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Groundwater Discharge to the Mississippi River and Groundwater Balances for the Interstate 94 Corridor Surficial Aquifer, Clearwater to Elk River, Minnesota, 2012–14

Scientific Investigations Report 2017–5114

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

Cover. View looking upstream the Mississippi River, just north of the MN-24 bridge in Clearwater, Minnesota (photograph taken by James Stark, U.S. Geological Survey, September 13, 2012).

Back cover. View looking across Mississippi River at two USGS hydrologic technicians taking an ADCP measurement (photograph taken by James Stark, U.S. Geological Survey, September 13, 2012).

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U.S. Department of the Interior
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U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
William H. Werkheiser, Deputy Director
exercising the authority of the Director

U.S. Geological Survey, Reston, Virginia: 2017

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
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)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per mile ($ft^3/s/mi$)	0.017595	cubic meter per second per kilometer ($m^3/s/km$)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)
bar	100	kilopascal (kPa)
inch of mercury at 60ºF (in Hg)	3.377	kilopascal (kPa)
	Energy	
kilowatt hour (kWh)	3,600,000	joule (J)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

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

$$°F = (1.8 \times °C) + 32.$$

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

$$°C = (°F - 32) / 1.8.$$

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.5400	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	264.2	gallon (gal)
cubic meter ($m^{3)}$	0.0002642	million gallons (Mgal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
cubic hectometer (hm^3)	810.7	acre-foot (acre-ft)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
meter per day (m/d)	3.281	foot per day (ft/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per second per kilometer (m^3/s/km)	56.83345	cubic foot per second per mile (ft^3/s/mi)
cubic meter per day (m^3/d)	35.31	cubic foot per day (ft^3/d)
cubic meter per day (m^3/d)	264.2	gallon per day (gal/d)
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)
	Pressure	
kilopascal (kPa)	0.009869	atmosphere, standard (atm)
kilopascal (kPa)	0.01	bar
kilopascal (kPa)	0.2961	inch of mercury at 60ºF (in Hg)
	Energy	
joule (J)	0.0000002	kilowatt hour (kWh)
	Hydraulic conductivity	
meter per day (m/d)	3.281	foot per day (ft/d)
	Transmissivity	
meter squared per day (m^2/d)	10.76	foot squared per day (ft^2/d)

Datums

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

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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

Supplemental Information

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

Abbreviations

ADCP	acoustic Doppler current profiler
CDL	Cropland Data Layers
ET_0	reference evapotranspiration
FAO	Food and Agriculture Organization
GIS	geographical information system
GPS	global positioning systems
GWMAs	groundwater management areas
HUC–12	hydrologic unit code 12
I–94	Interstate 94
lidar	light detection and ranging
MNDNR	Minnesota Department of Natural Resources
MWI	Minnesota Well Index
NLCD	National Land Cover Database
NWIS	National Water Information System
QBAA	Quaternary buried artesian aquifer
QWTA	Quaternary water-table aquifer
RTK	real-time kinematic
SCAN	Soil Climate Analysis Network
SWB	Soil-Water-Balance
USGS	U.S. Geological Survey

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Abstract

The Interstate 94 Corridor has been identified as 1 of 16 Minnesota groundwater areas of concern because of its limited available groundwater resources. The U.S. Geological Survey, in cooperation with the Minnesota Department of Natural Resources, completed six seasonal and annual groundwater balances for parts of the Interstate 94 Corridor surficial aquifer to better understand its long-term (next several decades) sustainability. A high-precision Mississippi River groundwater discharge measurement of 5.23 cubic feet per second per mile was completed at low-flow conditions to better inform these groundwater balances. The recharge calculation methods RISE program and Soil-Water-Balance model were used to inform the groundwater balances. For the RISE-derived recharge estimates, the range was from 3.30 to 11.91 inches per year; for the SWB-derived recharge estimates, the range was from 5.23 to 17.06 inches per year.

Calculated groundwater discharges ranged from 1.45 to 5.06 cubic feet per second per mile, a ratio of 27.7 to 96.4 percent of the measured groundwater discharge. Ratios of groundwater pumping to total recharge ranged from 8.6 to 97.2 percent, with the longer-term groundwater balances ranging from 12.9 to 19 percent. Overall, this study focused on the surficial aquifer system and its interactions with the Mississippi River. During the study period (October 1, 2012, through November 30, 2014), six synoptic measurements, along with continuous groundwater hydrographs, rainfall records, and a compilation of the pertinent irrigation data, establishes the framework for future groundwater modeling efforts.

Introduction

The concept of water sustainability in Minnesota (fig. 1) has received considerable attention during the last several years (2008 to present [2017]; Freshwater Society, 2008). State resource management agencies are under increasing pressure to manage groundwater resources, particularly in parts of Minnesota with intensive groundwater usage such as the Bonanza Valley (not shown) (Minnesota Department of Natural Resources, 2016). In 2012, the Minnesota legislature gave the Minnesota Department of Natural Resources (MNDNR) authority to delineate groundwater management areas (GWMAs; Minnesota Department of Natural Resources, 2016a) in regions with groundwater-related resource challenges. So far, the MNDNR has created three GWMAs that allow the MNDNR to potentially limit groundwater appropriations within a designated area to ensure sustainable water usage. Beyond the three identified GWMAs, another 13 groundwater areas of concern were identified in a 2013 Freshwater Society report on sustainable water usage (Freshwater Society, 2013). The Interstate 94 (I–94) Corridor was classified as a groundwater area of concern because of its limited available groundwater and potential for surficial aquifer contamination. The I–94 Corridor encompasses an area between St. Cloud (not shown) and the Minneapolis-St. Paul, Minnesota, metropolitan area (fig. 1; hereafter referred to as "the Twin Cities"). This region includes several municipalities experiencing rapid population growth and other areas with increasing demand for agricultural irrigation.

A challenge of water sustainability is to provide for all current (2017) and future societal needs without "unacceptable social, economic or environmental consequences" (VanBuren and Wells, 2007), which is the accepted Minnesota Department of Natural Resources (MNDNR) definition for sustainability. Minnesota statutes define sustainable development as "development that maintains or enhances economic opportunity and community well-being while protecting and restoring the natural environment upon which people and economies depend" (VanBuren and Wells, 2007). Commonly, characterizations related to water sustainability can be seen in subjective terms, as the local resource managers' definitions for acceptable consequences can differ. For example, an acceptable level of groundwater drawdown to meet regional

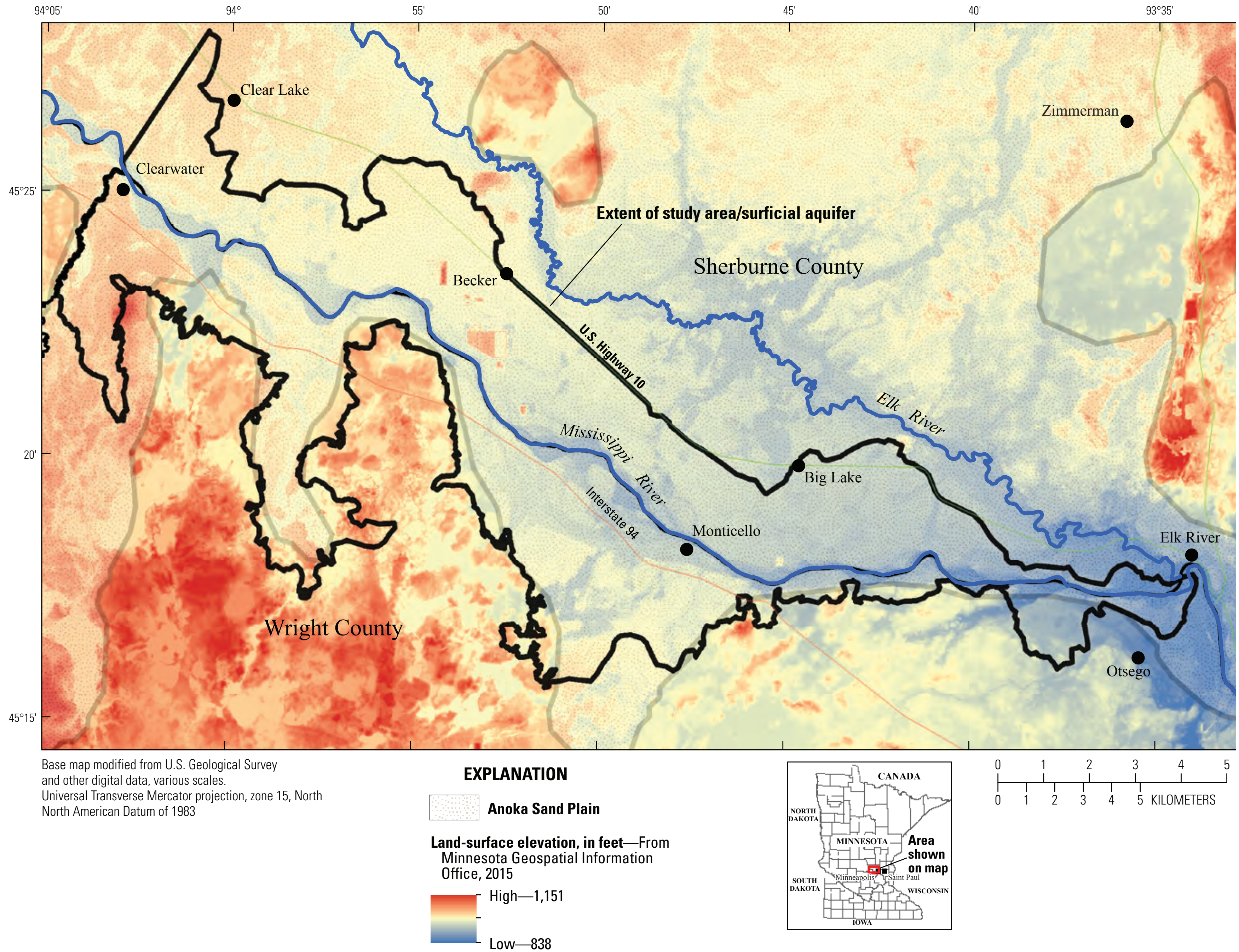


Figure 1. Topography and the Interstate 94 Corridor extent, including portions of the Anoka Sand Plain, central Minnesota.

groundwater demand could temporarily reduce base flow to connected surface-water resources (Alley and others, 1999). If groundwater levels are temporarily reduced during periods of substantial pumping stress and evapotranspiration, such as multiyear droughts, the aquifer may not fully recover, particularly if a collapse in open pore space permanently alters the aquifer storage capacity (Heath, 1983). Hence, to better define sustainable water resources, all water resources (groundwater and surface-water resources) need to be fully characterized to understand water availability as compared to water usage.

During the last four decades, several U.S. Geological Survey (USGS) groundwater aquifer appraisals in Minnesota have been used as a tool for water management purposes (Ericson and others, 1974; Lindholm and others, 1974; Lindholm, 1980; Cowdery, 1999; Reppe, 2005). However, these short-term groundwater resource appraisal studies commonly are ineffective because data collection does not continue with time and does not remain relevant in cases where resource demands on these limited groundwater aquifers increase. Furthermore, an important component repeatedly missing from these studies is the amount of discharge to nearby surface-water bodies. Water resource managers mistakenly can assume that the amount of water available for sustainable water development is equal to natural recharge (Bredehoeft, 1997; Sophocleous, 2002). However, an accurate groundwater appraisal also needs to consider the increased recharge and decreased discharge, referred to as capture, induced by groundwater pumping (Zhou, 2009).

Groundwater flow models are tools that can be used to interpret the dynamic character of capture because these models can examine the effects of groundwater pumping on capture. Ideally, before proceeding with a groundwater model, conceptual models need to exist for the underlying geology and nature of the aquifer materials. In Minnesota, the County Geologic Atlas program provides this basic information, including maps that detail the distribution and properties of rock and sediments that lie below the land surface (Setterholm, 2014). Also, a basic water balance that takes into account the primary sources and sinks of water can begin to determine if a particular area would benefit from a groundwater flow model. By measuring primary sources, such as precipitation, and estimating primary sinks such as groundwater discharge to rivers, groundwater pumping, and evapotranspiration, the initial step of determining how much water can be used without causing primary groundwater deficits can be realized (Alley and others, 1999).

In an effort to interpret water use and sustainability within the Interstate 94 (I–94) Corridor, the USGS, in cooperation with the MNDNR, led a hydrologic investigation in portions of Sherburne and Wright Counties (fig. 1) (part of the I–94 Corridor) to complete a series of groundwater balances and address potential stresses on the surficial aquifer. Funding for this study was provided through the Environmental Quality Board by the Minnesota Legislature during the 2011 special session (Laws of Minnesota 2011, 1st Special Session, Chapter 6, article 2, section 5[i]). Additional support was provided by U.S. Geological Survey Cooperative Matching Funds.

Purpose and Scope

Overall, the study focused on the surficial aquifer system and its interactions with the Mississippi River rather than the coupled surficial-buried aquifer complex because of the limitations of a water budget assessment of this nature that does not include groundwater flow modeling. Assessing the primary sources and sinks for the surficial aquifer system of the I–94 Corridor establishes the framework for future groundwater modeling efforts. Work for the project was divided into the following two distinct objectives: (1) a high-precision Mississippi River groundwater discharge measurement at low-flow conditions on September 13, 2012, to assess the groundwater discharge through a representative section of the I–94 Corridor and (2) a groundwater balance of the surficial aquifer for part of the I–94 Corridor, including the measurement of groundwater hydrographs to calculate recharge variability across the I–94 Corridor.

The purpose of this report is to present the USGS compiled data from the available county geological atlases for Sherburne and Wright Counties defining the approximate areal extent and volume of the surficial aquifer system, regional potentiometric-surface maps for the surficial aquifer system in part of the I–94 Corridor, and changes in groundwater levels as seasonal and annual groundwater balances during portions of the period from October 1, 2012, through November 30, 2014. Groundwater recharge to the surficial aquifer and discharge to the Mississippi River were measured and estimates of water use (in particular, surficial aquifer pumping), evapotranspiration, and return flow were used to calculate groundwater balances. As part of the groundwater balance, a Soil-Water-Balance model was produced with potential recharge rates for the study area at a 100-meter resolution (Smith, 2017).

Previous Studies

Several water resource reports that include parts of the I–94 Corridor have been published during the last 40 years, including Helgesen and others (1975), Helgesen and Lindholm (1977), Lindholm (1980), and Ruhl and Cowdery (2004). A large-scale water budget for an area that included the study area was calculated by Helgesen and others (1975). The water budget accounted for precipitation and evapotranspiration, with a general compilation of water usage. The geology and water-supply potential of the Anoka Sand Plain was compiled by Helgesen and Lindholm (1977). The areal extent of surficial aquifers across central Minnesota, including Sherburne and Wright Counties, and estimated annual recharge to the surficial aquifer was mapped by Lindholm (1980). Hydrologic properties such as saturated thickness, transmissivity, and hydraulic conductivities for the surficial aquifer also were described in Lindholm (1980). Groundwater-flow models for the surficial sand and gravel aquifers north of the study area, in portions of the Anoka Sand Plain with similar properties, were constructed by Ruhl and Cowdery (2004).

Since the 1980s, the USGS has led different water-quality studies that encompassed all or part of the study area. The effects of land use on groundwater quality, based on data collected from 100 wells across the Anoka Sand Plain between 1984 and 1987 were studied by Anderson (1993). Nitrogen isotopes were used by Komor and Anderson (1993) to indicate nitrate sources in groundwater. Samples collected from 29 wells in Sherburne County, including several of the observation wells used in this study, were analyzed for nutrients and pesticides (Ruhl and others, 2000). Nitrogen isotope ratios indicated the sources of nitrate were commercial fertilizer and soil organic matter.

Previous work in Minnesota to establish the gain or loss of streamflow in reaches of the Mississippi River has shown variable results. Published methods for assessing groundwater discharge to the Mississippi River from St. Cloud to the Twin Cities include Lindholm (1980) and Payne (1995). A measured gain in the Mississippi River of 2.5 to 4.9 cubic feet per second per mile ($ft^3/s/mi$), based on three low-flow periods from 1969 to 1976 was reported by Lindholm (1980). The measured gain was calculated by accounting for differences in gaged streamflow along the river and tributary inflows (Lindholm, 19890). An average groundwater discharge rate of 2.59 $ft^3/s/mi$ was reported by Payne (1995) between Fort Ripley and Anoka, Minn. (not shown). The methodology used by Payne (1995) was similar to the methodology used by Lindholm (1980). Model-derived groundwater discharge rates to the Mississippi River from 0.3 to 2.85 $ft^3/s/mi$ were calculated by Helgesen (1973) in reaches of the Mississippi River in Morrison County (not shown). Unpublished records of the USGS from miscellaneous streamflow measurements on the Mississippi River and tributaries made on November 8 and 9, 2006, between Monticello, Minn. (fig. 1) and Dayton, Minn. (not shown) indicate an inconsistent pattern of gains and losses. The average discharge was a loss of about 5.6 $ft^3/s/mi$ for the 18-mile reach.

Hydrologic Setting

The study area shown in figure 1 is underlain by part of the Anoka Sand Plain, a water-table, surficial aquifer, which overlies Paleozoic and Precambrian sedimentary and igneous rock. The Anoka Sand Plain consists primarily of glacial outwash sediments from several glacial advances and retreats during the most recent Quaternary glaciations. Anoka Sand Plain sediments, including those portions in Sherburne and Wright Counties, are highly complex because of the interaction of several distinct ice lobes with time and the differential erosion that occurred between the multiple advances and retreats of the Wisconsinan glaciation (Wright, 1972a, 1972b). Most of the surficial deposits within the I–94 Corridor are fine-grained sand and gravel that were deposited as fluvial and lake sediment near the end of the last glacial episode (Lusardi and Adams, 2013; Hobbs, 2013), including deposits from glacial Lake Anoka and the Mississippi River. Specifically, these glaciofluvial processes deposited sediments as glacial ice melted during the eastward diversion of the glacial Mississippi River around the Grantsburg sublobe of the Wisconsinan glaciations (Cooper, 1935; Farnham, 1956). In addition to the outwash deposits, the Anoka Sand Plain aquifer also includes glacial ice contact deposits and postglacial alluvial and terrace deposits. The extent of the surficial aquifer, in particular the Anoka Sand Plain, covers almost all of the I–94 Corridor in Sherburne County and thins out in northern Wright County. Gray till deposited by the Grantsburg sublobe is present at land surface on topographic high areas where outwash was not deposited. Underlying the outwash and gray till is red till deposited by the Superior lobe of the Wisconsinan glaciations (Cooper, 1935; Farnham, 1956). Since glaciation, soils developed in the surficial materials as well as peat accumulations in the local lakes and wetland depressions (Hobbs, 2013). Underneath the surficial sand and gravels, sands and gravels buried within the fine-grained glacial sediments form confined (buried) aquifers within the study area. The areal extent and interconnectedness of these aquifers are poorly known, specifically because of the complex history of burial, erosion, and redeposition of older deposits from later advances and retreats (Knaeble and others, 2013).

Elevation in the I–94 Corridor ranges from about 840 to 1,150 feet above sea level (fig. 1). Land surface generally slopes towards the Mississippi River along U.S. Highway 10 along the north side of the Mississippi River in Sherburne County, with more topographic relief in Wright County on the south side of the Mississippi River. The study area was chosen based upon surface-water divides in Sherburne County side (north), Wright County (south), and Hydrologic Unit Code 12 (HUC–12) divides (U.S. Department of Agriculture, 2016a). Generally, flow to the north of U.S. Highway 10 flows towards the Elk River (fig. 1) so this area was not included as part of the study area for the water balance. For the northwest and “upstream” extent of the study area, the study area design was based upon the upstream end of the groundwater discharge estimates (in Clearwater, Minn. [fig. 1]) and the chosen lower portion of the study area was the Elk and Mississippi Rivers confluence at Elk River, Minn. (fig. 1).

Water table depth below land surface generally ranges from 3 to 50 feet. These shallow depths make the aquifer vulnerable to land-surface sources of contamination. Hydraulic conductivity ranges from about 50 to as much as 1,000 feet per day (Anderson, 1993). The aquifer typically ranges in saturated thickness from about 20 to 115 feet and consists of medium to coarse sand interbedded with thin layers of clay, silt, silty sand, and gravel (Helgesen and Lindholm, 1977; Lindholm, 1980). However, in some places within the I–94 Corridor, particularly in Sherburne County, the surficial aquifer can be greater than 100 feet (30.5 meters) thick such as those areas where two or more sand and gravel units are juxtaposed with no intervening till layer (Lusardi and Lively, 2013). Also, the surficial aquifer can be hydrologically connected to some buried aquifers. Transmissivities range from about 5,000 to as much as 30,000 square feet per day (Lindholm, 1980).

About 20 percent of the aquifer is capable of yielding water to wells at a rate of at least 500 gallons per minute (Anderson, 1993). This yield rate indicates the capacity for substantial withdrawal rates but does not necessarily indicate corresponding recharge to support the use.

Recharge to the surficial aquifer can be attributed primarily to rain and snowmelt that readily infiltrates the sandy topsoil and percolates to the water table. Generally, most recharge follows snowmelt and spring rains, with a second period of recharge soon after the growing season in late fall. The reported average groundwater recharge rates to the aquifer is 8 inches per year, based on Lindholm (1980). Recharge estimates for the region extracted from a Soil-Water-Balance (SWB) potential recharge estimate of Minnesota range from 5.23 to 17.06 inches per year (Smith and Westenbroek, 2015). Shallow groundwater in the study area generally flows from topographically high to low areas and discharges to streams, lakes, and wetlands. Groundwater also discharges to the atmosphere by evapotranspiration during the growing season where the depth below land surface to the water table is less than about 10 feet (Anderson, 1993). The water table surface generally is a subdued reflection of the topography (Lindholm, 1980). Groundwater withdrawals, attributable to pumping high-capacity wells, create cones of depression in the water table and, therefore, affect groundwater flow.

Climate and Evapotranspiration

The climate of the study area is humid continental, with warm, humid summers and cold winters with heavy snowfall. Climate data from the St. Cloud Regional Airport (not shown; U.S. Department of Commerce, 2015), about 12 miles northwest of the study area, have a long period of record (1943 to the present) and are useful for putting short-term climate data collected within the study area into historical perspective. Based on this long-term record, the average January temperature is -12.2 degrees Celsius (°C) (10.0 degrees Fahrenheit [°F]), the average July temperature is 21 °C (69.8 °F), and most precipitation (17.0 inches) falls during the growing season (May–September) compared with 27.1 inches annually. Extensive hourly climate data have been recorded since 1994 at the Soil Climate Analysis Network (SCAN) Crescent Lake #1 station, operated by the U.S. Department of Agriculture (2016b), Natural Resources Conservation Service, near the center of the study area. Real-time and historical data are available online (U.S. Department of Agriculture, 2016b). Precipitation data also were recorded hourly at all other continuous groundwater-level stations used for this study during the nonfreezing portions of the year, approximately April through November.

Precipitation varies dramatically between wet and dry periods within the study area. Multiyear droughts such as those during 1959–61, 1974–76, and 1987–89 have caused depressions in the surficial water table, with full recovery during the postdrought year. The extreme annual precipitation totals during 1948–2015 for St. Cloud are 39.3 inches in calendar year 1965 and 14.9 inches in calendar year 1976 (U.S. Department of Commerce, 2015). Data for this study were collected during a period where precipitation was dry in water year 2013 (October 1, 2012, through September 30, 2013) and above normal in water year 2014 (October 1, 2013, through September 30, 2014). The annual precipitation at St. Cloud Regional Airport during the 2013–14 water years was 25.49 and 40.06 inches, respectively. During the 2013–14 water years, the average annual precipitation recorded from the precipitation gages for this study was less than the precipitation recorded at the St. Cloud Regional Airport—20.75 and 34.89 inches, respectively.

The reference evapotranspiration (ET_0) was calculated by the Food and Agriculture Organization (FAO) Penman-Monteith method (Allen and others, 1998). The ET_0 for the 2013 water year was 41.4 inches. The ET_0 for the 2014 water year was 40.9 inches. For both years, July had the highest monthly ET_0, with daily rates as high as 0.33 inch per day. The ET_0 for the 2013 and 2014 growing seasons (May through September) was 29.5 inches and 29.6 inches, respectively. Between the high ET_0 rates and the sandy soils indicative of the Anoka Sand Plain, heavy irrigation is necessary for the common row crops grown in the region, which include potatoes, field corn, and soybeans (Anderson, 1993).

Land Use and Land Cover

Land use and land-cover area were primarily agricultural, mixed with some urban, forest, and open water areas. The agricultural areas include irrigated and nonirrigated agricultural areas that were used to grow row crops such as potatoes, field corn, soybeans, and sweet corn (Ruhl and others, 2000). Land-cover data were obtained from the 2011 National Land Cover Database (NLCD) (Homer and others, 2015), available from the Multi-Resolution Land Characteristics Consortium. Also, analysis of the 2013 Cropland Data Layers (CDL), available from the National Agricultural Statistics Service (U.S. Department of Agriculture, 2013), were used to determine the amount of land devoted to cultivated crops.

For the NLCD–2011 dataset, the land-cover classification consists of 16 classes at a 30-meter spatial resolution. Of the 16 land-cover classes, 15 were present in the study area (fig. 2; table 1), with 14 of the 15 land-cover classes listed in table 1. For the land-cover class of cultivated crops, the CDL was substituted. Because of the substitution, the total land area is slightly higher than 100 percent because the NLCD–2011 dataset was used for the cultivated crop areas; however, the advantage to using a combined dataset is that more details on the agricultural land use are available with the CDL.

For the combined dataset (table 1), four classes account for approximately 58 percent of the land cover—deciduous forest (12.1 percent), pasture/hay (13.6 percent), corn (19.9 percent), and soybeans (12.7 percent). The row crops including corn, soybeans, and potatoes are commonly

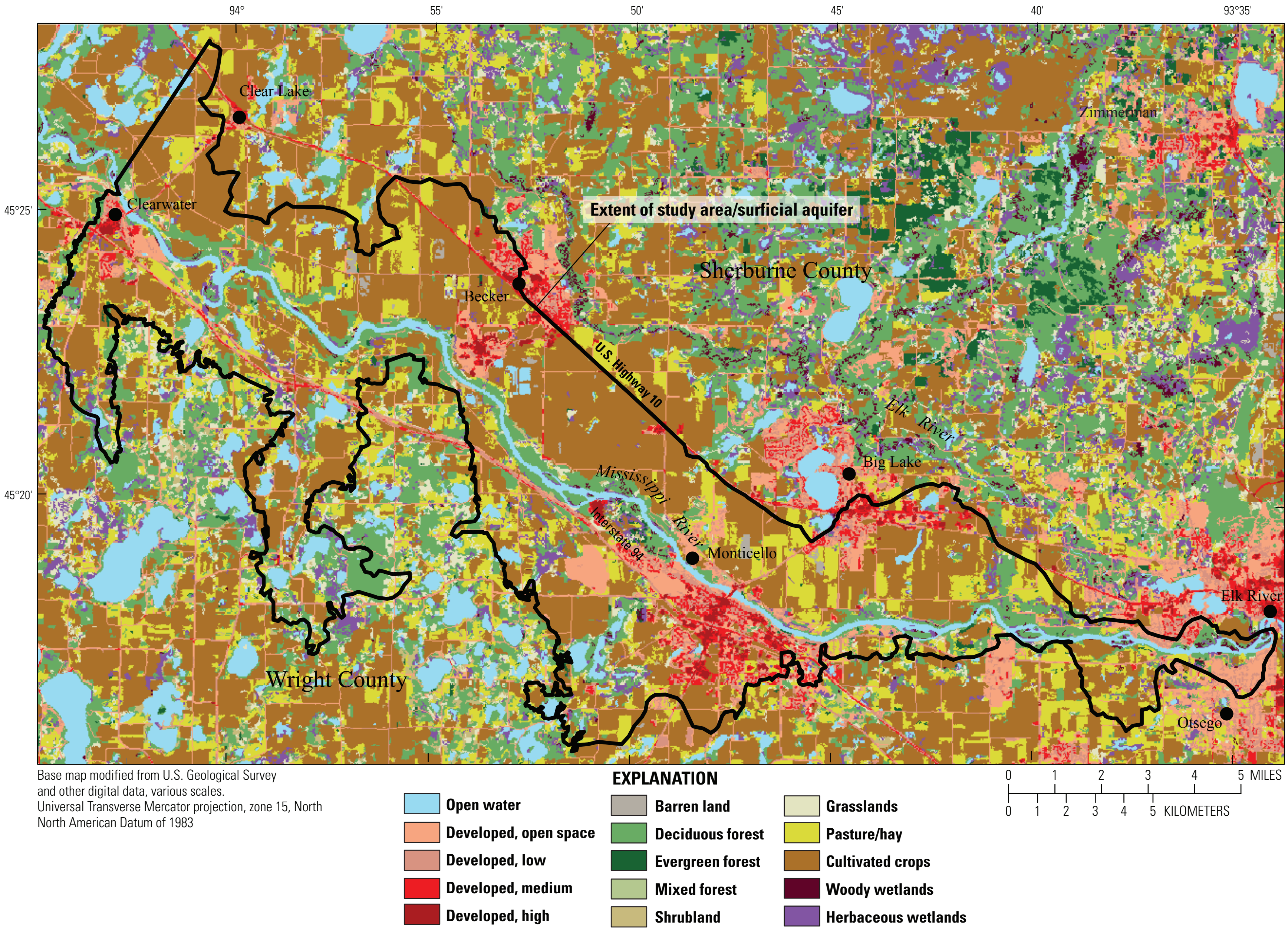


Figure 2. Land cover in Minnesota for the Interstate 94 Corridor study, central Minnesota, at a 30-meter resolution, from the 2011 National Land Cover Database (Homer and others, 2015).

Table 1. Distribution of land cover in the study area, based on the combined 2011 National Land Cover Dataset (Homer and others, 2015) and the 2013 Cropland Data Layers (U.S. Department of Agriculture, 2013).

Land cover class and description	Land-cover distribution, in percent
Open water	6.7
Developed, open space	7.9
Developed, low intensity	4.7
Developed, medium intensity	3.5
Developed, high intensity	1.3
Barren land (rock/sand/clay)	0.5
Deciduous forest	12.1
Evergreen forest	0.5
Mixed forest	0.0
Shrubland	0.9
Grasslands	2.6
Pasture/hay	13.6
Cultivated crops	
Corn	19.9
Soybeans	12.7
Potatoes	4.8
Other hay/nonalfalfa	2.3
Alfalfa	1.5
Sweet corn	0.7
Rye	0.5
Spring wheat	0.3
Fallow/idle cropland	0.1
Oats	0.1
All other crops	0.1
Woody wetlands	0.4
Herbaceous wetlands	3.4
Total	[1]101.1

[1]Exceeds 100 percent because of rounding.

irrigated, so a large percentage of the I–94 Corridor has supplemental irrigation with water from the surficial and buried aquifers.

Population and Water Use

Population in the I–94 Corridor from the 2010 U.S. Census Bureau dataset was 32,444 persons (U.S. Census Bureau, 2013). The census blocks for the I–94 Corridor were clipped from the statewide census dataset, which included housing unit and population counts by census block. Census blocks were derived from the TIGER/Line shapefiles (U.S. Census Bureau, 2013). An overlay of the permitted domestic wells in the I–94 Corridor with the census blocks yielded the census blocks which only contained domestic wells without community water supply wells; the number of permitted domestic wells in the I–94 Corridor was 3,430 wells (fig. 3). This method was the best approach available to estimate the number of non-community water supply users within the I–94 Corridor; this methodology was similar to an approach from Hayes and Horn (2009) and Medalie and Horn (2010). Through this methodology, the estimated population in the I–94 Corridor supplied by domestic wells was 12,084 persons.

For this report, annual water-use data were obtained from the MNDNR Water Appropriations Permit Program, which tracked monthly water use at sites using more than 10,000 gallons per day or 1 million gallons per year (Mgal/yr) (Minnesota Department of Natural Resources, 2016b). Reporting for these wells was required, but because data were self-reported, the accuracy was not well-constrained; the error associated with the self-reported water use for Minnesota has been estimated as 10 percent (Sean Hunt, Minnesota Department of Natural Resources, oral commun., 2015). Water use in the I–94 Corridor is primarily for irrigation (predominantly agricultural irrigation and to a lesser extent golf courses), thermoelectric-power cooling, domestic water usage, and municipal public supply usage (Minnesota Department of Natural Resources, 2016b).

The water-use table is presented as table 1–1 for calendar years 2013–14. Only permitted wells from the surficial aquifer are included as part of table 1–1 because the water balance for this report was restricted to the surficial aquifer. In addition, only wells that had reported usage for calendar years 2013–14 were included. The combination of permitted surficial aquifer wells and usage for calendar years 2013–14 resulted in 118 surficial wells (table 1–1; fig. 3). Some of the wells reported in table 1–1 were not classified in the Minnesota Well Index (MWI) as Quaternary water-table aquifer (QWTA) wells, the designation in MWI for the surficial aquifer (Minnesota Department of Health, 2016). However, based on checks of reported well depths compared to the calculated surficial aquifer for this study (described in the "Surficial Aquifer Extent and Volume" section), these wells were included for the purposes of water usage. Monthly water use for all other wells with reported usage during this period of record (calendar years 2013–14) are listed in table 1–2; these wells were either listed as a buried aquifer well (listed as QBAA or Quaternary buried artesian aquifer well in the MWI) or were deeper wells without a designation.

Methods

This study was designed to produce seasonal and annual groundwater balances for portions of the I–94 Corridor. Well information was collected from water-well stratigraphic logs available from the MWI (Minnesota Department of Health, 2016), formerly known as the County Well Index. Aquifer structure was determined from the two existing county geologic atlases for Sherburne and Wright Counties (Lusardi

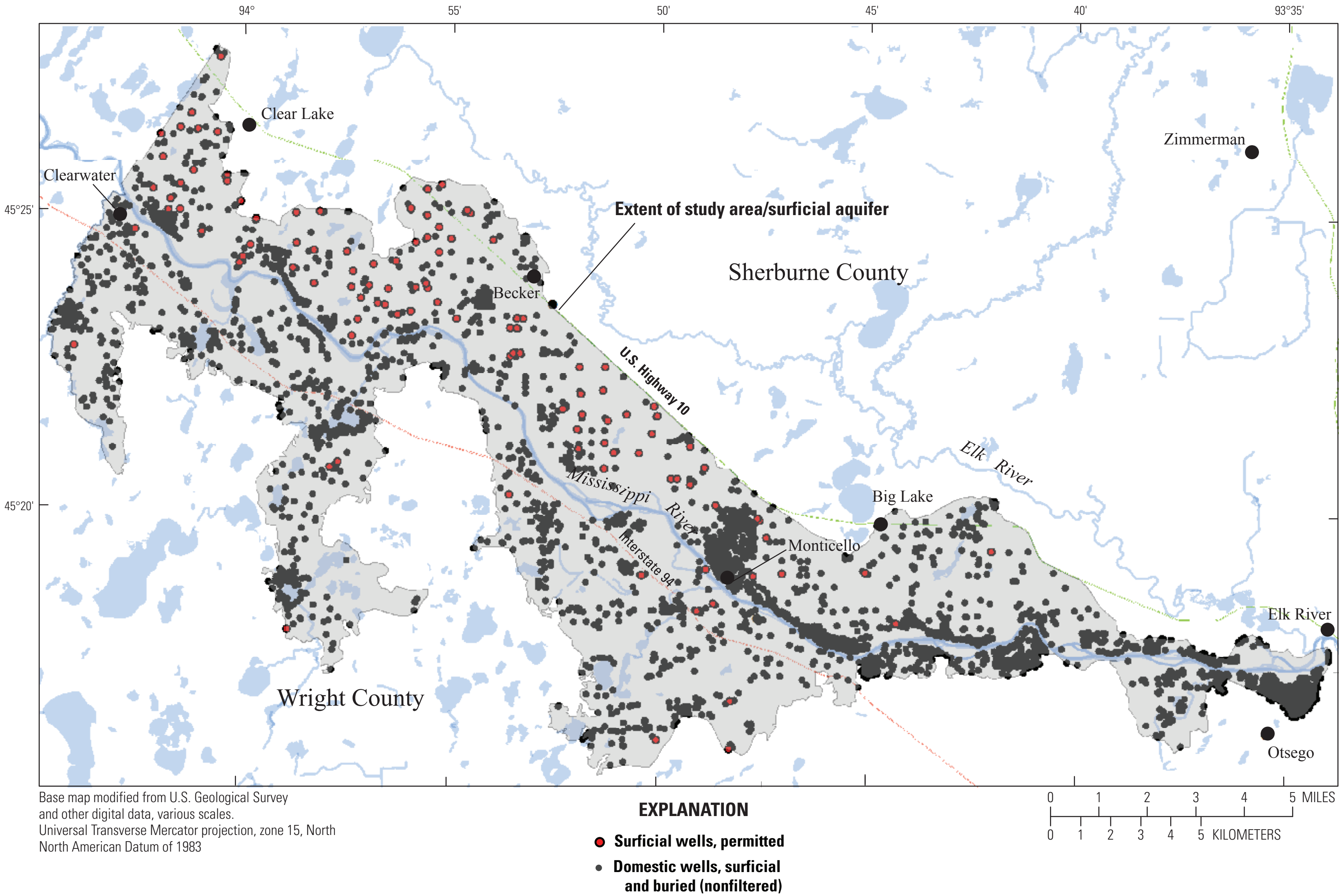


Figure 3. Total domestic wells in the Interstate 94 Corridor (3,430 wells) from surficial and buried aquifers. Total permitted wells (118 wells) with greater than 10,000 gallons per day (gal/d), or 1 million gallons per year (Mgal/yr), from the surficial aquifer only in the Interstate 94 Corridor.

and Adams, 2013; Hobbs, 2013), based upon detailed maps and geographical information system (GIS) coverages that included thicknesses of the different surficial aquifer lenses. Low-flow measurements on September 13, 2012, assisted in determining the groundwater discharge to the Mississippi River. Additional data collected for this study included synoptic water-level measurements, continuously recorded water levels, and precipitation at water-level sites. Surficial aquifer potentiometric-surface maps were compiled from synoptic water-level measurements made during six synoptic measurements in calendar years 2013–14.

Groundwater Discharge Estimates

Many methods for estimating groundwater discharge to streams are described in Rosenberry and LaBaugh (2008). The authors indicated that most of the field methods that are described are appropriate for smaller rivers and streams, either because of the scale of the measurement or because of measurement errors in larger rivers. A commonly used method for small streams is the seepage run, where streamflow measurements are made at selected sites on a river and the groundwater discharge (or recharge) is the difference in the streamflows at each site (eq. 1).

$$Q_o - Q_i - Q_{gw} = 0 \qquad (1)$$

where

Q_o is downstream outflow,
Q_i is upstream inflow, and
Q_{gw} is groundwater discharge.

The seepage run is a commonly used technique, and many examples of its use are cited in Rosenberry and LaBaugh (2008). Generally, seepage run usage in large rivers is limited by the measurement error of the streamflow measurement.

The working hypothesis for a seepage run measurement in a large river is an extension of the seepage run measurements for small streams. The law of conservation states that the total volume in, minus the total volume out, plus the change in storage, is zero. The groundwater discharge (Q_{gw}) is estimated (eq. 2) using a mass-balance equation (eq. 1) by reorganizing equation 1 and solving for Q_{gw}, because all other variables will be calculated, estimated, or assumed to be zero (in the case of the change in storage).

$$Q_o\Delta t - Q_i\Delta t - Q_{gw}\Delta t - V_{et} + \Delta S = 0 \qquad (2)$$

where

Q_o is discharge measured as outflow,
Δt is length of measurement period,
Q_i is discharge measured as inflow,
Q_{gw} is groundwater discharge,
V_{et} is volume of water for evapotranspiration, and
ΔS is change in storage.

For this study, the volume of Mississippi River water outflow was determined using simultaneous continuous acoustic Doppler current profiler (ADCP) measurements during an 8-hour period (Mueller and others, 2013). Additional ADCP measurements were attempted on two inflow tributaries to the Mississippi River on the Wright County side; however, the amount of flow was too shallow during the 8-hour period for these two tributaries. Dual ADCPs were used at the upstream (transects A and B) and downstream (transects C and D) ends of the study reach (fig. 4). During the test, four ADCPs were in the water at any point in time. A fifth ADCP was rotated in during the test period to compare each ADCP with the other ADCPs and control for any instrument bias. This activity was coordinated with the USGS Hydroacoustic Work Group on the collection of ADCP measurements to optimize the ADCP data collection process and the assessment of the standard error of the measured input and output flows.

The tributary inflow would have been measured by making one or more individual flow measurements, depending on the flow, and extrapolating the measurement for the 8-hour period. However, during the low-flow conditions on September 13, 2012, the tributary inflow in the study reach was negligible. The volume lost to evapotranspiration was estimated using the FAO Penman-Monteith method, which used information obtained from the SCAN station operated by the U.S. Department of Agriculture (2016b), and the estimate was applied to the area of the reach.

The change in storage during the 8-hour period was computed by deploying six pressure transducers that recorded the elevation of the water surface (fig. 4). The change in storage was the change in elevation at each pressure transducer applied to the respective area of the reach. The area of the reach was computed in the following two-step process: (1) recording locations along both banks and around islands using real-time kinematic (RTK) global positioning systems (GPS) for part of the study reach and (2) using the RTK results as ground-truth for aerial photography available with Google Earth to determine the total area of the reach. The groundwater discharge was estimated by setting the value for *Vgw* so that the sum was zero in equation 1.

Groundwater and Precipitation Sites

All groundwater data collected for this study came from sites listed in tables 2 and 3, with site locations shown in figure 5. Continuous water-level networks (table 2) were established in the study area, primarily collected from previously installed USGS piezometers. Precipitation gages were colocated at all the continuous water-level sites. The continuous water-level and precipitation gage sites measure variability in water budget components through time. A synoptic water-level network was established as part of this study, a combination of observation and domestic supply wells. The synoptic components documented the state of the surficial water table at a moment in time.

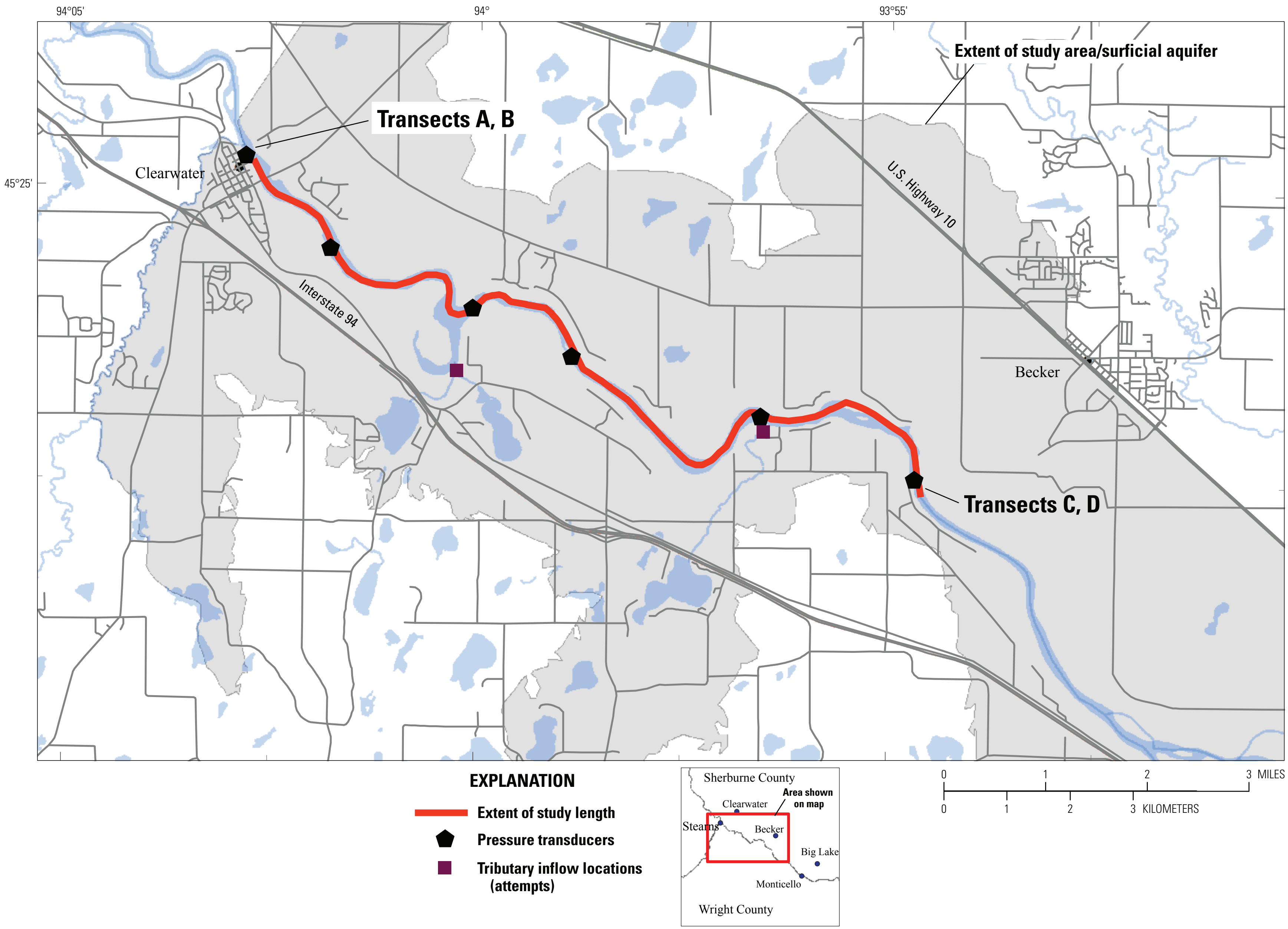


Figure 4. The study reach, delimited by a red line, where the groundwater discharge computation was made. Also denoted are the locations where streamflow measurements were attempted but the amount of flow was not measurable during the 8-hour period on September 13, 2012.

Table 2. Records of wells in network for continuous monitoring of groundwater levels, including site number, well type, latitude/longitude, screened intervals, and well depth.

[All wells had pressure transducers recording continuous (30-minute) water levels for at least a portion of the period from October 1, 2012, through September 30, 2014; precipitation gages were colocated at all of the continuous water-level sites. ID, identification; MUN, Minnesota unique well number; USGS, U.S. Geological Survey; OB–OTH, non-U.S. Geological Survey observation well; OB–USGS, U.S. Geological Survey observation well; --, unknown]

Well ID	Agency code	Site number	MUN	Type	Latitude[1]	Longitude[1]	Screened interval[2]	Well depth[2]
GC133	USGS	451943093504501	747059	OB–OTH	45.32958	-93.84563	21.49–31.49	31.49
ALUS–02	USGS	452428093591601	582132	OB–USGS	45.40744	-93.98669	14.86–19.86	19.86
ALUS–03	USGS	452545093571002	371006	OB–USGS	45.42943	-93.95335	34.91–36.91	36.91
ALUS–07	USGS	452609093553001	582135	OB–USGS	45.44370	-93.92131	10.66–15.66	15.66
ALUS–11	USGS	452229093525801	--	OB–OTH	45.37623	-93.88257	37.27–57.27	57.27
ALUS–18	USGS	452215093481001	582137	OB–USGS	45.37009	-93.80643	21.27–26.27	26.27
ALUS–20	USGS	451957093483201	582139	OB–USGS	45.33161	-93.81136	44.58–49.58	49.58
ALUS–25	USGS	451822093413201	582144	OB–USGS	45.30576	-93.68857	25.55–30.55	30.55
ALUS–31	USGS	452413093540701	685848	OB–USGS	45.40417	-93.90181	17.59–22.59	22.59
ALUS–32	USGS	451753093434801	685847	OB–USGS	45.29801	-93.73003	20.19–25.19	25.19
ALUS–33	USGS	452012093412701	685849	OB–USGS	45.33646	-93.69069	17.05–22.05	22.05
ALUS–35	USGS	452111093523402	620723	OB–USGS	45.35744	-93.88121	36.45–41.45	41.45

[1]Latitude/longitude in decimal degrees.

[2]Screened interval and well depth in feet below land surface.

Twelve wells from previous USGS studies (Anderson, 1993; Ruhl and others, 2000) were used for continuous water-level sites in this study (table 2; fig. 5). The water-level sites were selected to provide an even distribution of wells in the surficial aquifers throughout the study area. Well type, screened intervals, well depths, and latitude/longitudes in decimal degrees are listed in table 2. During the study, a few of the water-level sites had to be exchanged because the wells were consistently dry. Precipitation gages were colocated at all of the continuous water-level sites. The precipitation gages consisted of a tipping bucket rain gage to get accurate estimates of local precipitation during the nonfreezing part of the year.

The synoptic water-level network consists of 167 existing wells screened in the surficial water-table aquifer (fig. 5; table 3). Well type, screened intervals, well depths, and latitude/longitudes in decimal degrees are listed in table 3. Most of the synoptic water-level network wells were sampled for all six of the synoptic surveys in calendar years 2013–14.

Continuous water-level sites were outfitted with submersible pressure transducers to measure water level. Data were recorded at the well and uploaded to the USGS database semiannually. These data are available online on the National Water Information System (NWIS) (U.S. Geological Survey, 2016) for the 12 sites listed in table 2. Pressure transducers were calibrated after no longer than 6 months, and rain gages were calibrated annually. During the semiannual downloads and the six synoptic surveys, all rain gages were checked for any obstructions and cleaned, if necessary. Precipitation data by site location, summarized in monthly and annual precipitation totals (in inches), are listed in table 4.

Groundwater-Level Synoptic Study

The groundwater-level synoptic surveys, or the measurement of groundwater levels in many wells within a short period, for the surficial aquifer system in the study area were done six times in calendar years 2013–14—May 2013, July 2013, November 2013, March 2014, July 2014, and November 2014. Most of the synoptic measurements were made during a 5-day period to provide a “snapshot” of the potentiometric surface. Measurements were not made at a few of the wells during a 5-day period because of logistic challenges. All groundwater-level measurements were obtained by steel tape or electric tape, following the procedures of Cunningham and Schalk (2011). Measurements were made when wells were not being pumped; however, antecedent conditions and pumping status of nearby wells could have affected the groundwater levels included in this study. Well selection consisted of the combination of Minnesota Wells Index (Minnesota Department of Health, 2016) wells, coded as QWTA with good location coordinates, and the county parcel data. A participation survey was sent out to these potential well owners, and synoptic survey measurements were made only for wells with positive landowner confirmation and permission.

Wells used in this study were field located, and latitude/longitude coordinates either were provided by field-verified well locations in the MWI (Minnesota Department of Health, 2016) or were acquired from RTK–GPS data (Minnesota Geospatial Information Office, 2015). All land-surface altitudes were acquired by extracting elevations from a rectified high accuracy, bare-earth processed light detection and ranging

Table 3. Records of wells in network for synoptic monitoring of groundwater levels, including site number, well type, latitude/longitude, screened intervals, and well depth.

[ID, identification; MUN, Minnesota unique well number; GW–DO, existing domestic well; USGS, U.S. Geological Survey; OB–OTH, non-U.S. Geological Survey observation well; OB–USGS, U.S. Geological Survey observation well; --, unknown]

Well ID	Agency code	Site number	MUN	Type	Latitude[1]	Longitude[1]	Screened interval[1]	Well depth[1]
GC001	MN040	452517093552601	107218	GW–DO	45.42184	-93.92457	55–60	60
GC002	MN040	452518094030201	123290	GW–DO	45.42148	-94.05096	66–70	70
GC003	USGS	451706093354001	126710	GW–DO	45.28564	-93.59443	64–68	68
GC004	MN040	452610093571501	135565	GW–DO	45.43625	-93.95395	53–57	57
GC005	MN040	452705093582001	137492	GW–DO	45.45175	-93.97350	42–50	50
GC006	MN040	451852093474901	149772	GW–DO	45.31446	-93.79685	86–93	93
GC007	MN040	452420093590701	157357	GW–DO	45.40467	-93.98569	64–68	68
GC008	MN040	452224093464401	160684	GW–DO	45.37384	-93.77954	51–56	56
GC009	USGS	451634093492301	160696	GW–DO	45.27589	-93.82306	60–69	69
GC010	USGS	452229093540301	161488	OB–OTH	45.37462	-93.90097	75–100	100
GC011	USGS	452242093533701	161491	OB–OTH	45.37837	-93.89362	45–65	65
GC012	USGS	452242093532801	161493	OB–OTH	45.37844	-93.89124	50–70	70
GC013	USGS	452235093533702	161494	OB–OTH	45.37646	-93.89364	35–60	60
GC014	USGS	452235093533701	161495	OB–OTH	45.37646	-93.89360	50–75	75
GC015	MN040	452304094043401	165818	GW–DO	45.38449	-94.07649	44–48	48
GC016	MN040	452039093481201	166953	GW–DO	45.34441	-93.80445	73–78	78
GC017	USGS	452224093544101	167993	GW–DO	45.37328	-93.91152	39–48	48
GC018	MN040	451819093464001	169510	GW–DO	45.30499	-93.77768	56–61	61
GC019	USGS	451851093503701	169573	GW–DO	45.31394	-93.84361	34–40	40
GC020	MN040	451949093490801	169575	GW–DO	45.33012	-93.81929	71–76	76
GC021	MN040	451949093480301	169587	GW–DO	45.33005	-93.80156	76–81	81
GC022	MN040	451951093481601	169623	GW–DO	45.33026	-93.80491	76–81	81
GC023	MN040	452417093590201	178431	GW–DO	45.40466	-93.98440	64–68	68
GC024	MN040	452312094042001	188734	GW–DO	45.38583	-94.06952	64–69	69
GC025	MN040	452916093581101	191166	GW–DO	45.48785	-93.97005	46–51	51
GC027	USGS	452539093593701	225795	GW–DO	45.42750	-93.99428	38–48	48
GC028	MN040	452627093594901	225796	GW–DO	45.44123	-93.99743	42–46	46
GC029	USGS	451955093424901	242900	OB–OTH	45.33181	-93.71346	50–52	52
GC030	USGS	452340093521401	244449	OB–OTH	45.39451	-93.87092	25–27	30
GC032B	USGS	452038093491302	792546	OB–OTH	45.34400	-93.82018	38–48	48
GC033	USGS	451741093365401	400278	GW–DO	45.29474	-93.61521	87–92	92
GC034	MN040	451629093501901	412237	GW–DO	45.27441	-93.83220	49–54	54
GC035	MN040	451936093482401	412501	GW–DO	45.32542	-93.80600	50–54	54
GC036	USGS	451703093353201	416754	GW–DO	45.28429	-93.59237	60–65	65
GC037	USGS	451942093485201	420161	GW–DO	45.32836	-93.81456	70–80	80
GC038	USGS	451815093362401	421121	GW–DO	45.30414	-93.60680	51–56	56
GC039	MN040	452346094000801	422017	GW–DO	45.39654	-94.00207	73–77	77
GC040	USGS	452300093560201	437529	GW–DO	45.38312	-93.93388	98–108	108
GC041	MN040	452500094020301	440185	GW–DO	45.41635	-94.03437	84–87	87
GC042	MN040	452627093553301	447668	GW–DO	45.44097	-93.92556	48–52	55
GC043	USGS	451934093485101	447733	GW–DO	45.32628	-93.81442	82–86	87
GC044	MN040	451930093480401	449886	GW–DO	45.32552	-93.80162	51–56	56
GC045	MN040	451810093450501	451728	GW–DO	45.30225	-93.75391	23–33	33
GC046	MN040	452045093440801	451808	GW–DO	45.34588	-93.73566	40–46	46
GC047	MN040	452422093595801	451863	GW–DO	45.40596	-93.99802	66–78	78
GC048	MN040	452007093475201	452558	GW–DO	45.33526	-93.79816	76–81	81
GC049	MN040	451625093485901	453072	GW–DO	45.27329	-93.81720	70–74	74
GC050	MN040	452445094014201	455182	GW–DO	45.41265	-94.02812	69–73	73
GC051	USGS	452145093571201	456063	GW–DO	45.36241	-93.95390	60–64	64

Table 3. Records of wells in network for synoptic monitoring of groundwater levels, including site number, well type, latitude/longitude, screened intervals, and well depth.—Continued

[ID, identification; MUN, Minnesota unique well number; GW–DO, existing domestic well; USGS, U.S. Geological Survey; OB–OTH, non-U.S. Geological Survey observation well; OB–USGS, U.S. Geological Survey observation well; --, unknown]

Well ID	Agency code	Site number	MUN	Type	Latitude[1]	Longitude[1]	Screened interval[1]	Well depth[1]
GC052	USGS	452127093474801	456209	GW–DO	45.35764	-93.79644	55–60	60
GC053	MN040	452351093522001	456977	GW–DO	45.39607	-93.87457	22–42	42
GC054	USGS	452459094015401	461768	GW–DO	45.41639	-94.03211	66–74	74
GC055	USGS	452615093572901	466072	GW–DO	45.43775	-93.95764	63–67	67
GC056	USGS	452007093462701	472052	GW–DO	45.33521	-93.77418	52–57	57
GC057	USGS	452316093542001	474023	OB–OTH	45.38787	-93.90568	36–46	46
GC058	USGS	452347093540601	474024	OB–OTH	45.39650	-93.90167	30–40	40
GC059	USGS	452333093542501	474026	OB–OTH	45.39260	-93.90690	29–39	39
GC060	USGS	452452094014901	477722	GW–DO	45.41458	-94.03041	59–63	63
GC061	MN040	451714093352403	487848	GW–DO	45.28602	-93.59091	60–65	65
GC062	USGS	451937093452501	490906	GW–DO	45.32701	-93.75714	19–22	22
GC063	USGS	452455094014901	494538	GW–DO	45.41520	-94.02989	110–114	114
GC064	USGS	451731093494501	501289	GW–DO	45.29183	-93.82912	63–67	67
GC065	MN040	452755093585801	507192	GW–DO	45.46584	-93.98318	52–60	60
GC066	USGS	452810093572101	507633	GW–DO	45.46935	-93.95592	51–55	55
GC067	MN040	452452094013801	510303	GW–DO	45.41384	-94.02820	71–91	104
GC068	MN040	451708093352403	514739	GW–DO	45.28638	-93.59165	70–80	80
GC069	USGS	451832093494901	515671	GW–DO	45.30871	-93.83043	75–80	80
GC070	MN040	451634093541701	517726	GW–DO	45.34746	-93.88886	56–60	60
GC071	MN040	452158093482001	517784	GW–DO	45.37124	-93.80200	54–64	64
GC072	USGS	451710093351901	523006	GW–DO	45.28588	-93.58848	95–100	100
GC073	USGS	452108093532201	527793	GW–DO	45.35200	-93.88937	51–55	55
GC074	USGS	451812093513101	528284	GW–DO	45.30308	-93.85862	82–86	86
GC075	USGS	452738093585901	530022	GW–DO	45.46074	-93.98299	88–92	92
GC076	USGS	452035093491601	530043	GW–DO	45.34320	-93.82142	48–63	63
GC077	USGS	452312093575201	537551	GW–DO	45.38648	-93.96403	91–95	95
GC078	USGS	451957093523701	539759	GW–DO	45.33240	-93.87664	71–75	75
GC079	USGS	451659093345401	545303	GW–DO	45.28254	-93.58198	40–48	48
GC080	USGS	451704093350901	546854	GW–DO	45.28423	-93.58565	97–102	102
GC081	USGS	451926093405101	550467	GW–DO	45.32342	-93.68043	35–40	40
GC082	USGS	452307094035901	554566	GW–DO	45.38538	-94.06647	63–67	67
GC083	USGS	452457094020901	554568	GW–DO	45.41597	-94.03592	50–54	59
GC084	USGS	452319093575001	554671	GW–DO	45.38846	-93.96397	70–80	80
GC085	USGS	452309093560001	560096	GW–DO	45.38565	-93.93341	53–57	57
GC086	USGS	452438094034001	560129	GW–DO	45.41044	-94.06105	81–85	85
GC087	USGS	452510094021101	560140	GW–DO	45.41954	-94.03638	50–54	54
GC088	USGS	452458094021001	575260	GW–DO	45.41616	-94.03608	63–68	68
GC089	USGS	452201093534101	580544	OB–OTH	45.36887	-93.89327	33–43	43
GC090	USGS	452201093534102	582995	OB–OTH	45.36510	-93.87733	34–44	44
GC091	USGS	452034093434501	585508	GW–DO	45.34276	-93.72878	56–60	60
GC092	USGS	452444094014301	586928	GW–DO	45.41211	-94.02911	63–67	67
GC093	USGS	451811093480001	589304	GW–DO	45.30316	-93.79993	5–15	15
GC094	USGS	452314093580001	592234	GW–DO	45.38713	-93.96725	67–71	71
GC095	USGS	452001093525501	593870	GW–DO	45.33358	-93.88198	61–66	66
GC096	USGS	452356094012201	603677	GW–DO	45.39873	-94.02347	83–91	91
GC097	USGS	452134093471601	605363	GW–DO	45.35953	-93.78796	68–77	77
GC098	USGS	452316093580201	612347	GW–DO	45.38775	-93.96723	83–88	88
GC099	USGS	452640093562401	617418	GW–DO	45.44441	-93.94008	72–77	77
GC100	USGS	452304093593401	621518	GW–DO	45.38417	-93.99286	64–68	68

Table 3. Records of wells in network for synoptic monitoring of groundwater levels, including site number, well type, latitude/longitude, screened intervals, and well depth.—Continued

[ID, identification; MUN, Minnesota unique well number; GW–DO, existing domestic well; USGS, U.S. Geological Survey; OB–OTH, non-U.S. Geological Survey observation well; OB–USGS, U.S. Geological Survey observation well; --, unknown]

Well ID	Agency code	Site number	MUN	Type	Latitude[1]	Longitude[1]	Screened interval[1]	Well depth[1]
GC101	USGS	452147093573901	621721	GW–DO	45.36316	-93.96124	99–109	109
GC102	USGS	452132093464901	621780	GW–DO	45.35641	-93.77723	94–104	104
GC103	USGS	451907093482101	627514	GW–DO	45.31866	-93.80582	108–111	111
GC104	USGS	452559093560301	638415	GW–DO	45.43303	-93.93404	56–60	60
GC105	USGS	452103093513801	639979	GW–DO	45.35089	-93.86062	21–31	31
GC106	USGS	452102093521401	639981	GW–DO	45.35058	-93.87060	26–36	36
GC107	USGS	452130093575901	640199	GW–DO	45.35840	-93.96671	56–64	64
GC108	USGS	452222093501701	642037	GW–DO	45.37279	-93.83758	36–40	40
GC109	USGS	451903093481401	665803	GW–DO	45.31748	-93.80411	97–107	107
GC110	USGS	451742093415301	669910	GW–DO	45.29511	-93.69803	51–56	56
GC111	USGS	452050093514701	679507	GW–DO	45.34723	-93.86312	19–29	29
GC112	USGS	452057093521401	679530	GW–DO	45.34904	-93.87054	27–37	37
GC113	USGS	452421093591601	684090	GW–DO	45.40606	-93.98791	60–65	65
GC114	USGS	451854093525201	689992	OB–OTH	45.31489	-93.88106	29–34	34
GC115	USGS	452108093475101	690569	GW–DO	45.35233	-93.79709	75–80	80
GC116	USGS	452415093575801	690573	GW–DO	45.40406	-93.96546	64–69	69
GC117	USGS	452352094033801	690997	GW–DO	45.39764	-94.06061	73–78	78
GC118	USGS	452641093573801	693561	GW–DO	45.44483	-93.96058	72–77	77
GC119	USGS	452244093464301	693706	GW–DO	45.37876	-93.77884	45–55	55
GC120	USGS	452558093560801	705266	GW–DO	45.43258	-93.93568	50–54	54
GC121	USGS	451953093502801	706817	OB–OTH	45.33144	-93.84122	60–65	65
GC122	USGS	451918093484601	707598	GW–DO	45.32155	-93.81279	61–70	70
GC123	USGS	451630093341001	708372	OB–OTH	45.27429	-93.57076	11–21	21
GC124	USGS	451803093353901	709890	GW–DO	45.30098	-93.59419	65–85	85
GC125	USGS	452047093530801	711437	GW–DO	45.34630	-93.88557	88–93	93
GC126	USGS	452821093594101	713932	GW–DO	45.47242	-93.99453	25–35	35
GC127	USGS	452611093572701	718181	GW–DO	45.43635	-93.95738	77–81	81
GC128	USGS	451819093435701	718912	GW–DO	45.30541	-93.73264	76–84	84
GC129	USGS	452157093522001	722087	OB–OTH	45.36548	-93.88432	25–44	44
GC130	USGS	452529093581601	731085	GW–DO	45.42474	-93.97123	24–28	38
GC131	USGS	452311093560301	732408	GW–DO	45.38651	-93.93422	53–58	58
GC132	USGS	452223093505401	742339	GW–DO	45.37309	-93.84820	59–67	67
GC133	USGS	451943093504501	747059	OB–OTH	45.32958	-93.84563	21.49–31.49	31.49
GC134	USGS	452347093544301	747065	OB–OTH	45.39657	-93.91168	25–35	37
GC135	USGS	452421093592801	749053	GW–DO	45.40553	-93.99126	70–80	80
GC136	USGS	452129093512001	752256	GW–DO	45.35798	-93.85557	26–36	36
GC137	USGS	452108093510201	752257	GW–DO	45.35226	-93.85055	22–32	32
GC138	USGS	452051093510301	752258	GW–DO	45.34744	-93.85093	20–30	30
GC139	USGS	452049093520701	752259	GW–DO	45.34701	-93.86850	28–38	38
GC140	USGS	452010093582201	757198	GW–DO	45.33580	-93.97241	68–73	73
GC141	USGS	452014093523101	785281	GW–DO	45.33717	-93.87540	63–73	73
GC142	USGS	452655093590001	785600	GW–DO	45.44850	-93.98329	41–50	50
GC143	USGS	451955093502201	786216	OB–OTH	45.33189	-93.83952	34–38	38
GC144	USGS	452245093542501	--	OB–OTH	45.37918	-93.90686	44.49–64.49	64.49
ALUS–02	USGS	452428093591601	582132	OB–USGS	45.40744	-93.98669	14.86–19.86	19.86
ALUS–03	USGS	452545093571002	371006	OB–USGS	45.42943	-93.95335	34.91–36.91	36.91
ALUS–04	USGS	452610093553001	582131	OB–USGS	45.43594	-93.92537	7.33–12.33	12.33
ALUS–06	USGS	452711093565501	582134	OB–USGS	45.45255	-93.94947	9.5–14.5	14.5
ALUS–07	USGS	452609093553001	582135	OB–USGS	45.44370	-93.92131	10.66–15.66	15.66

Table 3. Records of wells in network for synoptic monitoring of groundwater levels, including site number, well type, latitude/longitude, screened intervals, and well depth.—Continued

[ID, identification; MUN, Minnesota unique well number; GW–DO, existing domestic well; USGS, U.S. Geological Survey; OB–OTH, non-U.S. Geological Survey observation well; OB–USGS, U.S. Geological Survey observation well; --, unknown]

Well ID	Agency code	Site number	MUN	Type	Latitude[1]	Longitude[1]	Screened interval[1]	Well depth[1]
ALUS–11	USGS	452229093525801	--	OB–OTH	45.37623	-93.88257	37.27–57.27	57.27
ALUS–12	USGS	451953093484901	582149	OB–USGS	45.33031	-93.81406	38–43	43
ALUS–13	USGS	452030093511403	612777	OB–USGS	45.34206	-93.85481	17.50–22.50	22.50
ALUS–18	USGS	452215093481001	582137	OB–USGS	45.37009	-93.80643	21.27–26.27	26.27
ALUS–19	USGS	452040093463101	582138	OB–USGS	45.34756	-93.77981	16.14–21.14	21.14
ALUS–20	USGS	451957093483201	582139	OB–USGS	45.33161	-93.81136	44.58–49.58	49.58
ALUS–21	USGS	451924093474601	582140	OB–USGS	45.32319	-93.79705	30.22–35.22	35.22
ALUS–22	USGS	451811093445601	582141	OB–USGS	45.30338	-93.74511	10.29–15.29	15.29
ALUS–24	USGS	451835093400401	582143	OB–USGS	45.30786	-93.67657	6.31–11.31	11.31
ALUS–25	USGS	451822093413201	582144	OB–USGS	45.30576	-93.68857	25.55–30.55	30.55
ALUS–27	USGS	451921093445101	582145	OB–USGS	45.32170	-93.74759	3.42–8.42	8.42
ALUS–29	USGS	451730093423001	582147	OB–USGS	45.33505	-93.70692	9.86–14.86	14.86
ALUS–30	USGS	452036093423701	582148	OB–USGS	45.34324	-93.71094	4.08–9.08	9.08
ALUS–31	USGS	452413093540701	685848	OB–USGS	45.40417	-93.90181	17.59–22.59	22.59
ALUS–32	USGS	451753093434801	685847	OB–USGS	45.29801	-93.73003	20.19–25.19	25.19
ALUS–33	USGS	452012093412701	685849	OB–USGS	45.33646	-93.69069	17.05–22.05	22.05
ALUS–34	USGS	452223093521801	722086	OB–OTH	45.37311	-93.87221	35.66–45.66	45.66
ALUS–35	USGS	452111093523402	620723	OB–USGS	45.35744	-93.88121	36.45–41.45	41.45
ALUS–36	USGS	452720093552203	201509	OB–USGS	45.45541	-93.92311	16.55–25.55	25.55
ALUS–37	USGS	452408093553002	620684	OB–USGS	45.40184	-93.92445	33.61–43.61	43.61

(lidar) digital elevation model with a 1-meter resolution at all sites (Minnesota Geospatial Information Office, 2015). Elevation data has accuracies of plus or minus 0.06 to 0.11 meters taken from estimates of nearby Anoka, Benton, and Meeker Counties (not shown).

The water level measurements, in depth below land surface, for the six synoptic surveys are listed in appendix 2. The data from water year 2013 are listed in table 2–1, and the data from water year 2014 are listed in table 2–2. Between 158 and 167 measurements were made during each of the six synoptic surveys. Dates were kept as close as possible to each other from year to year; however, the first water-level synoptic survey was done in May 2013 rather than March 2013 because all of the well owner permissions had not been received by March.

Groundwater Recharge, Based on RISE Water-Table Fluctuation Method

The continuous water-level data collected for this study were used to estimate groundwater recharge using a water-table fluctuation method (Delin and others, 2007; Lorenz, 2016). The selected water-table fluctuation method uses the RISE program to estimate recharge from the product of groundwater-level rises and specific yield. This approach is based upon the RISE method for computing recharge from Rutledge (1997, 2002), which was designed for analyzing a groundwater-flow system that is characterized by diffuse areal recharge to the water table. This method assumes that recharge can be restricted to small time increments in hydrologic settings with thin unsaturated zones (Rutledge, 2002), such as the unsaturated zone in the I–94 Corridor.

As part of the DVstats package (Lorenz, 2016) for the R statistical environment (RStudio Team, 2016), groundwater recharge was calculated based on first calculating the daily rise events during the course of the groundwater record and subsequently aggregating the rise events into recharge events based on a preset specific yield. The RISE program is used to analyze the record for groundwater-level rises, and a second R function, aggregate (also part of DVstats), sums up the rising portions of the groundwater rises and multiplies by the specific yield to calculate groundwater recharge. Based on the common surficial aquifer materials of gravelly sand in the study area, a specific yield value of 25 percent was used for all of the wells (Johnson, 1967).

Groundwater Recharge, Based on the Soil-Water-Balance (SWB) Model

The SWB model was used as a second method for estimating groundwater recharge in the I–94 Corridor. The SWB model uses a modified Thornthwaite-Mather soil-water-balance approach (Thornthwaite and Mather, 1955, 1957). The water-balance approach of SWB estimates potential recharge

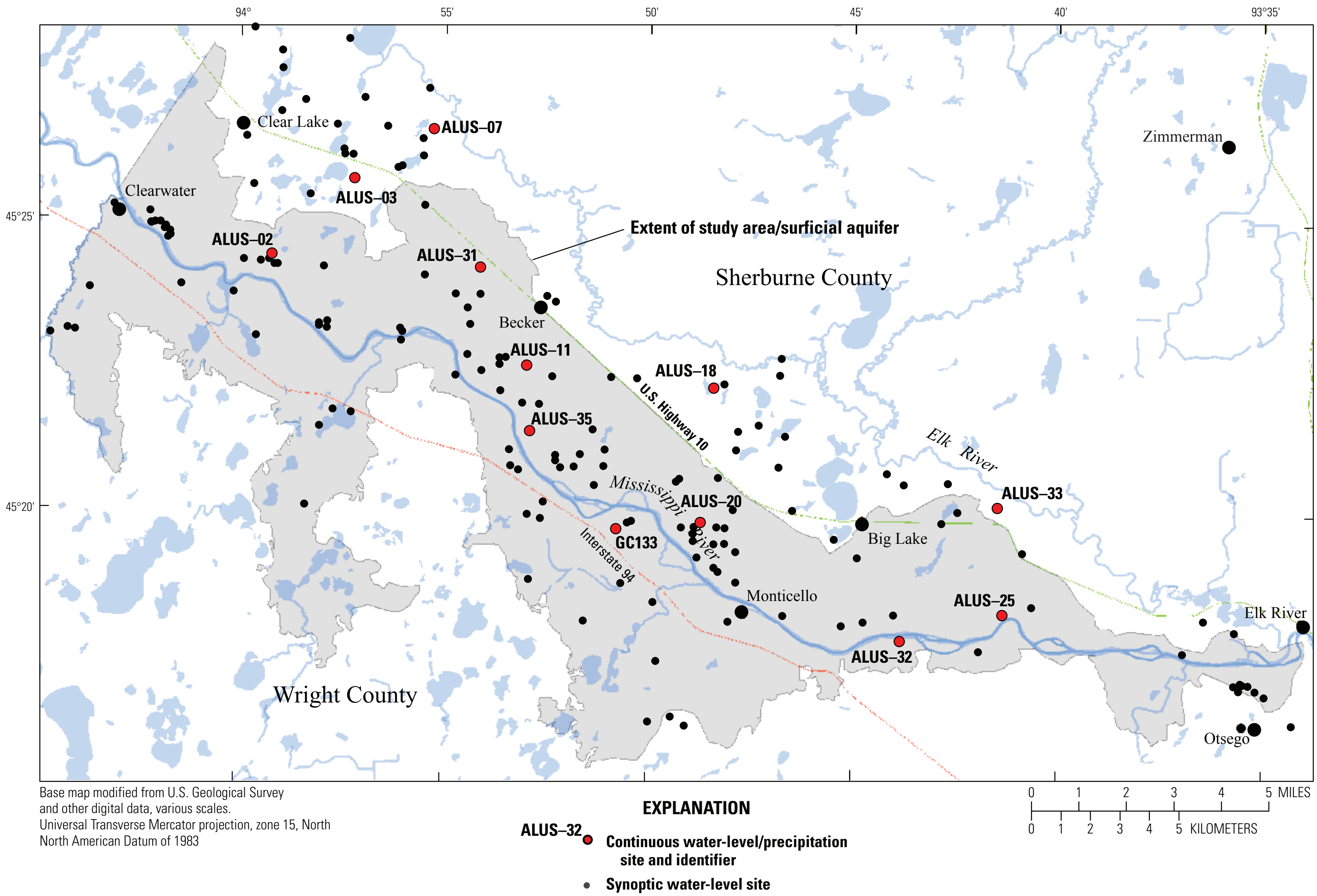


Figure 5. Continuous and synoptic water-level network, Interstate 94 Corridor study area, central Minnesota, 2012–14.

Table 4. Monthly total precipitation (in inches) data for the colocated precipitation gages, with monthly average rainfall for all available rainfall gages (in inches) with complete records. Also listed are the monthly total precipitation (in inches) data for the St. Cloud Regional Airport (U.S. Department of Commerce, 2015). Annual precipitation (in inches) data are listed for all complete records; annual precipitation (in inches) total without the period from November through March also are listed.

[ID, identification; --, no data; N.R., no record; P.R., partial record]

Well ID	Water year 2013													
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual precipitation, in inches	
	Precipitation, in inches												All 12 months	Without Nov.–Mar.
GC133	--	--	--	--	--	--	--	--	--	--	--	--	N.R.	N.R.
ALUS–02	--	--	--	--	--	--	1.93	4.18	5.04	2.51	1.10	1.65	P.R.	P.R.
ALUS–03	0.67	0.91	0.70	0.51	0.47	1.86	2.09	4.02	5.17	2.19	0.68	1.56	20.83	16.38
ALUS–07	0.65	0.90	0.68	0.55	0.62	1.97	2.46	4.16	4.86	1.74	0.64	1.75	20.98	16.26
ALUS–11	0.59	0.76	0.56	0.41	0.23	1.48	1.96	3.38	3.73	2.07	1.08	2.32	18.57	15.13
ALUS–18	0.59	0.77	0.73	0.51	0.79	1.83	2.28	3.22	4.03	2.75	0.85	2.59	20.94	16.31
ALUS–20	0.56	0.68	0.61	0.46	0.34	1.61	1.44	2.69	3.90	2.26	0.65	3.20	18.40	14.70
ALUS–25	0.86	0.74	0.69	0.60	0.51	1.64	2.07	2.80	4.58	3.30	0.72	2.77	21.28	17.10
ALUS–31	--	--	--	--	--	--	1.10	3.47	3.92	2.09	0.77	2.03	P.R.	P.R.
ALUS–32	0.69	0.91	0.55	0.62	0.72	1.82	2.62	3.01	4.85	3.68	0.91	3.79	24.17	19.55
ALUS–33	0.75	0.84	0.57	0.62	0.46	1.85	2.09	2.57	4.24	3.48	0.66	2.70	20.83	16.49
ALUS–35	--	--	--	--	--	--	--	--	--	--	--	--	N.R.	N.R.
Average for all precipitation gages with complete records	0.67	0.81	0.64	0.54	0.52	1.76	2.13	3.23	4.42	2.68	0.77	2.59	20.75	16.49
St. Cloud Regional Airport	0.73	1.05	1.51	0.45	1.33	2.63	2.90	4.98	5.76	1.43	0.85	1.87	25.49	18.52

Well ID	Water year 2014													
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual precipitation	
	Precipitation, in inches												All 12 months	Without Nov.–Mar.
GC133	--	--	--	0.25	0.24	0.72	5.07	8.02	6.89	2.20	5.32	3.58	P.R.	P.R.
ALUS–02	4.16	0.60	0.64	0.28	0.32	0.55	5.33	8.05	5.52	2.44	4.47	3.27	35.63	33.24
ALUS–03	3.62	0.62	0.63	0.18	0.27	0.60	5.99	9.72	5.86	1.78	3.72	2.56	35.55	33.25
ALUS–07	3.66	0.65	0.63	0.27	0.31	0.65	5.51	7.61	5.22	1.96	3.73	2.27	32.47	29.96
ALUS–11	3.65	0.71	0.35	0.12	0.23	0.52	5.66	7.73	5.31	3.15	4.42	2.04	33.89	31.96
ALUS–18	3.13	0.71	0.59	0.19	0.28	0.85	4.93	7.54	5.21	2.26	5.23	2.40	33.32	30.70
ALUS–20	3.39	0.68	0.43	0.14	0.10	0.63	4.35	8.72	6.65	2.11	5.28	3.39	35.87	33.89
ALUS–25	3.13	1.13	0.57	0.20	0.15	0.87	5.39	7.92	5.66	2.42	5.82	1.46	34.72	31.80
ALUS–31	3.18	0.54	0.38	0.22	0.23	0.40	5.08	10.02	5.07	2.20	4.35	1.98	33.65	31.88
ALUS–32	3.19	1.18	0.71	0.28	0.31	1.00	5.48	8.39	6.17	2.67	6.43	1.42	37.23	33.75
ALUS–33	3.16	1.28	0.75	0.27	0.42	0.81	5.22	8.64	5.40	2.00	6.35	2.30	36.60	33.07
ALUS–35	--	--	--	0.19	0.23	0.58	5.19	7.87	5.92	2.56	6.05	2.52	P.R.	P.R.
Average for all precipitation gages with complete records	3.43	0.81	0.57	0.22	0.26	0.69	5.29	8.43	5.61	2.30	4.98	2.31	34.89	32.35
St. Cloud Regional Airport	4.34	0.53	1.77	1.34	1.17	1.20	5.90	6.74	6.18	1.25	5.59	4.05	40.06	34.05

(Westenbroek and others, 2010) on a daily basis. The SWB model was used by Smith and Westenbroek (2015) to develop and publish gridded estimates of average potential groundwater recharge across Minnesota from 1996 through 2010 at a 1-kilometer (0.621-mile) resolution.

The SWB model uses a soil-water accounting method to calculate potential recharge for each grid cell in the model domain separately (Westenbroek and others, 2010). Computation of water-budget components relies on relations among surface runoff, land cover, hydrologic soil group, maximum soil-water capacity, evapotranspiration estimates, and temperature. Within the SWB approach, *potential recharge* is calculated within each grid cell of the model domain based on the difference among sources (*precipitation*, *snowmelt*, *inflow*), sinks (*interception*, *outflow*, *evapotranspiration*), and change in soil moisture (Δ*soil moisture*; eq. 3).

$$potential\ recharge = (precipitation + snowmelt + inflow) - (interception + evapotranspiration \quad (3)$$

Each of the water-budget components in equation 3 is handled by one or more modules within the SWB model. The *inflow* component (from adjacent cells) in the model was not included. Of the sinks, *evapotranspiration,* is handled by the model without user intervention, and only the Hargreaves-Samani *evapotranspiration* method (Hargreaves and Samani, 1985) is available for simulations with spatially varying gridded data. *Interception* is defined as the portion of precipitation intercepted by the plant canopy and lost to *evapotranspiration*; interception is controlled by user-defined values for each unique land-cover class in a lookup table. *Outflow* from each grid cell, also known as surface runoff, is calculated by the Natural Resources Conservation Service curve number rainfall-runoff relation (Cronshey and others, 1986). Changes in soil moisture (Δ*soil moisture*) are tabulated by the soil-water-balance methods published by Thornthwaite and Mather (1955, 1957) by using intermediary values. These changes in soil moisture are tabulated on a daily time step.

Additional theoretical and background details on *outflow* and the other hydrologic components were described by Westenbroek and others (2010). Further details pertaining to the Minnesota SWB model were included in Smith and Westenbroek (2015), particularly the calibration process for the soil and land-cover lookup table. The soil and land-cover lookup table cross-references the 15 land-cover classes in Minnesota to the 5 soil classes to assign the dimensionless curve number (Cronshey and others, 1986), the maximum recharge rate (inches per day), and the root-zone depth (feet). Additional information includes the interception storage values (inches) for the growing season and the dormant season.

For this report, the published statewide SWB model (Smith and Westenbroek, 2015) was re-run for the period 2010–14 to include the period of record for this study, including necessary climatic data such as daily precipitation, minimum daily temperature, and maximum daily temperature (Smith, 2017). All meteorological data were provided by the Daymet dataset, which included daily continuous surfaces of key climatological data (Thornton and others, 2014). Land-use was updated to NLCD–2011 (fig. 2) and the grid resolution was refined to 100-meter grid cells, including the other inputs such as the hydrologic soil groups and available soil-water capacity. All other parts for the I–94 Corridor re-run, including the calibrated lookup table for the Minnesota statewide potential recharge model (Smith and Westenbroek, 2015), were the same for this SWB application. The SWB model results were used for the following two purposes: (1) to compare extracted SWB potential recharge rates to water-level sites with available RISE recharge estimates and (2) to use SWB potential recharge rates as input for the water balance calculations.

Evapotranspiration Calculation

The ET_0 was calculated by the FAO Penman-Monteith method (Allen and others, 1998). Hourly climate data required for the ET_0 were obtained from a SCAN station, operated by the U.S. Department of Agriculture (2016b), Natural Resources Conservation Service, near the center of the study area. The FAO Penman-Monteith method is (eq. 4):

$$ET_0 = \frac{0.408\left(R_n - G\right) + \gamma \frac{900}{T+273} u_2 \left(e_s - e_a\right)}{+\gamma\left(1 + 0.34u_2\right)} \quad (4)$$

where

- ET_0 is reference evapotranspiration, in millimeters per day;
- Δ is slope vapor pressure curve, in kilopascals per degree Celsius;
- R_n is net radiation at the crop surface, in megajoules per meter per day;
- G is soil heat flux density, in megajoules per meter per day;
- γ is the psychrometric constant, in kilopascals per degree Celsius;
- T is mean daily air temperature at 2 meters height, in degrees Celsius;
- u_2 is wind speed at 2 meters height, in meters per second;
- e_s is saturation vapor pressure, in kilopascals; and
- e_a is actual vapor pressure, in kilopascals.

Daily evapotranspiration calculations were calculated from September 1, 2012, through November 30, 2014, for comparisons to the groundwater balances. Hourly evapotranspiration calculations were calculated for September 13, 2012, during the low-flow groundwater discharge estimate.

Surficial Aquifer Extent and Volume

The areal extent and the estimated volume of the surficial aquifer was derived for Sherburne and Wright Counties by using information from the County Geologic Atlases (part A).

The County Geologic Atlases include surficial geologic maps that depict the properties of the geologic materials that exist at the land surface (Setterholm, 2014). Atlases also include Quaternary subsurface geology maps that illustrate the geologic units associated with glaciation during the last 2 million years and modern processes (Setterholm, 2014).

As described in the “Hydrologic Setting” section, the Quaternary history is complicated for the I–94 Corridor. To include all of the surficial aquifer units that are likely a part of the surficial aquifer, a variety of information was used from each County Geologic Atlas (part A). Several plates are included with each county atlas; of the included plates, the surficial geology (Sherburne County [Lusardi and Adams, 2013]; Wright County [Hobbs, 2013]), the Quaternary stratigraphy (Sherburne County [Lusardi, 2013]; Wright County [Knaeble, 2013]), and the sand distribution model (Sherburne County [Lusardi and Lively, 2013]; Wright County [Knaeble and others, 2013]) plates all included information necessary for determining the aquifer areal extent and volume. Also included are raster surfaces of all of the geologic units described within the County Geologic Atlas (part A); these raster surfaces were useful for creating the combined surficial aquifer.

The surficial aquifer volumetric calculation was used to develop the water balance and could be considered an initial approach to groundwater flow modeling for the I–94 Corridor. As one of the primary objectives of this report, only the contributing area of groundwater discharge to the Mississippi River was important within the I–94 Corridor water balance. Therefore, portions that would likely flow away from the Mississippi River were not included.

Within the study area, several geologic formations were primarily sand and gravel; however, many of the sand and gravel units were from different glaciations. Because of the complex geological history of the region, these units were often divided by interbedded tills that impede vertical flow. However, based on interpretations from the various parts of the County Geologic Atlases, many of these interbedded tills were not continuous. For calculating the aquifer thicknesses, the interbedded tills that were not primarily sand and gravel were excluded. Instead, the sand and gravel units were added together and presented as one continuous unit. For the lower boundary of the surficial aquifer, the boundary was determined either as a fairly continuous till layer or the bedrock layer.

This simple conceptual model, although not the reality of the more complex geology, gives an initial estimate of the surficial aquifer thickness. Combined with the potentiometric-surface maps presented later in the report, the saturated thickness of the surficial aquifer can then be estimated. This estimate, however, does not indicate that all of the water in these units was available for groundwater withdrawal or that the water in the till layers was not available for groundwater withdrawal. However, given the inherent variability in this complex geology, without further modeling or geophysical exploration as to detect the true behavior of this complicated glacial geology, this estimate is sufficient for the purposes of this study.

Because the two sides of the Mississippi River were part of different atlases, different approaches were used to determine the aquifer extent and volume for each side of the river. Also, because atlases often were completed by different teams, the interpretation of unit boundaries could differ slightly, and units might not be contiguous (Setterholm, 2014). Between the two sides of the Mississippi River, the underlying geology in Wright County was more complex, but the complexity of subsurface units was partially a function of the amount of data available (Knaeble and others, 2013). If data were scarce, the cross-section units were generally modeled as continuous, with generally uniform thicknesses and minimal elevation change. With more data, the cross-section units were frequently modeled as discontinuous and variable in thickness, which reflected more accurately the complexity of glacial deposits (Knaeble and others, 2013).

Starting with the Sherburne County side of the Mississippi River, the surficial aquifer areal extent was based mainly on the HUC–12 boundaries (U.S. Department of Agriculture, 2016a) between the Elk River and the Mississippi River (fairly close to U.S. Highway 10), as shown in figure 6. For the surficial aquifer thickness, all of the sand layers on Sherburne County side were included; rasters were added together in ArcGIS and were a part of the surficial aquifer thickness map in figure 6. The following is a list of the units (and corresponding unit abbreviations) that were included for the surficial aquifer areal extent and the volume (Lusardi, 2013): sandy surface sediments (ss), New Brighton formation sandy glacial lake deposits (nbs), New Ulm formation sand and gravel (ns), Automba Phase sand and gravel (csa), St. Croix Phase sand and gravel (csr), Emerald Phase sand and gravel (cse), Sauk Centre Member sand and gravel (scs), Meyer Lake Member sand and gravel (mls), the St. Francis Formation sand and gravels (fs1, fs2), and the unknown sand and gravel units (suu).

On the Wright County side of the I–94 Corridor, the boundary condition was more difficult to interpret on the portions of the surficial aquifer that directly flow towards the Mississippi River. Also, the surficial aquifer was much thinner on the Wright County side than on the Sherburne County side. The following is a list of the units (and corresponding unit abbreviations) that were included for only the surficial aquifer (Knaeble, 2013): Holocene sand and pebbly sand (ha), Late Wisconsinan sand and gravelly sand (wmt), Heiberg Member sand (nhs), Villard and Twin Cities Members sand and gravel (nts), Moland Member sand and gravel (ms), Cromwell Formation sand and gravel outwash (cg, cg1), Hewitt Formation sand and gravel (hs), Sauk Centre sand and gravel (scs), Meyer Lake Member sand and gravel (mls), Unnamed Superior provenance sand and gravel (prs), unnamed sand and gravel deposits (pws), undifferentiated sand and gravel (psu), and basal sand and gravel (zus). sandy surface sediments (ss), New Brighton formation sandy glacial lake deposits (nbs), New Ulm formation sand and gravel (ns), Automba Phase sand and gravel (csa), St. Croix Phase sand and gravel (csr), Emerald Phase sand and gravel (cse), Sauk Centre Member sand and gravel (scs), Meyer Lake Member sand and gravel

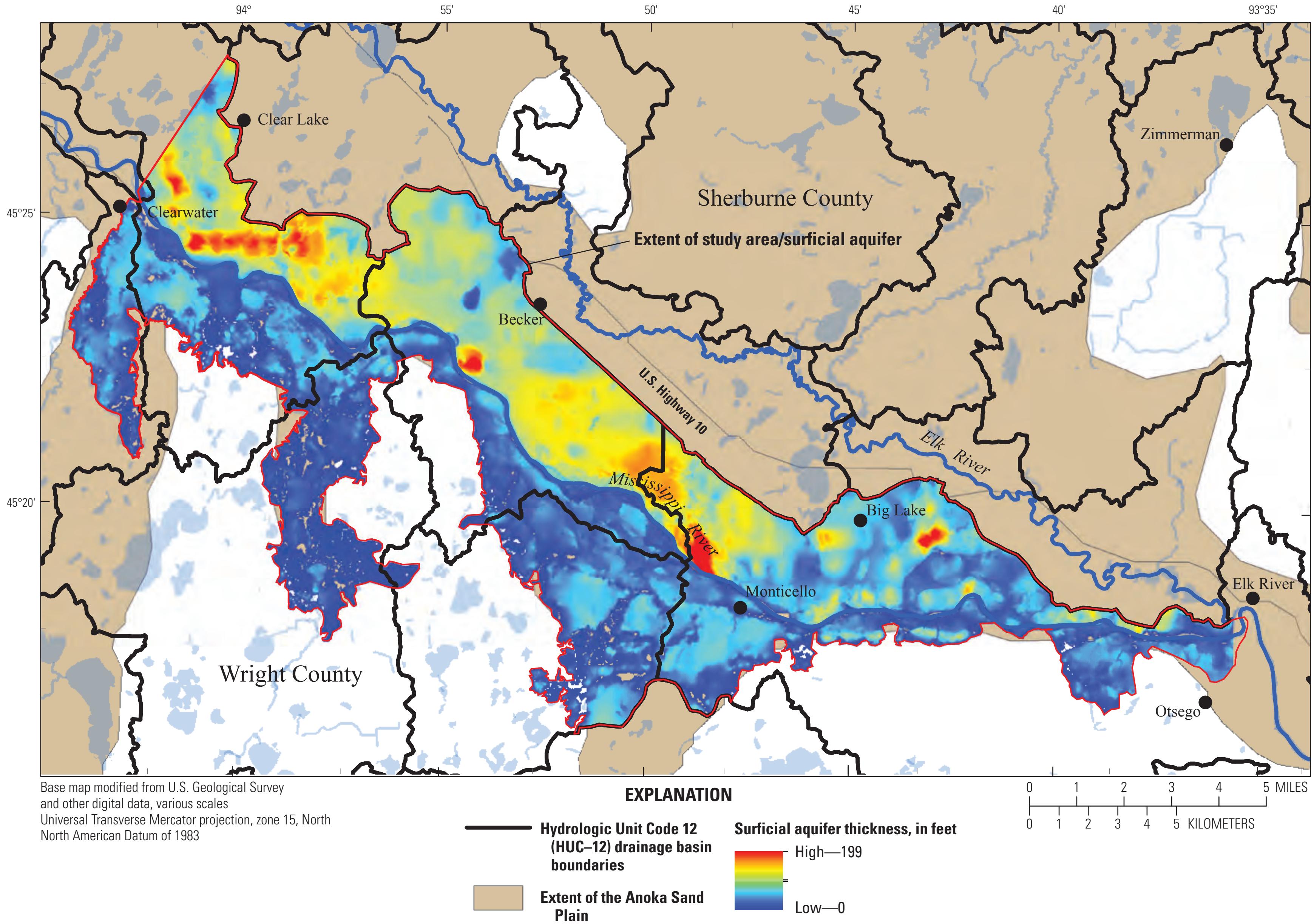


Figure 6. The surficial aquifer thickness, as determined from the sand distribution models for Sherburne (Lusardi and Lively, 2013) and Wright (Knaeble and others, 2013) Counties, as part of the respective County Geologic Atlases for both counties. Also included are the Hydrologic Unit Code 12 (HUC–12) divides (U.S. Department of Agriculture, 2016a) and the extent of the Anoka Sand Plain.

(mls), the St. Francis Formation sand and gravels (fs1, fs2), and the unknown sand and gravel units (suu). The following is a list of units (and corresponding unit abbreviations) that were included for only the surficial areal extent (Knaeble, 2013): Holocene sand and pebbly sand (ha), Late Wisconsinan sand and gravelly sand (wmt), Heiberg Member sand (nhs), and the Villard and Twin Cities Members sand and gravel (nts).

The surficial aquifer thickness map (fig. 6) also illustrates the surficial aquifer extent used for the groundwater balance and the determination of the I–94 Corridor, shown in the previous figures (figs. 1–5). Although the upstream and downstream boundaries of the I–94 Corridor were somewhat arbitrary, the original design for the study area was based upon the upper end of the groundwater discharge estimates (in Clearwater, Minn.) and the lower end as the confluence of the Elk and Mississippi Rivers. Otherwise, as mentioned earlier, the HUC–12 boundaries were used to help determine the extent on each side of the Mississippi River.

Potentiometric Surfaces and Difference Maps for the Surficial Aquifer

Potentiometric-surface maps for the calendar years 2013–14 water-level synoptic surveys were constructed for the surficial aquifer system. For the duration of the study period, six potentiometric-surface maps were constructed and are presented in the "Surficial Aquifer Potentiometric Surfaces" section; the groundwater-level measurements used to construct the potentiometric-surface maps are presented in table 2–1 (2013) and table 2–2 (2014).

The potentiometric-surface maps were created with data points from four sources. The methods used were similar to previous studies (Cowdery and others, 2008; Sanocki and others, 2009) and are outlined as follows: (1) groundwater levels were measured; (2) water levels were derived from river surface elevations where aquifers discharge to river systems, in particular the Mississippi River and Elk River; (3) water levels were derived from surface-water elevations, mainly lakes and prominent wetlands, where the water table is likely exhibited at the land surface; and (4) static groundwater levels were obtained from MWI data (Minnesota Department of Health, 2016). The MWI static groundwater levels were selected for the surficial aquifer as a means of bordering the potentiometric-surface interpolation to avoid truncation or artificial surfaces along the edges of the potentiometric-surface maps. The same MWI static groundwater levels were used for all six potentiometric-surface maps and were all outside of the I–94 Corridor. Static groundwater levels from MWI wells were compared to groundwater levels from the measured wells to identify and remove outliers. This process was used to produce a study area estimation of the potentiometric surface, fully based on measured groundwater levels. Likewise, river, lake, and wetland surface elevations were derived from lidar and assumed to be the same for all six potentiometric-surface maps. Although the river surface elevations change with time, the goals of the potentiometric-surface maps were to provide a static surficial aquifer potentiometric surface in time and to construct difference maps among different surficial aquifer potentiometric-surface maps to help understand changes in the aquifer volume with time.

ArcGIS 10.2 ModelBuilder (Environmental Systems Research Institute, 2015) was used to combine the four data point sources and build a water table tool using the natural neighbor interpolation in order to generate a raster representation of each potentiometric surface to generate a raster representation of each potentiometric surface (Sanocki and others, 2009). The raster calculator was used to avoid artificially drawing the potentiometric surface above land surface, and this raster surface was used to generate contours in ArcGIS. The final contours were edited to eliminate water-level measurements that caused artificially large peaks and holes; only a few wells were eliminated with this process. In addition, wells were eliminated from all other potentiometric-surface maps to remain consistent throughout the difference maps. These difference maps, or seasonal groundwater-level change maps, were constructed between seasons during calendar years 2013–14.

Water Balance

Seasonal and annual groundwater balances for the I–94 Corridor surficial aquifer were similar to the approach of equation 2 and to applying similar groundwater balance principles as applied to the Glacial Ridge National Wildlife Refuge (not shown; Cowdery and others, 2008). The groundwater balance was an estimate of all inputs and outputs. Inputs included precipitation, return flow, and groundwater inflow from buried aquifers. Outputs included evapotranspiration, groundwater pumping, groundwater discharge to surface water, and groundwater outflow to buried aquifers. All of the inputs and outputs were equal to a change in storage (ΔS) (eq. 5).

$$(V_{pre} + V_{rf,\ irr\text{-}surf} + V_{rf,\ irr\text{-}nonsurf} + V_{sr,\ dom\text{-}all} + V_{sr,\ ws\text{-}surf} + V_{sr,\ ws\text{-}nonsurf}) - (V_{et} + V_{p,\ permit} + V_{p,\ domestic} + V_{gw}) - V_{o,\ ba} + V_{i,\ ba} = \Delta S, \quad (5)$$

where

V_{pre} is incoming precipitation;

$V_{rf,\ irr\text{-}surf}$ is volume of irrigation return flow, pulled from the surficial aquifer;

$V_{rf,\ irr\text{-}nonsurf}$ is volume of irrigation return flow, pulled from the nonsurficial aquifers;

$V_{sr,\ dom\text{-}all}$ is volume of septic return flow, from domestic usage wells in the surficial aquifer;

$V_{sr,\ ws\text{-}surf}$ is volume of water supply septic return flow, pulled from the surficial aquifer;

$V_{sr,\ ws\text{-}nonsurf}$ is volume of water supply septic return flow, pulled from the nonsurficial aquifers;

V_{et} is volume of water for evapotranspiration;

$V_{p,\ permit}$ is volume of groundwater, pulled from permitted surficial aquifer groundwater wells;

$V_{p,\ domestic}$ is volume of groundwater, estimated from surficial aquifer domestic water usage;
V_{gw} is groundwater discharge to the Mississippi River;
$V_{o,\ ba}$ is volume of outflow to buried aquifers;
$V_{i,\ ba}$ is volume of inflow from buried aquifers; and
ΔS is change in storage.

Incoming precipitation (V_{pre}) minus evapotranspiration (V_{et}) was substituted with groundwater recharge ($V_{recharge}$). The change in storage (D*S*) was calculated as the difference in the potentiometric surface between two synoptic measurements.

An additional assumption for the groundwater balance was that the net flow between the surficial aquifer and the buried aquifers was zero, because direct measurements of the net flux between these aquifer bodies or indirect calculations from a groundwater-flow model do not currently [2017] exist. Because change in storage (D*S*) was known between two synoptic measurements, equation 5 was rearranged to solve for the groundwater discharge (V_{gw}) to the Mississippi River and then compared to the September 13, 2012, measurement (eq. 6).

$$\Delta S - (V_{recharge} + V_{rf,\ irr\text{-}surf} + V_{rf,\ irr\text{-}nonsurf} + V_{sr,\ dom\text{-}all} + V_{sr,\ ws\text{-}surf} + V_{sr,\ ws\text{-}nonsurf}) + (V_{p,\ permit} + V_{p,\ domestic}) = V_{gw}, \quad (6)$$

where

ΔS is change in storage;
$V_{recharge}$ is groundwater recharge, based on the extracted SWB potential recharge rates;
$V_{rf,\ irr\text{-}surf}$ is volume of irrigation return flow, pulled from the surficial aquifer;
$V_{rf,\ irr\text{-}nonsurf}$ is volume of irrigation return flow, pulled from the nonsurficial aquifers;
$V_{sr,\ dom\text{-}all}$ is volume of septic return flow, from domestic usage wells in the surficial aquifer;
$V_{sr,\ ws\text{-}surf}$ is volume of water supply septic return flow, pulled from the surficial aquifer;
$V_{sr,\ ws\text{-}nonsurf}$ is volume of water supply septic return flow, pulled from the nonsurficial aquifers;
$V_{p,\ permit}$ is volume of groundwater, pulled from permitted surficial aquifer groundwater wells;
$V_{p,\ domestic}$ is volume of groundwater, estimated from surficial aquifer domestic water usage; and
V_{gw} is groundwater discharge to the Mississippi River.

All of the irrigation return flows, from the surficial aquifer (table 1–1) and buried aquifers (table 1–2), were assumed to return 50 percent of the reported water usage. Return flow measurements did not exist for use in this study; therefore, a medium-range estimate of return flow was applied for the all irrigation return flow. For the 1987 national water summary (Carr and others, 1990), irrigation return flow for all sources was reported as 46.1 percent. However, estimates of return flows nationwide were discontinued after 1995 (Maupin and others, 2014), and return flows are known to vary spatially and temporally (Carr and others, 1990; Maupin and others, 2014). For domestic water usage, the self-supplied per capita use (in gallons per day) of 70 gallons per day for Minnesota was applied (Maupin and others, 2014). Based on assumptions from Carr and others (1990), an estimated 80.5 percent of self-supplied domestic water use and reported municipal water supply is return flow, on average, with the remaining 19.5 percent as consumptive use. All domestic wells were assumed to have four persons per well.

Groundwater Discharge to the Mississippi River

The groundwater discharge to the Mississippi River was computed on September 13, 2012, for a reach of the Mississippi River between the cities of Clearwater and Becker, Minn. (fig. 4). The selected reach was long enough to receive a measurable amount of groundwater discharge, was mostly free of islands, and had a small amount of water flowing in from tributaries. An analysis of variance of the corrected streamflow for the study reach indicated that the difference in flow was significant at the 5 percent alpha level, and a significant gain of 48.1 ft^3/s was along the 9.2-mile reach, for an average gain of 5.23 $ft^3/s/mi$.

The surface area of the reach was used for computing the FAO Penman-Monteith ET_0 (Allen and others, 1998) and change in storage. Because the change in stage was zero at all six temporary pressure transducers, the change in storage also was zero. An approximation of the total surface area was made by extrapolating the decrease in the surface area measured by RTK–GPS from the surface area determined from historical aerial photography. Although the difference between the RTK–GPS and the aerial photography was less than 5 percent, the correction factor was still applied to calculate an accurate total surface area for the September 13, 2012, measurement. Hourly FAO Penman-Monteith ET_0 calculations for September 13, 2012, are summarized in table 3–1; daily FAO Penman-Monteith ET_0 calculations for September 1, 2012, through November 30, 2014, are summarized in table 3–2.

The difference between each measured flow and the overall mean flow for each measurement section was computed to determine any instrument bias. The mean measured flow at each reach was used because the flow or storage did not change for the duration of the evaluation. An analysis of variance indicated that the difference among the five ADCPs was significant, so each individual measurement was adjusted by the amount listed in table 5. With these adjustments, the mean outflow was 2,176.5 ft^3/s (downstream) and the mean inflow was 2,128.4 ft^3/s (upstream), as shown in figure 7. By difference, the gain through the river section was 48.1 ft^3/s, with 95 percent confidence intervals of 33.7 ft^3/s and 62.6 ft^3/s. All uncorrected and corrected streamflow measurements listed in table 4–1.

Table 5. Acoustic Doppler current profiler (ADCP) measurement corrections, in cubic feet per second, listed by each ADCP serial number used for the September 13, 2012 streamflow measurements.

ADCP serial number	Correction, in cubic feet per second
399	9
789	7
851	14
1013	-25
1168	-19

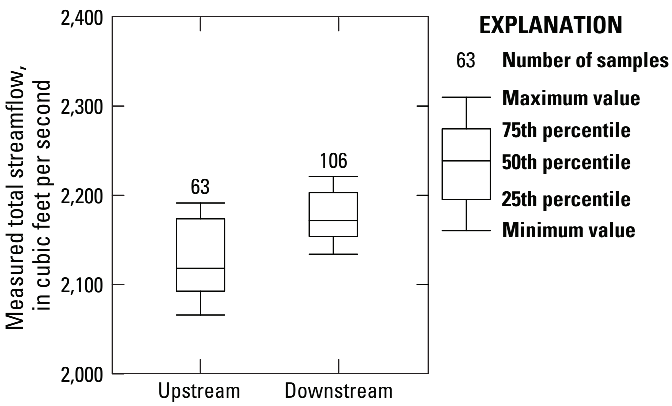


Figure 7. Truncated box plot (10th and 90th percentile) showing the overall mean flow in cubic feet per second for the upstream (A and B) transects and downstream (C and D) transects. Total number of measurements for the two locations are shown at the top.

The average gain of 5.23 ft^3/s/mi for the 9.2-mile reach was comparable to previous indirect groundwater discharge estimates to the Mississippi River in the reach from St. Cloud to the Twin Cities, including Lindholm (1980) and Payne (1995). Measured gains ranging from 2.5 to 4.9 ft^3/s/mi were reported by Lindholm (1980), and a measured gain of 2.59 ft^3/s/mi based on three low-flow periods from 1969 to 1976 was reported by Payne (1995). Farther upstream in Morrison County, model-derived groundwater discharge to the Mississippi River ranging from 0.3 to 2.85 ft^3/s/mi was reported by Helgesen (1973). The average gain from this study on September 13, 2012, is the first published attempt at a direct measurement of Mississippi River groundwater discharge.

Groundwater Balances for the Interstate 94 Corridor Surficial Aquifer

Seasonal and annual groundwater balances were calculated for the I–94 Corridor surficial aquifer. Groundwater balances can provide a means for evaluating the sustainability of a water supply (Healy and others, 2007). A water balance simply states that the rate of change in water stored in an area, such as a watershed, is balanced by the rate at which water flows into and out of the area. For the I–94 Corridor, an acceptable level of groundwater drawdown in order to meet regional groundwater demand could temporarily reduce groundwater base flow to the nearby surface-water bodies (Alley and others, 1999), in particular the Mississippi River.

As a precursor to the groundwater balances, all of the groundwater balance components, such as precipitation, evapotranspiration, recharge, and water use, were collected or calculated. Additionally, surficial aquifer potentiometric-surface maps were constructed. The differences between surficial aquifer potentiometric-surface maps from different time periods were used as an approximation of the changes in water storage.

Groundwater Levels, Evapotranspiration, Precipitation, and Water Use

Continuous groundwater levels were collected for 12 wells (water-level sites) throughout the I–94 Corridor (fig. 5); each water year had at least 10 wells with complete records. Because transducers were relocated during the study, two wells had incomplete records. Selection of wells were made based upon maximizing areal extent in an attempt to account for potential heterogeneity in the surficial aquifer of the study area.

The water table represented by continuous groundwater levels ranged from 7.2 to 45.5 feet below land surface (fig. 8). In late June 2014, after a 3-month period beginning in early April 2014, water elevations generally were the highest, by about 4.8 feet (fig. 8). Although no active continuous water-level gages of lakes and wetlands were across the study area, the water table approached zero where the surficial aquifer was in hydrologic contact with a wetland or lake. Therefore, in many cases, the water table surface tended to mimic the topography in the I–94 Corridor, a common characteristic of shallow surficial aquifers (Winter and others, 1998). For example, one well close to an ephemeral wetland (ALUS–07; USGS 452609093553001) generally had the shallowest water table elevation of the 12 continuous groundwater levels. The other well with a shallow table elevation, ALUS–32 (USGS 451753093434801), was within about 200 meters of the Mississippi River. The water levels in ALUS–32 tended to rise and fall more frequently and faster than the other wells, likely because of its contact with the Mississippi River.

In water years 2013 and 2014, water levels started rising in early April and reached peak levels in late June to mid-July. Groundwater rises were more subdued in water year 2013 than in water year 2014, which reflected the lack of precipitation in 2013 compared to 2014 (table 4; fig. 8). Water levels rose by an average of 1.62 feet in water year 2013 and by an average of 4.81 feet in water year 2014 (fig. 8). Average precipitation throughout the I–94 Corridor from April through September was 15.58 inches in 2013 and 28.92 inches in 2014. In water years 2013 and 2014, groundwater levels also declined rapidly

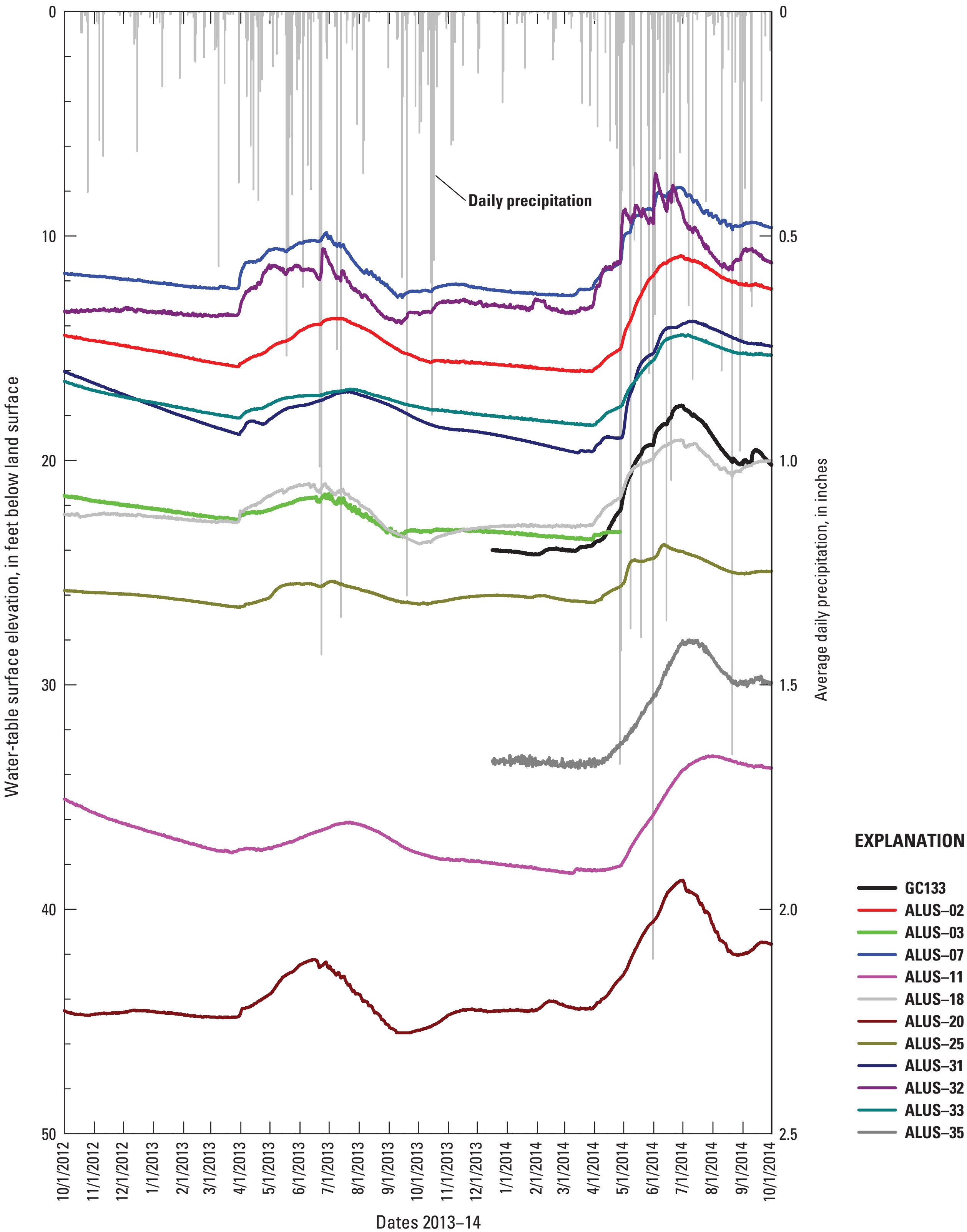


Figure 8. Water table surface elevation, in feet below land surface, for the 12 continuous groundwater-level records for water years 2013–14 in the Interstate 94 Corridor. An average daily precipitation of the 12 colocated precipitation gages with complete records also is shown in inches.

after reaching peak levels. The lowest groundwater levels were measured from mid-September to mid-October. These lower groundwater levels were partially attributable to less precipitation and the elevated evapotranspiration rates during these months. Although more precipitation fell in water year 2014 than in water year 2013, water levels declined at nearly the same rate in 2014 (1.74 feet) as in 2013 (1.91 feet).

Evapotranspiration rates from April through September were similar in 2013 and 2014. The ET_0 for the 2013 and 2014 growing seasons (May through September) was 32.6 inches and 33.0 inches, respectively. The largest difference between water year 2013 and water year 2014 was the amount of rain. Increased precipitation in 2014 led to increased aquifer replenishment and groundwater recharge of the surficial aquifer from April to early July 2014. When the evapotranspiration reached its highest levels in the summer, the aquifer depletion, which was within less than 0.2 feet between 2013 and 2014, led to shallower water table elevations in November 2014 compared to April 2014. For the same period a year earlier, however, water table elevations in November 2013 were similar to water table elevations in April 2013.

With nearly the same potential evapotranspiration during both growing seasons, average precipitation from July through September was 6.04 inches in water year 2013 and 9.59 inches in water year 2014 (table 4), based on the average for all precipitation gages with complete records. Groundwater levels declined nearly at the same rate, so part of the difference between 2013 and 2014 likely was a result of differences in pumping rates and irrigation. In calendar year 2013, water was withdrawn at a rate of approximately 3,014.4 Mgal/yr from surficial aquifer sources underlying the I–94 Corridor (table 1–1). In calendar year 2014, water was withdrawn at a rate of approximately 2,118.9 Mgal/yr from surficial aquifer sources underlying the I–94 Corridor (table 1–1). Because 2013 was a drier year than 2014, water use from the permitted wells was inversely proportional to precipitation, particularly in August. For example, water use was 29.7 percent less in calendar year 2014 than in calendar year 2013. In August 2014, water use was 41.9 percent less than August 2013; permitted water use from table 1–1 was 1,062.2 million gallons (Mgal) and 617.4 Mgal for August 2013 and August 2014, respectively.

Irrigation might have supplemented surficial aquifer water levels in 2013 and prevented water levels from declining more substantially from mid-summer to fall. This seems counterintuitive given the general assumption that irrigation causes further drawdown of the surficial aquifer; however, a substantial proportion of irrigation (approximately one-half) in the I–94 Corridor is from buried aquifer sources that might be limited in hydrologic connections to the surficial aquifer. Therefore, irrigation return flow sourced from the buried aquifer could have supplemented the surficial aquifer in 2013. In addition to supplementing crop growth and unsaturated zone moisture deficits, surficial and buried aquifer irrigation also might have supplemented the area of the unsaturated zone below the root zone to the surface of the water table to allow for less drawdown despite the drier conditions.

Groundwater Recharge

For this study, two methods were used to derive recharge rates to the surficial aquifer. In the context of the groundwater recharge rates derived for this study, recharge to the surficial aquifer was from the vertical infiltration of precipitation and snowmelt (areal recharge). Other recharge sources could be from surface waters, such as ephemeral wetlands, and the upward leakage of water from the buried aquifers; however, in this study, other methods were not available to define recharge from these other sources.

Recharge was estimated from the continuous hydrographs of 12 wells (water-level sites) in the surficial aquifer using the RISE program (Lorenz, 2016). Water year 2013 had 10 wells with complete records (11–12 months with monthly recharge rates), and water year 2014 had 11 wells with complete records (9–12 months with monthly recharge rates) (table 6). The monthly threshold for a complete record was lower for water year 2014 because 2 of the 12 wells were only missing data in the winter when recharge would be minimal or nonexistent.

The monthly groundwater recharge rates calculated using the RISE program and aggregate functions (Lorenz, 2016), including a summary of annual recharge rates, are listed in table 6. Given that recharge is unlikely during the winter, the nonwinter groundwater recharge rates were considered more realistic estimates of groundwater recharge rates and also are summarized in table 6. Well ALUS–32 likely was affected by water levels in the Mississippi River. Therefore, recharged estimates that include ALUS–32 may not accurately represent recharge from the surficial aquifer. Excluding ALUS–32, the annual, nonwinter recharge rates for water year 2013 ranged from 3.87 to 11.91 inches per year (table 6).

For water year 2014, nonwinter groundwater recharge rates ranged from 3.30 to 11.25 inches per year (excluding ALUS–32). Although precipitation increased during water year 2014, recharge rates are nearly identical to rates calculated for water year 2013. Because precipitation in water year 2013 was less than in water year 2014 (table 4), groundwater recharge rates were expected to be much lower in water year 2013 than in water year 2014. Recharge rates, however, were not much lower in 2013 than in 2014.

The SWB model (Westenbroek and others, 2010) also was used to estimate groundwater recharge rates for the I–94 Corridor. As discussed in the “Methods” section, the statewide SWB model (Smith and Westenbroek, 2015) was used to extract groundwater recharge rates for the different wells to compare methods and determine the water balances discussed later in this report. For this study, the statewide potential recharge model (Smith and Westenbroek, 2015) was updated to include climatological data through 2014 and had a finer grid resolution of 100 meters rather than 1 kilometer (Smith, 2017).

Table 6. Calculated groundwater recharge rates, based upon the RISE program (Rutledge, 2002; Delin and others, 2007). Only months with continuous monitoring data are listed. All calculations were completed using the R version of the RISE program and aggregate function, both included in the DVstats package (Lorenz, 2016).

[ID, identification; --, no data; N.R., no record; P.R., partial record]

Well ID	Water year 2013													
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual precipitation, in inches	
	Precipitation, in inches												All 12 months	Without Nov.–Mar.
GC13	--	--	--	--	--	--	--	--	--	--	--	--	N.R.	N.R.
ALUS–02	0.99	0.81	0.84	0.99	0.78	0.69	0.03	0	0.03	1.08	2.43	1.89	10.56	6.45
ALUS–03	0.81	0.72	0.69	0.93	0.69	0.54	0.27	0	0.99	4.44	3.60	1.50	15.18	11.61
ALUS–07	0.60	0.63	0.60	0.69	0.57	0.42	0.12	0.45	0.90	4.68	3.66	1.50	14.82	11.91
ALUS–11	1.20	1.92	1.44	1.29	1.11	0.81	0.51	0.15	0.00	0.30	1.83	2.01	12.57	6.00
ALUS–18	0.69	0.63	0.72	0.90	0.78	0.57	0	0.39	1.89	2.64	3.48	--	12.69	9.09
ALUS–20	0.72	0.27	0.36	0.75	0.51	3.00	0.03	0	1.74	4.23	4.26	--	15.87	10.98
ALUS–25	0.30	0.27	0.33	0.48	0.51	0.48	0	0	0.45	1.02	1.32	0.75	5.94	3.87
ALUS–31	1.59	1.47	1.50	1.47	1.23	1.14	0.39	0	0.03	0.36	1.41	1.95	12.54	5.73
ALUS–32	0.78	1.02	1.38	1.47	0.99	0.75	0.30	1.71	3.36	5.52	3.87	0.93	22.08	16.47
ALUS–33	1.23	0.90	0.78	0.87	0.69	0.66	0.09	0.03	0.12	0.15	1.20	1.05	7.77	3.87
ALUS–35	--	--	--	--	--	--	--	--	--	--	--	--	N.R.	N.R.

Well ID	Water year 2014													
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual precipitation, in inches	
	Precipitation, in inches												All 12 months	Without Nov.–Mar.
GC133	--	--	--	0.57	0.21	0.21	0	0.03	0.03	4.11	4.14	2.28	11.58	10.59
ALUS–02	0.84	0.84	0.66	0.99	0.57	0.66	0	0	0.03	2.10	1.92	1.08	9.69	5.97
ALUS–03	0.45	0.63	0.66	--	--	--	--	--	--	--	--	--	P.R.	P.R.
ALUS–07	0.30	0.69	0.63	0.75	0.45	0.27	0	0.21	0.69	4.53	2.46	0.87	11.85	9.06
ALUS–11	0.93	0.81	0.66	0.93	0.60	0.66	0.21	0	0	0.09	1.08	0.99	6.96	3.30
ALUS–18	0.18	0.12	0.36	0.93	0.63	0.75	0	0	0.09	3.30	2.22	0.09	8.67	5.88
ALUS–20	0.00	0.24	0.48	0.60	0.66	0.81	0	0	0	6.00	4.23	0.30	13.32	10.53
ALUS–25	0.15	0.00	0.09	0.30	0.57	0.36	0	0.21	0.93	1.65	1.35	0.18	5.79	4.47
ALUS–31	1.23	0.45	0.69	0.87	0.87	0.66	0.21	0.00	0	0.96	1.71	0.75	8.40	4.86
ALUS–32	0.60	1.08	1.59	1.44	2.16	0.93	0.51	4.98	8.58	6.39	2.52	2.04	32.82	25.62
ALUS–33	0.69	0.72	0.57	0.90	0.54	0.66	0	0	0	1.44	1.23	0.63	7.38	3.99
ALUS–35	--	--	--	4.29	2.22	3.69	1.56	0.18	0	3.36	4.02	2.13	21.45	11.25

The monthly groundwater recharge rates from the SWB method, including a summary of annual recharge rates, are listed in table 7. The 2010–14 mean annual potential recharge estimates across the I–94 Corridor (100-meter resolution) ranged from 0.70 to 14.87 inches per year (fig. 9), slightly lower than overall range for the annual recharge rates of 2013 to 2014. Because the SWB results were available at a 100-meter resolution for the study area, the overlapping grid cell for the individual wells was extracted for comparison to the RISE-derived estimates.

As with the RISE recharge rates, nonwinter groundwater recharge rates were considered more realistic estimates of groundwater recharge. Nonwinter groundwater recharge rates estimated using SWB are summarized in table 7. However, SWB already accounts for frozen ground, and these rates were mainly created for comparison to the RISE recharge rates. Little recharge was measured during the winter for SWB. For water year 2013, nonwinter groundwater recharge rates from SWB ranged from 5.23 to 7.99 inches per year, and for water year 2014, the nonwinter groundwater recharge rates from SWB ranged from 10.40 to 17.06 inches per year (table 7).

Considerable differences existed between the two groundwater recharge estimates. However, groundwater recharge is one of the most difficult components of a water budget to ascertain, so using multiple techniques helps to quantify variability of the potential recharge to an area (Healy and Scanlon, 2010). The RISE recharge rates were approximately the same compared to the SWB recharge rates for water year 2013, deviating by an average of 0.10 inch per year, with nonwinter differences ranging from -3.86 to 4.99 inches per year (table 8). However, RISE recharge rates underestimated SWB recharge rates for water year 2014 by an average of 7.65 inches per year, with nonwinter differences ranging from -12.35 to 0.19 inches per year (table 8).

Both techniques for estimating groundwater recharge have limitations and assumptions. Techniques based upon calculating recharge from well hydrographs, such as RISE, are particularly sensitive to small groundwater rises that are not necessarily caused by a precipitation event (Healy and Scanlon, 2010). The technique RISE also can underestimate recharge rates if the aquifer is well connected to land surface and recharge happens quickly. In contrast, SWB is a difference model, and any errors in the various hydrologic components (for example, precipitation, snowmelt, outflow, and evapotranspiration) will be superimposed on the potential recharge error. Errors from the original sources, such as precipitation or temperature (relating to snowmelt and evapotranspiration), are difficult to quantify; thus, assigning reasonable uncertainty to the potential recharge estimate is challenging (Smith and Westenbroek, 2015). Finally, the excess precipitation in 2014 might have compensated moisture deficits above the water table.

When using SWB to estimate potential recharge, users must assume that potential recharge eventually becomes actual recharge. Because the path or distance to the water table is not known, the SWB model only represents water leaving the root zone. Therefore, SWB does not take into account lateral movement of water that discharges to nearby surface-water bodies before reaching the water table. RISE, on the other hand, accounts for replenishing of the unsaturated zone between the top few meters and the surficial aquifer. This final point could explain the large discrepancy between RISE and SWB, particularly in 2014; the excess precipitation replenished moisture deficits below the root zone and above the water table, a zone unaccounted for within the SWB estimates.

Surficial Aquifer Potentiometric Surfaces

Potentiometric-surface maps were based on six water synoptic surveys completed in calendar years 2013 and 2014 (figs. 10–15) that correspond to May 2013, July 2013, November 2013, April 2014, July 2014, and November 2014, respectively. As much as possible, the year to year measurements were made during the same weeks. Data used to construct these potentiometric-surface maps are presented in appendix 2. Potentiometric-surface maps are used to infer the areal distribution of the water table and to construct difference maps and volume changes between synoptic surveys. As noted in the methods, lakes, rivers, and wetland surfaces were considered when contouring the water table up to land surface.

The potentiometric surface (figs. 10–15) generally sloped towards the Mississippi River on both sides of the river, indicative of a river gaining flow as it receives discharge from the aquifer. However, because the potentiometric surface generally mimics the land surface, southeastern portions of the I–94 Corridor sloped towards lakes and wetlands (fig. 1). These lakes and wetlands complicated the smooth transition of the potentiometric surface towards the river. Additionally, a lack of synoptic measurements in the southern portions of the I–94 Corridor led to less confidence in the true nature of the potentiometric surface. With the six potentiometric-surface maps (fig. 10–15), the changes among the time periods were subtle and can be better distinguished in the groundwater-level change maps presented in the following section.

Groundwater levels, in feet above North American Vertical Datum of 1988 (NAVD 88), for the 12 continuous groundwater level records are shown in figure 16. Generally, the lower the elevation, the closer the well was to the Mississippi River, which had the lowest elevations. Overall, the surficial aquifer potentiometric surface elevation ranged from about 850 feet near the confluence of the Mississippi and Elk Rivers (southeast corner of study area) to about 1,000 feet in the northwest corner of the study area (fig. 16). For the monitored continuous records, the observed range between ALUS–25 and ALUS–07 was almost 70 feet (fig. 16).

Groundwater-Level Changes

To illustrate the seasonal groundwater-level changes in the surficial aquifer, six difference maps were constructed as an approximation of the changes in water storage.

Table 7. Calculated groundwater recharge rates, based upon the soil-water-balance (SWB) model (Westenbroek and others, 2010; Smith and Westenbroek, 2015; Smith, 2017). The SWB lookup table based upon calibrated Minnesota-wide SWB model, as published in Smith and Westenbroek (2015). All values are in inches of potential recharge.

[ID, identification]

Well ID	Water year 2013													
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual precipitation, in inches	
	Precipitation, in inches												All 12 months	Without Nov.–Mar.
GC133	0	0	0	0	0	0	3.43	0.55	1.25	0	0	0	5.23	5.23
ALUS–02	0	0	0	0	0	0	4.54	0.89	2.02	0	0	0.35	7.80	7.80
ALUS–03	0	0	0	0	0	0	3.94	0.81	1.88	0	0	0	6.62	6.62
ALUS–07	0	0	0	0	0	0.18	4.53	1.09	2.23	0	0	0.03	8.06	7.87
ALUS–11	0	0	0	0	0	0.17	5.02	0.88	2.10	0	0	0	8.16	7.99
ALUS–18	0	0	0	0	0	0	4.62	0.75	1.88	0	0	0	7.26	7.26
ALUS–20	0	0	0	0	0	0.21	4.90	0.94	2.04	0	0	0	8.08	7.87
ALUS–25	0	0	0	0	0	0.12	5.26	0.72	1.75	0	0	0	7.85	7.73
ALUS–31	0	0	0	0	0	0.13	4.75	0.95	2.12	0	0	0	7.96	7.83
ALUS–32	0	0	0	0	0	0	5.12	0.68	1.79	0	0	0	7.58	7.58
ALUS–33	0	0	0	0	0	0.06	5.26	0.69	1.63	0	0	0	7.63	7.57
ALUS–35	0	0	0	0	0	0	4.75	0.67	1.97	0	0	0	7.39	7.39

Well ID	Water year 2014													
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual precipitation, in inches	
	Precipitation, in inches												All 12 months	Without Nov.–Mar.
GC133	0.21	0	0	0	0	0.33	4.38	2.23	3.21	0	0	0.38	10.73	10.40
ALUS–02	1.96	0	0	0	0	0.74	5.86	2.73	3.68	0	0.33	0.74	16.05	15.31
ALUS–03	1.66	0	0	0	0	0.68	5.26	2.52	3.45	0	0.22	2.33	16.14	15.45
ALUS–07	1.95	0	0	0	0	0.85	5.90	2.72	3.60	0	0.48	2.42	17.91	17.06
ALUS–11	1.83	0	0	0	0	0.84	5.95	2.86	4.09	0	0.28	0.64	16.50	15.65
ALUS–18	1.59	0.02	0	0	0	0.77	5.61	2.75	4.06	0	0.03	0.61	15.44	14.65
ALUS–20	0.86	0.11	0	0	0	0.79	5.74	2.84	4.30	0	0.27	0.64	15.55	14.65
ALUS–25	0.89	0.09	0	0	0	0.70	5.79	3.03	4.23	0	0.17	0.62	15.53	14.74
ALUS–31	1.81	0	0	0	0	0.80	5.92	2.78	3.88	0	0.29	0.61	16.08	15.28
ALUS–32	0.74	0.09	0	0	0	0.65	5.86	3.01	4.12	0	0.02	0.62	15.10	14.36
ALUS–33	0.69	0.04	0	0	0	0.66	6.06	2.83	4.47	0	0.10	0.61	15.46	14.75
ALUS–35	0.65	0	0	0	0	0.64	5.73	2.76	3.98	0	0.12	0.64	14.53	13.89

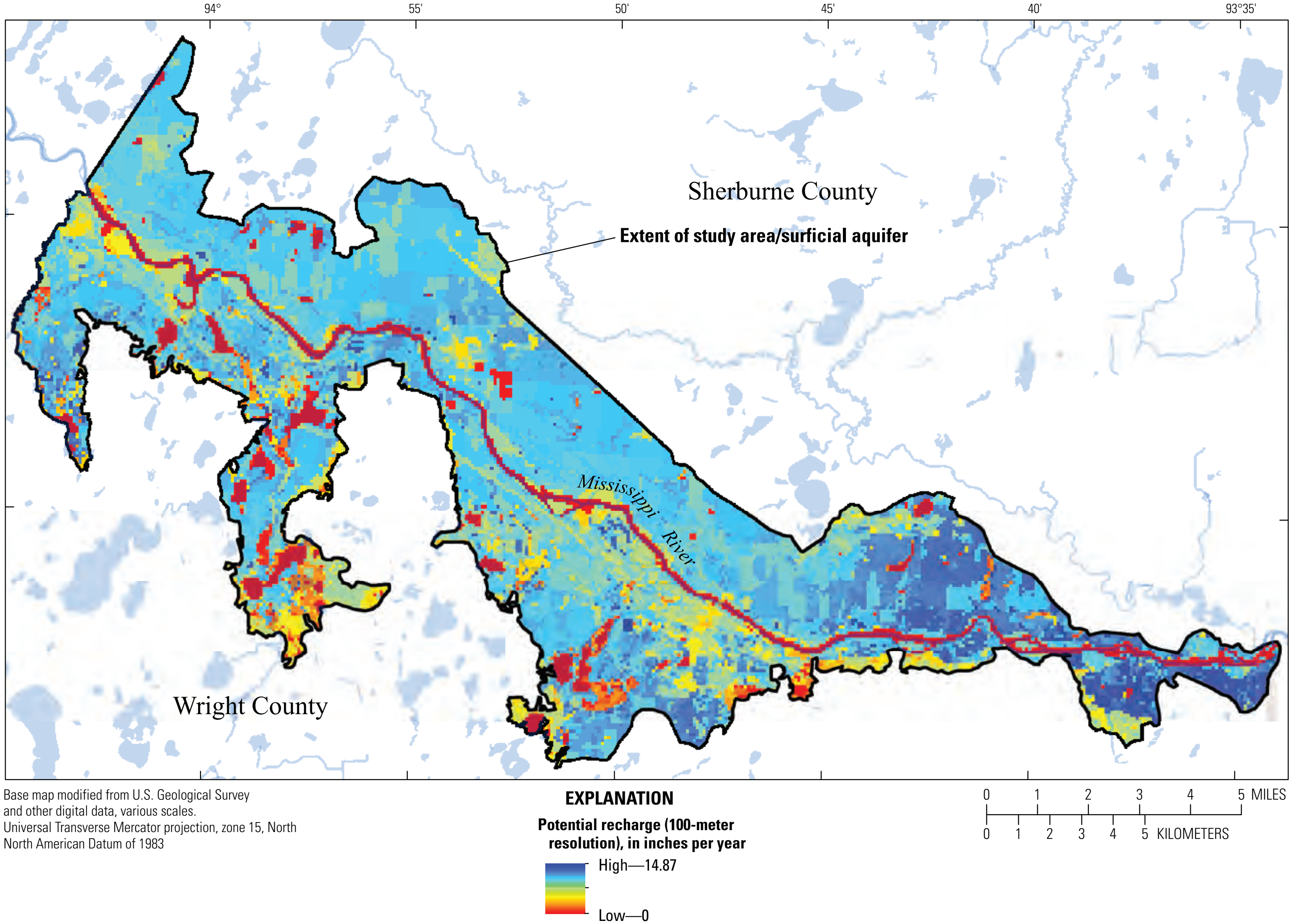


Figure 9. Mean annual potential recharge rates from 2010 through 2014 for the Interstate 94 Corridor, based on extracted results from an updated Minnesota Soil-Water-Balance (SWB) model (Smith, 2017).

Table 8. Annual groundwater recharge rates, based on the R version of the RISE method (Lorenz, 2016) and soil-water-balance (SWB) model (Smith, 2017). Difference in inches of recharge is listed, with the SWB recharge results subtracted from the RISE recharge rates for the entire year (12 months) and the nonwinter portion of the year (without November through March); ALUS–32 is not included.

[ID, identification; N.R., no record; --, no data; P.R., partial record]

Well ID	RISE				SWB				Difference (RISE minus SWB)			
	Water year 2013		Water year 2014		Water year 2013		Water year 2014		Water year 2013		Water year 2014	
	All 12 months	Without Nov.–Mar.	All 12 months	Without Nov.–Mar.	All 12 months	Without Nov.–Mar.	All 12 months	Without Nov.–Mar.	All 12 months	Without Nov.–Mar.	All 12 months	Without Nov.–Mar.
GC133	N.R.	N.R.	11.58	10.59	5.23	5.23	10.73	10.40	--	--	0.85	0.19
ALUS–02	10.56	6.45	9.69	5.97	7.80	7.80	16.05	15.31	2.76	-1.35	-6.36	-9.34
ALUS–03	15.18	11.61	P.R.	P.R.	6.62	6.62	16.14	15.45	8.56	4.99	--	--
ALUS–07	14.82	11.91	11.85	9.06	8.06	7.87	17.91	17.06	6.76	4.04	-6.06	-8.00
ALUS–11	12.57	6.00	6.96	3.30	8.16	7.99	16.50	15.65	4.41	-1.99	-9.54	-12.35
ALUS–18	12.69	9.09	8.67	5.88	7.26	7.26	15.44	14.65	5.43	1.83	-6.77	-8.77
ALUS–20	15.87	10.98	13.32	10.53	8.08	7.87	15.55	14.65	7.79	3.11	-2.23	-4.12
ALUS–25	5.94	3.87	5.79	4.47	7.85	7.73	15.53	14.74	-1.91	-3.86	-9.74	-10.27
ALUS–31	12.54	5.73	8.40	4.86	7.96	7.83	16.08	15.28	4.58	-2.10	-7.68	-10.42
ALUS–33	7.77	3.87	7.38	3.99	7.63	7.57	15.46	14.75	0.14	-3.70	-8.08	-10.76
ALUS–35	N.R.	N.R.	21.45	11.25	7.39	7.39	14.53	13.89	--	--	6.92	-2.64

Groundwater levels in the surficial aquifer for the I–94 Corridor declined as much as 9.46 feet and gained as much as 22.50 feet during the study period.

Maps were constructed to show the short-term groundwater-level changes between spring and mid-summer for May 2013 through July 2013 (fig. 17) and April 2014 through July 2014 (fig. 18). Additional maps were constructed to show short-term changes between mid-summer and late fall for July 2013 through November 2013 (fig. 19) and July 2014 through November 2014 (fig. 20). In 2013, the drier conditions in the 9 months preceding July 2013 (table 4; fig. 17) led to more of the surficial aquifer water volume being depleted between May 2013 and July 2013. This depletion resulted in less aquifer replenishment, including widespread losses in the surficial aquifer (as much as -11.55 feet). For the same period in 2014, most of the surficial aquifer gained water during April through July, with only a few isolated pockets of the surficial aquifer losing water during April 2014 (fig. 18). Overall, the surficial aquifer seasonal deficits were more substantial for 2013, and in 2014, the same areas that indicated large deficits gained as much as 9.46 feet in water table elevation.

The seasonal change maps illustrated deficits from mid-summer through late fall (figs. 19–20). Continuous groundwater levels that indicated seasonal declines in continuous groundwater levels from July through September and October, further support these deficits (figs. 9 and 16). However, the high amount of precipitation in the first one-half of calendar year 2014 prevented large aquifer volume deficits, with the exception of a couple areas in the central portions of the I–94 Corridor (fig. 20). These deficit areas corresponded to areas of higher groundwater pumping from the surficial aquifer (fig. 3).

Surficial aquifer storage changes during the 2013 and 2014 water years are shown in two other maps (figs. 21–22). From July 2013 through July 2014, most of the aquifer had gained water from the previous year because of above normal precipitation in late fall 2013 through spring 2014 and because of less overall surficial aquifer irrigation in 2014 (fig. 21; table 1–1; table 1–2). The areas with the highest amount of irrigation demand in 2013 indicated an overall gain between 2 and 4 feet by July 2014 and as high as 22.50 feet. For the final map that included the first and last synoptic survey measurements, May 2013 and November 2014, the north-central portions of the I–94 Corridor (fig. 22) had gains in the potentiometric surface as much as 3 feet or more. Isolated pockets with losses often were close to the river and corresponded to areas with higher concentrations of domestic wells that pulled water from the surficial and buried aquifers (fig. 3).

Overall, during the 2-year study, groundwater levels indicated the largest declines in groundwater levels were during short duration periods in late summer and early fall, which are the driest times of the year (figs. 19–20). Despite the elevated demand on the surficial aquifer resources from domestic pumping and irrigation, the high precipitation of late 2013 and the first one-half of 2014 replenished the surficial aquifer deficits from 2013.

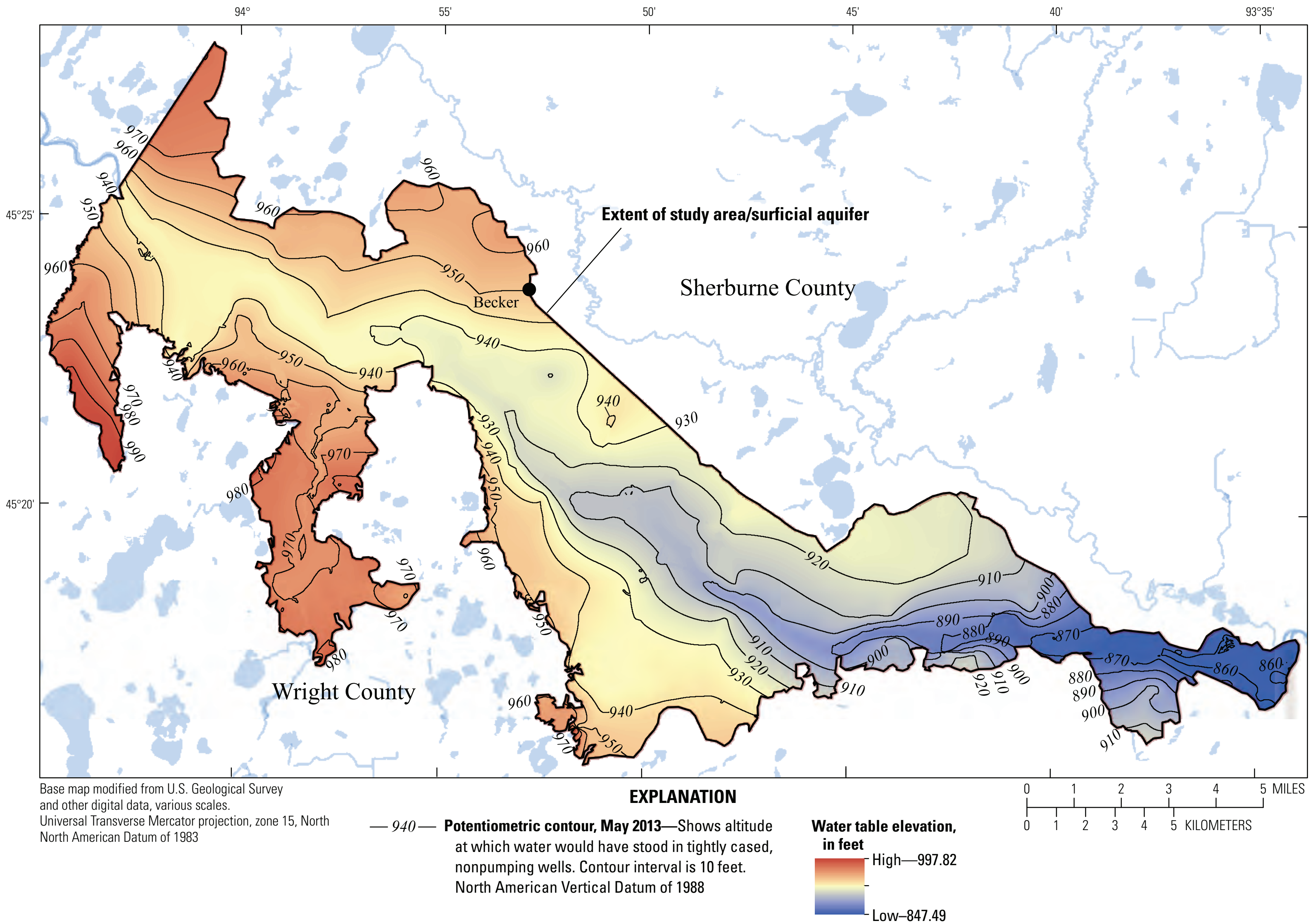


Figure 10. Potentiometric surface of the surficial aquifer within the Interstate 94 Corridor, May 2013; data used to construct the potentiometric surface are presented in appendix 2.

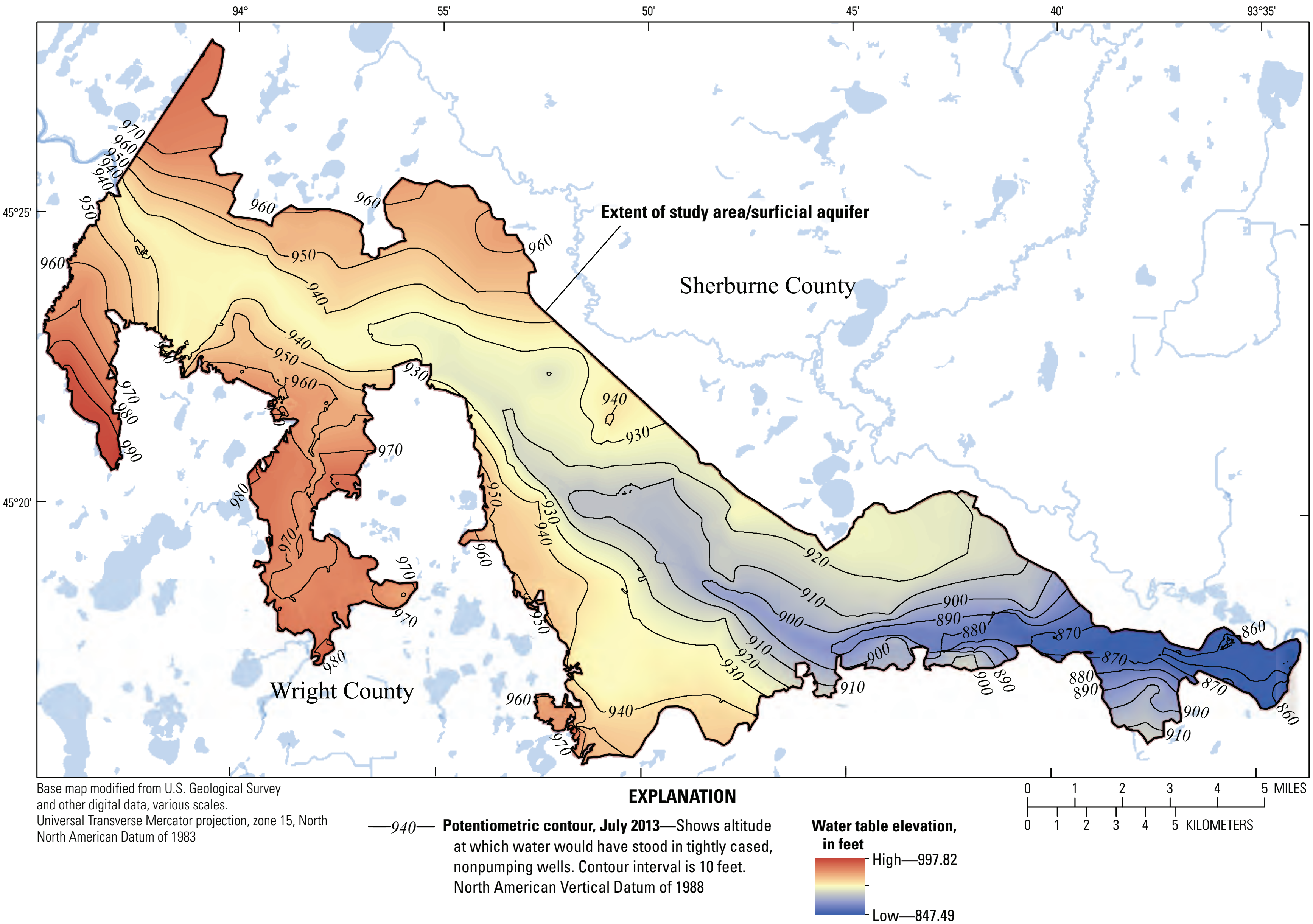
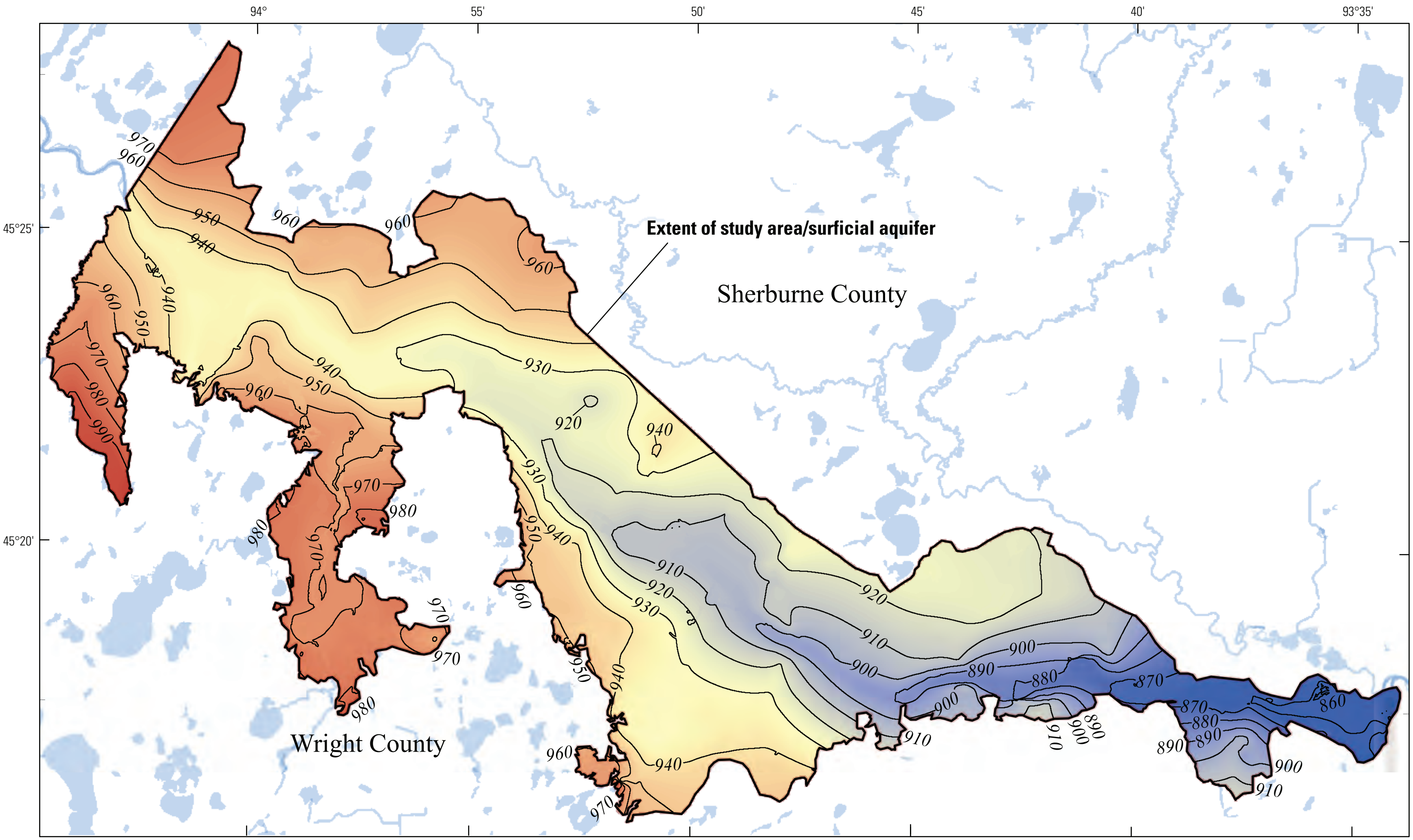


Figure 11. Potentiometric surface of the surficial aquifer within the Interstate 94 Corridor, July 2013; data used to construct the potentiometric surface are presented in appendix 2.



Base map modified from U.S. Geological Survey
and other digital data, various scales.
Universal Transverse Mercator projection, zone 15, North
North American Datum of 1983

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

EXPLANATION

—*940*— **Potentiometric contour, November 2013**—Shows altitude at which water would have stood in tightly cased, nonpumping wells. Contour interval is 10 feet. North American Vertical Datum of 1988

Water table elevation, in feet

High—997.82

Low—847.49

Figure 12. Potentiometric surface of the surficial aquifer within the Interstate 94 Corridor, November 2013; data used to construct the potentiometric surface are presented in appendix 2.

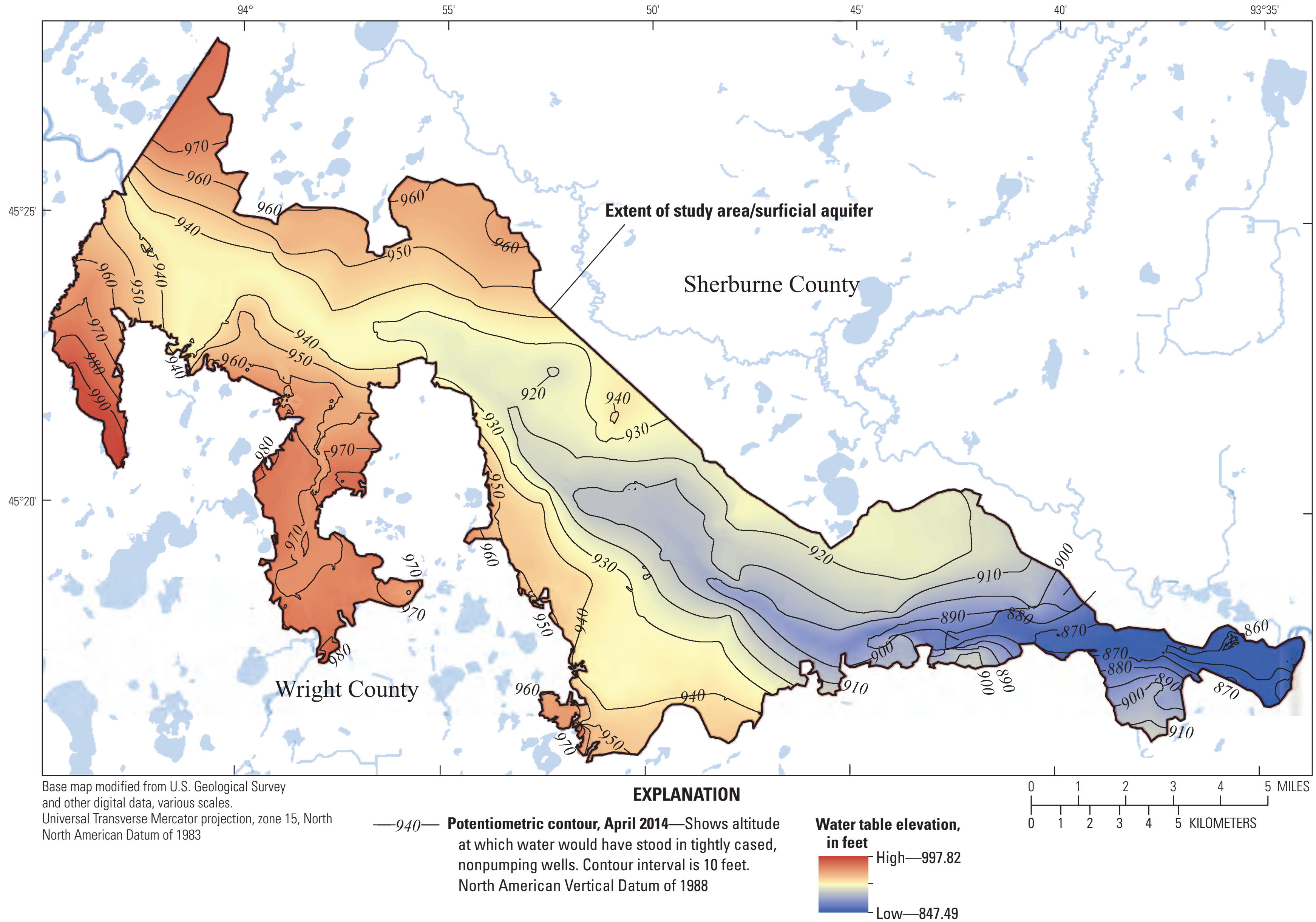


Figure 13. Potentiometric surface of the surficial aquifer within the Interstate 94 Corridor, April 2014; data used to construct the potentiometric surface are presented in appendix 2.

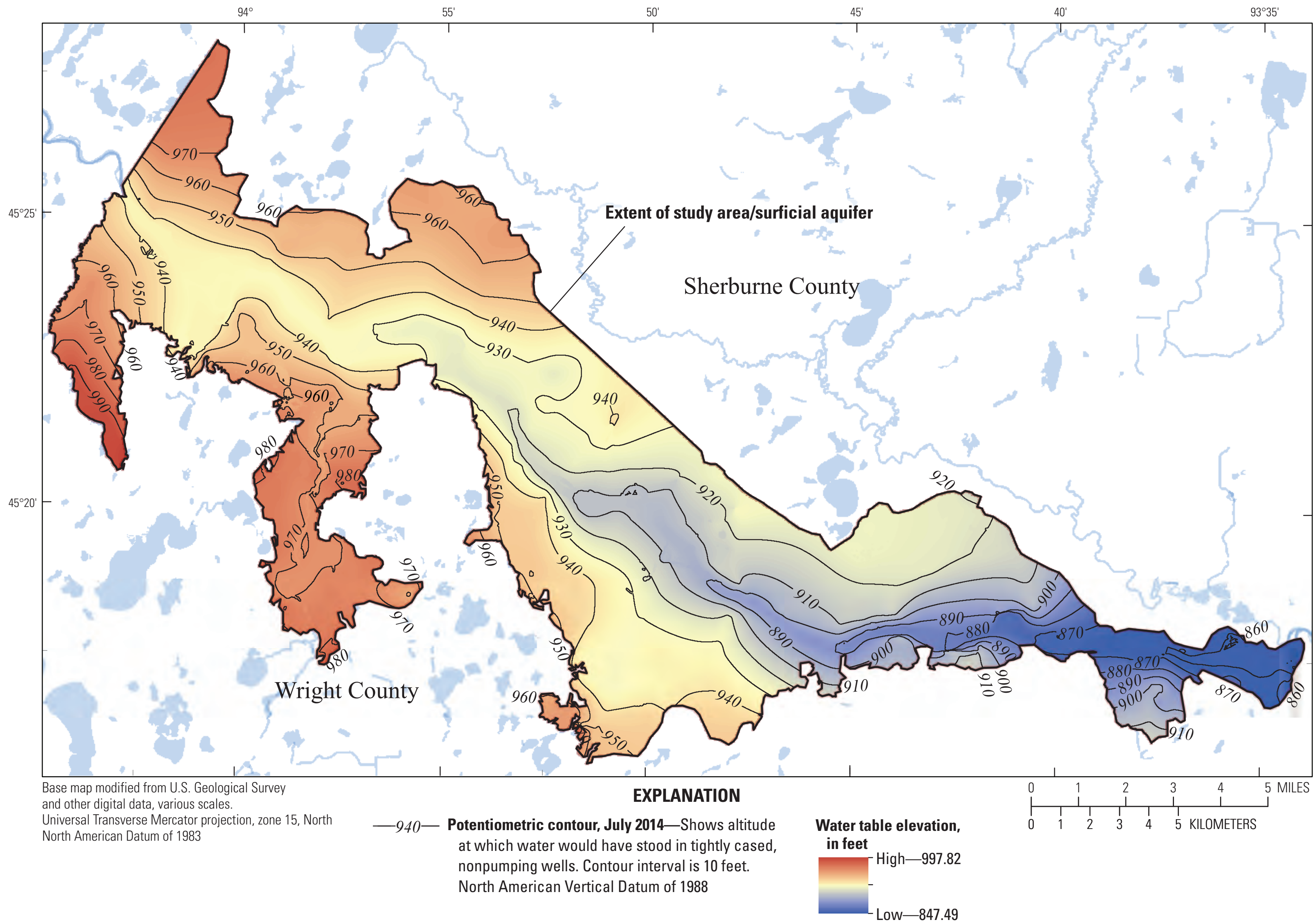
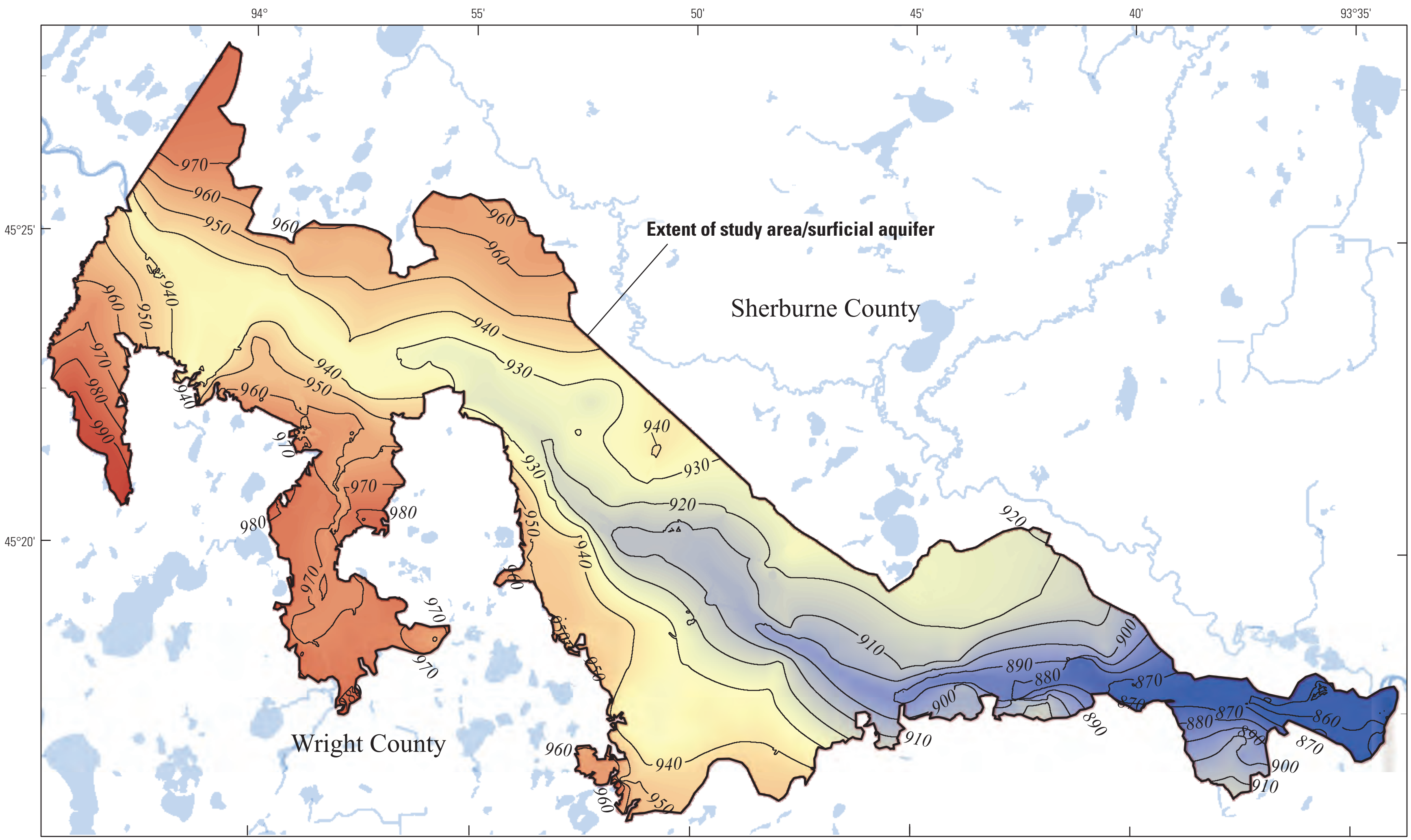


Figure 14. Potentiometric surface of the surficial aquifer within the Interstate 94 Corridor, July 2014; data used to construct the potentiometric surface are presented in appendix 2.



Base map modified from U.S. Geological Survey and other digital data, various scales.
Universal Transverse Mercator projection, zone 15, North
North American Datum of 1983

EXPLANATION

—940— **Potentiometric contour, November 2014**—Shows altitude at which water would have stood in tightly cased, nonpumping wells. Contour interval is 10 feet. North American Vertical Datum of 1988

Water table elevation, in feet

High—997.82

Low—847.49

0 1 2 3 4 5 MILES

0 1 2 3 4 5 KILOMETERS

Figure 15. Potentiometric surface of the surficial aquifer within the Interstate 94 Corridor, November 2014; data used to construct the potentiometric surface are presented in appendix 2.

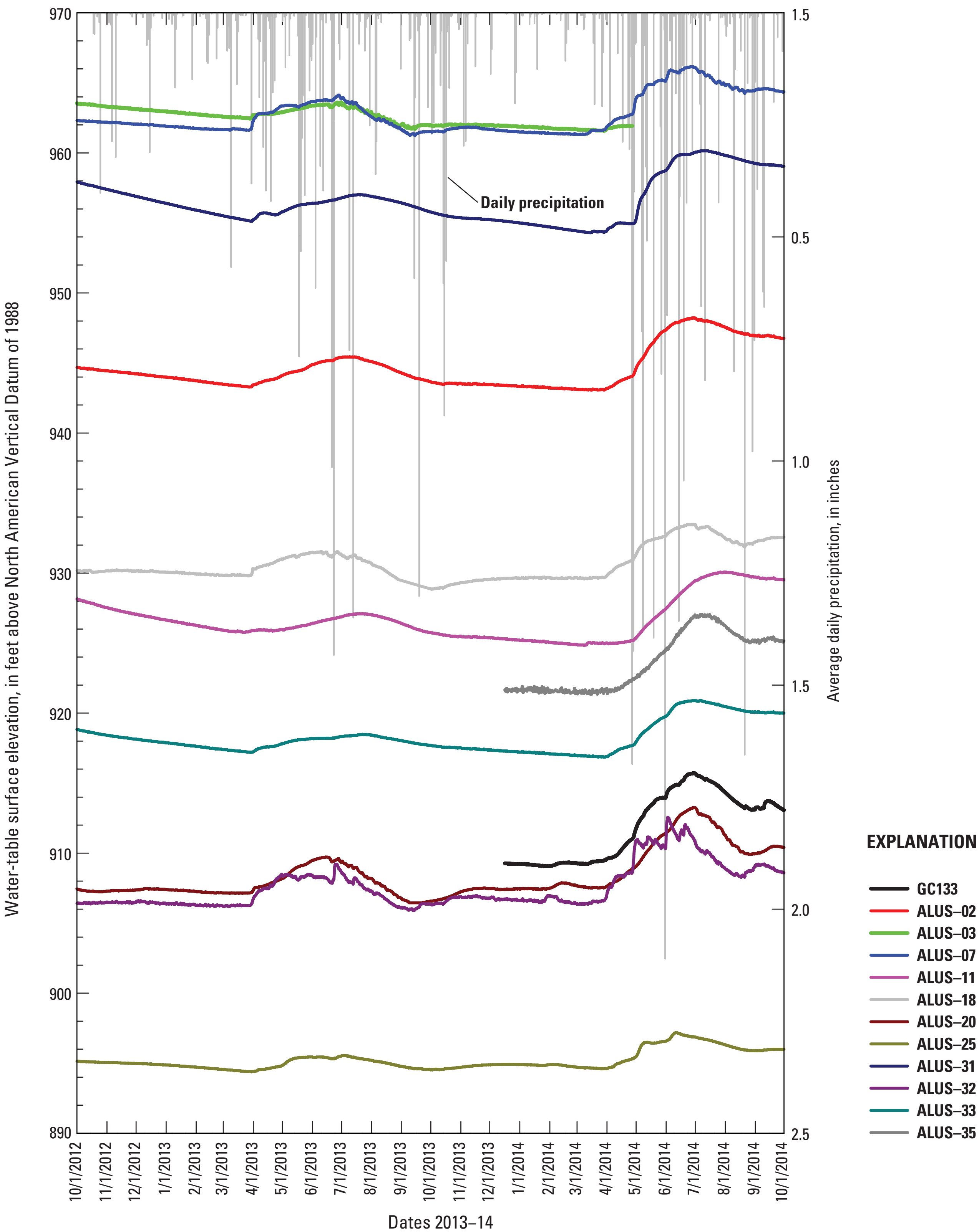


Figure 16. Water table surface elevation, in feet above North American Vertical Datum of 1988, for the 12 continuous groundwater-level records for wells in the Interstate 94 Corridor during water years 2013 and 2014. An average daily precipitation of the 12 colocated precipitation gages also is shown in inches.

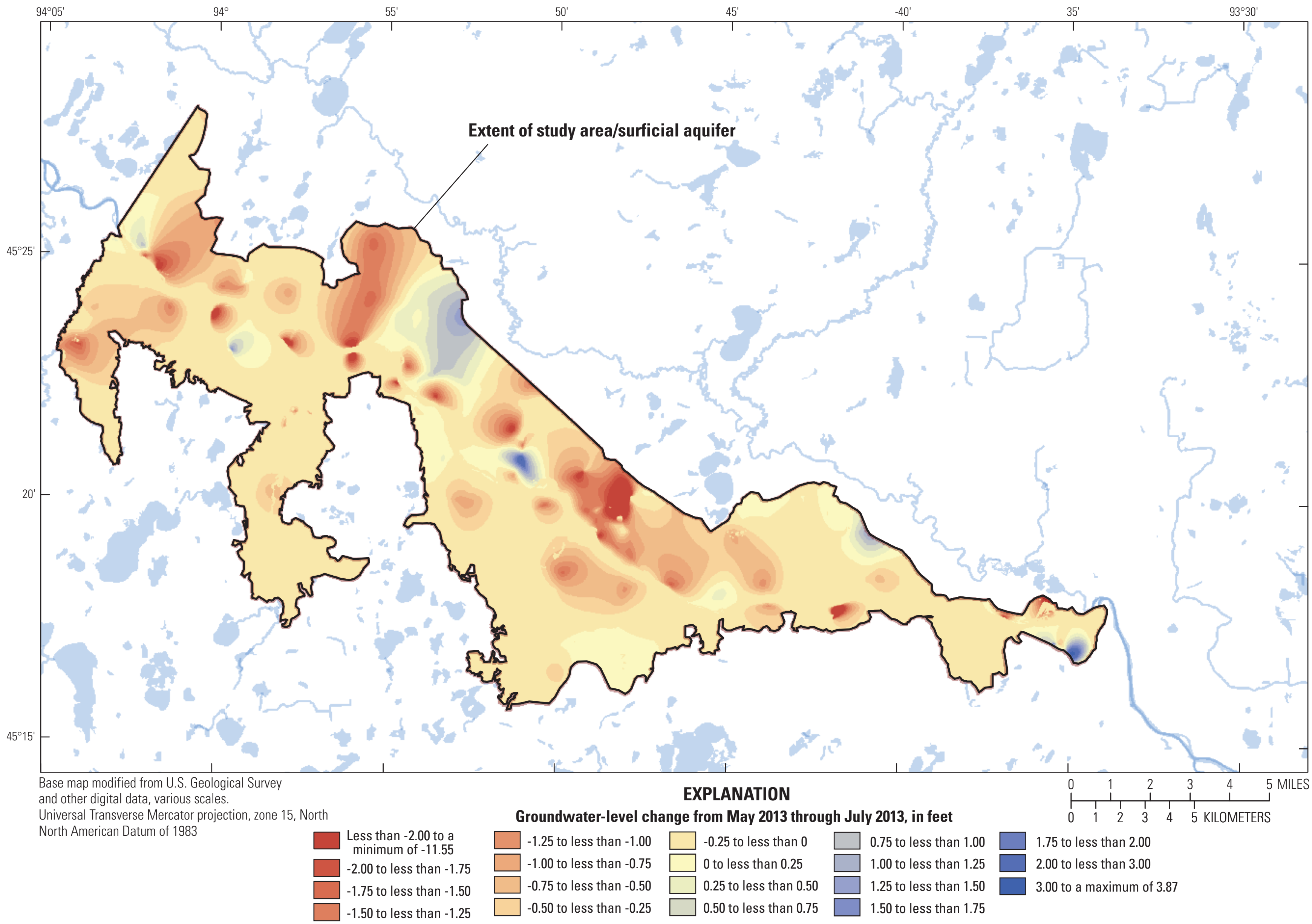


Figure 17. Groundwater-level changes in the Interstate 94 Corridor surficial aquifer from May 2013 through July 2013. Blue shades are levels rising; red shades are levels falling.

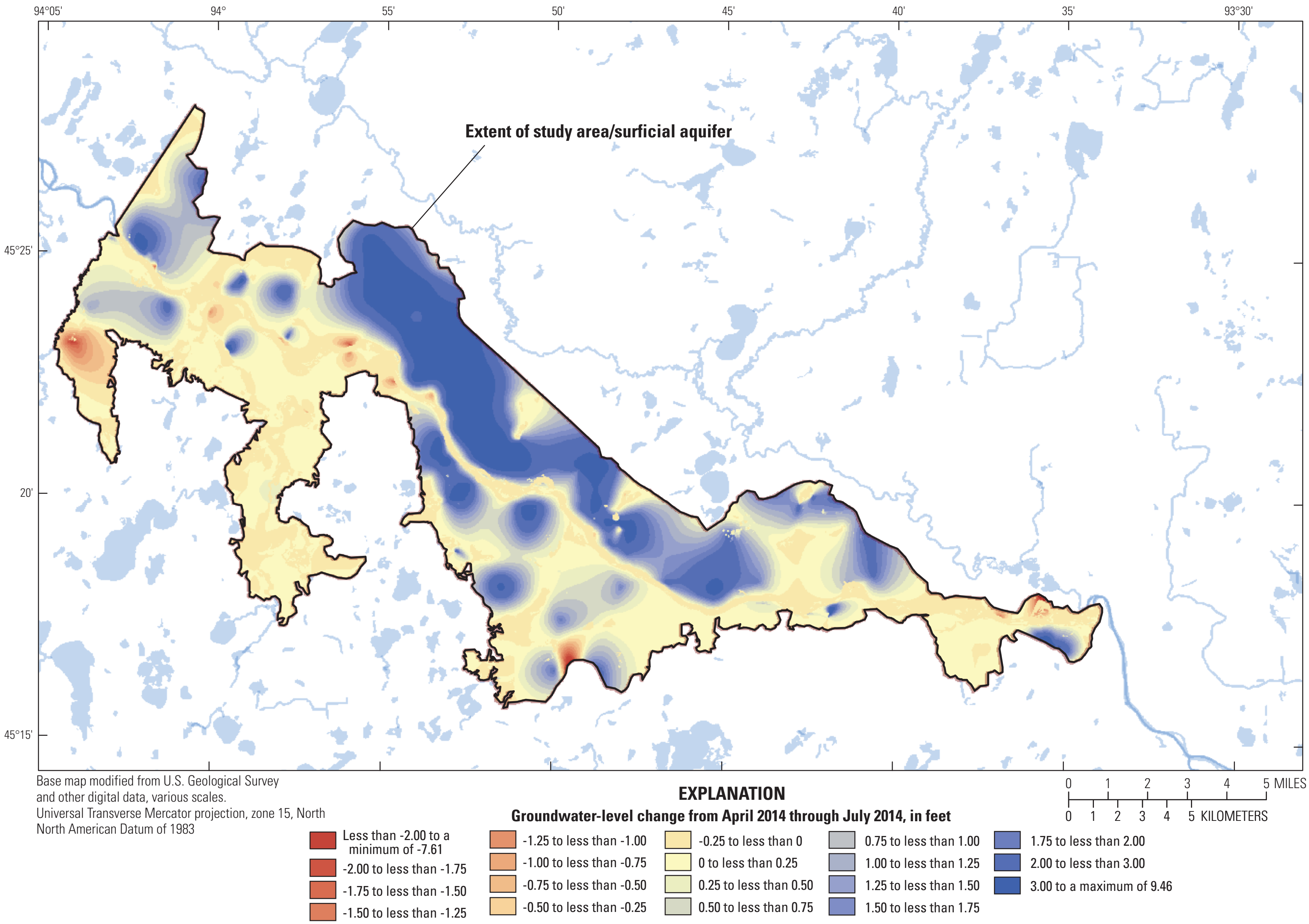


Figure 18. Groundwater-level changes in the Interstate 94 Corridor surficial aquifer from April 2014 through July 2014. Blue shades are levels rising; red shades are levels falling.

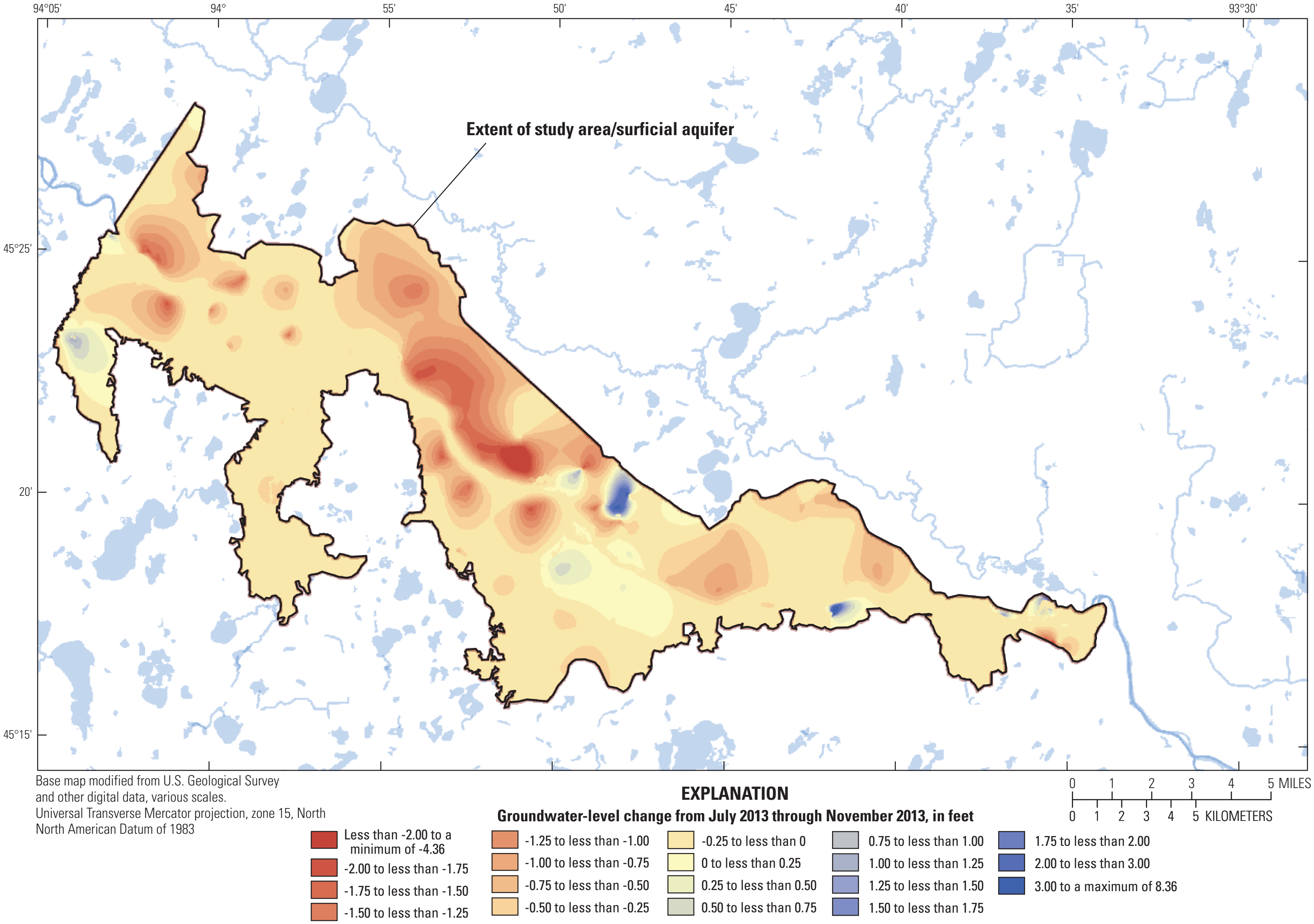


Figure 19. Groundwater-level changes in the Interstate 94 Corridor surficial aquifer from July 2013 through November 2013. Blue shades are levels rising; red shades are levels falling.

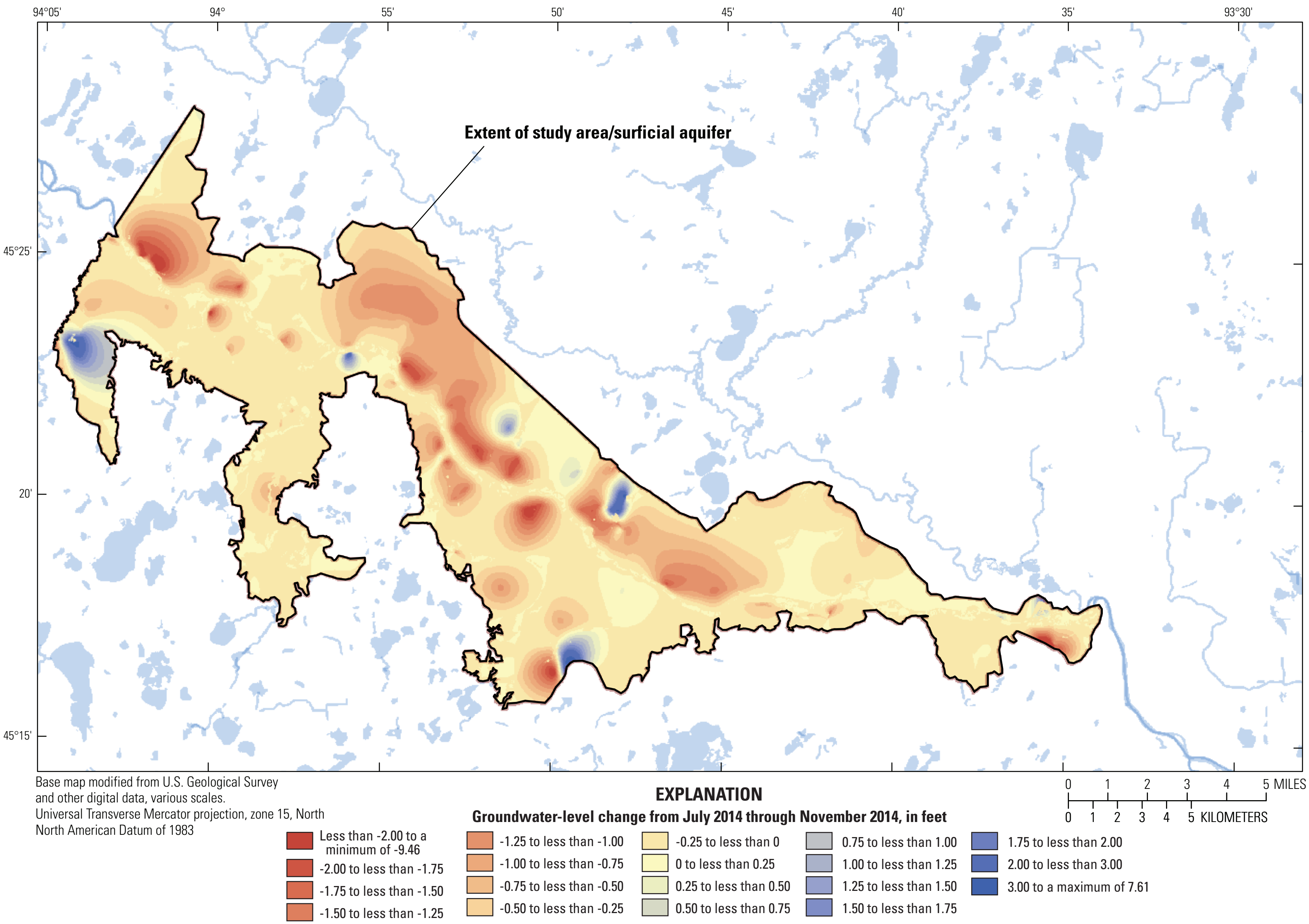


Figure 20. Groundwater-level changes in the Interstate 94 Corridor surficial aquifer from July 2014 through November 2014. Blue shades are levels rising; red shades are levels falling.

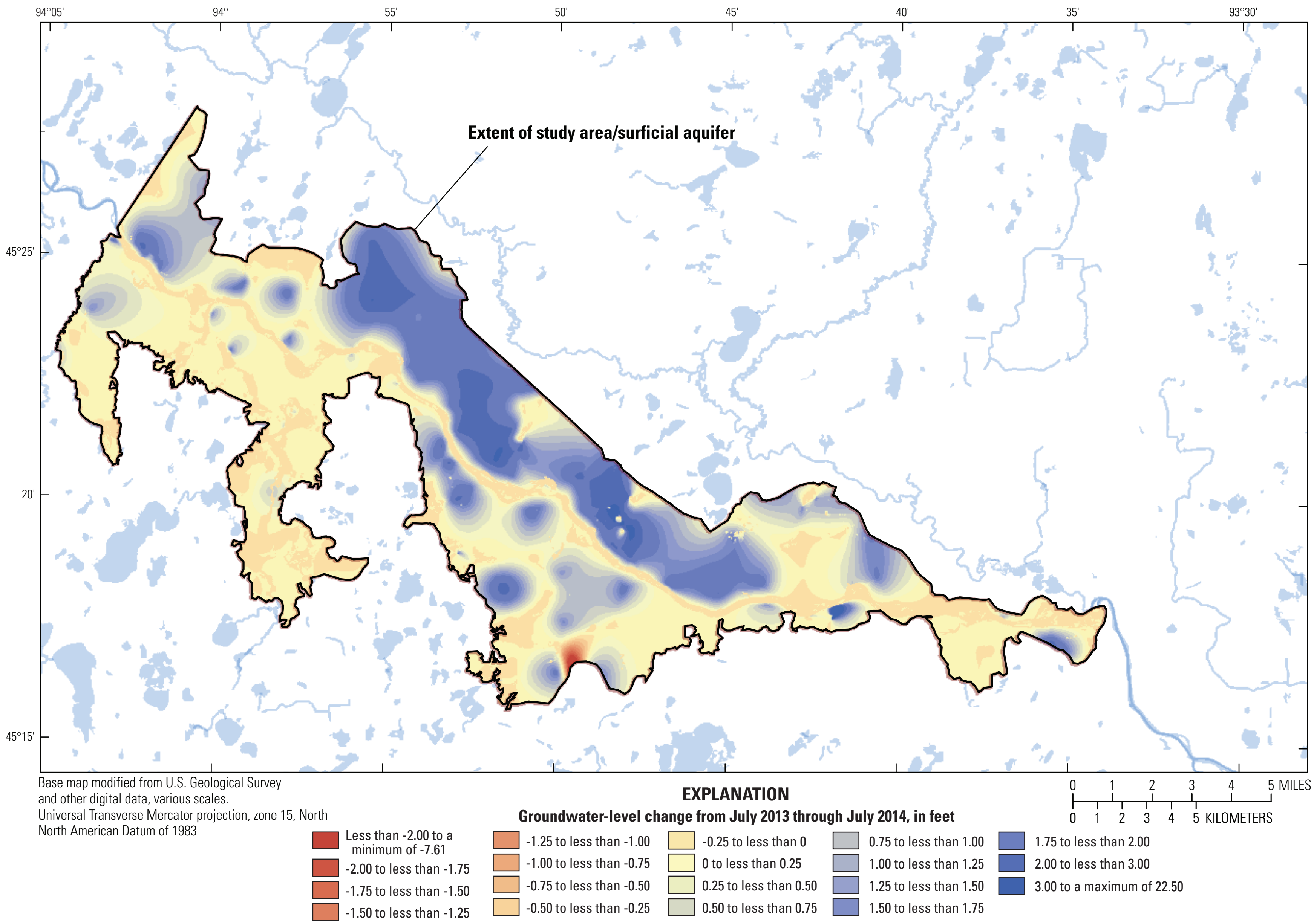


Figure 21. Groundwater-level changes in the Interstate 94 Corridor surficial aquifer from July 2013 through July 2014. Blue shades are levels rising; red shades are levels falling.

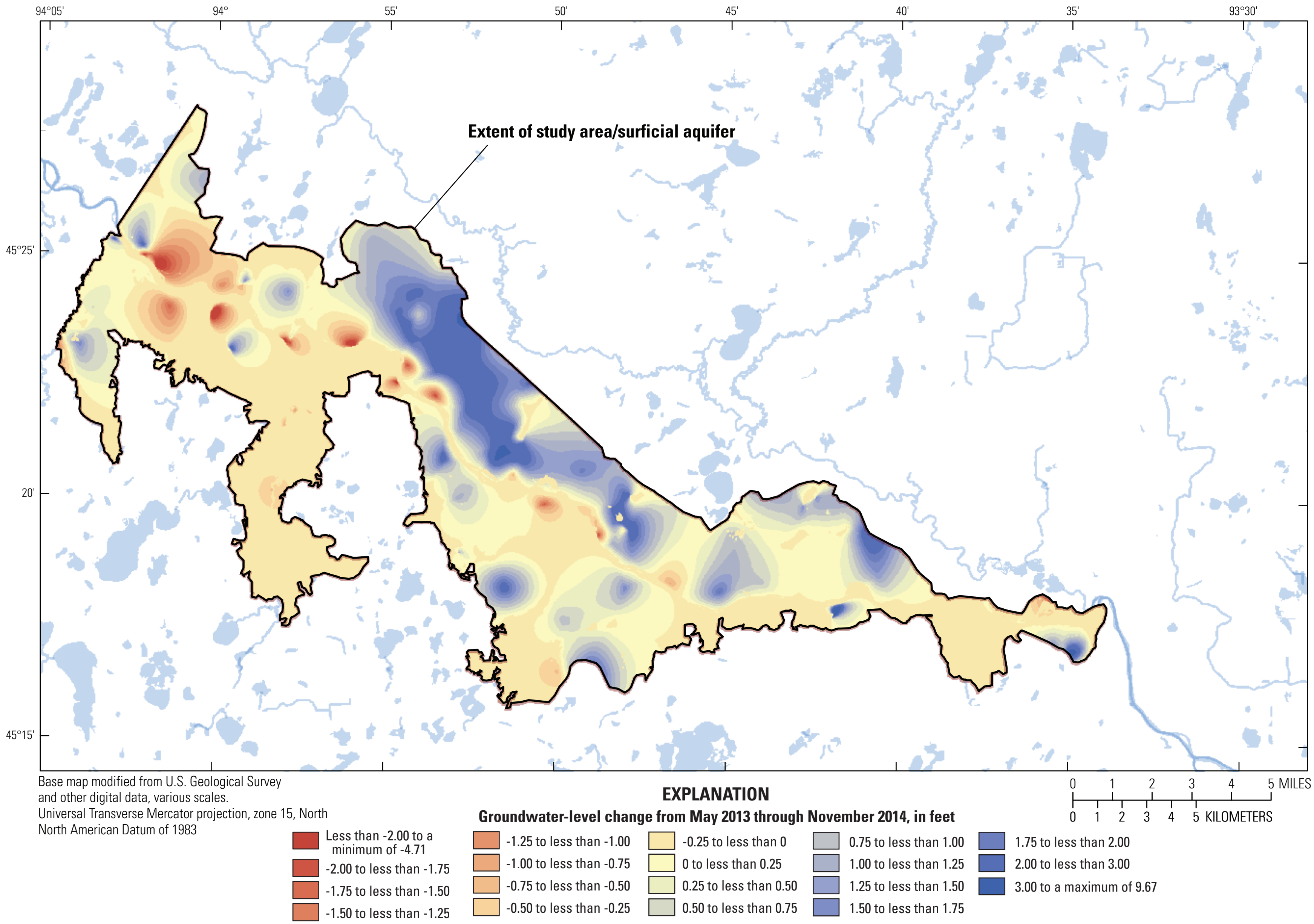


Figure 22. Groundwater-level changes in the Interstate 94 Corridor surficial aquifer from May 2013 through November 2014. Blue shades are levels rising; red shades are levels falling.

Groundwater Balance Comparisons

Six groundwater balances calculated for the surficial aquifer are summarized in table 9. Between seasons in 2013 and in 2014, four short-term groundwater balances were completed, and between 2013 and 2014, two longer-term (1 year or greater) groundwater balances were completed. The groundwater balance calculation periods correspond to the six potentiometric-surface difference maps illustrated in figs. 17–22. The change in surficial aquifer storage was calculated based on the amount of water gained or lost between any two synoptic surveys. The groundwater discharge to the Mississippi River, which was assumed to be the primary discharge body for the I–94 Corridor, was determined by using equation 6.

Equation 6 only accounted for permitted groundwater pumping from the surficial aquifer (table 1–1); however, equation 6 did account for irrigation return flow from the surficial and buried aquifers within the study area. Likewise, domestic water usage only was accounted for from the surficial aquifer, but equation 6 accounted for septic return flow from domestic wells (surficial and nonsurficial) and water-supply wells (surficial and nonsurficial). Total recharge for the groundwater balance was based on the summation of all SWB potential recharge grid cells that were within the study area domain.

Additional results from the six groundwater balance calculations are summarized in table 10, including the calculated groundwater discharge (V_{gw}) to the Mississippi River and the ratio of the calculated to the measured groundwater discharge estimate from September 13, 2012. The static, calculated surficial aquifer volume determined for the I–94 Corridor is reported in millions of gallons and in acre-feet. However, the provided estimate of total water does not indicate the percentage of water that is recoverable. Also, the total water estimate assumes a surficial aquifer specific yield of 25 percent (Heath, 1983). For the surficial aquifer underlying the study area, the estimated total volume was 224,000 Mgal, or 687,000 acre-feet (table 10).

The first two groundwater balances summarized in tables 9 and 10 were for May through July 2013 (fig. 17) and April through July 2014 (fig. 18), which are periods that incorporate a time of the year when more precipitation was expected. During both periods, evapotranspiration became an increasingly important factor by the end of June, and groundwater pumping increased as the year progressed. However, the 2013 period was considerably drier than the 2014 period. The 2013 period was shorter than the 2014 period (63 days as compared to 106 days); however, the 2014 period had nearly five times as much groundwater recharge (15,032 Mgal as compared to 3,085 Mgal) (tables 9–10).

Irrigation and septic return flows did differ between the two periods. However, the largest differences between the two periods were the amount of recharge, the change in the surficial aquifer storage (4,709 Mgal gained in 2014 as compared to 1,144 Mgal lost in 2013), and the large differences in the calculated groundwater discharge to the Mississippi River throughout the study area reach (table 10). In the 2014 period, the calculated groundwater discharge (5.06 $ft^3/s/mi$) from the water budget was 96.4 percent (table 10) of the measured groundwater discharge (5.23 $ft^3/s/mi$) from the ADCP measurements. The 2013 period, on the other hand, had a calculated groundwater discharge of 3.42 $ft^3/s/mi$, for a ratio of 65.1 percent to the measured discharge. The 2014 period had a 2.1 percent gain in aquifer volume as opposed to a 0.5 percent loss for the 2013 period. Groundwater pumping was 45.8 and 8.6 percent of the total recharge for the 2013 and 2014 spring to summer periods, respectively (table 10).

Groundwater balances for July through November 2013 (fig. 19) and July through November 2014 (fig. 18) are summarized in tables 9 and 10. In contrast to spring/early summer periods, less precipitation was expected during these periods. During July through November 2013 and July through November 2014, evapotranspiration reached peak levels before decreasing by November and while groundwater pumping for irrigation was still important. Total recharge was nearly identical, with losses of 1,327 Mgal (2013) and 1,216 Mgal (2014) (table 9). However, the amount of permitted surficial aquifer groundwater pumping was nearly double in 2013 (1,429 Mgal) compared to 2014 (780 Mgal) (table 9). Increased groundwater pumping from the surficial aquifer also increased the estimated return flows.

Overall, the net groundwater pumping (initial pumping minus return flow) from the surficial aquifer was higher in 2013. Pumping rates in 2013 likely were higher to make up for soil moisture deficits above the water table caused by the previously drier period from April through June 2013. Also, the ET_0 in the 2013 period was slightly higher at 0.36 meter as compared to 0.33 meter in 2014. However, the actual evapotranspiration might have been lower in 2014, and the 2013 actual evapotranspiration might have approached the theoretical ET_0. Calculated groundwater discharges for the July through November periods were nearly identical at 1.46 $ft^3/s/mi$ (2013) and 1.45 $ft^3/s/mi$ (2014) (table 10). Also, calculated groundwater discharge was 27.7 percent of the measured groundwater discharge for the July through November periods in 2013 and 2014. The largest difference between the two periods was the ratio of groundwater pumping to total recharge. In 2013, the ratio was 97.2 percent and in 2014 the ratio was 53.6 percent (table 10). In 2013, therefore, from the end of July to the beginning of November, almost all of the potential groundwater recharge was captured by groundwater pumping. The 2014 ratio was still high for more than one-half of the groundwater recharge captured.

Capture within the study area was lower for longer periods than for shorter periods, but capture induced by groundwater pumping was substantial regardless of period length. However, results of this study indicate that overall surficial aquifer storage is sustainable. The largest consequence of the groundwater pumping was the reduced groundwater discharge to nearby surface-water bodies, including the Mississippi River. The high ratio of groundwater pumping to total recharge for July through November 2013 indicates that sustained

Table 9. Six groundwater balances based on the same periods as the potentiometric-surface difference maps. All inputs (gains to the surficial aquifer), outputs (losses from the surficial aquifer), and change in surficial aquifer storage are reported in millions of gallons.

[ΔS, change in storage]

Groundwater balance / Calculation period	Potentiometric-surface (fig. number)	Change in surficial aquifer storage	Total recharge	Return flow, irrigation (surficial aquifer)	Return flow, irrigation (nonsurficial aquifer)	Septic return, domestic (all wells)	Septic return, water supply (surficial aquifer)	Septic return, water supply (nonsurficial aquifer)	Groundwater, permitted (surficial aquifer)	Groundwater, domestic (surficial aquifer)	Groundwater discharge to Mississippi River
			Gains to surficial aquifer						Losses from surficial aquifer		
		ΔS	$V_{recharge}$	$V_{rf, irr\text{-}surf}$	$V_{rf, irr\text{-}nonsurf}$	$V_{sr, dom\text{-}all}$	$V_{sr, ws\text{-}surf}$	$V_{sr, ws\text{-}nonsurf}$	$V_{p, permit}$	$V_{p, domestic}$	$V_{gw\text{-}dis}$
		In millions of gallons									
May 2013 and July 2013	17	-1,144	3,085	690	498	49	0	96	-1,401	-12	-4,149
April 2014 and July 2014	18	4,709	15,032	613	540	82	3	53	-1,266	-20	-10,328
July 2013 and November 2013	19	-1,327	1,488	693	518	76	0	92	-1,429	-18	-2,748
July 2014 and November 2014	20	-1,216	1,488	366	316	76	0	78	-780	-18	-2,743
July 2013 and July 2014	21	4,318	21,965	1,306	1,183	282	3	165	-2,756	-68	-17,762
May 2013 and November 2014	22	1,955	26,538	2,363	1,997	400	3	339	-4,937	-97	-24,651

Table 10. Results of six groundwater balance calculations, including the total change in surficial aquifer storage, total recharge (based on the soil-water-balance model), calculated groundwater discharge to the Mississippi River, ratio of the calculated groundwater discharge to the September 2012 measurement (in percent), the ratio of change in storage to overall surficial aquifer volume (in percent), and the ratio of groundwater pumping to change in total recharge.

[ΔS, change in storage]

Water balance calculation period	Change in surficial aquifer storage (ΔS), in millions of gallons	Groundwater, permitted and domestic (surficial aquifer), in millions of gallons	Total recharge, in millions of gallons	Calculated groundwater discharge to Mississippi River, in cubic feet per mile	Ratio of calculated discharge to measured (Sept. 2012) discharge, in percent	Estimated total surficial aquifer volume (study area), in millions of gallons	Estimated total surficial aquifer volume (study area), in acre-feet	Ratio of change in storage to estimated total surficial aquifer volume, in percent	Ratio of groundwater pumping to total recharge, in percent
May 2013 and July 2013	-1,144	1,413	3,085	3.42	65.1	224,000	687,000	-0.5	45.8
April 2014 and July 2014	4,709	1,286	15,032	5.06	96.4	224,000	687,000	2.1	8.6
July 2013 and November 2013	-1,327	1,447	1,488	1.46	27.7	224,000	687,000	-0.6	97.2
July 2014 and November 2014	-1,216	798	1,488	1.45	27.7	224,000	687,000	-0.5	53.6
July 2013 and July 2014	4,318	2,824	21,965	2.53	48.1	224,000	687,000	1.9	12.9
May 2013 and November 2014	1,955	5,034	26,538	2.47	47.1	224,000	687,000	0.9	19.0

groundwater recharge could be affected if a dry period were sustained for a long time (more than 1 or 2 years) or if future groundwater appropriation continues to increase.

The groundwater balance for July 2013 through July 2014 (fig. 21) is summarized in tables 9–10 and is an example of the average usage during a 1-year period. For 9 months before July 2013, conditions were drier than normal and the July 2013 through July 2014 period included a wetter than normal precipitation record. Because of the high amount of precipitation, the overall study area surficial aquifer gained 4,318 Mgal from July 2013 through July 2014. The calculated groundwater discharge of 2.53 $ft^3/s/mi$ was nearly one-half of the discharge measured in September 2012 but within the range of previous Mississippi River groundwater discharges. The ratio of groundwater pumping to total recharge was 12.9 percent, and the change in storage in relation to the overall aquifer storage was a 1.9 percent gain (table 10).

The groundwater balance for May 2013 through November 2014 (fig. 22) is summarized in tables 9–10. This period was the longest example available. The change in storage (0.9 percent gain) was less than the July 2013 through July 2014 period, mainly because of the inclusion of the stressed period from May through July 2013. Also, the ratio of groundwater pumping to total recharge was higher at 19 percent because of increased groundwater pumping during the stressed period. The calculated groundwater discharge for May 2013 through November 2014 was 2.47 $ft^3/s/mi$, which was similar to the 1-year period (July 2013 through July 2014) calculated groundwater discharge of 2.53 $ft^3/s/mi$, indicating that the long-term average groundwater discharge may be close to 2.5 $ft^3/s/mi$.

Limitations and Assumptions

Study limitations and assumptions must be considered carefully when evaluating study results. The potentiometric-surface maps and groundwater balances presented in this study are initial surficial aquifer estimates of groundwater storage and usage for the I–94 Corridor, and long-term changes likely are not represented in this 2-year study. Furthermore, all groundwater exchange between the surficial aquifer and deep aquifers was assumed to be at steady state.

The exchange between surficial and deep aquifers is poorly understood and likely is not at steady state. Furthermore, a small component of the actual (measured) groundwater discharge could have originated in the buried aquifers and would not be accounted for in equation 6. These factors likely affect the groundwater balance. Therefore, development of a regional groundwater model would enhance understanding of the exchange between the surficial and buried aquifers. However, a regional groundwater model is beyond the scope of this study and report.

For the groundwater balances, the largest inputs are the potential recharge estimates from the SWB model (Smith, 2017). The SWB conceptual model for this study (Smith, 2017) is a higher resolution version of the Minnesota statewide recharge model (Smith and Westenbroek, 2015). Therefore, the same assumptions apply to both model calibrations. The SWB model is a difference model, so errors in the various hydrologic components (for example, precipitation, snowmelt, outflow, and evapotranspiration) will be superimposed on the potential recharge error. Errors from original sources, such as precipitation or temperature (relating to snowmelt and evapotranspiration), are difficult to quantify; thus, assigning reasonable uncertainty to the potential recharge estimate is challenging. The assumption was that the potential recharge eventually became actual recharge; however, the SWB model only represented water leaving the root zone. Finally, HUC–12 boundaries used to define the study area boundaries were assumed to coincide with the aquifer watersheds (that is, the areas contributing recharge to the aquifer); however, these boundaries do not always coincide (Kanivetsky, 1979).

The return flow and septic return flow rates were not known for this study, so irrigation return flow was assumed to be 50 percent, and septic return flow was assumed to be 80.5 percent (Carr and others, 1990; Maupin and others, 2014). These rates vary with time and space (Carr and others, 1990; Maupin and others, 2014), and these assumptions had the highest consequences during shorter periods. The assumed rates were based on statements from these earlier reports and were not based on any studied return rates for Minnesota. For example, for the July through November 2013 period, the difference between the total recharge (1,488 Mgal) and irrigation return flow (693 Mgal and 518 Mgal, surficial and buried aquifer sources, respectively) was small, so variable return flow rates would have a large effect. However, during longer-term calculations, such as the July 2013 through July 2014 groundwater balance, the added irrigation return flow was only 10 percent of the total recharge. Therefore, the unknown magnitude of return flows and septic return flows was more important for the short-term calculations. All of the irrigation return flows were estimates based on a percentage of self-reported water use, which was estimated as having about a 10-percent error.

The surficial aquifer extent and the surficial aquifer volume was based on the Minnesota Geological Survey County Geologic Atlas conceptual models and raster surfaces developed for Sherburne and Wright Counties (Lusardi and Adams, 2013; Hobbs, 2013; Knaeble, 2013; Knaeble and others, 2013; Lusardi, 2013; Lusardi and Lively, 2013). These conceptual models and raster surfaces, including the areal extent and the thickness of the sand and gravel bodies that made up the surficial aquifer, were interpreted from stratigraphic logs provided by many sources (Setterholm, 2014). All surficial-aquifer areas were aggregated, and internal boundaries were dissolved to produce the surficial-aquifer extent map. The result is an estimate of the area where sand and gravel were assumed to be present at land surface and at depth.

The potentiometric-surface and difference maps were interpolated from the water level synoptic surveys. The surficial aquifer was assumed to be hydraulically interconnected, resulting in a spatially smooth potentiometric surface. The resulting interpolated smooth surface was a simplification of the actual water table; however, this simplification should not affect the difference maps. The same simplifications were used for all six potentiometric-surface maps that make up the different synoptic surveys. Land surface was based on lidar data with accuracy of plus or minus 0.06 to 0.11 meter as estimated from nearby Anoka, Benton, and Meeker Counties (not shown).

Summary

Water sustainability in Minnesota has received considerable attention during the last several years. Across the State of Minnesota, 16 groundwater areas of concern have been identified, one of which was identified as the Interstate 94 (I–94) Corridor because of its limited available groundwater and potential for surficial aquifer contamination. The I–94 Corridor encompasses an area between St. Cloud and the Minneapolis-St. Paul, Minnesota, metropolitan area. The region includes several municipalities with rapid population growth and other areas with an increasing demand for agricultural irrigation. In an effort to better understand water sustainability within the I–94 Corridor, the U.S. Geological Survey, in cooperation with the Minnesota Department of Natural Resources, led a hydrologic investigation in portions of the I–94 Corridor to complete a series of surficial aquifer groundwater balances.

Seasonal and annual groundwater balances were completed during portions of the period from October 1, 2012, through November 30, 2014, and a combination of continuous groundwater-level measurements and six groundwater-level synoptic measurements were used to construct regional potentiometric-surface maps for the surficial aquifer system. Within the I–94 Corridor, the surficial aquifer consists mainly of unconsolidated sand and gravel deposits commonly referred to as the Anoka Sand Plain. Overall, the study focused on the surficial aquifer system and its interactions with the Mississippi River rather than the coupled surficial-buried aquifer complex because of the limitations of a water budget assessment of this nature that does not include groundwater flow modeling.

A high-precision Mississippi River groundwater discharge measurement was completed on September 13, 2012, at low-flow conditions to assess the groundwater discharge from the surficial aquifer system and help inform the surficial aquifer groundwater budget. Annual water-use data were compiled for the I–94 Corridor from the Minnesota Department of Natural Resources Water Appropriations Permit Program. This permit program tracked monthly water use at sites using more than 10,000 gallons per day, or 1 million gallons per year. Also as part of the study, the U.S. Geological Survey used the available county geological atlases for Sherburne and Wright Counties to determine the approximate areal extent and volume of the surficial aquifer system. Additional data collected for this study included continuously recorded water levels and precipitation at wells.

The groundwater discharge to the Mississippi River was computed for a 9.2-mile reach of the Mississippi River between the cities of Clearwater and Becker, Minn. The average gain of 5.23 cubic feet per second per mile ($ft^3/s/mi$) for the 9.2-mile reach was comparable to previous indirect groundwater discharge estimates to the Mississippi River in the reach from St. Cloud to the Minneapolis-St. Paul, Minn., metropolitan area. The average gain from this study was on September 13, 2012, and was the first published attempt at a direct measurement of Mississippi River groundwater discharge.

Continuous groundwater levels were collected for 12 wells throughout the I–94 Corridor. The water table across the continuous groundwater levels ranged from 7.2 to 45.5 feet below land surface. Water levels rose by an average of 1.62 feet in 2013 and by an average of 4.81 feet in 2014; both years starting in early April until reaching the shallowest levels in late June to mid-July. Water levels across the surficial aquifer generally reached their shallowest levels in late June 2014. Groundwater levels also dropped rapidly both years after the peak levels, reaching the lowest levels in mid-September to mid-October. This was partially attributable to less precipitation and the elevated evapotranspiration rates during these months. Although more precipitation fell in 2014 than in 2013, water levels declined at nearly the same rate in 2014 (1.74 feet) as in 2013 (1.91 feet).

The two methods used to derive recharge rates to the surficial aquifer for this study are as follows: (1) recharge estimated from the hydrographs of 12 wells completed in the surficial aquifer using the RISE program and (2) potential recharge estimated with the Soil-Water-Balance (SWB) model. For the RISE-derived recharge estimates, the range was from 3.30 to 11.91 inches per year; for the SWB-derived recharge estimates, the range was from 5.23 to 17.06 inches per year. The RISE recharge rates were approximately the same compared to the SWB results for water year 2013, deviating by an average of 0.10 inch per year, with a nonwinter difference ranging from -3.86 to 4.99 inches per year. However, the RISE recharge rates considerably underestimated groundwater recharge compared to the SWB results for water year 2014 by an average of 7.65 inches per year, with a nonwinter difference ranging from -12.35 to 0.19 inches per year.

Groundwater-level synoptic surveys were done six times during the study—May 2013, July 2013, November 2013, March 2014, July 2014, and November 2014. Potentiometric-surface maps were created for all six synoptic measurements. These potentiometric-surface maps were used to infer the areal distribution of the water table and to construct difference maps and volume changes between synoptic measurements. The surficial aquifer potentiometric surface ranged from about 850 feet near the confluence of the Mississippi and Elk Rivers (southeast corner of study area) to about 1,000 feet in the northwest corner of the study area.

To illustrate the seasonal groundwater-level changes in the surficial aquifer, six difference maps were constructed. Groundwater levels in the surficial aquifer for the I–94 Corridor declined as much as 9.46 feet and gained as much as 22.50 feet. Maps were constructed to show the short-term groundwater-level changes between spring and mid-summer (2013, 2014) and between mid-summer to late fall (2013, 2014). The seasonal change maps between mid-summer to late fall illustrated deficits for both years, which also was supported by the continuous groundwater levels that indicated a seasonal decline from July to September and October. The largest declines in groundwater levels were during short duration periods in late summer and early fall, which are the driest times of the year. Despite the high demand on the surficial aquifer resources from domestic pumping and from irrigation, the high precipitation of late 2013 and the first one-half of 2014 replenished the surficial aquifer deficits from 2013.

A total of six groundwater balances for the I–94 Corridor were calculated for the surficial aquifer. Between seasons in 2013 and in 2014, four short-term groundwater balances were completed, and between 2013 and 2014, two longer-term (1 year or greater) groundwater balances were completed. Based on the groundwater balance, the calculated groundwater discharge ranged from 1.45 to 5.06 $ft^3/s/mi$, a ratio of 27.7 to 96.4 of measured groundwater discharge of 5.23 $ft^3/s/mi$. For the two longer period groundwater balances, the calculated groundwater discharge was 2.47 $ft^3/s/mi$ and 2.53 $ft^3/s/mi$, suggesting the long-term average groundwater discharge for this Mississippi River reach was close to 2.5 $ft^3/s/mi$. As a percentage of total recharge for the six groundwater balances, groundwater pumping ranged from 8.6 to 97.2 percent. The long-term calculations were between 12.9 and 19 percent, with the short-term calculations having a higher percentage. The 97.2 percent groundwater pumping to total recharge was during the period from July through November 2013, which was after almost a 1-year period of below normal precipitation. However, the high groundwater pumping to total recharge ratio for July through November 2013 suggested that caution should be exercised if such a dry period were sustained for a longer period or if groundwater appropriations continued to increase, particularly if groundwater pumping and usage were to exceed total recharge. Another important consideration was that the high water use would reduce groundwater discharge to nearby surface-water bodies. Although a decrease in groundwater discharge might be imperceptible for the Mississippi River, smaller lakes and wetlands that are connected to the surficial aquifer could be vulnerable to large water elevation drops with time.

Overall, the study included six synoptic surveys of groundwater levels in wells, along with continuous groundwater hydrographs, rainfall records, and a compilation of the pertinent irrigation data during the study period (October 1, 2012, through November 30, 2014). The combined hydrological investigation and included datasets establish necessary information in the I–94 Corridor for a future groundwater modeling framework.

References Cited

Allen, R.G., Pereira, L.S., Raes, Dirk, and Smith, Martin, 1998, Crop evapotranspiration–Guidelines for computing crop water requirements: Rome, Food and Agriculture Organization of the United Nations, FAO Irrigation and Drainage Paper 56, 300 p. [Also available at http://www.fao.org/docrep/X0490E/X0490E00.htm.]

Alley, W.M., Reilly, T.E., and Franke, O.L., 1999, Sustainability of ground-water resources: U.S. Geological Survey Circular 1186, 79 p. [Also available at https://pubs.usgs.gov/circ/circ1186/.]

Anderson, H.W., 1993, Effects of agricultural and residential land use on ground-water quality, Anoka Sand Plain aquifer, east-central Minnesota: U.S. Geological Survey Water-Resources Investigations Report 93–4074, 62 p. [Also available at https://pubs.er.usgs.gov/publication/wri934074.]

Bredehoeft, John, 1997, Safe yield and water budget myth: Ground Water, v. 35, no. 6, p. 929. [Also available at https://dx.doi.org/10.1111/j.1745-6584.1997.tb00162.x.]

Carr, J.E., Chase, E.B., Paulson, R.W., and Moody, D.W., 1990, National water summary 1987—Hydrologic events and water supply and use: U.S. Geological Survey Water-Supply Paper 2350, 553 p. [Also available at https://pubs.er.usgs.gov/publication/wsp2350.]

Cooper, W.S., 1935, The history of the Upper Mississippi River in late Wisconsin and post-glacial time: Minnesota Geological Survey Bulletin 26, 116 p.

Cowdery, T.K., 1999, Water resources of the Prairie Island Reservation, Minnesota, 1994–97: U.S. Geological Survey Water-Resources Investigations Report 99–4069, 36 p. [Also available at https://pubs.er.usgs.gov/publication/wri994069.]

Cowdery, T.K., Lorenz, D.L., and Arntson, A.D., 2008, Hydrology prior to wetland and prairie restoration in and around the Glacial Ridge National Wildlife Refuge, northwestern Minnesota, 2002–5: U.S. Geological Survey Scientific Investigations Report 2007–5200, 68 p. [Also available at https://pubs.er.usgs.gov/publication/sir20075200.]

Cronshey, Roger, McCuen, R.H., Miller, Norman, Rawls, Walter, Robbins, Sam, and Woodward, Don, 1986, Urban hydrology for small watersheds—TR–55 (2nd ed.): Washington, D.C., U.S. Department of Agriculture, Natural Resources Conservation Service, Conservation Engineering Division, Technical Release 55, 164 p., appendixes [Also available at http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044171.pdf.]

Cunningham, W.L., and Schalk, C.W., comps., 2011, Groundwater technical procedures of the U.S. Geological Survey: U.S. Geological Survey Techniques and Methods 1–A1, 151 p., accessed May 30, 2017, at https://pubs.usgs.gov/tm/1a1/.

Delin, G.N., Healy, R.W., Lorenz, D.L., and Nimmo, J.R., 2007, Comparison of local- to regional-scale estimates of ground-water recharge in Minnesota, USA: Journal of Hydrology, v. 334, nos. 1–2, p. 231–249. [Also available at https://dx.doi.org/10.1016/j.jhydrol.2006.10.010.]

Environmental Systems Research Institute, 2015, ArcGIS Desktop—Release 10.2: Environmental Systems Research Institute, Redlands, Calif.

Ericson, D.W., Lindholm, G.F., and Helgesen, J.O., 1974, Water resources of the Rum River watershed, east-central Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA–509, 3 pls., accessed May 30, 2017, at https://pubs.er.usgs.gov/publication/ha509.

Farnham, R.S., 1956, Geology of the Anoka Sand Plain, *in* Wright, H.E., assoc. ed., The Geological Society of America, Glacial geology, eastern Minnesota: Field Trip No. 3, p. 53–64.

Freshwater Society, 2008, Water is life—Protecting a critical resource for future generations: Excelsior, Minn., Freshwater Society, 51 p. [Also available at http://freshwater.org/wp-content/uploads/joomla/PDFs/publications/Water-is-Life-Report.pdf.]

Freshwater Society, 2013, Minnesota's groundwater—Is our use sustainable?: Freshwater Society, 24 p. [Also available at http://freshwater.org/wp-content/uploads/2013/04/Updated-MNs-Groundwater-Paper-lo-res.pdf.]

Hargreaves, G.H., and Samani, Z.A., 1985, Reference crop evapotranspiration from temperature: Applied Engineering in Agriculture, v. 1, no. 2, p. 96–99. [Also available at https://dx.doi.org/10.13031/2013.26773.]

Hayes, Laura, and Horn, M.A., 2009, Methods for estimating withdrawal and return flow by census block for 2005 and 2020 for New Hampshire: U.S. Geological Survey Open-File Report 2009–1168, 32 p. [Also available at https://pubs.usgs.gov/of/2009/1168/.]

Healy, R.W., and Scanlon, B.R., 2010, Estimating groundwater recharge: New York, N.Y., Cambridge University Press, 256 p.

Healy, R.W., Winter, T.C., LaBaugh, J.W., and Franke, O.L., 2007, Water budgets—Foundations for effective water-resources and environmental management: U.S. Geological Survey Circular 1308, 90 p. [Also available at https://pubs.usgs.gov/circ/2007/1308/.]

Heath, R.C., 1983, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 86 p. [Also available at https://pubs.er.usgs.gov/publication/wsp2220.]

Helgesen, J.O., 1973, Appraisal of ground water for irrigation in the Little Falls area, Morrison County, Minnesota: U.S. Geological Survey Water Supply Paper 2009–D, 40 p. [Also available at https://pubs.er.usgs.gov/publication/wsp2009D.]

Helgesen, J.O., Ericson, D.W., and Lindholm, G.F., 1975, Water resources of the Mississippi and Sauk Rivers Watershed, central Minnesota: U.S. Geological Survey Hydrologic Atlas 534, 3 plates. [Also available at https://pubs.er.usgs.gov/publication/ha534.]

Helgesen, J.O., and Lindholm, G.F., 1977, Geology and water-supply potential of the Anoka Sand-Plain aquifer, Minnesota: Minnesota Department of Natural Resources, Technical Paper no. 6, 17 p. [Also available at https://www.leg.state.mn.us/docs/pre2003/other/771897.pdf.]

Hobbs, H.C., 2013, Surficial geology—Geologic atlas of Wright County, Minnesota (Part A): Minnesota Geological Survey County Atlas Series C–30, Part A, plate 3. [Also available at http://conservancy.umn.edu/handle/11299/159422.]

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., and Megown, K., 2015, Completion of the 2011 National Land Cover Database for the conterminous United States—Representing a decade of land cover change information: Photogrammetric Engineering and Remote Sensing, v. 81, no. 5, p. 345–354. [Also available at http://www.mrlc.gov/nlcd2011.php.]

Johnson, A.I., 1967, Specific yield–Compilation of specific yields for various materials: U.S. Geological Survey Water Supply Paper 1662–D, 74 p. [Also available at https://pubs.er.usgs.gov/publication/wsp1662D.]

Kanivetsky, Roman, 1979, Regional approach to estimating the ground-water resources of Minnesota: St. Paul, Minn., University of Minnesota, Minnesota Geological Survey, Report of Investigations 22, 24 p. [Also available at http://purl.umn.edu/60457.]

Knaeble, A.R., 2013, Quaternary stratigraphy—Geologic atlas of Wright County, Minnesota (Part A): Minnesota Geological Survey County Geologic Atlas Series C–30, Part A, plate 4. [Also available at http://conservancy.umn.edu/handle/11299/159422.]http://purl.umn.edu/60457 http://purl.umn.edu/60457 http://purl.umn.edu/60457

Knaeble, A.R., Hamilton, J.D., and Lively, R.S., 2013, Sand distribution model—Geologic atlas of Wright County, Minnesota (Part A): Minnesota Geological Survey County Geologic Atlas Series C–30, Part A, plate 5. [Also available at http://conservancy.umn.edu/handle/11299/159422.]

Komor, S.C., and Anderson, H.W., Jr., 1993, Nitrogen isotopes as indicators of nitrate sources in Minnesota sand-plain aquifers: Ground Water, v. 31, no. 2, p. 260–270. [Also available at https://pubs.er.usgs.gov/publication/70018348.]

Lindholm, G.F., 1980, Ground-water appraisal of sand plains in Benton, Sherburne, Stearns, and Wright Counties, central Minnesota: U.S. Geological Survey Water-Resources Open-File Report 80–1285, 103 p. and 4 pls. [Also available at https://pubs.er.usgs.gov/publication/ofr801285.]

Lindholm, G.F., Farrell, D.F., and Helgesen, J.O., 1974, Water resources of the Crow River watershed, south-central Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA–528, 3 pls., accessed May 30, 2017, at https://pubs.er.usgs.gov/publication/ha528.

Lorenz, D.L., 2016, DVstats—Functions for manipulating daily values, R package version 0.3.3: U.S. Geological Survey, accessed September 30, 2016, at https://github.com/USGS-R/DVstats.

Lusardi, B.A., 2013, Quaternary stratigraphy—Geologic atlas of Sherburne County, Minnesota (Part A): Minnesota Geological Survey County Atlas Series C–32, Part A, plate 4. [Also available at https://conservancy.umn.edu/handle/11299/159393.]

Lusardi, B.A., and Adams, R.S., 2013, Surficial geology—Geologic atlas of Sherburne County, Minnesota (Part A): Minnesota Geological Survey County Atlas Series C–32, Part A, plate 3. [Also available at https://conservancy.umn.edu/handle/11299/159393.]

Lusardi, B.A., and Lively, R.S., 2013, Sand distribution model—Geologic atlas of Sherburne County, Minnesota (Part A): Minnesota Geological Survey County Atlas Series C–32, Part A, plate 5. [Also available at https://conservancy.umn.edu/handle/11299/159393.]

Maupin, M.A., Kenny, J.F., Hutson, S.S., Lovelace, J.K., Barber, N.L., and Linsey, K.S., 2014, Estimated use of water in the United States in 2010: U.S. Geological Survey Circular 1405, 56 p. [Also available at https://dx.doi.org/10.3133/cir1405.]

Medalie, Laura, and Horn, M.A., 2010, Estimated water withdrawals and return flows in Vermont in 2005 and 2020: U.S. Geological Survey Scientific Investigations Report 2010–5053, p. 62. [Also available at https://pubs.usgs.gov/sir/2010/5053/.]

Minnesota Department of Health, 2016, Minnesota well index (MWI): Minnesota Department of Health web page, accessed September 30, 2016, at http://www.health.state.mn.us/divs/eh/cwi/.

Minnesota Department of Natural Resources, 2016, Bonanza Valley groundwater management area plan, draft plan: Minnesota Department of Natural Resources, 130 p. [Also available at http://files.dnr.state.mn.us/waters/gwmp/area-bv/bv_plan.pdf.]

Minnesota Department of Natural Resources, 2016a, Groundwater management areas (GWMAs): Minnesota Department of Natural Resources web page, accessed March 14, 2016, at http://www.dnr.state.mn.us/gwmp/areas.html.

Minnesota Department of Natural Resources, 2016b, Minnesota water use data: Minnesota Department of Natural Resources web page, accessed March 31, 2016, at http://www.dnr.state.mn.us/waters/watermgmt_section/appropriations/wateruse.html.

Minnesota Geospatial Information Office, 2015, LiDAR elevation data for Minnesota: Minnesota Geospatial Information Office web page, accessed May 5, 2017, at http://www.mngeo.state.mn.us/chouse/elevation/lidar.html#data.

Mueller, D.S., Wagner, C.R., Rehmel, M.S., Oberg, K.A., and Rainville, Francois, 2013, Measuring discharge with acoustic Doppler current profilers from a moving boat (ver. 2.0, December 2013): U.S. Geological Survey Techniques and Methods, book 3, chap. A22, 95 p. [Also available at https://dx.doi.org/10.3133/tm3A22.]

Payne, G.A., 1995, Ground-water baseflow to the upper Mississippi River upstream of the Minneapolis-St. Paul area, Minnesota during July 1988, U.S. Geological Survey Open-File Report 94–478, 28 p. [Also available at https://pubs.er.usgs.gov/publication/ofr94478.]

Rosenberry, D.O., and LaBaugh, J.W., eds., 2008, Field techniques for estimating water fluxes between surface water and ground water: U.S. Geological Survey Techniques and Methods 4–D2, 128 p. [Also available at https://pubs.usgs.gov/tm/04d02/.]

Reppe, T.H.C., 2005, Ground-water availability from surficial aquifers in the Red River of the North Basin, Minnesota: U.S. Geological Survey Scientific Investigations Report 2005–5204, 54 p. [Also available at https://pubs.usgs.gov/sir/2005/5204/.]

RStudio Team, 2016, RStudio—Integrated development for R: Boston, Mass., RStudio, Inc., accessed July 3, 2017, at http://www.rstudio.org.

Ruhl, J.F., and Cowdery, T.K., 2004, Regional ground-water-flow models of surficial sand and gravel aquifers along the Mississippi River between Brainerd and St. Cloud, central Minnesota: U.S. Geological Survey Scientific Investigations Report 2004–5087, 21 p. [Also available at http://pubs.usgs.gov/sir/2004/5087/.]

Ruhl, J.F., Fong, A.L., Hanson, P.E., and Andrews, W.J., 2000, Water-quality assessment of part of the Upper Mississippi River Basin, Minnesota and Wisconsin—Ground-water quality in agricultural area of Sherburne County, Minnesota, 1998: U.S. Geological Survey Water-Resources Investigations Report 2000–4107, 46 p. [Also available at https://pubs.er.usgs.gov/publication/wri20004107.]

Rutledge, A.T., 1997, Model-estimated ground-water recharge and hydrograph of ground-water discharge to a stream: U.S. Geological Survey Water-Resources Investigations Report 97–4253, 29 p. [Also available at https://pubs.usgs.gov/wri/wri974253/.]

Rutledge, A.T., 2002, User guide for the PULSE program: U.S. Geological Survey Open-File Report 02–455, 34 p. [Also available at https://pubs.er.usgs.gov/publication/ofr02455.]

Sanocki, C.A., Langer, S.K., and Menard, J.C., 2009, Potentiometric surfaces and changes in groundwater levels in selected bedrock aquifers in the Twin Cities Metropolitan Area, March-August 2008 and 1988–2008: U.S. Geological Survey Scientific Investigations Report, 2009–5226, 76 p. [Also available at https://pubs.usgs.gov/sir/2009/5226/.]

Setterholm, D.R., 2014, Geologic atlas user's guide—Using geologic maps and databases for resource management and planning: Minnesota Geological Survey Open-File Report OFR–12–1, 24 p. [Also available at http://conservancy.umn.edu/handle/11299/166713.]

Smith, E.A., and Westenbroek, S.M., 2015, Potential groundwater recharge for the State of Minnesota using the Soil-Water-Balance model, 1996–2010: U.S. Geological Survey Scientific Investigations Report 2015–5038, 85 p. [Also available at https://dx.doi.org/10.3133/sir20155038.]

Smith, E.A., 2017, Soil-Water-Balance model data sets for the Interstate 94 Corridor surficial aquifer, Clearwater to Elk River, Minnesota, 2010–14: U.S. Geological Survey data release, https://dx.doi.org/10.5066/F7NZ864G.

Sophocleous, Marios, 2002, Interactions between groundwater and surface water—The state of the science: Hydrogeology Journal, v. 10, no. 1, p. 52–67. [Also available at https://dx.doi.org/10.1007/s10040-001-0170-8.]

Thornthwaite, C.W., and Mather, J.R., 1955, The water balance: Centerton, N.J., Laboratory of Climatology, Publications in Climatology, v. 8, no. 1, p. 1–104.

Thornthwaite, C.W., and Mather, J.R., 1957, Instructions and tables for computing potential evapotranspiration and the water balance: Centerton, N.J., Laboratory of Climatology, Publications in Climatology, v. 10, no. 3, p. 185–311.

Thornton, P.E., Thornton, M.M., Mayer, B.W., Wilhelmi, N., Wei, Y., Devarakonda, R., and Cook, R.B., 2014, Daymet—Daily surface weather on a 1-km grid for North America, version 2: Oak Ridge, Tenn., Oak Ridge National laboratory web page, accessed September 15, 2015, at http://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1219.

U.S. Census Bureau, 2013, TIGER/Line shapefiles and TIGER/Line files: U.S. Census Bureau web page, accessed September 30, 2016, at https://www.census.gov/geo/maps-data/data/tiger-line.html.

U.S. Department of Agriculture, 2013, 2013 Minnesota Cropland Data Layer: U.S. Department of Agriculture, National Agricultural Statistics Service, accessed April 8, 2016, at http://www.nass.usda.gov/Research_and_Science/Cropland/Release/index.php.

U.S. Department of Agriculture, 2016a, Watershed Boundary Dataset, hydrologic unit boundary layer to the subwatershed (12-digit) 6th level: U.S. Department of Agriculture, Natural Resources Conservation Service, accessed October 6, 2017, at https://datagateway.nrcs.usda.gov/GDGOrder.aspx.

U.S. Department of Agriculture, 2016b, Soil climate analysis network: U.S. Department of Agriculture National Water and Climate Center, Crescent Lake #1, Minnesota, accessed September 30, 2016, at http://wcc.sc.egov.usda.gov/nwcc/site?sitenum=2002&state=mn.

U.S. Department of Commerce, 2015, Annual climatological summary, 1948–2015, St. Cloud Regional Airport, MN, USA (COOP: 217294): U.S. Department of Commerce, National Oceanic and Atmospheric Administration, accessed September 5, 2015, at http://www.ncdc.noaa.gov/cdo-web/.

U.S. Geological Survey, 2016, National water information system (NWIS): U.S. Geological Survey web page, accessed September 30, 2016, at http://nwis.waterdata.usgs.gov/nwis.

VanBuren, Princesa, and Wells, John, 2007, Use of Minnesota's renewable water resources—Moving toward sustainability: Department of Natural Resources, Minnesota Environmental Quality Board, 26 p. [Also available at https://www.eqb.state.mn.us/sites/default/files/documents/UseofMinnesotasRenewableWaterResourcesApril2007.pdf.]

Westenbroek, S.M., Kelson, V.A., Dripps, W.R., Hunt, R.J., and Bradbury, K.R., 2010, SWB—A modified Thornthwaite-Mather Soil-Water-Balance code for estimating groundwater recharge: U.S. Geological Survey Techniques and Methods, book 6, chap. A31, 60 p. [Also available at https://pubs.usgs.gov/tm/tm6-a31/.]

Winter, T.C., Harvey, J.W., Franke, O.L., and Alley, W.M., 1998, Ground water and surface water: a single resource: U.S. Geological Survey Circular 1139, 79 p. [Also available at https://pubs.usgs.gov/circ/circ1139/.]

Wright, H.E., Jr., 1972a, Physiography of Minnesota, *in* Sims, P.K., and Morey, G.B., eds., 1972, Geology of Minnesota—A centennial volume: Minnesota Geological Survey, p. 561–578.

Wright, H.E., Jr., 1972b, Quaternary history of Minnesota, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota—A centennial volume: Minnesota Geological Survey, p. 515–546. [Also available at http://conservancy.umn.edu/handle/11299/59791.]

Zhou, Yangxiao, 2009, A critical review of groundwater budget myth, safe yield and sustainability: Journal of Hydrology, v. 370, nos. 1–4, p. 207–213. [Also available at https://dx.doi.org/10.1016/j.jhydrol.2009.03.009.]

Appendixes 1–4

Appendix 1. Monthly Water Usage, Calendar Years 2013–14

Monthly water usage for surficial aquifer system in the Interstate 94 Corridor, in millions of gallons, for the calendar years 2013–14 (Minnesota Department of Natural Resources, 2016b). Only surficial aquifer wells with reported usage during this period of record are listed in table 1–1, available for download as a Microsoft Excel® file at https://doi.org/10.3133/sir20175114. Other permitted surficial aquifer wells exist in the study area; however, those wells did not have reported usage in calendar years 2013–14.

Monthly water use for all other wells with reported usage during this period of record (calendar years 2013–14) is listed in table 1–2 (available for download as a Microsoft Excel® file at https://doi.org/10.3133/sir20175114); these wells were either listed as a buried aquifer well (listed as QBAA, or Quaternary buried artesian aquifer well in the Minnesota Well Index) or were deeper wells without a designation.

Other information for tables 1–1 and 1–2 includes permit number, well depths, primary water use, and county location.

Appendix 2. Synoptic Water-Level Measurements, Water Years 2013–14

Synoptic water-level survey measurements in water year 2013 (table 2–1, available for download as a Microsoft Excel® file at https://doi.org/10.3133/sir20175114) and water year 2014 (table 2–2, available for download as a Microsoft Excel® file at https://doi.org/10.3133/sir20175114). Each year included three measurement surveys, the date/time measured, and depth below land surface in feet (also in NAVD 88).

Appendix 3. Food and Agriculture Organization Penman-Monteith Reference Evapotranspiration Rates, 2012–14

Hourly (for September 13, 2012) and daily (September 1, 2012, through November 30, 2014) Food and Agriculture Organization (FAO) Penman-Monteith reference evapotranspiration rates, respectively, in table 3–1 and table 3–2, available for download as a Microsoft Excel® file at https://doi.org/10.3133/sir20175114. All data from Soil Climate Analysis Network Site Crescent Lake #1 (U.S. Department of Agriculture, 2016b).

Appendix 4. Low-Flow Study, Total Streamflow Measurements

Measured (uncorrected) and corrected total streamflow measurements, in cubic foot per second, for the low-flow measurement on September 13, 2012. Also listed are the transect reach, locations (upstream or downstream), mean time of the measurement, and serial numbers of acoustic Doppler current profilers. The data is available for download as a Microsoft Excel® file at https://doi.org/10.3133/sir20175114.

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