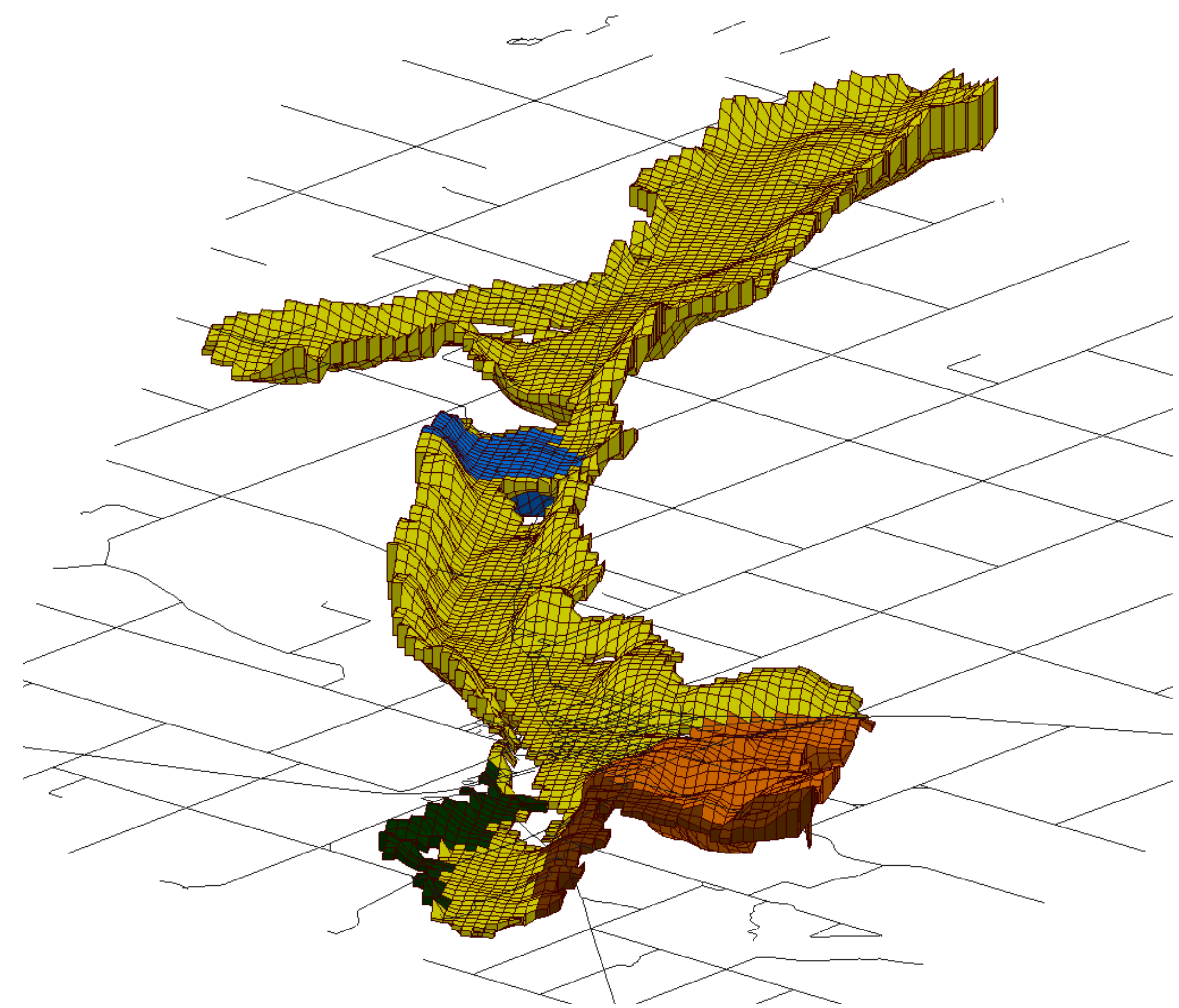
Cowdery—**Hydrogeology and Ground-Water/Surface-Water Interactions in the Des Moines River Valley, Southwestern Minnesota, 1997–2001**—Scientific Investigations Report 2005–5219

In cooperation with the Minnesota Department of Natural Resources, the cities of Windom and Jeffers, Minnesota, the Red Rock Rural Water System, and the Cottonwood County Environmental Office

Hydrogeology and Ground-Water/Surface-Water Interactions in the Des Moines River Valley, Southwestern Minnesota, 1997–2001



Scientific Investigations Report 2005–5219

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

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By Timothy K. Cowdery

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U.S. Geological Survey

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Datum, Abbreviated Water-Quality Units, Acronyms, and Abbreviations

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
$°F = (1.8 \times °C) + 32$

Vertical coordinate information is referenced to the 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.

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

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

CFC	Chlorofluorocarbon
DEM	Digital elevation model
DLG	Digital Line Graph
GMS	Groundwater Modeling System
GWSI	Ground Water Site Inventory
MGS	Minnesota Geological Survey
MNDNR	Minnesota Department of Natural Resources
NAWQA	National Water Quality Assessment
NWI	National Wetlands Inventory
NWS	National Weather Service
QC	Quality control
SF_6	Sulfur hexafluoride
TIN	Triangulated irregular network
USGS	U.S. Geological Survey
δ^2H	delta deuterium
$\delta^{18}O$	delta O-18
µm	micrometer

cm	centimeters
d	day
ft	feet
ft^3	cubic feet
gal	gallons
ha	hectares
in.	inches

Datum, Abbreviated Water-Quality Units, Acronyms, and Abbreviations, Continued

kg	kilograms
km	kilometers
km^2	square kilometers
L	liters
lbs	pounds
m	meters
m^3	cubic meters
Mgal	Millions of gallons
mi	miles
mi^2	square miles
min	minutes
mm	millimeters
MT	metric tonnes
yds	yards
yr	year

HYDROGEOLOGY AND GROUND-WATER/SURFACE-WATER INTERACTIONS IN THE DES MOINES RIVER VALLEY, SOUTHWESTERN MINNESOTA, 1997–2001

By Timothy K. Cowdery

Abstract

Increased water demand in and around Windom led the U.S. Geological Survey, in cooperation with the Minnesota Department of Natural Resources, local water suppliers, and Cottonwood County, to study the hydrology of aquifers in the Des Moines River Valley near Windom. The study area is the watershed of a 30-kilometer (19-mile) reach of the Des Moines River upstream from Windom.

Based on stratigraphic analysis, two hydrologically and genetically separate surficial aquifers underlie the study area. The Windom aquifer has a saturated thickness of 34 meters (111 feet), and the Des Moines aquifer has a saturated thickness of 33 meters (108 ft). The surficial aquifers are relatively isolated from deeper aquifers by till, but some leakage probably occurs. Recharge to the aquifers is from areal recharge, from Cottonwood Lake, and from edge recharge. Pumping at the Windom well field induces substantial amounts of Cottonwood Lake water into the aquifer. During this study, the water level in a well located between two Red Rock wells and the river was lower than the river level during two periods. During those periods, water in the Des Moines River had the potential to recharge the aquifer. Discharge from the aquifers is primarily to municipal wells, the Des Moines River, and other surface waters.

Most of the ground-water samples collected in the study area consisted of calcium-magnesium bicarbonate waters. Corn and soybean herbicides and their degradates were detected at low concentrations in 14 of 27 ground-water samples and in all 3 river samples. Metolachlor ethane sulfonic acid was the most commonly detected compound and also was detected at the highest concentrations. Nutrient concentrations in ground-water samples were skewed low with high outliers, and nutrient concentrations in river samples generally were less than analytical reporting limits.

Nearly all recharge to the aquifer in the ground-water simulation was from edge recharge (80 percent). Calibrated net areal recharge ranged from 17 to 30 percent of the average annual precipitation. Isotopic composition of ground water and Cottonwood Lake water indicated about one-half of the water withdrawn from the Windom aquifer is from Cottonwood Lake.

Scenarios tested with the calibrated model involved increased ground-water withdrawals and changes in recharge to simulate drier or wetter weather conditions. Doubling the withdrawals from all wells in the model had a small effect except in the Windom well-field area. Maximum head declines in the Red Rock well field and the Jeffers city well were less than 40 centimeters (15 inches). In the Windom well field, the maximum head decline was 11 meters (36 feet). The Windom well field does not induce recharge from the Des Moines River. The addition of a new well that pumped 2,000 cubic meters per day (0.44 million gallons per day) in the Augusta Lake Valley area caused a 0.83-meter-deep (2.72-foot-deep) cone of depression that extended to the valley walls. The drought scenario and the high-precipitation scenario resulted in head changes in the northern part of the Augusta Lake Valley area, in the southwestern part of the Red Rock area, and near the valley edges.

Long-term withdrawals of water for public supplies may cause a net decrease in ground-water discharge to surface water. Water that does not evaporate, or that is not exported, is discharged to the Des Moines River but with changed water quality. Because ground-water and surface-water qualities in the study area are similar, the ground-water discharge probably has little effect on river water quality.

Introduction

The city of Windom and the surrounding area water suppliers rely on ground water from surficial aquifers along the Des Moines River to supply water needs. Windom is located on the Cottonwood-Jackson County border in the southwestern part of the State (fig. 1). Unlike many parts of Minnesota, the area around Windom is semi-humid, has annual potential evapotranspiration that exceeds annual precipitation (Minnesota Department of Natural Resources, 2001a), and has limited

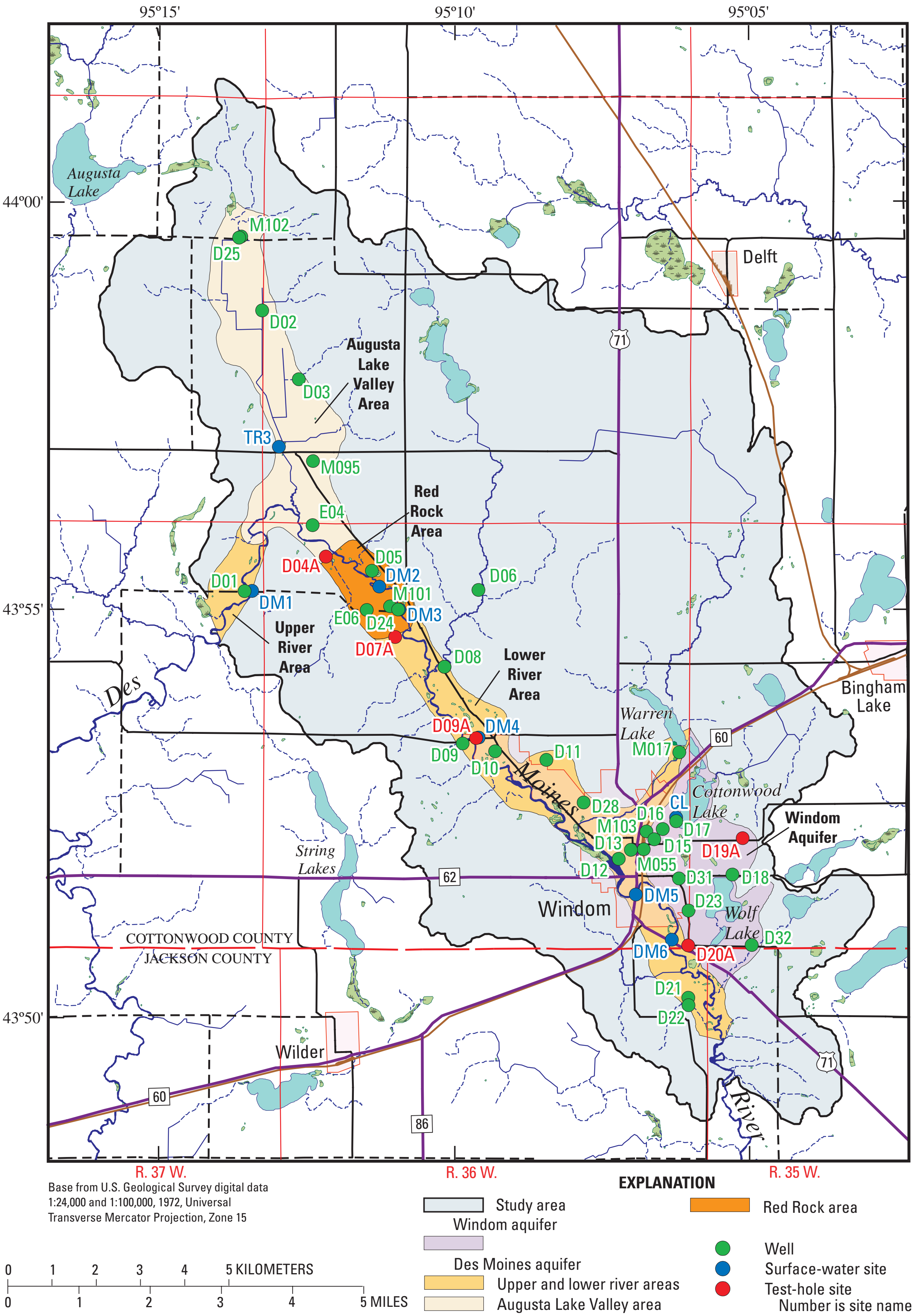

Figure 1. Des Moines River study area location, aquifer extent, and study sites, southwestern Minnesota.

water resources. Because increased water demand in the area has been met by the installation of new supply wells and because water suppliers expect the demand to continue to increase, local residents and State regulators are concerned that surface waters in the area, such as Cottonwood Lake and the Des Moines River, may lose water to the surficial aquifers. Therefore, to effectively manage water resources, water suppliers, government officials, and local residents need information about the extent of the surficial aquifers, how much water the aquifers can supply, and how the aquifers hydraulically interact with the rivers, lakes, and wetlands that overlie the aquifers. Water managers also are concerned about chemicals dissolved in the water, including the sources and fates of those chemicals.

To obtain the needed information, the U.S. Geological Survey (USGS), in cooperation with the Minnesota Department of Natural Resources (MNDNR), local water suppliers, and Cottonwood County, studied the hydrology of aquifers deposited by glacial processes (hereinafter referred to as glacial) and river processes (hereinafter referred to as alluvial) in the Des Moines River Valley near Windom. The objectives of this 1997–2001 study were to describe the hydrogeology of the study area and the ground-water/surface-water interactions during current (2000) and anticipated future conditions. The description of the hydrogeology was to include ground-water recharge sources and rates, ground-water flow rates and directions, ground-water age, and ground-water quality. The description of the ground-water/surface-water interactions was to include the effects of increased ground-water withdrawals, drought, and increased precipitation on the ground-water and surface-water flow and quality. This report is intended to provide technical documentation of the study for water managers and ground-water geologists.

Study Area Description

The study area is located in southern Cottonwood County and a small part of northern Jackson County in southwestern Minnesota. The area is defined by the watershed of a 30-km (19-mi) reach of the Des Moines River from the confluence of the stream that drains String Lakes to a point about 5 km (3 mi) south of the Cottonwood-Jackson County border (fig. 1). In the study area, the Des Moines River is an underfit stream that occupies a valley 1,000 m (1,100 yds) wide and about 25 m (82 ft) deep. The southern end of the study area is occupied by Windom, the Cottonwood County seat and home to 4,490 residents in the year 2000. The study area is about 27 km (17 mi) long and 14 km (9 mi) wide and encompasses an area of 208 km^2 (80 mi^2).

The study area is located near the headwaters of the Des Moines River. The watershed for this section of the Des Moines River is narrow and extends less than 8 km (5 mi) beyond the river valley. Upland parts of the watershed are formed of clayey grey till of the Altamont Moraine (Hobbs and Goebel, 1982) into which valleys were eroded by glacial meltwater. This till also underlies valley-fill deposits at depths that range from zero to more than 44 m (144 ft). Small intermittent rivers and ditches drain most of the watershed. Many of the small stream valleys end at the side of the main valley and do not reach the river.

In the northern part of the study area, the Des Moines River abruptly changes direction from northeast to southeast in a feature called “Great Bend”. An arm of the river valley continues north from Great Bend but contains no natural streams. This arm, hereinafter referred to as the Augusta Lake Valley, extends more than 20 km (12 mi) to the north and west from Great Bend. Much of the cropland in the Augusta Lake Valley is artificially drained and is irrigated from a surficial aquifer. Corn and soybean row-crop agriculture is the main land use throughout most of the study area, but residential and urban land uses dominate the area in and around Windom. Several gravel-mining and -washing businesses operate along the Des Moines River from Great Bend to Windom. A gravel-washing business also operates in a gravel pit on the south side of Cottonwood Lake in Windom. Areas of known point-source ground-water contamination in the study area include an old city dump, a landfill, an agrichemical sales and application plant, vehicle garages, gas stations along U.S. Highway 71 in Windom, and a meat-packing plant. Monitoring wells either exist for all these sites or have been drilled and abandoned.

Annual precipitation averaged 73.56 cm (28.96 in.) at the National Weather Service (NWS) station in Windom during 1971–2001 (National Climate Data Center, 2001). About 62 percent of this precipitation fell during the growing season (May–September). The annual precipitation standard deviation is 16.5 cm (6.51 in.). Average annual potential evapotranspiration during 1961–90 exceeded precipitation by 5 cm (2 in.) (Minnesota Department of Natural Resources, 2001a). During the last 20 years, the study area experienced two cycles of a relatively wet period followed by a relatively dry period (fig. 2). Wet-dry cycle 2, which occurred during 1990–99, was wetter than wet-dry cycle 1, which occurred during 1982–90. Data collection for this study began in October 1997 and ended in October 2001. Water levels were measured during August 1998–October 2001, and water-quality data were collected during April 1999–July 2000. Most of the data collection occurred during the dry period of wet-dry cycle 2. Fall rains during 2000 were sufficient to make that year part of a new wet cycle. Precipitation during water years 2000 and 2001 was near normal and averaged 78.12 cm (30.76 in.).

The primary sources of water in the study area are surficial glacial and alluvial aquifers, a buried Cretaceous bedrock aquifer, and surface water. During 2000, 2.604 million m^3 (687.9 Mgal) of water was used in the study area. The city of Windom, the Red Rock Rural Water System, the city of Jeffers, and industrial self-suppliers provided this water. The public suppliers pump water exclusively from the surficial glacial and alluvial aquifers, and the industrial self-suppliers pump water from

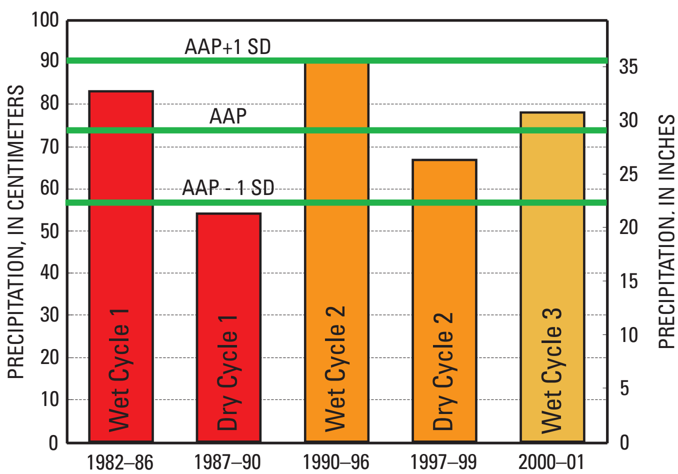

Figure 2. Average annual precipitation cycles at Windom, Minnesota, 1971–2001. [AAP, average annual precipitation; SD, standard deviation]

all three sources. The relative amounts of water pumped by the suppliers are given in table 1 along with recent changes in ground-water withdrawals (Minnesota Department of Natural Resources, 2001b). The water uses and water sources in the study area during 2000 are shown in figure 3. The meat-packing plant located in the study area used 66.5 percent of the self-supplied water during 2000. From 1997 to 2000, the city of Windom increased its ground-water withdrawals to supply water to a new ethanol production plant, which received 333,000 m^3 (88.0 Mgal) during 2000, and to the Red Rock Rural Water System, which received 138,000 m^3 (36.5 Mgal) during 2000. The Red Rock Rural Water System's service population increased 58 percent between 1996 and 2000. The slight decline in the Water System's supply during 2000 was offset by purchases from the city of Windom. Taking these water transfers into account, all three public water suppliers had relatively constant production during 1989–2000.

From 1991 through 1999, as many as four wells near the Windom well field pumped 4.099 million m^3 (1,083 Mgal) of water from a surficial glacial aquifer in the study area to remedy ground-water contamination at the old city dump site. The pumped water was sprayed through an irrigation nozzle into a wetland adjacent to and upgradient from the dump site. Hydrographs for the dump site indicate the aquifer was quickly recharged from the wetland. This remediation water use was not included in this study because the net consumption of water as a result of evaporation probably was small and was countered by increased recharge from the wetland. The maximum distance of redistribution is about 300 m (1,000 ft).

The surficial aquifers provide 76 percent of the water used in the study area. About two-thirds of that is supplied by the city of Windom from the Windom aquifer. The three wells owned by the meat-packing plant supply 19 percent of the study area's water and are the only wells screened in the Cretaceous aquifer. The remaining 5 percent of water used in the study area is from the Des Moines River or Cottonwood Lake (fig. 1) and is used for washing gravel. About 11 percent of the surface water used is from Cottonwood Lake, into which the water is discharged after use. Most of the water pumped from the surficial aquifers is used in residences (59 percent), ethanol production (17 percent), and commerce within Windom (11 percent).

Table 1. Annual water supply within the Des Moines River study area, 1989–2000.

[Data from Minnesota Department of Natural Resources, 2001b]

Producer	Year 2000			Percent increase from		
	Cubic meters	Million gallons	Percent	1991	1998	Million gallons
City of Windom	1,291,000	341	49.6	88.4	22.3	308
Red Rock Rural Water System	507,000	134	19.5	-5.7	-10.6	141
City of Jeffers	75,000	20	2.8	-2.7	14.4	19
Industrial self-suppliers	731,000	193	28.1	6.3	6.5	189
Total	2,604,000	688	100	31	9.6	657

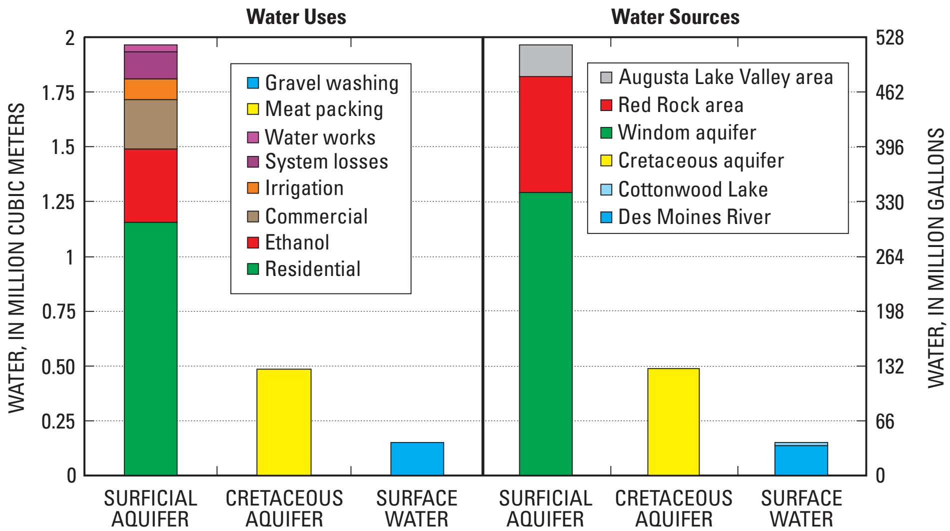

Figure 3. Water uses and water sources in the Des Moines River study area, southwestern Minnesota, 2000.

Based on a stratigraphic analysis that will be detailed in the Hydrogeology section of this report, two hydrologically and genetically separate surficial glacial and alluvial aquifers underlie the study area. Hereinafter these aquifers are referred to as the Windom aquifer, which is glacial, and the Des Moines aquifer, which is glacial and alluvial (fig. 1). The Des Moines aquifer has four relatively hydrologically separate areas. Hereinafter these areas are referred to as the Upper River, Augusta Lake Valley, Red Rock, and Lower River areas (fig. 1).

Previous Studies

Hydrogeological investigations in the study area began as early as 1907 with O.E. Meinzer's USGS investigation of the underground waters of Cottonwood and Jackson Counties (Hall and others, 1911). Meinzer's work is still valuable for its general description of the ground-water systems and for the stratigraphy provided by several deep well logs. A report by Thiel (1944) on the underground waters of Cottonwood and Jackson Counties contains much of the information given by Hall and others (1911) but also contains well logs, ground-water withdrawal data, and water analyses from the ensuing 4 decades. A hydrogeologic atlas of the Des Moines River watershed by Anderson and others (1976) contains geologic maps and sections, potentiometric-contour maps, and surface-water and water-quality data. The surficial aquifers in the study area were described and mapped by Adolphson (1983) as part of a USGS regional reconnaissance in southwestern Minnesota. In that work, the study area aquifers were mapped as part of the Des Moines aquifer. Many local ground-water studies also have addressed hydrogeology in the study area. Those studies were focused on ground-water exploration or water-quality issues and have produced data on aquifer extent, aquifer properties, water quality, and numerical ground-water models. The local studies that produced data used in this study are given in appendix 1.

Acknowledgments

Employees of the MNDNR provided many data, including Cottonwood Lake water levels and a surveyed lake staff gage. Staff of the local water utilities provided timely data and valuable discussions on water-use issues in the study area. Staff and consultants of Cottonwood County (the Solid Waste Division, Highway Department, and Environmental Office), the Windom Cooperative Association agrichemical plant, and the PM Windom meat-packing plant provided historical data and access to wells for water-level measurement and sample collection. Dennis Nelson, the Windom City Administrator, and Dominic Jones, the Red Rock Rural Water System Manager, were instrumental in building and maintaining the public and private coalition that requested and supported this study. Employees of Wenck Associates, Inc., supplied stratigraphic and modeling data and geologic sections of the Windom well-field area. Many landowners also allowed access to and installation of wells on their property. Cathy Martin, a technical editor with the USGS, extensively rewrote and edited the draft report for conformance to USGS policy and style guidelines. Robert Borgstede, an illustrator with the USGS, finalized many of the illustrations.

Study Design and Methods

This study was designed to combine complementary information about water flow and water quality in the study area. An understanding of a ground-water/surface-water flow system reveals much about the sources and fates of chemicals dissolved in the water. Likewise, examination of dissolved chemicals in ground water and surface water can indicate much about the interaction of the flow system that carries the chemicals.

The hydrologic-flow part of this study involved delineation of the aquifer extent in three dimensions, noting aquifer character and variability. Water-table maps produced from ground-water and surface-water levels indicated ground-water flow directions and gradients. The stratigraphic and water-level data were compiled from 334 drilling and test-boring (hereinafter referred to as well) logs. Sources for the well logs include the Minnesota Geological Survey (MGS) County Well Index database, MGS files of well logs not yet entered into the database, the USGS Ground-Water Site Inventory (GWSI) database, USGS files of well logs, and the consultants listed in appendix 1. Because the well logs include water levels measured when the wells were drilled, water-table maps based on these levels are average surfaces for a decades-long period of drilling and do not use every water level from every available log.

The 23 monitoring wells and 5 test holes drilled for this study supplemented the existing data and added stratigraphic detail to the aquifer characterization. Detailed water-table maps that represent various hydrologic conditions were interpreted from 23 synoptic water-level surveys conducted during September 1998–July 2001. The number of water levels measured during the synoptic surveys ranged from 17 to 84 for wells, zero to 5 for river sites, and zero to 1 for lake sites. Continuous water levels, recorded at five wells and two river sites (the U.S. Army Corps of Engineers, Rock Island District, recorded levels at one river site), provided details of water-level fluctuations. Hydrograph separation techniques applied to the continuous water-level hydrographs and rainfall data from the NWS helped define the timing and amount of ground-water recharge. Single-well slug tests were used to estimate aquifer hydraulic conductivity and its spatial variability at 20 5-cm (2-in.) diameter monitoring wells. Historic multiple-well aquifer tests for three water-utility well fields were used to estimate regional aquifer hydraulic conductivity. Streamflow discharge measurements (hereinafter referred to as seepage runs) made on the Des Moines River during periods of low surface-water flow (October 1997, October 1998, and March 2000) were used to estimate the ground-water contribution to streamflow and the spatial distribution of ground-water discharge to the river.

The water-quality part of this study involved sampling water from 18 of the 23 monitoring wells installed for this study, 5 additional monitoring wells, 3 supply wells, 1 unused stock well, and 4 river sites. The 31 sites form a spatial network designed to assess water quality in the study area as a whole (spatial sampling). A subset of these sites (four wells and one river site) forms a temporal network to define variability in water quality with time (temporal sampling). Wells in the temporal network were sampled five times during 1999–2000. The number of samples analyzed for each constituent group during each sampling period is given in appendix 2. Cottonwood Lake was sampled for water isotopic composition once during the summer of 2001.

A two-dimensional, numerical, ground-water flow model served two functions for this study. First, the model was used to verify the conceptual understanding of the flow system and the internal consistency of the data used to construct the model, and, second, the model was used to test the flow-system's response to anticipated future conditions of increased ground-water withdrawals from surficial aquifers, drought, and increased precipitation.

Sites for the wells drilled for this study were chosen to fill spatial gaps in stratigraphic information and to form a well-distributed water-quality sampling network. At the same time, sites were restricted by landowner permission and by accessibility for drilling and sampling vehicles. Surface-water sites were established at each bridge crossing the Des Moines River within the study area, at major tributaries upstream from their confluence with the Des Moines River, and at Cottonwood Lake.

Wells were installed in all test holes where water was encountered during drilling. Wells were constructed of 5-cm (2-in.) diameter, flush-threaded, schedule-40 polyvinyl-chloride casing and screens according to protocols used by the USGS National Water Quality Assessment (NAWQA) program (Lapham and others, 1995). Wells were screened either at the water table or in the uppermost confined aquifer to sample water that was affected by the most recent land use.

Sample Collection and Quality Control

Samples were collected from wells and at river sites using methods designed to obtain a representative sample of the water. Koterba and others (1995) presented the methods used to collect the ground-water samples, and Shelton (1994) presented the methods used to collect the surface-water samples. The samples were analyzed at USGS laboratories using the methods given in appendix 2. Constituents were divided into groups or "schedules" of similar chemicals. The results of a quality-control (QC) program indicated that equipment decontamination procedures generally were successful. The QC data document that herbicide concentrations are accurate to their respective analytical reporting limits, but major-ion and nutrient concentrations near their respective analytical reporting limits may be overestimated. Specifically, concentrations in blank samples that were processed through the sampling equipment after routine decontamination were slightly higher than the analytical reporting limits for several major ions and nutrients. Blank samples are samples of water known to contain major-ion and nutrient concentrations that are less than the analytical reporting limits. Except for fluoride and nutrients, the blank-sample concentrations were much lower than the ambient-sample concentrations. A synopsis of the water-quality sampling methods, departures from those documented by Koterba and others (1995) and Shelton (1994), and QC details are discussed in appendix 3.

Water Levels and Stream Discharge

Ground-water levels were measured during September 1998–July 2001 using a calibrated electric measuring tape. Surface-water levels were measured using a calibrated electric measuring tape, a steel measuring tape, or a staff gage. Water levels measured with those instruments generally are accurate to a nominal 3 mm (0.01 ft) from the site datum, which is referenced to NAVD 88. However, for this study, some river levels were measured from high bridges during high wind conditions and, thus, may be less accurate than the nominal accuracy. Of the 87 well site datums, the altitudes of 79 were surveyed to the nominal accuracy. The altitudes of the remaining eight well site datums were estimated from topographic maps and interpolated between contour lines or from nearby surveyed sites and were accurate to at least ±1.52 m (±5 ft). The surface-water site datums (five river sites and one lake site) were surveyed to the nominal accuracy. Datum altitudes were surveyed by staff of the USGS or the MNDNR or were taken from the consultant's reports given in appendix 1. Synoptic measurements were made within 24 hours during which time no precipitation fell. During the synoptic measurements, flow at 20 sites on ephemeral tributaries of the Des Moines River was noted, but stage was not measured.

Continuous water levels for wells D02, E04, D10, D15, and D17 (fig. 1) were recorded by dataloggers using floats connected to shaft encoders. The continuous river stage recorded at river site DM1 was measured with a pressure transducer installed in a well screen below the riverbed. Equipment-shelter temperature was recorded at all continuous water-level sites as was air temperature at well D02. At wells D02, E04, D10, and D17, the measurements were made hourly, and daily averages and current measurements were recorded at noon. At well D15, the measurements were made hourly, but averages and current measurements were recorded every 3 hours because of the well's proximity to a Windom high-capacity city well. At river site DM1, measurements were made and recorded every 15 minutes. The period of record for all continuous water-level sites is variable but starts in late summer 1998 and ends between mid-summer 2001 and spring 2002.

Des Moines River discharge was measured at river sites DM1 through DM6 during three seepage runs and before sample collection using standard USGS methods (Rantz and others, 1982). During the seepage runs, discharge also was measured in the 20 intermittent tributaries, but most of the tributaries were dry. The discharge measurements are accurate to ±5 percent.

Aquifer-Property Tests and Recharge Estimates

Slug tests were used to estimate aquifer hydraulic conductivity at 20 monitoring wells throughout the study area. Water was evacuated from the well casing by driving the water through the well screen into the aquifer with compressed nitrogen. The gas pressure in the well then was released instantly and the recovery of water in the casing was measured with a pressure transducer. The recovery was recorded every second or whenever the water level rose by at least 7 mm (0.02 ft). Recovery data were analyzed using the empirical Bouwer-Rice solution, modified by Zlotnik (1994), for slug tests in an unconfined aquifer (Bouwer and Rice, 1976; Bouwer, 1989).

Recharge was estimated from hydrographs for wells D02, E04, and D10 because those wells were unaffected by ground-water withdrawals or recharge from nearby surface-water bodies. Exponential decay curves were fit through the recession parts of the hydrographs. The vertical distance between a projected recession curve and the subsequent recharge peak is the ground-water rise from a recharge event. This rise, multiplied by the porosity of the aquifer (assumed to be 0.25), is the amount of recharge from that recharge event. The individual recharge events were summed for each year.

Simulation of Ground-Water Flow

A numerical simulation of ground-water flow in the study area aided in the understanding of the ground-water system and its response to water-management scenarios. The single-layer, steady-state, finite-difference model that was developed simulates ground-water flow using the USGS MODFLOW computer code (Harbaugh and McDonald, 1996). Ground-water flow directions were analyzed using the USGS MODPATH computer code (Pollock, 1994). Model input data were prepared using the ESRI, Inc., ARC/INFO geographic information system software (ARC) and the Department of Defense's Ground-water Modeling System (GMS) software (Environmental Modeling Systems, Inc., 2002). The GMS software also was used as a post processor to visualize simulation results.

The ground-water flow model was calibrated to a set of water-level altitudes, net river flux, and the proportion of lake water in well water in the Windom well-field area. The calibration altitudes included those for 84 ground-water levels and 4 river levels measured on September 30, 1999. After the steady-state ground-water flow model was calibrated, four scenarios were simulated to analyze aquifer response to increased ground-water withdrawals and decreased and increased net recharge (wetter and drier weather conditions).

Hydrogeology

Geology

Although aquifers within the study area are composed of unconsolidated sediments and consolidated bedrock, only the aquifers formed by unconsolidated surficial glacial and alluvial sediments were considered in the study. The unconsolidated sediments lie within a buried bedrock valley (Setterholm, 1990) that extends northwest–southeast from the confluence of the Des Moines River with the stream that drains String Lakes, through Windom. The buried bedrock valley is eroded into Early Proterozoic Sioux Quartzite (greater than 1.47 million years old) (Austin, 1972) to depths of 155 m (508 ft) below the Des Moines River. The Sioux Quartzite is exposed at land surface immediately north of the study area. Between the Sioux Quartzite and the unconsolidated sediments lies a wedge of Late Cretaceous shales and sandstones (89-98 million years old) (Setterholm, 1990; Haq and Van Eysinga, 1994). The wedge thins to the northeast from about 76 m (249 ft) thick on the southwestern edge of the study area where the buried bedrock valley is deepest to zero on the northern edge of the study area. Both the Sioux Quartzite and the Cretaceous sandstones can yield water to wells.

Within the study area, the present-day topography and surficial deposits are of glacial origin. The study area is located on the first lateral recessional moraine (the Altamont Moraine) of the Des Moines Lobe of the Laurentide Ice Sheet (Hobbs and Goebel, 1982). During the Altamont glacial phase (13,000 years before present; Gilbertson, 1990), the western margin of the Des Moines Lobe turned immediately northwest of Windom, from a southeastern to a southern direction, and formed a re-entrant in the ice margin. As the glacier melted, materials contained therein were deposited as hummocky glacial till upon deposits that filled the bedrock valley during earlier glacial advances. The re-entrant in the ice margin effectively concentrated meltwater and sediment from the southern and southwestern sides of the glacier into the study area. The meltwater streams formed by the glacier eroded the present-day Des Moines River and Augusta Lake Valleys, perhaps down to bedrock. Then, as the sediment load increased or the meltwater volume decreased, outwash sediment was deposited in the eroded valleys. Concurrently, ablation till from melting ice slumped, and adiabatic winds deposited loess into the valleys. Braiding meltwater streams continued to rework the sediments within the study area.

The depositional history of the study area produced glacial valley-fill deposits composed of the full range of unconsolidated sediments, including poorly sorted to well-sorted gravels, sands, and silts; loess (wind-deposited silt); clays; minor peats; and interbedded slumped ablation tills. None of the individual sediments is areally extensive nor is there a general sequence of sedimentation across the study area. The glacial sediments adjacent to the present-day course of the Des Moines River have been alluvially reworked and are of Holocene age. Both the Wisconsinan (glacial) and Holocene sediments were deposited primarily in a river environment and are difficult to distinguish. Because of their similar depositional environments, these sediments are hereinafter collectively referred to as glacial sediments.

Surface Water

The Des Moines River is the only perennial river in the study area. The till uplands that flank the valley are drained by intermittent rivers. The larger intermittent rivers, some of which begin at lakes, have channels that extend across the surficial aquifers to the Des Moines River. Some of the intermittent rivers end where they begin to cross the valley, and, at that point, recharge the ground water as they flow onto the aquifers. Ditches as deep as 5 m (16 ft) currently (2000) drain the Augusta Lake Valley. These ditches probably follow the pre-ditch intermittent rivers that once drained the valley.

The Des Moines River is incised several meters into the valley sediments across most of the study area. Flow in the river is highly variable, and periods exist when no flow occurs. Since 1936, the USGS has continuously measured flow at Jackson, about 32 km (20 mi) south of Windom. Although relatively little precipitation occurred in the study area during 1997–2001 (fig. 2), the median flow for the Des Moines River at Jackson was 43 percent higher during that period than during the entire period of record [3.40×10^5 m^3/d (139 ft^3/s) compared to 2.37×10^5 m^3/d (97 ft^3/s)]. The Des Moines River was dammed in Windom during previous years. The remnant of this dam still creates a pool and adjacent permanent wetlands about 3 km (2 mi) upstream from the dam. Within the study area, the intermittent rivers that have the greatest flow are the ditches that drain the Augusta Lake Valley and the stream that drains the Warren-Cottonwood Lakes chain. During periods of no runoff, groundwater usually discharges to the Des Moines River and the ditches in the Augusta Lake Valley, thus sustaining flows in the river and ditches.

Lakes and wetlands are common throughout the study area except in the Augusta Lake Valley. Wetlands are particularly numerous east of Windom and along the Des Moines River. Many wetlands are ephemeral and exist only during and immediately after spring snowmelt. Most permanent wetlands lie along the Des Moines River or adjacent to lakes.

Ground Water

Description of Aquifers

The study area contains two hydrologically separate surficial aquifers of different origin. The Windom aquifer formed as a small outwash plain, probably in a very small re-entrant in the Des Moines Lobe ice margin, east of the outwash stream that drained the main ice margin. The Des Moines aquifer formed as the outwash stream waned and is composed of four relatively hydrologically separate areas—the Upper River, Augusta Lake Valley, Red Rock, and Lower River areas (figure 1 for areas and figure 4 for aquifer connectedness). The Upper River area, which is thin and insignificant (fig. 4), will not be discussed further in this report. The hydrologic properties for the Windom aquifer and for the remaining three areas of the Des Moines aquifer are given in table 2. Aquifer thicknesses and control-point (geologic log) locations are shown in figure 4.

The Windom aquifer is structurally more complex, finer grained, and more variable than the Des Moines aquifer. The main part of the aquifer lies southwest of Cottonwood Lake (fig. 4). The Windom well field is centered in the thickest and most productive part of the aquifer. Beginning near the west shore of Cottonwood Lake, the aquifer splits eastward into a surficial and two or more buried parts. The surficial and buried parts are separated vertically by till. The surficial part of the aquifer thins rapidly in all directions from the Windom well-field area. The maximum measured saturated thickness is 34 m (111 ft). The Des Moines aquifer generally is lens-shaped across the Des Moines River Valley and has an undulating bottom along the valley. The maximum saturated thickness is about 33 m (108 ft).

The Windom aquifer consists of a variety of unconsolidated sediments. Although fine sand is dominant, the sediments range from well-sorted clay, silt, or sand to pebbly sand loam or till. The sediments often are less than 1 m (3 ft) thick and complexly interbedded. Individual layers usually are not traceable between boreholes that are 100 m (320 ft) apart. The first substantial amount of till [greater than 2 m (6 ft)] marks the bottom of the surficial part of the aquifer. However, in the Windom well-field area, the surficial and buried parts of the aquifer from Cottonwood Lake to the east interfinger with the strictly surficial part. The areal extent and the degree of surficial connection of the buried parts of the aquifer are unknown. Sediments in the area to the northeast of Cottonwood Lake and in the area that surrounds Wolf Lake are thin and very fine grained. The area that surrounds Wolf Lake lacks underlying, interfingered, buried parts and is composed mostly of silt.

The Des Moines aquifer in the Augusta Lake Valley area is relatively homogeneous. Most of the aquifer sediment consists of poorly sorted loamy sand to gravel that was deposited by sediment-choked streams. Lenses of well-sorted sands, silts, and clayey diamictons that are 2 to 7 m (5 to 20 ft) thick occur within the sediment. The diamictons probably are ablation tills that slumped off the melting ice front into the valley and hereinafter will be referred to as till. Most tills probably were altered by meltwater in the valley, and some actually may be clay overbank deposits. The areal extent of the sand, silt, and till lenses is unknown, but some of the lenses, particularly a surficial well-sorted sand lens that occurs in the area, may be extensive. The aquifer sediment lies directly on Sioux Quartzite in the northern part of the study area where bedrock is close to the surface and on till in the southern part of the study area.

The Des Moines aquifer in the Red Rock area is composed of very well sorted medium sand with some gravel and is isolated from other parts of the aquifer by till at or near the surface. The Red Rock Rural Water System well field is located in this area. Some well logs indicate that till layers as much as 6 m (20 ft) thick occur in the area. However, no layers can be traced more than 100 m (320 ft), and the till layers seem much less frequent than in other areas of the aquifer. Some well logs also indicate that some seams of coal or wood fragments occur in the area. The aquifer in this area is underlain by till and is similar to the part of the aquifer in the Lower River area.

The Des Moines aquifer in the Lower River area consists mostly of the poorly sorted loamy sand to gravel that is exposed in gravel pits throughout the area. The sediment is somewhat more poorly sorted than that in the Augusta Lake Valley area. Also, the lenses of well-sorted sands, silts, and clayey diamictons that occur in the area can be much thinner [less than 0.1 m (0.3 ft)], more numerous, and less extensive than those in the Augusta Lake Valley area. The aquifer in the Lower River area is thin [less than 2.5 m (8 ft)] at the northern end where it abuts the Red Rock area and along Minnesota Highway 60 from Warren Lake through Windom and farther south. The aquifer sediments are very well sorted and thick near wells D09 and D10 and are similar to the aquifer sediments in the Red Rock area. At well D10, for example, the sediments consist of more than 21 m (70 ft) of very well sorted medium to coarse sand. The aquifer in this area is underlain exclusively by till.

The junction between the Windom and Des Moines aquifers occurs along the change in topographic slope south and east of U.S. Highway 71 in Windom. This junction is thin [about 3 m (10 ft)], mostly unsaturated, and composed of poorly sorted silty sand and gravel. The aquifers are hydraulically connected, but ground-water flow interaction probably is small because of the low transmissivity of the junction materials and the thin saturated thickness.

Recharge and Discharge

Recharge to surficial aquifers in the study area is from vertical infiltration of rainfall and snowmelt (areal recharge), from surface waters (Cottonwood Lake to the Windom aquifer), from infiltration of overland flow from till uplands, and from hori-

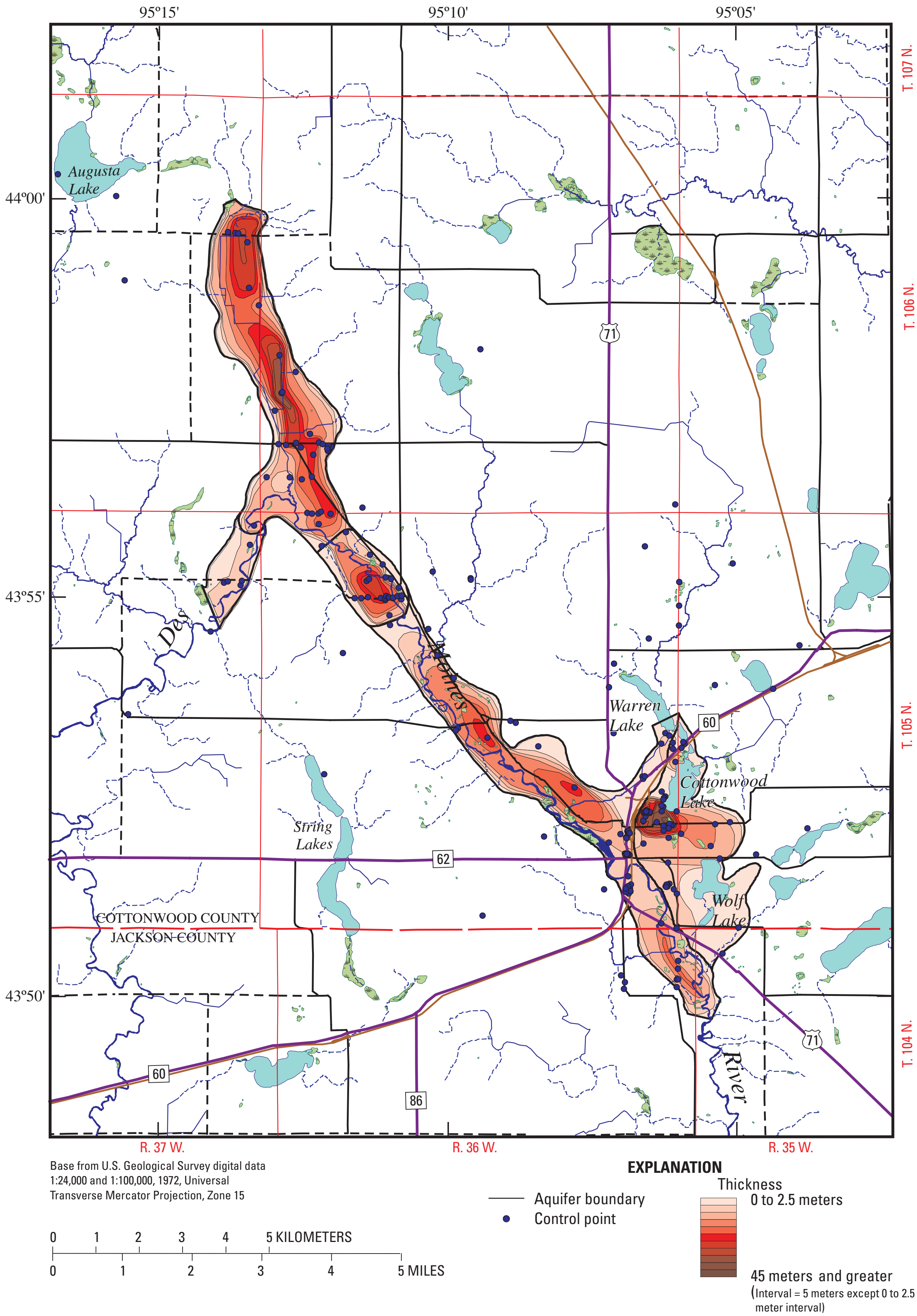

Figure 4. Aquifer thickness, Des Moines River study area, southwestern Minnesota.

Table 2. Hydrologic properties for the Windom and Des Moines aquifers, Des Moines River study area, southwestern Minnesota.

[ha, hectares; m, meters; >, greater than; m/d, meters per day; —, not determined; m^3/d, cubic meters per day; Min, minimum; Max, maximum; ft, feet; ft/d, feet per day; in/yr, inches per year; ft^3/s, cubic feet per second]

	Units	Windom aquifer	Des Moines aquifer		
			Augusta Lake Valley area	Red Rock area	Lower River area
Area	ha	840	1,154	272	1,486
Maximum thickness	m	44.2	36.3	26.2	>21.6
Maximum saturated thickness	m	33.8	32.9	22.3	>20.4
Maximum water depth	m	17.4	8.8	6.1	5.5
Hydraulic conductivity					
Slug tests	m/d	0.02–0.95	0.57–9.95	4.83–64.43	0.07–41.4
Aquifer tests	m/d	21–142	6–11	75–560	—
Digital simulation	m/d	0.5–30	90	80	90
Net areal recharge rates					
Hydrographs	m/d	—	3.6×10^{-4}–1.7×10^{-3}	—	7.1×10^{-4}–1.7×10^{-3}
Digital simulation	m/d	6.0×10^{-5}–4.5×10^{-4}	3.5×10^{-4}	6.0×10^{-4}	3.5×10^{-4}
Discharge rates					
Wells (total per aquifer or area)	m^3/d	3,634	473	1,432	186
Net discharge to streams (total area)			Min / Max		
Seepage measurements	m^3/d		25,934 / 71,293		
Digital simulation	m^3/d		76,457		

	Units	Windom aquifer	Des Moines aquifer		
			Augusta Lake Valley area	Red Rock area	Lower River area
Area	acres	2,076	2,852	673	3,671
Maximum thickness	ft	145	119	86	>71
Maximum saturated thickness	ft	111	108	73	>67
Maximum water depth	ft	57	29	20	18
Hydraulic conductivity					
Slug tests	ft/d	0.07–3.12	1.86–33	16–211	0.22–136
Aquifer tests	ft/d	69–466	20–36	246–1,840	—
Digital simulation	ft/d	1.6-98	295	262	295
Net areal recharge rates					
Hydrographs	in/yr	—	5.2–23.9	—	10.2–23.7
Digital simulation	in/yr	0.9-6.5	5	8.6	5
Discharge rates					
Wells (total per aquifer or area)	ft^3/s	1.49	0.19	0.59	0.08
Net discharge to streams (total area)			Min / Max		
Seepage measurements	ft^3/s		10.6 / 29.14		
Digital simulation	ft^3/s		31.25		

zontal seepage of water from tills and thin sands and gravels along the aquifer edges (edge recharge). Net areal recharge (total recharge minus evapotranspiration) to the Des Moines aquifer varied spatially and temporally within less than half an order of magnitude [from 0.00036 to 0.0017 m/d (5.2 to 23.9 in/yr); table 2] (18 to 82 percent of the 30-year average precipitation). The net areal recharge was estimated from ground-water hydrographs recorded for the Des Moines aquifer during 1997–2001.

Using an average net areal recharge rate of 0.0006 m/d (8.6 in/yr) for the Des Moines aquifer, total annual net areal recharge was 8.223 million m^3/yr (2,172 Mgal/yr). This average rate is greater than the net areal recharge rate of 0.00023 m/d (3.27 in/yr) estimated for a comparable aquifer in the Luverne area (Lindgren and Landon, 2000). However, Luverne receives about 25 mm (1 in.) less precipitation per year, and the sediments in that area are less conductive than those in the Des Moines aquifer.

The annual net areal recharge estimate is a maximum. Assuming that soils developed in less conductive parent material will convey less precipitation to the water table, the Windom aquifer, which is less hydraulically conductive than the Des Moines aquifer, probably receives less net areal recharge than the Des Moines aquifer. The thick, permeable northern part of the Windom aquifer is about 5 km^2 (2 mi^2) in area. Therefore, assuming an average net areal recharge rate of 0.0003 m/d (4.3 in/yr; one-half that of the Des Moines River aquifer), 42 percent of the water withdrawn from the Windom well field is from areal recharge. The remaining 58 percent of the water withdrawn from the well field must be from recharge from Cottonwood Lake or flow from interfingered buried aquifers to the east of the lake. Discharge from the Windom aquifer is primarily to municipal wells [1.291 million m^3 (341 Mgal) in 2000] and to surface waters, especially to the creek northwest of Cottonwood Lake.

Edge recharge (recharge to an aquifer at its horizontal edges) can be from infiltration of overland flow from till uplands that surround an aquifer, from infiltration of intermittent streamflow that drains the uplands, or from horizontal discharge of aquifers buried in the till uplands. For this study, no independent measurement of edge recharge was made. Rather, the magnitude of edge recharge was estimated using the numerical flow model constructed for the study.

The Des Moines aquifer discharges primarily to the Des Moines River, to ditches in the Augusta Lake Valley, to wetlands, and to other streams or ditches in the area. The aquifer also discharges by evapotranspiration near lakes, wetlands, streams, and ditches and to wells. The drought conditions that existed in the study area during 1997–99 were ideal for the measurement of net ground-water discharge to the Des Moines River. Measurements were made during October 1997, October 1998, and March 2000 when baseflow conditions occurred and flow in the Des Moines River was assumed to be entirely ground-water discharge. However, the release of water from Warren Lake to harvest fish compromised the 1998 measurement, and the 2000 measurement was made after an 8-month period of very low precipitation and no ground-water recharge, as indicated by well hydrographs. Therefore, the 1997 measurement of about 71,000 m^3/d (29 ft^3/s) probably is the most typical and applicable to a steady-state model of ground-water flow. Assuming that all discharge from the ground-water system was to the Des Moines River and that the 71,000 m^3/d (29 ft^3/s) is average for the year, net ground-water discharge to the Des Moines River was 26.04 million m^3/yr (8,879 Mgal/yr). Thus, the annual net areal recharge estimate accounts for about 32 percent of the flux through the ground-water system. Presumably a large part (68 percent) of the ground water that flows in the Des Moines aquifer is from edge recharge.

The amount of water discharged to other surface waters in the aquifers is unknown. However, the amount probably is small because these waters are located relatively high in the ground-water basin. Ground-water discharge to wells, some of which is exported from the basin through the rural water system and industrial use, also is small [about 2.13 million m^3/yr (563 Mgal/yr) or 8 percent of the ground-water flux]. Most of the ground water used in Windom is discharged to the Des Moines River at the wastewater-treatment plant outflow near Wolf Lake.

Ground-Water Flow

The direction of ground-water flow in the thick, permeable western part of the Windom aquifer is from the south and east toward the Windom well field. Because aquifer material to the north and east is thin and the hydraulic gradients are low, substantial amounts of ground water are not conducted in that area. A ground-water mound lies between Wolf Lake and the Des Moines River in the southern half of the Windom aquifer. The steep hydraulic gradients on this mound indicate the permeability of the aquifer in that area is low and suggest that the area has relatively little ground-water flow.

The direction of ground-water flow in the Des Moines aquifer is primarily from the aquifer edges at the valley walls toward the Des Moines River near the valley center (fig. 5; flow typically is perpendicular to the water-table contours). In the Augusta Lake Valley area, flow is toward the ditch system near the valley center but also toward the south, down the valley axis. Asymmetrically steep hydraulic gradients occur on the east side of this area. Little water enters the aquifer at the north end of the Augusta Lake Valley because the aquifer at that point is narrow and thin. The aquifer may extend upstream from the Upper River area and downstream from the Lower River area, but hydraulic gradients downstream appear to be shallow and ground-water flow into and out of the modeled area is assumed to be small. The Des Moines aquifer is thin [2 to 3 m (6 to 10

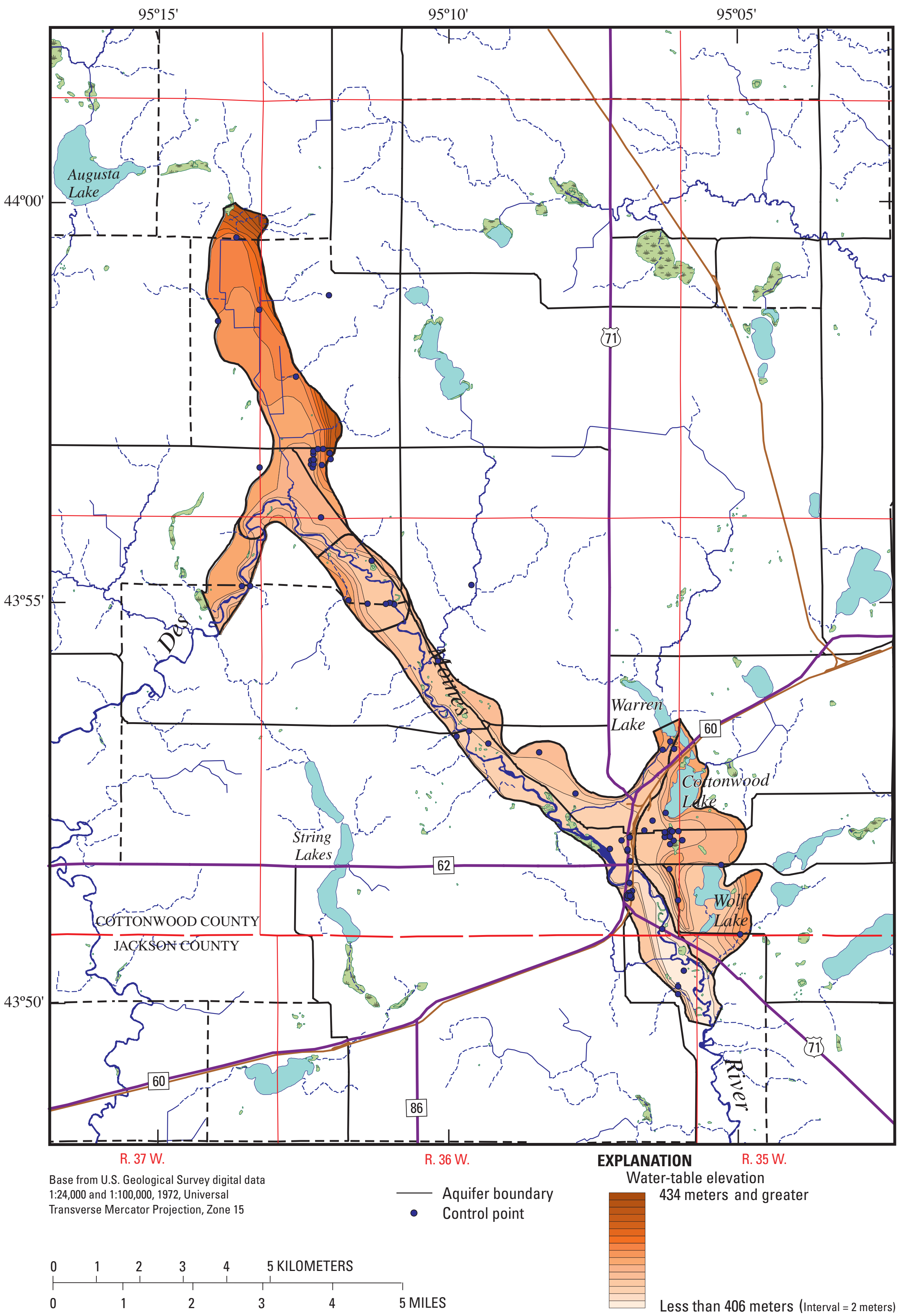

Figure 5. Water-table elevation, Des Moines River study area, southwestern Minnesota, September 30, 1999.

ft)] at the upstream end of the river area, but the nature of the aquifer at the downstream end is unknown. Adolphson (1983) mapped the aquifer as continuing south of the study area, down the Des Moines River Valley, but thinning. Although stratigraphic information does not exist for that area, the assumption that the aquifer thins is reasonable because of the variability of aquifer thickness in the study area.

Ground-Water/Surface-Water Interactions

During dry periods, ground-water discharge sustains flow in the Des Moines River and its larger tributaries. When the water level in the Des Moines aquifer is less than the level of the riverbed, flow in the river approaches zero. During periods of high surface-water levels (runoff from spring snowmelt or intense rainfall), surface water recharges the aquifer as indicated by the hydrograph for well D10 (fig. 6). Ground-water levels decline despite rainfall (May 10–11, June 12, July 5) when the ground-water level is higher than the river level and rise despite almost no rainfall (May 19 through June 10) when the ground-water level is lower than the river level. The small measured gain in streamflow during March 2000, after 8 months of very low precipitation and no ground-water recharge, is an example of the effect of low ground-water conditions when discharge to the river nearly ceased. Within the last 30 years, the Des Moines River has stopped flowing at Jackson during four periods, the longest of which was 47 days. During the period of record (1931–2001), the river has stopped flowing during 18 periods, the longest of which was 175 days during 1955–56.

Ground-water withdrawals from the Windom and Red Rock well fields change the natural ground-water/surface-water interactions substantially. The Windom well field is composed of seven actively pumped wells that range from 25 to 30 cm (10 to 20 in.) in diameter. Of the seven wells, four are located less than 200 m (660 ft) southwest of Cottonwood Lake, and three are located 500 to 600 m (1,600 to 2,000 ft) southwest of Cottonwood Lake. Combined, these wells pumped about 1.3 million m^3 (343 Mgal) of water in 2000. The Windom well field captures the equivalent volume of all water that infiltrates into the northern one-half of the Windom aquifer (fig. 5).

During the first half of this study, water levels in well D16, within the Windom well field, were slightly higher [at a maximum of 1.36 m (4.46 ft)] than those in well D13, between the well field and the Des Moines River. Thus, a hydraulic gradient existed that potentially could allow water to flow from Cottonwood Lake to the Des Moines River. After June 2000, water levels in well D13 were higher [at a maximum of 1.38 m (4.53 ft)] than those in well D16 and a ground-water divide formed between the Windom well field and the Des Moines River. This divide probably existed before June 2000 because the pumped wells would have had water levels that were lower than those in nearby monitoring wells. If water levels continue to fall in the area of the Windom well field, a hydraulic gradient could exist that potentially would allow water to flow from the Des Moines River to the Windom well field. The amount of flow would be negligible, however, because the aquifer between the river and the well field is less than 4 m (14 ft) thick and has a saturated thickness of only about 1 m (3 ft).

The Red Rock well field is composed of three wells that are 30 cm (12 in.) in diameter. The wells are located in the Red Rock area of the Des Moines aquifer within 200 m (660 ft) of the west bank of the Des Moines River. Combined, these wells pumped about 500,000 m^3 (132 Mgal) of water during 2000.

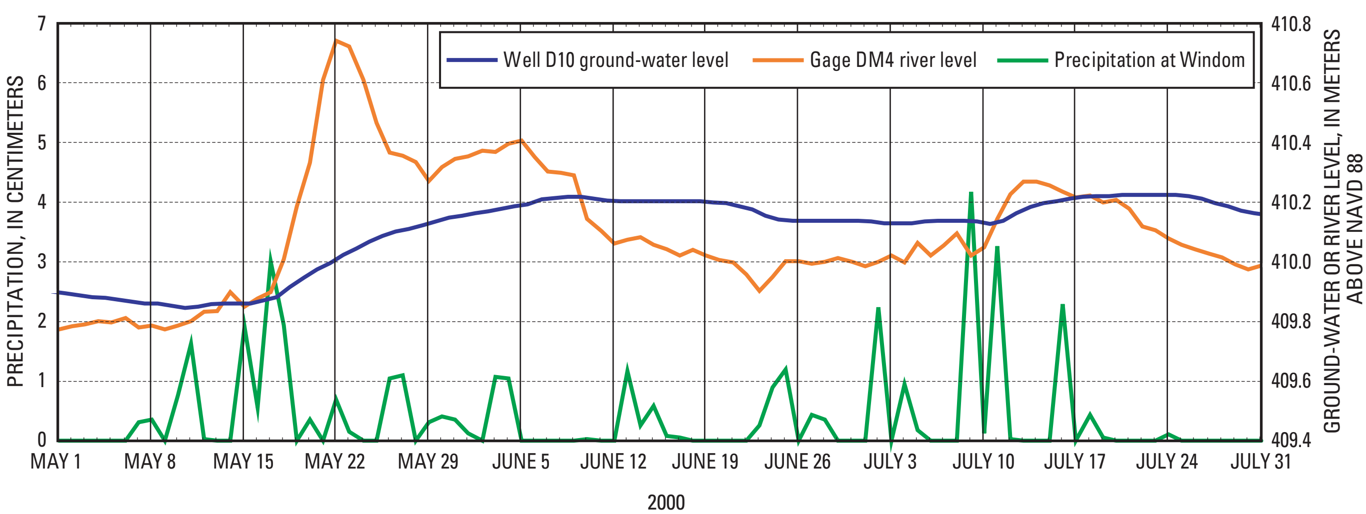

Figure 6. Ground-water levels, river levels, and precipitation near Windom, Minnesota, May–July 2000.

During this study, the water level in well D24, between two of the Red Rock wells and the river, was lower than the river level during two periods. The longest period occurred during December 1999–February 2001 when the water level in well D24 was as much as 0.319 m (1.05 ft) lower than the river level. During the two periods, water in the Des Moines River had the potential to recharge the aquifer. The amount of water that may have infiltrated is unknown but would have been dependent on the permeability of the riverbed sediments and the availability of water in the river. The riverbed sediments appear to be quite permeable in this area because substantial amounts of ground water discharge to the river in the area. At least once during the 1999–2001 period, the Des Moines River stopped flowing at the Red Rock well field (Rod Owre, Minnesota Department of Natural Resources, written commun., 2000).

Ground-Water Sources from Water Isotopes

The isotopic composition of ground water can yield information about the sources and seasonal timing of recharge. For settings where ground water may be recharged either from precipitation or leakage from surface water, the hydrogen and oxygen isotopes in the ground water can be used to estimate the amount of water each recharge source contributed to the ground water. This technique relies on the determination of a local relation between the isotopes of hydrogen (δ^2H) and the isotopes of oxygen ($\delta^{18}O$) in precipitation. The relation is called the local meteoric water line. Surface waters generally deviate from the local meteoric water line because the water molecules that are composed of relatively light isotopes preferentially evaporate and leave behind water molecules that are composed of relatively heavy isotopes. The isotopic composition of ground water whose source is a combination of precipitation and surface water will fall on a line between the local meteoric water line and the isotopic composition of the surface waters. The position on this line represents the proportion of ground water recharged from each source.

The isotopic compositions of ground-water samples collected in the study area and of Cottonwood Lake are shown in figure 7. The composition of most of the ground-water samples falls on a straight line (r^2 equals 0.97) that is similar to the local meteoric water line for precipitation near Princeton (Landon and others, 2000). The weighted mean oxygen isotope composition for the precipitation near Princeton and for the sites used in this study was calculated from global regression models (Yurtsever and Gat, 1981). The mean composition falls near the center of the compositions for ground water in the study area and near the composition for the precipitation near Princeton.

Ground-water samples collected from wells D08, M017, and M103 and the sample collected from Cottonwood Lake are isotopically heavier than precipitation and, thus, have an evaporative signature. The compositions of these samples fall on a line between the calculated isotopic composition of precipitation and the isotopic composition of the sample from Cottonwood Lake. Assuming the sample from Cottonwood Lake is representative of all surface water in the study area that has undergone evaporation, the line from the calculated composition of precipitation to the Cottonwood Lake sample forms a local surface-water evaporation line (fig. 7). The compositions of ground-water samples that are recharged from both precipitation and surface water that has undergone evaporation will fall

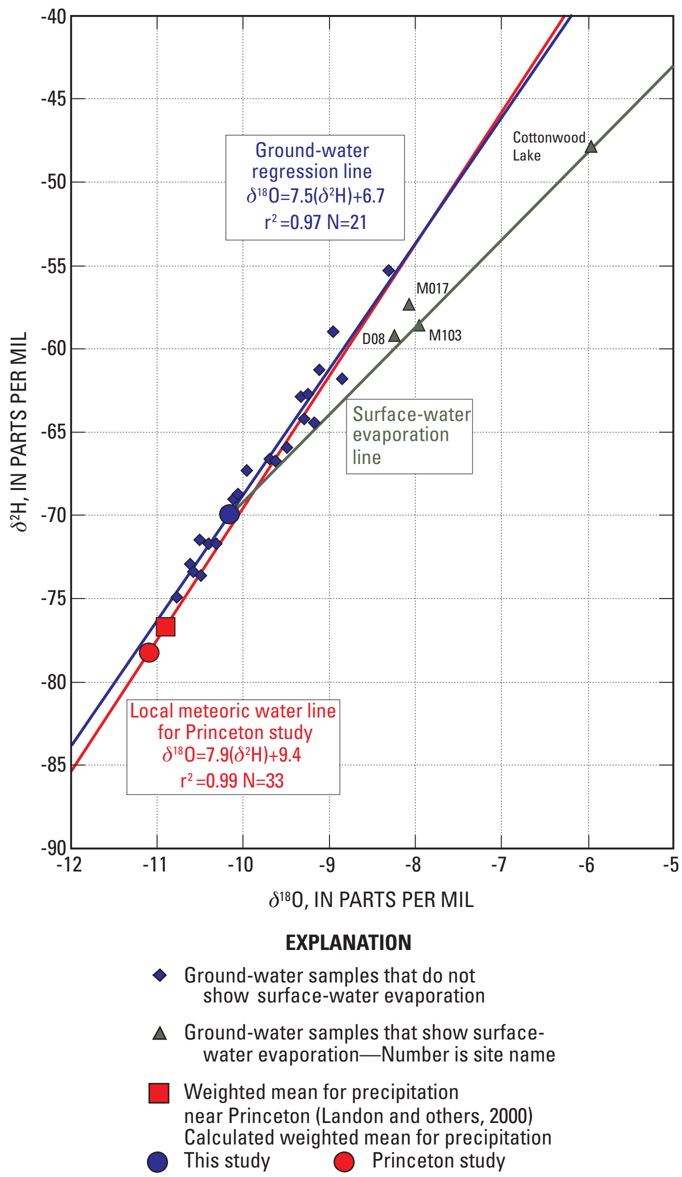

Figure 7. Isotopic compositions of ground-water samples and Cottonwood Lake, Des Moines River study area, southwestern Minnesota.

on this line. The position on the line indicates the proportion of water from each recharge source.

Well M103 is Windom city well number 8 (Minnesota Unique Well Number 490926). This well has two possible surface-water recharge sources: Cottonwood Lake and a small pond located immediately south of the lake. The pond possibly could have had a different composition than Cottonwood Lake because, during 1990–99, the pond received return effluent from a ground-water contamination treatment system located at the former city dump adjacent to the pond. The system sprayed ground water contaminated with organic compounds into the air to remove the contaminants by evaporation (Mike Haugen, Superintendent, Windom City Water Department, oral commun., 2000). Because of the evaporation caused by this treatment, the isotopic composition of the pond water probably was heavier than the isotopic composition of Cottonwood Lake. Results from the calibrated ground-water flow model used for this study (see Simulation of Ground-Water Flow section) indicate that, when the sample was collected from well M103 during July 2001, water recharging from the pond had not yet reached the well. Therefore, any surface water contained in the sample was assumed to originate primarily from Cottonwood Lake. Using the isotopic mixing analysis presented and assuming all recharge affected by evaporation was from Cottonwood Lake, about 52 percent of the water pumped from well M103 was from Cottonwood Lake. Wells closer to the lake have more of their capture zones within the area of the lake. Thus, a higher percentage of the water pumped from those wells would come from the lake. The estimated percentages are conservative because the isotopic composition of Cottonwood Lake during July 2001 probably was near its heaviest point during the year as a result of high evaporation during the summer. Because the average isotopic composition of Cottonwood Lake probably is lighter than during July 2001, more than 52 percent of the water pumped from well M103 probably was from Cottonwood Lake.

Well M017 is a monitoring well that is located next to the effluent pond of a meat-packing plant. The pond probably is the source of the water affected by evaporation in the well. The water in the pond evaporates from the pond surface and also during the meat-packing process.

Well D08 is a monitoring well that is near, but not adjacent to, an intermittent stream that drains a wetland. This stream, however, probably does not have sufficient flow to supply enough water affected by evaporation to the aquifer to fully explain the isotopic composition of the sample from the well.

Ground-Water Age from Dissolved Gasses

Ground-water age, which is the amount of time elapsed after water enters the ground as recharge, is useful for calibrating ground-water models and delineating well contributing areas. Water recharged more recently is termed “young”. The age for water in 25 wells used in this study (table 3) was determined using dissolved gas concentrations of three chlorofluorocarbon (CFC) compounds or sulfur hexafluoride (SF_6). However, because the water from two of the wells (wells D15 and M095) was contaminated with CFC compounds or SF_6, the ground-water ages for that water were invalid. The details of using CFC compounds or SF_6 to date ground water are given by Plummer and Busenberg (1999) and Busenberg and Plummer (2000).

In general, water infiltrates to the water table, builds up, and begins to flow horizontally. Thus, ground water is progressively older with depth below the water table and along the flow path. Further, the deeper the water is beneath the water table, the farther upgradient the water entered the ground as recharge. The thickness of a water layer that contains the recharge from 1 year will decrease with depth because some water is lost to discharge each year. Ground water begins to age when recharge reaches the water table, fills the voids in the unsaturated zone, and becomes isolated from the atmosphere. Therefore, water collected from areas that have a deep water table will appear young compared to water collected from areas that have a shallow water table. In all age dating, the assumption is made that ground water behaves like piston flow from recharge to discharge areas. However, edge recharge also is important in the aquifers in the study area. Water that enters an aquifer at the edges may be a complex mixture of runoff infiltration, buried-aquifer discharge, and areal recharge. Therefore, the apparent ages determined with CFC compounds or SF_6 may be from waters of many ages.

Ground-water ages determined for this study are composites for all water that enters the well screen. The ages for water collected from wells that have short screens are the most precise because only a vertically thin part of the aquifer is sampled. The ages for water collected from large water-supply wells that have long screens are skewed younger than the mean age of the water because a thick part of the aquifer is sampled and the water ages may vary by several decades through the screened interval. Assuming that water is drawn into a well evenly along the length of the screen and completely mixed in the well bore, young water will provide exponentially more CFC compounds and SF_6 to the composite sample because the concentration in the atmosphere increases exponentially with time. Therefore, the resulting composite age for water from wells that have long screens is skewed younger. For this study, all but four samples were collected from monitoring wells that had short screens [less than 1.52 m (5 ft)]. The exceptions were one 0.9-m (36-in.) diameter, unused livestock well (well E10) and three high-capacity public-supply wells (wells M101 through M103).

The ground-water age determinations for this study are given in table 3. Ground water in 21 of the wells was less than 30 years old, and ground water in 18 of the wells was less than 20 years old. Well D06 was screened in a confined aquifer out-

Table 3. Ground-water recharge dates and related well data, Des Moines River study area, southwestern Minnesota.

[Ground-water recharge date shading, darker is older; SF_6, sulfur hexafluoride; —, contaminated with all dating compounds; CFCs, chlorofluorocarbon compounds; CFC, chlorofluorocarbon; methane shading, methanogenic conditions; ND, not determined]

Site name	Ground-water recharge date	Dating tracer	Ground-water temperature (degrees Celsius)	Contamination	Degradation	Excess air (milligrams per liter)	Excess nitrogen gas (milligrams per liter)	Methane (milligrams per liter)	Depth from water table to top of screen (meters)	Screen length (meters)	Well depth (meters)	Depth to top of screen (meters)	Depth to bottom of screen (meters)	Well diameter (centimeters)	Water level (meters)	U.S. Geological Survey site number
D02	1983	SF_6	11	—	—	0.988	9.15	0.026	2.03	1.30	8.05	6.56	7.86	5.18	4.53	435842095132001
D03	1973–77	CFCs	6.6	CFC–113	—	1.489	2	0	4.31	1.30	7.53	6.04	7.34	5.18	1.73	435748095122901
D05	1988	SF_6	11.2	—	—	1.783	0	0	1.94	1.30	5.97	4.49	5.79	5.18	2.55	435533095111601
D06	1944–54	CFCs	3.9	CFC–113	—	6.134	0	0.010	5.71	1.30	7.02	5.54	6.83	5.18	-.17	435515095093601
D08	1994.5	SF_6	13	—	—	2.410	2	0	2.76	1.30	9.33	7.84	9.14	5.18	5.08	435417095101001
D09	pre–1940	CFCs	5.3	CFC–113	—	3.668	0	.206	7.67	1.30	12.22	10.76	12.05	5.13	3.08	435320095094901
D10	1985	CFCs	4.7	CFC–113 CFC–11	—	1.156	2	0	2.23	1.30	7.74	6.26	7.56	5.18	4.03	435310095082501
D11	1994	SF_6	5.9	Both contaminated		.331	2.5	0	1.94	1.30	6.18	4.69	5.99	5.18	2.74	435315095091601
D15	ND	CFCs	5.6	All CFCs	—	2.821	4	0	1.53	2.82	12.52	9.51	12.33	5.18	7.98	435211095063701
D16	1993–95	CFCs	9.6	—	CFC–11	1.757	1	0	.84	1.30	13.14	11.66	12.95	5.18	10.82	435218095062801
D18	1983–84	CFCs	6.6	CFC–113	CFC–11	-.020	4	0	1.47	1.49	10.88	9.39	10.88	5.18	7.92	435145095051701
D21	1988.5	SF_6	13.3	—	—	5.591	1	0	-.49	1.30	11.43	2.81	4.11	5.18	3.30	435014095060201
D22	1990.5	SF_6	12	—	—	7.987	0	0	.82	1.30	4.30	2.81	4.11	5.18	1.99	435008095060301
D24	1985–87	CFCs	3.9	CFC–113	CFC–11	4.855	1	.185	.28	1.30	6.26	4.76	6.06	5.18	4.48	435500095105701
D25	1971	CFCs	9.7	CFC–113	CFC–11	.389	6	0	4.06	1.30	8.98	7.60	8.90	5.18	3.55	435934095134701
D28	1989–94	CFCs	5.9	CFC–113	CFC–11	.454	2	0.001	1.09	1.30	6.21	4.75	6.04	5.13	3.66	435239095074801
D32	1981	SF_6	12	—	—	4.961	2.5	0	3.99	1.30	9.09	7.63	8.93	5.13	3.64	435054095045801
E04	1990	SF_6	7.9	—	—	1.291	6.5	.705	12.59S	1.5	19.26	17.74	19.26	5.13	5.15	435605095121201
E06	1983	CFCs	3.9	CFC–113	CFC–11	2.981	12	0	17.35S	3.0	24.38	21.34	24.38	5.1	3.99	435500095112401
E10	1970	CFCs	3.7	CFC–113	CFC–11	1.441	3	.029	ND	ND	4.59	ND	ND	ND	1.50	435026095055601
M017	1984	SF_6	11	—	—	15.164	0	18.143	.83	3.0	4.88	1.83	4.88	5.1	1.00	435311095061801
M095	ND	SF_6	9.2	SF_6	—	.551	1	0	-1.83	3.0	6.1	3.0	6.1	5.1	4.87	435647095122201
M101	1992	SF_6	6.3	—	—	3.197	9	.002	ND	ND	25.9	ND	ND	ND	9.45	435514095112201
M102	1984.5	SF_6	6.6	—	—	6.419	0	.050	ND	ND	29.0	ND	ND	ND	3.89	440426095112401
M103	1983.5	SF_6	7.4	—	—	.405	4.5	.016	ND	ND	40.8	ND	ND	ND	17.07	435217095063401

side the Windom and Des Moines aquifers and contained water that was 45-55 years old. The screened interval for well D09 is 7.67 m (25.18 ft) below the water table. Water that deep should be substantially older than water at the water table. Further, water from well D09 contained methane, indicating highly reducing conditions that may have degraded the CFC compounds upon which the age determination relies. Thus, the ground-water age determined for water from that well may be greater than the actual age. The general youth of the ground water represents the bias of the samples. Because most of the wells had short screens that intersected the water table, the water sampled would be expected to be young.

The three production wells sampled in this study also were sampled for age-dating gasses. The production wells, which are located near monitoring wells, have deep, long screens compared to the adjacent monitoring wells. The water in Windom city well number 8 (well M103 in this study) is about 17 years old, and the water in the adjacent monitoring well (well D16) is 5 years old. However, the actual difference between the mean ages of the water from those two wells probably is even greater than 12 years because the production-well screen is four times longer than the monitoring-well screen and the age of water from the production well is skewed younger. The remaining production wells do not show the same pattern. The water in Red Rock Rural Water System well number 3 (well M101 in this study) is 8 years old, which is younger than the water in the nearby monitoring wells (wells D24 and E06). The water in those wells was 13 and 16 years old, respectively. Well M101 may have younger water because its proximity to the Des Moines River may allow modern river water (age equals zero) to be induced into the well. Water from the Jeffers city well (well M102 in this study) also was younger than water from the adjacent monitoring well (well D25). The water in those wells was about 16 and 28 years old, respectively. A possible explanation for the young water in well M102 is aquifer heterogeneity, which is common in this area. Well M102 may be completed in a conductive channel-like deposit that transmits water faster than the surrounding aquifer.

Water Quality

The spatial assessment of water quality in the study area is based on samples collected from a network of 27 wells during July 1999 and June–July 2000 and on samples collected from 4 sites on the Des Moines River during September 1999. The water-quality data for the wells and sites are available at http://nwis.waterdata.usgs.gov/mn/nwis/qwdata using the USGS site numbers given in table 3 plus 435203095070101 for well D13 and 435205095065302 for well M055. Of the ground-water samples, 22 were collected from monitoring wells screened at the water table, 1 was collected from an abandoned stock well screened at the water table, 3 were collected from public-supply wells (wells M101 through M103) screened throughout the aquifer thickness, and 1 was collected from a monitoring well (well D06) screened in a thin [less than 1 m (3 ft)] buried sand and gravel lens beneath till. Thus, the resulting water-quality characterization is generally representative of water at the water table in the surficial aquifers. The herbicide samples collected at river sites DM4 and DM5 during September were lost so a herbicide sample collected at river site DM4 on April 27, 1999, was substituted for the sample collected at that site during September. Thus, three herbicide samples collected at river sites were used in the characterization.

Most of the ground-water samples collected in the study area consisted of calcium-magnesium bicarbonate waters. Dissolved-solids concentrations ranged from 220 to 718 mg/L. The only exceptions were the samples collected from wells D06 and M017. Well D06 is screened in a thin buried glacial aquifer east of the Des Moines River Valley. The sample from that well was dominated by sulfate anions and had a dissolved-solids concentration of 2,120 mg/L. Water in the buried glacial aquifer probably has a much longer residence time than water in surficial aquifers. Therefore, the water in the buried glacial aquifer has a more geochemically evolved highly concentrated quality. Well M017 is screened at the water table less than 10 m (30 ft) from a meat-packing plant sewage lagoon. The sample from that well was dominated by sodium and chloride ions and had a dissolved-solids concentration of 2,760 mg/L.

For the remaining 25 samples, cation composition, in milliequivalents per liter, varied less than 10 percent (58 to 68 percent calcium, 28 to 38 percent magnesium, and 2 to 12 percent sodium). The samples fell into two anionic groups depending on whether their bicarbonate concentrations were greater than or less than 70 percent, in milliequivalents per liter (18 samples and 7 samples, respectively). The high-bicarbonate samples were collected from surficial aquifer wells screened at the water table. Of the seven low-bicarbonate (relatively high sulfate concentrations) samples, three were collected from deep high-capacity production wells that had long screens or from shallow monitoring wells located near the production wells.

The anionic composition of the relatively high sulfate samples appears intermediate between the high-bicarbonate samples (from shallow surficial aquifer wells) and the sample collected from well D06 (from a deep buried glacial aquifer). This suggests that the relatively high sulfate samples may be affected by upwelling sulfate-rich ground water from deep aquifers. The upwelling water may be induced by withdrawals from high-capacity wells or may be natural in the case of wells D02, D08, E04, and M055.

River samples collected from the Des Moines River (river site DM5) by the USGS during October 1960–April 1962 were similar in composition to the relatively high sulfate ground-water samples. This suggests that ground-water discharge to the Des Moines River is from both surficial and deep aquifers.

Nutrients

The distribution of nutrient concentrations in ground-water samples is skewed toward low concentrations and high outliers. The statistical distribution of nutrients in ground water and surface water in the study area is shown in figure 8. The highest ammonia concentrations were in samples from a well next to a sewage lagoon near a meat-packing plant (well M017) and from a well screened in a buried aquifer (well D06). The reduced chemical condition at those locations is consistent with ammonia, a reduced form of nitrogen. Effluent recharged from the sewage lagoon probably accounts for the high concentration of ammonia in samples from well M017.

The highest nitrate concentrations were for samples collected from wells D13 and D15 within Windom. In other studies in the Mississippi River Basin in Minnesota (Stark and others, 1991; Anderson, 1993; Minnesota Pollution Control Agency, 1999; Fong, 2000), nitrate concentrations were higher in agricultural areas than in urban areas of surficial sand and gravel aquifers. Although nitrogen fertilizers are used both in agricultural areas and on home lawns, these results suggest that nitrogen fertilizer use rates or irrigation rates may be higher or more variable on lawns in the study area.

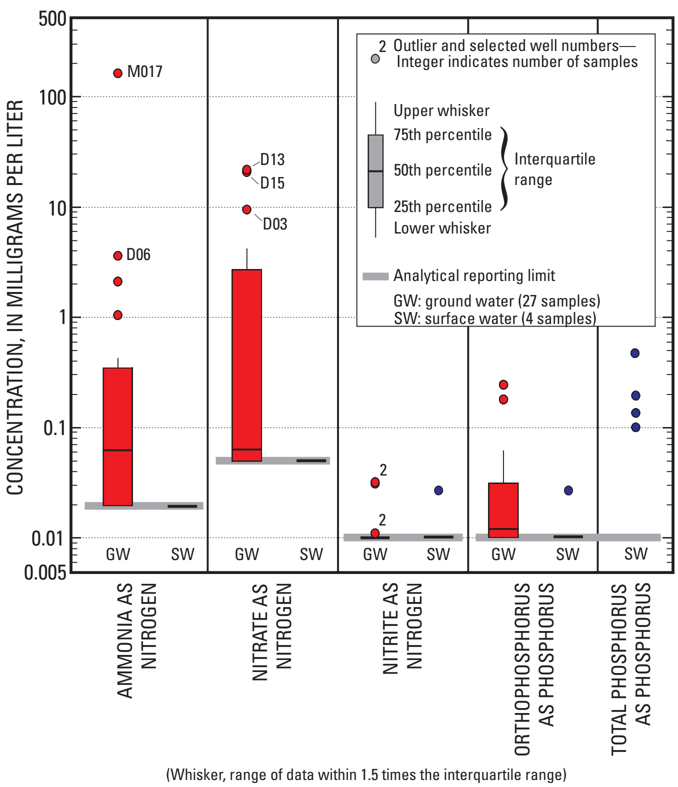

Figure 8. Nutrient concentrations in ground water and surface water, Des Moines River study area, southwestern Minnesota, 1999–2001.

Nutrient concentrations in river samples collected during September 1999 were less than analytical reporting limits except for total phosphorus (fig. 8) and organic nitrogen [1.07 to 2.73 mg/L as nitrogen (N)]. The concentrations were fairly close and unskewed because the samples were collected from the same river during a 3-day period.

Herbicides and Their Degradates

Water samples were analyzed for herbicides commonly used on corn and soybeans and for the compounds into which those herbicides degrade (degradates) (table 4). The chemicals for which samples were analyzed include 4 acetamide herbicides and 10 of their degradates and 9 triazine herbicides and 4 of their degradates. Not all samples were analyzed for all chemicals, and the analytical reporting limits were not the same for all analyses.

As shown in figure 9, 1 herbicide and 7 degradates were detected in 14 of 27 ground-water samples, and 1 herbicide and 5 degradates were detected in all 3 river samples. Except for alachlor oxynilic acid, alachlor ethane sulfonic acid, and metolachlor ethane sulfonic acid, all detected concentrations were less than 1 μg/L. The only chemical detected that was not an acetamide herbicide or degradate was prometon. Prometon is a nonselective, pre-emergence and post-emergence, annual and perennial broadleaf herbicide that is used to kill all plants around buildings and storage areas and in rights of way. This herbicide was detected in samples collected from wells D13 and M055 near such places within Windom. Metolachlor ethane sulfonic acid, a degradate of metolachlor, was detected in 10 of 27 ground-water samples and 2 of 3 river samples. The degradate was the most commonly detected compound and also was detected at the highest concentrations. The concentration for the ground-water sample collected from well D24 was 2.82 μg/L, and the concentration for the river sample collected at site DM4 was 2.13 μg/L.

The total herbicide concentration for each water sample is the sum of all herbicide and degradate concentrations greater than the detection limit. The total herbicide concentrations ranged from <1.10 to 4.03 μg/L. The minimum for this range is the sum of the minimum detection limits for all compounds for which samples were analyzed. The total herbicide concentration was greater than 1.35 μg/L for four ground-water samples and one river sample (fig. 9).

Water-Quality Variability

To assess the degree to which water quality may vary at a single site, a subset of sites was sampled four additional times

Table 4. Herbicides and degradates for which water samples were analyzed, Des Moines River study area, southwestern Minnesota.

[Analysis A and Analysis B indicate the samples were analyzed by two different methods that have different reporting limits; USGS, U.S. Geological Survey; <, less than; no shading, parent compound; shading, degraded compound; bold number indicates compound was detected; —, not determined]

Compound name	Analysis A		Analysis B			USGS laboratory analysis code
	Method reporting limit (micrograms per liter)	Number of ground-water samples	Method reporting limit (micrograms per liter)	Number of ground-water samples	Number of surface-water samples	
Acetamide herbicides						
Acetochlor	<0.05	24	<0.05	3	3	49260
Acetochlor ethane sulfonic acid	<.05	**24**	<.2	3	**3**	61029
Acetochlor oxynilic acid	<.05	**24**	<.2	3	3	61030
Alachlor	<.05	24	<.05	3	3	46342
Alachlor ethane sulfonic acid	<.05	**24**	<.2	3	**3**	50009
Alachlor oxynilic acid	<.05	**24**	<.2	3	**3**	61031
Metolachlor	<.05	24	<.05	3	**3**	39415
Metolachlor ethane sulfonic acid	<.05	**24**	<.2	3	**3**	61043
Metolachlor oxynilic acid	<.05	**24**	<.2	3	**3**	61044
Propachlor	<.05	24	<.05	3	3	04024
Dimethenamid ethane sulfonic acid	<.05	**15**	—	—	3	61951
Dimethenamid oxynilic acid	<.05	15	—	—	—	62482
Flufenacet ethane sulfonic acid	<.05	15	—	—	3	61952
Flufenacet oxynilic acid	<.05	15	—	—	—	62483
Triazine herbicides						
Atrazine	<.05	24	<.05	3	3	39632
Deethyl-atrazine	<.05	24	<.05	3	3	04040
Deisoprop-atrazine	<.05	24	<.05	3	3	04038
Hydroxy-atrazine	—	—	<.2	3	3	50355
Cyanazine	<.05	24	<.05	3	3	04041
Cyanazine-amide	<.05	24	<.05	3	3	50010
Prometon	<.05	**24**	<.05	3	3	04037
Propazine	<.05	24	<.05	3	3	38535
Simazine	<.05	24	<.05	3	3	04035

Table 4. Herbicides and degradates for which water samples were analyzed, Des Moines River study area, southwestern Minnesota.—Continued

[Analysis A and Analysis B indicate the samples were analyzed by two different methods that have different reporting limits; USGS, U.S. Geological Survey; <, less than; no shading, parent compound; shading, degraded compound; bold number indicates compound was detected; —, not determined]

Compound name	Analysis A		Analysis B			USGS laboratory analysis code
	Method reporting limit (micrograms per liter)	Number of ground-water samples	Method reporting limit (micrograms per liter)	Number of ground-water samples	Number of surface-water samples	
Other herbicides						
Ametryn	<.05	24	<.05	3	3	38401
Metribuzin	<.05	24	<.05	3	3	82630
Prometryn	<.05	24	<.05	3	3	04036
Terbutryn	<.05	24	<.05	3	3	38888

during April 1999–July 2000 for a subset of water-quality constituents (appendix 2). Selected results of this temporal sampling are shown in figures 10 and 11. Because of the small number of temporal samples collected, general features of concentration variability were difficult to determine and seasonal and long-term trends could not be ascertained. However, the samples did provide enough data to indicate that water quality does vary temporally at a site and to indicate the degree of variability. The water-quality data obtained during the temporal sampling are available at http://nwis.waterdata.usgs.gov/mn/nwis/qwdata. The results of the sampling illustrate most of the possible patterns of concentration variability. However, no site had a constituent that was usually detected at concentrations in a narrow range above the analytical reporting limit but occasionally was detected at a much higher concentration. Atrazine was the only herbicide or degradate detected in the temporal sampling that was not detected in the spatial sampling. Atrazine was detected once in well D03 at the analytical reporting limit of 0.05 µg/L and at river site DM4 at a concentration of 0.21 µg/L.

Generally, nutrient, herbicide, and degradate concentrations varied by about one-half an order of magnitude. The variability of the nitrate concentrations generally was higher for the river samples than for the ground-water samples (fig. 10), probably reflecting the fact that the Des Moines River receives nitrate from surface runoff that contains variable nitrate concentrations in addition to the nitrate contained in ground-water discharge. Herbicide and degradate concentrations generally were higher in river samples than in ground-water samples (fig. 11) for the same reason.

Water-Quality Implications

Among the chemicals for which samples were analyzed for this study, drinking-water standards have been established for nitrite, nitrate, atrazine, and simazine (U.S. Environmental Protection Agency, 2002). Except for prometryn and terbutryn, lifetime adult health advisories have been established for the herbicide parent compounds and for ammonia (U.S. Environmental Protection Agency, 2002). No standards or advisories have been established for the herbicide degradates or for the remaining nutrients.

Most wells (24 of 27) from which samples were collected for this study were shallow [within 1 m (3.3 ft) of the water table]. Therefore, the water from the wells generally was young and was affected by the most recent land use. The water was of variable quality in space and time but generally was fit for human consumption. Samples collected from wells D03, D13, and D15 had concentrations that, at least once, approached or exceeded the 10-mg/L drinking-water standard established by the U.S. Environmental Protection Agency (2002) for nitrate as nitrogen. Concentrations were near or above the standard in three of the four samples collected from well D03. The concentration in the fourth sample was below the analytical reporting limit. The sample collected from well M017 exceeded the ammonia lifetime health advisory level of 30 mg/L as N by more than a factor of five (162 mg/L), probably because of the well's proximity to a sewage lagoon.

The U.S. Environmental Protection Agency (2002) has established a drinking-water standard for one (atrazine) of the eight herbicide compounds (one parent and seven degradates) detected in ground water and a health advisory for another

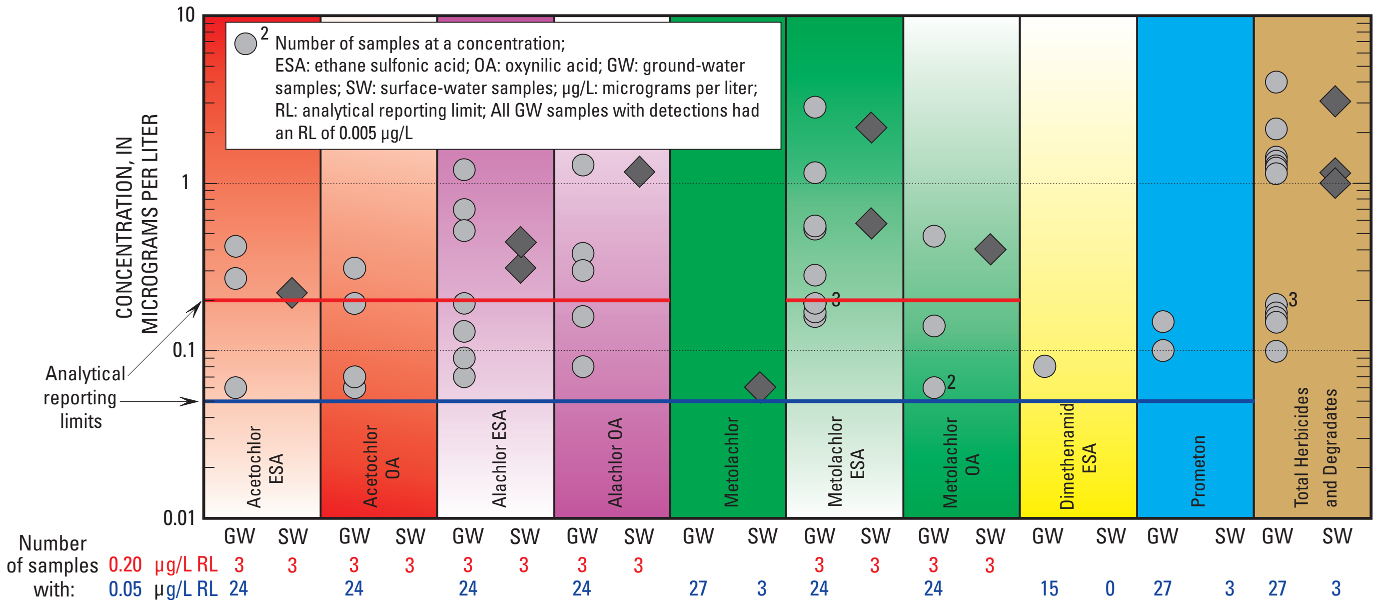

Figure 9. Detected herbicide and degradate concentrations, Des Moines River study area, southwestern Minnesota, 1999-2000.

(prometon). The standard for atrazine and the advisory for prometon were not exceeded.

Samples from the Des Moines River had variable but low concentrations of nutrients and agricultural herbicides. Concentrations in the samples did not exceed U.S. Environmental Protection Agency (2002) drinking-water standards or health advisories. The river sample collected on April 27, 1999, had a nitrate concentration of 7.16 mg/L as N, which was the highest nitrate concentration for river samples collected during this study. The sample was collected after spring runoff and during a time when fertilizer application in agricultural fields was prevalent. During sampling, the river was flowing at 3.599 million m^3/d (1,471 ft^3/s). Thus, assuming the concentration and flow remained constant, the load of nitrogen for the day was 25.77 MT (24.40 tons), which is equivalent to 31.29 MT (34.49 tons) of anhydrous ammonia. At a cost of 13 cents per pound, the value of the applied anhydrous ammonia represented by the nitrogen load that flowed down the Des Moines River past Windom on April 27, 1999, was $8,968.

Although the nitrate concentration in the river samples was less than the U.S. Environmental Protection Agency (2002) drinking-water standard, nitrate can affect aquatic ecosystems. An example of one of these effects is the eutrophication of the Gulf of Mexico around the Mississippi River Delta (Rabalais, 2004). Algae use the nitrogen in nitrate to build cells. As the Mississippi River delivers nitrate to the Gulf of Mexico, more algae are able to bloom in the water. As a result, light cannot penetrate deep into the water. As the algae die, decomposition uses up oxygen in the deep water and an anoxic zone is produced. Other organisms, which rely directly or indirectly on either sunlight or oxygen, are no longer able to survive in the algal areas and either die or move to clearer water. The anoxic area of the Gulf of Mexico is called the "dead zone" because only algae can live in the area. The size of the dead zone changes during the year and between years depending on the amount of nitrate delivered by the Mississippi River.

In 1999, the Mississippi River delivered 1.10 million MT (1.21 million tons) of nitrate as N to the Gulf of Mexico (Goolsby and Battaglin, 2000). In that year, the dead zone grew to an area of 20,015 km^2 (7,728 mi^2). The amount of nitrate as N in the Des Moines River above Windom on April 27, 1999, would be equivalent to 0.002 percent of the mass of nitrogen that entered the Gulf of Mexico via the Mississippi River in 1999. However, all of the nitrate as N above Windom probably would not reach the Gulf of Mexico because of chemical transformations or biological uptake.

The metolachlor ethane sulfonic acid concentration in a sample collected at river site DM4 on April 27, 1999, during spring high flow, presumably just after application, indicated 7.7 kg (17 lbs.) of this chemical flowed down the Des Moines River at Windom on that day. The assumption was made that the concentration and flow remained constant for the day.

Simulation of Ground-Water Flow

Development of a numerical ground-water flow model involves representing the conceptual model of a ground-water flow system, presented in the Hydrogeology section of this report, by a set of ground-water flow equations that are solved for head at each grid cell in the model. After the equations are solved for head, ground-water flow rates can be calculated. The model then is calibrated to agree with measured heads and flows. The calibrated model can be used to investigate aquifer response to future stresses to the system, including increased ground-water withdrawals from an aquifer, droughts, and increased precipitation.

Model Description

The ground-water flow model developed for this study was a single-layer, steady-state, finite-difference model. The Department of Defense's GMS software, version 3.1 (Environmental Modeling Systems, Inc., 2002), was used to model the aquifer volume and to produce the input data sets for the ground-water flow model. The USGS MODFLOW finite-difference ground-water flow model (Harbaugh and McDonald, 1996) was used to solve the ground-water flow equation, and GMS software was used to display and interpret model results. The post-processing package MODPATH (Pollock, 1989) was used to track particles to estimate ground-water traveltime to wells and from surface-water bodies.

The three-dimensional stratigraphy of the study area was modeled as a set of solid volumes that represented either hydraulically permeable (aquifer) or nonpermeable (nonaquifer) materials. The land-surface elevation, which represented the top of the aquifer volume, was interpolated from a 100-m digital elevation model (DEM) that was generalized from the USGS 30-m DEM (Minnesota Department of Natural Resources, 2000.). The bottom elevation of the aquifer volume was interpolated from a triangulated irregular network (TIN) that represented the bottom of the surficial aquifer. This TIN was constructed by connecting the elevations of the bottom of the surficial aquifer at each of 250 selected wells that had stratigraphic logs. The elevation at each well was calculated by subtracting the depth of the bottom of the surficial aquifer from the 100-m DEM land-surface elevation. Hand-drawn contour lines of the depth of the aquifer bottom at each of the wells are shown in figure 4 as aquifer thickness. The interpolated aquifer geometry does not include the interfingered buried aquifer that is shown in some well logs for the Cottonwood Lake area.

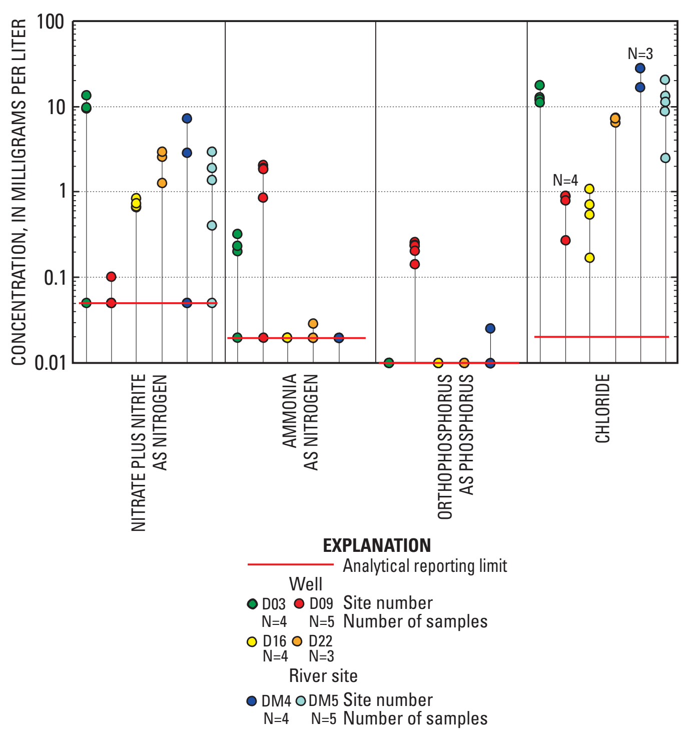

Figure 10. Variability of selected nutrient and chloride concentrations, Des Moines River study area, southwestern Minnesota, 1999-2000.

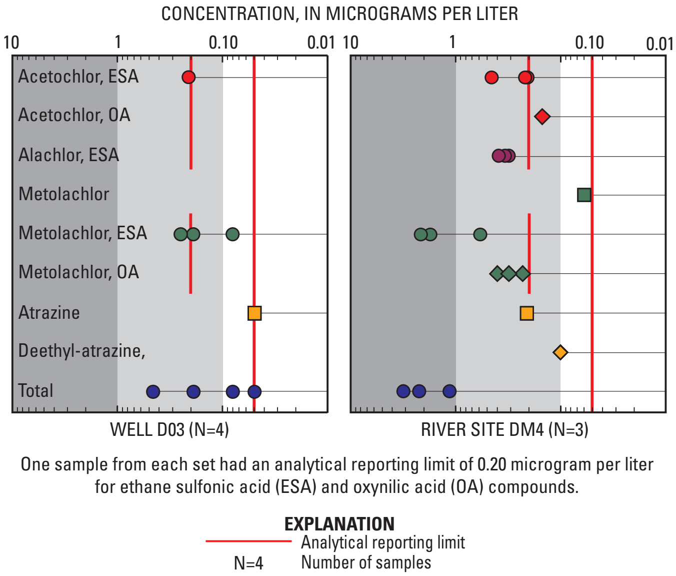

Figure 11. Variability of herbicide and degradate concentrations, Des Moines River study area, southwestern Minnesota, 1999-2000.

The solid volumes were digitized to a uniform 100-m (328-ft) model grid that represented the surficial aquifer volume as active model cells (fig.12). The grid dimension was small enough to ensure that the aquifer was represented by at least 10 grid cells across the width of the Des Moines River Valley but not so large that the model became difficult to solve. The grid was oriented 30 degrees west of north to match the general direction of the aquifer deposits.

Most cells at the edge of the Des Moines River Valley were less than a few meters thick. Any cell in the model that had an aquifer thickness of less than 1.5 m (4.92 ft) was considered too thin to transmit substantial amounts of ground water. Therefore, to reduce problems with model convergence, the thin areas of the aquifer were not simulated.

Flow was not simulated across the bottom and lateral sides of the aquifer to represent no flow from low-conductivity till adjacent to the aquifer. The upstream and downstream edges of the modeled area were chosen to coincide with lines of inferred ground-water flow to the river. By definition, no flow occurs perpendicular to these lines, so no flow was simulated across the lines.

For the purpose of modeling, the aquifer area was divided into five zones (fig. 12) that had separate hydraulic conductivity and recharge values. These zones generally corresponded to the aquifers and aquifer areas described earlier except for the following differences: (1) The Augusta Lake Valley and Lower River areas of the Des Moines aquifer were combined into one zone because slug-test data indicated no substantial difference in hydraulic conductivity between those areas, and (2) the part of the Des Moines River aquifer southwest of the Des Moines River in Windom (Des Moines River–SW) and the Windom aquifer south of County Road 17 (Windom–South) were separated from the main aquifer areas because those areas contain substantially less conductive and thinner aquifer materials than the main areas.

Evapotranspiration was not explicitly simulated in the model because values of extinction depth from other studies in the area are generalized to 1.5 m (5 ft) on the basis of gross root-zone depths and are not based on measurements of evapotranspiration. Because areas of expected high evapotranspiration, such as large wooded areas along the Des Moines River, are absent in the study area, all recharge values in the model were net values. Both areal and edge recharge were simulated. Areal recharge was uniform across each aquifer zone, and edge recharge represented water that enters the horizontal edge of the aquifer from infiltration of overland flow or intermittent streamflow from till uplands or that discharges laterally from permeable lenses buried beneath upland till. Edge recharge was applied as a MODFLOW general-head-boundary stress at the horizontal edge of the entire model except in the Windom aquifer area where no-flow conditions apply (fig. 12). General-head-boundary stress elevations were interpolated from the 100-m DEM land-surface elevation. A line was drawn between the nodes of the outermost active cells of the model where edge recharge was simulated, and the general-head-boundary stress elevations then were fixed 3 m (9.8 ft) below the DEM land-surface elevation at the end vertices (corners) of this line and linearly interpolated to cells between the vertices.

Hydrologic stresses are features within a model where water can enter or leave the model. For this model, hydrologic stresses were divided into three categories: drainage ditches and intermittent rivers that were simulated by MODFLOW drain stresses, perennial rivers that were simulated by MODFLOW river stresses, and lakes and wetlands that were simulated by MODFLOW general-head-boundary stresses. General-head-boundary stresses allow water into or out of a model in direct proportion to head difference and in inverse proportion to a connecting conductance, which, in this case, was a vertical conductance. Head difference in the general-head-boundary stresses was defined as the difference between the simulated ground-water elevation and an assigned stress elevation. Vertical conductance was the hydraulic conductivity of the sediments that underlie the surface-water body divided by the thickness of the sediments. Because flux to or from the model was dependent on head gradient, general-head-boundary stresses could simulate flux to or from lakes and wetlands more realistically than fixed-head boundaries. All modeled hydrologic stresses are shown in figure 12. A single type of stress is shown in each model grid cell, in the following order of precedence: wells, drains, rivers, and general head.

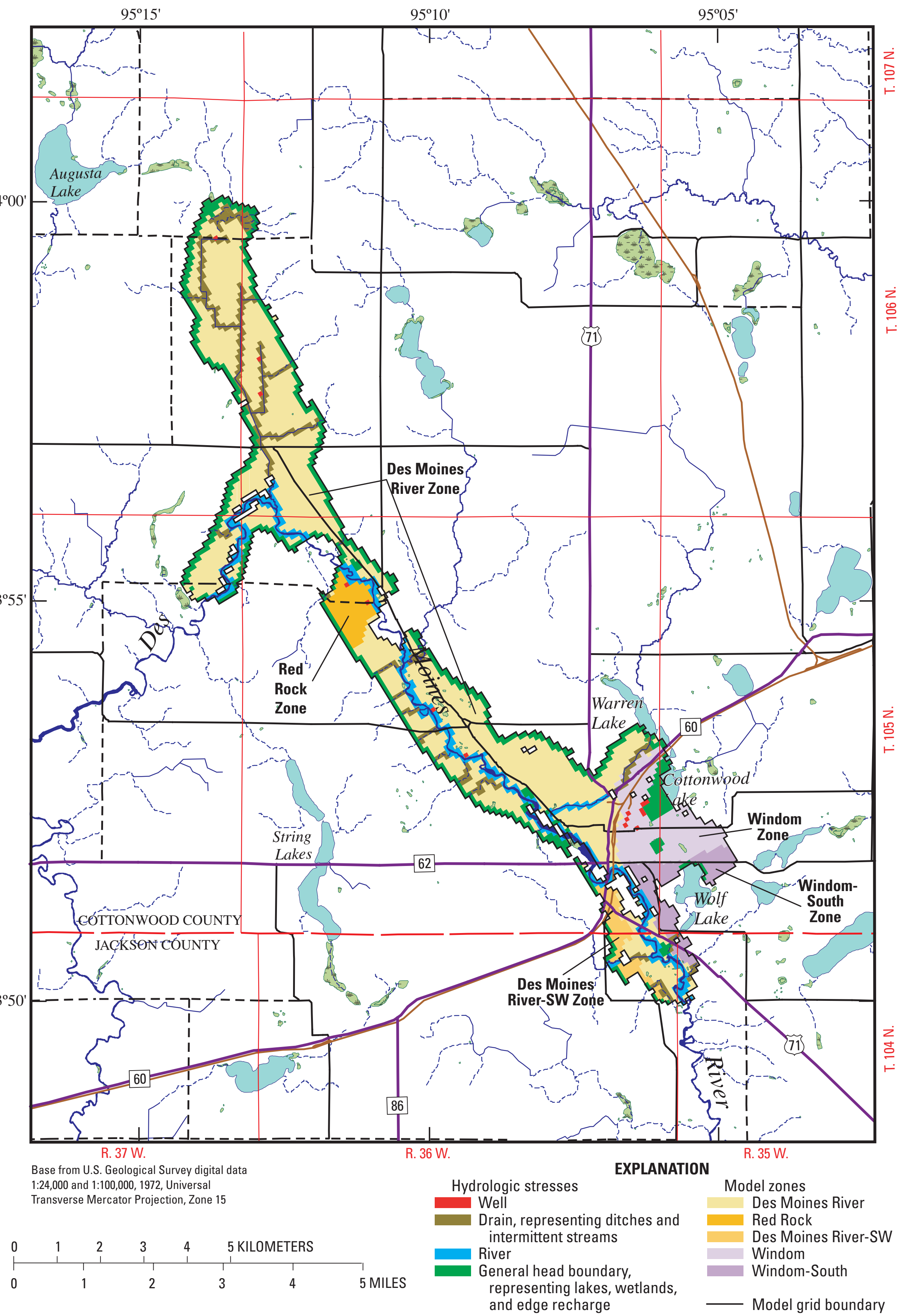

Figure 12. Model grid and hydrologic stresses, Des Moines River study area, southwestern Minnesota.

The extent of the surface-water bodies was obtained from U.S. Fish and Wildlife Service National Wetlands Inventory (NWI) digital data (U.S. Fish and Wildlife Service, 1991–94) and USGS 1:24,000 Digital Line Graph data (DLG) (Minnesota Department of Transportation, 1999). Hydrographic and land-surface elevations were interpolated from USGS 30-m DEM data (U.S. Geological Survey, 2003) and USGS 1:24,000-scale topographic maps. Elevations from these sources are accurate to ±1.52 m (±5 ft). The sources were combined to provide data for river, ditch, lake, and wetland hydrologic stresses. All areal hydrography data originated as polygons from the NWI data. Only polygons that represented areas where water remains year-round were included in the model because those areas were considered to be hydraulically connected to the ground-water system. Des Moines River polygons were divided into areas of equal elevation in 0.3-m (1-ft) increments interpolated from USGS 1:24,000 topographic-map elevations. Water-surface elevations were assigned to the polygons on the basis of measurements obtained at gaging sites on the calibration date (September 30, 1999). Lake-surface elevations were assigned from the 100-m DEM except for Cottonwood Lake, which was given an elevation that was measured during the calibration period. To account for possible sloped wetland surfaces, wetland polygons were divided into areas coincident with the 100-m DEM cells and assigned surface elevations from the DEM. These polygons then were re-aggregated into polygons of equal elevation to the nearest 0.1 m (4 in.).

Linear hydrography for other perennial rivers, intermittent rivers, and drainage ditches originated as lines from DLG and NWI data, with DLG data taking precedence. Areas were calculated from the linear hydrography assuming a constant width of 3 m (9.8 ft). The base of riverbed sediments was assumed to be 3 m (9.8 ft) below the water surface. Elevations from the 30-m DEM were assigned at the nodes of the line data that represented ditches and streams and were linearly interpolated along the line segments. Additional nodes were added where breaks in slope occurred.

Ground-water withdrawal data used in the model were collected by the MNDNR through their water-use permit program (Minnesota Department of Natural Resources, 2001b). Data for wells that required MNDNR withdrawal permits were the only data included in the model. Permits are required for wells that pump more than 37.85 m^3/d (10,000 gal/d) or 3,785 m^3/yr (1 Mgal/yr). Rates are yearly averages for the year of calibration.

Model Calibration and Sensitivity

The model developed for this study had difficulty converging because the aquifers in the study area are thin, narrow, and discontinuous. Normally, MODFLOW will turn off a model cell when the water level falls below the cell bottom, even while the model is trying to converge. The cells can be rewetted, but this technique makes the model oscillate and prevents it from converging. Therefore, for this study, the version of MODFLOW included with the GMS software was modified to optionally prevent cells in the lowest model layer from drying out, and a residual amount of water [0.85 m (2.8 ft)] was left in the cells.

Theoretically, this modification represents the possibility that ground water can flow through aquifer material that is not saturated permanently. Thus, areal recharge from intermittently saturated aquifer areas can still flow to saturated areas (for example, the area east of the Windom well field). Practically, this modification allows the model to converge and simplifies model inputs. Areal recharge can be applied across an intermittently saturated part of an aquifer at the same rate as for a saturated part. This eliminates the need to estimate or calibrate the recharge as specified flux at the edge of a saturated area. The water level in any area that has a saturated thickness that is less than the residual amount has no meaning because the water level is specified rather than simulated. In the water-level results for this report, those areas are labeled as intermittently saturated. The model has a convergence criterion of 0.05 m (2 in.) within 150 outer iterations. The solver used in this model is the preconditioned conjugate gradient method developed by Hill (1990).

To calibrate the model, the differences between the measured and simulated ground-water levels (head error) and the measured and simulated river and drain fluxes (flux error) was minimized. Heads were calibrated to a data set obtained on September 30, 1999, and fluxes were calibrated to seepage measurements made in October 1997. The September 30, 1999, data set was chosen for calibration for two reasons. First, the data measured on that day represent hydrologic conditions where no recent recharge has occurred and where ground-water levels are neither high nor low. This approximates the steady-state condition modeled. Second, the ground-water levels on that date were similar to those on October 6–8, 1997, when the calibration seepage measurements were made. The October 1997 seepage run was used to calibrate the net model flux because water levels measured during other seepage runs were lower than normal and inappropriate for modeling steady-state conditions. Of the 88 elevations in the synoptic calibration data set, all were measured to within ±3 mm (±0.01 ft). Measuring points for 81 of the elevations were known to within ±3 mm (±0.01 ft), and measuring points for the remaining 7 elevations were known to within ±1.52 m (± 5 ft). Most of the water levels in the calibration data set were measured on the same day to within ±6 mm (±0.02 ft). In the area of the Windom well field, ground-water flow to wells was calibrated to the proportion of well water entering the area from areal recharge and local surface-water infiltration. This proportion was measured at Windom city well number 8 (well M103 in this study) on July 26, 2000, using water isotopic composition. Measured and calibrated model input parameters are given in table 5. Because the results of the Des Moines River–SW and Windom–South zones are poorly constrained, the following discussion excludes those zones.

Table 5. Measured and calibrated model input parameters, Des Moines River study area, southwestern Minnesota.

[m/d, meters per day; ft/d, feet per day; shading, poorly constrained aquifer zones; —, not available; in/yr, inches per year; K, hydraulic conductivity; C, Groundwater Modeling System software]

Input parameter	Measured values				Calibrated values		
Aquifer hydraulic conductivity by model zone	**Slug tests (m/d)**	**Slug tests (ft/d)**	**Aquifer tests (m/d)**	**Aquifer tests (ft/d)**	**(m/d)**	**(ft/d)**	
Des Moines River	0.03–41.4	0.10–135	6–12	20–39	90	295	
Des Moines River-SW	—	—	—	—	45	148	
Red Rock	4.80–64.4	15.7–211	75–599	246–1,965	80	263	
Windom	0.57–0.95	1.87–3.11	22–2,348	72–7,703	30	98	
Windom-South	0.02–0.15	0.07–0.49	—	11	0.5	1.6	
Net recharge	**Hydrograph analysis (m/d)**				**(m/d)**	**(in/yr)**	**Precipitation percent[1]**
Areal							
Des Moines River	0.00036–0.0017				0.00035	5.0	17
Des Moines River-SW	—				0.000048	0	2
Red Rock	—				0.00060	8.6	30
Windom	—				0.00043	6.18	22
Windom-South	—				0.00006	0.9	3
Edge	—				[2]0.15	[2]2,157	—
Bed hydraulic conductivity by hydrologic stress					**K**	**K**	**C[3]**
Rivers (polygons)	—				1.33 m/d	4.4 ft/d	4 d^{-1}
Rivers (lines)	—				1.33 m/d	4.4 ft/d	12 m/d
Drains (lines)	—				0.44 m/d	1.4 ft/d	4 m/d
Lakes and wetlands (polygons)	—				0.0004 m/d	0.001 ft/d	0.0018 d^{-1}
Fixed values					**(m)**	**(ft)**	
River width (W)	—				3	9.84	
Riverbed thickness (T)	—				3	9.84	
Lake and wetland bed thickness (T)	—				4.5	16.4	

[1]Net areal recharge/precipitation.

[2]This recharge rate is applied on the top face of each cell that has edge recharge [area equals 1 hectare (2.5 acres)].

[3]C, Groundwater Modeling System software conductance, equals K/T for polygons or KW/T for lines.

Calibrated hydraulic-conductivity values for all zones were greater than the values measured by slug tests. However, slug tests have inherent inaccuracies because the tests measure hydraulic conductivity in a very small area around well screens that have been disturbed by drilling. Because all slug-tested wells for this study were near the water table and the land surface, those wells were not representative of the aquifer as a whole. Aquifer tests are more representative of an aquifer because aquifer tests measure the hydraulic conductivity of a larger part of an aquifer. For this study, calibrated hydraulic-conductivity values were within the range of values measured by aquifer tests except for the Des Moines River zone. Values for that zone were from an aquifer test at the Jeffers city well, which is at the northern edge of the aquifer and may not be representative of the aquifer as a whole. Calibrated hydraulic-conductivity values for the Red Rock and Windom zones are at the low end of the aquifer-test hydraulic-conductivity ranges, possibly because aquifer-test results represent hydraulic conductivity in the most productive parts of the heterogeneous aquifers and calibrated hydraulic conductivity represents an average across an assumed homogeneous aquifer.

Calibrated net areal recharge ranged from 17 to 30 percent of the average annual precipitation. This is slightly less than the range of recharge estimated from hydrograph analysis for the Des Moines River zone. Net areal recharge from a ground-water model developed for a genetically similar (formed in the same way) aquifer in the Rock River Valley, 80 km (50 mi) west of the study area, was about one-half the calibrated value for the model developed for this study (Lindgren and Landon, 2000).

Calibrated net areal recharge for the Rock River Valley model was 0.00023 m/d (3.27 in/yr), which was 12 percent of the average annual precipitation.

Nearly all recharge to the aquifer in the ground-water simulation was from edge recharge [79.7 percent; 65,510 m^3/d (17.31 Mgal/d)], net areal recharge [17.1 percent; 14,030 m^3/d (3.71 Mgal/d)], Cottonwood Lake [2.2 percent; 1,791 m^3/d (0.47 Mgal/d)], and other lakes and wetlands [1 percent; 862 m^3/d (0.23 Mgal/d)]. For the Windom aquifer, areal recharge and Cottonwood Lake each supply about half of the water. Edge recharge that otherwise would recharge the Windom aquifer is captured by Cottonwood Lake. Some of this water enters the aquifer through the lake, and the remainder flows through surface waters to the Des Moines River.

River, ditch, lake, and wetland bed hydraulic conductivities were not measured for this study. However, Lindgren and Landon (2000) measured bed hydraulic conductivity in the Rock River and its tributaries using a falling-head permeameter. The river and ditch bed hydraulic conductivities calculated from the calibrated conductance values from the model developed for this study are within the range of those measured for the Rock River study [0.06 to 122 m/d (0.2 to 401 ft/d)].

Details of the agreement between the measured and calibrated model heads and fluxes are given in table 6. The mean error in the calibrated model heads is 0.10 m (0.33 ft), and the mean of the absolute value of head error (the mean absolute error) is 0.31 m (1.02 ft). The calibrated model heads were within 1 m (3.28 ft) of the measured heads at the 59 sites for which water levels were simulated by the model. The difference between the interpolated measured and simulated heads is shown in figure 13 along with cells where water levels were at or below the minimum saturated thickness of 0.85 m (2.8 ft). Because those cells are intermittently saturated, the simulated water level has no meaning. Intermittently saturated cells occur at the edge of the aquifer where the aquifer is thinnest. Hydrologic stresses (areal recharge, edge recharge, and leakage to and from lakes, streams, and wetlands) in intermittently saturated cells continue to supply or remove water from the simulated aquifer by transmitting the water through the intermittently saturated cells to normally active model cells.

Net river and drain flux out of the model was within +7 percent of the flux measured in October 1997. In the area of the Windom well field, the model was able to supply 51 percent of the water in the aquifer from areal recharge and 49 percent from Cottonwood Lake while producing measured heads. This suggests that the model, containing the stratigraphic simplifications noted earlier, does well in reproducing the ground-water flow system.

Although the overall flux out of the model was in good agreement with the October 1997 measured flux, some segments of the model were not in good agreement (table 7). During the flux measurement, the ditch (TR3) draining the Augusta Lake Valley area of the Des Moines aquifer was flowing at 4,991 m^3/d (2.04 ft^3/s). The simulated flux to ditches in this area, however, was 4.19 times that amount. At the same time,

Table 6. Measured and calibrated model values, Des Moines River study area, southwestern Minnesota.

[m, meters; ft, feet; m^3/d, cubic meters per day; ft^3/s, cubic feet per second; —, not measured]

Heads (84 ground-water and 4 surface-water levels)			
Mean error	0.10 m	0.33 ft	
Mean absolute error	0.31 m	1.02 ft	
Root mean square error	0.41 m	1.35 ft	
Fluxes			**Percent of measured value**
Measured			
Net river flux (total gain)	71,293 m^3/d	29.14 ft^3/s	100
Augusta Lake Valley ditch flux	4,991 m^3/d	2.04 ft^3/s	100
Cottonwood Lake flux	50 percent	50 percent	100
Simulated			
Total river flux in	3,939 m^3/d	1.61 ft^3/s	—
Total river flux out	55,362 m^3/d	22.63 ft^3/s	—
Total drain flux out	24,912 m^3/d	10.18 ft^3/s	—
Net river and drain flux out	76,335 m^3/d	31.20 ft^3/s	107
Augusta Lake Valley net ditch flux out	20,915 m^3/d	8.55 ft^3/s	419
Windom areal recharge	1,838 m^3/d	0.75 ft^3/s	—
Cottonwood Lake flux	1,773 m^3/d	0.72 ft^3/s	98

simulated discharge to the Des Moines River in the area was only 78 percent of the measured amount. The flux to the ditches could not be reduced, nor the flux to the river increased, without producing unrealistic heads throughout the aquifer. However, the model could have been modified with a separate aquifer zone in the Augusta Lake Valley area. The head errors and the errors in flux to the rivers and ditches probably could have been decreased by decreasing the hydraulic conductivity of the aquifer, decreasing the edge recharge, and possibly decreasing the bed conductance of the ditch in the Augusta Lake Valley zone. Aquifer-test data from the Jeffers city well suggest that decreasing the aquifer hydraulic conductivity may be justified, but no measurements exist for the other values. Further data collection and the incorporation of an Augusta Lake Valley aquifer zone into the model would substantially improve the aquifer simulation for the Augusta Lake Valley area.

Simulated discharge for the small reaches between river sites DM2 and DM3 and between river sites DM5 and DM6 was smaller than measured discharge for those reaches. Increasing areal recharge and/or edge recharge and increasing hydraulic conductivity in the Red Rock, Des Moines River–SW, and Windom–South zones probably would produce a better fit with heads and fluxes in those zones. Aquifer-test data for the Red Rock zone indicate this change may be justified. However, recharge and hydraulic-conductivity data were not available for the other zones so the change could not be supported.

A model sensitivity analysis determines the sensitivity of the simulated heads and fluxes to changes in the values used for the major input parameters. In this model, values for four parameters were changed to determine the effect on the simulated heads and on the net river and drain flux out of the model (fig. 14). Parameters for each model zone were changed by the same factor for each model run. The bed conductance parameter included changes in bed conductance for ditches, rivers, lakes, and wetlands. The model is sensitive to different parameters with respect to head and to net river and drain flux. Simulated heads are most sensitive to reductions in aquifer hydraulic conductivity and increases in net areal recharge and least sensitive to changes in edge recharge. Simulated net river and drain flux, however, is most sensitive to changes in edge recharge and least sensitive to changes in bed conductance.

Hypothetical Simulations

A total of four hypothetical simulations of scenarios that affect ground water were tested with the calibrated model. Of the four scenarios, two involved increased ground-water withdrawals and two involved changes in recharge to simulate drier or wetter weather conditions. Because the model simulates steady-state conditions, the assumption was made that the changes in the condition occurred during a period that was long enough for the aquifer to reach a new equilibrium condition. The differences between the calibrated heads and the various simulated heads are shown in figures 15 through 18. The heads for some cells in some scenarios were less than the valid saturated thickness minimum of 0.85 m (2.8 ft). Therefore, those cells are shown as intermittently saturated cells.

Increased Ground-Water Withdrawals

In the first scenario, ground-water withdrawals from all existing wells were doubled. In the second scenario, ground-water withdrawals from existing wells were unchanged but a new well that pumped 2,000 m^3/d (440,000 gal/d) was added to the Augusta Lake Valley area. Doubling the withdrawals from all wells in the model had a small effect except in the Windom well-field area (fig. 15). Maximum head declines in the Red Rock well field and in the Jeffers city well (well M102; fig. 1) were 6 and 37 cm (2 and 15 in.), respectively. In the Windom well field, the maximum head decline was 11 m (36 ft). These declines represent an average for the entire 1-ha (2.5-acre) model grid cell and would be much greater in the well bore itself. Heads in most cells at the edges of the Windom aquifer fell below the valid saturated thickness minimum, indicating substantial dewatering of the aquifer. Some minor head decline occurred west of the Windom aquifer, showing an expansion of the well field zone of capture into the adjacent river area of the Des Moines aquifer. Based on flow-budget analysis, the additional flow accounted for 47 percent of the increased withdrawals in the Windom well field. However, because the Windom aquifer material in this area is thin and poorly sorted, a substantial amount of the increased withdrawals (35 percent) was provided by increased infiltration of water from Cottonwood Lake (table 8). The remaining increased withdrawals were provided by decreased ground-water flow to creeks (10 percent) and increased infiltration of water from other ponds and wetlands (8 percent). In both the calibrated model and the increased ground-water withdrawals scenarios, Cottonwood Lake, based on flow-budget analysis, supplied about half (49 and 48 percent, respectively) of the water withdrawn from the Windom well field.

The addition of a new well in the Augusta Lake Valley area caused a 0.83-m-deep (2.72-ft-deep) cone of depression in the water table in that area (fig. 16). The head decline in the cell containing the Jeffers city well was minimal [0.09 m (3.5 in.)]. The new cone extended to both valley walls. Decreased discharge to ditches accounted for most (93 percent) of the 2,000-m^3/d (440,000-gal/d) withdrawal from the new well. The remainder of the withdrawal was from increased recharge from edge recharge at the boundaries of the aquifer.

Drought

In the drought scenario, the areal recharge rate and the edge recharge conductance were decreased to 72 percent of the

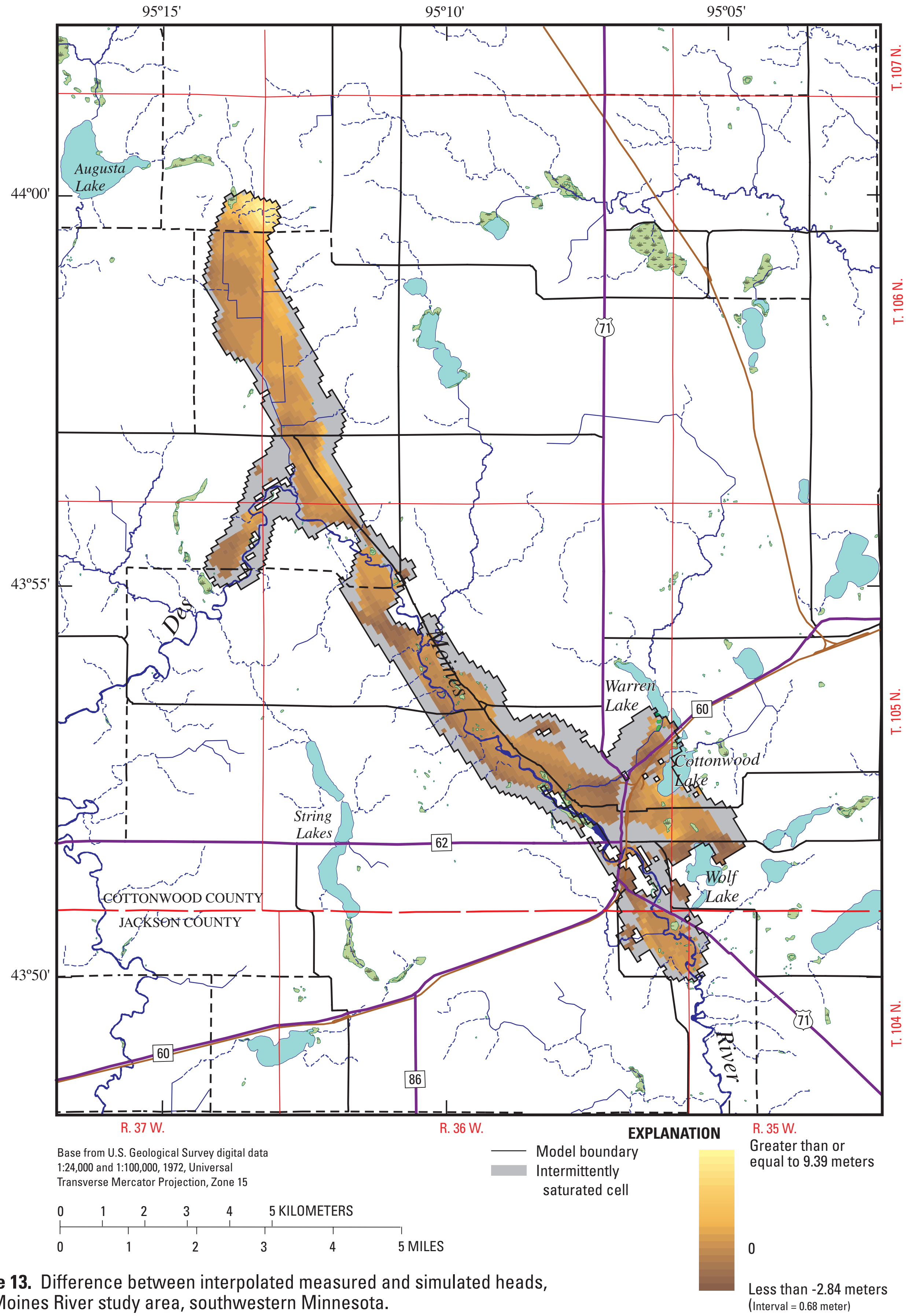

Figure 13. Difference between interpolated measured and simulated heads, Des Moines River study area, southwestern Minnesota.

Table 7. Measured and simulated surface-water flows, October 8, 1997, Des Moines River study area, southwestern Minnesota.

[m³/day, cubic meters per day; ft³/s, cubic feet per second; —, not determined]

Site	Measured		Simulated gain (m^3/d)	Simulated/ measured (percent)	Measured		Simulated gain (ft^3/s)	Simulated/ measured (percent)
	Flow (m^3/d)	Gain (m^3/d)			Flow (ft^3/s)	Gain (ft^3/s)		
DM1	5,285	—	—	—	2.16	—	—	—
TR3	4,991	4,991	20,915	419	2.04	2.04	8.55	419
DM2	34,252	23,976	17,308	72	14.00	9.80	7.07	72
DM3	42,815	8,563	3,171	37	17.50	3.50	1.30	37
DM4	Pooled	—	—	—	Pooled	—	—	—
DM5	74,376	31,561	31,791	101	30.40	12.90	12.99	101
DM6	76,578	2,202	3,150	143	31.30	0.90	1.29	143
Total gain		71,293	76,335	107		29.14	31.20	107

calibrated model values to represent the dry period that occurred during 1987–90 (fig. 2). The decrease in edge recharge conductance resulted in a 19-percent decrease in edge recharge. Edge recharge decreased less than areal recharge because edge recharge flux is dependent on the simulated head within the cell and is not specified explicitly. Heads in some cells at the edges of the aquifers fell below the valid saturated thickness minimum (fig. 17). The largest head decline was 1.37 m (4.49 ft) in the Windom–South zone of the Windom aquifer. The decline was attributed to the zone's low hydraulic conductivity. Substantial declines also occurred in the northern part of the Augusta Lake Valley area and in the southwestern part of the Red Rock area of the Des Moines aquifer. Head declines were smallest near the Des Moines River, probably because the simulated river stage was not changed for the scenario. Head declines were largest toward the valley edges.

Based on flow-budget analysis, recharge to the Windom aquifer from Cottonwood Lake increased 11 percent in response to decreased net areal recharge and comprised 61 percent of the water withdrawn from the Windom well field. Heads in the well field declined a maximum of 0.68 m (2.23 ft). In the drought scenario, net flow from the aquifer to the Des Moines River decreased by 21 percent to 60,498 m^3/d (2.14 Mgal/d).

High Precipitation

In the high-precipitation scenario, the areal recharge rate and the edge recharge conductance were increased to 122 percent of the calibrated model values to represent the wet period that occurred during 1990–96 (fig. 2). The increase in edge recharge conductance resulted in a 12-percent increase in edge recharge. The pattern of head increases produced by the increased recharge is opposite that for the drought scenario (figs. 17 and 18). The largest head increase was 1.12 m (3.67 ft) near Wolf Lake southwest of Windom. As in the drought scenario, the low hydraulic conductivity of the aquifer material in that area produced large head changes from relatively small recharge changes. Head increases of about one-half meter (1.5 ft) occurred in the northern part of the Des Moines aquifer and in the southwestern part of the Red Rock area of the Des Moines aquifer. Generally, head increases were largest along the valley edges and smallest along the Des Moines River where river stage was not changed.

Based on flow-budget analysis, recharge to the Windom aquifer from Cottonwood Lake decreased 8 percent in response to increased net areal recharge and comprised 44 percent of the water withdrawn from the Windom well field. Heads in the well field increased a maximum of 0.50 m (1.64 ft). In the high-precipitation scenario, net flow from the aquifer to the Des Moines River increased by 14 percent to 87,337 m^3/d (3.08 Mgal/d).

Model Limitations

A numerical model of ground-water flow is a simplification of a complex natural system. In this model, large aquifer areas are assumed to have uniform hydraulic conductivity, every streambed is assumed to have uniform thickness and hydraulic conductivity, all stresses to the system are assumed to be uniform in time, and net areal recharge is assumed to be uniform in time and space over large aquifer areas. The heads and fluxes produced by the model are dependent on these simplifications and are inaccurate to the degree that these assumptions deviate from actual conditions. The challenge of a modeler is to simplify the ground-water system so that a model can be developed but to still retain enough of the ground-water system's complexity to make the model useful.

The model developed for this study was calibrated to a set of measured head and flux data. The measured head and flux data contain uncertainty and the calibrated model results deviate from the measured data, producing more uncertainty. In addition, combinations of parameters other than those used in the calibrated model may produce heads and fluxes that agree with the measured data equally well. All of these uncertainties produce inaccuracies in model results that must be considered before results are used.

For this study, three limitations of the model are most important. First, the model is a steady-state simulation of ground-water flow. Therefore, the model results are predicated on the assumption that inflows to and outflows from the aquifers are constant in time and equal to one another. Model results are not valid for situations where large variations of inflows or outflows occur, especially over short time periods. Recharge during spring melt is a good example of a situation when model results will be in poor agreement with actual conditions. Second, the model is regional in scale and has a cell size of 1 ha (2.5 acres). The model provides no details of ground-water heads or flows on a scale of less than several grid cells [several hundred meters (about 1,000 ft)]. The actual drawdown in a pumping well is an example of a situation where model results will be in poor agreement with actual conditions. Third, the model was calibrated to hydraulic conditions considered "normal" during the last 30 years, and the results of the model are most accurate for those hydraulic conditions. The model results become less reliable as scenario conditions deviate from the "normal" condition, such as for the extreme drought of 1956 when edge recharge would have been greatly reduced.

Hydrologic values for both the Des Moines River–SW and the Windom–South zones of the model are poorly constrained. Few well data and no river and drain flux data were available as

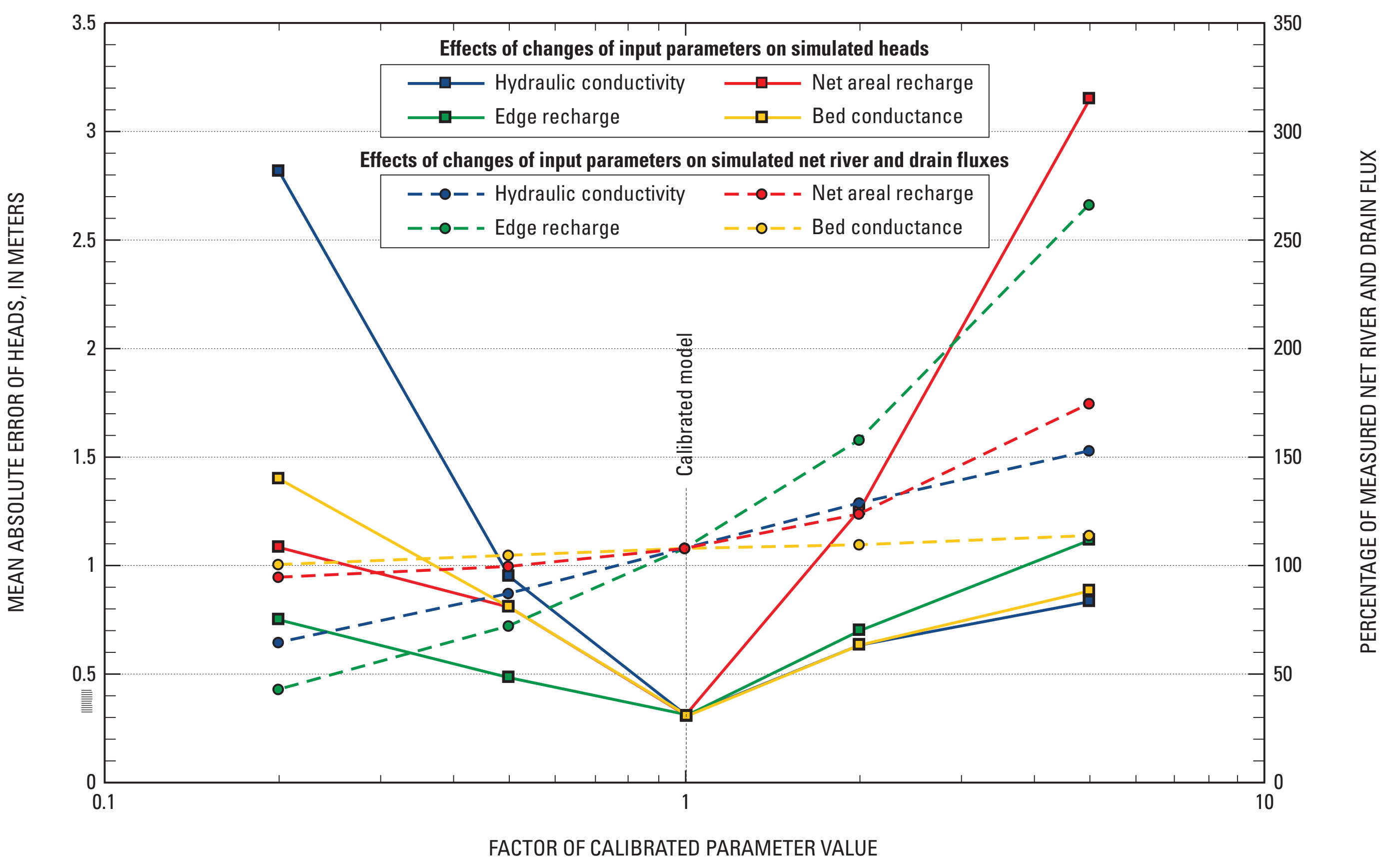

Figure 14. Sensitivity of model input parameters, Des Moines River study area, southwestern Minnesota.

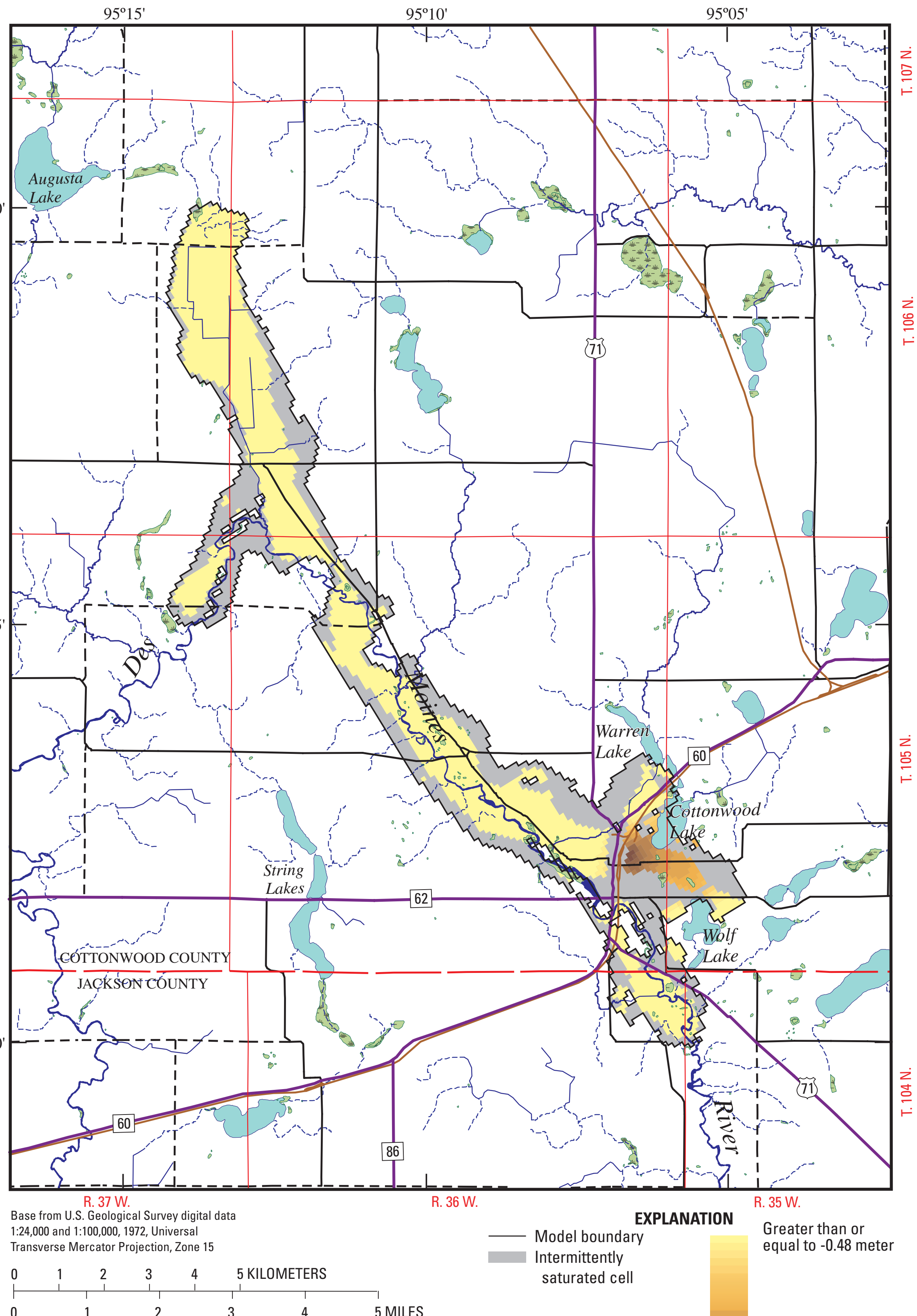

Figure 15. Difference between calibrated model heads and simulated heads for a scenario in which withdrawals from existing wells were doubled, Des Moines River study area, southwestern Minnesota.

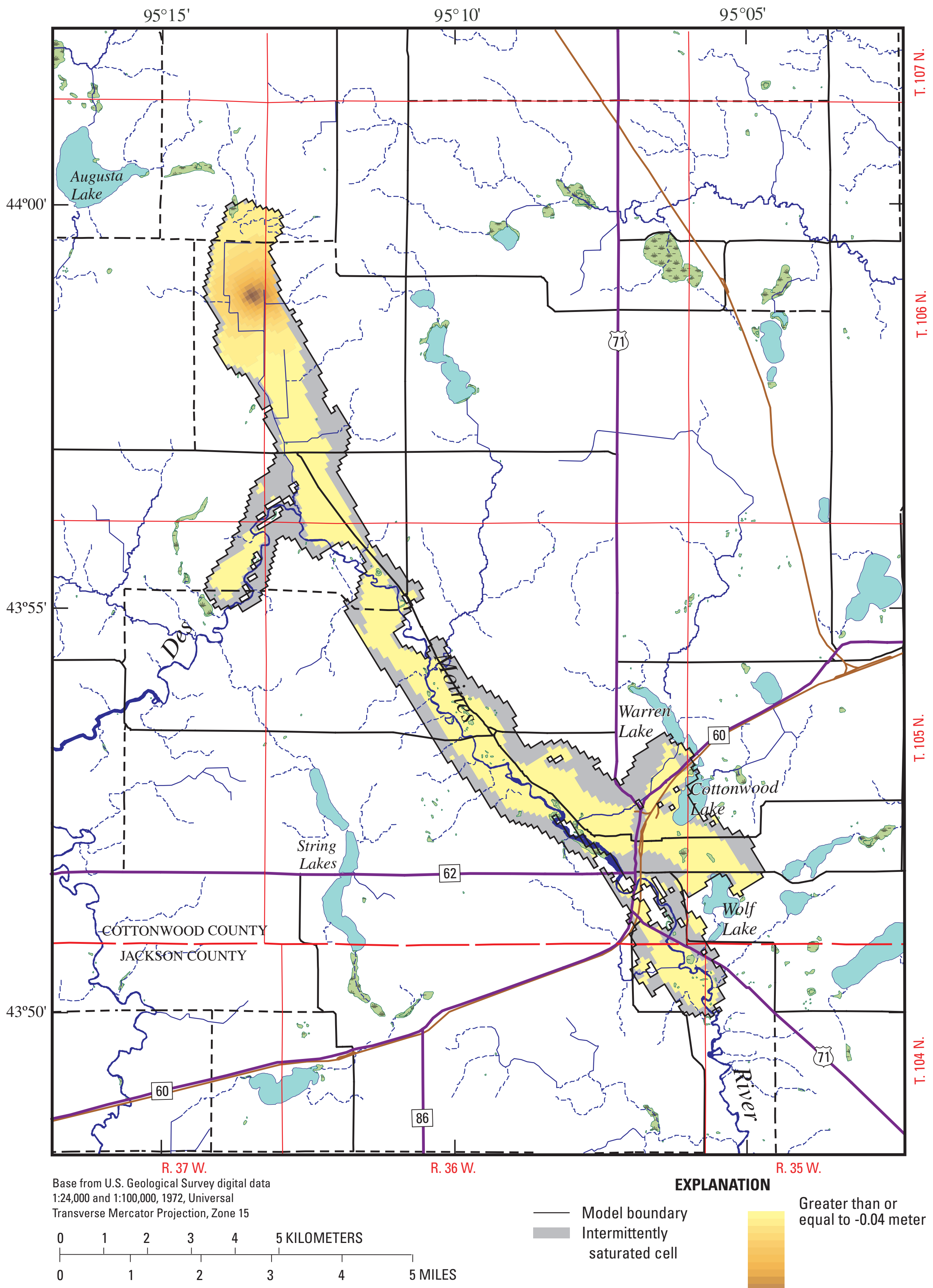

Figure 16. Difference between calibrated model heads and simulated heads for a scenario in which a new well that pumped 2,000 cubic meters per day was added to the Augusta Lake Valley area, Des Moines River study area, southwestern Minnesota.

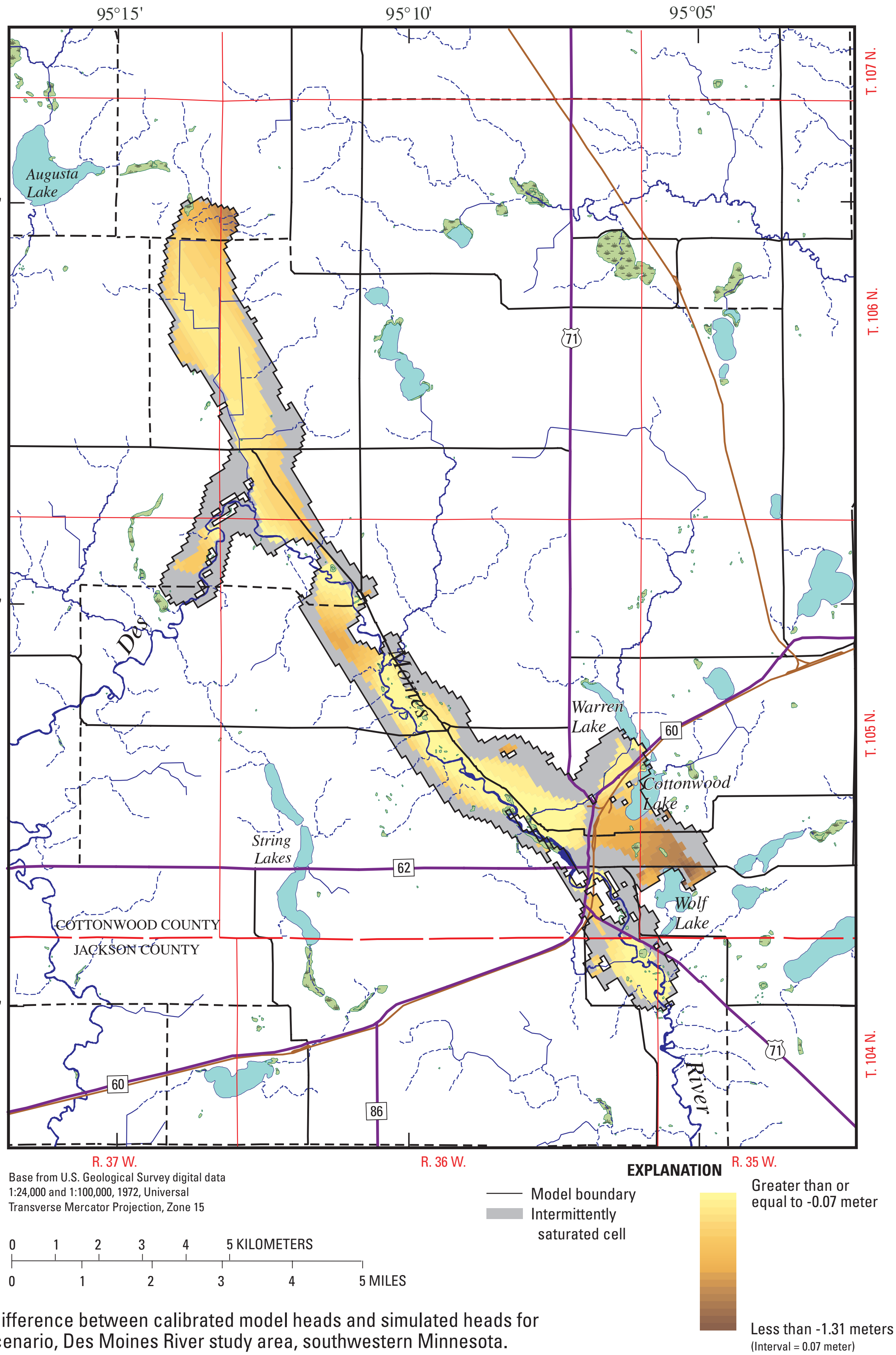

Figure 17. Difference between calibrated model heads and simulated heads for a drought scenario, Des Moines River study area, southwestern Minnesota.

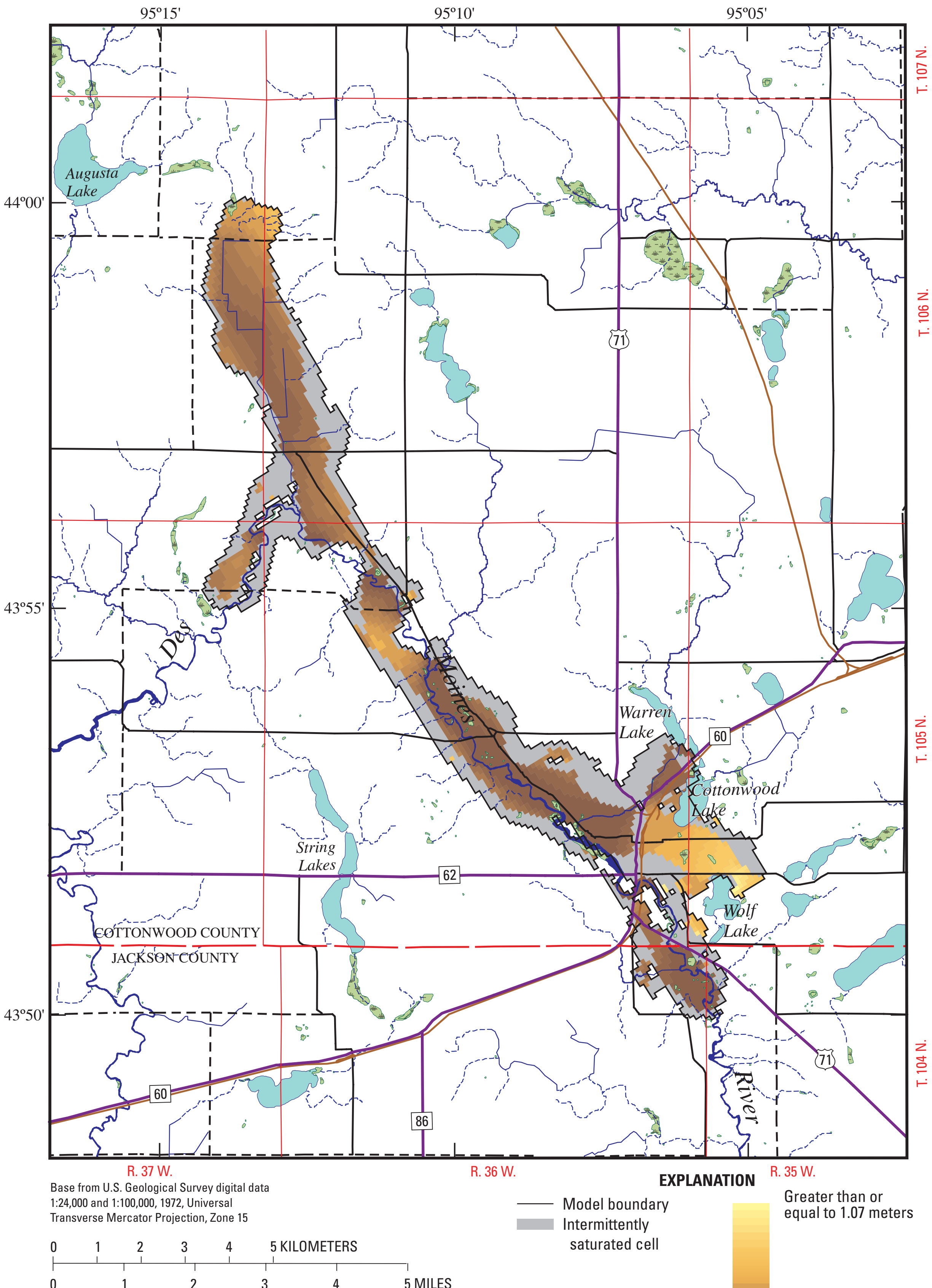

Figure 18. Difference between calibrated model heads and simulated heads for a high-precipitation scenario, Des Moines River study area, southwestern Minnesota.

control points for calibration. Therefore, any simulated results for those zones should be used with caution.

The aquifers simulated in the model developed for this study are thin, narrow, and discontinuous. Aquifers of that type are a challenge for finite-difference models. For this study, the model was stable only by the requirement that 0.85 m (2.8 ft) of water remained in all active cells (intermittently saturated cells). Although the head in these cells has no meaning, the cells transmit water recharged areally and from adjacent cells. Results of the model should be interpreted carefully in consideration of this limitation. Particular uncertainty may exist in edge recharge flux changes from the scenarios tested with the model. Many of the model cells that contain general-head-boundary stresses that represent edge recharge were intermittently saturated in the calibrated model and the scenarios. Thus, head changes in the aquifer that result from the different stresses of the scenarios would have little or no effect on the edge recharge flux because, in all scenarios, the general-head-boundary stresses would add a maximum amount of water to the model.

Effects of Ground-Water Withdrawals on Ground-Water/Surface-Water Interactions

The water-flow and water-quality data generated in this study help describe the state of shallow ground-water resources in the Des Moines River Valley near Windom and how these resources function. Human modification of the natural flow system is substantial and affects the quality of the water and how it moves through the system.

Water withdrawn from the hydrologic system by humans generally is changed in quality and reintroduced into the flow system at a different location. In the study area, water is withdrawn from the Des Moines River, Cottonwood Lake, surficial aquifers, and a Cretaceous aquifer. Water withdrawn directly from surface water is used for gravel washing or irrigation and is quickly released back to the surface-water body. However, gravel washing increases the turbidity of the return water, and irrigation can increase the concentration of nutrients and pesticides in the return water and increase its temperature. Some water pumped for irrigation also is lost to evapotranspiration.

Indirect withdrawals of surface water occur at the Windom and Red Rock well fields. The isotopic composition of water samples indicates that the Windom well field induces recharge to the Windom aquifer from Cottonwood Lake, which contributes about one-half of the water withdrawn from the well field. About two-thirds of this water is released to the Des Moines River at the Windom wastewater-treatment plant. Water from Cottonwood Lake naturally flows to the Des Moines River through the stream that drains Warren Lake during times of high lake levels. Induced infiltration has the effect of exporting water from Cottonwood Lake to the river or out of the basin, even during times of low lake levels. Municipal use of water withdrawn from the Windom aquifer increases the concentrations of nutrients and manmade chemicals in the wastewater effluent released to the Des Moines River. Infiltration of lake water into the Windom aquifer imparts surface-water quality to the ground water. Although the ground-water and surface-water qualities usually are similar, they may differ, especially during times of substantial runoff.

The Windom well field does not induce recharge from the Des Moines River. The Windom aquifer is separated from the river by thin, poorly sorted, nearly unsaturated sand and gravel. Although the head in the pumping center of the Windom well field is lower than the river stage, intervening saturated aquifer materials that are capable of transmitting water from the river are absent. A lower connected aquifer possibly may extend from the well field to the west, but the till that underlies the Des Moines aquifer in Windom probably separates any lower aquifer from the river. These aquifer characteristics were built into the ground-water model, and model results confirm that river water does not flow toward the Windom well field.

Cell flow budgets in the steady-state ground-water model indicate no infiltration of river water to the Red Rock well field. However, hydrographs for monitoring wells around the well field indicate extended periods during which heads in the production wells were lower than heads in the adjacent river and during which no ground-water divide existed between the two. This condition implies river-water induction into the aquifer and flow to the wells. During November 1998–January 1999 and December 1999–May 2001, the cone of depression of the Red Rock well field intersected the Des Moines River; thus, river water was allowed to recharge the aquifer. The November 1998–January 1999 and December 1999–May 2001 periods, which accounted for more than one-half of the time during which water levels were measured for this study, were during a time of low precipitation and areal recharge to the aquifer. The amount of river water induced into the aquifer during those periods and the percentage of pumped water derived from the river are unknown.

Long-term withdrawals of water for public supplies may cause a net decrease in ground-water discharge to surface water that is approximately equal to the amount of water withdrawn. The water withdrawn from the Windom well field otherwise would remain in Cottonwood Lake and evaporate or flow to the Des Moines River. The water used within Windom discharges to the Des Moines River through sanitary and storm sewers. However, in 2000, 36 percent of the water withdrawn from the well field [471,000 m^3 (124.4 Mgal)] was exported outside the Des Moines River Basin. Thus, water withdrawn from the Windom well field possibly may cause either a net increase or a net decrease in flow in the Des Moines River. If the river flow changes, the change is dynamic and varies in magnitude and sign (net increase or net decrease in flow) over periods of

Table 8. Mass balances for calibrated model and hypothetical simulations, Des Moines River study area, southwestern Minnesota.

[All numbers for in, out, and in-out are in cubic meters per day; all numbers for difference are in percent; —, not applicable]

	Total model				Windom aquifer				Cottonwood Lake			
Number of cells	4,052				586				46			
Calibrated												
Sources/sinks	In	Out	In-Out	Difference	In	Out	In-Out	Difference	In	Out	In-Out	Difference
Drains	0	-24,912.00	-24,912.00	—	0	-1,660.00	-1,660.00	—	0	0	0	—
General heads	68,252.90	-137.80	68,115.10	—	2,119.88	-35.61	2,084.27	—	1,773.36	0	1,773.36	—
Rivers	3,939.15	-55,362.10	-51,422.95	—	0	-17.31	-17.31	—	0	0	0	—
Wells	0	-5,728.00	-5,728.00	—	0	-3,635.00	-3,635.00	—	0	-354.00	-354.00	—
Recharge	13,958.20	0	13,958.20	—	1,837.80	0	1,837.80	—	197.80	0	197.80	—
Sources/sinks total	86,150.30	-86,139.90	10.40	0.01	3,957.68	-5,347.92	-1,390.24	-35.13	1,971.16	-354.00	1,617.16	82.04
Cell-to-cell total	772,112.00	-772,112.00	0	0	37,303.40	-35,913.10	1,390.30	3.73	6,347.86	-7,965.01	-1,617.15	-25.48
TOTAL FLOW	858,262.30	-858,251.90	10.40	0	41,261.08	-41,261.02	0.06	0	8,319.02	-8,319.01	0.01	0
Doubled ground-water withdrawals												
Sources/sinks	In	Out	In-Out	Difference	In	Out	In-Out	Difference	In	Out	In-Out	Difference
Drains	0	-24,049.20	-24,049.20	—	0	-1,292.27	-1,292.27	—	0	0	0	—
General heads	70,288.50	-120.69	70,167.82	—	4,102.13	-18.71	4,083.42	—	3,462.44	0	3,462.44	—
Rivers	4,611.45	-53,228.60	-48,617.15	—	0	-16.756	-16.76	—	0	0	0	—
Wells	0	-11,456.00	-11,456.00	—	0	-7,270.00	-7,270.00	—	0	-708.00	-708.00	—
Recharge	13,958.20	0	13,958.20	—	1,837.80	0	1,837.80	—	197.80	0	197.80	—
Sources/sinks total	88,858.15	-88,854.49	3.66	0	5,939.93	-8,597.74	-2,657.81	-44.74	3,660.24	-708.00	2,952.24	80.66
Cell-to-cell total	798,006.00	-798,006.00	0	0	61,706.40	-59,048.50	2,657.90	4.31	12,408.90	-15,361.10	-2,952.20	-23.79
TOTAL FLOW	886,864.15	-886,860.49	3.67	0	67,646.33	-67,646.24	0.09	0	16,069.14	-16,069.10	0.04	0
New well												
Sources/sinks	In	Out	In-Out	Difference	In	Out	In-Out	Difference	In	Out	In-Out	Difference
Drains	0	-23,053.40	-23,053.40	—	0	-1,660.00	-1,660.00	—	0	0	0	—
General heads	68,393.20	-137.80	68,255.40	—	2,119.88	-35.61	2,084.27	—	1,773.36	0	1,773.36	—
Rivers	3,939.15	-55,361.00	-51,421.85	—	0	-17.31	-17.31	—	0	0	0	—
Wells	0	-7,728.00	-7,728.00	—	0	-3,635.00	-3,635.00	—	0	-354.00	-354.00	—
Recharge	13,958.20	0	13,958.20	—	1,837.80	0	1,837.80	—	197.80	0	197.80	—
Sources/sinks total	86,290.55	-86,280.20	10.35	0.01	3,957.68	-5,347.92	-1,390.24	-35.13	1,971.16	-354.00	1,617.16	82.04
Cell-to-cell total	769,730.00	-769,730.00	0	0	37,303.40	-35,913.10	1,390.30	3.73	6,347.86	-7,965.01	-1,617.15	-25.48
TOTAL FLOW	856,020.55	-856,010.20	10.35	0	41,261.08	-41,261.02	0.06	0	8,319.02	-8,319.01	0.01	0

Table 8. Mass balances for calibrated model and hypothetical simulations, Des Moines River study area, southwestern Minnesota.—Continued

[All numbers for in, out, and in-out are in cubic meters per day; all numbers for difference are in percent; —, not applicable]

	Total model				**Windom aquifer**				**Cottonwood Lake**			
Number of cells	4,052				586				46			
Drought												
Sources/sinks	In	Out	In-Out	Difference	In	Out	In-Out	Difference	In	Out	In-Out	Difference
Drains	0	-19,355.50	-19,355.50	—	0	-1,359.08	-1,359.08	—	0	0	0	—
General heads	56,323.00	-84.72	56,238.28	—	2,148.82	-20.96	2,127.86	—	1,963.70	0	1,963.70	—
Rivers	4,422.36	-45,564.70	-41,142.34	—	0	-13.44	-13.44	—	0	0	0	—
Wells	0	-5,728.00	-5,728.00	—	0	-3,635.00	-3,635.00	—	0	-354.00	-354.00	—
Recharge	9,983.66	0	9,983.66	—	1,323.86	0	1,323.86	—	142.60	0	142.60	—
Sources/sinks total	70,729.02	-70,732.92	-3.90	-0.01	3,472.68	-5,028.48	-1,555.80	-44.80	2,106.30	-354.00	1,752.30	83.19
Cell-to-cell total	665,568.00	-665,568.00	0	0	35,381.80	-33,826.40	1,555.40	4.40	6,689.98	-8,442.28	-1,752.30	-26.19
TOTAL FLOW	736,297.02	-736,300.92	-3.90	0	38,854.48	-38,854.88	-0.40	0	8,796.28	-8,796.28	0	0
High precipitation												
Sources/sinks	In	Out	In-Out	Difference	In	Out	In-Out	Difference	In	Out	In-Out	Difference
Drains	0	-28,758.50	-28,758.50	—	0	-1,865.95	-1,865.95	—	0	0	0	—
General heads	76,155.40	-212.08	75,943.32	—	1,968.78	-73.53	1,895.25	—	1,630.91	0	1,630.91	—
Rivers	3,605.42	-62,184.30	-58,578.88	—	0	-20.36	-20.36	—	0	0	0	—
Wells	0	-5,728.00	-5,728.00	—	0	-3,635.00	-3,635.00	—	0	-354.00	-354.00	—
Recharge	17,103.60	0	17,103.60	—	2,223.26	0	2,223.26	—	239.20	0	239.20	—
Sources/sinks total	96,864.42	-96,882.88	-18.46	-0.02	4,192.04	-5,594.84	-1,402.80	-33.46	1,870.11	-354.00	1,516.11	81.07
Cell-to-cell total	845,496.00	-845,496.00	0	0	38,842.00	-37,439.10	1,402.90	3.61	6,132.00	-7,648.11	-1,516.11	-24.72
TOTAL FLOW	942,360.42	-942,378.88	-18.46	0	43,034.04	-43,033.94	0.10	0	8,002.11	-8,002.11	0	0

months or less. The change in river flow is dependent on the balance between decreased evaporation from Cottonwood Lake and increased exports of water from the basin.

The Red Rock Rural Water System's service area is widely distributed and large parts of the area are outside the Des Moines River Basin. The city of Jeffers is entirely outside the basin. Therefore, nearly all water pumped from these public supplies reduces flow in the Des Moines River. The pumped water would otherwise discharge from the aquifer to streams and ditches that drain to the river or would discharge to the river itself.

During periods of low flow, the Des Moines River is sustained by ground-water discharge from the Des Moines aquifer in the study area and possibly other upstream areas. During those periods, the river water quality is essentially the same as the aggregate ground-water quality. Sample results for this study indicate the ground-water and surface-water qualities in the study area are similar. Therefore, ground-water discharge captured by public-supply wells probably has little effect on river water quality.

Summary

Increased water demand in and around Windom led the U.S. Geological Survey, in cooperation with the Minnesota Department of Natural Resources, local water suppliers, and Cottonwood County, to study the hydrology of aquifers in the Des Moines River Valley near Windom. The hydrogeology of the study area and the ground-water/surface-water interactions during current and anticipated future conditions were described. The study area is the watershed of a 30-kilometer (19-mile) reach of the Des Moines River upstream from Windom. Corn and soybean agriculture is the main land use throughout most of the study area, but residential and urban land uses dominate the area in and around Windom. Most of the data collection occurred during a relatively dry period (1997-99).

The primary sources of water in the study area are surficial glacial and alluvial aquifers, a buried Cretaceous aquifer, and surface water. The city of Windom, the Red Rock Rural Water System, and the city of Jeffers are the principal water suppliers and pumped 72 percent of the 2.604 million cubic meters (687.9 million gallons) of water used during 2000. These public suppliers pump water exclusively from the surficial aquifers. Total water use in the study area increased 31 percent during 1991–2000. The surficial aquifers provide 76 percent of the water used, and the Des Moines River and Cottonwood Lake provide 5 percent of the water used. Most of the water pumped from the surficial aquifers is used in residences (59 percent), ethanol production (17 percent), and commerce within Windom (11 percent).

Based on stratigraphic analysis, two hydrologically and genetically separate surficial aquifers underlie the study area. The Windom aquifer is located east of Windom, and the Des Moines aquifer is located in the Des Moines River Valley. The surficial aquifers are relatively isolated from deeper aquifers by till, but some leakage probably occurs. The surficial aquifers closely interact with surface waters in the study area. The Windom aquifer, which is structurally more complex, finer-grained, and more variable than the Des Moines aquifer, thins in all directions from the Windom well-field area and has a maximum saturated thickness of 34 meters (111 feet). The Windom aquifer is strictly surficial in the west near the Windom well field. To the east, the aquifer may interfinger with till and have both surficial and buried parts. The Des Moines aquifer has a maximum saturated thickness of 33 meters (108 feet) and generally thins toward the edges of the Des Moines River Valley. The aquifer consists of poorly sorted loamy sand to gravel and has lenses of well-sorted sands, silts, and clayey diamictons. Aquifer materials at the junction between the Windom and Des Moines aquifers are thin and poorly conductive.

Recharge to the aquifers is from areal recharge, from Cottonwood Lake, and from edge recharge. Net areal recharge to the Des Moines aquifer was estimated from ground-water hydrographs to be between 0.00036 and 0.0017 meter per day (5.2 to 23.9 inches per year). Discharge from the Windom aquifer is primarily to municipal wells and to surface waters. The Des Moines aquifer discharges primarily to the Des Moines River and to ditches in the Augusta Lake Valley. A low-flow seepage measurement for the Des Moines River in October 1997 indicated ground-water discharge was 71,000 cubic meters per day (29 cubic feet per second), which probably is a reasonable average rate. Baseflow measurements for the Des Moines River, hydrograph recharge estimates, and ground-water modeling indicate annual net areal recharge accounts for about 32 percent of the flux through the ground-water system. The remaining 68 percent of the ground water that flows in the Des Moines aquifer presumably is from edge recharge. Ground-water flow in the western part of the Windom aquifer is toward the Windom well field, and ground-water flow in the Des Moines aquifer is primarily from the aquifer edges toward the Des Moines River or toward the ditch system in the Augusta Lake Valley area.

During dry periods, ground-water discharge sustains flow in the Des Moines River and its larger tributaries. When the water level in the aquifer is less than the level of the riverbed, flow in the river approaches zero. During periods of high surface-water levels, surface water recharges the aquifer. The Des Moines River has stopped flowing during four periods within the last 30 years. During this study, the water level in a well located between two Red Rock wells and the river was lower than the river level during two periods. During those periods, water in the Des Moines River had the potential to recharge the aquifer. The amount of water that may have infiltrated is unknown but would have been dependent on the permeability of the riverbed sediments and the availability of water in the river. Based on water levels, isotope data, and ground-water modeling, pumping at the Windom well field induces substantial amounts of Cottonwood Lake water into the aquifer. Isotopic composition of ground water and Cottonwood Lake water indicated about one-half of the water withdrawn from the Windom aquifer is recharged areally and one-half is recharged from Cottonwood Lake. Chlorofluorocarbon and sulfur hexafluoride concentrations in ground-water samples indicated most ground water near the water table was less than 20 years old.

Most of the ground-water samples collected in the study area consisted of calcium-magnesium bicarbonate waters. However, a sample from a thin buried glacial aquifer was dominated by sulfate anions and had a dissolved-solids concentration of 2,120 milligrams per liter. Samples collected from seven wells during this study and from the Des Moines River during the 1960's had relatively high sulfate concentrations, suggesting ground-water discharge to the Des Moines River is from both surficial and deep aquifers. Nutrient concentrations in ground-water samples were skewed low with high outliers. The highest concentrations were for samples collected from two wells within Windom. Nutrient concentrations in river samples were less than analytical reporting limits except for total phosphorus and organic nitrogen. Corn and soybean herbicides and their degradates were detected in 14 of 27 ground-water samples and in all 3 river samples. Most of the detected concentrations were less than 1 microgram per liter, and most detections were degradates of acetamide herbicides. Metolachlor ethane sulfonic acid was the most commonly detected compound and also was detected at the highest concentrations. Nutrient, herbicide, and degradate concentrations varied by about one-half an order of magnitude at each sampling site during 1999–2000. The variability generally was lower for the ground-water samples than for the river samples. Nitrate concentrations were near or above the drinking-water standard in three of four samples collected from one well.

Samples from the Des Moines River had variable but low concentrations of nutrients and agricultural herbicides. Concentrations in the samples did not exceed drinking-water standards or health advisories. The river sample collected on April 27, 1999, had the highest nitrate concentration for river samples collected during this study. At a cost of 13 cents per pound, the value of the applied anhydrous ammonia represented by the nitrogen load that flowed down the Des Moines River past Windom on April 27, 1999, was $8,968.

The single-layer, steady-state, finite-difference ground-water flow model developed for this study was used to simulate heads and fluxes in the surficial aquifers and to simulate ground-water/surface-water interactions. The bottom elevation of the aquifer was interpolated from 250 wells that had stratigraphic logs. Flow was not simulated across the bottom and lateral sides of the aquifer to represent no flow from low-conductivity till adjacent to the aquifer. The aquifers were divided into five zones that had separate hydraulic conductivity and recharge values. Evapotranspiration was not explicitly simulated in the model. Edge recharge represented water that infiltrates from overland flow or intermittent streamflow from till uplands or that discharges laterally from lenses buried beneath upland till. Edge recharge was applied as a general-head-boundary stress at the horizontal edge of the model. Hydrologic stresses incorporated into the model included drainage ditches and intermittent rivers, perennial rivers, and lakes and wetlands.

The model was calibrated to 84 ground-water measurements, a low-flow seepage measurement on the Des Moines River, and the Cottonwood Lake recharge percentage. Calibrated model aquifer hydraulic conductivity ranged from 0.5 to 90 meters per day (1.6 to 295 feet per day), and net areal recharge ranged from 0.00006 to 0.00060 meter per day (0.9 to 8.6 inches per year). Calibrated net areal recharge ranged from 17 to 30 percent of the average annual precipitation. Nearly all recharge to the aquifer in the ground-water simulation was from edge recharge (80 percent) and net areal recharge (17 percent). The mean of the absolute value of head error was 0.31 meter (1.02 feet). Simulated net river and drain flux was 107 percent of the measured value, and simulated Cottonwood Lake flux was 98 percent of the measured value. Simulated flux out of the ditches draining the Augusta Lake Valley was 4.19 times the measured flux. Simulated heads were most sensitive to reductions in aquifer hydraulic conductivity and increases in net areal recharge. Simulated net river and drain flux was most sensitive to changes in edge recharge.

Scenarios tested with the calibrated model involved increased ground-water withdrawals and changes in recharge to simulate drier or wetter weather conditions. Doubling the withdrawals from all wells in the model had a small effect except in the Windom well-field area. Maximum head declines in the Red Rock well field and the Jeffers city well were small [less than 40 centimeters (15 inches)]. In the Windom well field, the maximum head decline was 11 meters (36 feet). The addition of a new well that pumped 2,000 cubic meters per day (0.44 million gallons per day) in the Augusta Lake Valley area caused a 0.83-meter-deep (2.72-foot-deep) cone of depression that extended to the valley walls. The drought scenario resulted in head declines in the northern part of the Augusta Lake Valley area, in the southwestern part of the Red Rock area, and near the valley edges. The high-precipitation scenario resulted in head increases in those areas.

The ground-water model is a simplification of a complex natural system. Large aquifer areas are assumed to be homogeneous and unchanging. The heads and fluxes produced by the model are dependent on these simplifications and are inaccurate to the degree that these assumptions deviate from actual conditions. The model is a steady-state simulation of ground-water flow. Therefore, model results are predicated on the assumption that inflows to and outflows from the aquifers are constant in time and equal to one another. The model is regional in scale and has a cell size of 1 hectare (2.5 acres). The model provides no details of ground-water heads or flows on a scale of less than several hundred meters (about 1,000 feet). The model was calibrated to hydraulic conditions considered normal during the last 30 years. Model results become less reliable as scenario conditions deviate from the normal conditions.

Water withdrawn from aquifers in the study area affects how ground water interacts with surface water. Indirect withdrawals of surface water occur at the Windom and Red Rock well fields. About one-half of the water withdrawn from the Windom well field is from Cottonwood Lake. Two-thirds of this water is released to the Des Moines River at the Windom wastewater-treatment plant. The Windom well field does not induce recharge from the Des Moines River. Cell flow budgets indicate no infiltration of river water to the Red Rock well field, but heads in the production wells were lower than heads in the adjacent river during extended periods. During those periods, river water recharged the aquifer, but the amount of river water induced by pumping is unknown. Long-term withdrawals of water for public supplies may cause a net decrease in ground-water discharge to surface water. Water that does not evaporate, or that is not exported, is discharged to the Des Moines River but with changed water quality. Because ground-water and surface-water qualities in the study area are similar, the ground-water discharge probably has little effect on river water quality.

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APPENDIXES 1–3

Appendix 1. Local ground-water studies in the Des Moines River study area, southwestern Minnesota.

[P, pumped well; —, none; O, observation well; VOCs, volatile organic compounds]

Organization	Consultant	Address	Date	Study purpose	Aquifer tests	Water-quality data
City of Jeffers	Bruce A. Liesch	Wayzata, Minnesota	1975	Ground-water supply study	1 P	—
Cottonwood County Landfill	Short Elliott Hendrickson, Inc.	St. Paul, Minnesota	2000	Contamination remediation	—	Ions, nutrients, VOCs, metals
Red Rock Rural Water System	De Wild Grant Reckert and Associates Co.	Rock Rapids, Iowa	1982	Ground-water supply study	—	Ions, nutrients, metals, radio-active chemicals
Red Rock Rural Water System	De Wild Grant Reckert and Associates Co.	Rock Rapids, Iowa	1993	Ground-water withdrawal permit	1 P, 3 O	—
Cottonwood County Highway Department	Dahl and Associates, Inc.	St. Paul, Minnesota	1998	Contamination remediation	—	VOCs
City of Windom	Bonestroo, Rosene, Auderlik and Associates	St. Paul, Minnesota	1974	Ground-water supply study	2 P, 2 O	—
City of Windom	Wenck Associates, Inc.	Wayzata, Minnesota	1989	Contamination remediation	—	VOCs
City of Windom	Hickok and Associates		1989	Contamination remediation	3 O	—
City of Windom	Bruce A. Liesch Associates, Inc.	Minneapolis, Minnesota	1990	Ground-water supply study	—	—
City of Windom	Wenck Associates, Inc.	Maple Plain, Minnesota	1997	Ground-water supply study	1 P, 2 O	—
Brown-Nicollet-Cottonwood Counties	Brown-Nicollet Comm. Health Services	St. Peter, Minnesota	1992	Water-quality study	—	Ions, nutrients, pesticides, tritium, bacteria

Appendix 2. Number of samples analyzed for constituent groups, Des Moines River study area, southwestern Minnesota.

[USGS, U.S. Geological Survey; G, ground water; S, surface water; --, no data; NWQL, National Water-Quality Laboratory; OGRG, Organic Geochemistry Research Group Laboratory; RCL, Reston Chlorofluorocarbon (CFC) Laboratory; LC/MS, Liquid chromatography/mass spectrometry; HPLC, High pressure liquid chromatography; SF_6, sulfur hexafluoride; bold number indicates sample is repeated from spatial sampling column]

Analyte Group	Spatial sampling: April 1999 through July 2000		Temporal sampling: April 1999		July 1999		September 1999		May 2000		July 2000		USGS laboratory	Laboratory reference[1]	Analytical method reference
	G	S	G	S	G	S	G	S	G	S	G	S			
Major ions	27		--	--	**3**	--	--	--	--	--	--	--	NWQL	573	Fishman, 1993
Chloride and sulfate	--	3	--	(1)	--	--	4	1	4	1	4	1	NWQL	1218	Fishman, 1993
Nutrients	27		1	--	**3**	--	4	--	4	--	4	--	NWQL	101	Fishman, 1993
Nutrients	--	4	--	(1)	--	--	--	1	--	1	--	1	NWQL	86, 2702	Fishman, 1993
Herbicides	27		1	(1)	**3**	--	3	--	4	1	4	1	OGRG	SMHRB	Kish and others, 2000
Degradates: LC/MS	24		1	--	**3**	--	--	--	4	1	4	1	OGRG	LCAA	Lee and others, 2001
Degradates: HPLC	3		--	(1)	--	--	4	--	--	--	--	--	OGRG	HPAA	Hostetler and Thurman, 1999
Water isotopes	24		--	--	**3**	--	--	--	--	--	--	--	NWQL	1142	Fishman and Friedman, 1989
Age dating: CFC	12		--	--	**3**	--	--	--	--	--	--	--	RCL	none	Busenberg and Plummer, 1992
Age dating: SF_6	13		--	--	--	--	--	--	--	--	--	--	RCL	none	Busenberg and Plummer, 2000
Dissolved gasses	25		--	--	**3**	--	--	--	--	--	--	--	RCL	none	Busenberg and Plummer, 1992

[1]Reference is USGS laboratory constituent group code.

Appendix 3. Water-Quality Sampling Methods and Quality Control

Ground water was collected after purging each well of three casing volumes of water using a submersible, positive-displacement pump and after conductance, pH, water temperature, and dissolved oxygen values stabilized. River samples were depth integrated. Constituents for which samples were analyzed include major ions, nutrients, herbicides (triazines, acetamids, and their degradation products), stable isotopes of hydrogen and oxygen, and chlorofluorocarbons or sulfur hexafluoride (used to determine ground-water age). Sampling equipment for all water samples analyzed for herbicides were constructed of Teflon and stainless steel to minimize cross-contamination of water samples. Water was delivered from the pump to an enclosed sampling chamber through Teflon lines and stainless-steel valves and connectors so the water had little contact with the atmosphere and was never under pressure less than atmospheric. This system also ensured that the chemical concentrations, particularly the dissolved-gas composition of the sample water, changed as little as possible during sample collection. Samples analyzed for CFC compounds contacted only metal and ultra-pure nitrogen gas before being sealed in glass vials.

Sample containers were chosen and prepared to avoid contamination from the containers, dissolved constituents adsorbing to the containers, or constituent degradation. Pump flow rate was adjusted to about 2 L/min (0.5 gal/min) to avoid particulate suspension in the well casing. Samples for major ions and nutrients were filtered through a 0.45-µm nitrocellulose filter. Herbicide samples were filtered through a 0.7-µm baked glass-fiber filter. All other samples were unfiltered. Sample containers were filled in a consistent order, as quickly as possible, to maintain constant effective filtration (due to filter loading) for each sample type. Cation samples were preserved with nitric acid. Nutrient and herbicide samples were shipped to the analyzing laboratory in ice-filled coolers the same day they were collected. Alkalinity was determined in the field by incremental titration.

All equipment was decontaminated in the field between each sample collected. Decontamination consisted of washing the equipment with nonphosphate detergent and local ground water and rinsing it with local ground water and deionized water. Any equipment that would touch sample water was stored in aluminum foil. Weekly decontamination of all equipment was the same as field decontamination except that the equipment also was rinsed with herbicide-free methanol after which it was rinsed with deionized water. Weekly decontamination also was performed after the equipment was stored unused longer than 2 weeks. These procedures helped produce samples that represented the river or the ground water in the aquifer near each well screen and minimized sampling bias.

The QC program consisted of field blank samples and duplicate samples, which gauged the precision and accuracy of the ambient samples collected. A total of three blank samples were collected in the field after ground-water sampling and decontamination to demonstrate the degree of cross-contamination of the sampling procedure. Of these blank samples, one was analyzed for major ions, nutrients, and herbicides. The major-ion concentrations in the blank sample were less than the analytical reporting limits except for calcium, magnesium, and sodium. Concentrations for those constituents were at or less than 1.5 percent of the concentrations in the ambient sample. The nutrient concentrations in the blank sample were less than the analytical reporting limits except for nitrate plus nitrite and orthophosphorus, which had concentrations that were slightly greater than the analytical reporting limits. Because the nutrient concentrations in the ambient sample were small, however, the concentrations in the blank sample were within the range of those for the ambient samples. The herbicide concentrations in the blank sample were less than the analytical reporting limits. The two remaining blank samples were analyzed for anions and nutrients. The fluoride concentration in one of those blank samples was twice the analytical reporting limit and 35 percent higher than the concentration in the ambient sample. The nutrient concentrations in those samples were less than the analytical reporting limits.

A total of two duplicate ambient-sample sets were collected to determine concentration reproducibility. A duplicate ground-water sample set was analyzed for field properties, major ions, nutrients, and herbicides. Herbicide concentrations in this set were less than the analytical reporting limits in both samples. The differences between the two samples for all field-property, major-ion, and nutrient values were within 5 percent except for dissolved oxygen, which had values that were near zero and differed by 0.01 mg/L. Most of the field-property values differed by less than 0.2 percent. A duplicate river sample set was analyzed for field properties, anions, and nutrients and had values that differed by no more than 2 percent except for total phosphorus, which had values that differed by 5 percent (0.006 mg/L). Results for the duplicate ambient-sample sets indicate water-quality values generally were reproducible to within 2 percent but may have differed by as much as 6 percent for all values except herbicides. The herbicide concentrations were reproducible below the analytical reporting limits, but their reproducibility above the limits is unknown.