

The simulated TCE plume did not conform to measured TCE concentrations at 14 of 26 selected locations in the deep flow zone of the surficial aquifer system (fig. 20); for example, neither the furnished northern source area nor the furnished southern source area were the source of measured TCE concentrations of 120, 89, 20, 13, or 3.7 µg/L in the deep flow zone and upgradient of the northern source area. Other sources of TCE most probably exist (fig. 2) in addition to the two furnished source areas for this preliminary TCE transport model simulation. Near the northern source area, measured TCE concentrations of 78 and 58 µg/L were not bounded by simulated 10- and 100-µg/L TCE concentration contours. In the deep flow zone, downgradient of East River Road, measured TCE concentrations of 180, 65, 46, 37, and 35 µg/L were not bounded by simulated 10-, 100-, or 1,000-µg/L TCE concentration contours. A TCE concentration of 110 µg/L was measured in an area outside the simulated plume where the simulated TCE concentration was less than 3 µg/L.

The simulated TCE plume did not conform to measured TCE concentrations at Fridley well 13 and well 5–PC completed in the Shakopee aquifer and Oneota confining unit. Fridley well 13 and well 5–PC are upgradient of the furnished northern and southern source areas such that volatile organic compounds from these source areas might not have contributed to groundwater contamination near these wells (figs. 12 and 13). Other sources of TCE most probably exist (fig. 2) in addition to the furnished source areas for this preliminary TCE transport model simulation.

The degree to which the simulated TCE plume does not match TCE measurements in the surficial aquifer



Base furnished by U.S. Department of the Navy
North American Datum of 1983

0 250 500 750 1,000 FEET
0 50 100 150 200 250 METERS

EXPLANATION

Intermediate clay

Main Naval Industrial Reserve Ordnance Plant building

Simulated trichloroethene concentration, simulation layer 3, in micrograms per liter
3, 10, 100, 1,000, 10,000

AT-5A Extraction well and identifier

37 **Well in intermediate flow zone of surficial aquifer system and measured trichloroethene concentration, in micrograms per liter, 2001**—Concentration and location furnished by U.S. Department of the Navy

Figure 19. Simulated and measured trichloroethene concentrations in 2001 in the intermediate flow zone of the surficial aquifer system, at and near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.

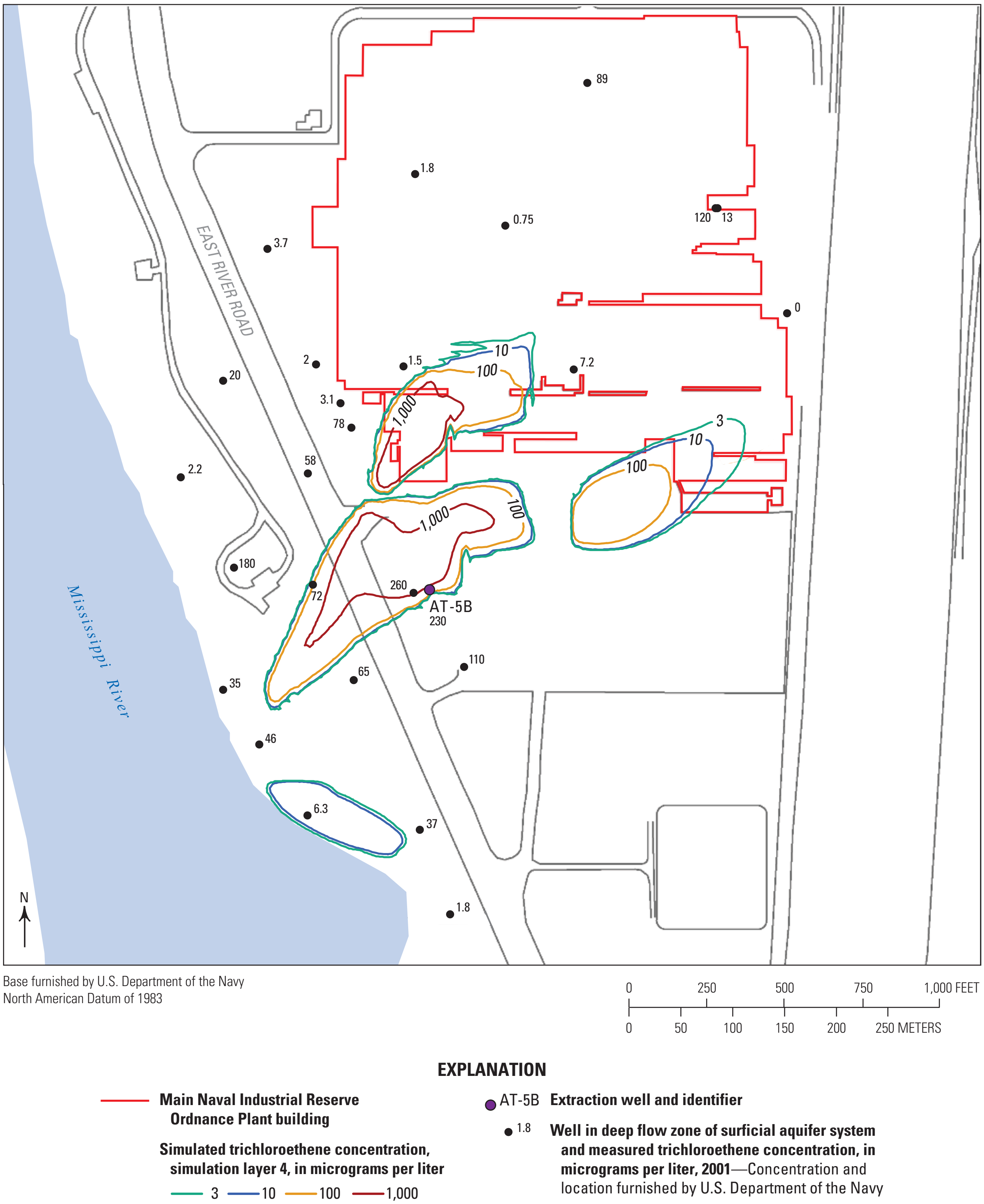


Figure 20. Simulated and measured trichloroethene concentrations in 2001 in the deep flow zone of the surficial aquifer system, at and near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.

system (figs. 18–20) suggests that one or more postulations from this preliminary model simulation were not valid; for example, additional TCE source areas most probably exist (fig. 2), TCE concentrations in the hydrogeologic system may be different than furnished concentrations used in this preliminary simulation, DNAPL transport processes may be important, or TCE source geometry may be different than furnished source geometry. Postulations for simulated hydrogeologic parameters—such as hydraulic conductivity, dispersivity coefficients, or porosity—may explain some differences between simulated and measured TCE concentrations; however, it is unlikely that these hydrogeologic parameter postulations alone explain differences between simulated and measured TCE concentrations north and upgradient of furnished source areas such as measurements in Fridley well 13 and well 5–PC. Other sources of TCE most probably exist at NIROP or in Fridley, Minn. (fig. 2), in addition to the furnished source areas used in this preliminary TCE transport simulation.

The TCE transport model simulation was mass conservative. Trichloroethene entered the study area across constant concentration boundaries of furnished source areas. Trichloroethene exited the study area across constant concentration boundaries, through wells and drains, or as benthic discharge flux to the Mississippi River. The difference between TCE mass entering the study area and leaving the study area was 10^{-2} percent of the TCE mass entering the study area.

Preliminary Application to Hypothetical Trichloroethene Source Areas

Preliminary groundwater flow and TCE transport simulators were applied to the groundwater extraction and treatment system at NIROP (Davis and King, 2016), to investigate the performance of the treatment system. The first preliminary application investigated the effect of newer extraction wells AT–11, AT–12, and AT–13 on a plume generated by a furnished northern source area. A set of four preliminary applications investigated the effect of extraction wells AT–11, AT–12, and AT–13 on a plume generated by a furnished source area that covered most of the main NIROP building. Preliminary applications were hypothetical and not intended to represent historical conditions.

Northern Source Area

The Navy replaced extraction well AT–3A with extraction wells AT–11, AT–12, and AT–13 in 2011. Based on hypothetical extraction rates (table 5), preliminary groundwater flow and TCE transport model simulators (appendixes 1 and 2) were used to investigate the effect of new extraction wells on TCE transport from the furnished northern source area (fig. 18). Hypothetical, simulated, constant TCE concentrations were identical to furnished concentrations used for the 2001 simulation of the northern source area: 1,000 µg/L in the upper part of the shallow flow zone of the surficial aquifer system (fig. 21) and 50,000 µg/L in the lower part of the shallow flow zone of the surficial aquifer system (not shown); other source areas were not simulated in this hypothetical application. This application investigated the response of part of the NIROP groundwater extraction system to some of the TCE in the NIROP subsurface. The southern source area and other TCE source areas in Fridley, Minn., were not included in this application. Stresses from extraction wells at the FMC Corp. (Fridley Plant) EPA Superfund site were included in this application.

Extraction rates ranged from 13 gal/min at extraction well AT–8 from the upper part of the shallow flow zone of the surficial aquifer system to 150 gal/min at extraction wells AT–12 and AT–13 from the intermediate flow zone of the surficial aquifer system. Extraction rates for wells AT–11, AT–12, and AT–13 were hypothetical; extraction rates for other wells in table 5 were the average for the period between August 2010 and August 2011. In the hypothetical model simulation, 297 gal/min (groundwater) were extracted from the shallow flow zone through four extraction wells (AT–5A, AT–7, AT–8, and AT–9), 405 gal/min were extracted from the intermediate flow zone through four additional extraction wells (AT–10, AT–11, AT–12, and AT–13), and 64 gal/min were extracted from the deep flow zone through extraction well AT–5B. As a DNAPL, TCE may be present where TCE concentration in groundwater is greater than 14,720 µg/L at 25 °C. In this preliminary application, DNAPL transport processes were not incorporated at the northern source area where TCE concentration was 50,000 µg/L.

In this application, simulated TCE was transported to the west in the upper part of the shallow flow zone of the surficial aquifer system from the northern source area to extraction

Table 5. Groundwater extraction rates for hypothetical simulations of trichloroethene transport, at the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.

[Well locations are shown in figure 3. gal/min, gallon per minute]

Well name	Surficial aquifer system flow zone	Groundwater extraction rate (gal/min)
AT–5A	Shallow, lower part	126
AT–5B	Deep	64
AT–7	Shallow, upper part	44
AT–8	Shallow, upper part	13
AT–9	Shallow, upper part	114
AT–10	Intermediate	20
AT–11	Intermediate	85
AT–12	Intermediate	150
AT–13	Intermediate	150

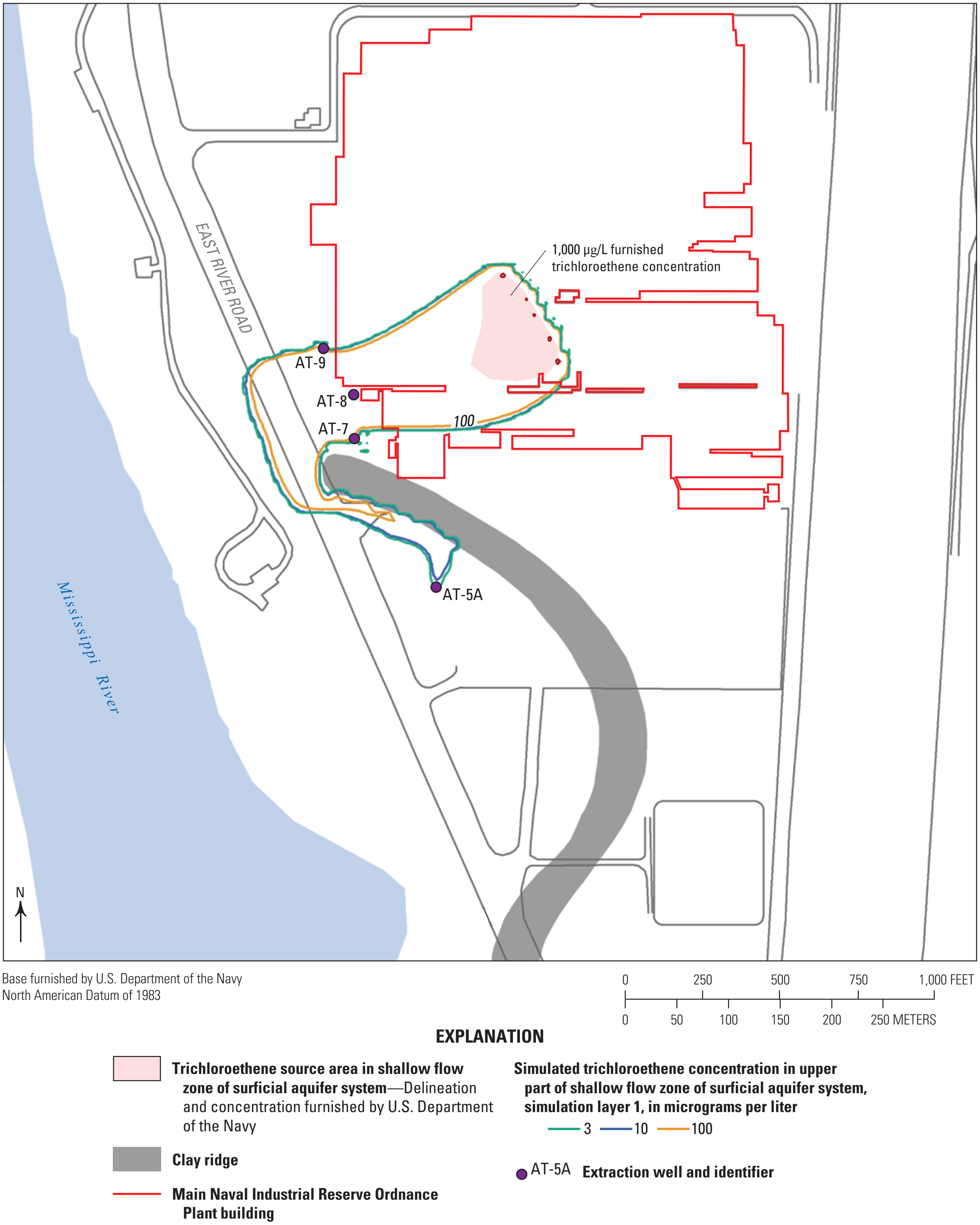


Figure 21. Simulated trichloroethene concentrations for a hypothetical period in the upper part of the shallow flow zone of the surficial aquifer system, at and near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota, for a model simulation in which trichloroethene was transported from the northern source area only.

wells AT–7, AT–8, and AT–9 (fig. 21). The maximum, simulated, 100-μg/L TCE concentration contour extended from the northern source area east of the extraction wells, to the subsurface west and downgradient of the extraction wells. The simulated TCE plume in the upper part of the shallow flow zone near extraction wells AT–7, AT–8, and AT–9 was directed southward by the area of relatively lower hydraulic conductivity between the Mississippi River and extraction wells AT–7, AT–8, and AT–9 (figs. 21, 1–12*A*, and 1–12*B*). The simulated TCE plume was forced southeastward by extraction well AT–5A and hydraulic conductivity in the crescent-shaped clay ridge that is orders of magnitude lower than proximate units. The simulated plume narrows along the southern side of the clay ridge with a maximum, simulated, 100-μg/L TCE concentration contour. Extraction well AT–5A captured remaining simulated TCE at concentrations greater than 3 μg/L in the upper part of the shallow flow zone of the surficial aquifer system; in this preliminary, hypothetical application, simulated TCE at concentrations greater than 3 μg/L were not transported downgradient to the Mississippi River (fig. 21).

In this application, simulated TCE was transported from an area under the northern source area in the lower part of the shallow flow zone, to extraction wells AT–11, AT–12, and AT–13 (fig. 22) in the intermediate flow zone of the surficial aquifer system, to the southwest. The maximum, simulated, 10,000-μg/L TCE concentration contour extended from the northern source area to extraction well AT–12. All simulated TCE concentrations greater than 3 μg/L were removed from the intermediate flow zone by extraction wells AT–11, AT–12, and AT–13. In this application, simulated TCE at concentrations greater than 3 μg/L were not transported to extraction well AT–10 (fig. 3) downgradient of extraction wells AT–11, AT–12, and AT–13. Simulated TCE at concentrations greater than 3 μg/L also were not transported downgradient to any area under the Mississippi River (fig. 22).

In this preliminary, hypothetical application, simulated TCE was transported from the northern source area to extraction well AT–12 in the deep flow zone of the surficial aquifer system, to the southwest (fig. 23). All simulated TCE at concentrations greater than 3 μg/L were removed from the deep flow zone by extraction well AT–12. In this application, simulated TCE at concentrations greater than 3 μg/L were not transported to extraction wells AT–5B, AT–11, or AT–13. Simulated TCE at concentrations greater than 3 μg/L also were not transported downgradient to any area under the Mississippi River (fig. 23).

Part of the NIROP groundwater extraction system removed all simulated TCE at concentrations greater than 3 μg/L that were transported from part of the TCE source area at NIROP. Specifically, extraction wells AT–5A, AT–7, AT–8, AT–9, AT–11, AT–12, and AT–13 removed simulated TCE at concentrations greater than 3 μg/L from a northern source area. Extraction wells AT–5B and AT–10 were included in this hypothetical model simulation, but did not remove any TCE at concentrations greater than 3 μg/L from the study area. The southern source area and other TCE sources at NIROP and in Fridley, Minn., were not considered in this application. Stresses from extraction wells at the FMC Corp. (Fridley Plant) EPA Superfund site were included in this application.

Main Naval Industrial Reserve Ordnance Plant Building Source Area

Preliminary groundwater flow and TCE transport model simulators (appendixes 1 and 2) using hypothetical extraction rates (table 5) were used to investigate the effect of new extraction wells AT–11, AT–12, and AT–13 on hypothetical TCE source areas under most of the main NIROP building (figs. 24–27). These preliminary, hypothetical applications were used to investigate the response of part of the NIROP groundwater extraction system to furnished TCE source areas. Trichloroethene source areas outside the footprint of the main building were not included in these applications. Stresses from extraction wells at the FMC Corp. (Fridley Plant) EPA Superfund site were included in these applications. Extraction rates for this application were the same as extraction rates for the northern source area application (table 5).

For the first of four preliminary, hypothetical applications, the furnished TCE concentration was 10,000 μg/L in the upper part of the shallow flow zone of the surficial aquifer system under most of the main NIROP building (fig. 24). Trichloroethene source areas were not furnished for any other part of the shallow flow zone, for any other flow zone in the surficial aquifer system, or at any other location for this first of four preliminary applications. The maximum, 10,000-μg/L, simulated TCE concentration contour extended from the building to East River Road (fig. 24). Lesser simulated concentration contours extended west of East River Road. All simulated TCE at concentrations greater than 3 μg/L were removed from the upper part of the shallow flow zone by extraction wells AT–5A, AT–7, AT–8, and AT–9. Simulated TCE at concentrations greater than 3 μg/L were not transported downgradient to the Mississippi River (fig. 24). Between extraction wells AT–7 and AT–5A, the simulated TCE plume behaved in a manner similar to other applications (figs. 18, 21, and 24). The plume was directed southward by an area of relatively lower hydraulic conductivity between the Mississippi River and extraction wells AT–7, AT–8 and AT–9 (figs. 24, 1–12*A*, and 1–12*B*); and the plume was directed southeastward, and forced by extraction well AT–5A and hydraulic conductivity in the crescent-shaped clay ridge that is orders of magnitude lower than proximate units. The plume narrowed along the southern side of the clay ridge. The maximum, simulated TCE concentration contour at extraction wells AT–7, AT–8, and AT–9 was 10,000 μg/L. The maximum, simulated TCE concentration contour at extraction well AT–5A was 100 μg/L.

For the second application, the furnished TCE concentration was 10,000 μg/L in the lower part of the shallow flow zone of the surficial aquifer system under most of the main NIROP building (fig. 25). Trichloroethene source areas

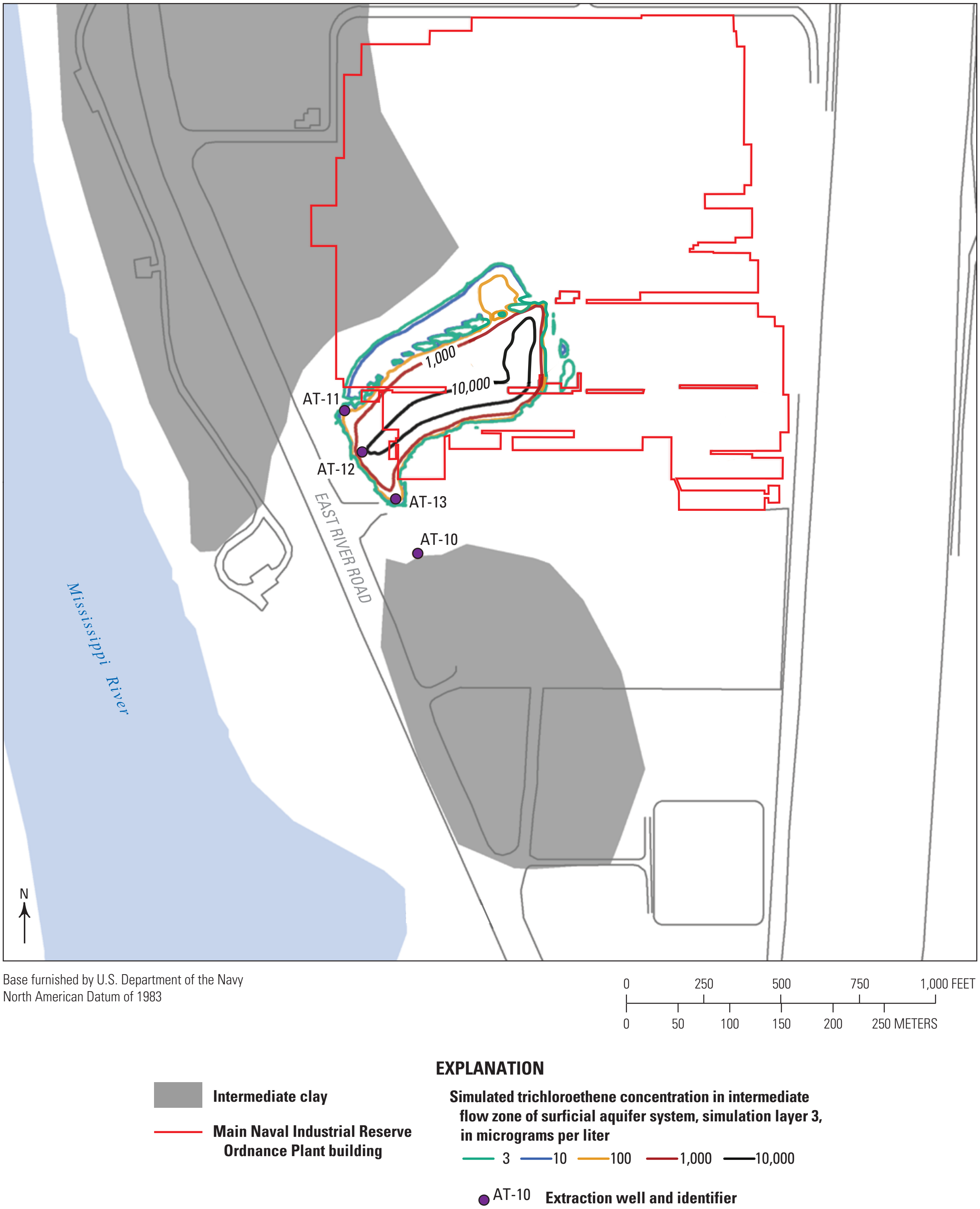


Figure 22. Simulated trichloroethene concentrations for a hypothetical period in the intermediate flow zone of the surficial aquifer system, at and near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota, for a model simulation in which trichloroethene was transported from the northern source area only.

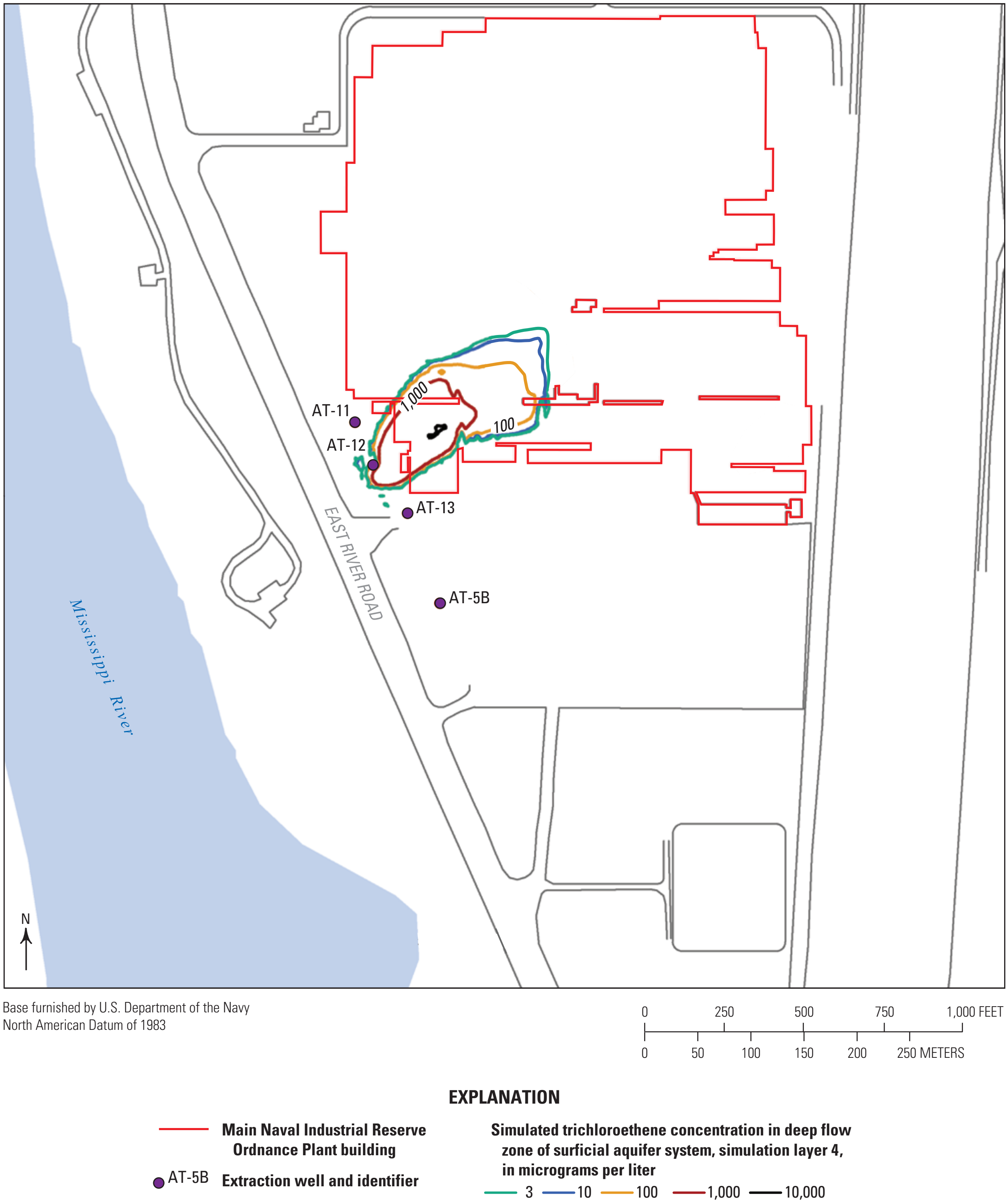


Figure 23. Simulated trichloroethene concentrations for a hypothetical period in the deep flow zone of the surficial aquifer system, at and near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota, for a model simulation in which trichloroethene was transported from the northern source area only.

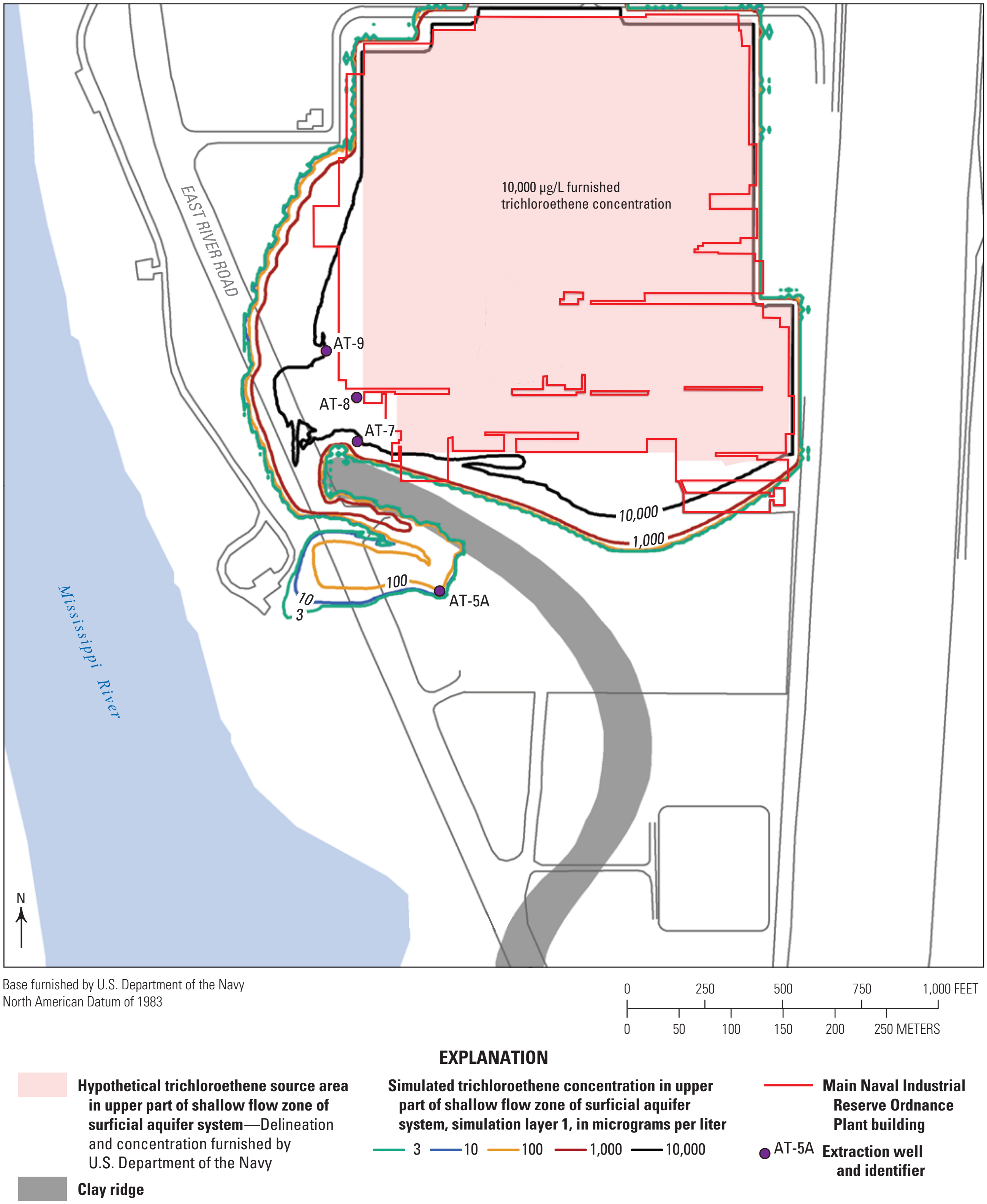


Figure 24. Simulated trichloroethene concentrations for a hypothetical period in the upper part of the shallow flow zone of the surficial aquifer system, for a model simulation in which trichloroethene was transported from a source area that covered the main building at the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.

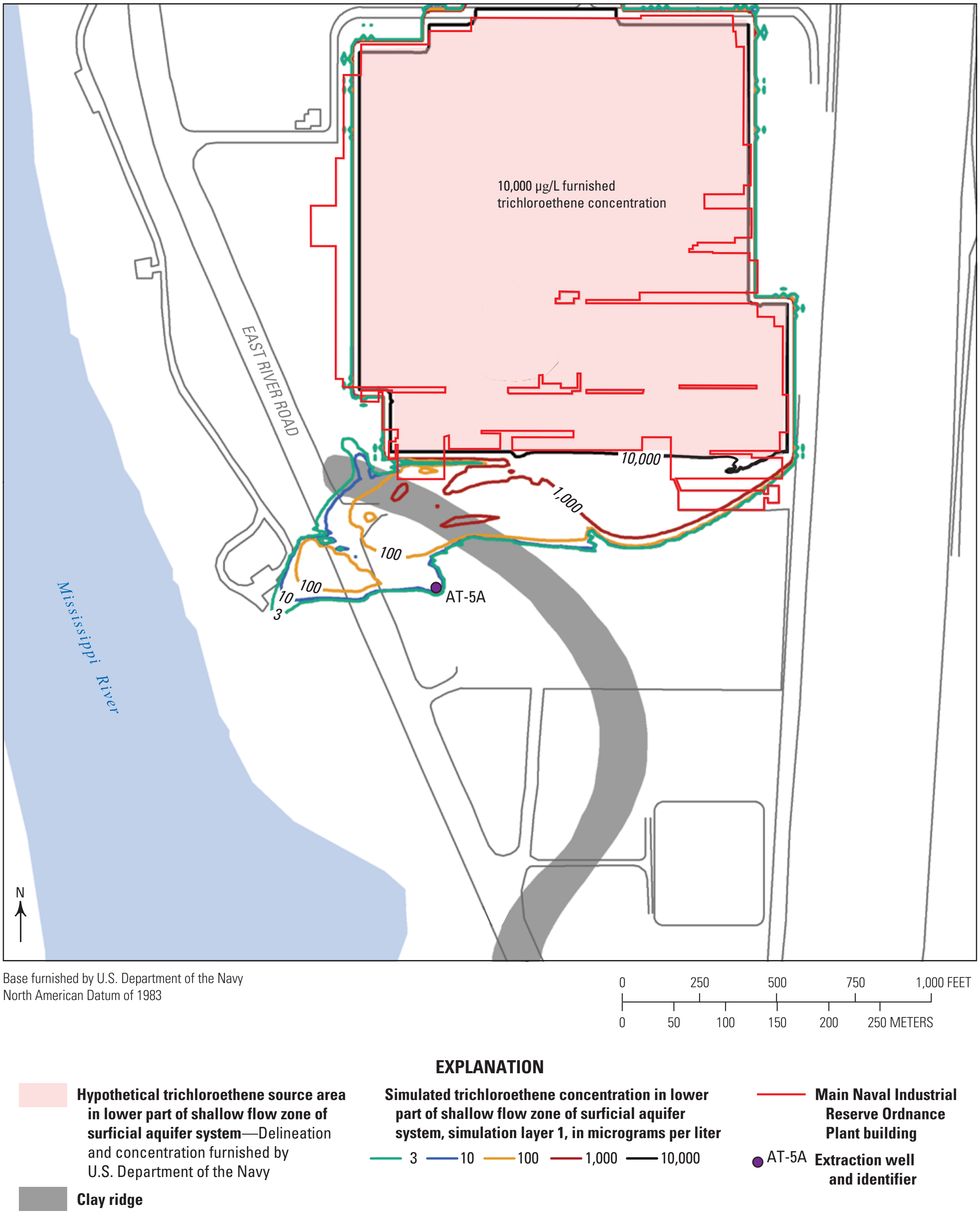


Figure 25. Simulated trichloroethene concentrations for a hypothetical period in the lower part of the shallow flow zone of the surficial aquifer system, for a model simulation in which trichloroethene was transported from source area that covered the main building at the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.

were not furnished for any other flow zone in the surficial aquifer system, in any other part of the shallow flow zone, or at any other location for this second of four preliminary applications. The maximum, 10,000-µg/L, simulated TCE concentration contour extended no more than 50 ft from the NIROP building. The maximum, simulated TCE concentration contour that extended west of East River Road was 100 µg/L (fig. 25). All simulated TCE at concentrations greater than 3 µg/L was removed from the lower part of the shallow flow zone by extraction well AT–5A. Simulated TCE at concentrations greater than 3 µg/L was not transported downgradient to areas under the Mississippi River. The maximum, simulated TCE concentration contour at extraction well AT–5A was 10 µg/L.

For the third application, the furnished TCE concentration was 10,000 µg/L in the intermediate flow zone of the surficial aquifer system under most of the main NIROP building (fig. 26). Trichloroethene source areas were not furnished for any other flow zone of the surficial aquifer system or at any other location for this third of four preliminary applications. The maximum, 10,000-µg/L, simulated TCE concentration contour did not extended beyond the footprint of the NIROP building (fig. 26). The 1,000-µg/L TCE concentration contour was the maximum, simulated contour to extend to East River Road. Lesser simulated concentration contours extended west of East River Road. All simulated TCE at concentrations greater than 3 µg/L was removed from the upper part of the shallow flow zone by extraction wells AT–5B, AT–10, AT–11, AT–12, and AT–13. Simulated TCE at concentrations greater than 3 µg/L was not transported downgradient to areas under the Mississippi River (fig. 26). The maximum, simulated TCE concentration contour at extraction wells AT–11, AT–12, and AT–13 was 1,000 µg/L. The maximum, simulated TCE concentration contour at extraction well AT–10 was 100 µg/L. The maximum, simulated TCE concentration contour at extraction well AT–5B was 10 µg/L.

For the fourth of four applications, the furnished TCE concentration was 10,000 µg/L in the deep flow zone of the surficial aquifer system under most of the main NIROP building (fig. 27). Trichloroethene source areas were not furnished for any other flow zone of the surficial aquifer system or at any other location for this fourth of four preliminary applications. The maximum, 10,000-µg/L, simulated TCE concentration contour extended no more than 150 ft from the NIROP building. The 1,000-µg/L, simulated TCE concentration contour extended to East River Road. The 100-µg/L contour was the maximum TCE concentration contour to extend west of East River Road. All simulated TCE at concentrations greater than 3 µg/L was removed from the deep flow zone by extraction wells AT–5B, AT–11, AT–12, and AT–13. Simulated TCE concentrations greater than 3 µg/L were not transported downgradient to areas under the Mississippi River. The 1,000-µg/L contour was the maximum, simulated TCE concentration contour at extraction wells AT–11, AT–12, and AT–13 in the deep flow zone (fig. 27). The 100-µg/L contour was the maximum, simulated TCE concentration contour at extraction well AT–5B in the deep flow zone (fig. 27).

Sensitivity Analyses

The sensitivity of simulated potentiometric head to variation in hydraulic conductivity was calculated using PEST (Doherty, 2010, 2014).

The objective function

$$\Phi = \sum \left(o_i - r_i \right)^2 \qquad (1)$$

is minimized by PEST, where

- Φ is the objective function,
- Σ is the sum,
- o is the i[th] measurement, and
- r_i is the i[th] model simulation result.

The objective function, Φ, quantifies the fit between measurements and results. A simulation that generates a lower valuation of Φ explains measurements better than a simulation that generates a higher valuation.

An optimal set of model simulation parameters can be identified using PEST by minimizing Φ with

$$\mathbf{Xb} = \mathbf{r} \qquad (2)$$

where

- $\mathbf{X}$ is an $m \times n$ matrix of immutable, independent simulation elements,
- $\mathbf{r}$ is an order m vector of simulation results,
- $\mathbf{b}$ is a parameter set: an order n vector of adjustable simulation parameters,
- m is the number of simulation results and the number of measurements, and
- n is the number of adjustable simulation parameters;

then,

$$\Phi = \left(\mathbf{o} - \mathbf{Xb} \right)^t \left(\mathbf{o} - \mathbf{Xb} \right) \qquad (3)$$

where

- $\mathbf{o}$ is an order m vector of measurements in which elements of **o** are independent, and
- ^{t} is the matrix transpose operation.

The difference between the number of observations and the number of adjustable simulation parameters ($m-n$) is the dimension of or degrees of freedom in the parameter set, **b**, in which ($m-n$) independent pieces of information must be known to define **b**. The vector **b** that minimizes Φ is then

$$\mathbf{b} = \left(\mathbf{X}^t \mathbf{X} \right)^{-1} \mathbf{X}^t \mathbf{o} \qquad (4)$$

where

- $^{-1}$ is the matrix inversion operation.

This overview of basic PEST concepts was brief; Doherty (2010, 2014), Doherty and Hunt (2010), and Doherty and others (2010a, 2010b) described PEST in more detail.

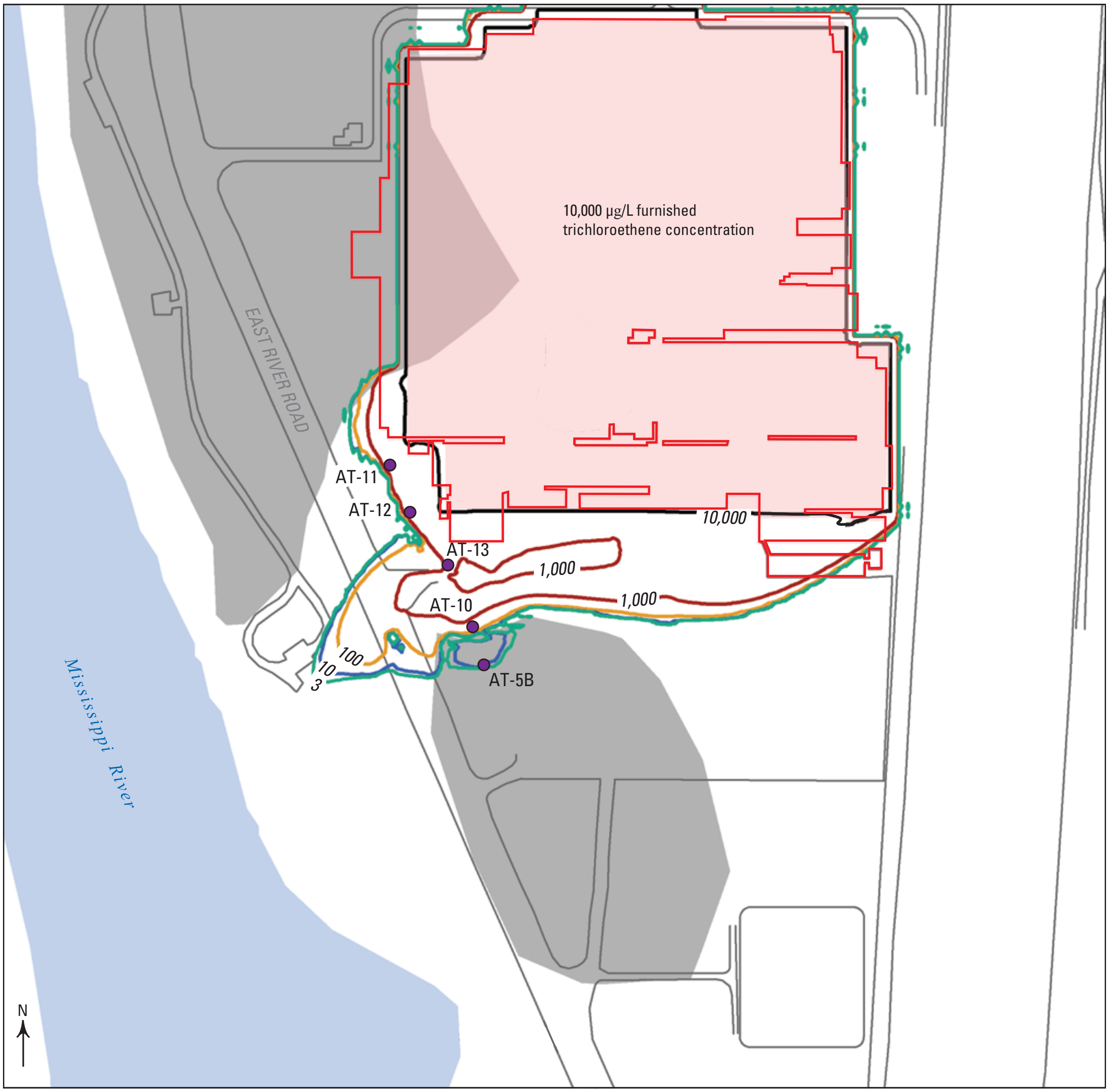


Figure 26. Simulated trichloroethene concentrations for a hypothetical period in the intermediate flow zone of the surficial aquifer system, for a model simulation in which trichloroethene was transported from a source area that covered the main building at the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.

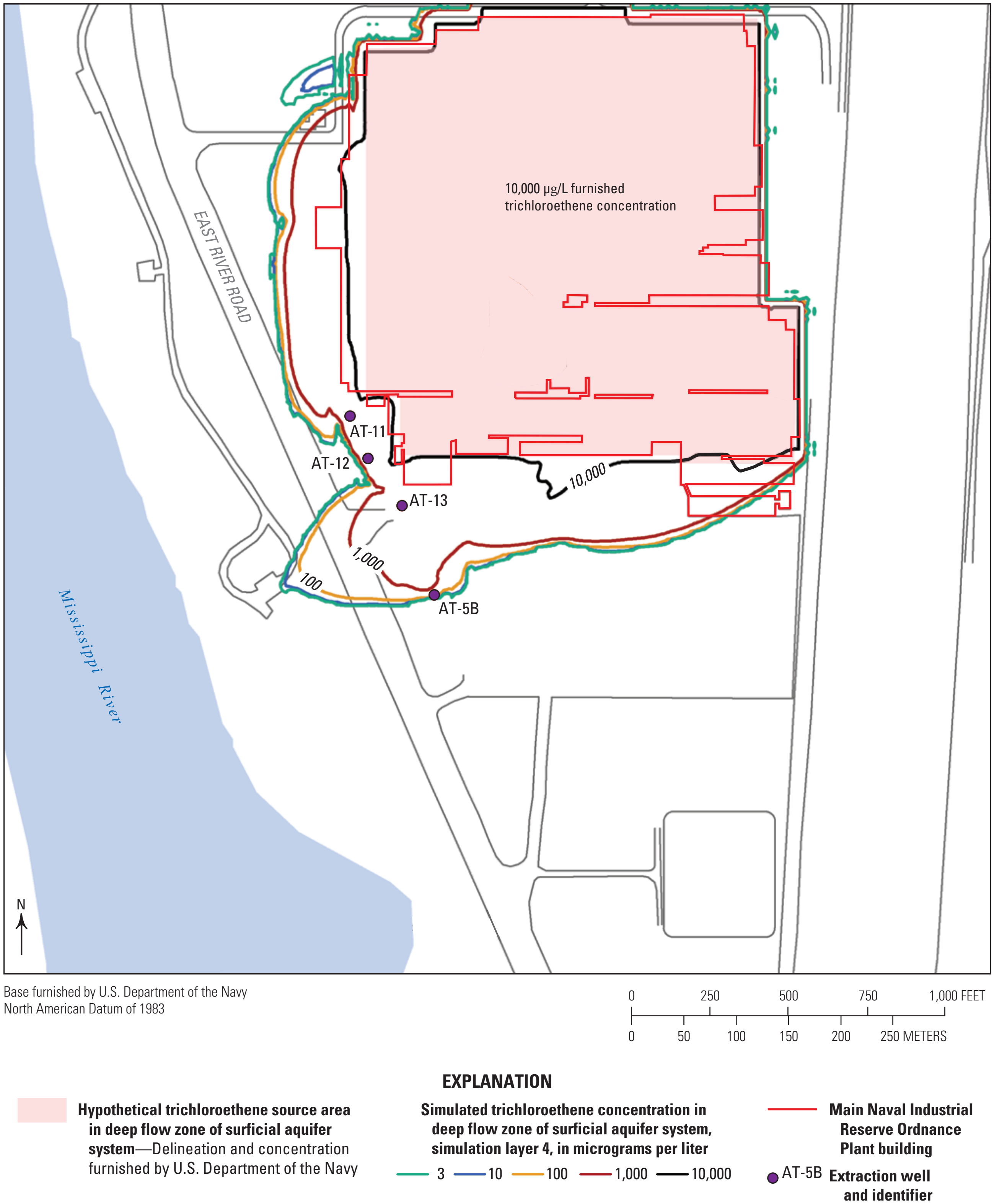


Figure 27. Simulated trichloroethene concentrations for a hypothetical period in the deep flow zone of the surficial aquifer system, for a model simulation in which trichloroethene was transported from a source area that covered the main building at the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.

The sensitivity of simulated potentiometric head to variation in hydraulic conductivity was expressed in the units of the model simulation prediction (potentiometric head in feet) per units of the parameter (hydraulic conductivity in feet per day). The relative magnitude, or relative scale, of PEST sensitivity for a parameter, with respect to PEST sensitivities for other parameters in a simulation parameter set, is a function of the relative magnitude of the parameter with respect to magnitudes of other parameters in the parameter set; for example, a unit increase in a relatively small magnitude parameter is more likely to have a larger effect on the simulation prediction than a unit increase in a relatively large magnitude parameter. A unit increase in the horizontal hydraulic conductivity of the crescent-shaped clay ridge from, for example, 10^{-4} ft/d to 1.0001 ft/d is more likely to have a larger effect on simulated potentiometric head than a unit increase in the horizontal hydraulic conductivity of an adjacent hydrogeologic unit from 400 ft/d to 401 ft/d. The magnitude effect, or scaling effect, was normalized by calculating the product of PEST sensitivity and the parameter value. In this application, the units of this product were [(feet)/(feet/day)]×(feet/day)=(feet)/[(feet/day)/(feet/day)] such that the sensitivity product is expressed in the units of the simulation prediction (potentiometric head in feet) per a dimensionless percent change in the parameter, hydraulic conductivity. This sensitivity product is similar to scaled sensitivity (Hill, 1998).

Sensitivity products for horizontal and vertical hydraulic conductivity parameters, with respect to potentiometric head measurements, were divided into quartiles for selected hydrogeologic units in the following flow zones or parts of flow zones of the surficial aquifer system near NIROP: the upper part of the shallow flow zone (fig. 28), lower part of the shallow flow zone (fig. 29), intermediate flow zone (fig. 30), and deep flow zone (fig. 31). The upper quartile represented hydraulic conductivities with more effect on potentiometric head than hydraulic conductivities in the lower quartile.

The model simulation prediction was generally more sensitive to changes in horizontal hydraulic conductivity west of the Mississippi River than to changes in horizontal hydraulic conductivity under the river. The simulation prediction was more sensitive to vertical hydraulic conductivity in areas under the Mississippi River because this area governs potentiometric heads that force benthic discharge flux to the river.

Postulations and Limitations

Although some aspects of the study described in this report were quantitative, the preliminary interpretation is qualitative. The quantitative nature of model simulations and applications might suggest to some readers that accurate, deterministic, and quantitative findings are possible. This suggestion is not correct; postulations and limitations inherent in numerical simulations prohibit overreliance on quantitative results.

A steady-state groundwater flow system was postulated for the model simulation and applications. Transport of TCE was simulated for 3,000 days, from June 3, 1993, to August 20, 2001. It was a postulation of this simulation that 3,000 days of transport was sufficient for TCE concentration to reach a steady state. Transience in groundwater flow was not simulated during the 3,000-day-long stress period.

Differences between the postulated steady state and the actual transient conditions may introduce differences between model simulation results and the behavior of the actual system. The steady-state postulation was not rigorously tested. Measured potentiometric heads in groundwater wells, and measured surface elevations of surface water vary at and near NIROP. The steady-state simulation is postulated to represent an average condition for potentiometric head and surface elevation. Different groundwater extraction rates have been used at and near NIROP, throughout the history of groundwater extraction at and near NIROP. The steady-state simulation is postulated to represent average groundwater extraction rates.

Strictly, a steady state rarely exists in hydrologic systems. However, steady state is a reasonable postulation for a preliminary investigation. The steady-state postulation introduces limitations into science findings. Specifically, the model simulation and applications did not describe transient hydrologic forcing that existed in the hydrologic system; for example, it was not possible to use the results of the simulation to develop science findings related to flood events in the Mississippi River or during a drought in Minnesota. Steady state is a common postulation in the hydrologic sciences; numerous science findings have been developed throughout the history of hydrologic science using the steady-state postulation.

At some locations, the Metropolitan Council (2009) used interface elevations between lithostratigraphic units as interface elevations between hydrogeologic units. The interface between lithostratigraphic units and hydrogeologic units are not coincident everywhere in the Cambrian-Ordovician aquifer system (Runkel and others, 2006c; Tipping and others, 2006); for example, the Shakopee aquifer roughly corresponds with the Shakopee Formation and the upper one-third of the Oneota Dolomite (Runkel and others, 2003). Another example is where a fine clastic rock component exists at the top of the Jordan Sandstone, this component is a lower part of the Oneota confining unit (Runkel and others, 2003). Metropolitan Council (2009) built a digital elevation model from models by Tipping and Mossler (1996), Runkel and others (2003), and Runkel and Tipping (2006). Metropolitan Council (2009) also built a new digital elevation model from the Minnesota County Well Index. Strictly, some of the source digital elevation models represented interface elevations between lithostratigraphic units, not interface elevations between hydrogeologic units. The effect of possible error in postulated coincidences of geologic unit and hydrogeologic unit interfaces on findings was not investigated in this preliminary study.

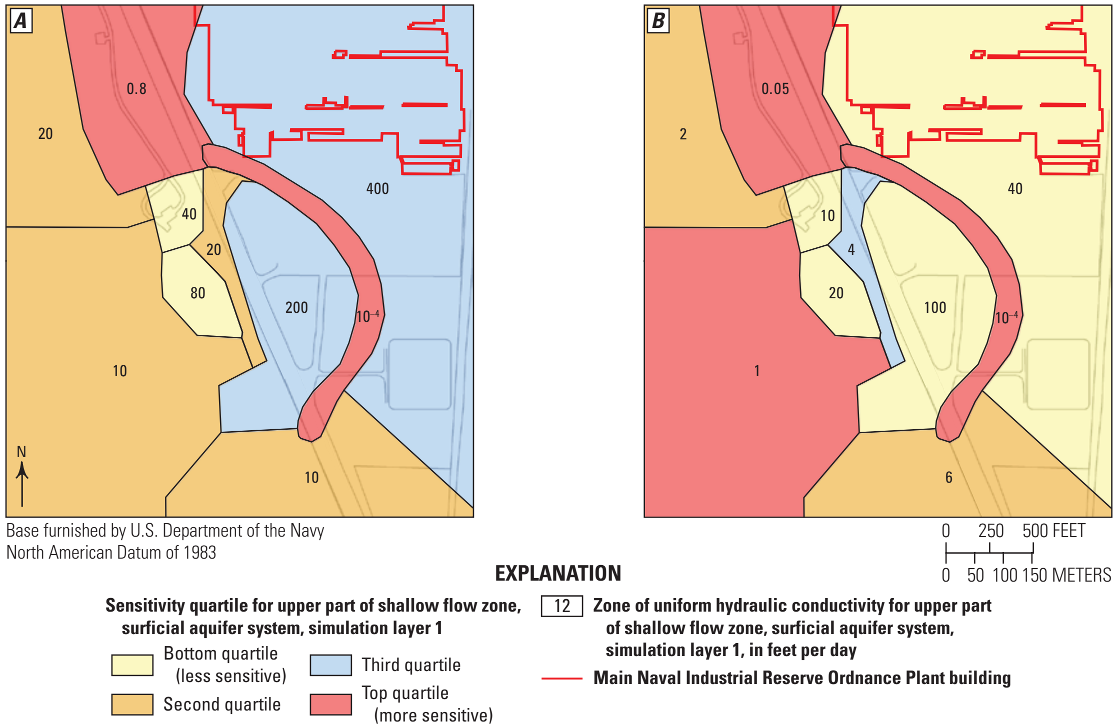


Figure 28. Zones of uniform hydraulic conductivity in the upper part of the shallow flow zone of the surficial aquifer system (model simulation layer 1), at and near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota, and sensitivity of simulated potentiometric head, depicted in quartiles, to changes in conductivities. *A*, horizontal conductivity. *B*, vertical conductivity.

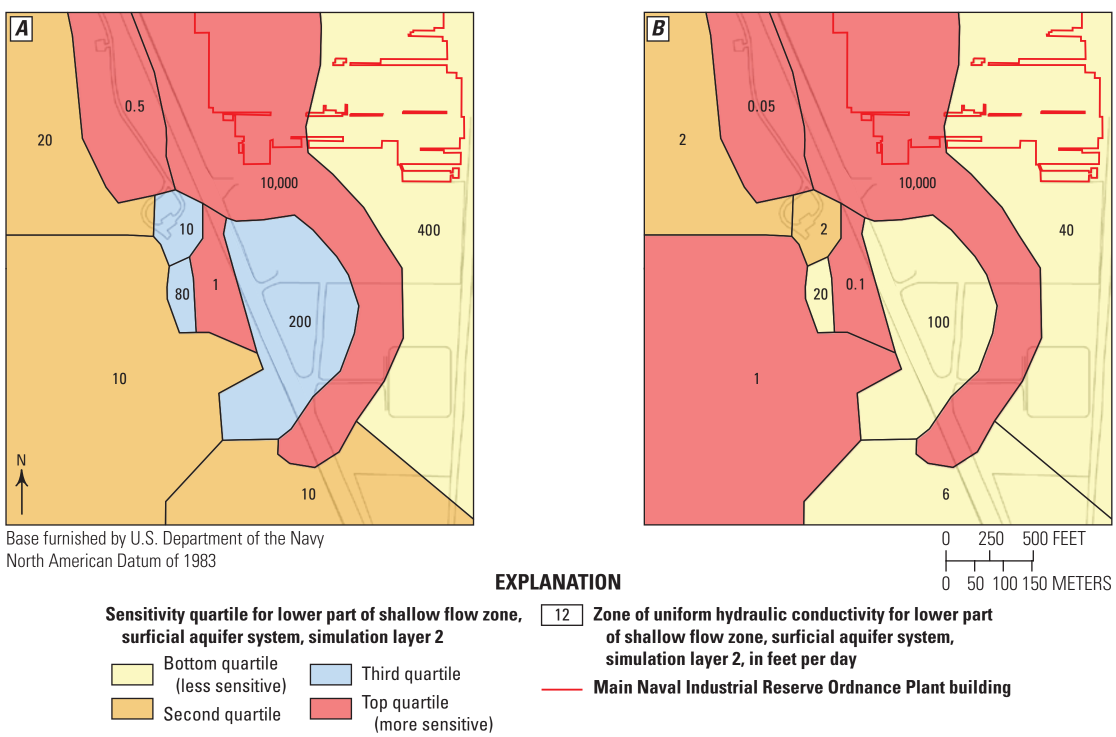


Figure 29. Zones of uniform hydraulic conductivity in the lower part of the shallow flow zone of the surficial aquifer system (model simulation layer 2), at and near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota, and sensitivity of simulated potentiometric head, depicted in quartiles, to changes inconductivities. *A*, horizontal conductivity. *B*, vertical conductivity.

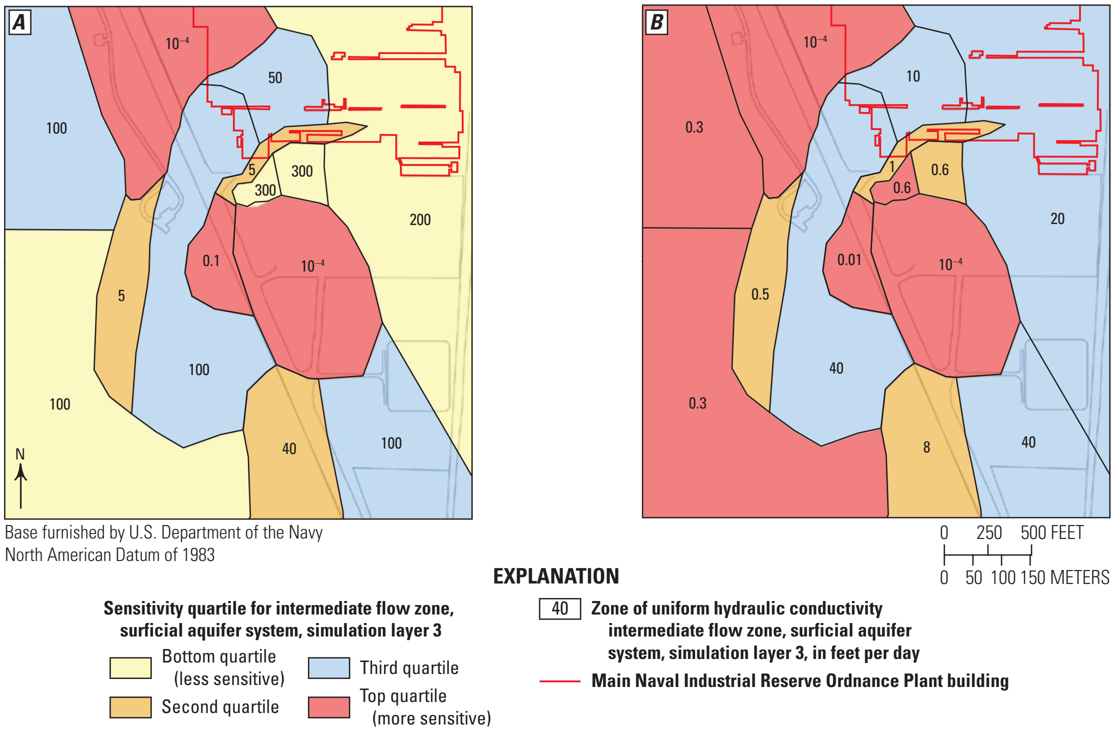


Figure 30. Zones of uniform hydraulic conductivity in the intermediate flow zone of the surficial aquifer system (model simulation layer 3), at and near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota, and sensitivity of simulated potentiometric head, depicted in quartiles, to changes in conductivities. *A*, horizontal conductivity. *B*, vertical conductivity.

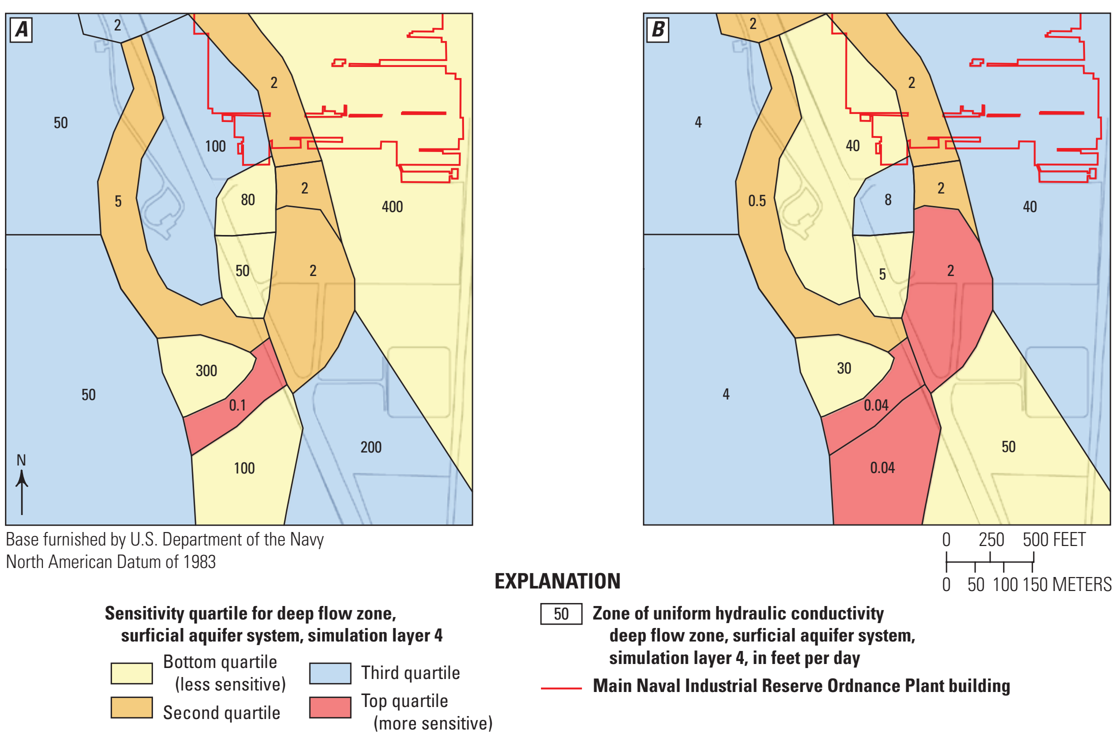


Figure 31. Zones of uniform hydraulic conductivity in the deep flow zone of the surficial aquifer system (model simulation layer 4), at and near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota, and sensitivity of simulated potentiometric head, depicted in quartiles, to changes inconductivities. *A*, horizontal conductivity. *B*, vertical conductivity.

Darcy's Law was postulated as valid. Darcy's Law requires the following postulations and imposes the following limitations:

- The fluid was single-phase, nonreactive, and incompressible;
- The porous medium was saturated;
- The material derivative of the product of the velocity vector and the density field was zero;
- The Navier-Stokes equations for fluid flow reduced to the Stokes equation for creeping flow;
- Kinetic energy was not a component of the energy balance;
- Viscous forces contributed more to the force balance than inertial forces;
- Reynolds numbers were less than 10;
- Groundwater flow was laminar;
- Viscous stress in the fluid was a linear function of the rate of change in velocity; and
- Specific discharge was a linear function of potentiometric-head gradient.

The Darcy postulation is common in numerical model simulation using MODFLOW. Reimann and others (2011a) investigated some aspects of the Darcy postulation within the MODFLOW framework. If the Darcy postulation is not valid, some unquantified error may exist in the groundwater flow simulation, TCE transport simulation, and the application of groundwater flow and TCE transport simulators to hypothetical problems.

It was a postulation of this preliminary study that a simple, intergranular, groundwater flow component contributed more to the flow system than a groundwater flow component through secondary pores. The intergranular flow postulation is also common in numerical model simulation. Reimann and others (2011b, 2011c) investigated some aspects of secondary flow systems. The TCE transport simulation may not accurately represent TCE concentration where a dominant secondary flow system in the surficial or Cambrian-Ordovician aquifer systems exists that differs from the intergranular flow system represented in the preliminary numerical groundwater flow and TCE transport simulations, or preliminary application of numerical simulators to hypothetical source areas.

Hydrogeologic properties were averaged over a representative elementary volume of porous media. The model simulation and applications were applicable at the macroscopic scale of the numerical grid; the simulation and applications were not applicable at the pore scale of the matrix. Hydrogeologic properties were postulated constant in each grid cell; for example, the area of the cell in the extreme northern corner of the study area was 23 acres. This cell was 18 mi northwest of NIROP. Hydrogeologic parameters were postulated homogeneous in each simulation layer of this cell such that, for example, Shakopee aquifer porosity was constant throughout the cell. Although homogeneity throughout the area represented by the grid cell was not valid at a sub-grid-cell pore scale, the representative elementary volume postulation was acceptable because simulated TCE concentrations were not interpreted at the sub-grid-cell scale in this 23-acre cell 18 mi northwest of NIROP.

It was postulated that the principal axes of anisotropy were aligned with the grid; off-diagonal terms in the permeability tensor k_i equaled zero. The tensor was described by three on-diagonal terms (k_x, k_y, and k_z), which were oriented perpendicular to Cartesian planes *y-z*, *x-z*, and *x-y*, respectively. This postulation of no off-diagonal terms is common in MODFLOW simulation. If principal axes of anisotropy in the hydrogeologic system were not aligned with Cartesian planes, some unquantified error may exist in the groundwater flow simulation, TCE transport simulation, or application of groundwater flow and TCE transport model simulators.

Differences were identified between measurements and results of preliminary groundwater flow and TCE transport model simulators used for preliminary application to the furnished northern source area and the furnished main NIROP building source area. Some differences may have been due to differences between the simulated and actual hydrogeologic system; for example, although the preliminary simulation included groundwater extraction and treatment systems at both NIROP and the FMC Corp. (Fridley Plant) EPA Superfund site, simulated potentiometric head was 5.47 ft greater than measured potentiometric head near extraction well RW–4 on the FMC Corp. (Fridley Plant) EPA Superfund site in the shallow flow zone of the surficial aquifer system (fig. 14). This difference may have been caused by simulated stress being less than actual stress on August 20, 2001, or simulated transmissivity being less than actual transmissivity, or the steady-state postulation. In a second example, Davis (2007) detailed a crescent-shaped, clay ridge (fig. 9) that governs groundwater flow and TCE transport in part of the shallow flow zone of the surficial aquifer system southwest of NIROP, between NIROP and the Mississippi River. Potentiometric-head measurements suggested connectivity of the clay unit between logged wells. Strictly, these wells only confirmed the existence of the unit at the location of the wells. It is not known whether the crescent-shaped clay ridge is a homogeneous hydrogeologic unit of dense clay that does not transmit groundwater or allow the transport of TCE through the ridge, as represented in the simulation and application, or whether the ridge is composed of heterogeneous silts and clays that transmit groundwater and transport TCE through the ridge.

Trichloroethene source area concentrations and plume geometries were furnished for the preliminary model simulation. Differences may exist between furnished source areas and concentrations, and source areas and concentrations that may exist, or may have historically existed, at, near, and upgradient of NIROP. These possible differences may explain why simulation results did not match measured TCE concentrations at some locations; for example, the measured, 43,000-μg/L TCE concentration was bounded by 10- and 100-μg/L, simulated TCE concentration contours in the intermediate flow zone of the surficial aquifer system (fig. 19). Other explanations may also exist. It is not clear how deviations between August 20, 2001, potentiometric-head measurements and simulation results, affected groundwater flow and TCE transport simulator applications to the postulated northern source area and the main NIROP building source area (see "Preliminary Application to Hypothetical Trichloroethene Source Areas" section).

Fluid density was postulated as constant in the simulator. The density of water and TCE are 1,000 and 1,460 kilograms per cubic meter, respectively. A 46-percent difference exists between water density and TCE density; however, the typical concentration of TCE in the surficial aquifer system was not sufficient to generate an appreciable density gradient; for example, the mass of 1 m^3 of groundwater with an atypically high, miscible TCE concentration of 10,000 μg/L is less than 1×10^{-2} kg more than the mass of 1 m^3 of groundwater with a TCE concentration of 0 μg/L. The constant density postulation caused a potentiometric-head error of less than 10^{-2} percent at a location where the TCE concentration is 10,000 μg/L. This error is small for the atypically high, miscible TCE concentration. This error is smaller for groundwater with lower TCE concentrations. The constant density postulation was acceptable for this preliminary study.

Natural attenuation, such as volatilization, adsorption, biological degradation, or abiotic degradation, of volatile organic compounds was not simulated. Biological degradation may exist at some locations; for example, Tetra Tech (2013b) suggested that biological degradation existed in the surficial aquifer system because 1,2-DCE concentrations increased at some locations where TCE concentrations decreased. Under the biological reductive dechlorination pathway for chlorinated ethenes, PCE reduces to TCE, which reduces to 1,2-DCE, which reduces to vinyl chloride (Minnesota Pollution Control Agency, 2006). The limited scope of this preliminary study did not permit analyses of natural attenuation of volatile organic compounds. It is not certain whether model simulation of natural attenuation would increase or decrease TCE concentrations at NIROP. Simulated TCE plumes more likely represented the distribution of TCE if groundwater flow and source area geometry and concentration remained stable for a period greater than the time scale of the investigation.

As a DNAPL, TCE may have been present at NIROP between October 1, 1983, and December 6, 2001 (see "Brief History of Subsurface Contamination at the Naval Industrial Reserve Ordnance Plant and Selected Reference to Other Subsurface Contamination in Fridley, Minnesota" section). This determination was made based on TCE concentration measurements tabulated by Tetra Tech (2013b) and conditions specified by the U.S. Environmental Protection Agency (1992a, 2004). The model simulation and applications described in this report did not consider DNAPL transport processes. As a DNAPL, TCE may be transported faster, deeper, and farther than TCE in a less dense, aqueous phase. As a DNAPL, TCE may have been present at NIROP or in Fridley, Minn., in areas that were not sampled. More sophisticated methods than the conditions specified by the U.S. Environmental Protection Agency (1992a, 2004) may yield alternative conclusions about the possible presence of TCE as a DNAPL at NIROP.

Hydrogeologic parameters used in the model simulation might differ from parameters detailed in the literature. Simulation parameters were relevant to groundwater flow and TCE transport in the surficial and Cambrian-Ordovician aquifer systems at NIROP at the temporal and spatial scale of the simulation. Parameters used in previous investigations were relevant to scales and scopes of those investigations. Parameters might differ because of scale differences between areas of simulation. The parameter set used in the preliminary simulation might not be unique. Multiple sets of parameters might yield the same or qualitatively similar simulation results. Nonuniqueness of the simulation parameter set does not undermine preliminary, qualitative findings.

The study described in this report was preliminary. Additional analyses, measurement, and model simulation may reduce uncertainty in science findings; for example, additional measurements are needed to further characterize fracture networks in the Cambrian-Ordovician aquifer system (Runkel and others, 2006a, 2007; Tipping and others, 2006) focused on numerical model simulation of groundwater flow and TCE transport, and specifically focused on simulation at NIROP. Analyses, measurements, and simulation are needed to reduce differences between measured and simulated potentiometric head; and to reduce differences between measured and simulated TCE concentrations. For example, PEST or other simulation optimization tools can be used in a more sophisticated manner than was used in the study described in this report to minimize an objective function that describes the difference between measured and simulated potentiometric head and TCE concentration by refining multiple hydrogeologic parameters including, but not limited to the following: a heterogeneous, anisotropic hydraulic conductivity tensor; porosity; dispersivity coefficients; fracture geometry and density; and parameters that affect subsurface DNAPL behavior such as viscosity, specific gravity, effective solubility, chemical composition, and wetting characteristics. Improved field estimates of hydraulic conductivity or other hydrogeologic parameters will constrain more sophisticated parameter estimation analyses. Additional simulation is needed to incorporate transient groundwater flow and TCE transport, and transient stresses from the groundwater extraction system at the FMC Corp. (Fridley Plant) EPA Superfund site. Additional measurements are needed to fully characterize the distribution and concentration of TCE in the subsurface at NIROP and in Fridley, Minn. (fig. 2). Additional research may be necessary to better understand the history of volatile organic compounds in the subsurface at NIROP. Further refinement to the Cambrian-Ordovician aquifer system hydrogeologic framework is needed to ensure that interfaces between hydrogeologic units are specified at correct elevations. Additional characterization of the crescent-shaped, clay ridge may be warranted. Additional analyses, measurements, and simulation are needed to characterize the biological degradation and other natural attenuation of volatile organic compounds in the subsurface at NIROP, and to consider DNAPL transport processes.

Summary and Conclusions

This report describes a preliminary characterization of trichloroethene transport in the surficial and Cambrian-Ordovician aquifer systems at the Naval Industrial Reserve Ordnance Plant in Fridley, Minnesota. The U.S. Geological Survey, in cooperation with the U.S. Department of the Navy, used a steady-state, uniform-density groundwater flow model to simulate measured potentiometric heads in aquifer systems on August 20, 2001; and a transient, single phase, miscible transport model to simulate trichloroethene concentrations in aquifer systems, measured in 2001. Trichloroethene source areas and concentrations were furnished by the U.S. Department of the Navy. The 120-square-mile study area was a subdomain of a simulation of the surficial and Cambrian-Ordovician aquifer systems in a 4,913-square-mile study area that included the Twin Cities Metropolitan Area.

Simulated potentiometric head matched measured potentiometric head at about 90 percent of selected locations in the surficial aquifer system on August 20, 2001. The absolute value of the difference between simulated potentiometric head and measured potentiometric head was less than 2 feet at 49 of 56 selected locations in the shallow flow zone, 38 of 44 selected locations in the intermediate flow zone; and 33 of 36 selected locations in the deep flow zone of the surficial aquifer system. The absolute value of the difference between measured and simulated potentiometric head was a maximum of 5.47 feet. Groundwater flows from deeper units of the Cambrian-Ordovician aquifer system, through the surficial aquifer system, to the Mississippi River based on simulated potentiometric-head gradients.

The U.S. Department of the Navy furnished trichloroethene source delineations and concentrations. Specifically, trichloroethene concentrations were 1,000 micrograms per liter at two source areas in the upper part of the shallow flow zone of the surficial aquifer system, and 50,000 and 12,000 micrograms per liter below these source areas in the lower part of the shallow flow zone.

The trichloroethene transport model simulated a trichloroethene plume that matched measured trichloroethene concentrations at some locations and not at other locations. Specifically, simulated trichloroethene concentrations did not match measured trichloroethene concentrations at 45 of 86 selected locations in the surficial aquifer system and at 2 selected locations in the underlying bedrock; for example, downgradient of extraction well AT–5A in the upper part of the shallow flow zone, three trichloroethene concentration measurements that ranged from 1,100 to 17,000 micrograms per liter existed in an area where simulated trichloroethene concentrations were not greater than 1,000 micrograms per liter. Between the simulated trichloroethene plume and the Mississippi River, which is also in the upper part of the shallow flow zone, five measured trichloroethene concentrations ranging from 22 to 170 micrograms per liter existed in an area where simulated trichloroethene concentrations were not greater than 3 micrograms per liter. In the intermediate flow zone downgradient of East River Road, a measured trichloroethene concentration of 930 micrograms per liter existed in an area where simulated trichloroethene concentrations ranged from 10 to 100 micrograms per liter. In the deep flow zone, a measured trichloroethene concentration of 110 micrograms per liter existed in an area outside the simulated trichloroethene plume where the simulated concentration was less than 3 micrograms per liter.

The degree to which the simulated trichloroethene plume did not match trichloroethene concentration measurements in the surficial aquifer system in 2001 suggests that furnished trichloroethene source delineations and concentrations did not describe all trichloroethene at and near the Naval Industrial Reserve Ordnance Plant or in Fridley, Minnesota. The following postulations may have also contributed to the degree to which the simulated trichloroethene plume did not match trichloroethene concentration measurements. Groundwater flow and trichloroethene transport at the plant were postulated to be steady state even though recharge and other forcing mechanisms are seasonal and transient. A simple, intergranular, groundwater flow component was postulated to have contributed more to the flow system than a groundwater flow component through secondary pores; however, secondary pores and conduit flow paths may have played a role in trichloroethene transport. A crescent-shaped, clay ridge was postulated to be a homogeneous hydrogeologic unit of dense clay that does not transmit groundwater or allow the transport of trichloroethene through the ridge; however, the ridge may be composed of heterogeneous silts and clays that transmit groundwater and allow for the transport trichloroethene through the ridge. Trichloroethene was postulated to be a conservative constituent with respect to transport; however, natural attenuation of trichloroethene may exist at the plant. Although dense nonaqueous phase liquids were postulated to not exist at the plant, they may exist, or may have existed at the plant in the past.

Trichloroethene discharged to the Mississippi River during the 2001 model simulation through the shallow flow zone of the surficial aquifer system. Under the Mississippi River, the maximum, simulated trichloroethene concentration contour was 100 micrograms per liter in shallow and intermediate flow zones, and the maximum, simulated trichloroethene concentration contour was 10 micrograms per liter in the deep flow zone. A simulated 900-foot-long zone of benthic trichloroethene discharge flux existed in the shallow flow zone across which simulated trichloroethene discharged from the surficial aquifer system to the Mississippi River at trichloroethene concentrations that ranged from 3 micrograms per liter to more than 100 micrograms per liter.

Groundwater flow and trichloroethene transport model simulators were applied to two hypothetical trichloroethene source areas forced by extraction wells AT–5A, AT–5B, AT–7, AT–8, AT–9, AT–10, AT–11, AT–12, and AT–13. These applications were hypothetical and not intended to represent historical conditions. For the first of five applications, the trichloroethene source area was in the shallow flow zone of the surficial aquifer system; other source areas were not simulated in the first application. For the other four applications, trichloroethene source areas were under most of the main building at the Naval Industrial Reserve Ordnance Plant, in the following four flow zones of the surficial aquifer system: upper part of the shallow flow zone, lower part of the shallow flow zone, intermediate flow zone, and deep flow zone; one flow zone was used per application. For these four applications, trichloroethene source areas that were not under the main building were not simulated. For each hypothetical application, extraction wells removed simulated trichloroethene from the surficial aquifer system such that for these hypothetical applications, simulated trichloroethene did not bypass extraction wells at a concentration greater than 3 micrograms per liter, and simulated trichloroethene was not transported to the Mississippi River at a concentration greater than 3 micrograms per liter.

Differences between trichloroethene source areas and actual trichloroethene sources may explain differences between 2001 measurements and model simulation results. The effect of differences between simulated trichloroethene source areas and actual trichloroethene source areas may cause differences between hypothetical application results and the actual performance of the U.S. Department of the Navy groundwater extraction system at the Naval Industrial Reserve Ordnance Plant in Fridley, Minnesota.

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Appendixes

Appendix 1. Summary of Groundwater Flow Simulation Components

Technical aspects of the preliminary groundwater flow model simulation (Davis and King, 2016) are described in this appendix. Objectives, results, postulations, limitations, and sensitivity analyses of the groundwater flow simulation are described in the “Introduction,” “Preliminary Simulation of Groundwater Flow,” “Sensitivity Analyses,” and “Postulations and Limitations” sections of this report.

The objective of the preliminary groundwater flow model simulation was to generate a steady-state groundwater flow field for August 20, 2001, to force a general trichloroethene (TCE) transport simulation representative of 2001 (appendix 2). The August 20 simulation used MODFLOW 2000 (Harbaugh and others, 2000) version 1.19.01 03/25/2010, which was based on McDonald and Harbaugh (1988), who used the finite difference method to calculate potentiometric head on an orthogonal grid. The terms “potentiometric head” and “hydraulic head” are equivalent. McDonald and Harbaugh (1988) and Harbaugh and others (2000) detailed governing equations. McDonald and Harbaugh (1988) required that the density of groundwater was constant. McDonald and Harbaugh (2003) identified other investigators involved in the development of the groundwater flow model described in McDonald and Harbaugh (1988).

Metropolitan Council (2009, 2014) simulated steady-state, regional, groundwater flow in the surficial and Cambrian-Ordovician aquifer systems to incorporate land use into water supply plans, assess current and future groundwater withdrawals, assess future groundwater availability, and identify water supply alternatives. The 4,913-square-mile Metropolitan Council (2009) study area (see “Previous Investigations” section, fig. 5) included all or parts of several counties (not shown) in Minnesota and Wisconsin (see “Previous Investigations” section, fig. 5). Metropolitan Council (2009) used MODFLOW-96 (Harbaugh and McDonald, 1996) to provide the best available water demand, land use, and hydrogeologic data to promulgate a consensus, regional, calibrated, predictive planning tool for use by multiple governmental entities. Metropolitan Council (2014) updated Metropolitan Council (2009) by using MODFLOW-NWT (Niswonger and others, 2011), incorporating transience, updating the stratigraphic framework, and implementing a new recharge calculation.

Although the regional groundwater flow model simulation documented in Metropolitan Council (2014) updated a prior simulation documented in Metropolitan Council (2009), the more local August 20, 2001, groundwater flow simulation at the Naval Industrial Reserve Ordnance Plant (NIROP) was primarily constructed prior to 2014 and was, therefore, based on the results described in Metropolitan Council (2009) with selected refinements—described in appendixes 1 and 2—necessary to characterize TCE transport at NIROP (see “Previous Investigations” section). Metropolitan Council (2009) used MODFLOW-96 (Harbaugh and McDonald, 1996), which is also based on McDonald and Harbaugh (1988).

Geographic Extent of Study Area and Boundary Conditions

Ideally, groundwater flow model simulation boundaries are specified where hydrogeologic units either terminate against impermeable rocks, or intersect hydrologic elements with known temporal and spatial potentiometric-head variation such as rivers or lakes. A challenge of disparate spatial resolution existed with numerical simulation of TCE transport at NIROP; the regional-scale resolution of the Cambrian-Ordovician aquifer system is considerably larger than the local-scale resolution required to simulate TCE transport. Ideal simulation boundaries were, therefore, not practical. This challenge of disparate spatial scales is common in the numerical simulation of contaminant transport. A telescoping grid was used to manage the challenge (figs. 1–1*A* and 1–1*B*). The Metropolitan Council (2009) study area was truncated around Fridley, Minnesota (see “Previous Investigations” section, fig. 5), to reduce an unnecessary numerical burden that would be required to simulate groundwater flow throughout the entire Metropolitan Council (2009) study area.

The truncated model simulation area is an inset within the Metropolitan Council (2009) study area (see “Previous Investigations” section, fig. 5). Potentiometric heads on the boundary of the truncated simulation area were from the simulation of the Twin Cities Metropolitan Area, described in Metropolitan Council (2009). Potentiometric heads from each layer in the Metropolitan Council (2009) simulation were used as constant potentiometric head boundaries for the corresponding layer in the August 20, 2001, simulation of the surficial and Cambrian-Ordovician aquifer systems at NIROP. It is possible to define a model extent within an inset to a parent model, along a highly irregular polyline that does not have hydrogeologic importance. Information from the parent simulation are extracted along the boundary of the inset, such that the child simulation accurately mimics the performance of the parent simulation within the inset.

Metropolitan Council (2009) identified hydrologic features that were useful in defining the geographic extent of a study area necessary to characterize TCE transport at NIROP. Metropolitan Council (2009) identified a ridge (fig 1–1) in the potentiometric surface of the Shakopee and Jordan aquifers (see “Previous Investigations” and “Cambrian-Ordovician Aquifer System” sections) between a point that was about 1 mile east of Oneka Lake (fig. 1–2*A*), and a point west of Interstate 35 (fig. 1–2*A*) and south of Howard Lake (fig. 1–2*A*). Groundwater to the northeast of this ridge flows to the northeast, and groundwater to the southwest of this ridge flows to the southwest. The northeastern boundary of the study area (fig. 1–1*A*) was coincident with this ridge where a no-flow boundary was specified in MODFLOW using the IBOUND array of the DIS discretization package (fig. 1–1*A*). Metropolitan Council (2009) identified constant potentiometric heads in the Prairie du Chien aquifer, west of the Mississippi River (see “Introduction” section, figs. 1 and 5), along a line that extends from a point south of

State Highway 100 (fig. 1–2*A*) to a point north of Interstate 694 (fig. 1–2*A*); the southwestern boundary of the study area was coincident with this line of constant potentiometric head where potentiometric head was specified in MODFLOW as 849.74 feet (ft) above the North American Vertical Datum of 1988 (NAVD 88) (fig. 1–1*A*).

Metropolitan Council (2009) was used to delineate the approximate location and orientation of groundwater flowlines in the surficial and Cambrian-Ordovician aquifer systems. Groundwater flowlines are effective no-flow study area boundaries because groundwater does not flow across flowlines; for example, an approximate flowline connected the northern corner of the northeastern study area boundary to the northern corner of the southwestern study area boundary (see “Description of Study Area” section, fig. 1). An approximate flowline also connected the southern corner of the northeastern study area boundary to a point in the Mississippi River downstream from the North 42nd Avenue bridge (see “Description of Study Area” section, fig. 1) and upstream from the North Lowry Avenue bridge (see “Description of Study Area” section, fig. 1). Finally, an approximate flowline connected the southern corner of the southwestern boundary to the point in the Mississippi River. Potentiometric heads from each layer in the Metropolitan Council (2009) model simulation along these approximate flowlines were used as constant potentiometric head boundaries for the corresponding layer in the August 20, 2001, simulation.

Vertical Spatial Discretization

The model simulation described in this report adopted a modified version of Metropolitan Council’s (2009) simulation layer top and bottom elevations as hydrogeologic unit interface elevations. Metropolitan Council (2009) combined 15 geologic units into 9 hydrogeologic units (see “Previous Investigations” section, fig. 4). Metropolitan Council (2009) built simulation layers from digital elevation models of geologic and hydrogeologic unit interfaces. Digital elevation models were constructed by the Minnesota Geological Survey, Tipping and Mossler (1996), Runkel and others (2003), and Runkel and Tipping (2006). Metropolitan Council (2009) also built a new digital elevation model from the Minnesota County Well Index (Minnesota Department of Health, 2008). Metropolitan Council (2009) used stratigraphic elevations from the index in areas where digital elevation models were not published by the Minnesota Geological Survey. Metropolitan Council (2009) allowed the surficial aquifer system to occupy more than one simulation layer to represent hydrogeologic units that discharge groundwater to bedrock valleys filled with glacial and fluvial deposits. Metropolitan Council (2009) defined the top elevation of glacial and fluvial deposits at land surface and the bottom elevation as coincident with the top of the highest bedrock unit. Metropolitan Council (2009) incorporated fault zones into simulation layers by adjusting hydraulic conductivity; simulation layer elevations were not adjusted to detail offsets across fault zones because fault zone locations and offsets were not well known.

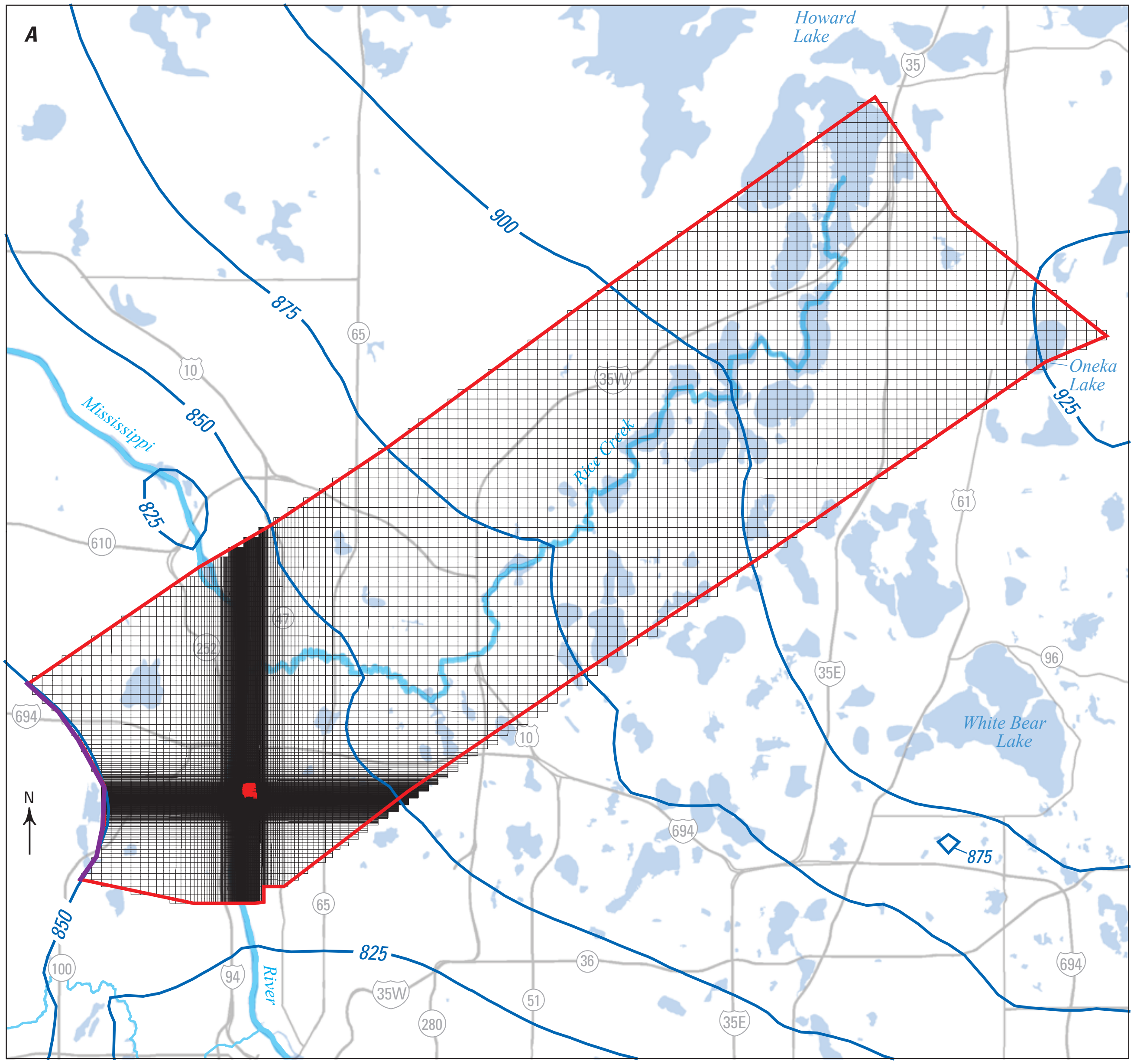
The preliminary model simulation adopted Metropolitan Council (2009) simulation layer top and bottom elevations as hydrogeologic unit interface elevations with the following exceptions: in conformance with Davis (2007) and Tetra Tech (2002), the surficial aquifer system was divided into shallow, intermediate, and deep flow zones of approximately equivalent thickness (see “St. Peter Aquifer and Lower St. Peter Confining Unit” section, figs. 7 and 8); and the shallow flow zone of the surficial aquifer system was divided into two simulation layers to simulate the presence of a subsurface clay ridge, where one shallow flow zone layer represented the clay ridge and the other layer represented glacial and fluvial deposits. In areas away from the ridge, both shallow flow zone layers represent glacial and fluvial deposits, there is no hydrogeologic difference between the two layers, and identical parameters were used to represent both layers, such that both simulation layers act as one unit. A total of 10 simulation layers were used (figs. 1–2 through 1–11).

At some locations, Metropolitan Council (2009) postulated that lithostratigraphic and hydrogeologic interfaces are coincident. Runkel and others (2006) and Tipping and others (2006) determined that lithostratigraphic and hydrogeologic interfaces are not coincident everywhere.

Metropolitan Council (2009) simulated groundwater flow in the Ironton and Galesville Sandstones, the Eau Claire Sandstone, and the Mount Simon-Hinckley Sandstones. Mossler (2008) renamed the Ironton and Galesville Sandstone as the Wonewoc Sandstone. Jones and others (2013) and this report used the geologic unit name of Wonewoc Sandstone (hydrogeologic name of Wonewoc aquifer). Groundwater flow or TCE transport were not simulated in the Eau Clair confining unit, upper Mount Simon aquifer, middle Mount Simon confining unit, or lower Mount Simon aquifer. The permeability of the Eau Claire confining unit is relatively low compared to the Wonewoc aquifer. Because the upper and lower Mount Simon aquifers are not likely to influence groundwater flow and TCE transport in the surficial aquifer system, the interface between the Wonewoc aquifer and the lower-permeability Eau Claire confining unit was represented in an abstract fashion as impermeable in the preliminary model simulation and preliminary applications of the simulator (see “Subjacent Units” section).

Vertical Datum Postulation

Elevation data in this report were referenced to NAVD 88. Elevation data referenced to some other sea level vertical datum were not strictly converted to NAVD 88 for use in this report because the elevation error of the original data exceeds the difference between NAVD 88 and other sea level datum; for example, at NIROP, NAVD 88 is 0.2 ft higher than the National Geodetic Vertical Datum of 1929 (NGVD 29) on the basis of conversion of earth elevation 840 ft NGVD 29 at 45° 03’ 24.77” N, 93° 16’ 36.11” W with the U.S. National Geodetic Survey’s (2013) Orthometric Height Conversion calculator. If the vertical accuracy of 840 ft NGVD 29 was ±10 ft, this elevation was acceptably represented as 840 ft NAVD 88 ±10 ft; conversion of this elevation to 840.2 ft NAVD 88 ±10 ft was not deemed necessary.



Base modified from Minnesota Department of Transportation
Survey and Mapping, 1:24,000 scale
North American Datum of 1983

0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

EXPLANATION

- **Simulation grid**
- **No-flow boundary**
- **Specified-head boundary**
- *825* **Potentiometric heads in the Shakopee and Jordan aquifers**—Contour interval 25 feet. Datum is North American Vertical Datum of 1988. Data from Metropolitan Council (2009)
- **Main Naval Industrial Reserve Ordnance Plant building**

Figure 1–1. Location and orientation of the model simulation grid for groundwater flow and trichloroethene transport simulations. *A*, the study area in and near Fridley, Minnesota. *B*, in an area between the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota, and the Mississippi River.

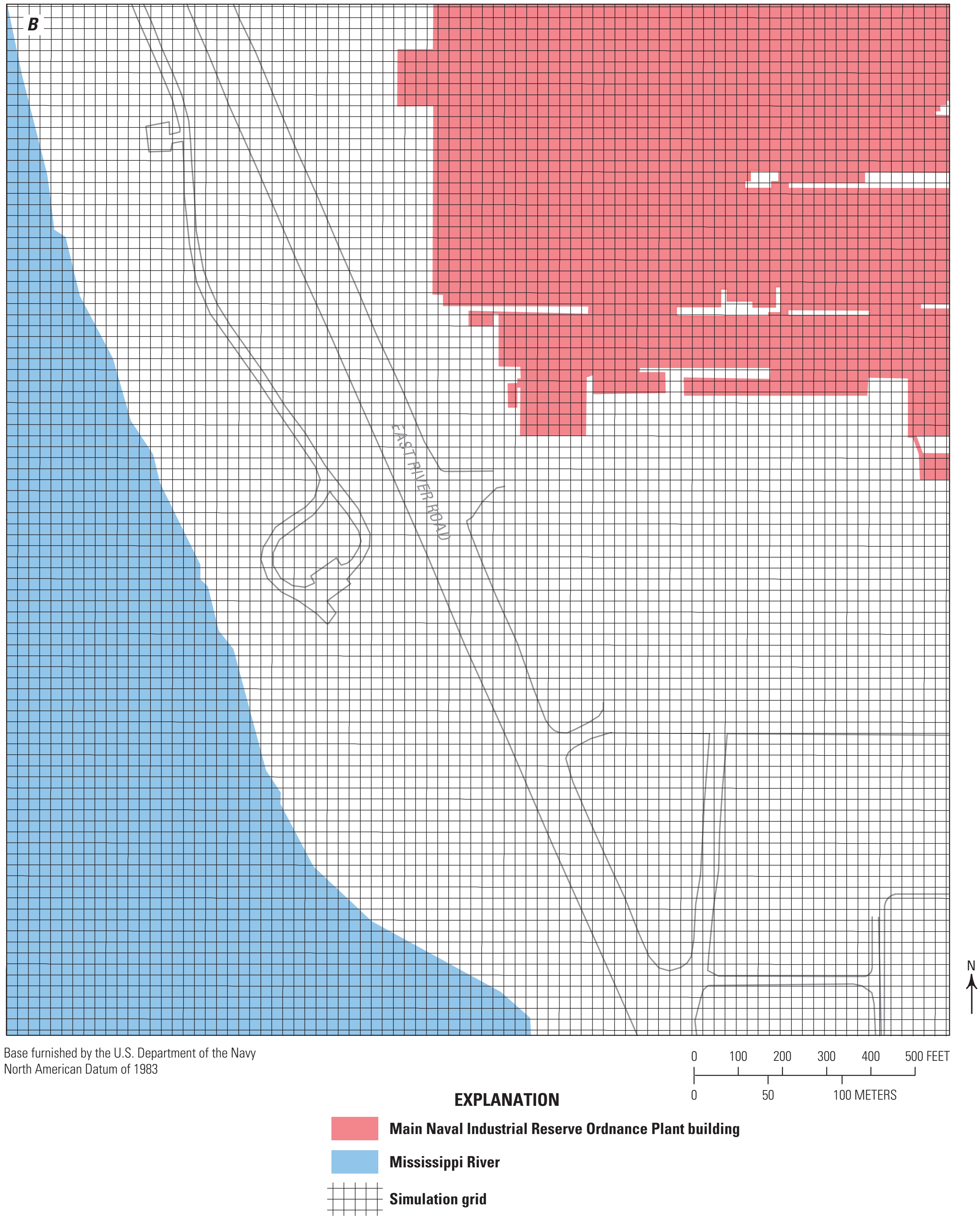
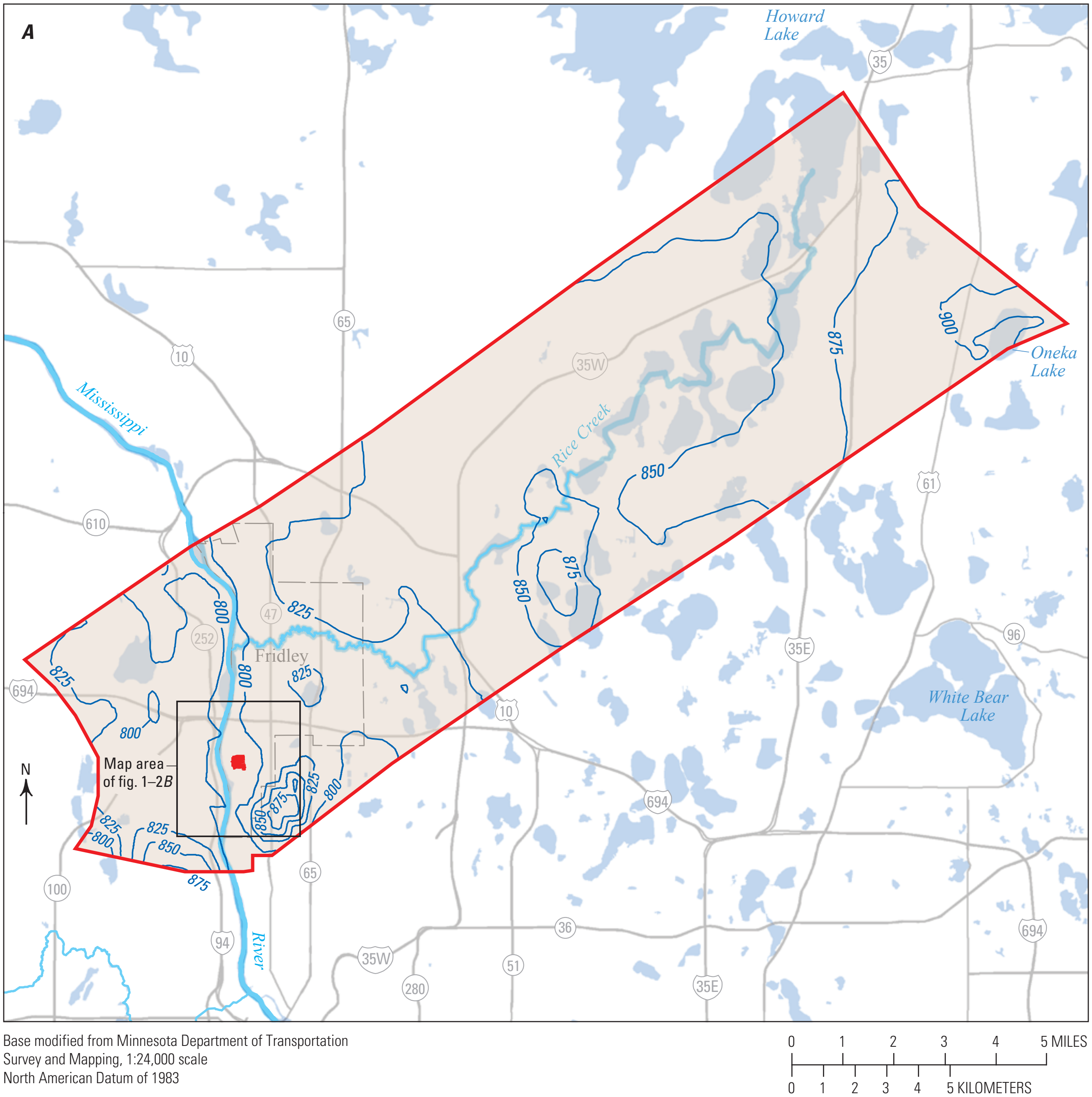


Figure 1–1. Location and orientation of the model simulation grid for groundwater flow and trichloroethene transport simulations. *A*, the study area in and near Fridley, Minnesota. *B*, in an area between the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota, and the Mississippi River.—Continued



EXPLANATION

Study area

850 **Interface elevation contour between upper and lower parts of shallow flow zone, surficial aquifer system**—Contour interval 25 feet. Datum is North American Vertical Datum of 1988

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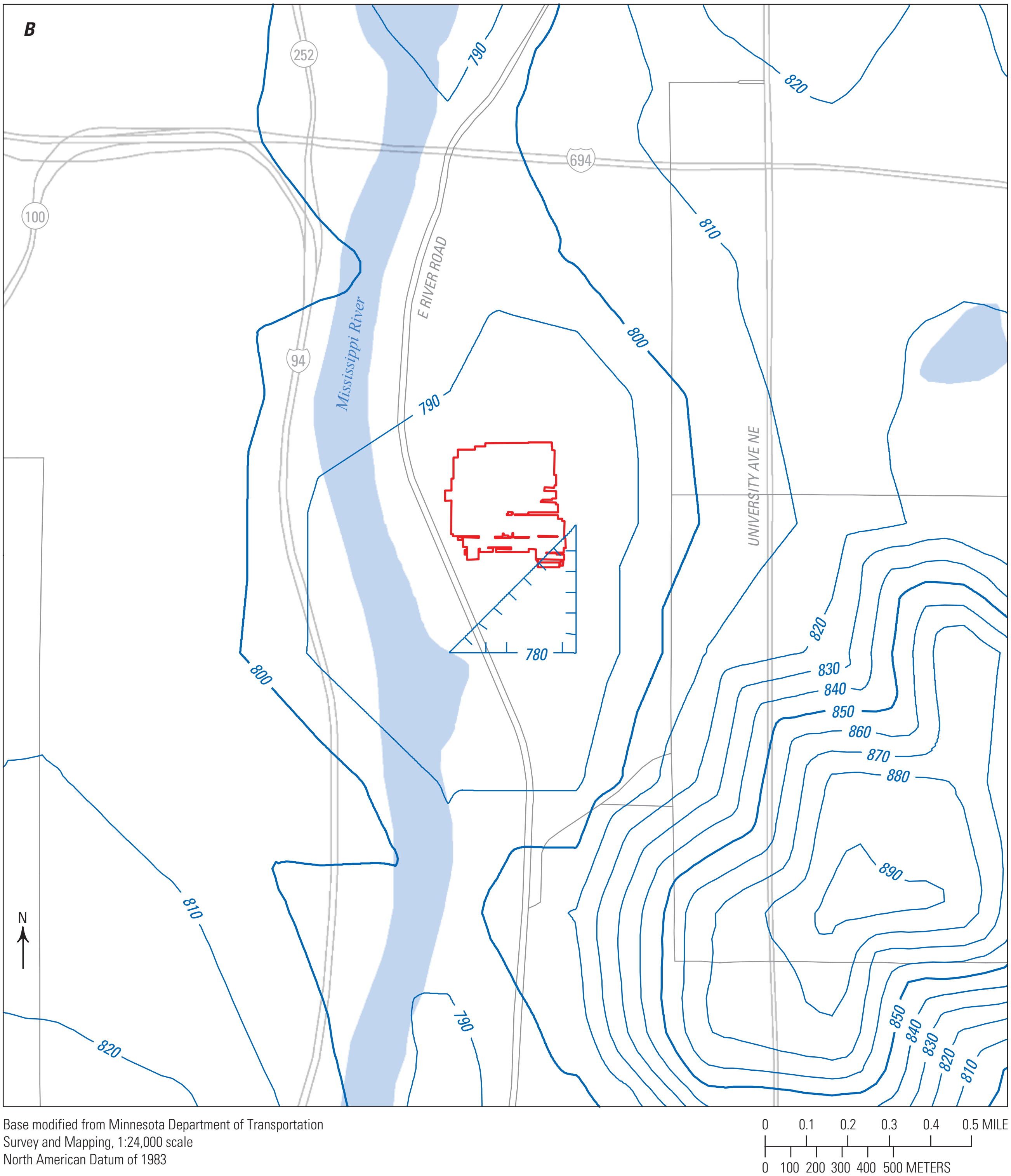
Figure 1–2. Elevation of the interface between the bottom of the upper part of the surficial aquifer system shallow flow zone (model simulation layer 1) and the top of the lower part of the suficial aquifer system shallow flow zone (model simulation layer 2). *A*, the study area, in and near Fridley, Minnesota. *B*, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.

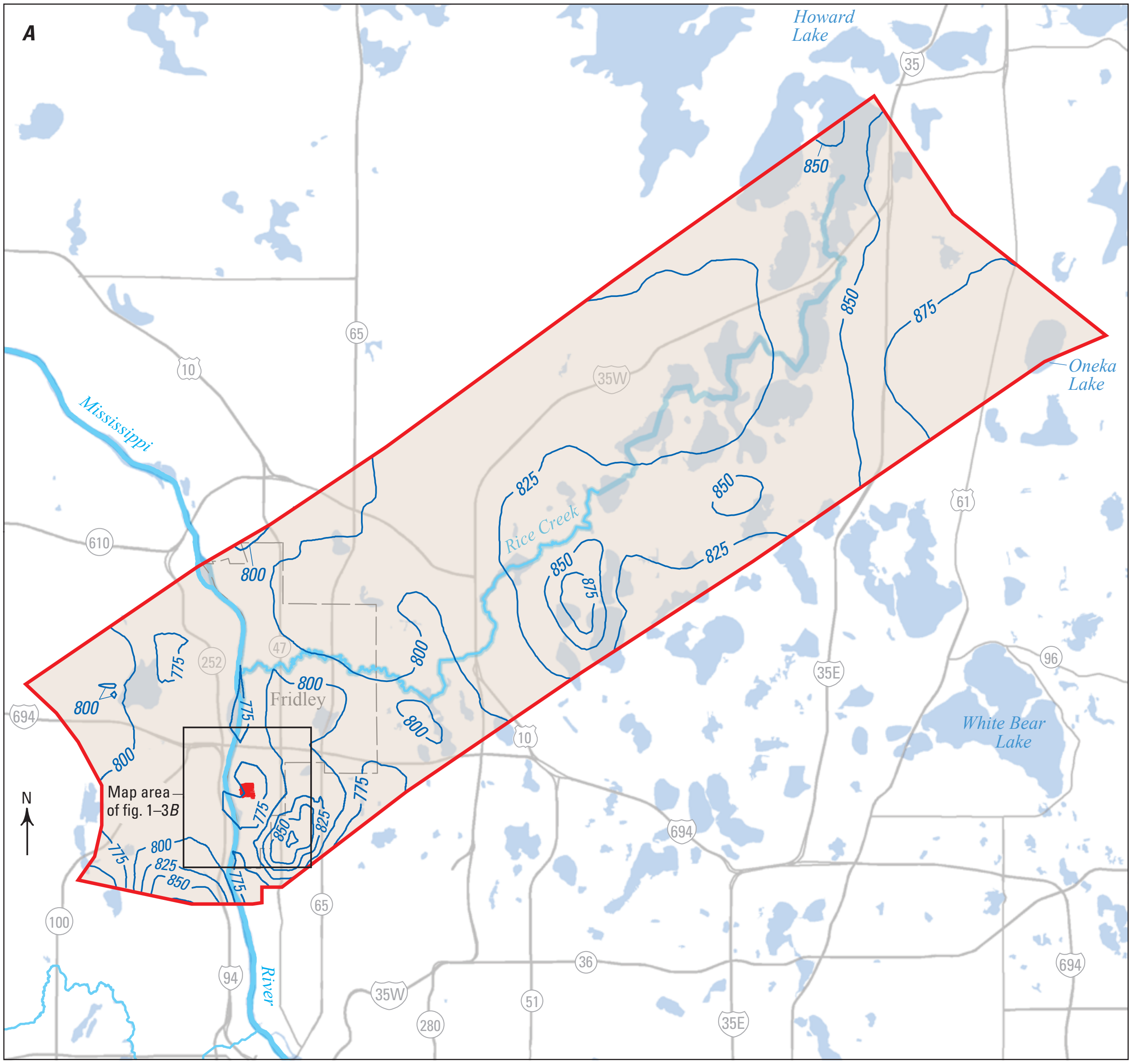


EXPLANATION

— 800 — **Interface elevation contour between upper and lower parts of shallow flow zone, surficial aquifer system**—Hachures indicate depression. Contour interval 10 feet. Datum is North American Vertical Datum of 1988

Main Naval Industrial Reserve Ordnance Plant building

Figure 1–2. Elevation of the interface between the bottom of the upper part of the surficial aquifer system shallow flow zone (model simulation layer 1) and the top of the lower part of the suficial aquifer system shallow flow zone (model simulation layer 2). *A*, the study area, in and near Fridley, Minnesota. *B*, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.—Continued



Base modified from Minnesota Department of Transportation Survey and Mapping, 1:24,000 scale
North American Datum of 1983

0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

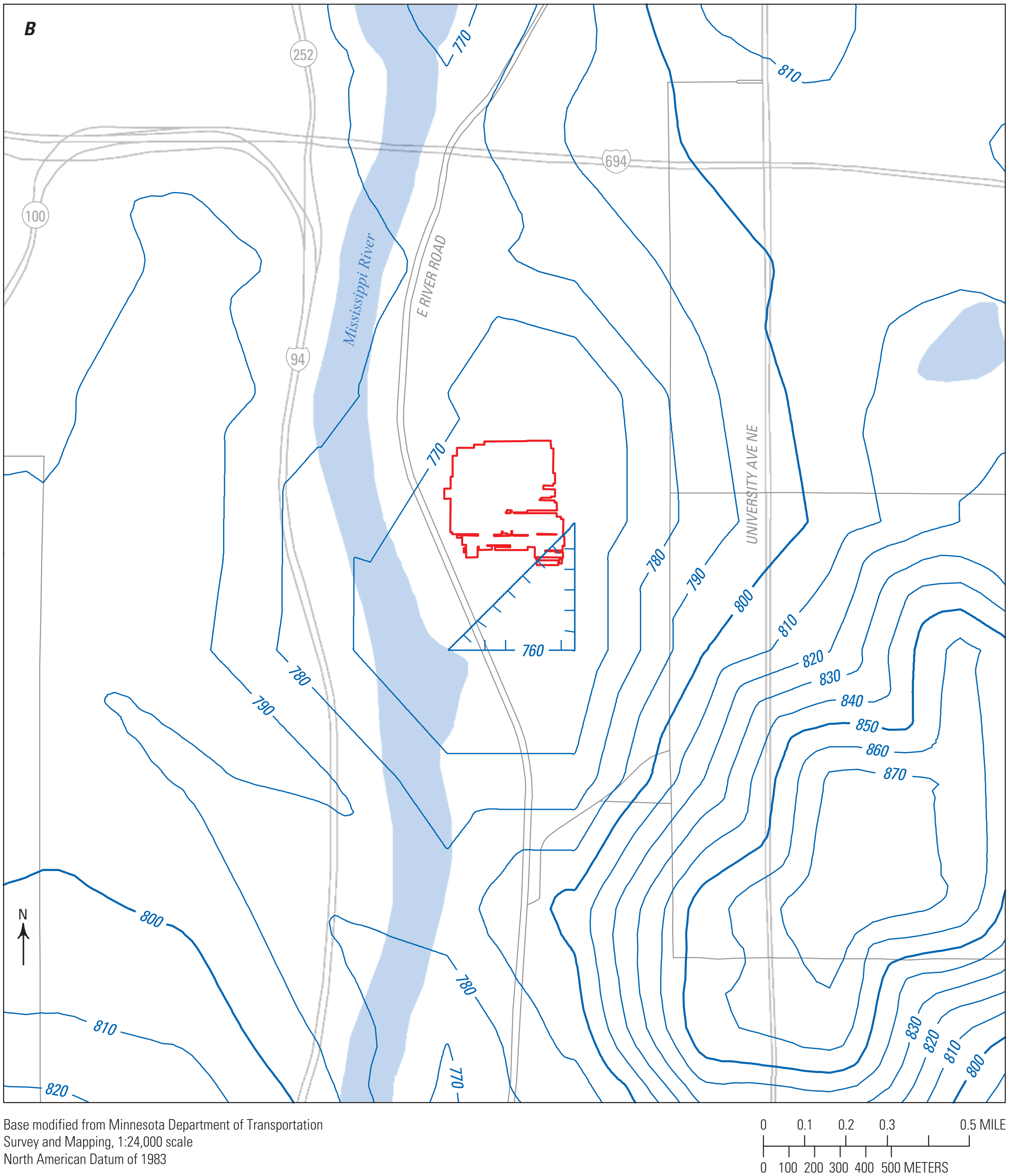
EXPLANATION

Study area

800 **Interface elevation contour between shallow and intermediate flow zones, surficial aquifer system**—Contour interval 25 feet. Datum is North American Vertical Datum of 1988

Main Naval Industrial Reserve Ordnance Plant building

Figure 1–3. Elevation of the interface between the bottom of the lower part of the surficial aquifer system shallow flow zone (model simulation layer 2) and the top of the surficial aquifer system intermediate flow zone (model simulation layer 3). *A*, for the study area, in and near Fridley, Minnesota. *B*, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.

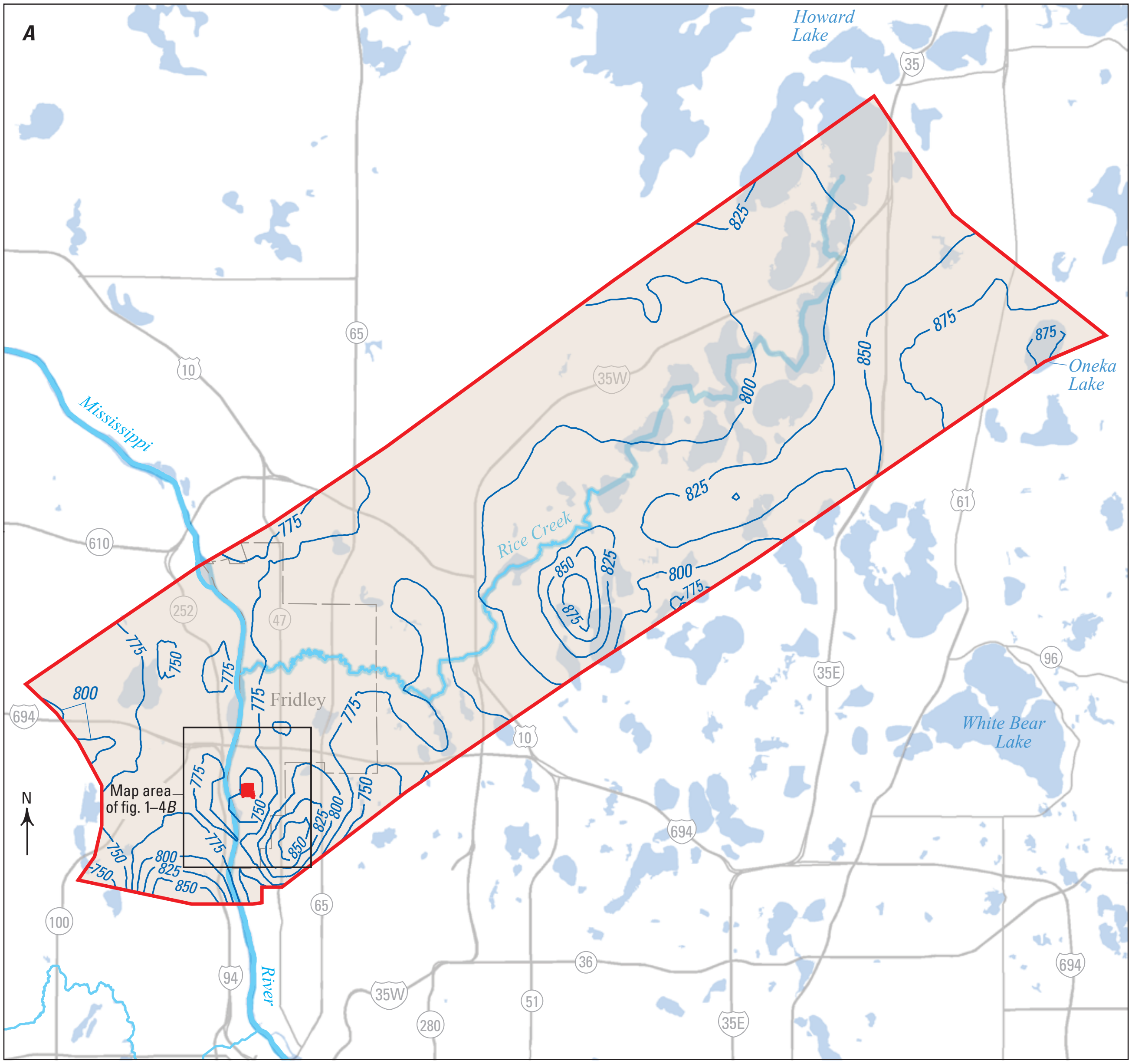


EXPLANATION

800 — **Interface elevation contour between shallow and intermediate flow zones, surficial aquifer system**—Hachures indicate depression. Contour interval 10 feet. Datum is North American Vertical Datum of 1988

Main Naval Industrial Reserve Ordnance Plant building

Figure 1–3. Elevation of the interface between the bottom of the lower part of the surficial aquifer system shallow flow zone (model simulation layer 2) and the top of the surficial aquifer system intermediate flow zone (model simulation layer 3). *A*, for the study area, in and near Fridley, Minnesota. *B*, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.—Continued



Base modified from Minnesota Department of Transportation
Survey and Mapping, 1:24,000 scale
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0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

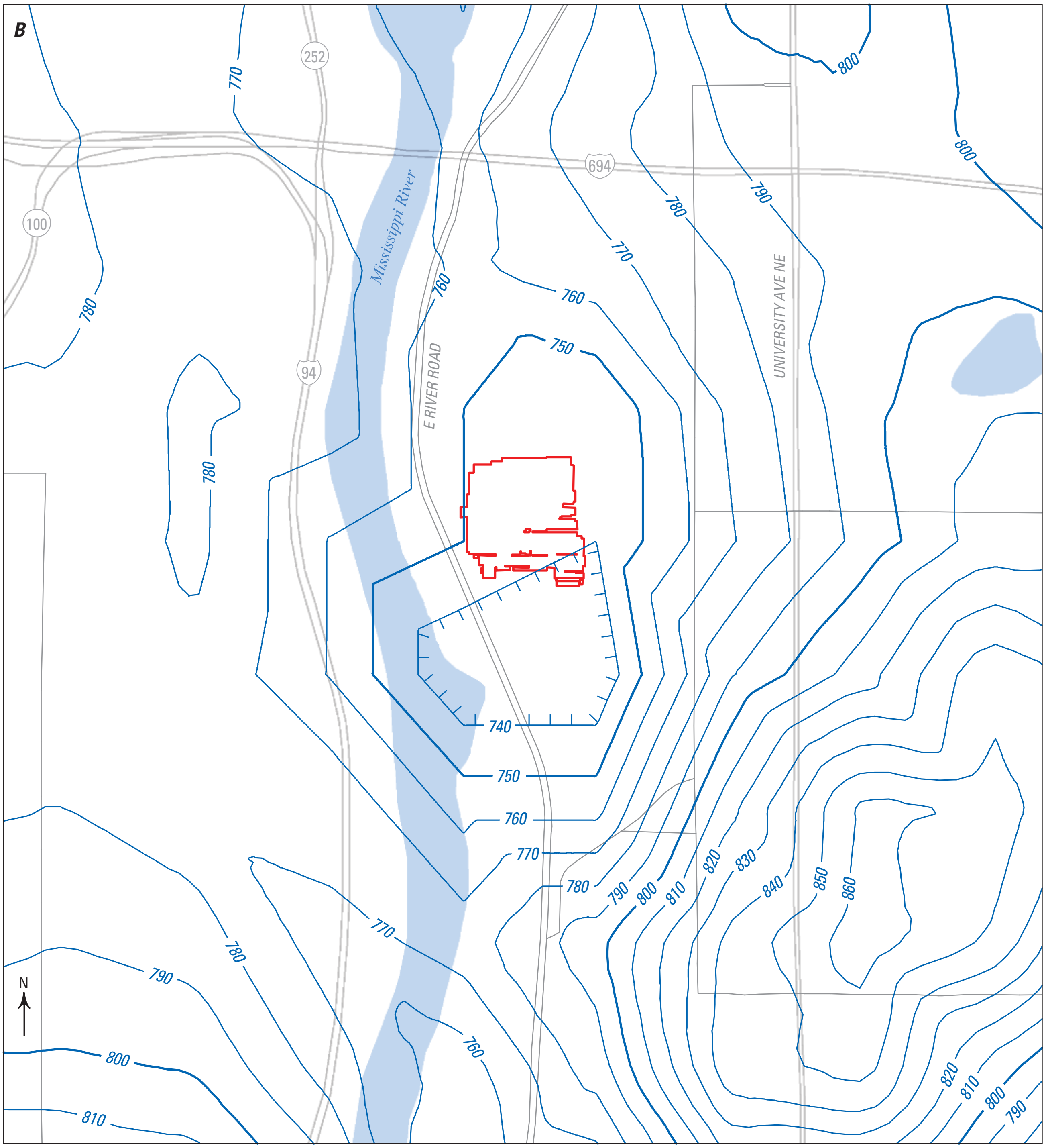
EXPLANATION

Study area

800 **Interface elevation contour between intermediate and deep flow zones, surficial aquifer system**—Contour interval 25 feet. Datum is North American Vertical Datum of 1988

Main Naval Industrial Reserve Ordnance Plant building

Figure 1–4. Elevation of the interface between the bottom of the surficial aquifer system intermediate flow zone (model simulation layer 3) and the top of the surficial aquifer system deep flow zone (model simulation layer 4). *A*, for the study area, in and near Fridley, Minnesota. *B*, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.



Base modified from Minnesota Department of Transportation
Survey and Mapping, 1:24,000 scale
North American Datum of 1983

0 0.1 0.2 0.3 0.5 MILE
0 100 200 300 400 500 METERS

EXPLANATION

800 **Interface elevation contour between intermediate and deep flow zones, surficial aquifer system**—Hachures indicate depression. Contour interval 10 feet. Datum is North American Vertical Datum of 1988

Main Naval Industrial Reserve Ordnance Plant building

Figure 1–4. Elevation of the interface between the bottom of the surficial aquifer system intermediate flow zone (model simulation layer 3) and the top of the surficial aquifer system deep flow zone (model simulation layer 4). *A*, for the study area, in and near Fridley, Minnesota. *B*, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.—Continued

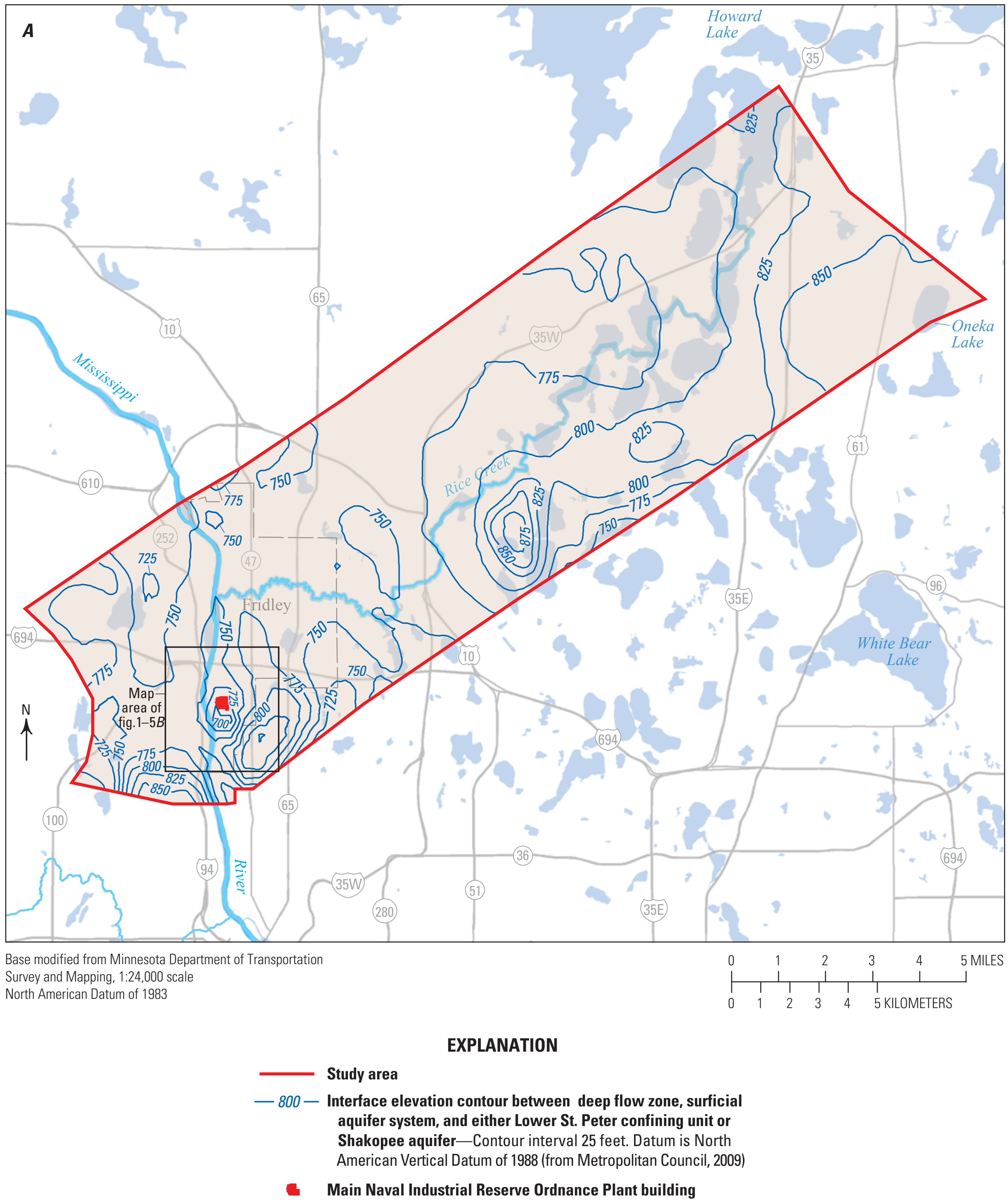
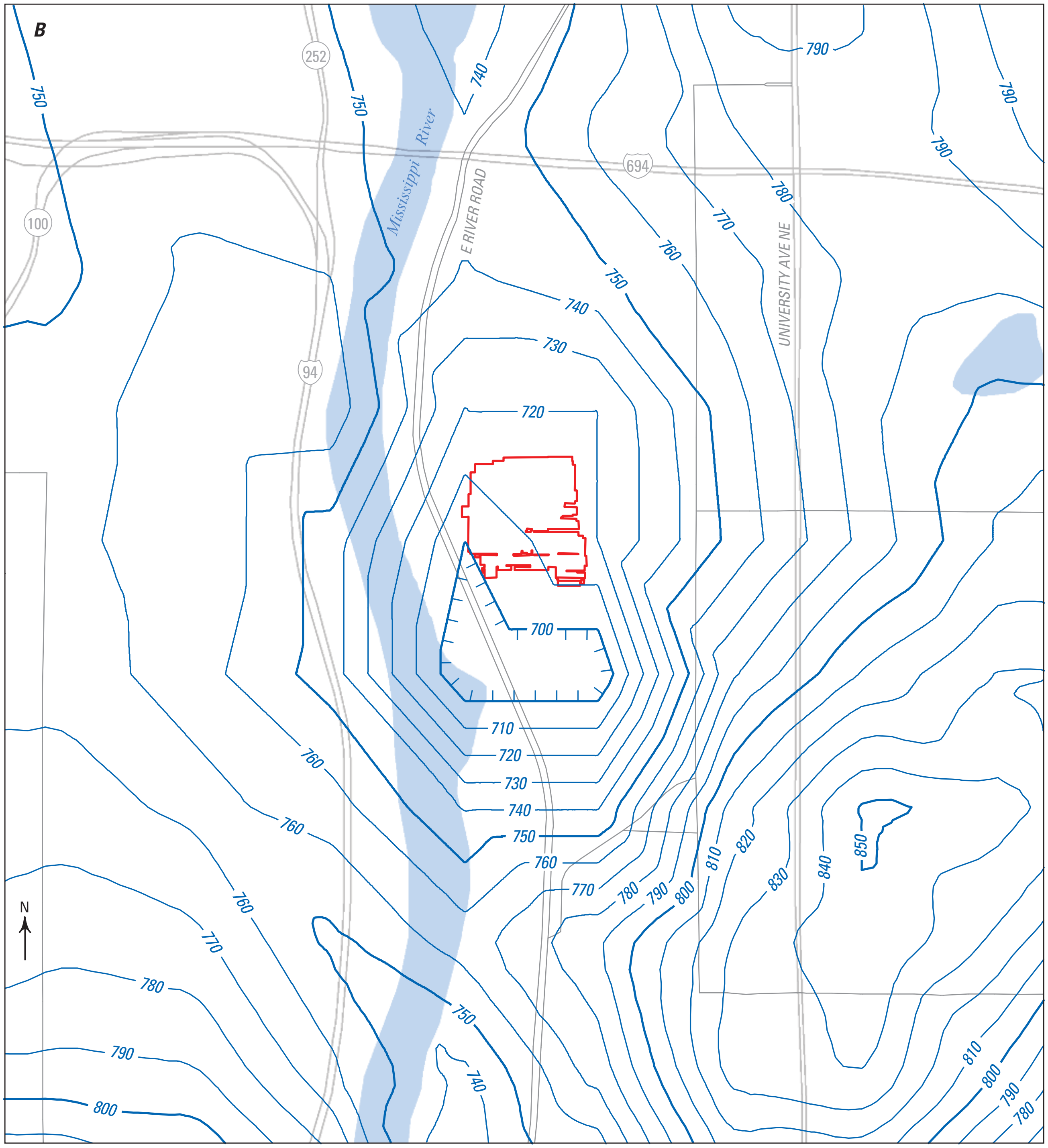


Figure 1–5. Elevation of the interface between the bottom of the surficial aquifer system deep flow zone (model simulation layer 4) and the top of either the lower St. Peter confining unit, where present, or the Shakopee aquifer, where the lower St. Peter confining unit does not exist (model simulation layer 5). *A*, for the study area, in and near Fridley, Minnesota. *B*, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.



Base modified from Minnesota Department of Transportation
Survey and Mapping, 1:24,000 scale
North American Datum of 1983

0 0.1 0.2 0.3 0.5 MILE
0 100 200 300 400 500 METERS

EXPLANATION

800 — **Interface elevation contour between deep flow zone, surficial aquifer system, and either Lower St. Peter confining unit or Shakopee aquifer**—Hachures indicate depression. Contour interval 10 feet. Datum is North American Vertical Datum of 1988 (from Metropolitan Council, 2009)

Main Naval Industrial Reserve Ordnance Plant building

Figure 1–5. Elevation of the interface between the bottom of the surficial aquifer system deep flow zone (model simulation layer 4) and the top of either the lower St. Peter confining unit, where present, or the Shakopee aquifer, where the lower St. Peter confining unit does not exist (model simulation layer 5). *A*, for the study area, in and near Fridley, Minnesota. *B*, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.—Continued

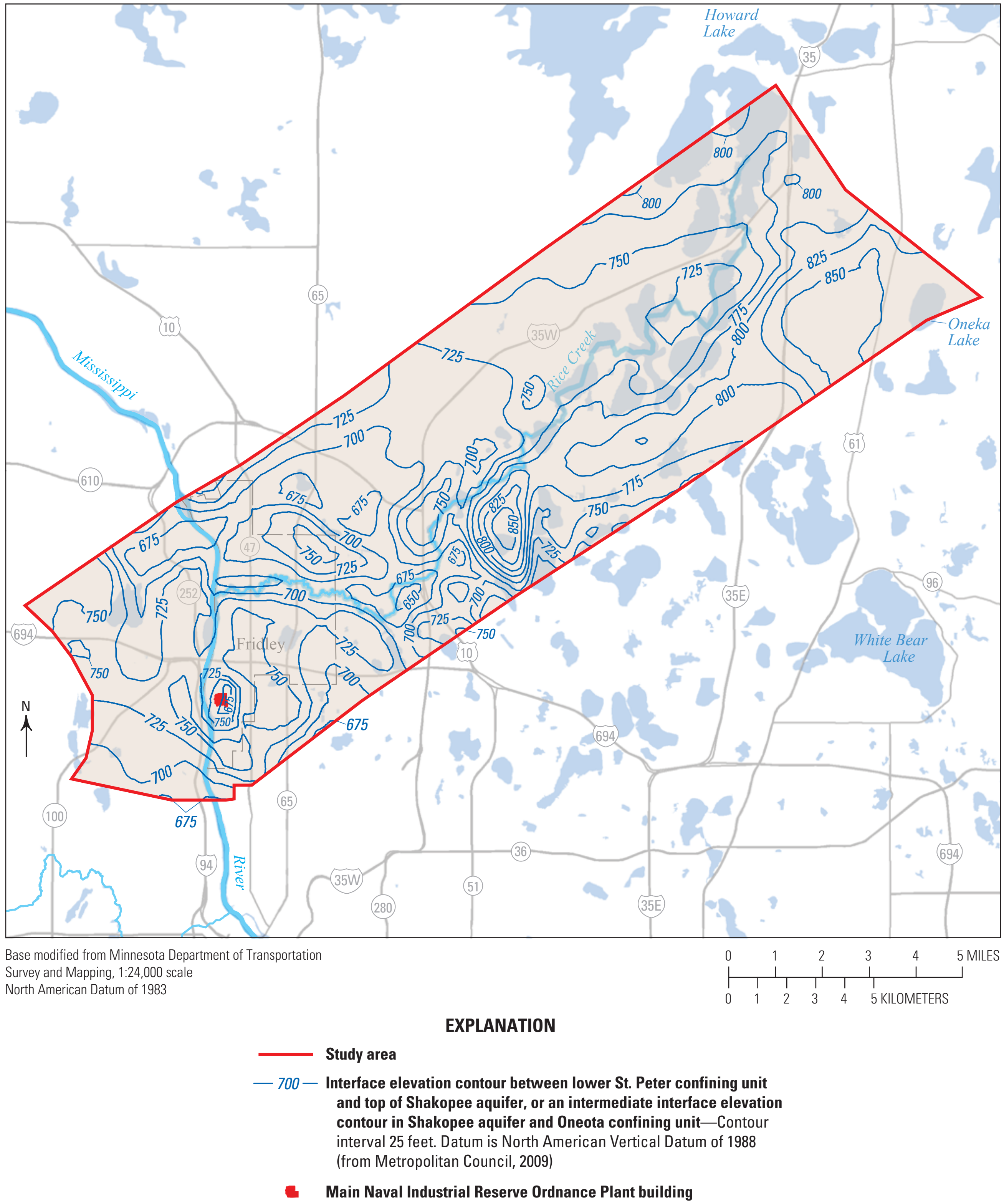
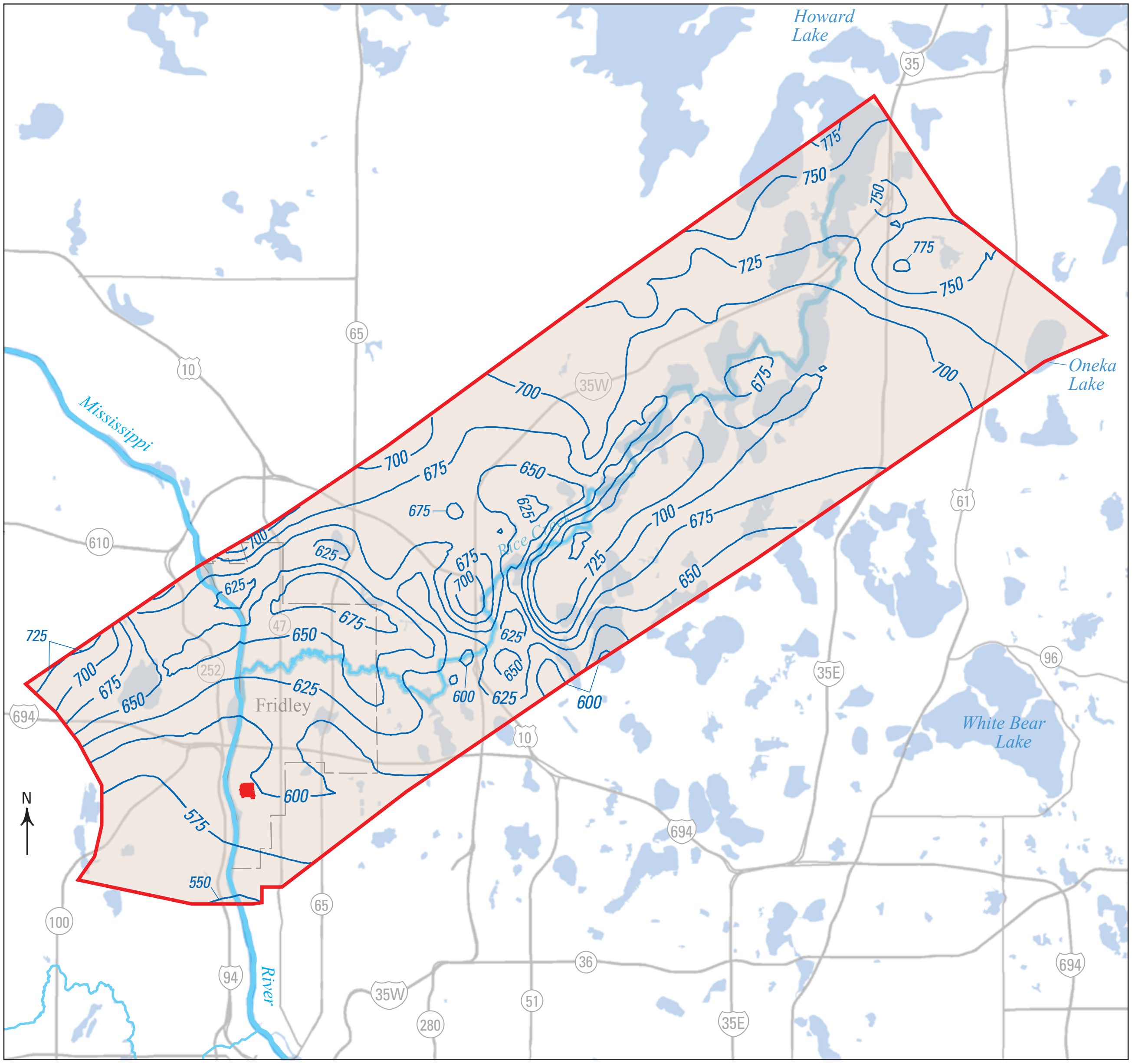


Figure 1–6. Elevation of the interface between the bottom of the lower St. Peter confining unit (model simulation layer 5), where present, and the top of the Shakopee aquifer (model simulation layer 6) or an intermediate interface elevation contour in the Shakopee aquifer and Oneota confining unit where the lower St. Peter confining unit does not exist (in which the Shakopee aquifer and Oneota confining unit were combined and simulated as layers 5 and 6) in an near Fridley Minnesota.



Base modified from Minnesota Department of Transportation
Survey and Mapping, 1:24,000 scale
North American Datum of 1983

0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

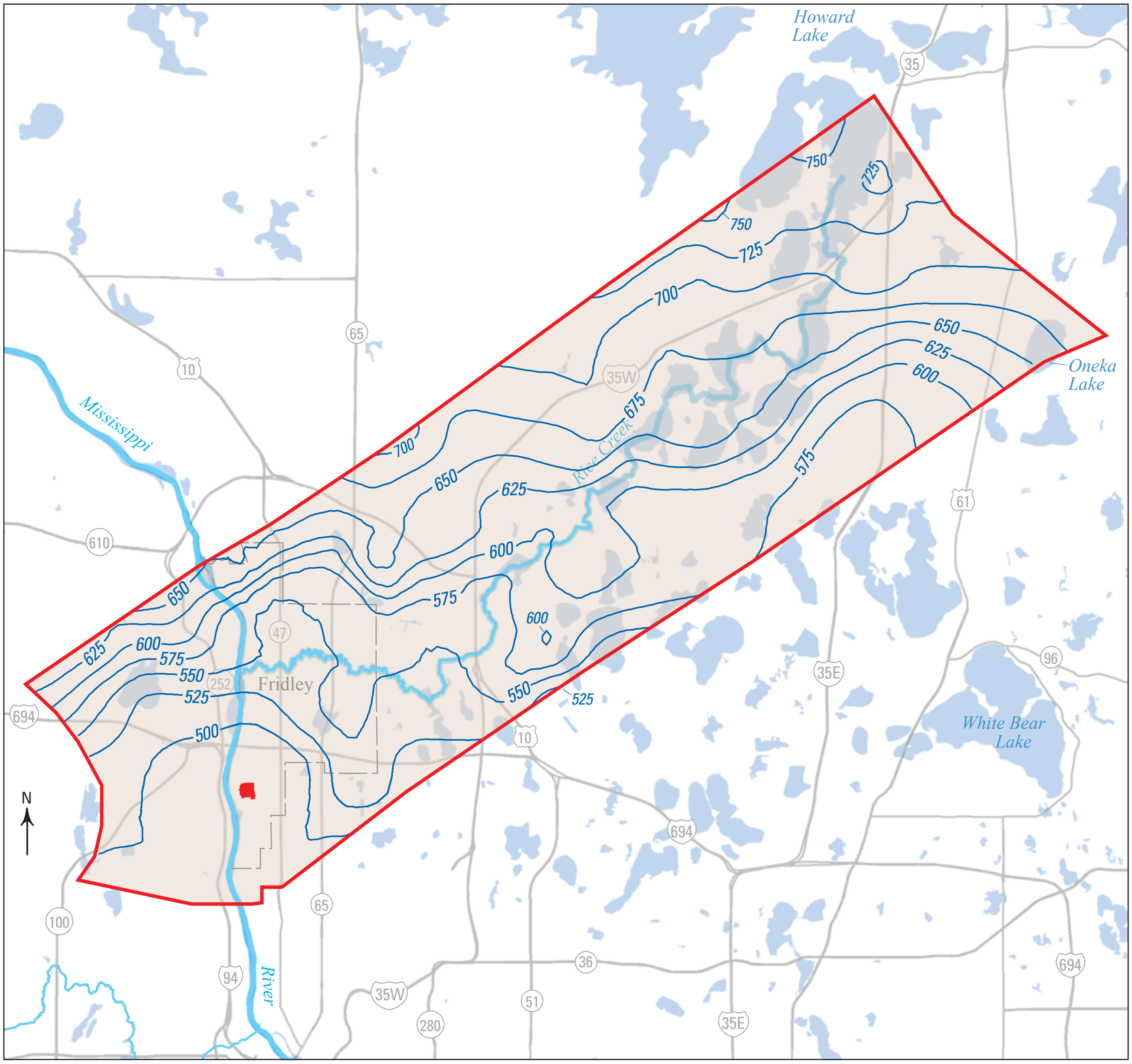
EXPLANATION

Study area

700 **Interface elevation contour between Oneota confining unit and Jordan aquifer**—Contour interval 25 feet. Datum is North American Vertical Datum of 1988 (from Metropolitan Council, 2009)

Main Naval Industrial Reserve Ordnance Plant building

Figure 1–7. Elevation of the interface between the bottom of the Oneota confining unit (model simulation layer 6) and the top of the Jordan aquifer (model simulation layer 7) in and near Fridley, Minnesota.



Base modified from Minnesota Department of Transportation
Survey and Mapping, 1:24,000 scale
North American Datum of 1983

0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

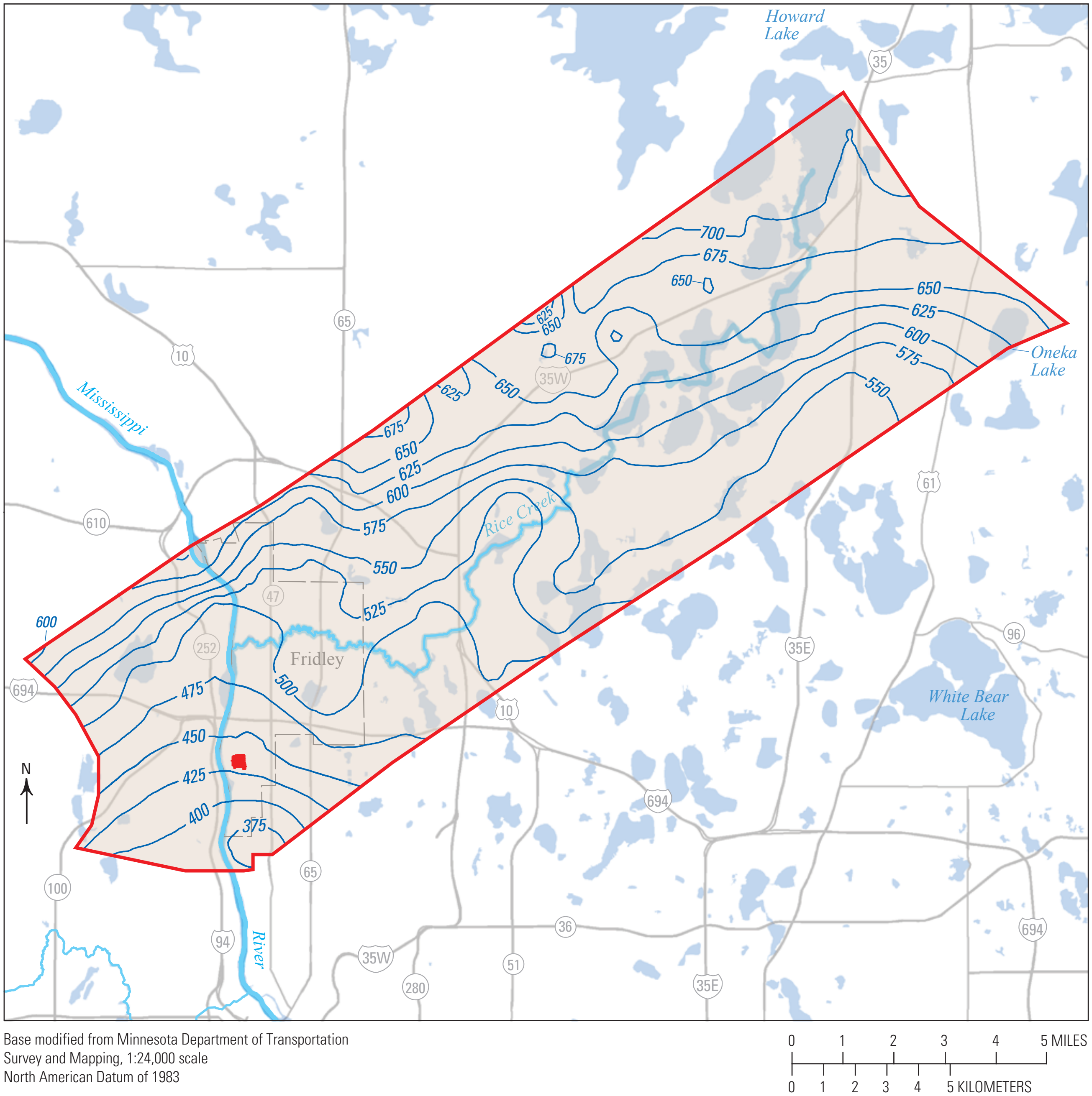
EXPLANATION

Study area

600 **Interface elevation contour between Jordan aquifer and St. Lawrence confining unit**—Contour interval 25 feet. Datum is North American Vertical Datum of 1988 (from Metropolitan Council, 2009)

Main Naval Industrial Reserve Ordnance Plant building

Figure 1–8. Elevation of the interface between the bottom of the Jordan aquifer (model simulation layer 7) and the top of the St. Lawrence confining unit (model simulation layer 8) in and near Fridley, Minnesota.



EXPLANATION

Study area

500 — **Interface elevation contour between St. Lawrence confining unit and Upper Tunnel City aquifer**—Contour interval 25 feet. Datum is North American Vertical Datum of 1988 (from Metropolitan Council, 2009)

Main Naval Industrial Reserve Ordnance Plant building

Figure 1–9. Elevation of the interface between the bottom of the St. Lawrence confining unit (model simulation layer 8) and the top of the upper Tunnel City aquifer (model simulation layer 9) in and near Fridley, Minnesota.

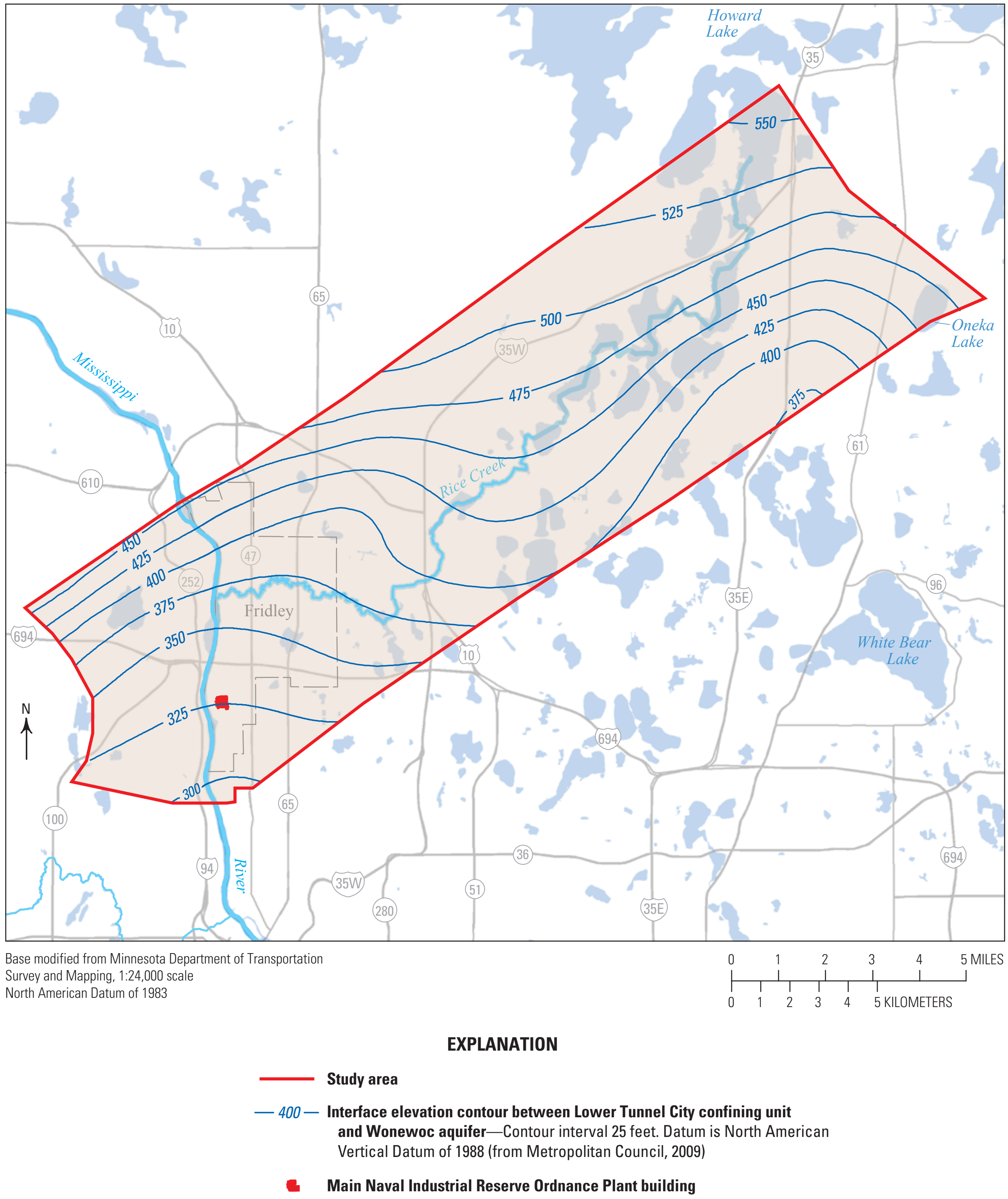
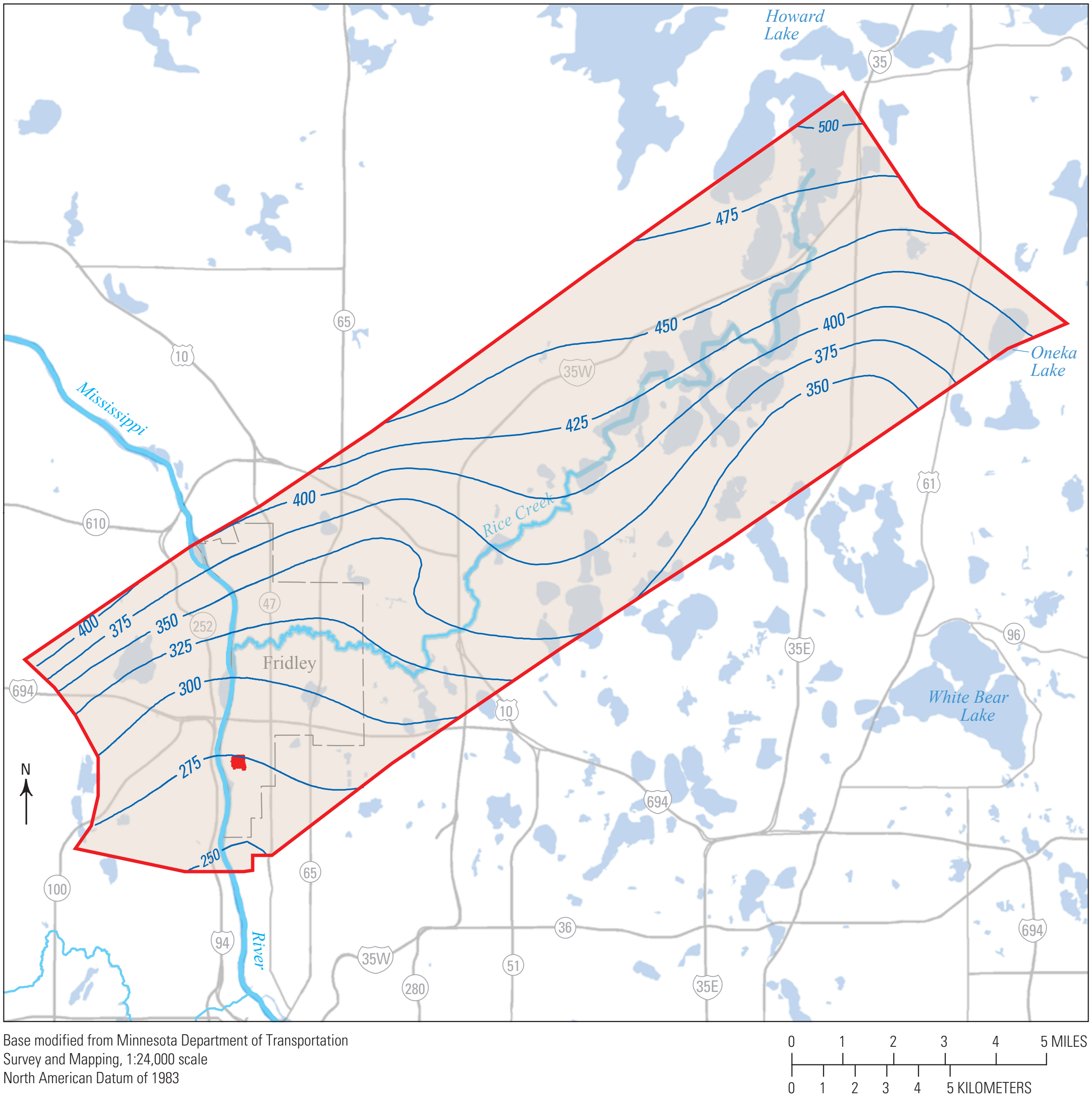


Figure 1–10. Elevation of the interface between the bottom of the lower Tunnel City confining unit (model simulation layer 9) and the top of the Wonewoc aquifer (model simulation layer 10) in and near Fridley, Minnesota.



EXPLANATION

Study area

300 **Interface elevation contour between Wonewoc aquifer and Eau Claire confining unit**—Contour interval 25 feet. Datum is North American Vertical Datum of 1988 (from Metropolitan Council, 2009)

Main Naval Industrial Reserve Ordnance Plant building

Figure 1–11. Elevation of the interface between the bottom of the Wonewoc aquifer (model simulation layer 10) and the top of the Eau Claire confining unit in and near Fridley, Minnesota.

Metropolitan Council (2009) built hydrogeologic unit interface digital elevation models from the Minnesota County Well Index and Minnesota Geological Survey digital elevation models. Hydrogeologic unit interface elevations in the Index were estimated using 7.5-minute topographic maps of land-surface elevation and depth to hydrogeologic unit interface below land-surface elevation. The typical elevation contour interval for these maps was 10 ft (Streitz, 2003).With respect to the Minnesota Geological Survey digital elevation models, Tipping and Mossler (1996) described unit interface elevations for selected units in the seven-county Twin Cities Metropolitan Area (see “Introduction” section, fig. 1), Runkel and others (2003) described elevations for selected units in the northwestern Twin Cities Metropolitan Area, and Runkel and Tipping (2006) described elevations for selected units in Scott County, Minn. (see “Introduction” section, fig. 1).

Runkel and others (2003) described unit interface elevations for the Eau Claire Sandstone, Ironton-Galesville Sandstones, and Mount Simon Sandstone in the northwestern Twin Cities Metropolitan Area. They constructed digital elevation models from literature sources that included plug porosity analysis, plug permeability analysis, visual porosity logs, vertical fracture abundance analysis, field measurements, borehole logs, borehole cuttings, pump and slug tests, borehole geophysical logs, dye trace investigations, water chemistry, and potentiometric heads. Elevation data from these sources were typically derived from 7.5-minute topographic maps of land-surface elevation, referenced to NGVD 29, with an accuracy of ±5 ft.

Runkel and Tipping (2006) described unit interface elevations for the St. Peter Sandstone, Prairie du Chien Group, Jordan Sandstone, St. Lawrence Formation, Franconia Formation, Ironton-Galesville Sandstones, Eau Claire Sandstone, and Mount Simon Sandstone in Scott County, Minn. The elevation of the interface between the Shakopee Formation and Oneota Dolomite, which are both of the Prairie du Chien Group, were not detailed. Runkel and Tipping (2006) constructed bedrock topography, and depth to bedrock and bedrock geology models that reference elevation to sea level.

Mossler (2008) renamed the Ironton and Galesville Sandstones as the Wonewoc Sandstone and the Franconia Formation as the Tunnel City Group. Jones and others (2013) and this report used geologic unit names of Wonewoc Sandstone and Tunnel City Group (hydrogeologic names of Wonewoc aquifer, and upper Tunnel City aquifer and lower Tunnel City confining unit, respectively). Metropolitan Council (2009) used the geologic unit names of Ironton and Galesville Sandstones and Franconia Formation. Interface elevations of the Ironton and Galesville Sandstones from Runkel and others (2003) and Runkel and Tipping (2006) that were incorporated in Metropolitan Council (2009), were adopted in the study described in this report as Wonewoc aquifer interface elevations; Franconia Formation interface elevations from Runkel and Tipping (2006) and represented in Metropolitan Council (2009) were adopted as upper Tunnel City aquifer interface elevations.

Sources and Sinks

Water enters the study area as recharge—the difference between infiltration and evapotranspiration—and through benthic recharge flux from surface-water bodies. Groundwater exits the study area through wells, benthic discharge flux to surface-water bodies, and a storm drain into the Mississippi River.

A uniform recharge rate of 7.9 inches per year (in/yr) was used in the model simulation described in this report. A part of the Metropolitan Council (2009) nonuniform recharge distribution that covered the study area (fig. 1–1*A*) was averaged, and the average was used as a first estimate of uniform recharge to the study area. The Metropolitan Council (2009) nonuniform recharge distribution was based on Dripps and Bradbury’s (2007) daily soil water balance method. The average was adjusted during calibration to 7.9 in/yr to ensure representative benthic discharge flux to Rice Creek (fig. 1–2*A*). The MODFLOW RCH recharge package was used. Recharge was not applied to grid cells that represent impermeable surfaces at NIROP.

The recharge estimate was in general agreement with previous estimates of groundwater recharge in the surficial aquifer system; for example, Delin and others (2007) determined that regional recharge ranged from 5.9 to 9.8 in/yr in Minnesota. Schoenberg (1990) estimated 1.5 to 4.5 in/yr recharge to the surficial aquifer system. Norvitch and others (1973) estimated 4 to 10 in/yr recharge to the surficial aquifer system. Recharge is greater in the Anoka Sand Plain (not shown) of the surficial aquifer system in northern and eastern parts of the study area than in other regions to the south and west. The Naval Industrial Reserve Ordnance Plant is on the southern edge of the Anoka Sand Plain in a region of the surficial aquifer system with relatively higher recharge than areas to the south and west.

Surface water also recharges the surficial aquifer system; for example, Lake Waconia (not shown), Lake Minnetonka (not shown), Forest Lake (not shown), Big Marine Lake (not shown), White Bear Lake (see “Description of Study Area” section, fig. 1), and the Byllesby Reservoir (not shown) recharge aquifers at a benthic recharge flux of 0.7 in/yr (Lindgren, 1990). Benthic discharge and recharge were simulated at 9,290 locations. Conductance values between groundwater and surface water in the preliminary model simulation were from Metropolitan Council (2009) and ranged from 7.1×10^{-3} square feet per day (ft^2/d) along the east bank of the Mississippi River, downstream from NIROP, to 4.7×10^{5} ft^2/d in the bed of the Mississippi River, downstream from State Highway 610 (fig. 1–2*A*). River bottom and water surface elevations at each location also were from Metropolitan Council (2009). Benthic conductance and elevation data from Metropolitan Council (2009) were not adjusted to calibrate the simulation. The MODFLOW RIV river package was used to incorporate water exchange between the surficial aquifer system and each of the following water bodies: the Mississippi River (fig. 1–2*A*), Palmer Lake (not shown), Moore Lake (not shown), Laddie Lake (not shown), Spring Lake (not shown), Turtle Lake (not shown), Poplar Lake (not shown), Amelia Lake (not shown), Oneka Lake (fig. 1–2*A*), Rice Creek, and the part of the Rice Creek Chain of Lakes (not shown) downstream from Howard Lake (fig. 1–2*A*). At some locations in the model simulation described in Metropolitan Council (2009), the elevation of a simulated reach of river bottom was less than the elevation of the bottom of the corresponding hydrogeologic unit layer to which the river reach drains. At some locations, this elevation difference resulted in a simulated potentiometric elevation lower than the elevation of the bottom of the corresponding hydrogeologic unit layer to which the river reach drains. This elevation difference is considered a simulation construction error by the model check algorithm in the U.S. Geological Survey graphical user interface ModelMuse (Winston, 2009). Correction of elevation differences, or justification for elevation differences, should be part of any revision to the preliminary simulation. In the Twin Cities Metropolitan Area, the surficial aquifer system, and the St. Peter, Shakopee, and Jordan aquifers drain as benthic discharge flux to the Mississippi, Minnesota (not shown), and St. Croix (not shown) Rivers, or discharge groundwater to these rivers through preglacial bedrock valleys that were filled with glacial and fluvial deposits.

At some locations, the direction of regional groundwater flow has changed, and may continue to change in response to groundwater extraction from flow toward primary rivers to flow toward the cone of depression. With favorable potentiometric-head gradients, rivers also recharge aquifers; for example, because groundwater elevation in well FMC–21 (see “Introduction” section, fig. 3) correlates with river surface elevation (Lindgren, 1990), it is inferred that the unconfined part of the surficial aquifer system at NIROP is efficiently connected to the Mississippi River at that location. Well FMC–21 is less than 100 ft east of the Mississippi River and is completed in an unconfined part of the surficial aquifer system.

Groundwater extraction rates for the preliminary model simulation were from Metropolitan Council (2009), except at NIROP where site-specific information was used. The MODFLOW WEL well package was used to incorporate groundwater extraction rates for 180 wells within the August 20, 2001, groundwater flow and the 2001 TCE transport simulations (see “Surficial Aquifer System” section, table 3). At least 1 well taps each of the 10 simulation layers. The maximum simulated groundwater extraction rate for wells not at NIROP or on the FMC Corp. (Fridley Plant) EPA Superfund site was 435.8 gallons per minute (gal/min) from the Jordan aquifer in well 203258 (not shown, see Minnesota Department of Health [2008]) near Evergreen Park (not shown). For the August 20, 2001, simulation, 12,070 gal/min were extracted from parts of the surficial and Cambrian-Ordovician aquifer systems within the study area.

Drain withdrawal from a Mississippi River storm drain was simulated. The MODFLOW DRN drain package was used to simulate the storm drain using 14 cells arranged along an east-west oriented line on the west bank of the Mississippi River downstream from NIROP. Groundwater flows out of the study area if potentiometric head in the upper part of the shallow flow zone of the surficial aquifer system exceeds the drain elevation of 799.0 ft above NAVD 88. Simulated conductance along the drain varied from 5.4×10^4 to 2.5×10^5 ft^2/d.

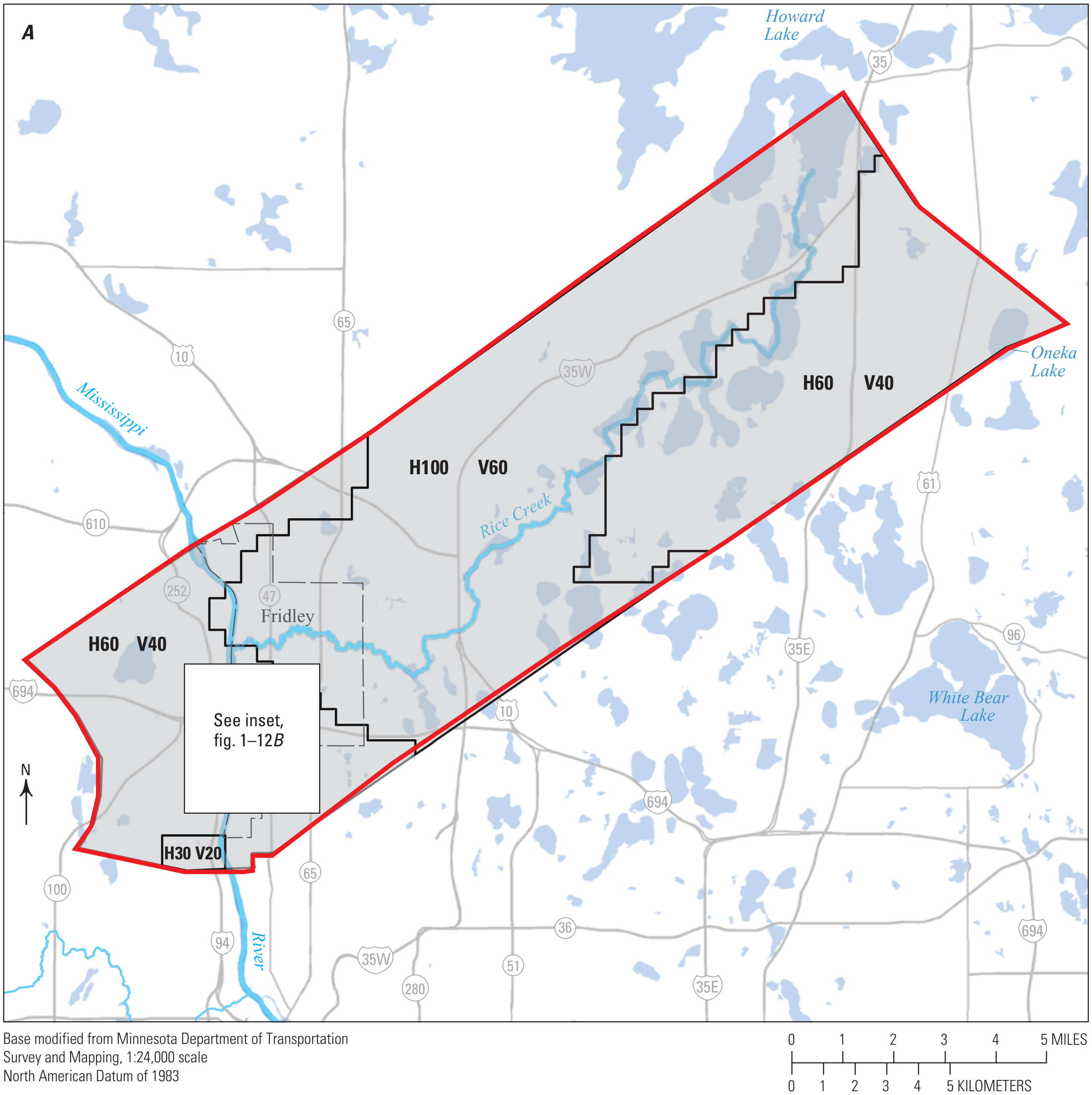
Horizontal Spatial Discretization

The study area was discretized using a telescoping grid, centered on NIROP, such that grid cells on and near NIROP were smaller than grid cells on the edges of the study area. The smallest grid cells were 25×25 ft (fig. 1–1*B*), whereas the largest were 1,000×1,000 ft (fig. 1–1*A*). The grid was 242 cells in the north-south direction by 266 cells in the east-west direction. Grid cell axes were aligned with Cardinal directions such that vertical faces of each grid cell were parallel to either an east-west oriented or north-south oriented axis.

Flow Parameters

The governing equation for flow in porous media (McDonald and Harbaugh, 1988) includes hydraulic conductivity, K. Hydraulic conductivity was represented in three dimensions using vertical and horizontal components (figs. 1–12 through 1–21). The study area was simulated as isotropic in the horizontal plane such that at any given location, hydraulic conductivity components were equivalent along two horizontal axes of anisotropy. The study area was simulated as anisotropic in the vertical dimension such that horizontal and vertical hydraulic conductivity were not necessarily equivalent at any given location. Because the model simulation was steady state, the partial differential of potentiometric head with respect to time, $\partial h/\partial t$, in the governing equation for flow in porous media was zero; therefore, specification of specific storage, Ss, was not necessary.

Near NIROP, hydraulic conductivities in the surficial aquifer system (figs. 1–12*B*, 1–13*B*, 1–14*B*, and 1–15*B*), and in the St. Peter Sandstone (fig. 1–16*B*) were represented using zones of piecewise homogeneity such that conductivity in a zone was uniform and constant, and conductivity changed between zones. Zones roughly corresponded with a conceptual deposition model described in Davis (2007) (see “St. Peter Aquifer and Lower St. Peter Confining Unit” section, figs. 7 and 8) and shown in AGVIQ-CH2MHill (2013) and Tetra Tech (1999, 2002); for example, a crescent-shaped clay area (see “Hydrogeology of the Surficial Aquifer System at the Naval Industrial Reserve Ordnance Plant” section, fig. 9; and fig.1–12*B*) was represented using isotropic, homogeneous horizontal and vertical hydraulic conductivities of 10^{-4} ft/d. The sand unit northeast of the crescent-shaped clay area was represented in the preliminary model simulation using a homogeneous horizontal hydraulic conductivity of 400 ft/d and a homogeneous vertical hydraulic conductivity of 40 ft/d.

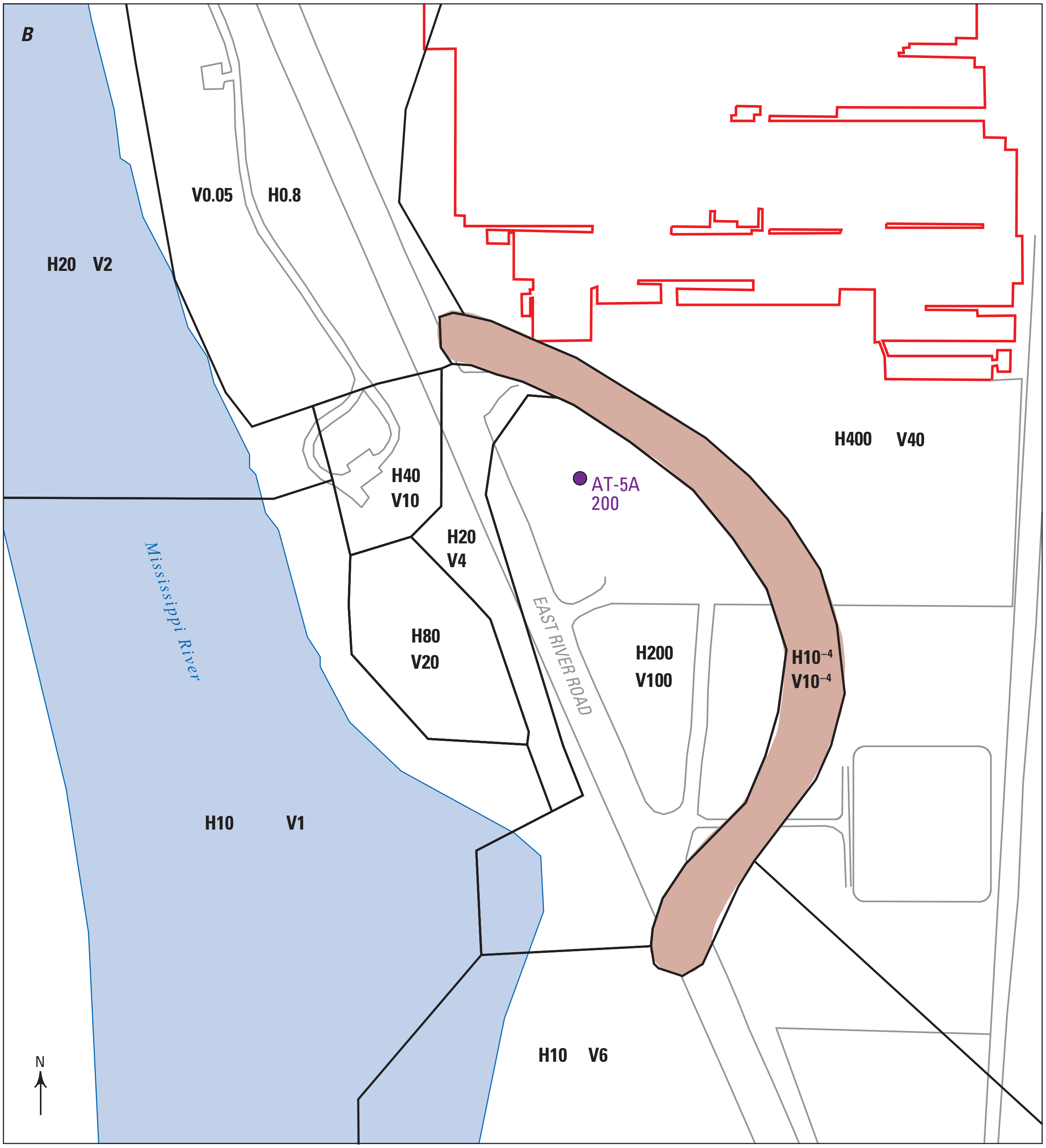


EXPLANATION

Study area

H30 V20 **Hydraulic conductivity in upper part of shallow flow zone, surficial aquifer system, simulation layer 1, in feet per day—** H, horizontal; V, vertical

Figure 1–12. Simulated horizontal and vertical hydraulic conductivities for the upper part of the surficial aquifer system shallow flow zone (model simulation layer 1). *A*, for the study area, in and near Fridley, Minnesota. *B*, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.



Base furnished by U.S. Department of the Navy
North American Datum of 1983

EXPLANATION

H10 V6	**Hydraulic conductivity in upper part of shallow flow zone, surficial aquifer system, simulation layer 1, in feet per day**—H, horizontal; V, vertical
	Clay ridge
	Main Naval Industrial Reserve Ordnance Plant building
AT-5A 200	**Extraction well and identifier**—Hydraulic conductivity, in feet per day, determined by aquifer testing

Figure 1–12. Simulated horizontal and vertical hydraulic conductivities for the upper part of the surficial aquifer system shallow flow zone (model simulation layer 1). *A*, for the study area, in and near Fridley, Minnesota. *B*, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.—Continued

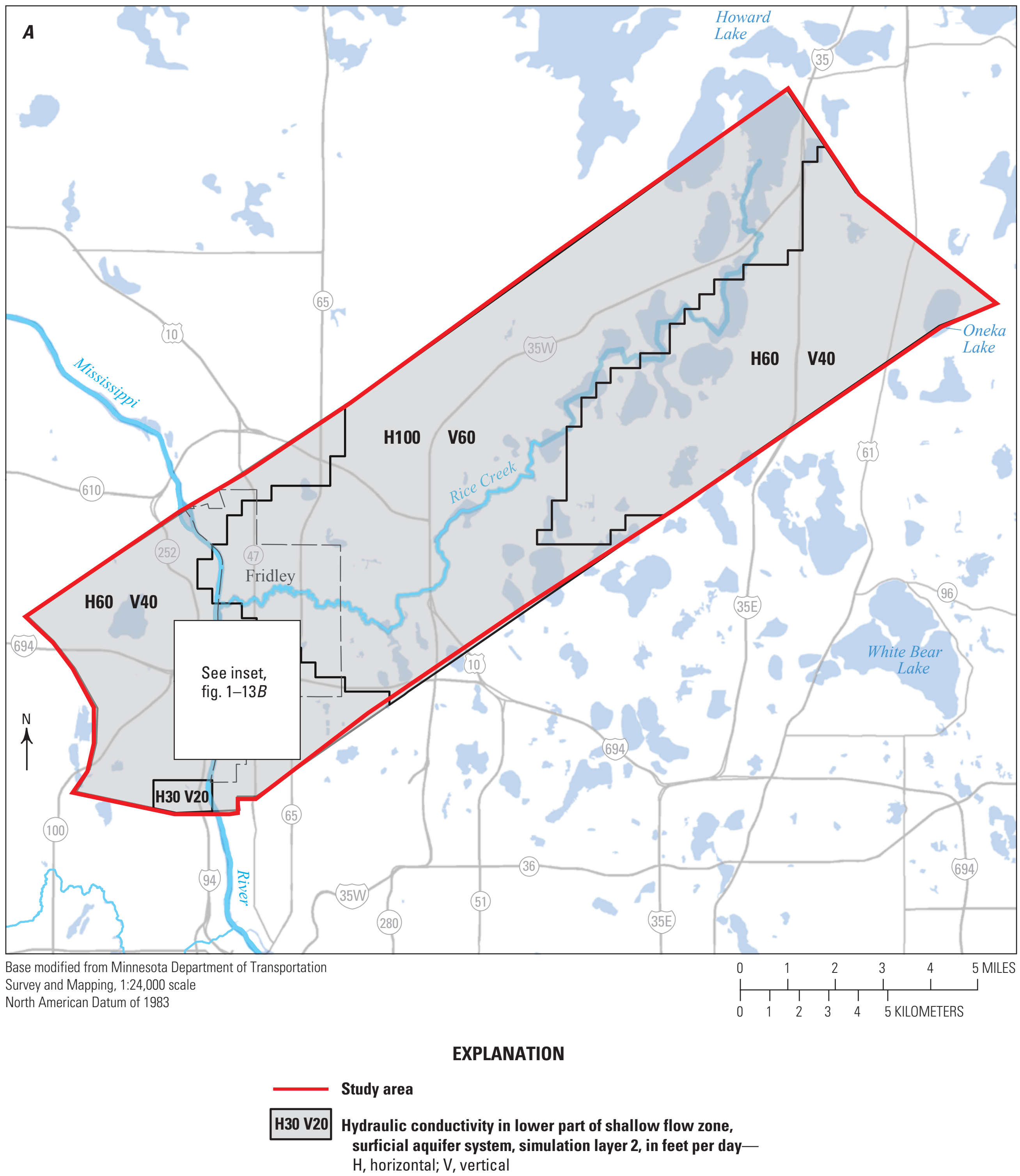
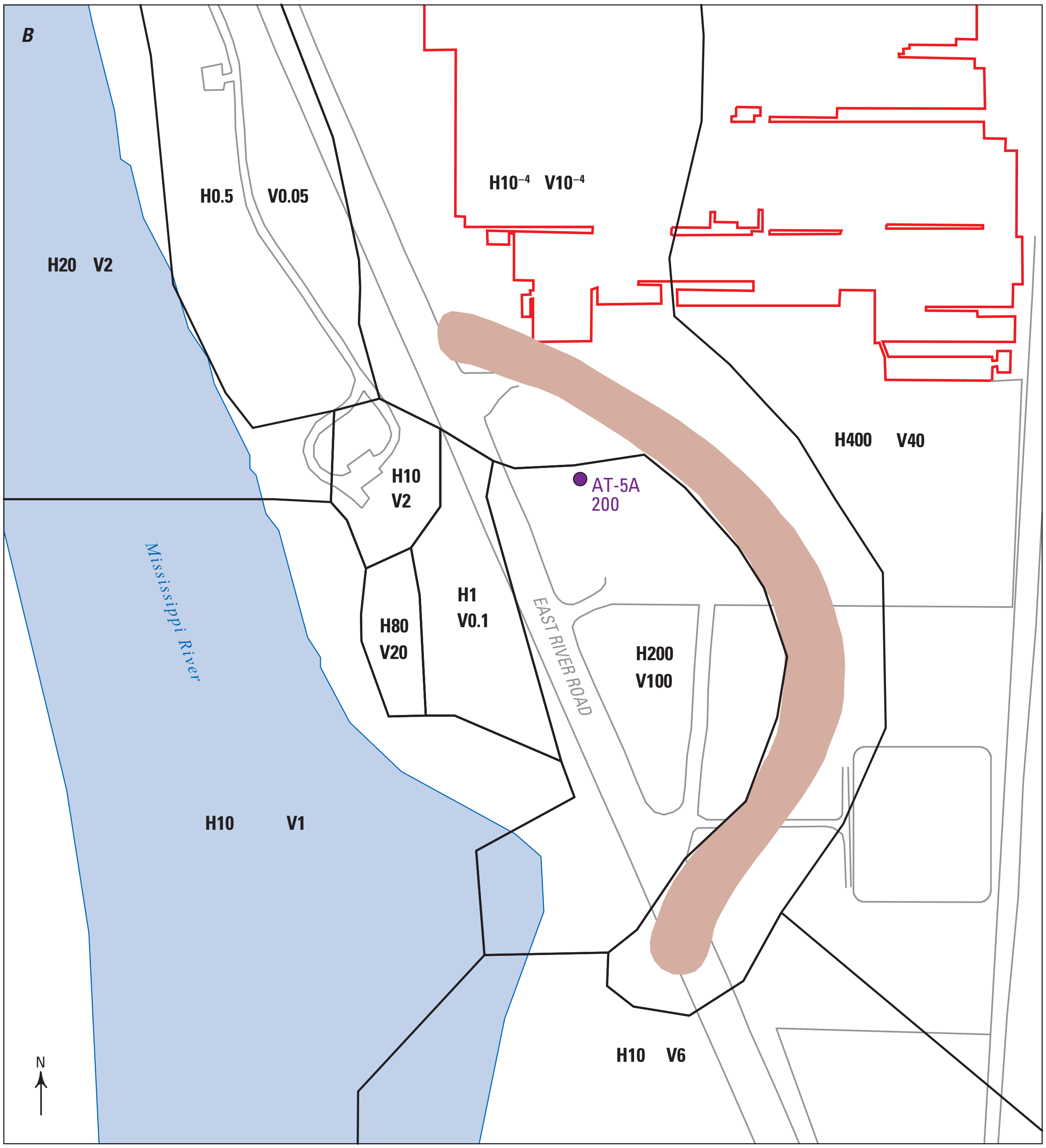
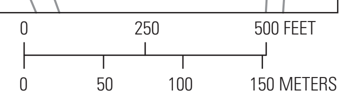


Figure 1–13. Simulated horizontal and vertical hydraulic conductivities in the lower part of the shallow flow zone, in the surficial aquifer system (model simulation layer 2). *A*, for the study area, in and near Fridley, Minnesota. *B*, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.



Base furnished by U.S. Department of the Navy
North American Datum of 1983



EXPLANATION

H10 V6 **Hydraulic conductivity in lower part of shallow flow zone, surficial aquifer system, simulation layer 2, in feet per day**—H, horizontal; V, vertical

Clay ridge

Main Naval Industrial Reserve Ordnance Plant building

AT-5A 200 **Extraction well and identifier**—Hydraulic conductivity, in feet per day, determined by aquifer testing

Figure 1–13. Simulated horizontal and vertical hydraulic conductivities in the lower part of the shallow flow zone, in the surficial aquifer system (model simulation layer 2). *A*, for the study area, in and near Fridley, Minnesota. *B*, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.—Continued

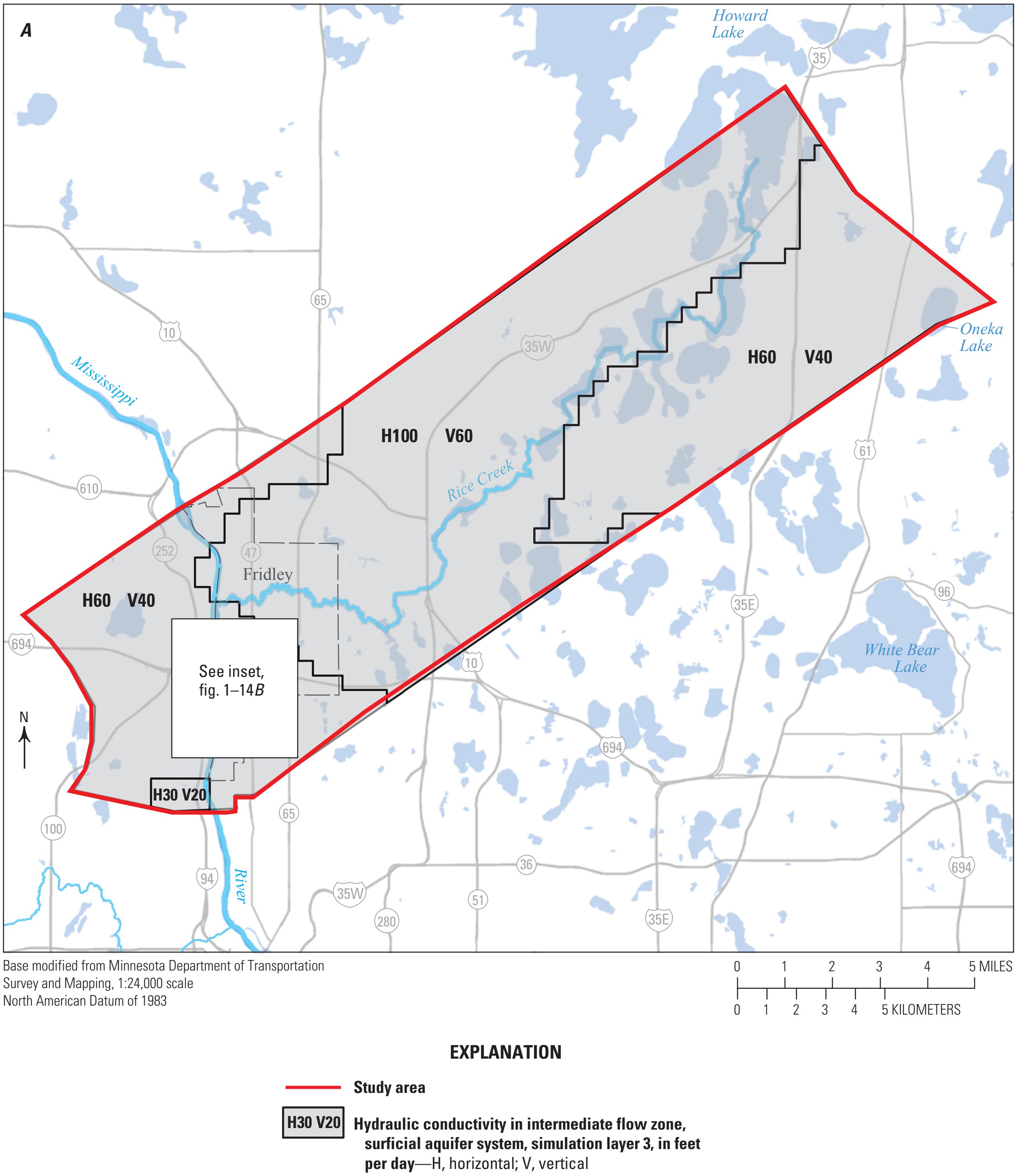


Figure 1–14. Simulated horizontal and vertical hydraulic conductivities in the intermediate flow zone of the surficial aquifer system (model simulation layer 3). *A*, for the study area, in and near Fridley, Minnesota. *B*, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.

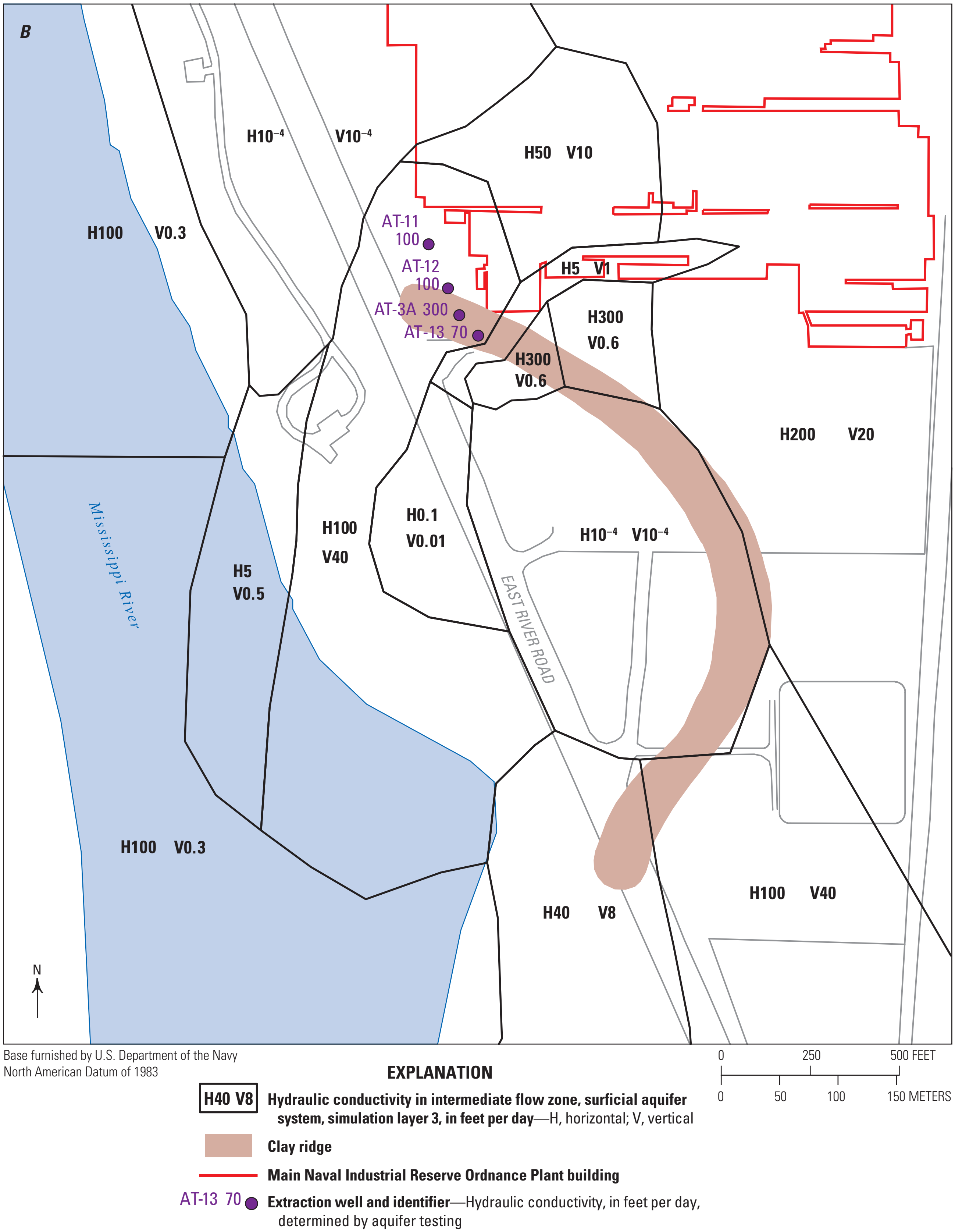


Figure 1–14. Simulated horizontal and vertical hydraulic conductivities in the intermediate flow zone of the surficial aquifer system (model simulation layer 3). *A*, for the study area, in and near Fridley, Minnesota. *B*, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.—Continued

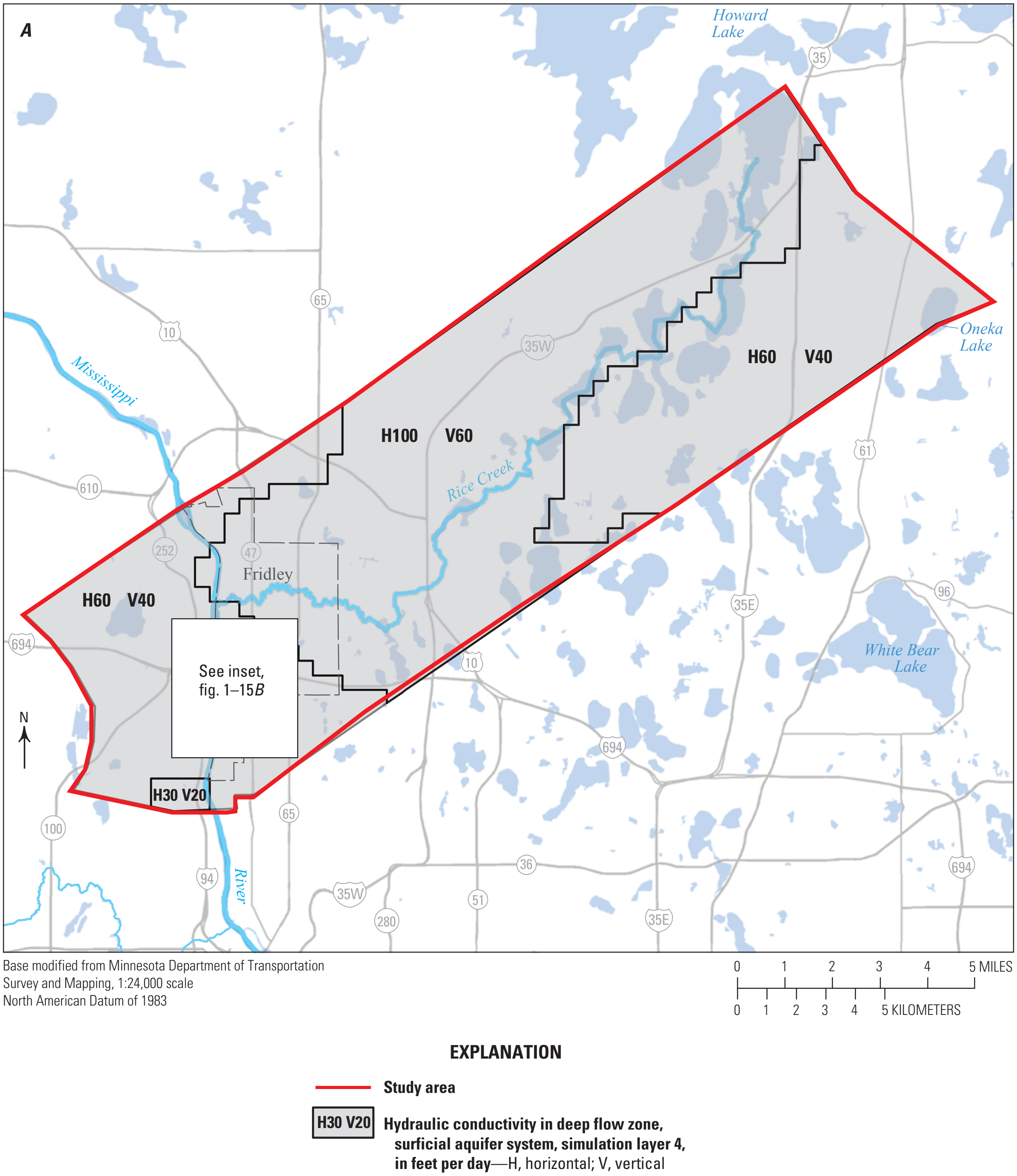


Figure 1–15. Simulated horizontal and vertical hydraulic conductivities in the deep flow zone of the surficial aquifer system (model simulation layer 4). *A*, for the study area, in and near Fridley, Minnesota. *B*, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.

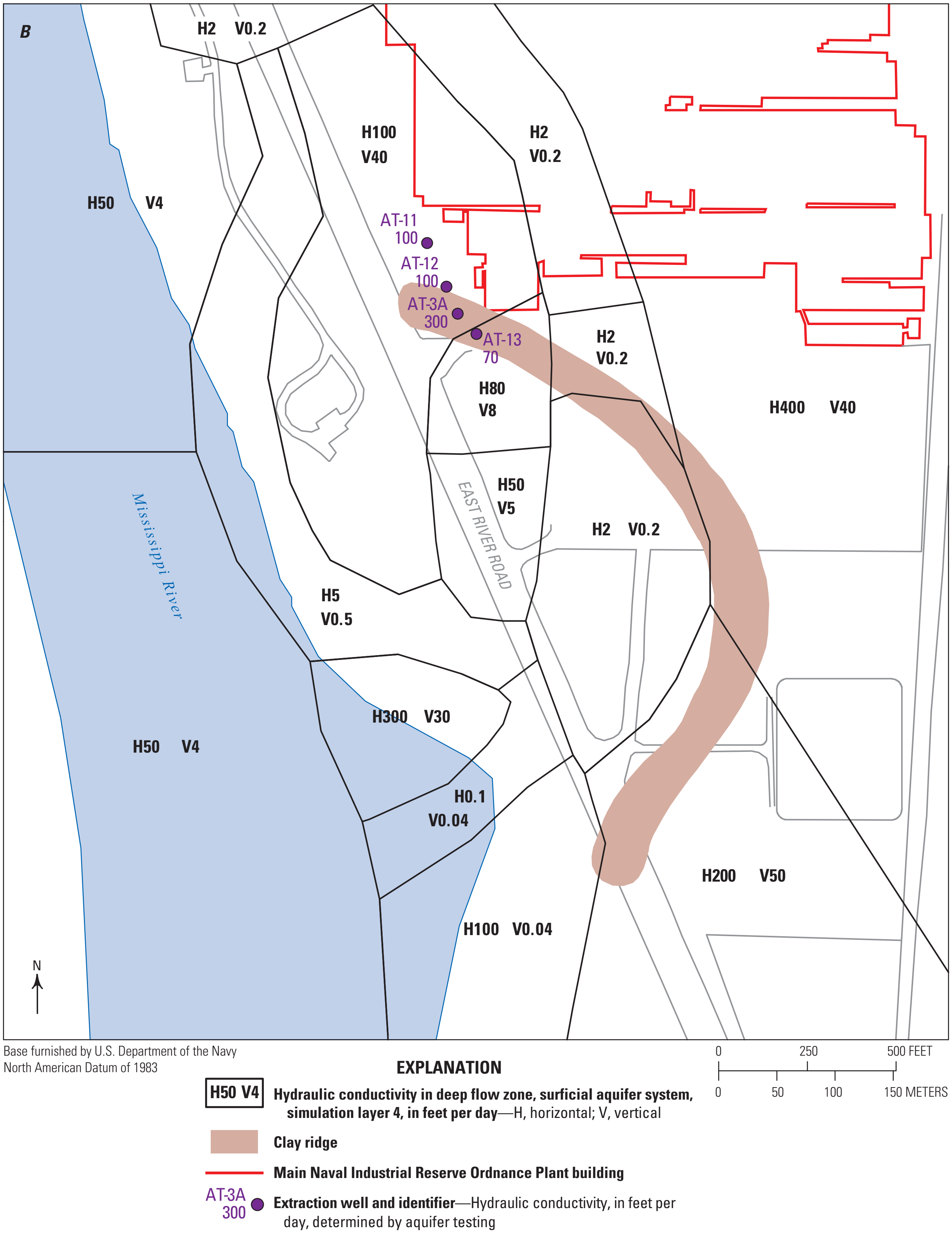


Figure 1–15. Simulated horizontal and vertical hydraulic conductivities in the deep flow zone of the surficial aquifer system (model simulation layer 4). *A*, for the study area, in and near Fridley, Minnesota. *B*, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.—Continued

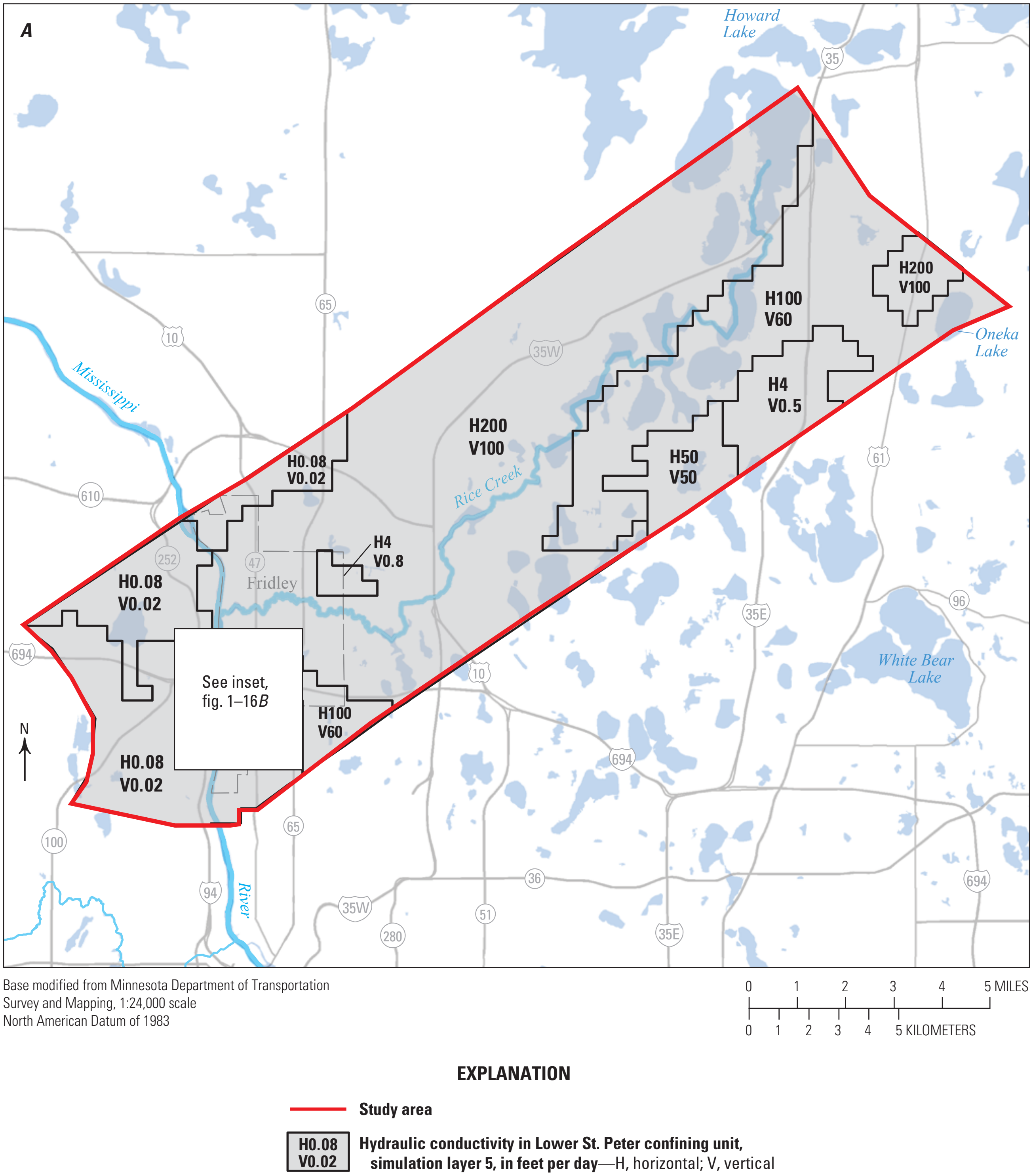


Figure 1–16. Simulated horizontal and vertical hydraulic conductivities in the lower St. Peter confining unit (model simulation layer 5). *A*, for the study area, in and near Fridley, Minnesota. *B*, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.

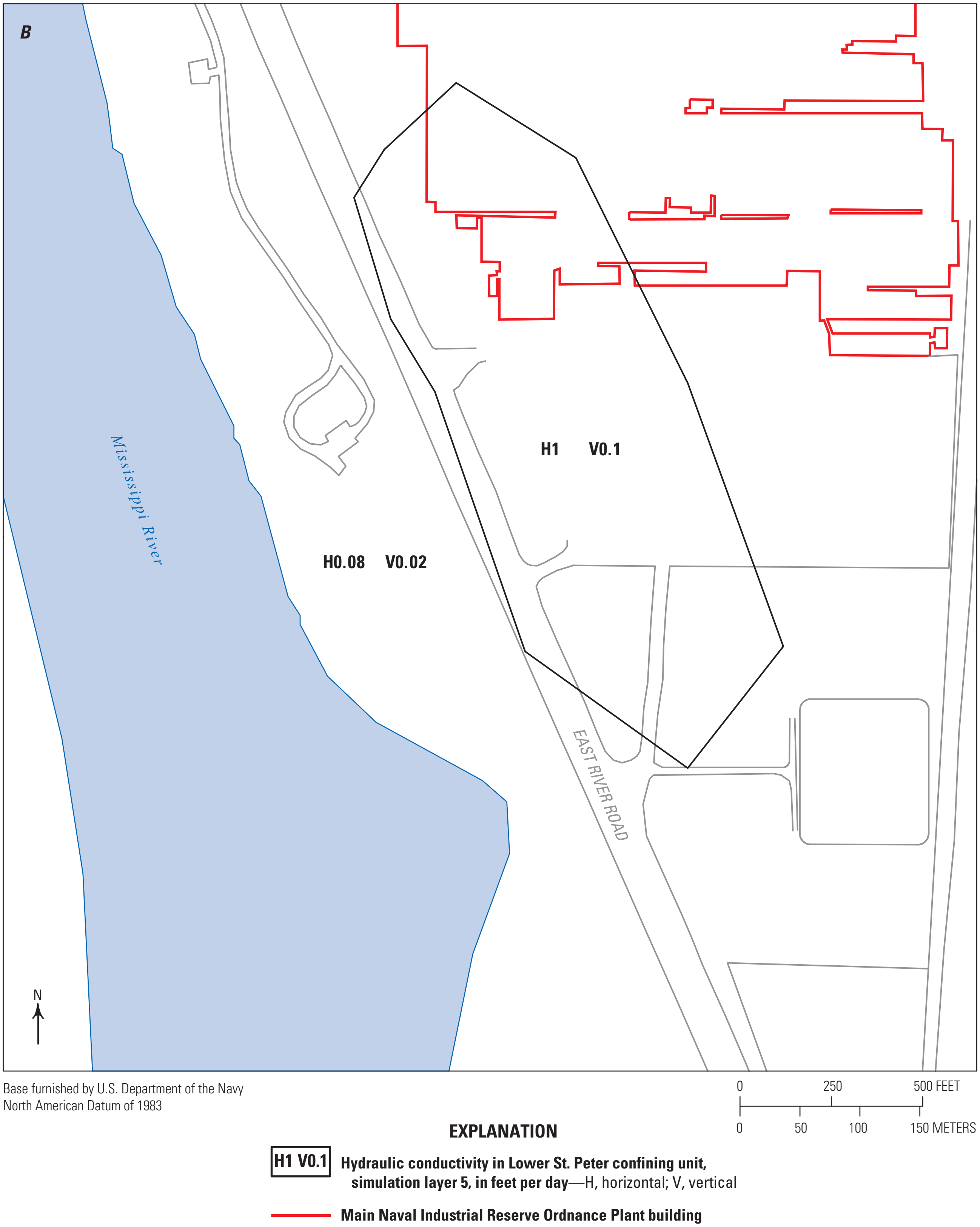
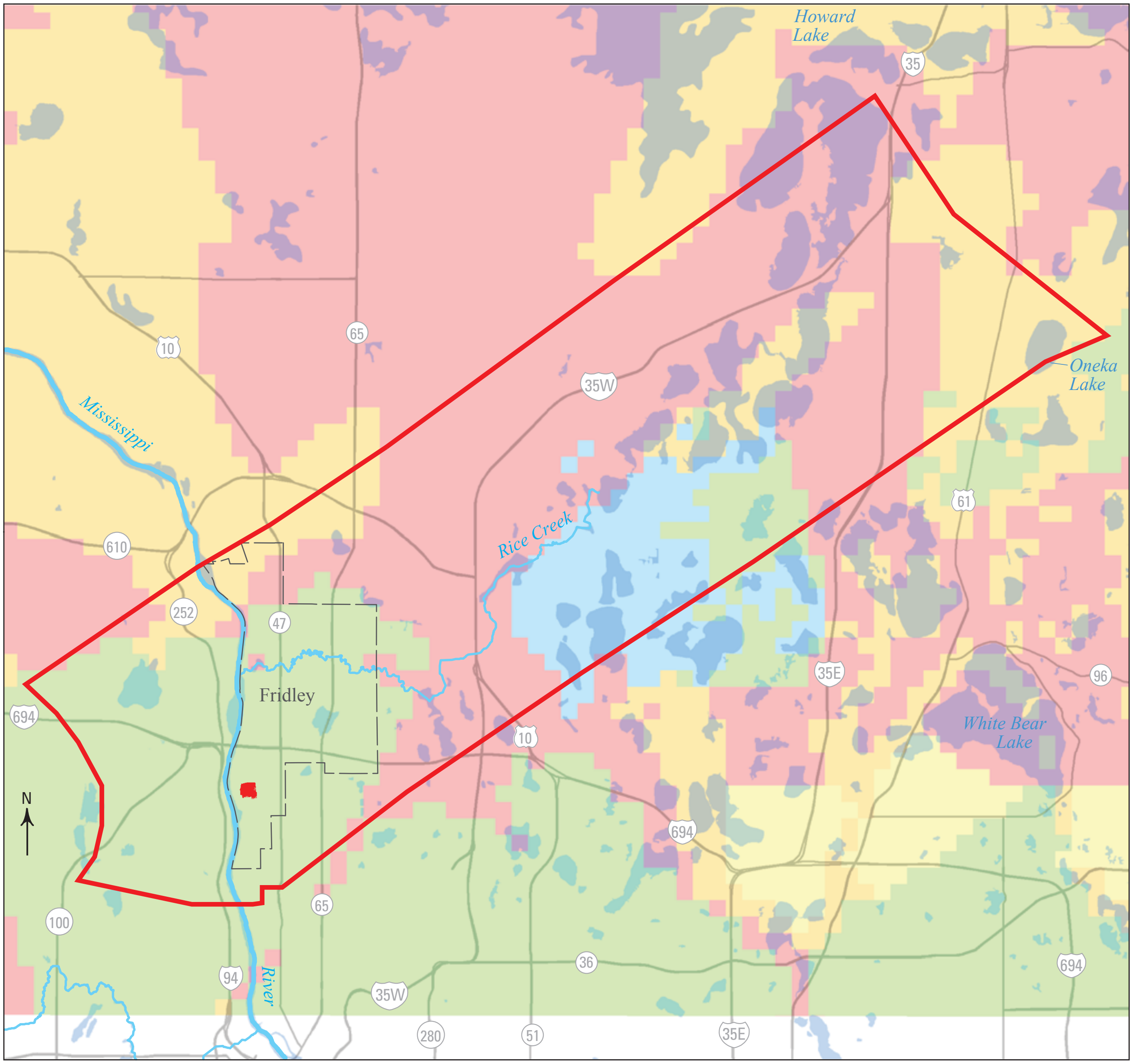


Figure 1–16. Simulated horizontal and vertical hydraulic conductivities in the lower St. Peter confining unit (model simulation layer 5). *A*, for the study area, in and near Fridley, Minnesota. *B*, near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.—Continued



Base modified from Minnesota Department of Transportation
Survey and Mapping, 1:24,000 scale
North American Datum of 1983

0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

EXPLANATION

Study area

Main Naval Industrial Reserve Ordnance Plant building

Hydraulic conductivity in Shakopee aquifer and Oneota confining unit, simulation layer 6, in feet per day

- 5 to 10
- Greater than 10 to 20
- Greater than 20 to 50
- Greater than 50 to 100
- Greater than 100 to 200

Figure 1–17. Simulated horizontal hydraulic conductivities in the Shakopee aquifer and Oneota confining unit (model simulation layer 6) in and near Fridley, Minnesota.

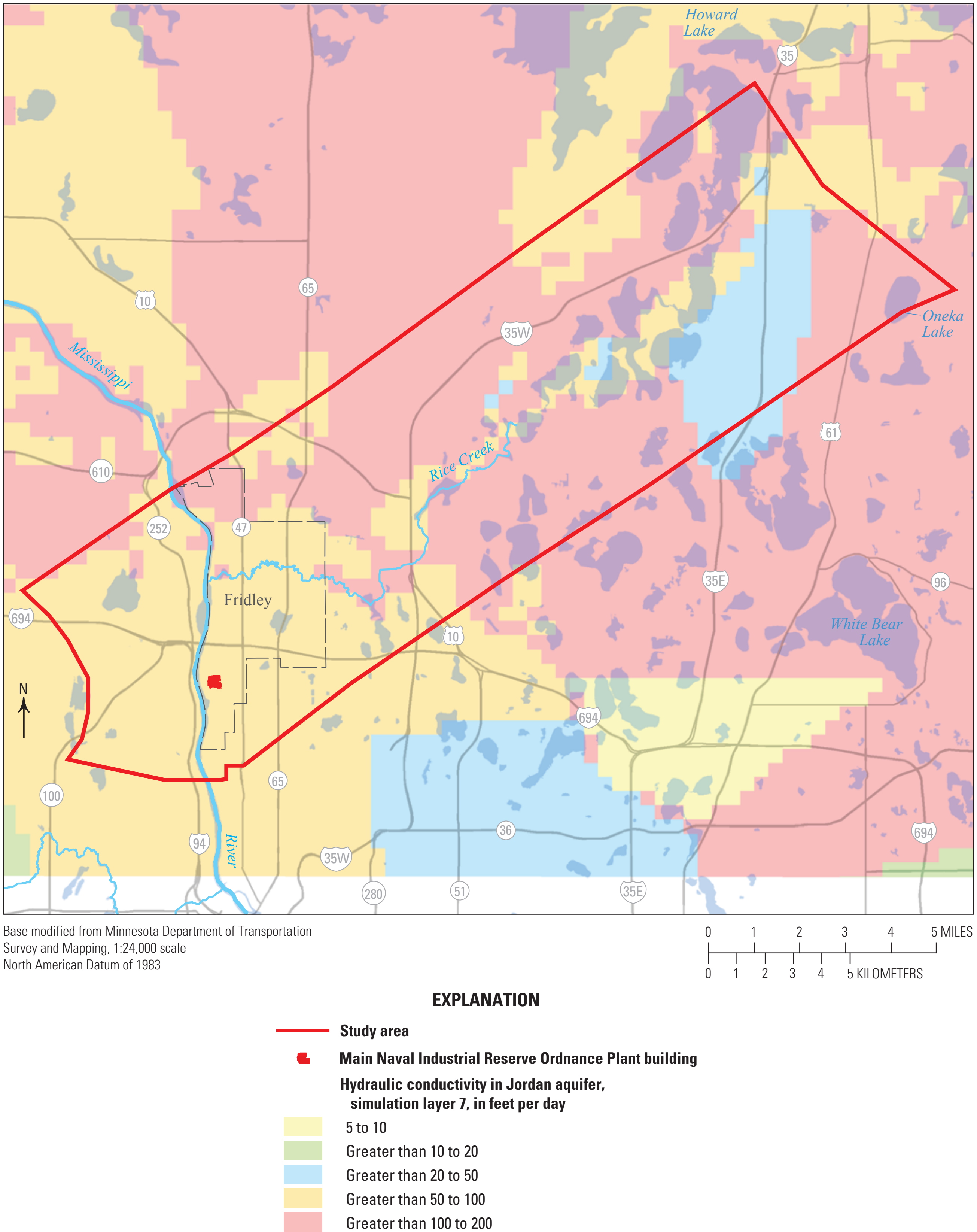


Figure 1–18. Simulated horizontal hydraulic conductivities in the Jordan aquifer (model simulation layer 7) in and near Fridley, Minnesota.

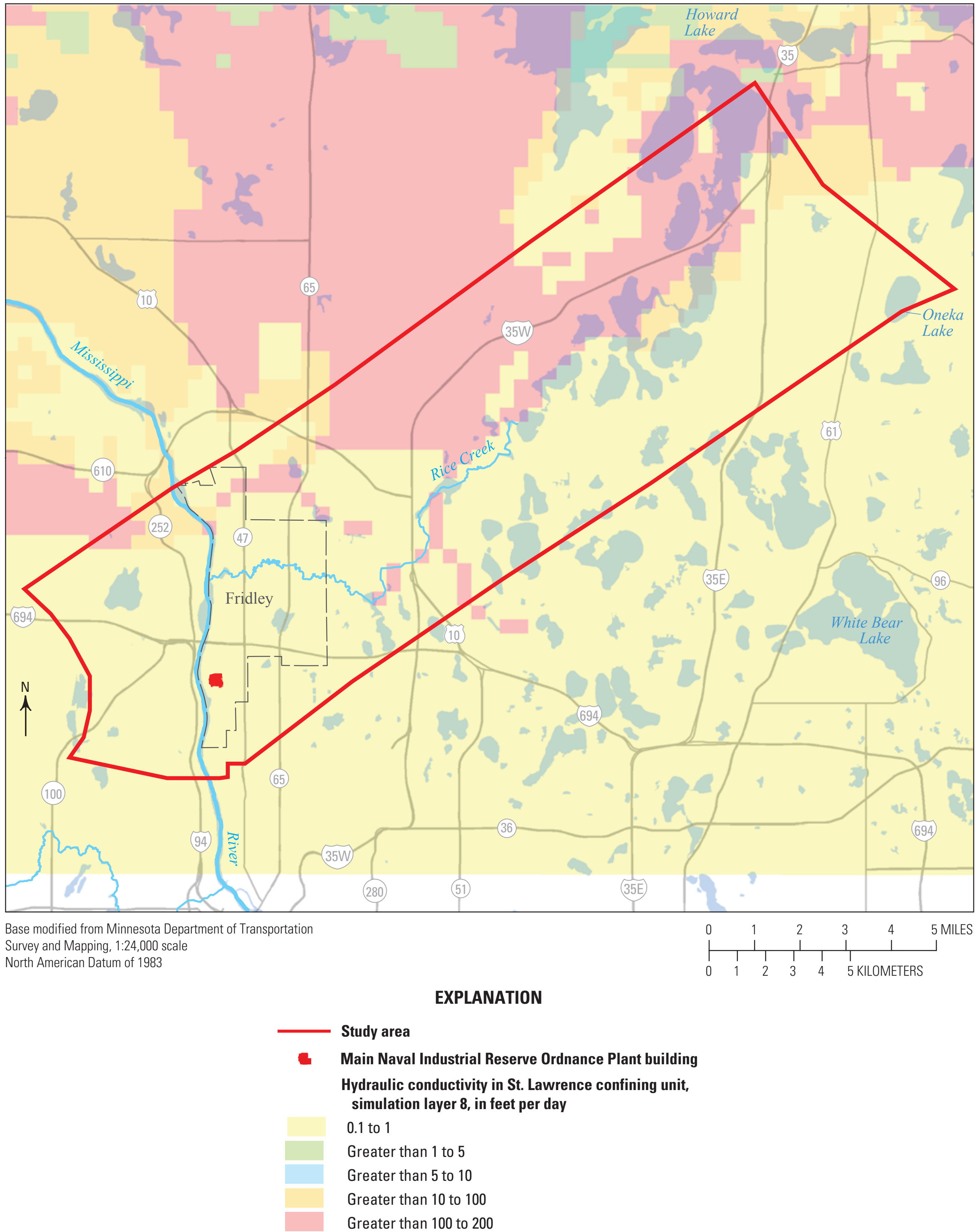
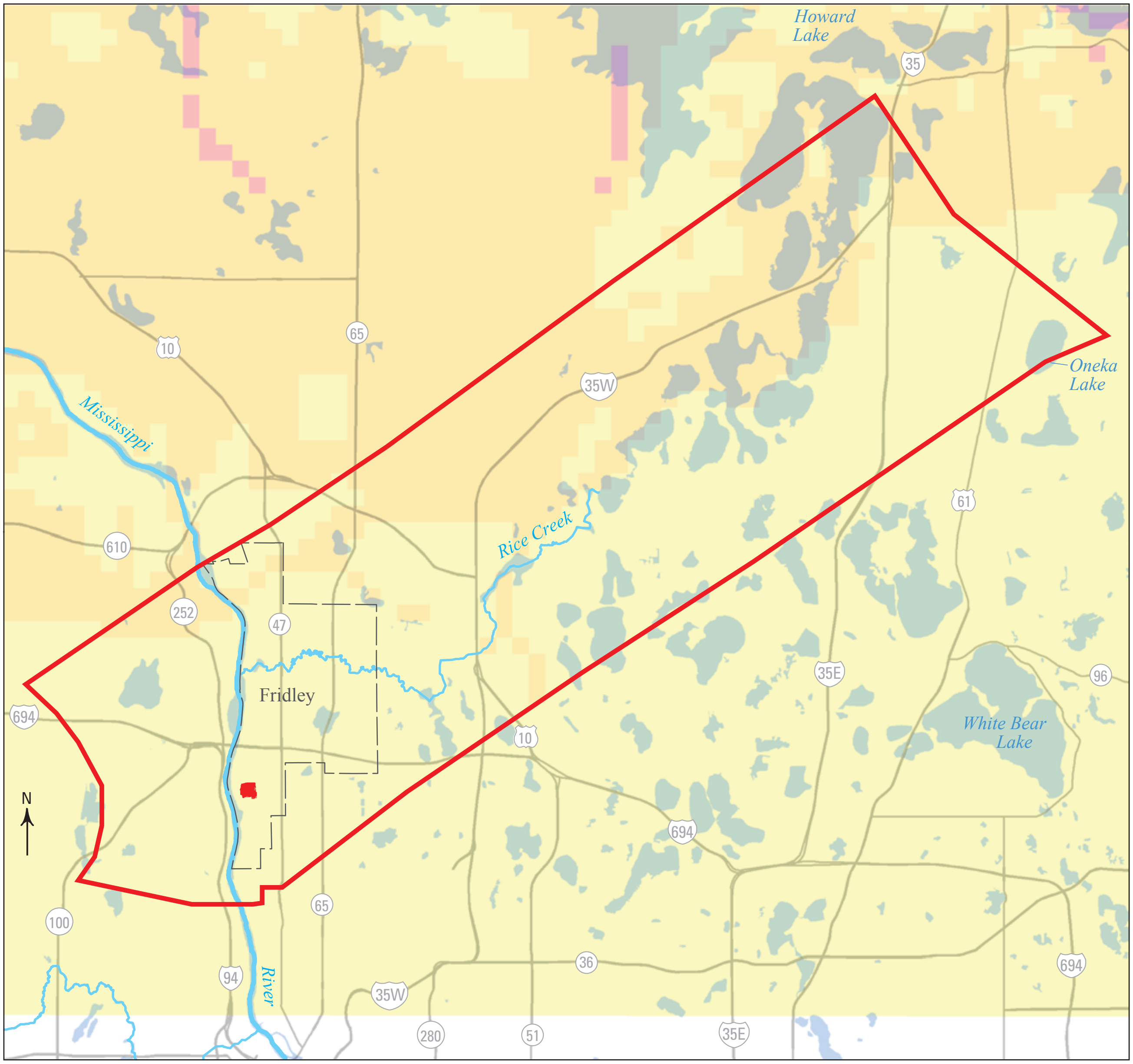


Figure 1–19. Simulated horizontal hydraulic conductivities in the St. Lawrence confining unit (model simulation layer 8) in and near Fridley, Minnesota.



Base modified from Minnesota Department of Transportation
Survey and Mapping, 1:24,000 scale
North American Datum of 1983

0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

EXPLANATION

Study area

Main Naval Industrial Reserve Ordnance Plant building

Hydraulic conductivity in Upper Tunnel City aquifer and Lower Tunnel City confining unit, simulation layer 9, in feet per day

- 1 to 10
- Greater than 10 to 20
- Greater than 20 to 50
- Greater than 50 to 100
- Greater than 100 to 200

Figure 1–20. Simulated horizontal hydraulic conductivities in the upper Tunnel City aquifer and lower Tunnel City confining unit (model simulation layer 9) in and near Fridley, Minnesota.

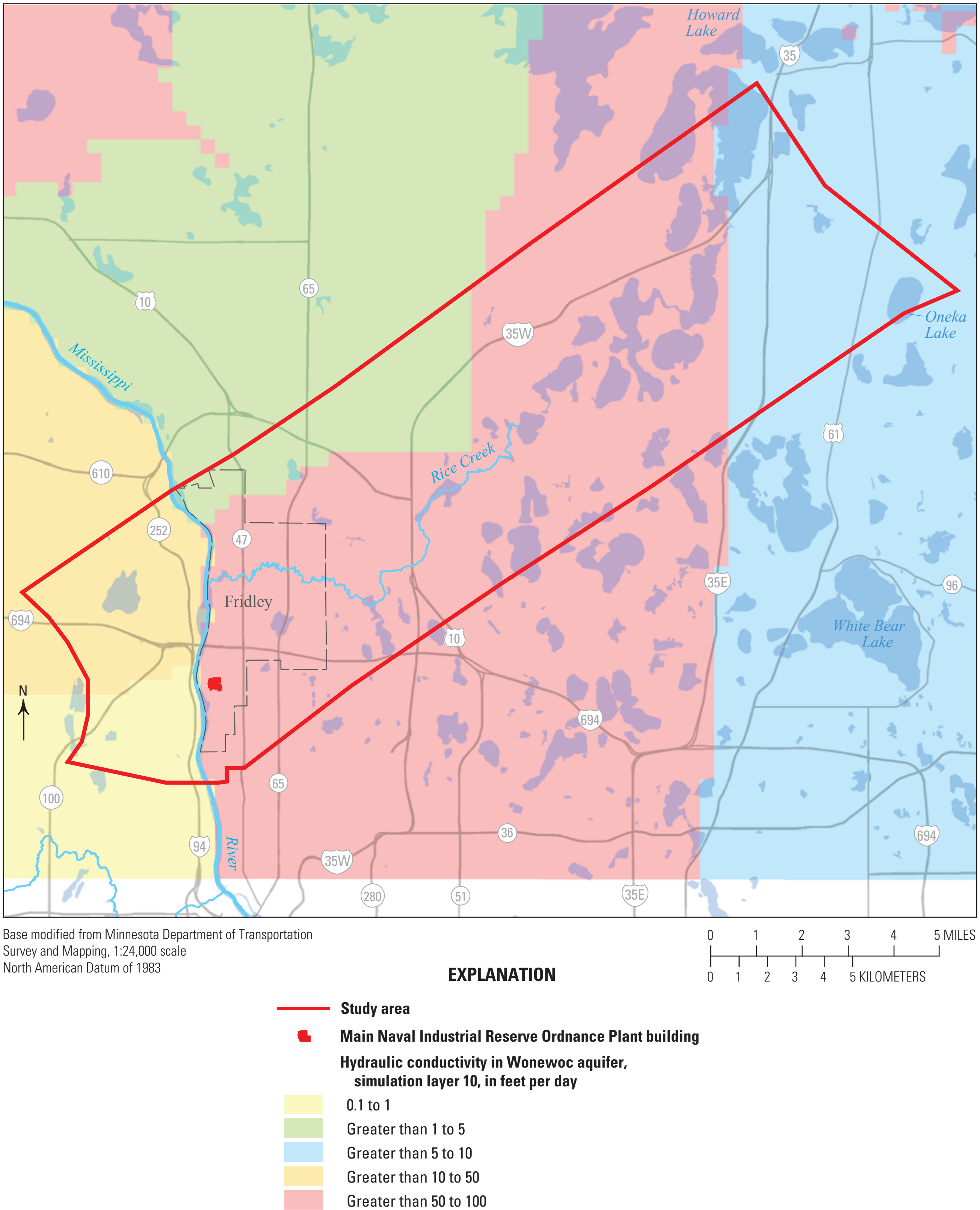


Figure 1–21. Simulated horizontal hydraulic conductivities in the Wonewoc aquifer (model simulation layer 10) in and near Fridley, Minnesota.

Davis and Ruhl (2000), Davis (2000), and CH2MHill (2012) completed aquifer tests at NIROP. Davis (2000) estimated 200 ft/d hydraulic conductivity at extraction well AT–5A (see “Introduction” section, fig. 3; and fig. 1–12*B*) in the shallow flow zone of the surficial aquifer system. The calibrated horizontal hydraulic conductivity was an equivalent 200 ft/d in the zone of piecewise homogeneity that contained extraction well AT–5A in model simulation layers 1 and 2. Extraction wells AT–3A, AT–11, AT–12, and AT–13 (see “Introduction” section, fig. 3) are in the same zone of piecewise homogeneity in the intermediate flow zone of the surficial aquifer system. Davis and Ruhl (2000) estimated 300 ft/d hydraulic conductivity at extraction well AT–3A (fig. 1–14*B*). CH2MHill (2012) estimated 100, 100, and 70 ft/d hydraulic conductivities at extraction wells AT–11, AT–12, and AT–13, respectively (fig. 1–14*B*). The calibrated horizontal hydraulic conductivity was 100 ft/d in this zone of piecewise homogeneity, within the limits of 70 to 300 ft/d, from aquifer tests.

Away from NIROP—in areas outside the inset on figures 1–12*A* to 1–15*A*—hydraulic conductivities in the surficial aquifer system and St. Peter Sandstone also were represented using zones of piecewise homogeneity. Zones represented an area under the Rice Creek drainage basin upstream from Baldwin Lake (not shown) and south of Rice Creek, other areas under the Rice Creek drainage basin (north and south of Rice Creek, downstream from Baldwin Lake, and north of Rice Creek upstream from Baldwin Lake), a small area under the Mississippi River downstream from the 42nd Avenue bridge, and other areas of the study area (which included the subsurface west and east of the Mississippi River, and outside the Rice Creek drainage basin). Vertical hydraulic conductivities were different in deep (40 ft/d, fig. 1–15*A*) and intermediate (60 ft/d, fig. 1–14*A*) surficial aquifer system flow zones in the subsurface north and south of Rice Creek downstream from Baldwin Lake, and north of Rice Creek upstream from Baldwin Lake. Horizontal hydraulic conductivities were equivalent in deep (120 ft/d, fig. 1–15*A*) and intermediate (120 ft/d, fig. 1–14*A*) flow zones in the surficial aquifer system in this area. Hydraulic conductivities in each zone of piecewise homogeneity were equivalent in shallow, intermediate, and deep flow zones of the surficial aquifer system (figs. 1–12*A*, 1–13*A*, 1–14*A*, and 1–15*A*) in other areas such that hydraulic conductivities in the intermediate and deep flow zones of the surficial aquifer system were equivalent in the area downstream from the 42nd Avenue bridge, but different in the subsurface downstream from the 42nd Avenue bridge and the subsurface west of the Mississippi River (figs. 1–14*A* and 1–15*A*).

Combined conductivities govern the regional groundwater flow and constituent transport response of each hydrogeologic unit to potentiometric-head gradients. Combined conductivities average zones of relatively higher conductivity with zones of relatively lower conductivity where both zones are in the same hydrogeologic unit; for example, in a hydrogeologic framework of Paleozoic bedrock in southeastern Minnesota, Runkel and others (2003) divided the Prairie du Chien Group into a Shakopee aquifer above an Oneota confining unit. Metropolitan Council’s (2009) representation of horizontal hydraulic conductivity in the Prairie du Chien Group (fig. 1–17) combined the contribution of the Shakopee aquifer and the Oneota confining unit into one conductivity term in which the combined horizontal hydraulic conductivity was probably more representative of horizontal hydraulic conductivity in the Shakopee aquifer than horizontal hydraulic conductivity in the Oneota confining unit. Metropolitan Council (2009) distinguished combined horizontal and vertical hydraulic conductivities in the Shakopee aquifer and Oneota confining unit from conductivities in the Jordan aquifer (fig. 1–18). Combined, horizontal and vertical hydraulic conductivities in the St. Lawrence confining unit (fig. 1–19), upper Tunnel City aquifer and lower Tunnel City confining unit (fig. 1–20), and Wonewoc aquifer (fig. 1–21) also were from Metropolitan Council (2009). Hydraulic conductivities in these bedrock units were simulated as heterogeneous.

Mossler (2008) renamed the Ironton and Galesville Sandstones as the Wonewoc Sandstone; Mossler (2008) also renamed the Franconia Formation as the Tunnel City Group. Jones and others (2013) and the study described in this report use geologic unit names of Wonewoc Sandstone and Tunnel City Group (hydrogeologic names of Wonewoc aquifer, and of upper Tunnel City aquifer and lower Tunnel City confining unit, respectively). Metropolitan Council (2009) used geologic unit names of Ironton and Galesville Sandstones and Franconia Formation. Horizontal and vertical hydraulic conductivities of the Ironton and Galesville Sandstones from Metropolitan Council (2009) were adopted as horizontal and vertical hydraulic conductivities for the Wonewoc Sandstone for this report; horizontal and vertical hydraulic conductivities for the Franconia Formation from Metropolitan Council (2009) were adopted as combined horizontal and vertical hydraulic conductivities for the upper Tunnel City aquifer and lower Tunnel City confining unit for this report.

Representations of horizontal and vertical hydraulic conductivities (figs. 1–12 to 1–22) were refined during calibration to fit simulated potentiometric heads to measured potentiometric heads. Metropolitan Council (2009) also adjusted hydraulic conductivities to fit simulated potentiometric head to measured potentiometric head.

Temporal Discretization and Numerical Solution for Potentiometric Head

The flow model simulation was steady state. The MODFLOW PCG2 preconditioned conjugate gradient solver was used to solve for potentiometric head. Potentiometric-head change criterion was 0.01 ft. Residual change criterion was 1.0 cubic foot per day (ft^3/d). Iteration was complete if the change in potentiometric head between the current iteration and the last iteration was less than 0.01 ft, and the change in residual was less than 1.0 ft^3/d.

Calibration

The groundwater flow model simulation was calibrated to measured potentiometric heads on August 20, 2001 (see “Preliminary Simulation of Groundwater Flow” section, table 2). The simulation included groundwater extraction wells in Metropolitan Council (2009), which were in the study area (see “Description of Study Area” section, fig. 1).

The following actions were completed to refine and calibrate the simulation:

- Metropolitan Council (2009) included benthic flux between surface waters—such as Rice Creek and the Mississippi River—and the top simulation layer: a combined representation of the surficial aquifer system, Decorah Shale, Platteville Limestone, and Glenwood Formation (see “Previous Investigations” section, fig. 4). Surface-water boundary delineations from Metropolitan Council (2009) were refined for the higher resolution computational grid.

- Metropolitan Council (2009) detailed recharge to the surficial aquifer system. The Metropolitan Council (2009) representation of recharge was refined to eliminate recharge to the surficial aquifer system under impermeable surfaces at NIROP. The recharge rate in Metropolitan Council (2009) was averaged across the study area (see “Description of Study Area” section, fig. 1) to develop an equivalent, uniform recharge rate. The uniform rate was then adjusted to 7.9 in/yr to ensure a representative 26.7 ft^3/d surface-water flow rate in Rice Creek. The Rice Creek flow rate predicted by Metropolitan Council (2009) was 24.6 ft^3/d—an acceptable 9 percent less than the 26.7 ft^3/d flow rate predicted by the preliminary simulation described in this report.

- Hydraulic conductivity in the surface simulation layer was adjusted to reflect Meyer’s (2012) representation of the surficial aquifer system.

- Metropolitan Council (2009) stratigraphy was refined to represent the absence of St. Peter Sandstone (see “Hydrogeologic Setting” section, fig. 6; and “St. Peter Aquifer and Lower St. Peter Confining Unit” section, fig. 7) at some geographic locations. At these locations, the Shakopee aquifer was in contact with the deep flow zone of the surficial aquifer system.

- AGVIQ-CH2MHill (2013), Davis (2007), and Tetra Tech (1999, 2002) described geologic features in the surficial aquifer system at NIROP. Horizontal and vertical hydraulic conductivities were adjusted to simulate the effects of these features on groundwater flow.

- Davis and Ruhl (2000), Davis (2000), and CH2MHill (2012) performed aquifer tests at NIROP. Horizontal hydraulic conductivities were adjusted to reflect the results of these tests.

- Horizontal and vertical hydraulic conductivities were adjusted from conductivities in Metropolitan Council (2009) to reduce the difference between simulated and measured potentiometric head.

The actions to refine and calibrate the simulation yield potentiometric heads that were within 2 ft of measured potentiometric heads at most locations (fig. 1–22).

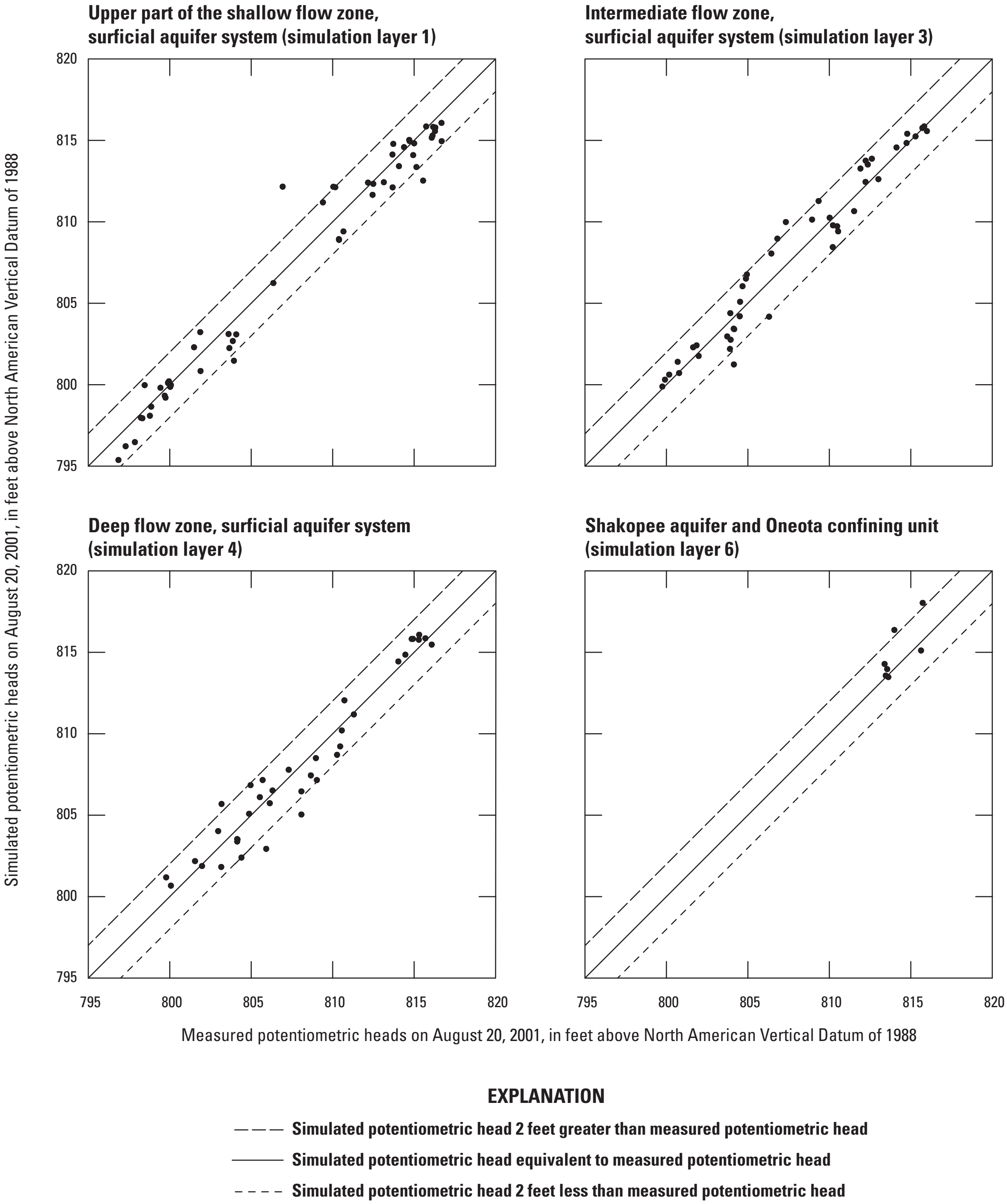


Figure 1–22. Simulated potentiometric head compared to measured potentiometric head on August 20, 2001, in the surficial aquifer system, at and near the Naval Industrial Reserve Ordnance Plant, Fridley, Minnesota.

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Appendix 2. Summary of Trichloroethene Transport Simulation Components

Technical aspects of preliminary trichloroethene (TCE) transport model simulations (Davis and King, 2016) are described in this appendix. Objectives, results, postulations, limitations, and applications of the TCE transport simulation are described in the "Introduction," "Preliminary Simulation of Trichloroethene Transport," "Postulations and Limitations," and "Preliminary Application to Hypothetical Trichloroethene Source Areas" sections of this report.

The objective of the preliminary TCE transport model simulation was to develop a general characterization of TCE transport at and near the Naval Industrial Reserve Ordnance Plant (NIROP) for 2001 forced by a steady-state groundwater flow simulation for August 20, 2001 (appendix 1). The TCE transport simulation used MT3DMS (Zheng and Wang, 1998) version 5.3. Zheng and Wang (1998) used the finite difference method to calculate concentration on an orthogonal grid for transient, single phase, miscible transport. Zheng and Wang (1998) detailed governing equations.

Although Metropolitan Council (2014) updated Metropolitan Council (2009), because the TCE transport model simulation at NIROP was built before publication of Metropolitan Council (2014), the TCE transport simulation was primarily built from Metropolitan Council (2009) with selected refinements—described in appendixes 1 and 2—necessary to characterize TCE transport at NIROP.

Spatial and Temporal Discretization

The computational grid for TCE transport was coincident with the computational grid for groundwater flow (figs. 1–1*A* and 1–1*B*). The groundwater flow model simulation was steady state. The TCE transport simulation was transient with one stress period. Trichloroethene concentration transitions from the initial condition to quasi-steady-state concentrations during a single, 3,000-day-long stress period. This stress period was divided into ten, 300-day-long subperiods. Transport step size in each subperiod was a function of numerical stability criteria.

The preliminary model simulation detailed a characterization of TCE transport at NIROP in 2001. A steady-state transport solution is forced by a steady-state groundwater flow solution applied to steady-state constituent source areas until the transient concentration of the transported constituent does not change or oscillates about some mean concentration. Transport of TCE was simulated for 3,000 days from June 3, 1993, to August 20, 2001, to allow TCE concentrations to reach a steady state. Simulated concentrations during this 3,000-day-long stress period were not intended to represent concentration on any given day during the period. Postulations of this simulation included, but were not limited to the following (see "Postulations and Limitations" section): TCE source area geometries and concentrations did not diminish with time, forcing of the groundwater flow system did not change over the stress period, and 3,000 days of transport was sufficient for TCE concentrations to reach a steady state. The steady-state postulation was not tested. Transience in groundwater flow was not simulated during the 3,000-day-long stress period.

Initial Trichloroethene Concentrations

Preliminary groundwater flow and TCE transport model simulators were applied to investigate the performance of the groundwater extraction and treatment system at NIROP. Initial TCE source areas and concentrations for simulators and applications described in this report were furnished by the U.S. Department of the Navy (herein referred to as "the Navy"). Source areas of TCE were specified using constant concentration cells in the MT3DMS SSM source-sink mixing package. Furnished source areas were informed by collected data.

For the TCE transport model simulation of 2001 (see "Preliminary Simulation of Trichloroethene Transport" section, figs. 18–20), northern and southern TCE source areas were furnished. For the northern source area, a constant TCE concentration of 1,000 micrograms per liter (µg/L) was furnished for the upper part of the shallow flow zone in the surficial aquifer system (simulation layer 1), and a constant TCE concentration of 50,000 µg/L was furnished for the lower part of the shallow flow zone (simulation layer 2). For the southern source area, a constant TCE concentration of 1,000 µg/L was furnished in the upper part of the shallow flow zone (simulation layer 1), and a constant TCE concentration of 12,000 µg/L was furnished in the lower part of the shallow flow zone (simulation layer 2). With the exception of these defined source areas, initial TCE concentration was 0 µg/L throughout other parts of the study area; TCE concentrations on all study-area boundaries were also 0 µg/L.

For a hypothetical model simulation that was not intended to represent an historical condition, only the northern source area was simulated (see "Northern Source Area" section, figs. 21–23). The Navy replaced extraction well AT–3A (see "Introduction" section, fig. 3) with extraction wells AT–11, AT–12, and AT–13 (see "Introduction" section, fig. 3) in 2011. The preliminary groundwater flow and TCE transport simulators (appendixes 1 and 2) were forced by hypothetical extraction rates (see "Northern Source Area" section, table 5) to investigate the effect of the new extraction wells on the northern source area. This application investigated the response of part of the NIROP groundwater extraction system to some of the TCE in the NIROP subsurface. A constant TCE concentration of 1,000 µg/L was specified in the upper part of the shallow flow zone of the surficial aquifer system (simulation layer 1); and a constant TCE concentration of 50,000 µg/L was specified in the lower part of the shallow flow zone (simulation layer 2).

For four hypothetical model simulations that also were not intended to represent an historical condition, an area that covered the northern part and most of the southern part of the main NIROP building was postulated to be a source area of uniform TCE concentration (see “Main Naval Industrial Reserve Plant Building Source Area” section, figs. 24–27). Preliminary groundwater flow and TCE transport simulators (appendixes 1 and 2) were forced by hypothetical extraction rates (see “Northern Source Area” section, table 5) to investigate the effect of new extraction wells AT–11, AT–12, and AT–13 on hypothetical TCE source areas under most of the main NIROP building. These preliminary, hypothetical applications investigated the response of part of the NIROP groundwater extraction system to furnished TCE source areas. Any TCE sources outside the footprint of the main NIROP building were not simulated. For the first of four hypothetical simulations (see “Main Naval Industrial Reserve Plant Building Source Area” section, fig. 24), a constant, 10,000-µg/L TCE concentration was postulated to exist in the upper part of the shallow flow zone of the surficial aquifer system (simulation layer 1). Postulated TCE sources did not exist in any other hydrogeologic unit or simulation layer for this first hypothetical simulation. For the second, third, and fourth (see “Main Naval Industrial Reserve Plant Building Source Area” section, figs. 25–27) hypothetical simulations, a constant, 10,000-µg/L TCE concentration was postulated to exist in the lower part of the shallow flow zone (second simulation), the intermediate flow zone (third simulation), and the deep flow zone (fourth simulation) of the surficial aquifer system, respectively (simulation layers 2, 3, and 4, respectively). For each hypothetical simulation, TCE sources existed in one simulation layer; TCE sources did not exist in any other simulation layer. With the exception of these defined source areas, initial TCE concentration was 0 µg/L throughout other parts of the study area; TCE concentrations on all study-area boundaries were also 0 µg/L.

Transport Parameters

Longitudinal, transverse, and vertical dispersivities were 1.0, 0.18, and 0.018 ft, respectively, throughout the study area. Gelhar and others (1992) compiled a critical review of dispersivity measurements at 59 field sites, some of which are similar to NIROP. Gelhar and others (1992) tabulated aquifer type; hydraulic properties; flow configuration; type of monitoring network; tracer; method of data interpretation; overall scale of observation; and longitudinal, horizontal transverse, and vertical transverse dispersivity from original sources. From Gelhar and others (1992), longitudinal dispersivity of 1.0 ft corresponds to a transport scale of about 1 to 300 ft; transverse dispersivity of 0.18 ft also corresponds to a transport scale of about 1 to 300 ft—orders of magnitude appropriate for NIROP. Gelhar and others (1992) did not present sufficient data to relate vertical dispersivity to observation scale.

Porosity was 0.30. Molecular diffusion was not simulated. Porosity and dispersivity parameters were postulated.

Numerical Solution for Trichloroethene Concentration

The MT3DMS GCG generalized conjugate gradient solver was used to solve for TCE concentration. Concentration change criterion was 10^{-4} µg/L. Iteration was complete and the GCG solver moved to the next transport step if the change in concentration between the current iteration and the last iteration was less than 10^{-4} µg/L. The advection solution used the total variation diminishing scheme of the MT3DMS ADV advection package and a Courant number of 1.0.

Calibration

Lane and others (2003, 2004, 2006, 2007), Lane (2005), and Witten and Lane (2003) described borehole geophysical observations of aquifer geochemistry during biostimulation. They used vegetable oil to biostimulate groundwater contaminated with chlorinated hydrocarbons—including TCE—in a 2,000-square-foot area of Anoka County Riverfront Regional Park (see “Introduction” section, fig. 2) downgradient of NIROP adjacent to the Mississippi River (see “Introduction” section, figs. 1 and 5). Horizontal and vertical hydraulic conductivities were adjusted to conform to TCE concentration measurements made by these investigators, and Tetra Tech’s (2013) observation that TCE existed in the subsurface at this location (see “Preliminary Simulation of Trichloroethene Transport” section, figs. 18–20).

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