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Prepared in cooperation with the Minnesota Department of Na
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Water-Resources Investigations Report 99–4157

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

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By R.J. Lindgren and M.K. Landon

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U.S. Department of the Interior

Bruce Babbitt, Secretary

U.S. Geological Survey

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Mounds View, Minnesota, 2000

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Conversion Factors, Abbreviated Water-Quality Units, and Abbreviations

Multiply	By	To obtain
inch (in.)	2.54	centimeter
inch per year (in./yr)	2.54	centimeter per year
foot (ft)	.3048	meter
foot per day (ft/d)	.3048	meter per day
foot per mile (ft/mi)	.1894	meter per kilometer
cubic foot per second (ft^3/s)	.02832	cubic meter per second
gallon (gal)	3.785	liter
gallon per minute (gal/min)	3.785	liter per minute
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
degree's Celsius (^oC)	1.8 (^oC)+32	degrees Fahrenheit

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Chemical concentrations are given in metric units. Chemical concentrations of substances in water are given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as mass (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million. Specific conductance values are given in units of microsiemens per centimeter (µS/cm) at 25^oC.

Abbreviations used in this report:

<	less than
>	greater than
‰	per mil
$\delta^{18}O$	stable isotope of oxygen in reference to a standard
δD	stable isotope of hydrogen in reference to a standard
acetochlor ESA	acetochlor ethane-sulfonic acid (metabolite of acetochlor)
acetochlor OA	acetochlor oxanilic acid (metabolite of acetochlor)
alachlor ESA	alachlor ethane-sulfonic acid (metabolite of alachlor)
alachlor OA	alachlor oxanilic acid (metabolite of alachlor)
atrazine plus metabolites	Sum of atrazine plus metabolites de-ethylatrazine and de-isopropylatrazine
CFC	chlorofluorocarbon
DEA	deethylatrazine (metabolite of atrazine)
DIA	deisopropylatrazine (metabolite of atrazine)
DO	dissolved oxygen
ELISA	enzyme-linked immunosorbent-assay
GC/MS	gas-chromatographic mass-spectrometry
HPLC	high pressure liquid chromatography
K	horizontal hydraulic conductivity
K_v	vertical hydraulic conductivity
K_s	hydraulic conductivity of streambed
LUV	Luverne supply well
MCL	Maximum Contaminant Level
MDH	Minnesota Department of Health
MDNR	Minnesota Department of Natural Resources
metolachlor ESA	metolachlor ethane-sulfonic acid (metabolite of metolachlor)
metolachlor OA	metolachlor oxanilic acid (metabolite of metolachlor)
N_2	nitrogen gas
nitrate-N	nitrite plus nitrate nitrogen
PVC	polyvinyl chloride
NWQL	National Water-Quality Laboratory
RW	Rock County Rural Water District supply well
TU	tritium units
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

Glossary

Alluvial deposits: Gravel, sand, silt, and clay deposited in channels and floodplains of modern streams.

Aquifer: Formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs.

Areal recharge: Recharge to the aquifer by infiltration of precipitation to the saturated zone.

Base flow: Sustained streamflow, consisting mainly of ground-water discharge to a stream.

Confined aquifer: Aquifer bounded above by a confining unit. An aquifer containing confined ground water. Synonymous with buried aquifer.

Confining unit: Body of material with low vertical permeability stratigraphically adjacent to one or more aquifers.

Dissolved: Constituents in a representative water sample that pass through a 0.45-μm (micrometer) membrane filter. The dissolved constituents are determined from subsamples of the filtrate.

Drawdown: Vertical distance between the static (nonpumping) hydraulic head and hydraulic head caused by pumping.

Evapotranspiration: Water discharged to the atmosphere by evaporation from water surfaces and moist soil and by plant transpiration.

Gaining stream: Stream or reach of a stream whose flow is being increased by inflow of ground water.

Ground water: The part of subsurface water that is in the saturated zone.

Ground-water contributing area: That part of a ground-water-flow system supplying water to a well.

Ground-water evapotranspiration: Water discharged to the atmosphere from ground water by direct evaporation from the water table where it is at or near land surface and transpiration from vegetation where the water table is above the root zone or within reach of roots through capillary action; does not include evapotranspiration losses occurring above the water table.

Head, hydraulic: The height, above a standard datum, of the surface of a column of water that can be supported by the static pressure at a given point.

Hydraulic conductivity: Capacity of porous material to transmit water under pressure. The rate of flow of water passing through a unit section or area under a unit hydraulic gradient.

Hydraulic gradient: The change in hydraulic head per unit distance of flow in a given direction. Synonymous with potentiometric gradient.

Induced infiltration: Flow induced to move directly from the stream channel into the aquifer as a result of ground-water withdrawals by wells.

Intercepted subsurface flow: Ground-water flow en route to the stream channel that would have eventually discharged into the stream but is intercepted by pumped wells.

Isotope: Any of two or more species of atoms of a chemical element with the same number and position in the periodic table and nearly identical chemical behavior, but with differing atomic mass or mass number and differing physical properties.

Losing stream: Stream or reach of a stream whose flow is being decreased by leakage to ground water.

Outwash: Washed, sorted, and stratified drift deposited by water from melting glacier ice.

Permeability: Measure of the relative ease with which a porous medium can transmit a fluid under a potential gradient.

Potentiometric surface: A surface that represents the static head of water in an aquifer, assuming no appreciable variation of head with depth in the aquifer. It is defined by the levels to which water will rise in tightly cased wells from a given point in an aquifer.

Reporting limit: The lowest measured concentration of a constituent that may be reliably reported using a given analytical method.

Saturated zone: The zone in which all voids are ideally filled with water. The water table is the upper limit of this zone. Water in the saturated zone is under pressure equal to or greater than atmospheric.

Specific capacity: The rate of discharge of water from a well divided by the drawdown of water level within the well.

Specific yield: The ratio of the volume of water that an aquifer material will yield by gravity drainage to the volume of the aquifer material.

Steady-state: Equilibrium conditions whereby hydraulic heads and the volume of water in storage do not change substantially with time.

Storage coefficient: The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In an unconfined aquifer, it is the same as the specific yield.

Stream-aquifer leakage: Movement of water between a stream and the underlying aquifer, not restricted to either direction of flow.

Stream depletion: A reduction in streamflow as a result of ground-water withdrawals by wells. Includes induced infiltration and intercepted subsurface flow.

Surficial aquifer: The saturated zone between the water table and the first underlying confining unit. Synonymous with unconfined aquifer.

Till: Unsorted, unstratified drift deposited directly by glacier ice.

Transmissivity: The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

Unconfined aquifer: The saturated zone between the water table and the first underlying confining unit. Synonymous with surficial aquifer.

Water table: The surface in an unconfined ground-water body at which the water pressure is atmospheric. Generally, this is the potentiometric surface of the upper part of the zone of saturation.

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By R.J. Lindgren and M.K. Landon

ABSTRACT

A better understanding of the ground-water and surface-water resources of the Rock River Valley in southwestern Minnesota was needed due to concerns surrounding future reliable sources of water for public supply. The Rock River Valley aquifer consists of a surficial sand and gravel unit that underlies the entire Rock River Valley and a buried sand and gravel unit that is present only in the vicinity of the Luverne Municipal and Airport well fields. The surficial and buried units of the aquifer are separated by a clay and till layer ranging in thickness from 1 to 38 feet. The combined maximum saturated thickness of the aquifer is 52 feet, with a median of 22 feet. The thickness of the buried unit ranges from 3 to 17 feet. Recharge to the Rock River Valley aquifer occurs primarily by infiltration of precipitation to the saturated zone (areal recharge) and by induced infiltration from the Rock River due to withdrawals from supply wells near the river. Discharge from the aquifer occurs primarily as leakage to streams and ground-water evapotranspiration.

The water budget for the calibrated steady-state simulation indicated that areal recharge accounts for 38 percent of the sources of water to the Rock River Valley aquifer and leakage from streams contributes 58.7 percent. The largest discharge from the aquifer is leakage to streams, (71.1 percent). The net stream-aquifer leakage is approximately 5 cubic feet per second from the aquifer to the streams. The simulated contributing areas for the wells in the three well fields generally extend to the aquifer boundaries on the west and are generally truncated at the Rock River. The simulated transient water budget for 1996 indicated that the principal sources of water to the aquifer were as follows: (1) winter, spring, and late summer stress periods— leakage from streams and water released from storage and (2) early summer and fall stress periods—areal recharge and leakage from streams. The principal discharges from the aquifer were leakage to streams for all stress periods, ground-water evapotranspiration for the early and late summer stress periods, and addition to storage for the early summer and fall stress periods.

The herbicides atrazine, alachlor, metolachlor, acetachlor, and cyanazine, and metabolites of these herbicides, occurred in concentrations of 0.05 to 11.5 micrograms per liter in the Rock River at Luverne during major runoff events following application of herbicides in the spring. Atrazine and metabolites, alachlor ESA (a metabolite of alachlor), metolachlor and metabolites, metolachlor ESA and metolachlor OA, and acetochlor metabolites acetochlor ESA and acetochlor OA, were detected at concentrations of 0.05 to 2.8 micrograms per liter in municipal supply wells less than 500 feet from the river during November 1995 through August 1997. The Rock River is the major source of the herbicides and metabolites. However, concentrations of atrazine and metabolites, alachlor ESA, metolachlor ESA, and metolachlor OA in supply wells may also reflect sources of these herbicides and metabolites in the ground-water contributing areas to the supply wells. Nitrite plus nitrate nitrogen concentrations in supply wells and in the ground-water contributing area to the Luverne Municipal well field were generally less than 1.5 milligrams per liter. Nitrite plus nitrate nitrogen concentrations of 2.4 to 8.5 milligrams per liter in the Rock River in the Rock County Rural Water well field and 14 to 18 milligrams per liter in the ground-water contributing area to the Rock County Rural Water supply wells are not having a substantial affect on nitrite plus nitrate nitrogen concentrations in most supply wells. Isotopic mixing calculations indicate that proportions of river water withdrawn from supply wells less than 500 feet from the river range from 5 to 60 percent of total withdrawals.

The Rock River is a gaining stream in most reaches, but is losing water to the aquifer in the vicinity of the Luverne Municipal and Rock County Rural Water well fields, located 150 to 1,500 feet from the river. Simulated streamflow losses due to ground-water withdrawals in the well fields were approximately 2.1 cubic feet per second. Because an average of about 1.5 cubic feet per second of the water pumped by Luverne is returned to the Rock River as wastewater discharge, the net steady-state simulated streamflow loss for the study area is 0.6 cubic feet per second. The streamflow losses as a result of ground-water withdrawals are insignificant in comparison to typical streamflow, and are likely to have a measurable effect on streamflow only during low-flow conditions of less than approximately 10 cubic feet per second.

Model results indicate that the additional water withdrawn by wells due to anticipated increased ground-water withdrawals was derived from a decrease in net leakage of ground water from the aquifer to the streams. The simulations indicated that the increased ground-water withdrawals and normal precipitation resulted in an increase in induced infiltration from the Rock River of 0.1 cubic feet per second for the Luverne Municipal well field and 0.3 cubic feet per second for the Rock County Rural Water well field. Maximum drawdowns ranged from 0.5 to 1.4 feet near the three well fields. For drought conditions, the simulated streamflow losses constituted approximately 30 percent and nearly 65 percent of the flows in the Rock River for the Luverne Municipal and Rock County Rural Water well fields, respectively. Maximum drawdowns ranged from 3.8 to 7.0 feet near the three well fields. Transient simulations with anticipated increased ground-water withdrawals and drought conditions indicated declines in hydraulic heads ranging from 0.2 to 0.4 feet per year in the vicinity of the three well fields, except for near the Rock River.

INTRODUCTION

Increased demand for water in southwestern Minnesota has resulted in the increased development of surficial aquifers. These surficial aquifers are composed of outwash and alluvial material in river valleys. One of the largest and most productive of these aquifers is the Rock River Valley aquifer (Adolphson, 1983) (fig. 1). The Rock River Valley aquifer is the source of water for the city of Luverne, Minnesota (population of 4,625 in 1997) and the Rock County Rural Water District (served about 2,700 people in 1997). The Rock River Valley aquifer is currently the only viable source for public water supply in the area. Test-hole drilling and geophysical exploration in Rock County have not found deeper aquifers that are viable for public supply (Berg, 1997; Chandler, 1997; Lindgren, 1997). Local water managers have considered importing water from the Missouri River in South Dakota (Red Arndt, Public Utilities Manager, City of Luverne, oral commun., 1997). Opponents of water importation have argued that local water resources are sufficient if greater water conservation measures are practiced. The concerns surrounding future reliable sources of water for public supply have led to the need for greater understanding of the ground-water and surface-water resources of the Rock River Valley in Rock County.

Many of the public supply wells in Rock County are located adjacent to the Rock River and have the potential to induce leakage from the river. The MDNR is concerned about the effects of ground-water withdrawals from wells on streamflow in the Rock River (Sarah Tufford, Minnesota Department of Natural Resources, Division of Waters, oral commun., 1994). Typically, changes in water supply that occur gradually, such as long-term changes in pumping rates, are detected first in the aquifer and show up later as reduced streamflow (Barker and others, 1983). The effect of recent well development and the possible effects of future development on flow in the Rock River are not well understood.

The effects of withdrawals by supply wells on streamflow in the Rock River is part of a broader need to delineate the areas contributing ground water to these wells. Delineation of areas to wells will allow local water managers to determine if ground water affected by potential contamination sources could reach the wells. Ground-water withdrawals from wells also affect local ground-water flow directions. Assessing changes in the contributing areas as a result of anticipated development, stream depletion, and drought conditions also is important.

Potential sources of contamination to the Rock River may be present upstream from the supply wells. Ground-water withdrawals by supply wells may induce flow from the Rock River to the aquifer and to the supply wells. Contaminants in the river water could thereby reach supply wells as a result of ground-water withdrawals. Water-quality data will be useful to help assess the interaction between the Rock River and the aquifer and potential degradation of water quality in the aquifer.

To address these concerns, and to further the understanding of stream-aquifer systems, a study was conducted from 1995–98 by the USGS, in cooperation with the MDNR. The objectives of this study were to: (1) determine changes in hydraulic heads in the Rock River Valley aquifer and stream depletion in the Rock River as related to ground-water withdrawals under current and anticipated development conditions; (2) determine the contributing area of ground-water flow to supply wells under current and anticipated development conditions; and (3) determine the effects of ground-water withdrawals on ground-water quality as related to induced infiltration from the river.

The purpose of this report is to describe the results of the study. This report describes results of field data collection during 1995–97, sources and types of data used in constructing a numerical ground-water-flow model, the model calibration process, and results of model simulations.

Description of Study Area

The study area covers approximately 112 mi^2 in eastern Rock County in the southwestern corner of Minnesota (fig. 1). The Rock River Watershed Unit, which includes all of Rock County, is drained by small streams that flow south and west into Iowa and South Dakota to the Big Sioux River and eventually into the

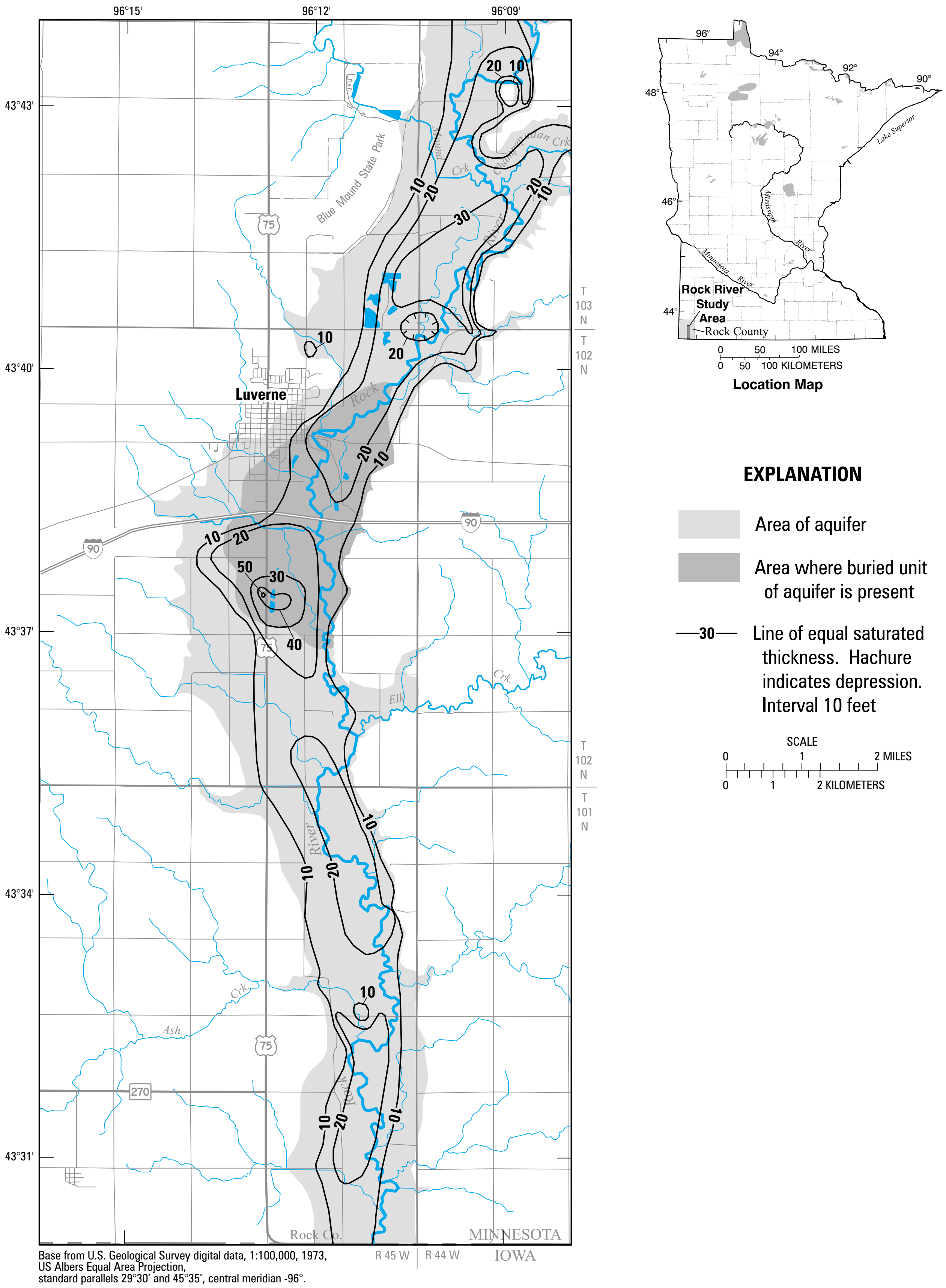


Figure 1. Location of Rock River study area, and extent and generalized saturated thickness of Rock River Valley aquifer, eastern Rock County, Minnesota.

Missouri River (Anderson and others, 1976). The watershed is on the southwestern flank of the Coteau des Praires, a prominent highland plain (Flint, 1955) that traverses the southwestern corner of Minnesota. The watershed is predominantly a dissected, well-drained upland plain (Anderson and others, 1976). The northeastern boundary of the watershed is the Mississippi-Missouri Rivers watershed boundary. The headwaters of the Rock River are in Pipestone County approximately 25 mi north of the study area. The primary area of interest within the study area is the Rock River Valley, underlain by the Rock River Valley aquifer. The Rock River Valley in southwestern Minnesota is 0.5–2 mi wide and about 40 mi long (Anderson and others, 1976; Adolphson, 1983).

The Rock River Valley contains alluvial and glacial outwash deposits composed primarily of fine to coarse sand interbedded with silt and gravel. The sand and gravel deposits locally may be under confined conditions. Glacial till underlies most of the surficial outwash. The uplands surrounding the valley are mostly composed of till or till overlain by windblown sediment. Glacial deposits are underlain by low-permeability rocks of Cretaceous age or the Sioux Quartzite of Precambrian age. The uplands north of Luverne, in the vicinity of Blue Mound State Park (fig. 1), are composed of outcrops of the Sioux Quartzite.

Land use in the Rock River Watershed Unit is predominantly agricultural. Cultivated fields account for a majority of the land area in the watershed, particularly in the alluvial valley of the Rock River. Corn and soybeans are the predominant crops. There are also extensive pasture lands in the higher-relief upland areas in the watershed.

Average annual precipitation at Luverne during 1960–97 was 27.8 in. (U.S. Department of Commerce, 1998). About 63 percent of annual precipitation normally falls during May through September. Moisture is adequate for optimum plant growth in spring and early summer during a normal year, but a moisture deficiency during August and September results in less than optimum growth. Rural and municipal water shortages were common during droughts occurring in the 1930's, 1970's, and 1980's. Annual precipitation during 1995, 1996, and 1997 was 28.7, 28.2, and 18.6 in., respectively. Precipitation in 1995 and 1996 was similar to the long-term average precipitation; whereas, 1997 was one of only six years during 1960–97 having less than 20 in. of precipitation. Precipitation in 1997 was less than average primarily because July through November 1997 precipitation was less than monthly averages. The maximum daily precipitation during October 1995 through November 1997 was 2.59 in. on June 16, 1996.

The only substantial ground-water withdrawals from the Rock River Valley aquifer in the study area are by public supply wells. Total annual withdrawals by the three pumped irrigation wells located in the study area are very small compared to public-supply withdrawals and during 1995 were 0.14 ft^3/s (64 gal/min) (Gregory Mitton, U.S. Geological Survey, written commun., 1996). There are three public-supply well fields in the study area (fig. 2a). Water for the City of Luverne is pumped from the Municipal well field, located along the eastern edge of Luverne near the Rock River, and the Airport well field located about 1.5 mi south of Luverne. These wells supply water for drinking and other domestic uses and industrial uses for Luverne, which had a population of 4,625 in 1997. The other well field supplies the Rock County Rural Water District and is located about 6 mi south of Luverne (fig. 2a). The Rock County Rural Water District supplies water primarily for drinking and other domestic purposes to a population of about 2,700 people in rural southern Rock County and secondarily, supplies water for some livestock and agribusiness. The District primarily supplies water to rural customers and small communities that are located outside the alluvial valley of the Rock River, in the surrounding uplands, as these areas are without a reliable source. The water use by the District is primarily a net export of water from the Rock River Valley.

Ground-water use for public supply at Luverne began at least in the early 1900's and increased in the 1950's and 1960's. Reliable data on pumping rates for Luverne were available for 1976–97. During this period, annual average pumping rates varied from a minimum of 1.11 ft^3/s (497 gal/min) in 1981 to a maximum of 2.53 ft^3/s (1,136 gal/min) in 1988; whereas, pumping rates have fluctuated from year to year during 1976–97, they generally have increased by an average of about 3 percent per year. The most rapid rate of increase occurred during 1981–88, with the increase during 1989–97 being slower. For 1995–97, annual pumping rates for Luverne from both well fields ranged from 2.10 to 2.20 ft^3/s (941 to 988 gal/min).

The City of Luverne projects that ground-water withdrawals will increase by about 2 percent per year in the future due to population growth (Red Arndt, Public Utilities Manager, City of Luverne, oral commun., 1997). In addition, a meat-packing plant at Luverne, that had been using 600,000 gal/d (416 gal/min) of water, shut down operations in March 1998 and a new ethanol-production plant is expected to begin operations during the latter part of 1998 and will use 300,000 gal/d (208 gal/min). The net effect of these two changes will be a net decrease in pumping rates of 300,000 gal/d (208 gal/min) (Red Arndt, Public Utilities Manager, City of Luverne, oral commun., 1998). The cumulative effect of population growth, the closing of the meat-packing plant, and the opening of the ethanol-production plant will result in an increase in ground-water withdrawals of about 11.5 percent (0.26 ft^3/s, 117 gal/min) over 20 years. The City of Luverne expects to meet the projected increased demand for water using existing wells (Red Arndt, Public Utilities Manager, City of Luverne, oral commun., 1998).

The well field for the Rock County Rural Water District was developed in 1979 and consisted of six wells. Complete pumping-rate data were available for 1980–97. Annual average pumping rates increased steadily from a minimum of 0.40 ft^3/s (180 gal/min) in 1980 to a maximum of 0.99 ft^3/s (440 gal/min) in 1989, an increase averaging 26 percent per year. During 1990–97, annual pumping rates have been between 0.83 and 0.94 ft^3/s (370–420 gal/min). The District projects that ground-water withdrawals will increase by 43 percent during 1996–2015, an increase of about 2 percent per year (Dan Cook, Manager, Rock County Rural Water District, oral commun., 1996). The District expects to expand its well field up to 1 mi to the north and install as many as five additional wells to meet the projected increased demand for water (Dan Cook, Rock County Rural Water District, oral commun., 1998).

Previous Investigations

Anderson and others (1976) presented an overview of the water resources of the Rock River Watershed Unit in Minnesota. The Rock River Valley aquifer was described and mapped by Adolphson (1983). The water resources of the Rock River alluvial aquifer in Iowa were described by Thompson (1987). The surficial geology (Patterson, 1995; Patterson, 1997), Quaternary stratigraphy (Patterson and others, 1995), surficial hydrogeology (Brandt, 1997a), and sensitivity of surficial aquifers to contamination (Brandt, 1997b) were mapped in an area covering parts of nine counties (including Rock County) in southwestern Minnesota by the Regional Hydrogeologic Assessment Program of the MDNR and the Minnesota Geological Survey. Studies have been conducted to explore for deeper aquifers in Rock County using geophysical techniques (Chandler, 1997) and deep test-hole drilling (Berg, 1997; Lindgren, 1997). Reports concerning development of groundwater for public supply have been prepared for the City of Luverne (Liesch Associates, 1974, 1975a, 1975b, 1989, 1990) and the Rock County Rural Water District (DeWild and others, 1979). Samples were collected from the Rock River at Luverne by the USGS as part of a previous study to determine the geographic and seasonal distribution of herbicides in about 150 streams in 10 Midwestern states in 1989–90 (Thurman and others, 1991, 1992, 1996; Goolsby and Battaglin, 1993; Scribner and others, 1993).

Methods of Investigation

Previously collected data on the hydrogeology, water use, hydraulic properties, and water quality of the stream-aquifer system in the Rock River Valley of eastern Rock County were compiled from a variety of sources including water-well logs, geologic maps, State and Federal data bases, water-use records, published reports, and consultant reports. Additional test drilling and well installation, aquifer properties testing, measurements of water levels and stream discharge, and water-quality sampling was done for this study (figs. 2a-2d).

Test Drilling and Well Installation

Water-well and test-hole logs were obtained from the Minnesota Geological Survey's County Well Index for Rock County, the USGS Ground-Water Site Inventory data base, consulting reports, and the MDH. Forty-four test holes were drilled for this study and observation wells were installed in 39 of the test holes.

Values of saturated thickness, aquifer thickness, and height of water level above or below the top of the alluvial sand and gravel were determined for 123, 127, and 163 sites, respectively, from drillers' logs and test-hole information. The saturated thickness and height of the water table above or below the top of the alluvial sand and gravel were calculated for the date of water-level measurement on the geologic log. Because the data set reflects water levels measured at different times of the year during 1961–97, the data set is generalized and not specific to a particular date. Saturated thickness at a particular location could fluctuate by as much as 6 ft, the maximum seasonal water-level fluctuation observed in the aquifer.

Aquifer-Properties Testing

Results of aquifer tests conducted in the area prior to this study were compiled from consulting reports in the files of the City of Luverne and Rock County Rural Water District and from an aquifer-test data base for Minnesota on file at the USGS office in Mounds View, Minnesota. A 72–hour multi-well aquifer test, 26 single-well aquifer tests, and 21 slug tests were conducted during 1996–97 to determine aquifer properties. Supply well LUV23 was used as the pumped well during a 72–hour aquifer test conducted on November 5–8, 1996 (fig. 2c). This aquifer test site was selected because of the relatively close spacing of existing wells and because the test site was unaffected by ground-water withdrawals from the other Luverne Airport supply wells located southwest of the test site. Supply well LUV7 was shut down during the test so that there were no other nearby stresses on the aquifer. The aquifer test results were analyzed using AQTESOLV for Windows 95, version 1.17 (Duffield, 1996). Estimates of aquifer transmissivity and storage properties (specific yield and storage coefficient) were calculated using the Theis, Cooper-Jacob, and Quick Neuman methods (Kruseman and de Ridder,1990; Duffield, 1996).

Single-well aquifer tests were used to estimate K values elsewhere in the aquifer and to evaluate spatial

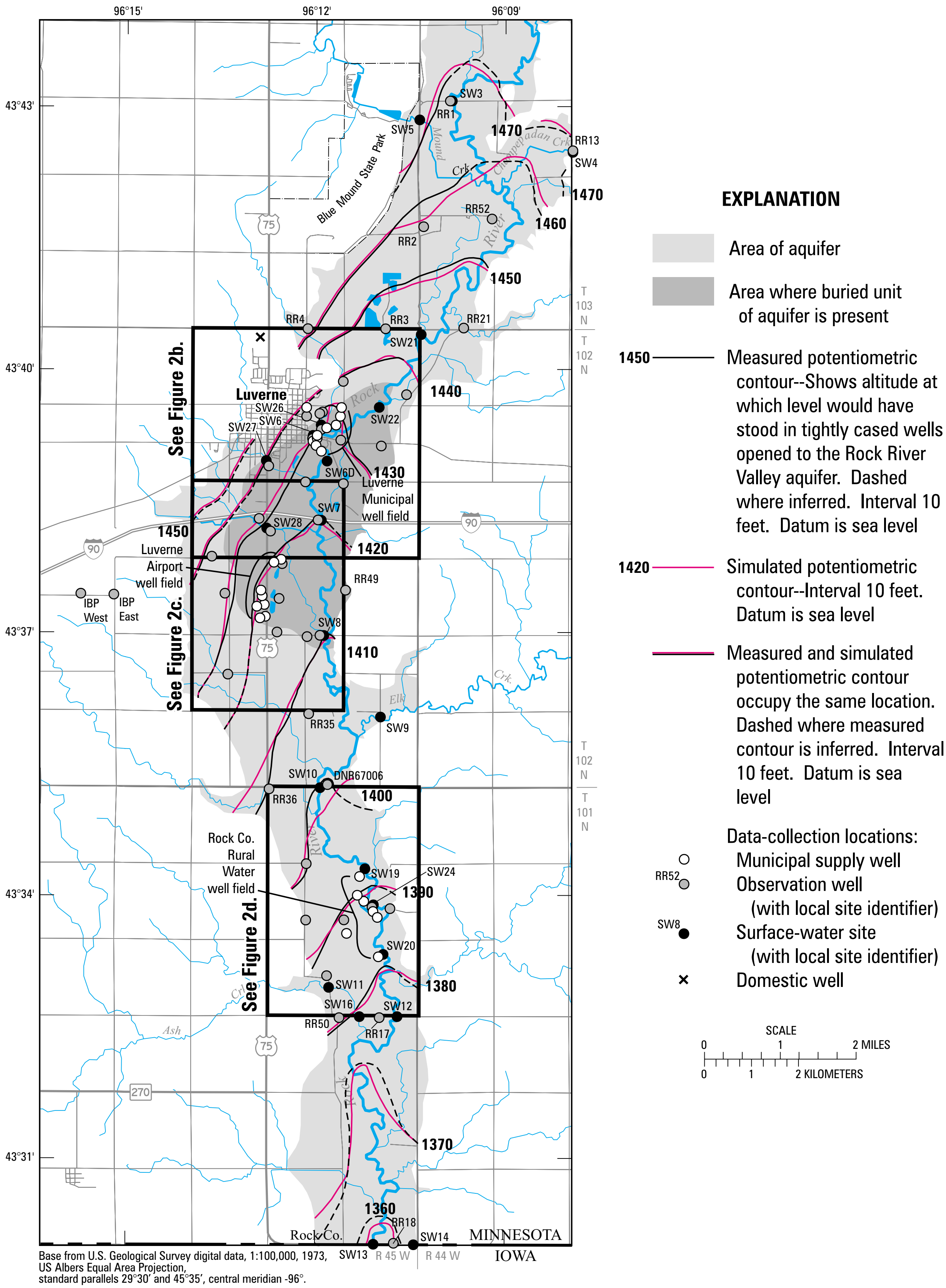
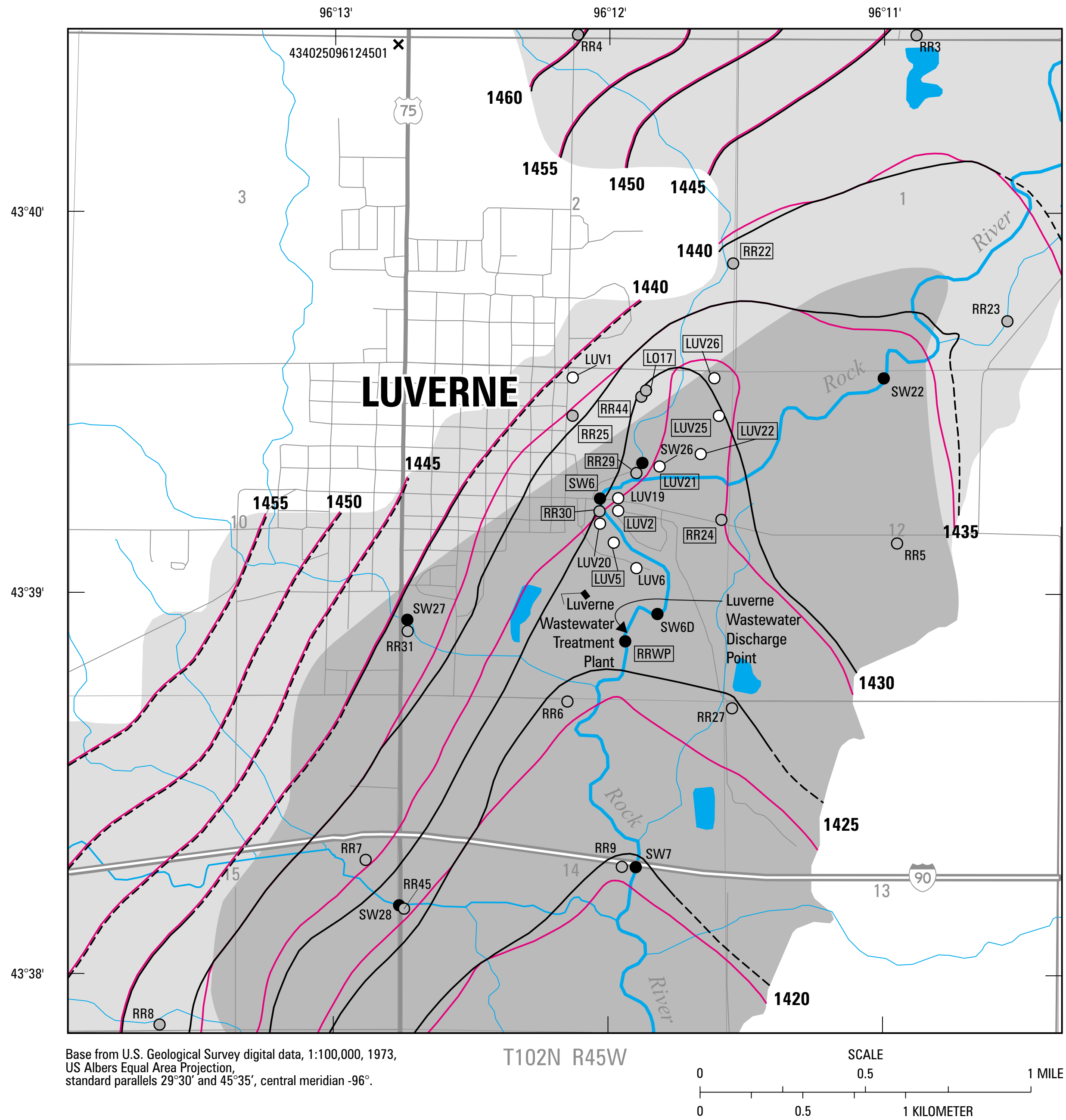


Figure 2a. Hydrologic data-collection sites, altitude of potentiometric surface of Rock River Valley aquifer, October 1996, and simulated altitude of potentiometric surface, steady-state conditions, in the Rock River study area, eastern Rock County, Minnesota.



EXPLANATION

Area of aquifer

Area where buried unit of aquifer is present

1450 — Measured potentiometric contour--Shows altitude at which level would have stood in tightly cased wells open to the Rock River Valley aquifer. Dashed where inferred. Interval 5 feet. Datum is sea level

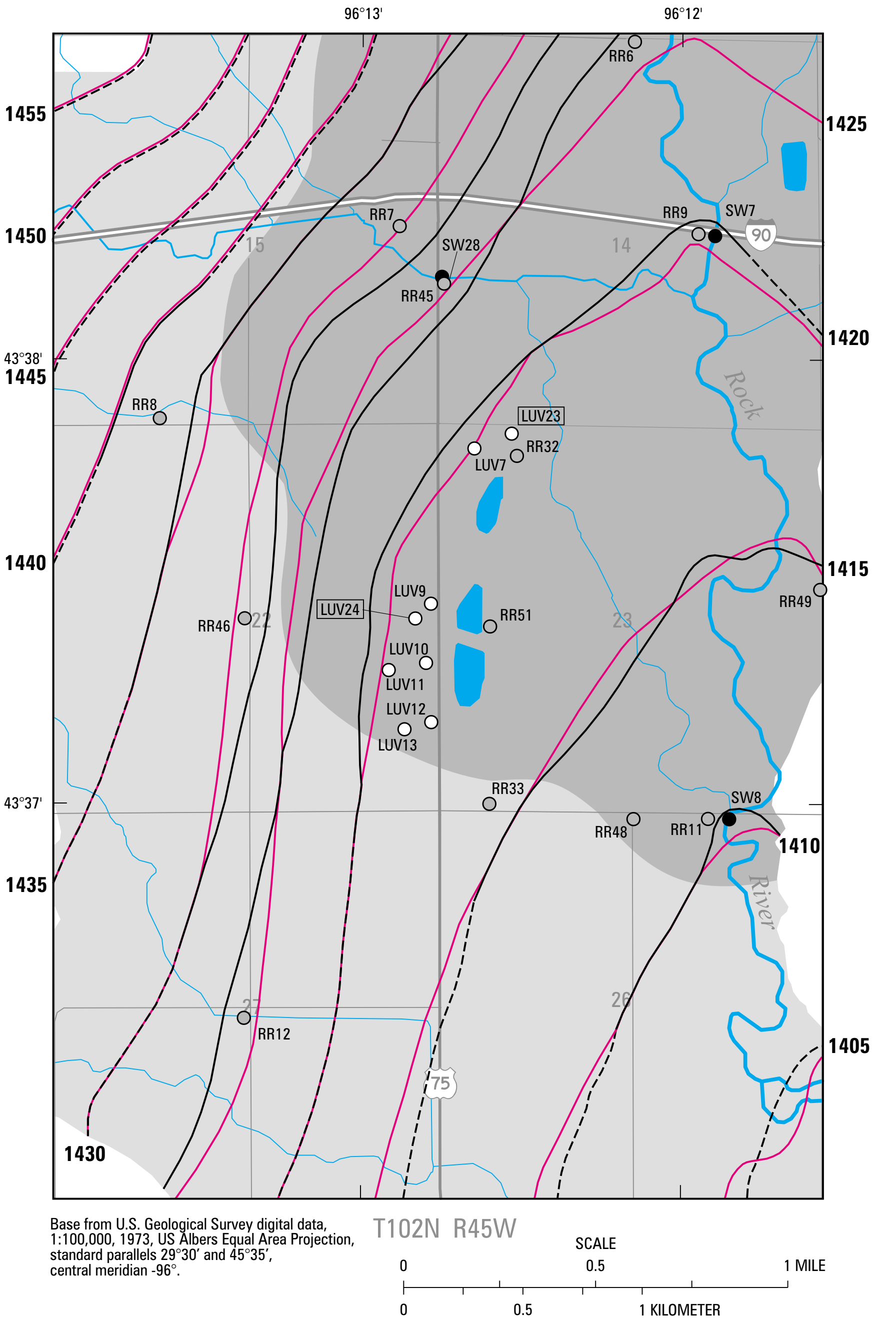
1420 — Simulated potentiometric contour--Interval 5 feet. Datum is sea level

Measured and simulated potentiometric contour occupy the same location. Dashed where measured contour is inferred. Interval 5 feet. Datum is sea level

Data-collection locations:

- LUV2 — Municipal supply well (with local site identifier)
- RR6 — Observation well (with local site identifier)
- SW7 — Surface-water site (with local site identifier)
- × — Domestic well (with USGS site identifier)
- LO17 — Water-quality sampling site

Figure 2b. Hydrologic data-collection sites, altitude of potentiometric surface of Rock River Valley aquifer, October 1996, and simulated altitude of potentiometric surface, steady-state conditions, in the Luverne Municipal well field area, eastern Rock County, Minnesota.



EXPLANATION

Area of aquifer

Area where buried unit of aquifer is present

1450 Measured potentiometric contour. Shows altitude at which level would have stood in tightly cased wells open to the Rock River Valley aquifer. Dashed where inferred. Interval 5 feet. Datum is sea level

1420 Simulated potentiometric contour--Interval 5 feet. Datum is sea level

Measured and simulated potentiometric contour occupy the same location. Dashed where measured contour is inferred. Interval 5 feet. Datum is sea level

Data-collection locations:

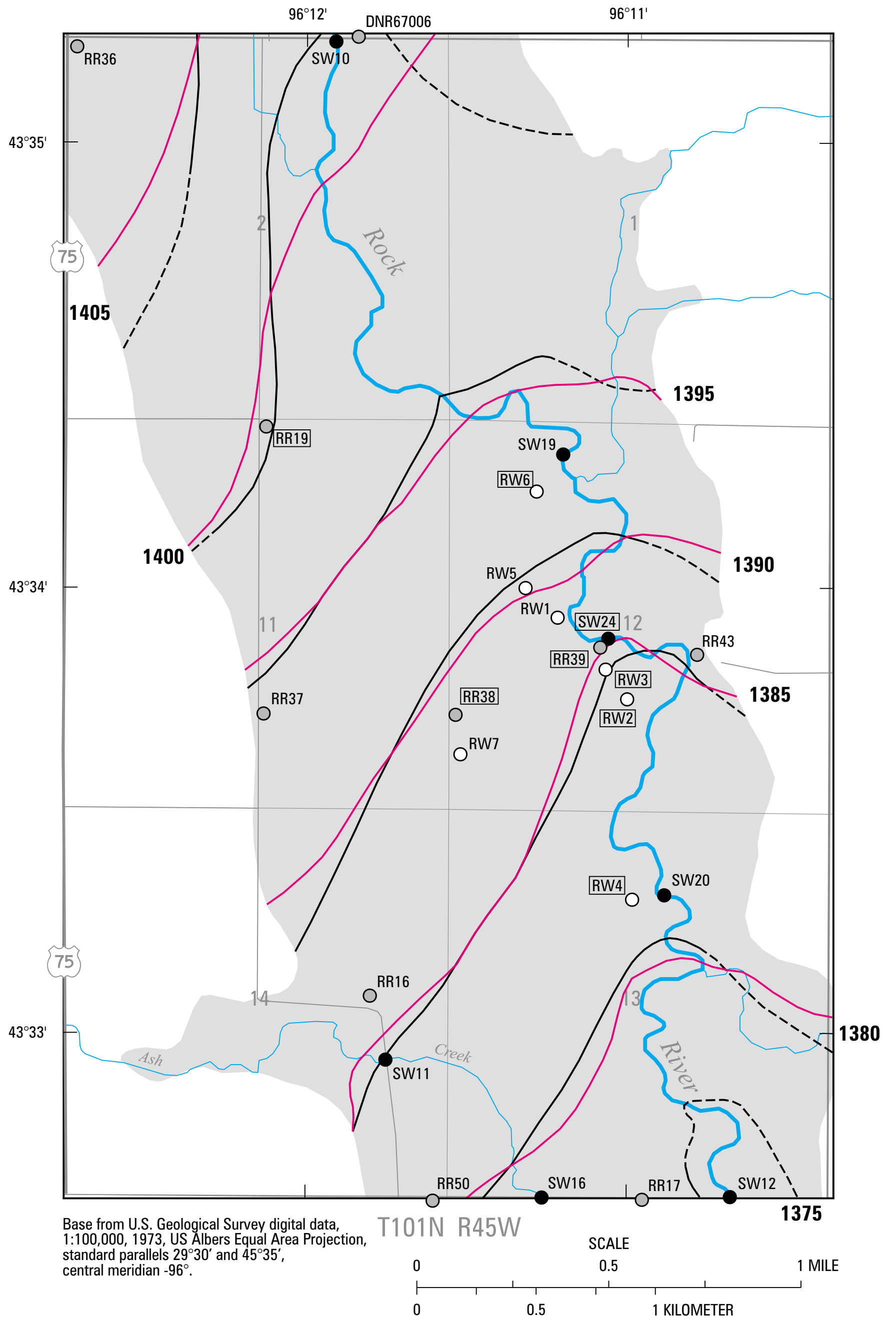
LUV9 Municipal supply well (with local site identifier)

RR33 Observation well (with local site identifier)

SW8 Surface-water site (with local site identifier)

LUV23 Water-quality sampling site

Figure 2c. Hydrologic data-collection sites, altitude of potentiometric surface of Rock River Valley aquifer, October 1996, and simulated altitude of potentiometric surface, steady-state conditions in the Luverne Airport well field area, eastern Rock County, Minnesota.



EXPLANATION

Area of aquifer

1400 — Measured potentiometric contour--Shows altitude at which level would have stood in tightly cased wells open to the Rock River Valley aquifer. Dashed where inferred. Interval 5 feet. Datum is sea level

1390 — Simulated potentiometric contour--Interval 5 feet. Datum is sea level

Measured and simulated potentiometric contour occupy the same location. Dashed where measured contour is inferred. Interval 5 feet. Datum is sea level

Data-collection locations:

RW1 Municipal supply (with local site identifier)

RR39 Observation well (with local site identifier)

SW24 Surface-water site (with local site identifier)

RW4 Water-quality sampling site

Figure 2d. Hydrologic data-collection sites, altitude of potentiometric surface of Rock River Valley aquifer, October 1996, and simulated altitude of potentiometric surface, steady-state conditions, in the Rock County Rural Water well field area, eastern Rock County, Minnesota.

variations in K. Single-well aquifer tests were performed in all observation wells that would sustain a steady pumping rate over the length of the test. Slug tests were conducted at all wells that would not sustain the required pumping rate and at selected observation wells that would sustain a steady pumping rate. Both single-well aquifer tests and slug tests were done in 10 observation wells to compare the results of these two methods. The drawdown versus time from start of the single-well aquifer tests was analyzed using Single Well Solutions 2.0 (Streamline Groundwater Applications, 1997). The test results were analyzed using the Theis method applied to the recovery phase data (20 wells) (Kruseman and deRidder, 1990, p. 232–233) and the Hurr and Worthington method applied to the pumping phase data (26 wells) (Kruseman and deRidder, 1990, p. 226–229). Two to four slug tests were conducted in 21 observation wells. The processed data of water-level displacement from initial water levels versus time were analyzed using the method of Bouwer and Rice (1976) in AQTESOLV.

Field constant-head permeameter tests, following the method of McMahon and others (1995), were conducted to determine K_s at 13 river cross sections and seven tributary cross sections. Three tests were conducted at each location along a cross section. The average of the three tests was used as the best estimate of K_s at that location. Permeameter tests were conducted at four to six locations along a section across the river at 13 surface-water sites on the mainstem of the Rock River (sites shown on fig. 2a). Permeameter tests were conducted at one to three locations along a section across narrower tributaries at seven surface-water sites (fig. 2a). For each river or tributary cross section, the median K_s was computed.

Water Levels and Stream Discharge

From March 1995 through October 1997 water levels were measured monthly at 43 observation wells and stage was measured at 13 stream sites. Water levels were also measured monthly in Rock County Rural Water observation wells located within 50 ft of the Rock County Rural Water pumped wells. Water levels were measured in all Luverne municipal supply wells at frequencies ranging from once a year to every two weeks, depending upon the well.

The altitudes of all measurement points were determined by surveying done by the USGS (Charles Smith, written commun., 1997) and DeWild Grant Reckert and Associates Company (Kevin Jongerious, written commun., 1996). Altitudes of measuring points less than approximately one-quarter mi of each other or near the well fields were measured with a precision of 0.02 ft. Altitudes of widely spaced measuring points were measured with a precision of 0.10 ft. Water levels were measured using submersible pressure transducers and recorded by data loggers at six observation wells (RR29, RR30, RR39, RR45, RW3A, and LUV19), one pumped well (LUV21), and two Rock River sites (SW6 and SW24) (figs. 2b, 2c, and 2d). Rock County Rural Water observation well RW3A is located within 30 ft of supply well RW3. Water levels were also recorded in a tributary stream (SW28). Manual water-level measurements were periodically made to verify the accuracy of the recorded water levels.

Precipitation was measured every half-hour during April through October of 1996 and 1997 by a tipping-bucket rain gage installed at well RR30 (fig. 2b). Daily records of precipitation amounts during November through March were obtained from the Luverne Wastewater Treatment Plant, which operates a precipitation gage that records hourly precipitation. Monthly precipitation for 1960–97 at the Luverne Airport was obtained from the U.S. Department of Commerce (1998).

A continuous record streamflow station was installed on the Rock River at Luverne (site SW6) on April 10, 1996 and was operated until November 30, 1997. Stream stage was recorded by a submersible pressure transducer every 30 minutes. Periodic streamflow measurements were made to update the rating curve for the stage-discharge relation for the site. Measurements of streamflow were made with current meters using standard USGS methods (Carter and Davidian, 1968; Buchanan and Somers, 1969). Computation of daily mean flows for the Rock River at Luverne were made using USGS standard methods (Kennedy, 1983 and 1984). The streamflow record for October 1, 1995 through April 9, 1996 was estimated using precipitation data and records from the nearest continuous record sites (Greg Mitton, U.S. Geological Survey, oral commun., 1996).

The long-term low-flow characteristics of the Rock River at Luverne were estimated from regression equations and the long-term flow characteristics at nearby continuous record stations using low-flow measurements from 1967 through 1997. Regression relations between streamflow at the Rock River at Luverne and at the nearby continuous record stations were developed following the approach of Riggs (1972) and Lindskov (1977). The continuous record stations and periods of record used were: (1) Rock River at Rock Rapids, Iowa (about 20 miles downstream from Luverne), 1960–74, and(2) Redwood River near Marshall, Minnesota (about 50 miles north of Luverne), 1940–96.

Synoptic sets of low-flow measurements were made to determine gaining and losing reaches of the Rock River and to quantify streamflow gains and losses. Data on return flow from the Luverne Wastewater Treatment Plant on the dates of low-flow measurements were obtained from the City of Luverne. Low-flow measurements were made on the Rock River and tributaries on January 22–25, 1996 at 14 sites, on July 29–August 1, 1996 at 18 sites, and on October 6–8, 1997 at 20 sites. The assumed accuracy of individual streamflow measurements was 5 percent.

Synoptic sets of ground-water/surface-water head-gradient measurements were made using a hydraulic potentiomanometer (minipiezometer) (Winter and others, 1988) during June 19–26, 1996 at 13 river and tributary cross sections under relatively high-flow conditions and during July 30 through August 8, 1996, at 19 river and tributary cross sections under relatively low-flow conditions. The hydraulic potentiomanometer measurements were made at the surface-water sites shown in figures 2a-2d. The hydraulic potentiomanometer measurements were made at the same time as the field constant-head permeameter tests to determine K_s. At least three sets of measurements were recorded at each location and the average vertical head gradient computed. Hydraulic potentiomanometer measurements were made within about 3 ft of the field constant-head permeameter tests along stream cross sections. Using Darcy's Law, the average volumetric discharge was calculated for each segment of the river cross section represented by a hydraulic potentiomanometer/permeameter measurement and the values were summed to calculate the stream-aquifer leakage for the entire river cross-section.

An analytical model developed by Wilson (1993) (also evaluated by Conrad and Beljin, 1996) for calculating induced infiltration from a stream due to pumping in a nearby well was used to estimate streamflow losses near well fields. The analytical model calculates the induced infiltration rate as a function of the pumping rate, distance from the stream to the well, aquifer hydraulic conductivity, average aquifer thickness, and the regional ground-water hydraulic gradient. The calculated values for individual wells were summed to calculate total induced infiltration for a well field. The analytical model was run for minimum, average, and maximum 1995–97 monthly pumping rates.

Modeling of Ground-Water Flow

A numerical ground-water-flow model was constructed and calibrated to aid in understanding the interaction between the Rock River Valley aquifer and the Rock River. The model was calibrated for both steady-state and transient conditions using hydraulic-property, water-level, and water-use data compiled during the study. The numerical model used was the USGS modular three-dimensional, finite-difference ground-water-flow model developed by McDonald and Harbaugh (1988) (MODFLOW). The model was calibrated using water levels and stream stages measured monthly in 43 observation wells and at 13 stream sites, respectively. Three synoptic sets of low-flow streamflow measurements made on the Rock River and its tributaries at 14 to 20 sites were also used to calibrate the model. The measured streamflows and derived estimates of stream-aquifer leakage were compared to simulated values. Visual MODFLOW was used as a preprocessor to input the required data, to run the MODFLOW simulations, and as a post processor to visualize and analyze the results of the simulations (Guiguer and Franz, 1994).

Streamflows were simulated using the streamflow-routing package developed by Prudic (1989). The streamflow-routing package accounts for the amount of flow in streams and simulates the interaction between streams and ground water. Streams are divided into segments and reaches. Each reach corresponds to individual cells in the finite-difference grid used to simulate ground-water flow. Segments are numbered sequentially from the farthest upstream segment to the last downstream segment (figs. 3a and 3b), as are reaches within each segment. Stream-aquifer leakage is calculated for each reach on the basis of the head difference between the stream and aquifer and a conductance term that includes streambed thickness and vertical hydraulic conductivity. Measured, rather than model-computed, stream stages were used as a basis for all simulations done for this study. The Rock River, four major tributaries, and three minor drainages were simulated (figs. 3a and 3b). The four major tributaries, in downstream order, are Mound Creek, Champepadan Creek, Elk Creek, and Ash Creek. The three minor drainages are located in or near Luverne. The simulated streams in the study area were divided into a total of 26 segments. The four major tributaries and three minor drainages each constitute a segment, with the Rock River being divided into 19 segments. The number of reaches (model cells) in a segment range from two for segment 4 (a minor drainage in the Luverne Municipal well field) to 80 for segment 26 (the southernmost Rock River segment).

A particle-tracking post-processing package termed MODPATH (Pollock, 1989) was used to compute ground-water-flow path lines based on output from the calibrated steady-state simulation obtained with MODFLOW. In addition to three-dimensional path lines, MODPATH computes the position of particles at specified points in time and the total time of travel for each particle. Particle tracking was used to determine areas contributing ground-water flow to the high-capacity wells in the three well fields present in the study area. The particle-tracking program was used by specifying a ring of hypothetical water particles around each pumped well. The particles were then tracked backward in time through the flow field until they reached a boundary such as a river. All water particles entering a cell containing a well were assumed to discharge to these relatively strong sinks. The area encompassing the starting points of water particles

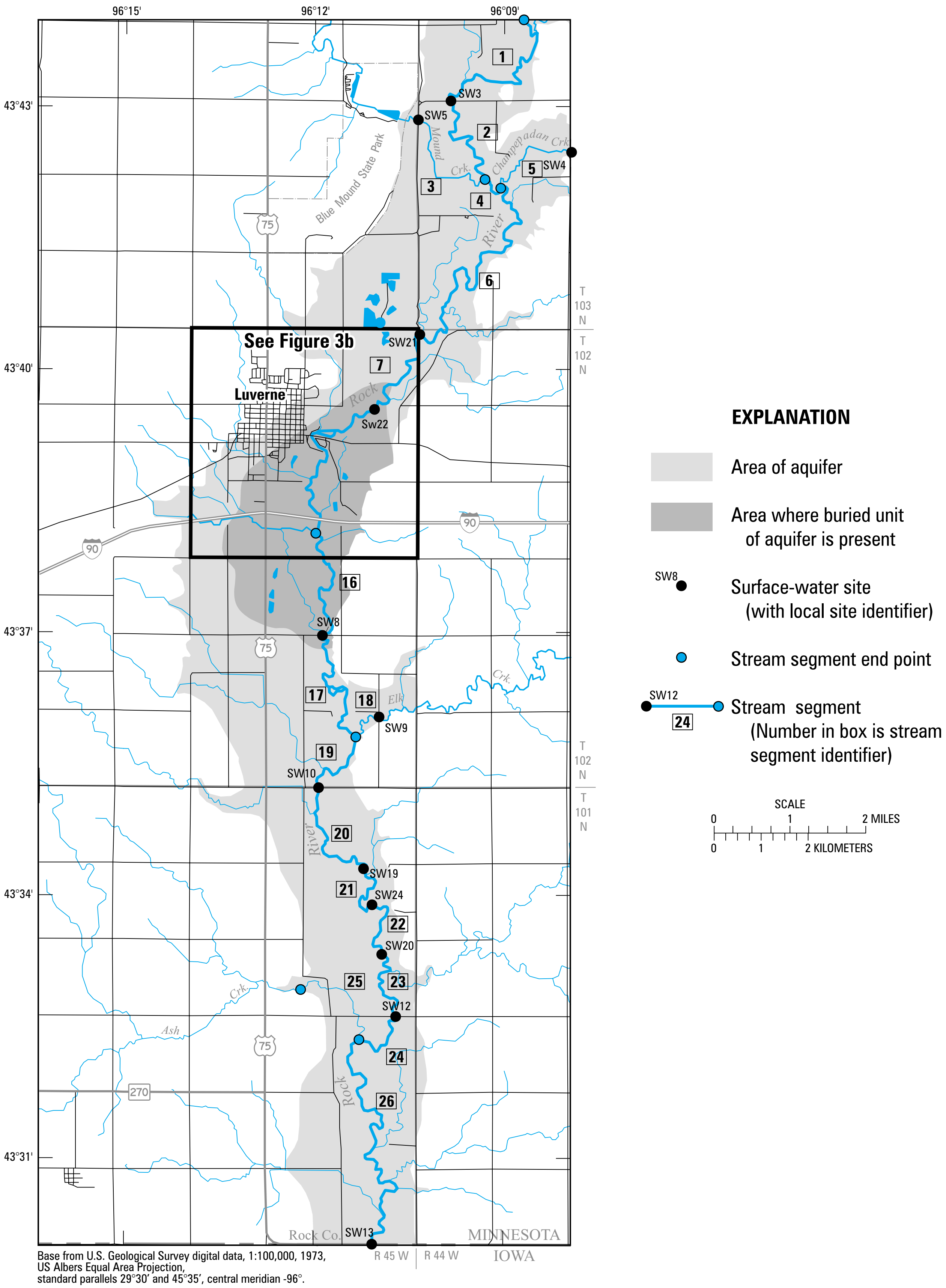


Figure 3a. Surface-water sites and stream segments in the Rock River study area, eastern Rock County, Minnesota.

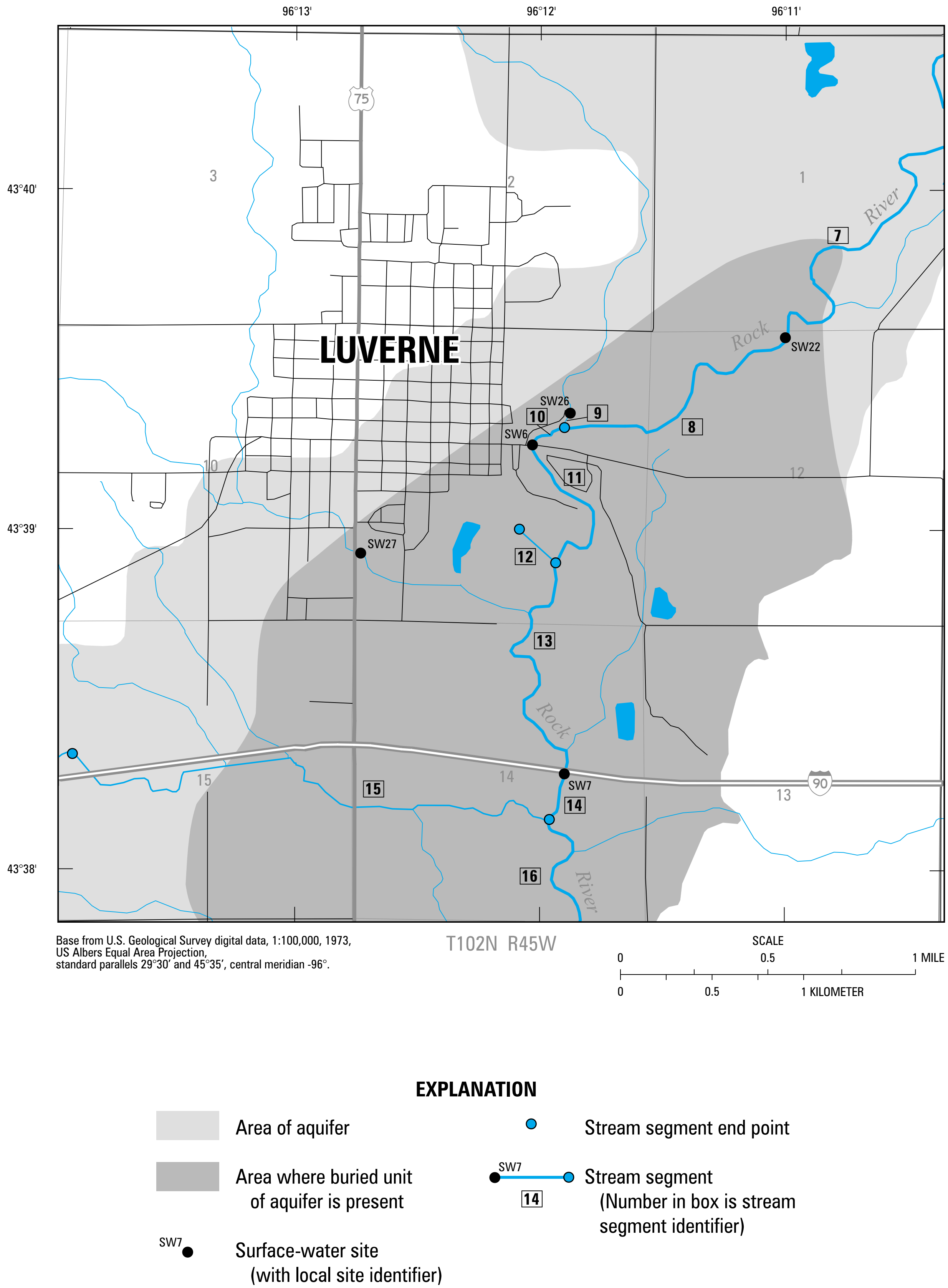


Figure 3b. Surface-water sites and stream segments in the Luverne Municipal well field area, eastern Rock County, Minnesota.

traced to each well delineated the ground-water contributing area for that well. A capture zone was delineated by encompassing the starting points of water particles traced to a given well for a specified travel time (for example, 1, 5, or 10 years). The ground-water contributing area for a well is equivalent to a capture zone for infinite travel time.

Once calibrated to steady-state and seasonal (transient) hydrologic conditions, model results were used to analyze ground-water gain or loss from the Rock River. The model also was used to estimate; (1) the effects of current and historical pumping on hydraulic heads and streamflow; (2) the decline in hydraulic heads and the decrease in streamflow that may result from increased pumping;, (3) changes in the flow directions and ground-water contributing areas as a result of increased pumping; and (4) the effects of increased pumping rates and differing precipitation conditions on hydraulic heads and streamflow.

Water-Quality Sampling and Analysis

Water samples were collected to evaluate surface-water quality and the movement of water and contaminants from the Rock River to supply wells. Water samples were also collected from observation wells within the ground-water contributing areas to supply wells to compare ground-water and surface-water quality and to identify the influences of ground-water and surface-water sources on water-quality in the supply wells. Samples were collected from selected observation wells in the areas surrounding the well fields (figs. 2b, 2c, and 2d) and were considered to be representative of the water-quality of regional ground water moving towards supply wells. Within the context of the water-quality discussion in this report, the term ground-water contributing area refers to areas around the supply well field whose water quality is representative of regional ground water moving toward the well field. As defined, ground water that is between the Rock River and supply wells is not part of the ground-water contributing area because flow is from the river towards the well and, therefore, is probably more influenced by river water quality than regional ground-water quality.

Water-quality samples were collected primarily within or in close proximity to the Luverne Municipal and Rock County Rural Water well fields (figs. 2b and 2d). Supply wells in these well fields were located less than 1,500 ft from the Rock River with the exception of LUV1, a little used well (figs. 2a, 2b, and 2d). Only a few samples were collected from the Luverne Airport well field because it is located 0.5 to 0.75 mi from the Rock River (fig. 2c). Samples were collected from 26 sites, including 3 river sites, 12 supply wells, 7 observation wells in the ground-water contributing areas to supply wells, 1 domestic well screened in a buried sand layer in an upland adjacent to the Rock River Valley aquifer, and 3 observation wells located between the Rock River and nearby supply wells. Samples were collected most frequently at SW6 to evaluate seasonal changes in surface-water quality; 13 samples were collected during November 1995 through August 1997. The time intervals between sample collection at SW6 varied from a maximum of about four months during winter to a minimum of 11 days during May and June following herbicide application. The timing of herbicide application was estimated in consultation with the Rock County Soil and Water Conservation District. Samples were collected from selected municipal-supply and observation wells, in addition to the river, during November 1995, April, May, August, and November 1996, and April, June, July, and August 1997 to evaluate seasonal variations in water quality.

Stream samples were collected following standard methods of the USGS (Horowitz and others, 1994). Samples were collected from multiple sampling points across the stream at estimated equal discharge increments and then composited. Standard USGS protocols for collection of ground-water samples were followed (Wood, 1981; Claassen, 1982; Fishman and Friedman, 1989). The field specific conductance, pH, DO, and temperature of the water pumped were monitored until the values stabilized. Selected samples were analyzed for alkalinity, which was measured in the field the day of collection by performing incremental titrations following the methods of Wells and others (1990). Samples from selected sites were analyzed in the field for fecal coliform and fecal streptococcal bacteria using standard USGS procedures described by Britton and Greeson (1987).

Field blanks and replicates were collected as quality-control samples following standard USGS protocols described by Mueller and others (1997). Field blanks accounted for about 3 percent of the total samples collected. Replicates provide a measure of the variability introduced during sample processing and analysis. Replicates accounted for about 6 percent of the total samples collected. The field-blank data indicated that there were no problems with contamination of samples due to sampling procedures. The replicate data indicated that concentration variability as a result of the sampling process was very small compared to variability in environmental concentrations.

Samples were analyzed for concentrations of nitrite-plus-nitrate nitrogen, nitrite nitrogen, and selected herbicides and metabolites. Because concentrations of nitrite nitrogen were much smaller than concentrations of nitrite-plus-nitrate nitrogen, nitrite-plus-nitrate nitrogen is abbreviated as nitrate-N in the rest of this report. Selected samples were also analyzed for ammonia nitrogen and dissolved major cations and anions at the USGS NWQL in Arvada, Colorado using methods described in Fishman and Friedman (1989).

Samples were analyzed for selected herbicides and metabolites at the USGS Organic Geochemistry Research Laboratory in Lawrence, Kansas using: (1) GC/MS methods as described by Thurman and others (1990) and Meyer and others (1993), (2) ELISA techniques (Aga and others, 1994), and (3) a HPLC method described by Ferrer and others (1997).

Values of $\delta^{18}O$ and δD were used to calculate mixtures of river and ground-water contributing area water withdrawn from supply wells using the following equations:

$$\delta_{well} = \delta_r P_r + \delta_{gw} P_{gw}$$

$$P_r + P_{gw} = 1.0$$

where,

δ_{well}, δ_r, and δ_{gw} = measured isotopic values of water from the supply well, river, and ground-water contributing area, respectively, and

P_r and P_{gw} = proportion of supply well water composed of river and ground-water contributing area water, respectively.

The water withdrawn from a supply well during a given sampling period was assumed to represent a mixture of river and ground-water contributing area water. Values of $\delta^{18}O$ and δD were determined by mass spectrometry at the USGS Stable Isotope Fractionation Laboratory in Reston, Virginia. Isotope results are reported in δ‰ relative to Vienna standard mean ocean water.

Selected samples were analyzed for caffeine using GC/MS to determine if it could be used as a tracer of river water affected by the Luverne Wastewater Treatment Plant that moved to supply wells downstream of the wastewater treatment plant. Caffeine has previously been shown to be an indicator of river water impacted by municipal wastewater discharges (Barber and others, 1995).

Ground-water samples were collected from three municipal supply wells (LUV26, LUV23, and RW2) (figs. 2b, 2c, and 2d) on August 29–30, 1996 and analyzed for concentrations of CFCs, tritium, and dissolved gases to determine ground-water recharge age. The ground-water samples for recharge-age dating were analyzed at the USGS CFC laboratory in Reston, Virginia, and the ages estimated using procedures described by Busenburg and Plummer (1992). Tritium analyses using the enriched tritium technique were completed at the Environmental Isotope Laboratory, University of Waterloo, Waterloo, Ontario, Canada.

Acknowledgments

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SURFACE WATER

The surface drainage area of the Rock River at Luverne is 425 mi^2. The largest tributaries of the Rock River in the study area are Champepadan Creek and Elk Creek, with drainage areas of approximately 76 mi^2 and 62 mi^2, respectively, above the measurement stations on these streams (fig. 2a). Mound Creek and Ash Creek are smaller tributaries that flow, except during periods of drought. Other tributaries within the study area are unnamed and generally only flow following rainstorms and snowmelt. Flow in the Rock River is unregulated. Because surface water is not generally used as a source of irrigation water, there are not significant surface-water diversions in the study area. The Luverne Wastewater Treatment Plant acted as a perennial stream to the Rock River during 1995–96 by discharging an average of about 1.5 ft^3/s to the Rock River just downstream of Luverne (fig. 2b).

Streamflow is derived from rainfall, snowmelt, and ground-water discharge. Increases in streamflow generally corresponded to precipitation events (figs. 4a and 4b). Events for which streamflow and precipitation did not correspond were during spring snowmelt in March and April of each year (fig. 4a and b) and during a few smaller rainfall events north of Luverne. Median streamflow during the 1996–97 water years (October 1, 1995 to September 30, 1997) was 110 ft^3/s (fig. 5a) and the average was 250 ft^3/s. Lower flows occurred during the winter and during the late summer or early fall (fig.

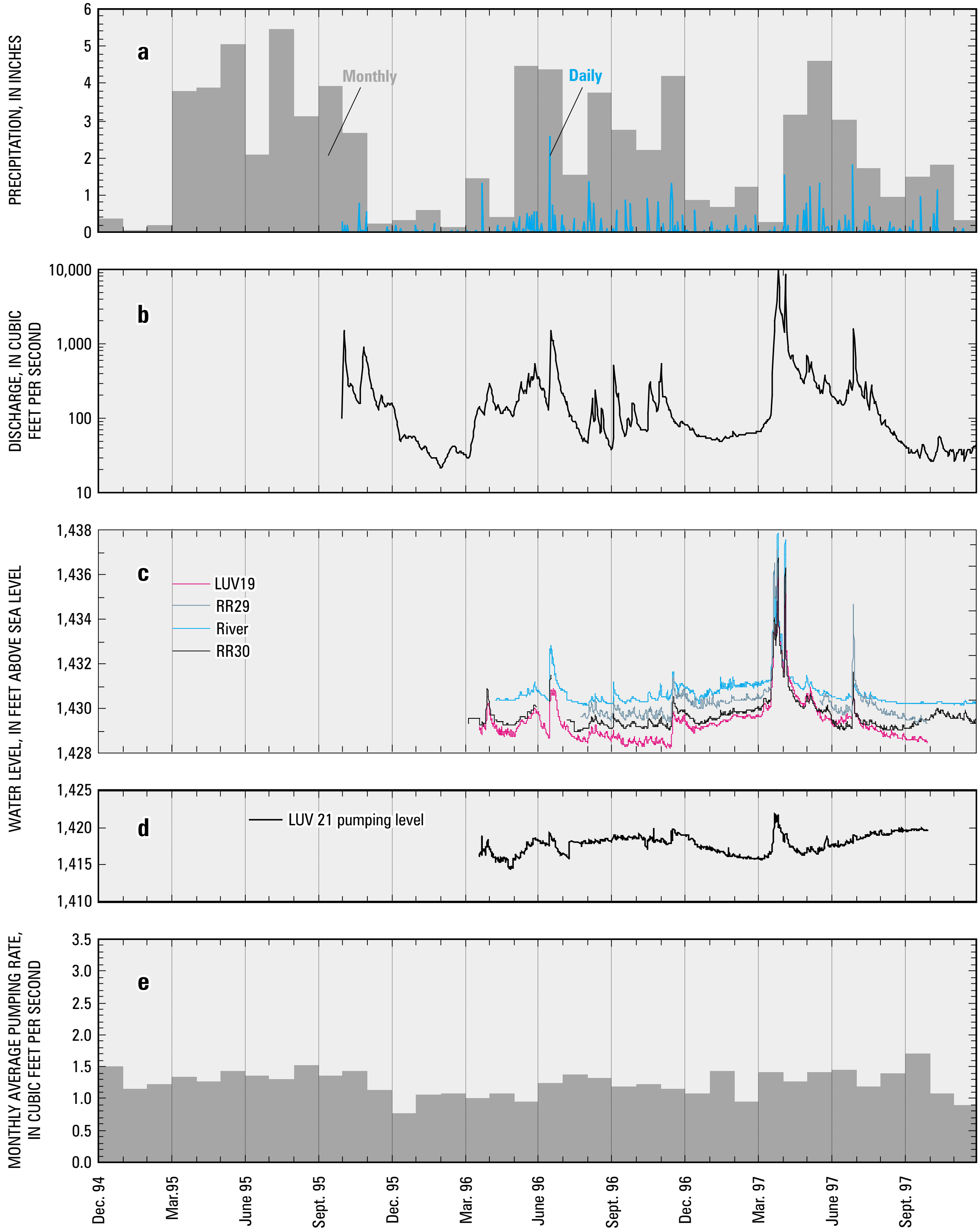


Figure 4. a) Daily (10/95-11/97 only) and monthly precipitation at Luverne, b) streamflow in the Rock River at Luverne, c) water-levels in the Rock River and in observation wells in the Luverne Municipal well field, d) water-level in LUV21, a municipal supply well, e) monthly average pumping rate for the Luverne Municipal well field, December 1994 - November 1997.

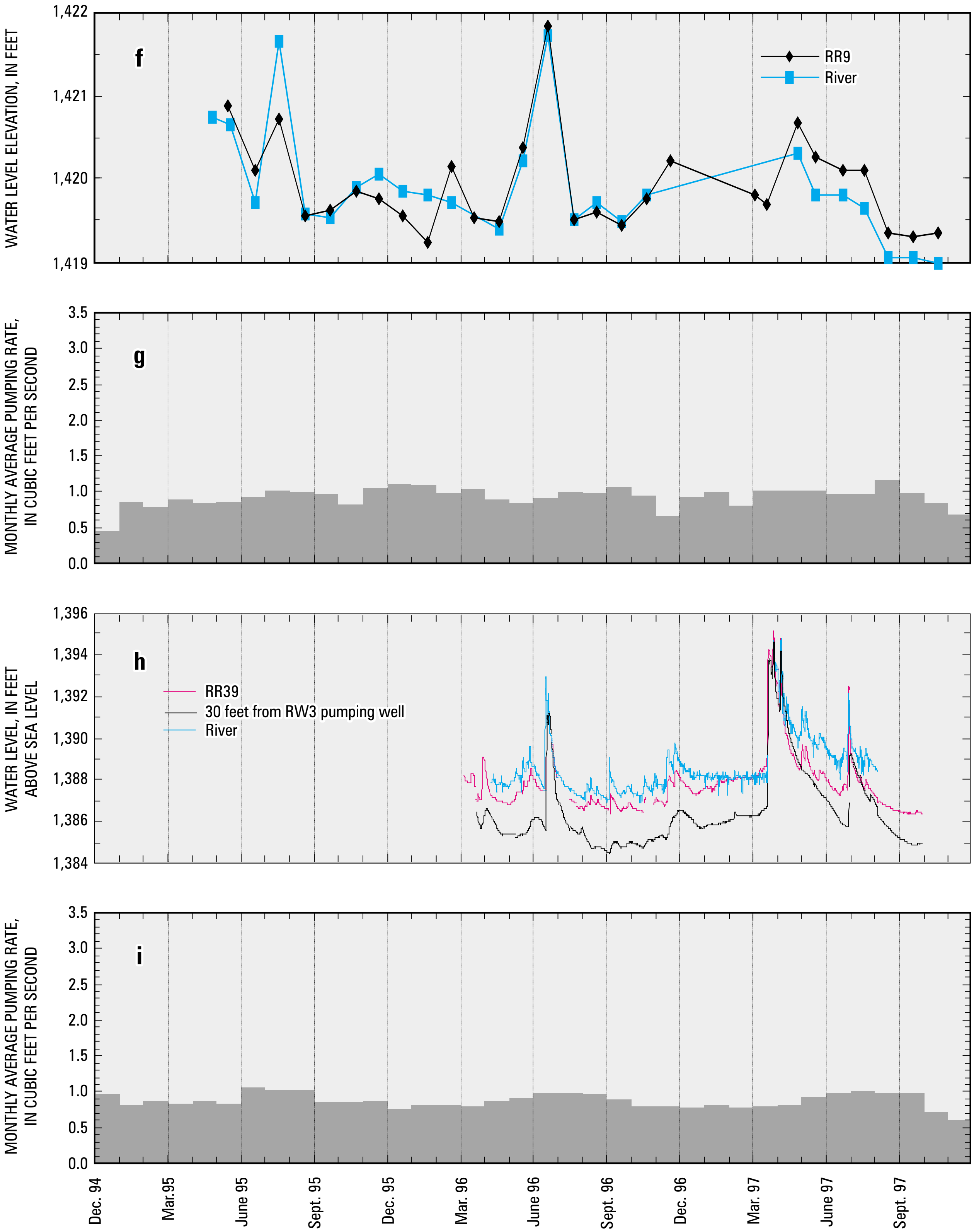


Figure 4 cont. f) water-level altitudes in the Rock River and in an observation well on the river reach by the Luverne Airport well field, g) monthly average pumping rate for the Luverne Airport well field, h) water-levels in the Rock River and in observation wells in the Rock County Rural Water well field, and i) monthly average pumping rate for the Rock County Rural Water well field, December 1994 - November 1997.

4b). The minimum daily streamflow during the study was 22 ft^3/s on February 1, 1996. The highest flows occurred either following spring snowmelt or following spring or summer rainstorms. The maximum daily streamflow of 10,000 ft^3/s occurred on March 28, 1997 following rapid melting and runoff of a large snowpack.

An understanding of the lowest streamflows occurring in the Rock River is important because streamflow losses caused by ground-water withdrawals will be larger in proportion to streamflow under low-flow conditions. Losses of 1 ft^3/s may be insignificant when streamflow is 40 ft^3/s, but may become significant when streamflow is 10 ft^3/s.

Analysis of historical low-flow records for the Rock River at Luverne and records from nearby continuous-record stations indicates that streamflow lower than the minimums measured during the 1996–97 water years can be expected to occur. Regression of low-flow measurements for the Rock River at Luverne with daily mean streamflow for the Rock River at Rock Rapids, Iowa indicated that the estimated streamflow that is exceeded 90 percent of the time for the Rock River at Luverne was about 8.0 ft^3/s during 1960–74. Similar regression of low-flow measurements for the Rock River at Luverne with the Redwood River at Marshall indicated that the estimated streamflow that is exceeded 90 percent of the time for the Rock River at Luverne was 14.5 ft^3/s during 1940–96. These estimated long-term values are much less than the flow of 39 ft^3/s that was exceeded 90 percent of the time during the 1996–97 water years (fig. 5a). Seventeen streamflow measurements made in 11 different years during 1967–88 had streamflow less than the 1996–97 minimum of 22 ft^3/s. The lowest streamflow measured in the Rock River at Luverne was 2.32 ft^3/s on August 18, 1976. Annual precipitation at Luverne in 1976 was 12.1 in., less than half the annual 1960–97 average (27.8 in.). The determination that lower flows than the lowest measured in the 1996–97 water years are likely to occur is important because streamflow losses caused by ground-water withdrawals could be more significant in proportion to streamflow than would be suggested by the 1996–97 data alone. Measured streamflow losses caused by ground-water withdrawals (induced infiltration) ranged from about 0.3–6 ft^3/s near the three well fields for the three synoptic sets of low-flow measurements conducted for this study (figs. 5a, 5b, and 5c).

Baseflow separation was done using an automated computer program called BFI (Base Flow Index) (Wahl and Wahl, 1995). The baseflow separations indicated that ground water accounted for 40 percent of total streamflow in the Rock River at Luverne during the 1996–97 water years.

GROUND WATER

Extent and Thickness of Aquifer and Confining Unit

The Rock River Valley aquifer consists of a surficial (unconfined) sand and gravel unit underlying the entire Rock River Valley and a buried (confined) sand and gravel unit in the middle part of the study area. The buried unit of the aquifer is present in the vicinity of the Luverne Municipal and Airport well fields (figs. 1 and 2a). The southern supply wells in the Luverne Airport well field are located less than one-half mi from the western boundary of the buried unit. The surficial and buried units of the aquifer are separated by a typically thin clay and till layer ranging in thickness from 1 to 38 ft. This confining unit generally is less than 10 ft thick, and in the vicinity of the Luverne Airport well field generally is less than 3 ft thick. The available test-hole information indicates that the confining unit, although thin, is continuous in the well field areas. Test-hole information east of the Luverne Airport well field and in the area between the well fields is scant, and the continuity of the confining unit and the extent of the buried unit in these areas is uncertain. The confining unit is generally thicker and sandier in the vicinity of the Luverne Municipal well field than near the Luverne Airport well field.

The sand and gravel deposits of the Rock River Valley aquifer extend less than 1 mi west of the Luverne Municipal well field and do not extend into terraces west of the well field. However, well logs indicate that sand and gravel deposits are present at altitudes higher than the top of the Rock River Valley aquifer in the terrace deposits west of the Luverne Airport well field.

Saturated thickness of the Rock River Valley aquifer is generally greatest in the center of the Rock River Valley and decreases towards the margins of the aquifer (fig. 1). The maximum combined saturated thickness of the surficial and buried units of the aquifer is 52 ft, with a median (based on data at well-log sites) of 22 ft. In most areas, saturated thickness near the center of the valley is between 20 and 30 ft. However, lesser saturated thicknesses of 10 to 20 ft are present near the center of the valley in some areas. Saturated thicknesses of over 30 ft were found south of Luverne in the Luverne Airport well field and northeast of Luverne. The surficial sand and gravel deposits are overlain by 5 to 10 ft of silt and/or clay in some areas and locally may be under confined conditions. At 80 percent of the sites, the water level was between 3 ft above and 9 ft below the top of the sand and gravel deposits. The buried unit of the aquifer ranges in thickness from 3 to 17 ft. The unit is composed of coarser material and is thicker underlying the Luverne Airport well field than it is underlying the Luverne Municipal well field.

Hydraulic Properties of Aquifer and Confining Unit

The results of hydraulic testing indicated that hydraulic properties are highly variable in the Rock River Valley aquifer (table 1, at the back of the report). The different methods of analyzing the multi-well aquifer test yielded very similar results for K (table 1, at the back of the report) of about 380 ft/d and storage coefficient of about 0.05. The values determined in the multi-well aquifer test represent the aquifer properties in the buried unit of the aquifer, as LUV23 is screened below a 1-to 2-ft-thick clay layer. The K determined in the multi-well aquifer test is slightly greater than values from 12 multi-well aquifer tests conducted in the well fields prior to this study, which ranged from 67 to 324 ft/d with a median of 190 ft/d (Liesch Associates, 1975b, 1989). However, values from the previous tests and the multi-well aquifer test are reasonably similar considering the uncertainty involved in aquifer tests, aquifer heterogeneity, and the range of test methods used.

Values of K determined in the multi-well aquifer test were greater than values determined using slug tests or the Hurr and Worthington method of analysis of single-well aquifer tests (table 1, at the back of the report). Values determined using single-well aquifer tests were greater than those determined using slug tests for wells with relatively high hydraulic conductivities. However, for wells with medium or low hydraulic conductivities, values determined using slug tests were greater. Variability between methods is expected because the different methods are based upon different assumptions and test different volumes of aquifer material. The multi-well aquifer test should yield a more representative determination of K than the single-well aquifer tests and slug tests because this method tests the largest volume of the aquifer. Wells were categorized into sites with relatively high (at least one estimated value > 40 ft/d), medium (all estimated values < 40 ft/d and at least one estimated value > 10 ft/d), or low K (all estimated values < 10 ft/d) K (table 1, at the back of the report).

Tests on wells located near the edge of the aquifer (RR12, RR23, RR25, RR31, RR37, RR43, RR7, RR8, RR49, and RR5) commonly indicated relatively low K (figs. 2a-d, and table 1, at the back of the report). However, wells RR36, RR50, and RR4 indicating relatively high K, and RR21 indicating a medium K were also located near the edge of the aquifer. Several wells located close to the Rock River indicated medium (RR6, RR29, and RR30) or low (RR1 and RR45) K. However, because wells RR39 and RR9, also located near streams, indicated high K, it could not be concluded that zones of lower K always occurred near the river. Values for high K sites are probably most representative of the K throughout most of the Rock River Valley aquifer, based on the results of the multi-well aquifer test.

Specific yield for unconfined aquifers can range from 0.01 to 0.30 (Freeze and Cherry, 1979), but typically ranges from about 0.10 to 0.30 (Heath, 1983). Previous studies in Minnesota have most commonly reported specific yields in unconfined aquifers that range from 0.10 to 0.30 (Lindholm, 1980; Lindgren, 1990). Storage coefficient values determined in seven aquifer tests prior to this study ranged from 0.0016 to 0.12; values less than 0.05 in five of these tests indicate locally confined aquifer conditions. Values greater than 0.05, indicating unconfined conditions, were obtained in previous tests at RW1 and RW2 (figs. 2b and 2d), with values of 0.12 and 0.07, respectively. The storage coefficient value of 0.05, determined in the Theis-method analysis of the multi-well aquifer test, is near the lower end of the range of expected values for unconfined aquifers and likely represents locally confined conditions.

No field tests were conducted for this study to determine the hydraulic properties of confining units. Based on previous studies, the K of tills and clays in the study area were considered to range from 0.1 to 1.0 ft/d. A value of 1 ft/d for the K of alluvial clay in the Arkansas River Valley in Colorado was given by Lohman (1972, p. 53). A value of 1 ft/d is also at the upper limit for K values for till given by Heath (1983, p.13). Stark and others (1991) reported that ground-water-flow model analysis indicated values from 0.1 to 1.0 ft/d are reasonable values of K for the uppermost confining unit in the Bemidji-Bagley, Minnesota area.

The K_v of till and glacial-lake deposits (confining units) generally is much lower than the K. Based on the analysis of 12 aquifer tests, Delin (1986) estimated the mean K_v of till in the area of Morris, Minnesota, to be 0.025 ft/d. This compares favorably with the value of 0.018 ft/d for the K_v of till in the Detroit Lakes area in Minnesota (Miller, 1982). Norris (1962) listed values of K_v of glacial till in South Dakota ranging from 4.0×10^{-5} to 6.7×10^{-2} ft/d, with an average value of 9.4×10^{-3} ft/d.

No information on storage coefficients for confining units was available in or near the study area. Freeze and Cherry (1979) indicate that storage coefficients in confined aquifers range in value from 0.005 to 0.00005.

Recharge and Discharge

Recharge to the Rock River Valley aquifer occurs by infiltration of precipitation to the saturated zone (areal recharge) and by induced infiltration from the Rock River due to ground-water withdrawals from supply wells near the river. A lesser amount of recharge probably occurs to the aquifer by subsurface inflow from sand and gravel terrace deposits to the west of the Luverne Airport well field. Recharge to the buried unit

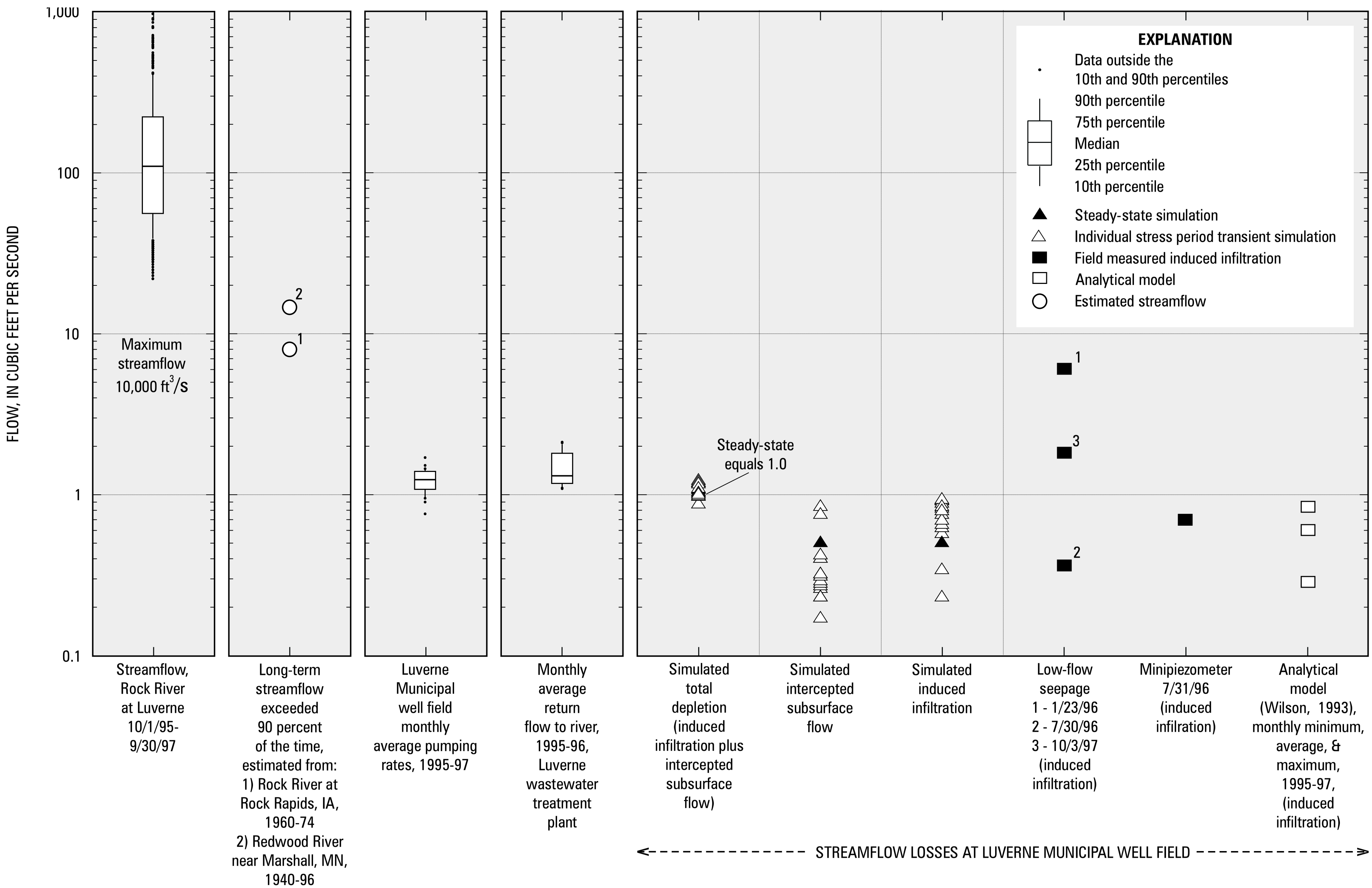


Figure 5a. Streamflow, pumping rates, wastewater returns, and streamflow losses at the Luverne Municipal well field.

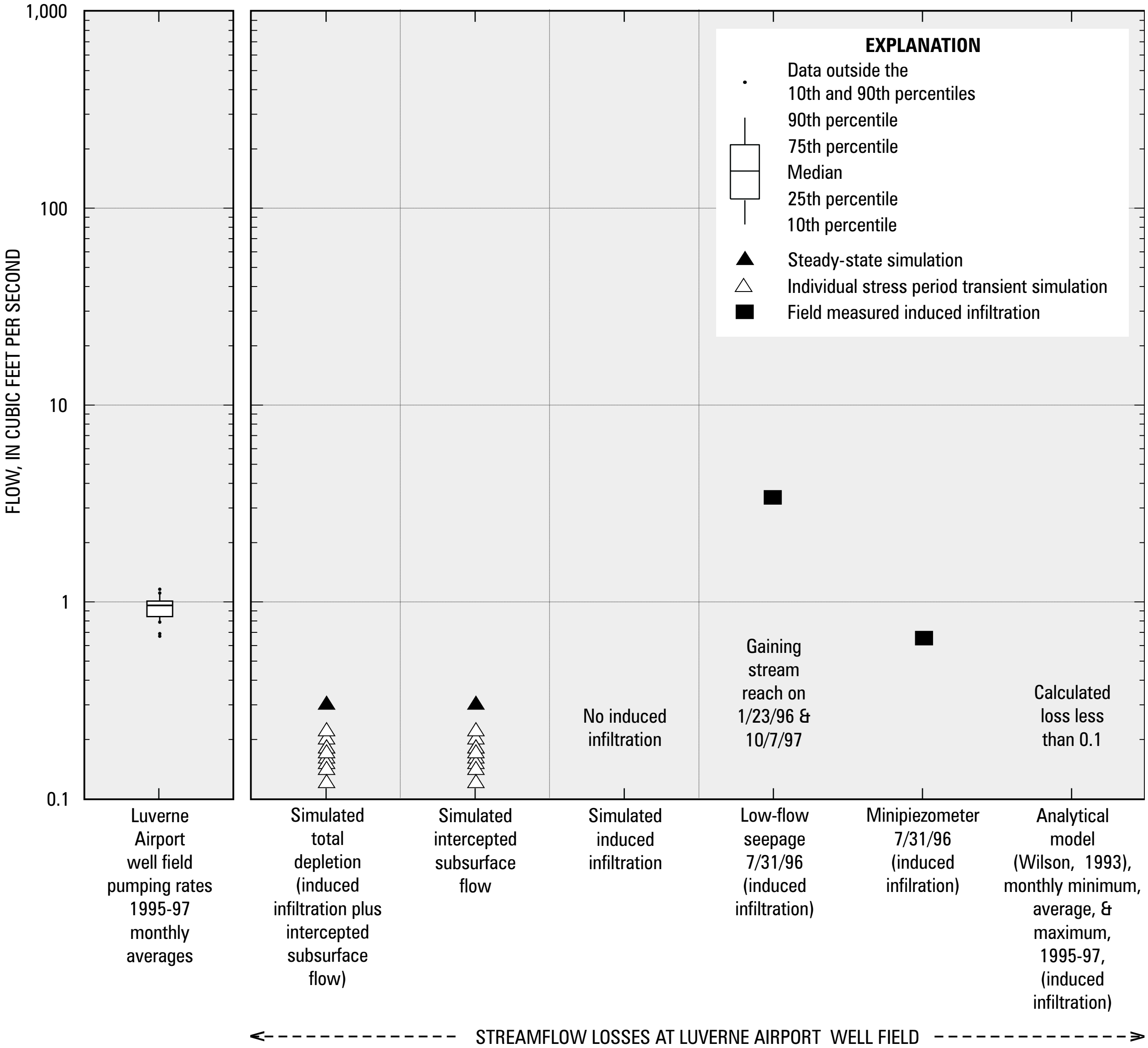


Figure 5b. Pumping rates and streamflow losses at the Luverne Airport well field.

of the aquifer is by leakage of water downward from the overlying surficial unit through the confining unit.

Areal recharge rates to the Rock River Valley aquifer were estimated from monthly water-level measurements from 16 observation wells using the method of hydrograph analysis (Rasmussen and Andreasen, 1959). The method assumes that all water-level rises in the well result from areal recharge to the aquifer. A value of 0.15 for specific yield, an approximate average value for unconfined outwash aquifers, was used in the areal recharge calculations. Estimated areal recharge ranged from 6.9 to 8.1 in. during 1995, with an average of 7.2 in./yr, based on data from four observation wells, and from 2.9 to 8.2 in. during 1996, with an average of 4.8 in./yr, based on data from 16 observation wells. The higher rates tended to be near the center of the valley and near the Rock River, with lower rates near the valley margins.

Discharge from the Rock River Valley aquifer occurs as ground-water discharge to streams, ground-water evapotranspiration, and ground-water withdrawals by wells. Low-flow measurements conducted during the study indicated that the Rock River is predominantly a gaining stream in the study area, with a gain of 8.7 ft^3/s over 26.9 river mi (from SW3 to SW13, fig. 2a) from ground-water discharge in October 1997.

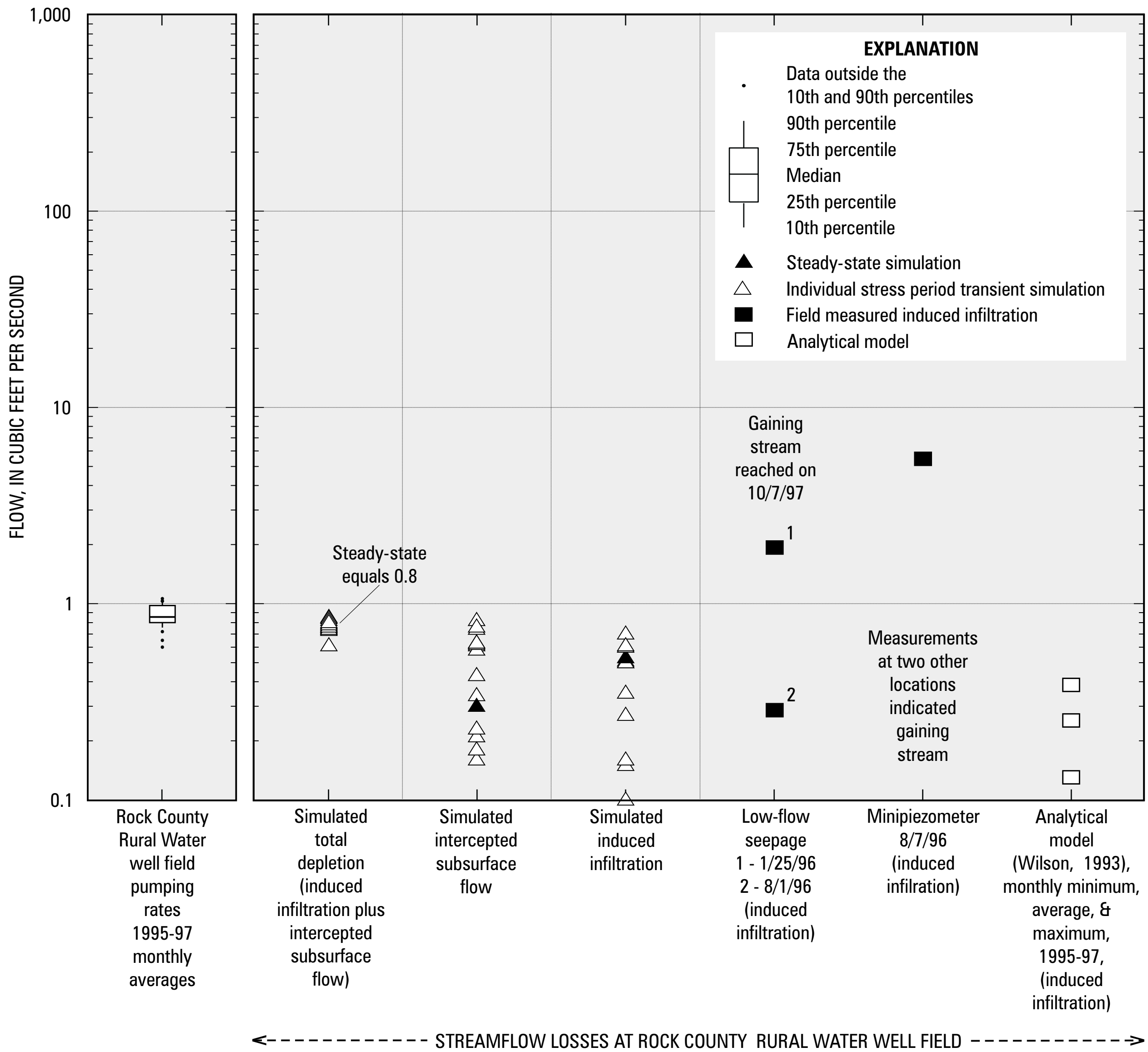


Figure 5c. Pumping rates and streamflow losses at the Rock County Rural Water well field.

Ground-water evapotranspiration is a function of the depth of the water table below land surface. Ground-water evapotranspiration is maximum where the water table is at land surface and decreases to zero where the water table is below the root-zone depth. The water table is generally shallowest, and ground-water evapotranspiration greatest, near streams. The approximate maximum root-zone depth for vegetation in Minnesota ranges from 5 to 10 ft (Lindgren, 1990). Baker and others (1979, p. 14) reported that corn roots do not normally exceed a depth of 5 ft. The rate of ground-water evapotranspiration is estimated to be a maximum of 30.8 in./yr in the study area where water levels are at land surface, based on mean annual pan evaporation rates. Evaporation from lakes can be used to estimate the maximum ground-water evapotranspiration rate that occurs when the water table is at land surface. A commonly accepted estimate for lake evaporation rates is about 70 percent of the observed class A pan-evaporation rates (Baker and others, 1979, p. 12). In the study area, the mean annual pan-evaporation rate is about 44 in. (Baker and others, 1979), which corresponds to an estimated average annual lake-evaporation rate of 30.8 in. The amount of ground-water loss to evapotranspiration also depends on solar energy supplied, air temperature, and humidity of the air. Large quantities of water are discharged from ground water through evapotranspiration during the summer. These losses decrease in the fall and are near zero in the winter.

Because sustainable well yields in individual supply wells in the area are generally less than 200 gal/min, both Luverne and the Rock County Rural Water District have installed multiple wells to provide sufficient water for public supply. There are currently 10 wells in the Luverne Municipal well field, five of which (LUV2, LUV21, LUV22, LUV25, and LUV26, fig. 2a) supplied about 90 percent of the total water pumped from this well field during December 1994 through November 1997. Well LUV19, screened in the buried unit of the Rock River Valley aquifer, is no longer used for public supply and was used as an observation well during this study. Supply wells LUV2 and LUV20 are screened in the surficial unit of the aquifer and partially in the confining unit. The rest of the wells in the Luverne Municipal well field are screened only in the surficial unit of the aquifer. The average pumping rate for the Luverne Municipal well field was about 1.23 ft^3/s (550 gal/min) during December 1994 through November 1997 (fig. 4e). Pumping rates were usually slightly greater during May through September, with an average of about 1.4 ft^3/s (630 gal/min), than during other times of the year (fig. 4e). There are currently eight wells in the Luverne Airport well field (fig. 2c), three of which (LUV7, LUV23, and LUV24) supplied about 96 percent of the total water pumped from this well field during December 1994 through November 1997. All the wells in the Luverne Airport well field that withdrew water during December 1994 through November 1997 are screened in the buried unit of the aquifer. The average pumping rate for the Luverne Airport well field was about 0.93 ft^3/s (420 gal/min) during December 1994 through November 1997 (fig. 4g). Pumping rate fluctuations for the well field are shown in figure 4g.

There were six wells in the Rock County Rural Water well field during 1995–97 (fig. 2d). A seventh well, RW7, was installed in 1997 approximately one-half mi west of the existing well field (fig. 2d), and began operation in October 1997, near the end of this study. All seven wells are screened in the surficial unit of the Rock River Valley aquifer. The average pumping rate for the Rock County Rural Water well field was about 0.87 ft^3/s (390 gal/min) during December 1994 through November 1997 (fig. 4i). Pumping rates were usually slightly greater during May through September, with an average of about 0.96 ft^3/s (430 gal/min), than during other times of the year (fig. 4i).

Water levels in the Rock River Valley aquifer fluctuate 3–5 ft annually in response to seasonal variations in recharge and discharge (figs. 6a and 6b). Ground-water levels rise in spring because recharge from snowmelt and spring rain is greater than discharge from the aquifer. Conversely, ground-water levels decline in summer because discharge by ground-water evapotranspiration and ground-water withdrawals by wells exceed recharge. Net recharge to the aquifer also occurs in the fall most years, due to rainfall and low ground-water evapotranspiration rates. Ground-water withdrawals from supply wells in the three well fields are uniform during each year. Water levels in the aquifer near the Rock River and other streams are influenced by stream stage. Figure 4 indicates the close correspondence between stream stage and water levels in nearby wells, reflecting a high degree of hydraulic connection between the Rock River and the ground water. Water levels in wells near the river respond rapidly to stream stage fluctuations.

Seasonal high water levels were observed during 1995–97 in most of the observation wells during the spring or early summer and, to a lesser extent, during the fall. During the winter and late summer, water levels were stable or declining. Water levels rose 2–4 ft in most wells during spring or early summer 1995–97. The observed spring peaks during 1995 to 1997 were similar each year for a given well. During 1996, however, the spring peak occurred, during the early summer. The spring peak occurred later during 1996 due to a smaller than normal amount of spring snowmelt and March-April precipitation. Water-level rises during the fall were 1 ft or less. Although fall precipitation during 1996 was much higher than during 1995 or 1997, fall water-level rises during 1996 in observation wells distant from the Rock River were much less pronounced than in observation wells near the river. The substantial rise during fall 1996 in observation wells near the river was due to bank-storage effects caused by high stream stages. Stream stage exhibits a short-term faster and larger response to precipitation events than do ground-water levels, and water levels in wells near the river rise in response to these short-term rises in stream stage. The movement of water from the river into the aquifer is a short-term event due to bank-storage effects. As stream stage declines, the direction of flow is reversed, with water moving from the aquifer into the river.

The available hydrologic data in and near the study area indicate that the ground-water levels fluctuate in response to seasonal variations in recharge and discharge around mean water levels that remain relatively constant in time. The ground-water system is in a dynamic equilibrium, or steady-state, condition in which discharges from the system are balanced by recharge to the system. Ground-water levels may rise or decline for a period of a few years in response to periods of above-normal or below-normal precipitation, but long-term declines in levels have not occurred in the study area (observation well DNR 67006, 1978–97). Fall and winter water levels from a given year approximate steady-state conditions.

Ground-Water Flow

The general pattern of ground-water flow in the Rock River Valley aquifer in the study area is predominantly from north to south and toward the Rock

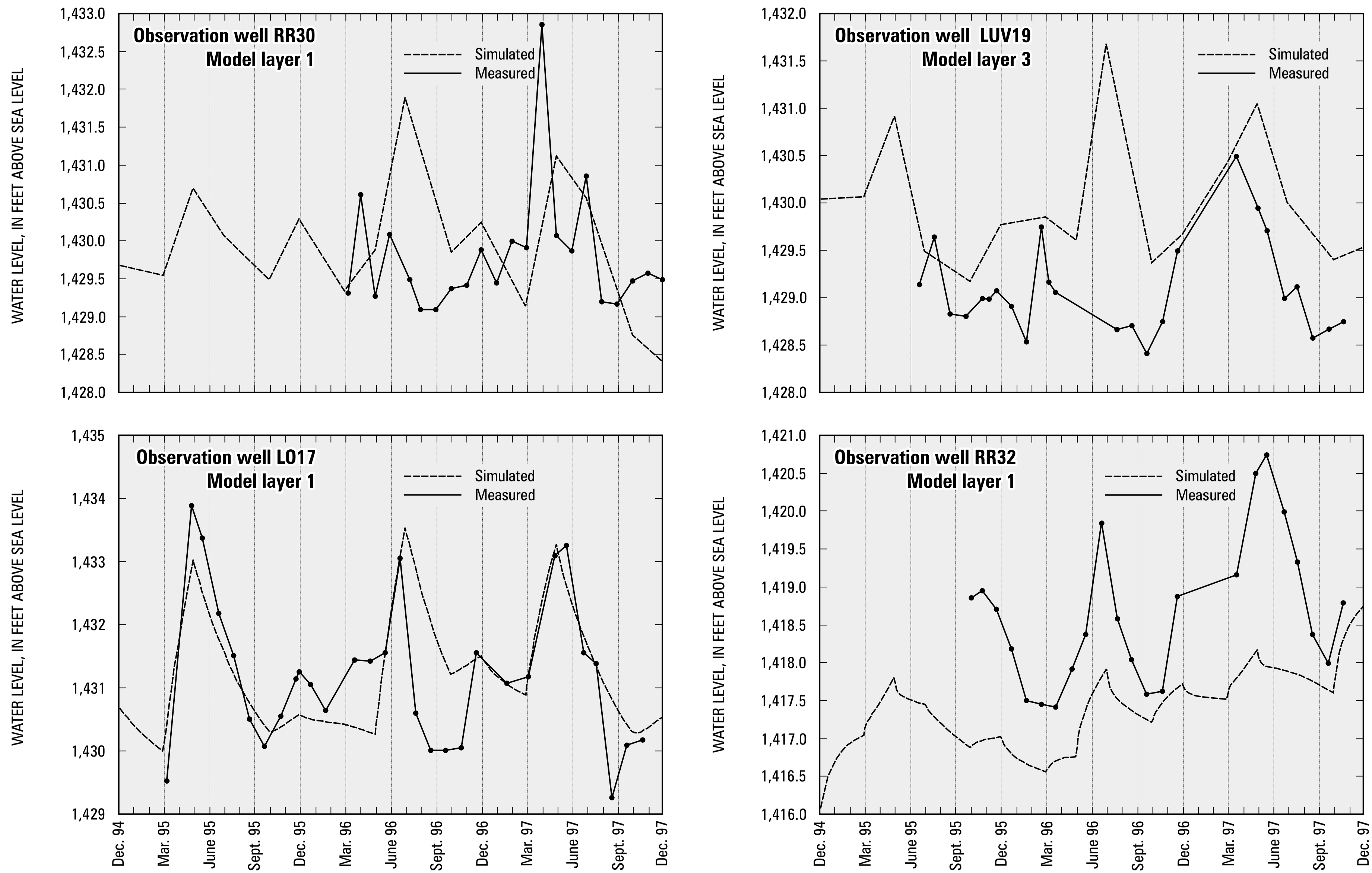


Figure 6a. Measured and simulated hydraulic heads for observation wells RR30, LUV19, LO17, and RR32, transient simulation 1994-97, eastern Rock County, Minnesota.

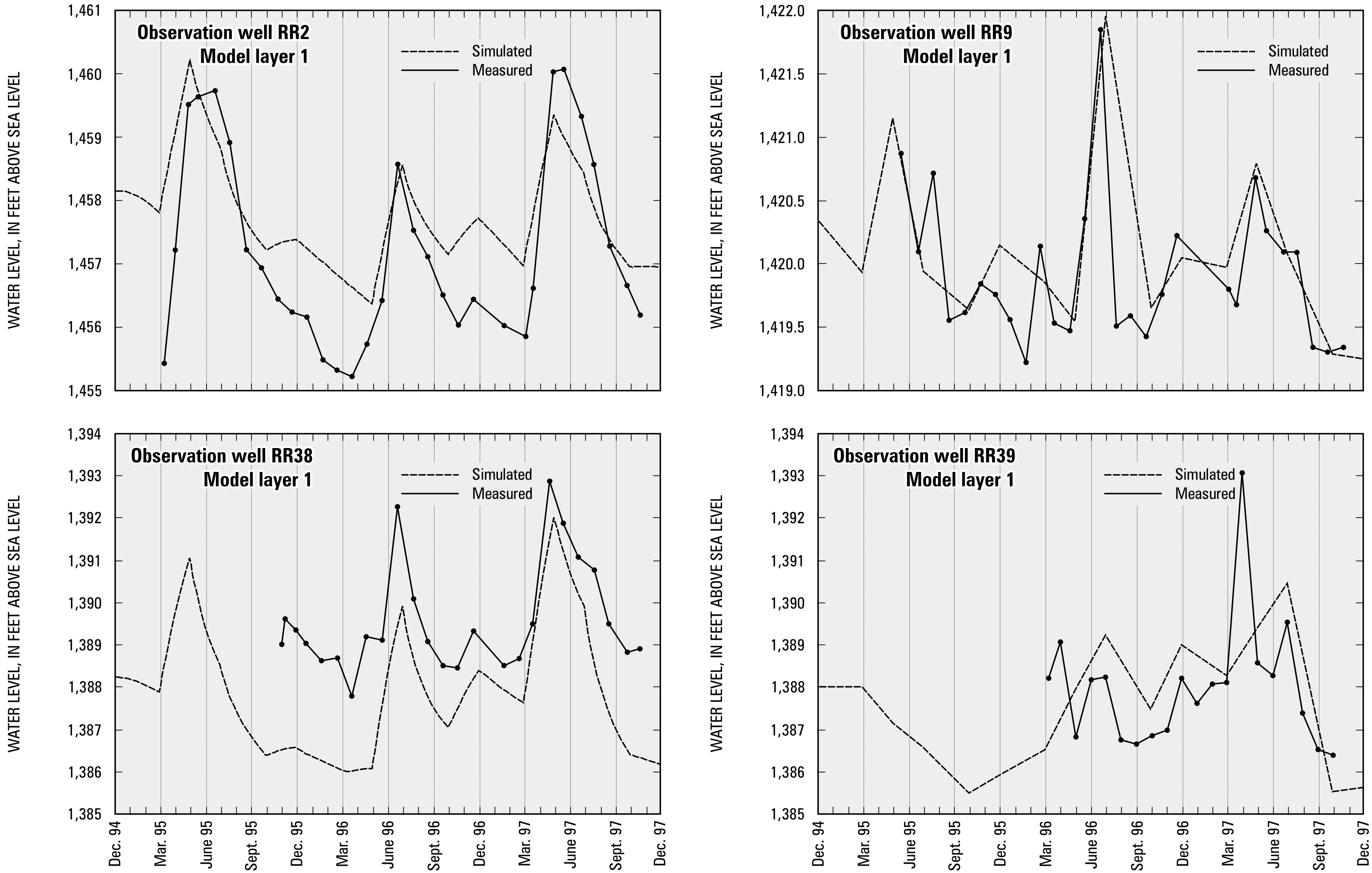


Figure 6b. Measured and simulated hydraulic heads for observation wells RR2, RR9, RR38, and RR39, transient simulation 1994-97, eastern Rock County, Minnesota.

River (fig. 2a). Water in the aquifer enters the study area by ground-water flow through the north, west-central, and Champepadan Creek study area boundaries. Water in the aquifer leaves the study area by flow out the southern study area boundary. The Rock River is the major discharge area and generally acts as a sink within the stream-aquifer system. In the vicinity of the three well fields, ground water moving toward the Rock River is captured by pumped wells. The potentiometric surface and ground-water flow directions for the buried unit of the aquifer are similar to those for the overlying surficial unit. Flow in aquifers is predominantly horizontal; whereas, flow in confining units is predominantly vertical, due to differences in grain size and hydraulic conductivities for the materials comprising the units (Heath, 1983, p. 24).

The horizontal hydraulic gradient in the aquifer ranges from about 5 to 20 ft/mi, as inferred from the spacing of the potentiometric-surface contours (figs. 2a–2d). The largest hydraulic gradients occur southwest of Luverne near the west-central margin of the aquifer, reflecting the greater slope of land surface and the presence of aquifer materials with lower K. The horizontal hydraulic gradients in the central part of the river valley away from the aquifer margins range from 5 to 10 ft/mi.

The effects of current (1995–97) ground-water withdrawals from the three public supply well fields on ground-water levels are minimal. Cones of depression of very limited areal extent were present near individual pumped wells during 1995 through 1997. Water-level measurements in pumped wells and nearby observation wells indicate drawdowns of as much as 3 ft at pumped wells in the Rock County Rural Water well field, 10 ft in the Luverne Municipal well field, and 15 ft in the Luverne Airport well field. Ground-water flow directions in the vicinity of the three well fields are not appreciably affected by ground-water withdrawals, except near wells LUV22, LUV25, and LUV26 in the Luverne Municipal well field (fig. 2b) and near wells RW2 and RW3 in the Rock County Rural Water well field (fig. 2d). Ground-water flow toward the Rock River is altered by the presence of these pumped wells, with components of flow toward the wells. Study results indicate that wells LUV22, LUV25, and LUV26 alter the potentiometric surface in the Luverne Municipal well field north of the Rock River somewhat by creating an east-west component of flow toward the pumped wells, in contrast to the north-south direction of flow toward the Rock River that would prevail in that area without the presence of the pumped wells. The presence of pumped wells RW2 and RW3 in the Rock County Rural Water well field alter the potentiometric surface near the two wells. Study results indicate that the direction of ground-water flow near the well sites prior to ground-water withdrawals by wells was to the south and east toward the Rock River. With ground-water withdrawals, the direction of flow near the wells is to the south and west toward the pumped wells.

STREAM-AQUIFER INTERACTIONS

Ground-water flow in the Rock River Valley aquifer is integrally linked to flow in the Rock River. Because the aquifer is relatively narrow, ground-water levels and rates and directions of water movement are strongly influenced by stream stage. In an alluvial aquifer system in a humid temperate climate with no ground-water development (natural condition), streams typically gain water (gaining stream). However, even under natural conditions streams can also lose water (losing stream).

Development of ground-water resources can affect stream-aquifer leakage and, consequently, streamflow. A reduction in streamflow as a result of ground-water development is called stream depletion. Stream depletion includes two components, induced infiltration and intercepted subsurface flow (Barker and others, 1983; Pucci and Pope, 1995; Winter, 1995; Jian and others, 1997). Stream-aquifer leakage usually is restricted by the streambed. The rate and direction of leakage through the streambed depends on K_s and the hydraulic gradient between the stream and the aquifer. Measurements of K_s and analysis of stream-aquifer leakage in the study area are described in the sections that follow.

Streambed Hydraulic Properties

Published values for K_s of streams in glacial terrain commonly range from 0.5 to 10 ft/d (Norris and Fidler, 1969; Jorgensen and Ackroyd, 1973; Prince and others, 1987). The field constant-head permeameter tests conducted for this study at 58 locations at 13 sections across the Rock River indicated values of K_s ranging from 0.2 to 401 ft/d with a median of 37 ft/d (table 2, at the back of the report). These $K_s$values for approximately the upper 1 ft of the streambed are within the range of K values determined for the aquifer (table 1, at the back of the report); this is reasonable considering the streambed is in most cases composed of similar sediments. K_s is often considered to be lower than the average K of an adjacent aquifer due to the presence of fine-grained or organic deposits in the stream sediments. However, the Rock River streambed is composed of clean sand and gravel at most of the measurement locations. The K_s values are within the range of values expected for silty sand to coarse clean sand (Heath, 1983, p. 13).

The K_s values of the major tributaries in the study area, Champepadan and Elk Creeks (sites SW4 and SW9, respectively, fig. 2a), ranged from 13 to 226 ft/d, with medians of 140 ft/d and 40 ft/d, respectively (table 2, at the back of the report). The values are similar to K_s of the Rock River (table 2, at the back of the report) and K of the aquifer (table 1, at the back of the report).

However, field permeameter tests in smaller tributaries in the study area (sites SW5, SW26, SW27, SW28, and SW11, fig. 2a) indicated K_s values of 0.15 ft/d or less (table 2, at the back of the report). Values of <0.01 ft/d for sites SW5, SW27, and SW11 indicate that no water flowed out of the permeameter when water was added and that the K_s was smaller than could be measured using the field permeameter test. These relatively small K_s values in small tributaries are consistent with observations that the bottoms of these small tributaries and ditches consist of clayey organic sediments as much as several feet thick.

Stream-Aquifer Leakage

Low-flow measurements on the Rock River and its tributaries indicated that the Rock River is predominantly a gaining stream through the study area (table 3, at the back of the report). The results of the October 6–8, 1997 low-flow measurements were the most useful for understanding stream-aquifer leakage because these measurements were done under the lowest open-water flow conditions during the study period. The January 22–25, 1996 measurements were made under ice and there is greater uncertainty associated with these results. The July 29–August 1, 1996 measurements were at a higher discharge rate than for the other two measurement periods. Streamflow gains and losses were less than the accuracy of streamflow measurements (5 percent) in many of the reaches during the low-flow measurements. Gains and losses that were greater than the measurement accuracy are referred to as significant in this discussion. Gaining and losing reaches were somewhat inconsistent between low-flow measurement periods as a result of gains and losses being near or below the measurement accuracy and due to variations in flow conditions.

Streamflow increased by 15.3 ft^3/s through the study area in October 1997 with 6.59 ft^3/s of the increase from tributary inflow and 8.71 ft^3/s from ground-water discharge to streams (table 3, at the back of the report). The values for the January 1996 low-flow measurements were similar except that tributary inflow of 7.61 ft^3/s was slightly larger than ground-water discharge to streams of 6.19 ft^3/s (table 3, at the back of the report). During the July–August 1996 low-flow measurements, tributary inflow was 22.92 ft^3/s, approximately three times greater than during the other low-flow measurement periods, and ground-water discharge to streams was slightly greater at 11.68 ft^3/s.

The measurements during October 1997 and January 1996 identified losing river reaches by the Luverne Municipal and Rock County Rural Water well fields (table 3, at the back of the report). Other reaches were either gaining or had gains or losses that were insignificant, with the exception of the reach between SW8 and SW10 during January 1996, which had a significant loss of 5.72 ft^3/s. This apparent loss either reflects measurement error, natural streamflow losses unrelated to ground-water withdrawals in a well field, or unknown factors. All other reaches with significant losses during the three low-flow measurement periods were located next to well fields. The reach between SW7 and SW8, adjacent to the Luverne Airport well field, showed a loss of 3.31 ft^3/s during the July–August 1996 low-flow measurements. One of the three reaches adjacent to the Rock County Rural Water well field was identified as a losing reach during both the October 1997 and January 1996 low-flow measurement periods. However, a different reach was losing in October 1997 than in January 1996 (table 3, at the back of the report).

Streamflow losses near the Luverne Municipal and Rock County Rural Water well fields were 1.9 to 6.4 times larger than the volume of water being pumped by the wells. The anomalously high streamflow losses probably are due to measurement error in the low-flow measurements. Streamflow losses of similar magnitude to the pumping rates would have been less than the 5 percent uncertainty in the streamflow measurements and would not have been significant.

Head gradients between the Rock River and nearby wells in the Luverne Municipal and Rock County Rural Water well fields indicate that the Rock River was losing water to the aquifer in the vicinity of supply wells (figs. 4c, 4d, and 4h). In the Luverne Municipal well field, river altitude at SW6 was on average 0.52, 1.02, and 1.40 ft higher than water-level altitude in observation wells RR29, RR30, and LUV19 (not pumped), respectively (fig. 4c). Water levels in the river were also higher than the water level during pumping in LUV21 (figs. 4c and 4d) and other pumped wells near the river. In the Rock County Rural Water well field, river altitude at SW24 was on average 0.75 ft higher than the water-level altitude in observation well RR39, based upon water levels recorded every 6 hours during April 1996 through September 1997 (fig. 4h).

Head gradients between the Rock River and ground water in the Luverne Municipal and Rock County Rural Water well fields were reversed only during high-flow periods, when the water moved from the aquifer into the river. At high stream stage, water moved from the river into bank storage. As stream stage declined the flow direction was reversed. Storage water that had entered the aquifer moved back into the river. As the high streamflows subsided and ground-water levels lowered in response to ground-water withdrawals by wells, the more usual movement of water from the river into the aquifer was re-established. Gradient reversals occurred only during the high-flow events of June 1996, March–April 1997, and June–July 1997 (fig. 4c and 4h).

At observation well RR9 and surface-water site SW7 (fig. 2c), the sites along the Rock River closest to the Luverne Airport well field, water-level altitudes were sometimes greater in the river and sometimes greater in the aquifer (fig. 4f). Because the gradients frequently reversed, it is unlikely that substantial losses from the river occur in this reach.

Ground-water altitudes were greater than surface-water altitudes most of the time at places away from the well fields. Ground-water altitudes were consistently greater than surface-water altitudes at the following paired ground-water/surface-water measurement sites (from north to south): RR1/SW3, RR13/SW4, RR11/SW8, DNR67006/SW10, RR17/SW12, and RR18/SW13 (fig. 2). All of these sites are located on the Rock River except for RR13/SW4, which is located along Champepadan Creek, the largest tributary. These head gradients indicate that ground water is primarily discharging into the river and major tributaries at locations away from the well fields.

Ground-water/surface-water relations are different on minor tributaries than on the Rock River and major tributaries. Surface-water and ground-water altitudes recorded by a data logger from March through September 1997 on a small tributary ditch (sites SW28 and RR45, fig. 2c) indicated that there was a large head gradient downward from the tributary into the aquifer. The surface-water altitude was almost level while the ground-water altitude declined by nearly 4 ft during the period of record. Ground-water altitude dropped below the bottom of the streambed in late summer so that the tributary was perched and not in direct hydraulic connection with the ground water. The stream did not go dry under these conditions because K_s of the streambed is very low (0.15 ft/d), based on a constant-head permeameter test at this site. Permeameter tests in other small tributaries in the study area indicated similarly small (in some cases unmeasureably low) K_s values. At site RR16/SW11 on Ash Creek (fig. 2a), monthly measurements indicated that surface-water altitude was nearly always above ground-water altitude, sometimes by as much as 3 ft. The implication of these findings is that leakage to ground water from these small tributary streams and ditches is not likely to be a substantial source of recharge to the aquifer.

Rates of flux between streams and the aquifer were highly variable and likely reflect local-scale variations. The hydraulic potentiomanometer measurements indicate ground-water/surface-water gradients at the point of measurement. Comparison of stream-aquifer leakage rates calculated from hydraulic potentiomanometer measurements to the results of low-flow measurements and head gradients between wells and streams was complicated by the fact that the latter two types of measurements integrate stream-aquifer leakage over much larger areas. In spite of the differences in scale, hydraulic potentiomanometer measurements generally indicated stream-aquifer leakage rates of similar magnitude to those indicated by other methods of calculating leakage (figs. 5a, 5b, and 5c). The analytical model of Wilson (1993) indicated streamflow losses that were of generally similar magnitude to losses calculated using the other methods (fig. 5a, 5b, 5c).

SIMULATION OF GROUND-WATER FLOW

A conceptual model is a qualitative description of the known characteristics and functioning of the Rock River Valley aquifer. The conceptual model was formulated from knowledge of the hydrogeologic setting, aquifer characteristics, distribution and amount of recharge and discharge, and aquifer boundaries. A numerical model of ground-water flow was constructed based on the conceptual model of the aquifer.

Numerical Model Description

The study area was subdivided into rectangular finite-difference grid cells within which the properties of the hydrogeologic unit represented are assumed to be uniform. The center of a grid cell is referred to as a node and represents the location for which the hydraulic head is computed by the model. Properties of the hydrogeologic units and stresses are assigned to the cells and are assumed to represent average conditions within grid cells. The variably-spaced finite-difference grid used to spatially discretize the model area has 92 rows and 87 columns (figs. 7a-7c). Notation of the form (11,24), where the first number in parentheses indicates the row and the second number indicates the column, is used to refer to the location of an individual cell within the grid. The dimensions of the grid cells range from 150 to 660 ft along rows and from 300 to 1,320 ft along columns. The smallest cells are in the vicinity of the three well fields, where the most detailed hydrogeologic information is available and the model results are of greatest interest to water managers. Hydrologic properties assigned to the cells away from the well fields are averaged over larger areas than for cells near the well fields. The area modeled was extended to the north and south of the well fields sufficient distances to be located beyond any boundary effects of current or projected ground-water withdrawal rates.

The Rock River Valley aquifer in the model area was subdivided vertically into three layers, corresponding to generally horizontal hydrogeologic units. The altitudes of the layer tops and layer bottoms were specified for each model cell for the three layers. The thickness of a cell representing a hydrogeologic unit is incorporated in the transmissivity term for the cell. Simulation of leakage of water between model layers is dependent on the thicknesses and K_v between adjacent layers. A more detailed discussion of leakage of water between model layers can be found in McDonald and Harbaugh (1988).

The hydrogeologic units represented in the ground-water-flow model are: (1) the surficial unit of the Rock

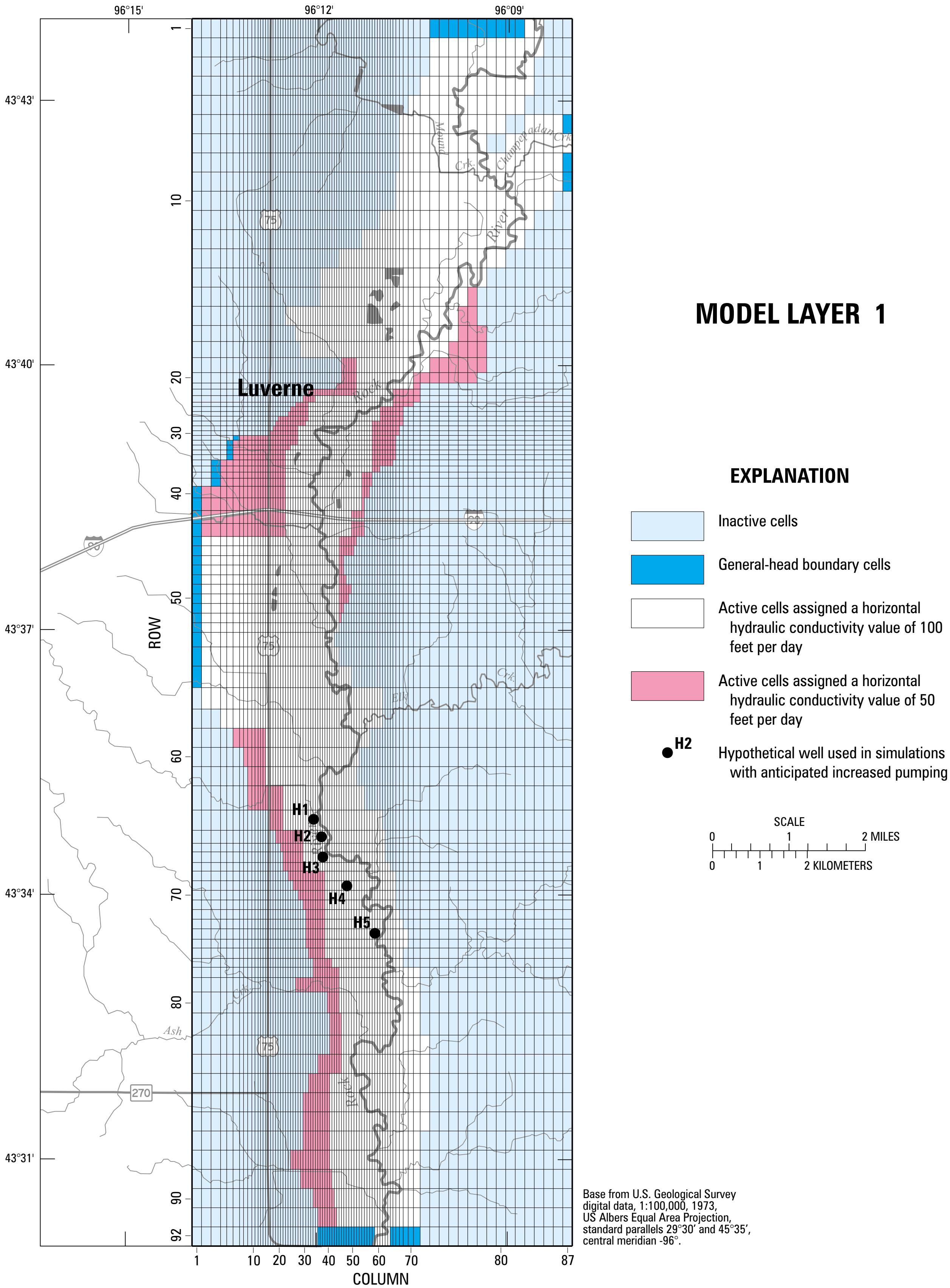


Figure 7a. Finite-difference grid, boundary conditions, and horizontal hydraulic conductivity zones for ground-water-flow model layer 1, eastern Rock County, Minnesota.

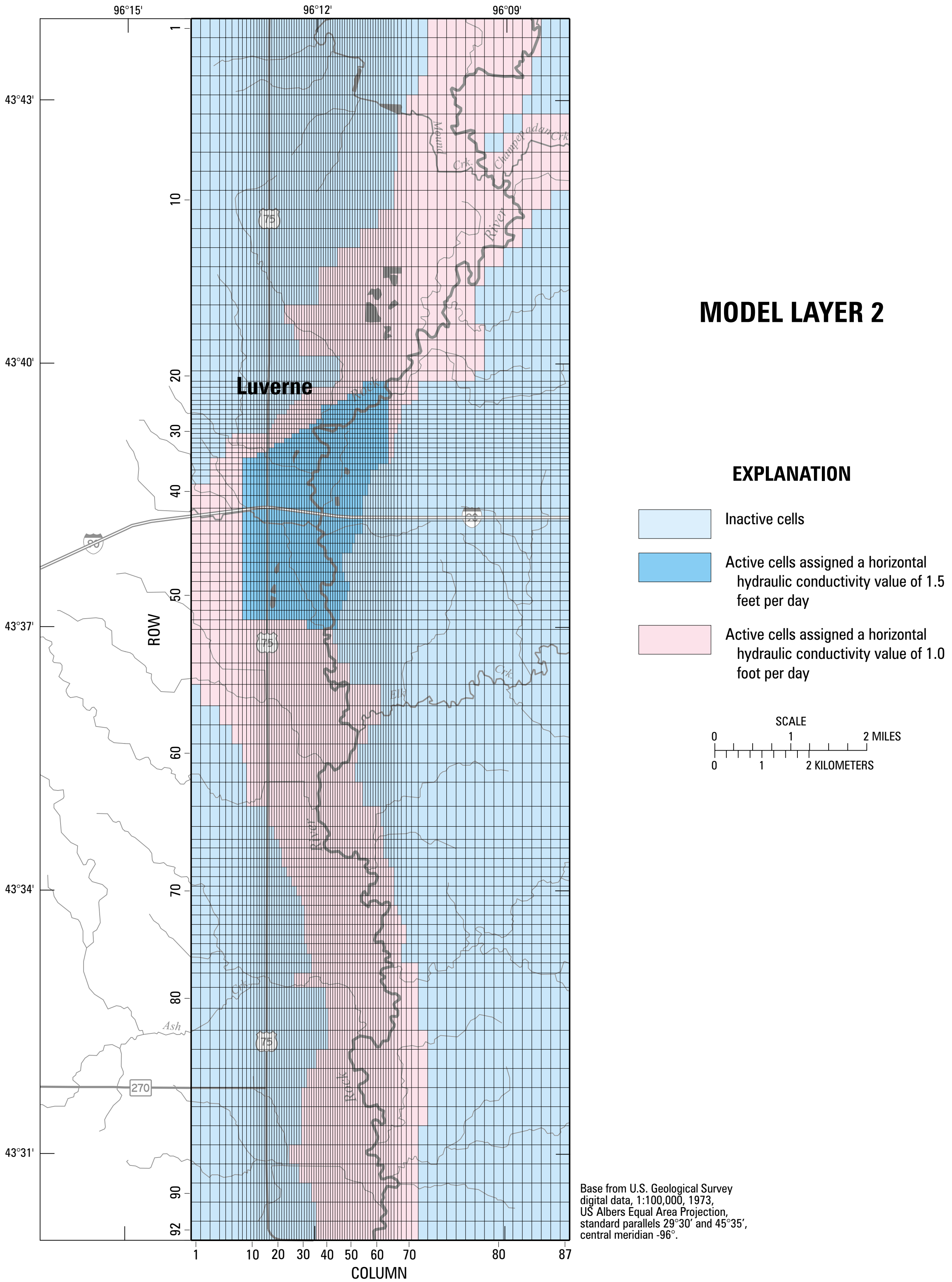
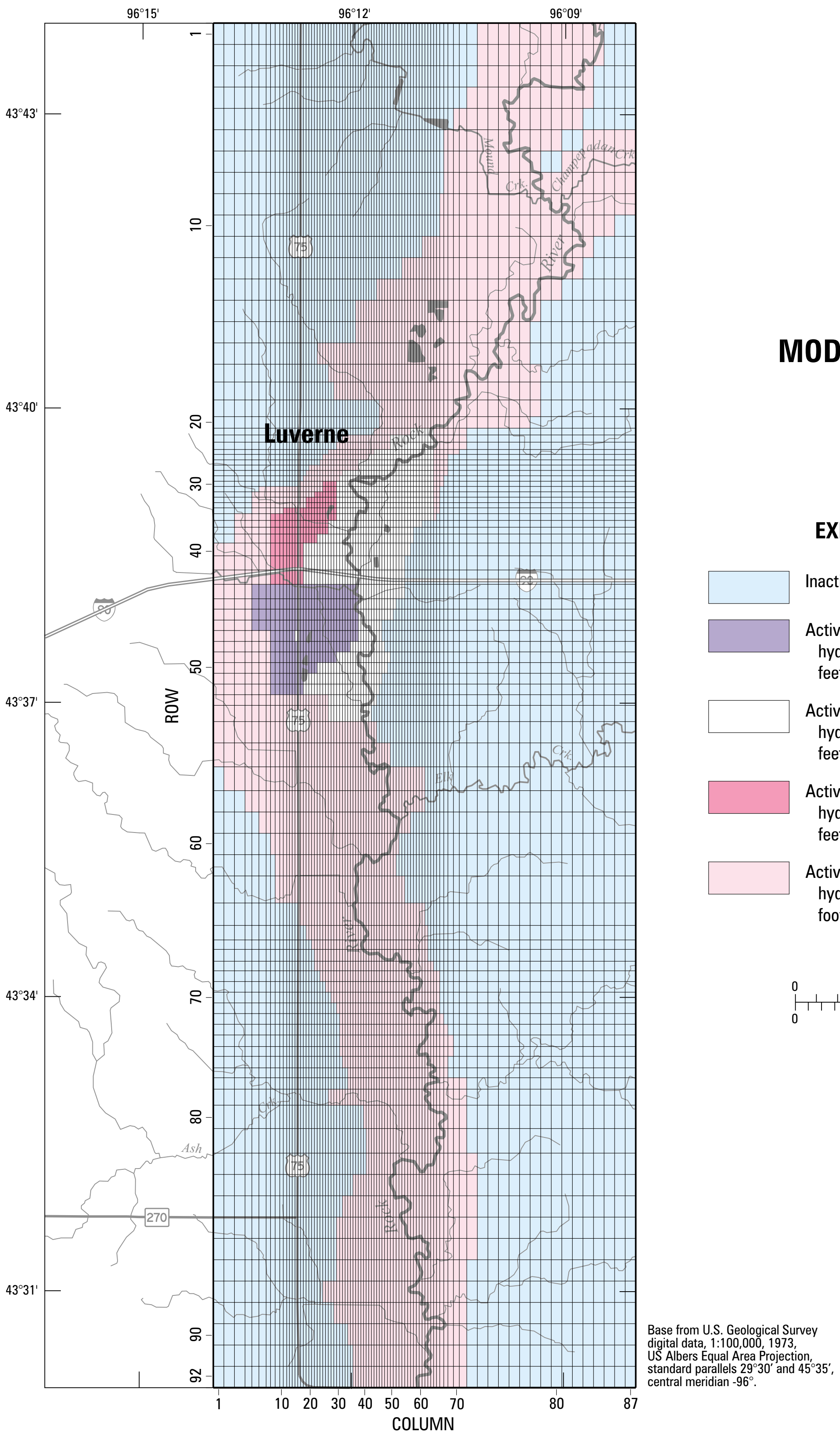


Figure 7b. Finite-difference grid, boundary conditions, and horizontal hydraulic conductivity zones for ground-water-flow model layer 2, eastern Rock County, Minnesota.



MODEL LAYER 3

EXPLANATION

- Inactive cells
- Active cells assigned a horizontal hydraulic conductivity value of 350 feet per day
- Active cells assigned a horizontal hydraulic conductivity value of 100 feet per day
- Active cells assigned a horizontal hydraulic conductivity value of 50 feet per day
- Active cells assigned a horizontal hydraulic conductivity value of 1.0 foot per day

SCALE
0 1 2 MILES
0 1 2 KILOMETERS

Figure 7c. Finite-difference grid, boundary conditions, and horizontal hydraulic conductivity zones for ground-water-flow model layer 3, eastern Rock County, Minnesota.

River Valley aquifer (model layer 1), (2) the confining unit underlying the surficial unit of the aquifer (model layer 2), and (3) the buried unit of the aquifer and laterally adjacent clay and till (model layer 3). Where the buried unit of the aquifer is present, cells in model layer 3 were assigned the hydrogeologic properties of the aquifer. Where the buried unit of the aquifer is absent, cells in model layer 3 were assigned the hydrogeologic properties of clay and till.

The transmissivities associated with the model cells representing the surficial unit of the Rock River Valley aquifer vary as the saturated thicknesses vary. The transmissivities assigned to the model cells representing the confining unit and buried unit of the aquifer are constant in time.

A number of simplifying assumptions about the Rock River Valley aquifer and boundary condition specifications were required to make mathematical representation of the aquifer possible:

1. The surficial unit of the aquifer is unconfined. The buried unit present in the vicinity of the Luverne well fields is confined.

2. The volume of water that moves vertically across the bottom of the buried unit of the aquifer is small relative to horizontal flow; thus, the aquifer bottom of the buried unit is represented as a no-flow boundary.

3. The lateral boundaries for the aquifer are no-flow boundaries where the physical limits of the aquifer are defined by the boundaries of the Rock River Valley, except for the west-central boundary.

4. Surficial sand deposits located west of the Luverne Airport well field are a source of water to the aquifer through lateral inflow. The west-central boundary was represented as a general-head boundary to simulate this lateral inflow.

5. The arbitrarily imposed boundaries where the physical limits of the aquifer lie outside the model area are general-head boundaries.

6. The Rock River and simulated tributaries are head-dependent flow boundaries. Stream-aquifer leakage is simulated in the model as head-dependent flow nodes (McDonald and Harbaugh, 1988; Prudic, 1989). The surficial unit of the aquifer is hydraulically connected to the streams.

7. Ground-water evapotranspiration is a linear function of the depth of the water table below land surface.

Ideally, all model boundaries should be located at the physical limits of the aquifer system or at other hydrologic boundaries, such as a major river. Practical considerations, such as limitations concerning the size of the area modeled may necessitate the use of arbitrarily imposed model boundaries where the natural hydrologic boundaries lie outside the model area. The northern, southern, and a small portion of the eastern boundary (where Champepadan Creek enters the model area) for model layer 1 are arbitrarily imposed boundaries where the natural hydrologic boundaries lie beyond the practical limits of the model.

The lateral boundaries for model layer 1 are mostly located at the physical limits of the Rock River Valley aquifer; therefore, no-flow boundaries were used. General-head boundaries, however, were used for portions of the western and eastern lateral boundaries (fig. 7a). A general-head boundary was used west of the Luverne Airport well field to simulate the lateral ground-water inflow to the aquifer from sand and gravel terrace deposits located west of the model boundary at altitudes higher than the top of the aquifer. The degree of hydraulic connection between these terrace deposits and the aquifer, and the extent of the sand and gravel terrace deposits, is uncertain due to a lack of geologic information. General-head boundaries were also used to simulate the lateral ground-water inflow to the aquifer from surficial outwash deposits underlying the Champepadan Creek valley and the northern model boundary. A general-head boundary was used to simulate the outflow of ground water across the southern model boundary.

The use of general-head boundaries requires knowledge of (1) hydraulic head at the external source or sink of water to the model boundary and (2) hydraulic conductance of the interface between the model boundary and the external boundary be specified. A K of 100 ft/d was used for all general-head boundaries because the geologic deposits of the interface between the external boundary and the model boundary are similar to those comprising the surficial unit of the Rock River Valley aquifer. The hydraulic heads specified for the general-head boundaries were derived from the hydraulic heads measured in observation wells located about 4 mi or less outside the model boundaries. General-head boundaries were only used for model layer 1 because at all boundaries for model layers 2 and 3 the geologic deposits are clay and till.

The lateral boundaries of the Rock River Valley aquifer, other than those represented by general-head boundaries, are bounded by clay and till deposits. The clay and till uplands adjacent to the aquifer are a potential source of water by ground-water inflow to the aquifer. The effect of the use of no-flow boundary conditions to simulate these lateral boundaries was investigated by using general-head boundaries in place of no-flow boundaries for steady-state conditions. A hydraulic conductance of 1.0 ft/d was used to represent the bounding upland clay and till deposits that comprise the interface between the model cells and the general-head boundary. The hydraulic heads used were derived from a regional water-table map for the area (Brandt, 1997a). The change from no-flow boundaries to general-head boundaries for model layer 1 resulted in simulated hydraulic head changes of 0.2 ft or less. Changes in the simulated water budget indicated that using those general-head boundaries resulted in a net influx to the aquifer of 0.1 ft^3/s, about 8 percent of the inflow from the other general-head boundaries. No-flow boundaries were used for the lateral boundaries of model layer 1 in areas adjacent to clay and till uplands because of: (1) the minimal effects on hydraulic heads and flows, (2) uncertainty regarding the hydraulic conductance of the clay and till, and (3) scant hydraulic head information in the surrounding uplands.

The lateral boundaries for model layer 2, representing the confining unit, were imposed to coincide with the lateral boundaries for model layer 1 (fig. 7b). Because flow in confining units is predominantly vertical, no-flow boundary conditions were used for all lateral boundaries for model layer 2.

The lateral boundaries for model layer 3, representing the buried unit of the Rock River Valley aquifer, where present, and clay and till in other areas, were also arbitrarily imposed to coincide with the lateral boundaries for model layer 1 (fig. 7c). Model layer 3 represents clay and till at all boundaries, and therefore no-flow boundary conditions were used.

A specified-flux boundary was used to represent areal recharge to the surficial unit of the Rock River Valley aquifer. Areal recharge to the aquifer represents the net difference between precipitation and evapotranspiration losses occurring above the water table.

Stream-aquifer leakage between the Rock River Valley aquifer and the Rock River, four major tributaries, and three minor drainages was simulated with head-dependent flux nodes (McDonald and Harbaugh, 1988, Chapter 6; Prudic, 1989). The major tributaries to the Rock River simulated in the model, in downstream order, were Mound Creek, Champepadan Creek, Elk Creek, and Ash Creek. Three minor drainages in the vicinity of Luverne were also simulated—a small creek entering the Rock River just upstream from SW6, a return flow drainage from the Luverne Wastewater Treatment Plant, and drainage from the Luverne sewage ponds (fig. 3b). Stream-aquifer leakage was simulated between streams and the surficial unit of the aquifer (model layer 1) in the model. The streams were divided into reaches, each of which is completely contained in a single cell. Stream-aquifer leakage through a reach of streambed is approximated by Darcy's Law as

QRIV = [KLW/M] (HRIV-HAQ)

where

QRIV = stream-aquifer leakage through the reach of the streambed (L^3/T),

K = vertical hydraulic conductivity of the streambed (L/T),

L = length of the reach (L),

W = width of the stream (L),

M = thickness of the streambed (L),

HAQ = head in the aquifer (L), and

HRIV = head in the stream (L).

The length of the streambed in each river cell was measured from USGS 7.5-minute-quadrangle topographic maps. The average width of the Rock River streambed, estimated at stream stage and discharge measurement sites within the model area, is about 75 ft. Average streambed widths for the other streams simulated in the model were 25 ft for Champepadan Creek, 15 ft for Elk Creek, 10 ft for Mound Creek, and 5 ft for Ash Creek and the three minor drainages. The thickness of the streambed was assumed to be 1 ft for the model because the lower limit of the streambed is poorly defined and not easily measurable. Stream stage for each river cell between measured stream stage sites was interpolated based on the length of the stream reach in the cell. The initial value used in the model for K_s of the Rock River streambed was 30 ft/d, based on field measurements conducted for this study. The initial values for K_s of the streambed for the other simulated streams, also based on field measurements, were 30 ft/d for Champepadan Creek, 3.0 ft/d for Elk Creek, 0.1 ft/d for Mound and Ash Creeks, and 0.01 ft/d for the three minor drainages. Streamflows used in the streamflow-routing package were those measured on October 6–8, 1997.

Discharge by ground-water evapotranspiration occurs from the surficial unit of the Rock River Valley aquifer (model layer 1). The model simulates evapotranspiration from the saturated zone only. The initial maximum ground-water evapotranspiration rate specified in the model was 30.8 in./yr, which corresponds to the estimated average annual lake-evaporation rate in the model area. The ground-water evapotranspiration rate in the model decreases linearly with depth below land surface and becomes zero at the extinction depth. The extinction depth corresponds to a depth below land surface minimally greater than the rooting depth of the plants present. The plausible range for evapotranspiration extinction depth was assumed to be from 5 to 10 ft with an average value of 7 ft. The altitude of the land surface for each cell was determined from USGS 7.5-minute-quadrangle topographic maps.

Ground-water is withdrawn by high-capacity water-supply wells from both the surficial and buried units of the Rock River Valley aquifer. Ground-water withdrawal rates for 1995 through 1997 were obtained from the records of the City of Luverne and the Rock County Rural Water District. The withdrawals are represented in the model by specified flux from model cells corresponding to the locations and screened aquifer units (surficial or buried) of the wells. Annual average ground-water withdrawals from the surficial unit (model layer 1) of the aquifer were 2.02 ft^3/s and from the buried unit (model layer 3) were 1.13 ft^3/s for the steady-state simulation.

The initial and final calibrated values of hydraulic properties and fluxes represented in the model are listed in table 4, at the back of the report. Initial values for hydraulic conductivity for each hydrogeologic unit were based on slug tests and single-well recovery aquifer tests done for this study and published values in the literature. The initial value for areal recharge was 6.0 in./yr, the average rate for 1995 and 1996 estimated from hydrograph analysis. The ground-water evapotranspiration rate and extinction depth were derived as explained previously in this report.

Numerical Model Calibration

Model calibration is the process in which initial estimates of aquifer properties and boundary conditions are adjusted until simulated hydraulic heads and flows acceptably match measured water levels and flows. For this study, aquifer properties were adjusted to produce an acceptable match between the simulated stream-aquifer leakage between the Rock River and the Rock River Valley aquifer and that estimated from measured streamflows during October 1997. Calibration and evaluation of the ground-water-flow model were conducted for steady-state (equilibrium) conditions and for transient conditions. No storage terms are included in the steady-state simulation. Transient simulations incorporate the storage property of the aquifer and are time dependent. Changes in storage in the aquifer occur when the amount of water entering the aquifer and the amount of water leaving the aquifer are not equal.

Steady-State Simulation

Water levels in 43 observation wells during October 1996 and streamflows at 20 sites during October 1997 were used to calibrate the model under steady-state conditions. The model was calibrated by varying the simulated values of (1) hydraulic properties of the aquifer system (K and K_v), (2) areal recharge to the surficial unit of the Rock River Valley aquifer, (3) ground-water evapotranspiration rate and extinction depth, and (4) K_s values. The final calibrated values are listed in table 4, at the back of the report. The match between measured and simulated hydraulic heads and stream-aquifer leakage was improved by (1) reducing K for the main body of the surficial and buried units of the aquifer to 100 ft/d and for the margins to 50 ft/d (figs. 7a and 7c), (2) decreasing the K of the buried unit of the aquifer in the vicinity of the Luverne Airport well field to 350 ft/d (fig. 7c), (3) increasing the K of the confining unit between the surficial and buried units of the aquifer to 1.5 ft/d (fig. 7b) and the K_v to 0.15 ft/d, (4) increasing the areal recharge rate to the surficial unit of the aquifer to 7.0 in./yr, and (5) decreasing the ground-water evapotranspiration extinction depth to 5.0 ft. The value of 30 ft/d for K_s of the Rock River streambed, although higher than commonly published values for K_s of streams in glacial terrain, provided the best match between estimated and simulated stream-aquifer leakage. The above changes are considered acceptable because they are all within ranges of values measured for this study or reported by previous studies.

The best-match simulated hydraulic heads were within 2 ft of measured water levels at all but four of the 43 wells for which water-level data were available. The largest difference between measured and simulated hydraulic heads was 3.7 ft. The difference ranged from 2.1 to 2.3 ft at three other observation wells and was less than 2.0 ft at the rest of the wells. The difference was less than 1.0 ft at 23 of the 43 wells. The mean absolute difference between simulated and measured hydraulic heads, computed as the sum of the absolute values of the differences divided by the number of wells, for the 43 wells is 1.02 ft. The mean algebraic difference between simulated and measured hydraulic heads, computed as the algebraic sum of the differences divided by the number of wells, is -0.09 ft, indicating the positive differences were approximately balanced by the negative differences.

Comparison of measured streamflows in the Rock River during October 1997 and estimated stream-aquifer leakage and simulated streamflows and stream-aquifer leakage was also used to evaluate how well the model simulates the stream-aquifer system. Accuracy of stream-discharge measurements is plus or minus 5 percent. Estimates of stream-aquifer leakage are likely less than the measurement error for the reach between SW3 and SW21, the reach between SW24 and SW20, and the reach between SW20 and SW12 (table 5, at the back of the report). The model generally duplicated the correct magnitude and direction of stream-aquifer leakage, except for the reaches between SW3 and SW21, and between SW19 and SW24. However, two of the three sets of streamflow measurements conducted for this study indicated net losses of streamflow (gain to the aquifer) of 4.10 ft^3/s and 0.60 ft^3/s for the reach from SW19 to SW20; a streamflow measurement was not done at SW24 for the other two sets of measurements. The model simulation results indicated a net loss of streamflow of 0.5 ft^3/s for the reach between SW19 and SW20, which is consistent with two of the three sets of streamflow measurements for this reach (table 3, at the back of the report).

A water budget is an accounting of inflow to, outflow from, and storage change in the aquifer. For steady state, inflow (sources) to the aquifer equals outflow (discharges) from the aquifer (fig. 8, table 6, at the back of the report). Areal recharge accounts for 38 percent of the sources of water to the Rock River Valley aquifer and leakage from the streams to the aquifer contributes 58.7 percent. The remaining 3.3 percent comes from inflow through sand and gravel deposits adjacent to the model area (into general-head boundaries). Approximately 67 percent of the inflow through these adjacent sand and gravel deposits occurs through the west-central boundary. The remainder occurs through the adjacent sand and gravel deposits

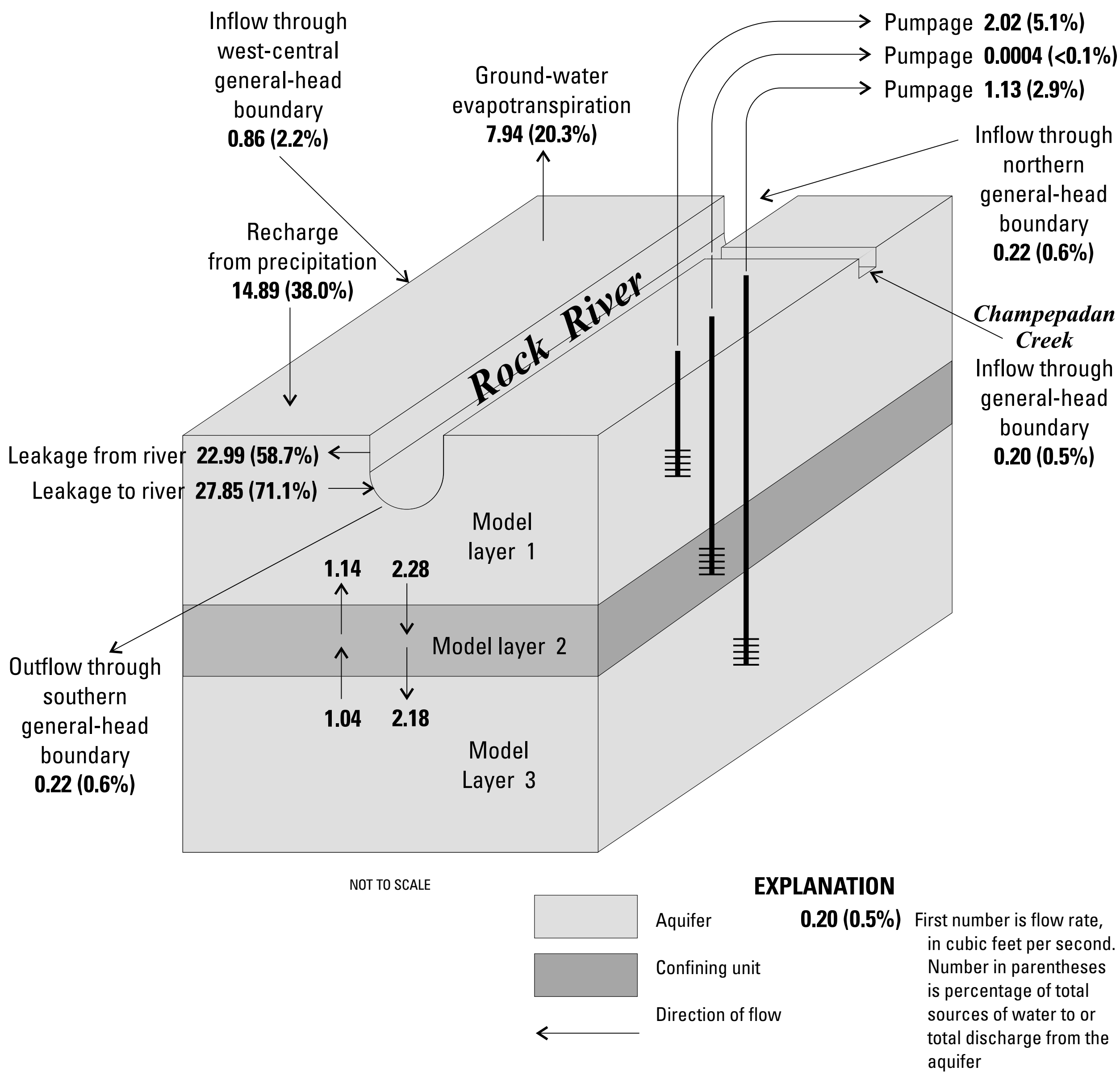


Figure 8. Simulated water budget for steady-state simulation, eastern Rock County, Minnesota

near Champepadan Creek and the northern model boundary. The largest discharge from the aquifer is leakage from the aquifer to streams, 71.1 percent. The other discharges from the aquifer are ground-water evapotranspiration (20.3 percent), withdrawals by wells (8 percent), and outflow through sand and gravel deposits adjacent to the model area (out of general-head boundaries) (0.6 percent). All outflow through adjacent sand and gravel deposits occurs across the southern model boundary. The net stream-aquifer leakage is approximately 5 ft^3/s from the aquifer to the streams, indicating that the Rock River is a gaining stream overall in the model area. The net discharge from the aquifer to the streams of 4.86 ft^3/s represents approximately 33 percent of the areal recharge.

Water flows vertically through the confining unit (model layer 2) in both downward and upward directions. The model simulation indicates a net flow downward of 1.14 ft^3/s from the surficial unit of the Rock River Valley aquifer (model layer 1), to the buried unit of the aquifer and adjacent clay and till (model layer 3), through the confining unit (model layer 2) (table 6, at the back of the report). The simulation also indicates a flow of 1.04 ft^3/s upward from layer 3 to layer 1 through layer 2. Approximately 0.1 ft^3/s of water flows downward from layer 1 to layer 2 and subsequently returns through flow upward from layer 2 to layer 1. Approximately 36 percent of flow downward from the surficial to the buried unit of the aquifer occurs in the area encompassing the Luverne Airport well field, and only approximately 3.5 percent in the vicinity of the Luverne Municipal well field. Approximately 14 percent of upward flow occurs in the area encompassing the Luverne Municipal well field and approximately 9 percent in the area encompassing the Luverne Airport well field.

The solution to the steady-state calibration simulation discussed in this report is considered to be reasonable because (1) K values of the aquifer are known within a relatively small range of values and (2) reasonable estimates of the major discharges from the aquifer in the study area—ground-water discharge to the Rock River and ground-water withdrawals by wells—are available. Also, the simulation results generally duplicated the correct magnitude and direction of leakage between the Rock River and the aquifer.

The simulated contributing areas for the wells in the Luverne Municipal well field, which are all screened in the surficial unit of the Rock River Valley aquifer, extend to the aquifer boundaries on the west and to the north approximately one mile from well LUV26 (fig. 9a). The simulated contributing areas for the wells are generally truncated at the Rock River, which is a strong internal source of water at the well field where the wells are near the river. The simulated contributing area for well LUV25 extends to the east beyond the Rock River and for well LUV2 extends to the west beyond the river, however, indicating that the wells are capturing water moving vertically upward from model layers 2 and 3 in the vicinity of the river. From an inspection of the simulated contributing areas, it is evident that the size and shape of the contributing areas of some wells are altered by the effect of ground-water withdrawals from the other wells. For example, the particle-tracking path lines for wells LUV21, LUV22, and LUV25 are in close proximity and their contributing areas probably overlap. The MODPATH results indicated that simulated travel times of water particles from the aquifer boundary west of the well field to wells located near the river is about 10 years. Simulated travel times of water particles reaching well LUV26 from farthest north are about 30 years and to well LUV25 from farthest east of the Rock River are 50 to 60 years.

It is important in the interpretation of the simulated contributing areas to note that the model results represent steady-state conditions. Therefore, all stresses on the aquifer system, including pumping rates, stream-aquifer leakage, and areal recharge, are simulated as constant in time. Real pumping rates and aquifer recharge and discharge vary seasonally, however, thus altering the contributing areas of a well. Also, the simulated contributing areas differ under steady-state conditions with different pumping rates and precipitation regimes (figs. 10a–10d), as will be discussed later in the report. Therefore, for the above reasons and due to the effects of ground-water withdrawals from nearby wells, it may be prudent to consider the contributing area for the entire well field rather than for individual wells.

The simulated contributing areas for the wells in the Luverne Airport well field extend to the western boundary of the aquifer (fig. 9b). The wells at the Luverne Airport well field are screened in the buried unit of the Rock River Valley aquifer and the simulated contributing areas to the wells include water contributed from both the surficial and buried units of the aquifer. The physical limits of the surficial unit of the aquifer (model layer 1, fig. 7a), extend farther west than the physical limits of the buried unit of the aquifer (model layer 3, areas with K > 1.0 ft/d, fig. 7c). Therefore, the simulated contributing areas to the wells in model layer 1 extend farther west than do the contributing areas in model layer 3. The MODPATH results indicated that simulated travel times of water particles from the western aquifer boundary to the wells are about 10 years for the two southern wells and about 15 to 20 years for the two northern wells.

The simulated contributing areas for the wells in the Rock County Rural Water well field extend from the Rock River to the western boundary of the aquifer (fig. 9c). As for the Luverne Municipal well field, the size and shape of contributing areas of some wells are altered by ground-water withdrawals from the other wells. The only wells with contributing areas unaffected by the other wells are probably the northernmost (RW6) and southernmost (RW4) wells. The simulated contributing areas for well RW3 and well RW6 are limited to the area near the Rock River because flow paths near the wells are nearly north to south, or east to west due to induced infiltration, and intersect the river. The contributing area for well RW1 is restricted by the presence of pumped well RW5 to the northwest. The simulated travel times of water particles from the western aquifer boundary to the wells are about 25 to 30 years.

Transient Simulation

The model was calibrated under transient conditions using seasonally variable ground-water withdrawals, areal recharge and ground-water evapotranspiration rates, and stream stages and streamflows and the resulting fluctuations in potentiometric surfaces during December 1994 through November 1997. Reported monthly ground-water withdrawals by high-capacity wells within the model area were compiled and used in the transient simulation. Hydraulic conductivity values for the hydrogeologic units were the same as for the steady-state simulation. The initial values of specific yield for the surficial unit of the Rock River Valley aquifer were 0.15 and 0.10 based on aquifer tests previously conducted in the study area (table 4, at the back of the report). The initial storage coefficients specified for the buried unit of the aquifer were 0.05, 0.01, and 0.005, based on a multi-well aquifer test conducted for this study and aquifer tests previously conducted in the study area. The initial value of storage coefficient assigned to the confining unit (model layer 2) was 0.00001, somewhat lower than the lowest value for a confined aquifer.

To simulate transient conditions during December 1994 through November 1997, five stress periods were specified each year. The stress periods specified were winter (December-February), spring (March-April), early summer (May-June), late summer (July-September), and fall (October-November). Simulated ground-water withdrawals during 1996 for the specified stress periods ranged from 2.85 ft^3/s for spring to 3.18 ft^3/s for late summer. The withdrawal rates for each stress period during 1995 and 1997 were similar to the 1996 rates. The starting heads used in the transient simulation were the simulated hydraulic heads from the calibrated best-fit steady-state simulation.

Initial values of seasonal areal recharge to the surficial unit of the Rock River Valley aquifer were derived from the steady-state simulation areal recharge rate and monthly precipitation reported at Luverne. The initial values for areal recharge rates for each stress period are shown in table 7, at the back of the report, and were calculated as follows:

A x B x C = areal recharge rate (in./yr)

where

A = steady-state simulation areal recharge rate ÷ 30-year (1961–90) normal annual precipitation (1/yr)

B = actual precipitation during stress period (in.)

C = number of days in year ÷ number of days in stress period

Ground-water evapotranspiration rates also vary seasonally. Reported monthly pan-evaporation rates at Sioux Falls, South Dakota, during 1995–97 ranged from zero for January, February, March, April, October, November, and December to a maximum of 9.23 in. during July 1995. The initial values for maximum ground-water evapotranspiration rates used for each stress period in the transient simulation (table 7, at the back of the report) were estimated from the following relation:

D x E x C = maximum ground-water evapotranspiration rate (in./yr)

where

D = steady-state maximum ground-water evapotranspiration rate ÷ average annual pan evaporation (1/yr)

E = actual pan evaporation during stress period (in.)

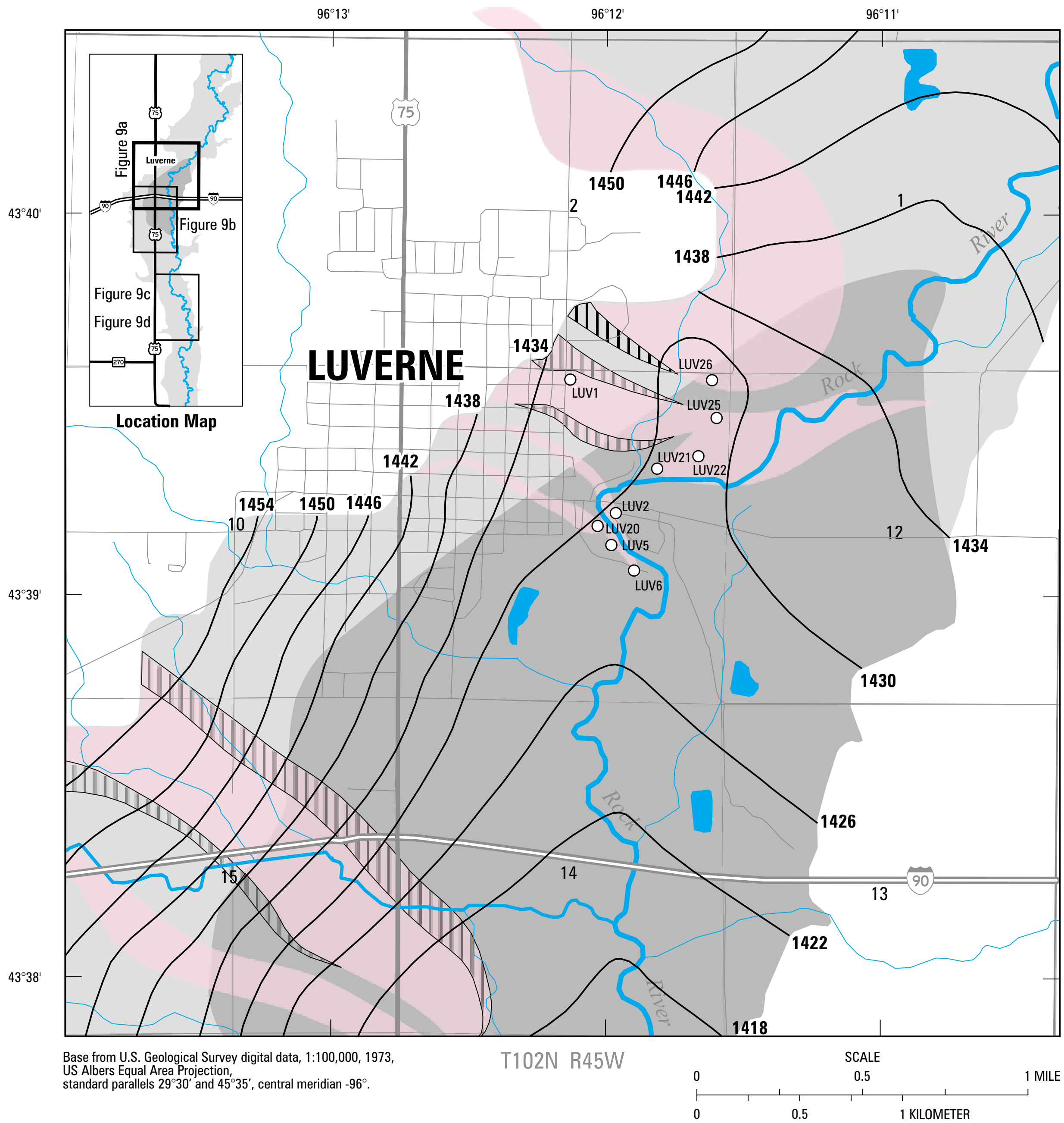
C = number of days in year ÷ number of days in stress period

In addition to areal recharge and ground-water evapotranspiration, seasonal variations in general-head boundary hydraulic heads, stream stages, and streamflows were simulated. The seasonal variations in general-head boundary hydraulic heads were derived from the hydraulic heads measured in the same observation wells used for the steady-state simulation. Seasonal variations in stream stages were derived from monthly stage measurements at 13 stream sites during the study.

Seasonal variations in streamflows were derived from the continuous-record streamflow data for the Rock River at Luverne. Regression relations between measured streamflow at Luverne and measured streamflows at six other sites were used to estimate seasonal variations in streamflows for use in the streamflow-routing package for the transient simulation. Streamflows were estimated for each stress period for gaging sites at SW3 (Rock River, fig. 2a), SW4 (Champepadan Creek), SW5 (Mound Creek), SW9 (Elk Creek), SW11 (Ash Creek), and SW28 (sewage ponds drainage near Luverne).

The model was calibrated to transient conditions by adjusting specific yield and storage coefficient values and stress-period areal recharge and ground-water evapotranspiration rates until the simulated stress-period hydraulic heads and streamflows in the Rock River acceptably matched seasonal measured water levels in wells and streamflows at Luverne during December 1994 through November 1997. Monthly water-level measurements were available for 17 observation wells in the model area beginning in spring 1995 (two of these were unused Luverne supply wells LUV13 and LUV19) and for another 16 observation wells by fall 1995. An additional 10 observation wells were installed by late summer 1996. Initial simulated areal recharge to the surficial unit of the Rock River Valley aquifer varied by stress period and ranged from 0.69 to 14.36 in./yr (table 7, at the back of the report). The match between simulated hydraulic heads and flows and measured water levels and flows was improved by (1) lowering the specific yield for the main body of the surficial unit of the aquifer to 0.10 (table 4, at the back of the report), (2) revising the stress-period areal recharge rates (table 7, at the back of the report), and (3) revising the stress-period ground-water evapotranspiration rates (table 7, at the back of the report). The changed value for specific yield is within the range of commonly reported values for unconfined aquifers (table 4, at the back of the report).

The initial values for stress-period areal recharge rates were revised because the initial precipitation conceptualization from which they were derived failed to account adequately for spring snowmelt and seasonal ground-water evapotranspiration rates. The initial values were revised to better simulate the seasonal high water levels resulting from spring snowmelt and



EXPLANATION

Area of aquifer

Area where buried unit of aquifer is present

Contributing area of ground-water flow to pumping well

Reduction in the contributing area due to anticipated increased pumping

Expansion in the contributing area due to anticipated increased pumping

1426 — Simulated potentiometric contour. For simulation with anticipated increased pumping and normal precipitation. Interval 4 feet. Datum is sea level

LUV6 ○ Supply well (with local site identifer)

Figure 9a. Simulated altitude of potentiometric surface, anticipated increased pumping and normal precipitation, and contributing areas of ground-water flow to pumped wells, present pumping and climatic conditions and anticipated increased pumping and normal precipitation, in the Luverne Municipal well field area, eastern Rock County, Minnesota.

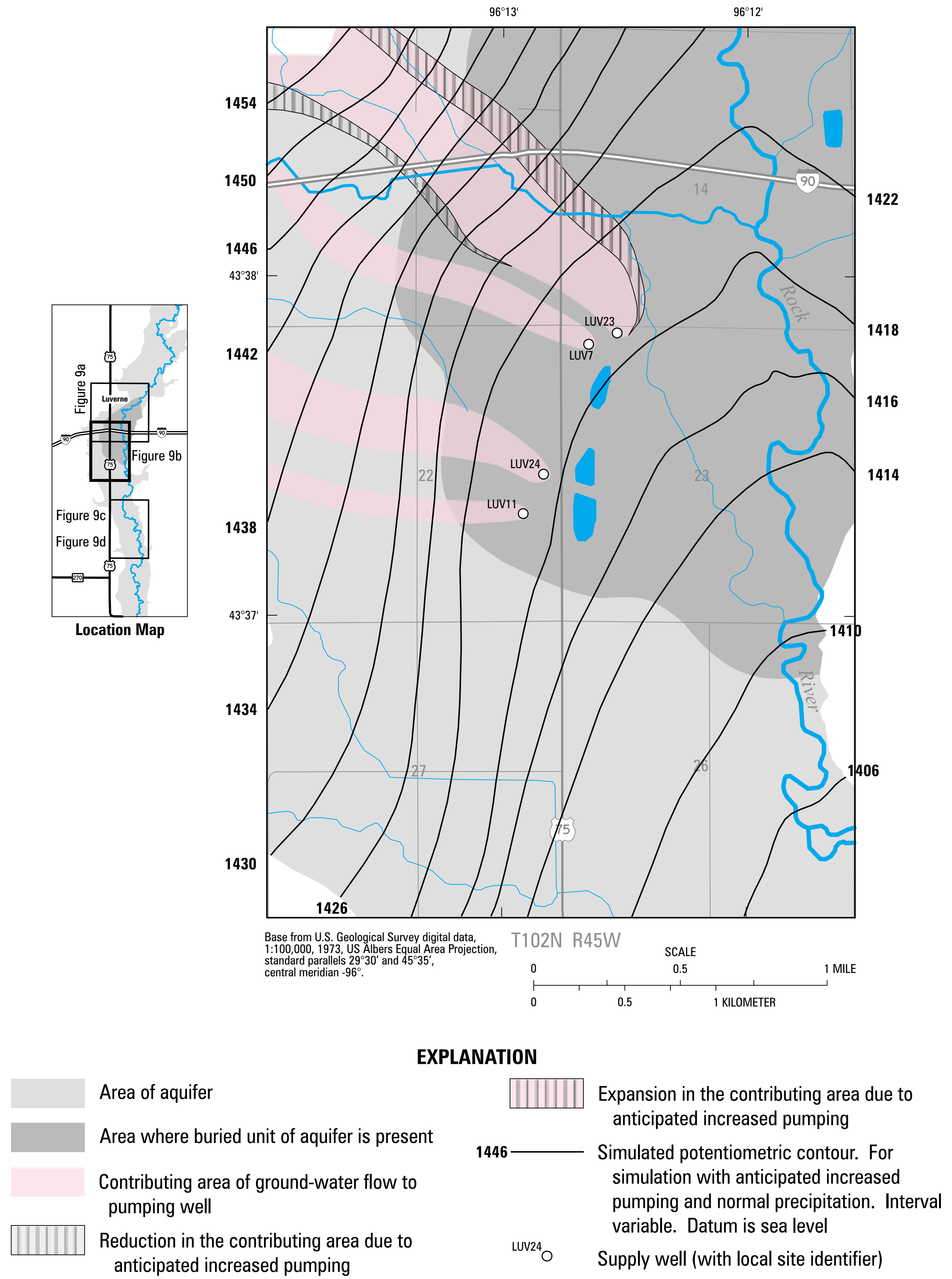
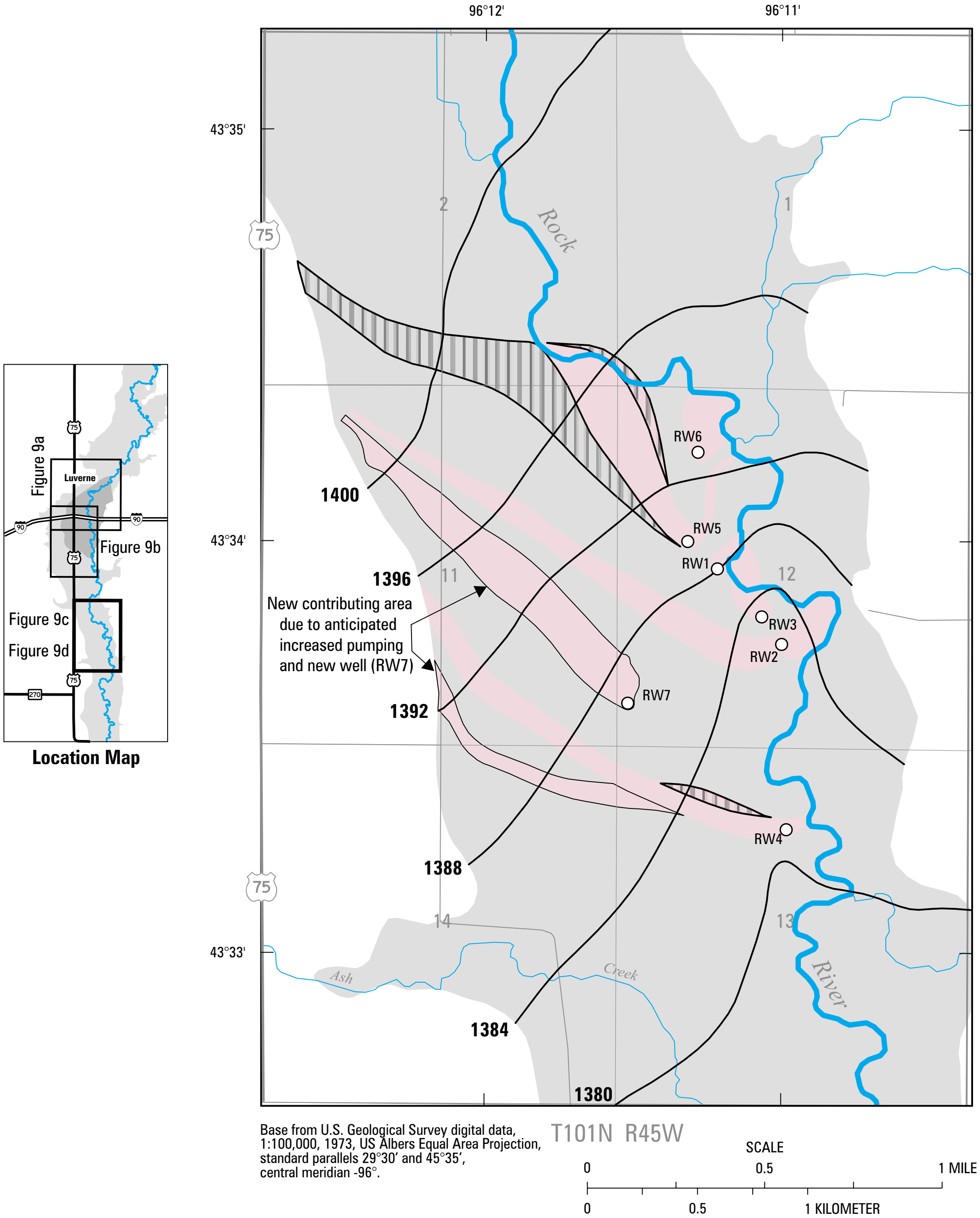


Figure 9b. Simulated altitude of potentiometric surface, anticipated increased pumping and normal precipitation, and contributing areas of ground-water flow to pumped wells, present pumping and climatic conditions and anticipated increased pumping and normal precipitation, in the Luverne Airport well field, eastern Rock County, Minnesota.



EXPLANATION

Area of aquifer

Contributing area of ground-water flow to pumping well

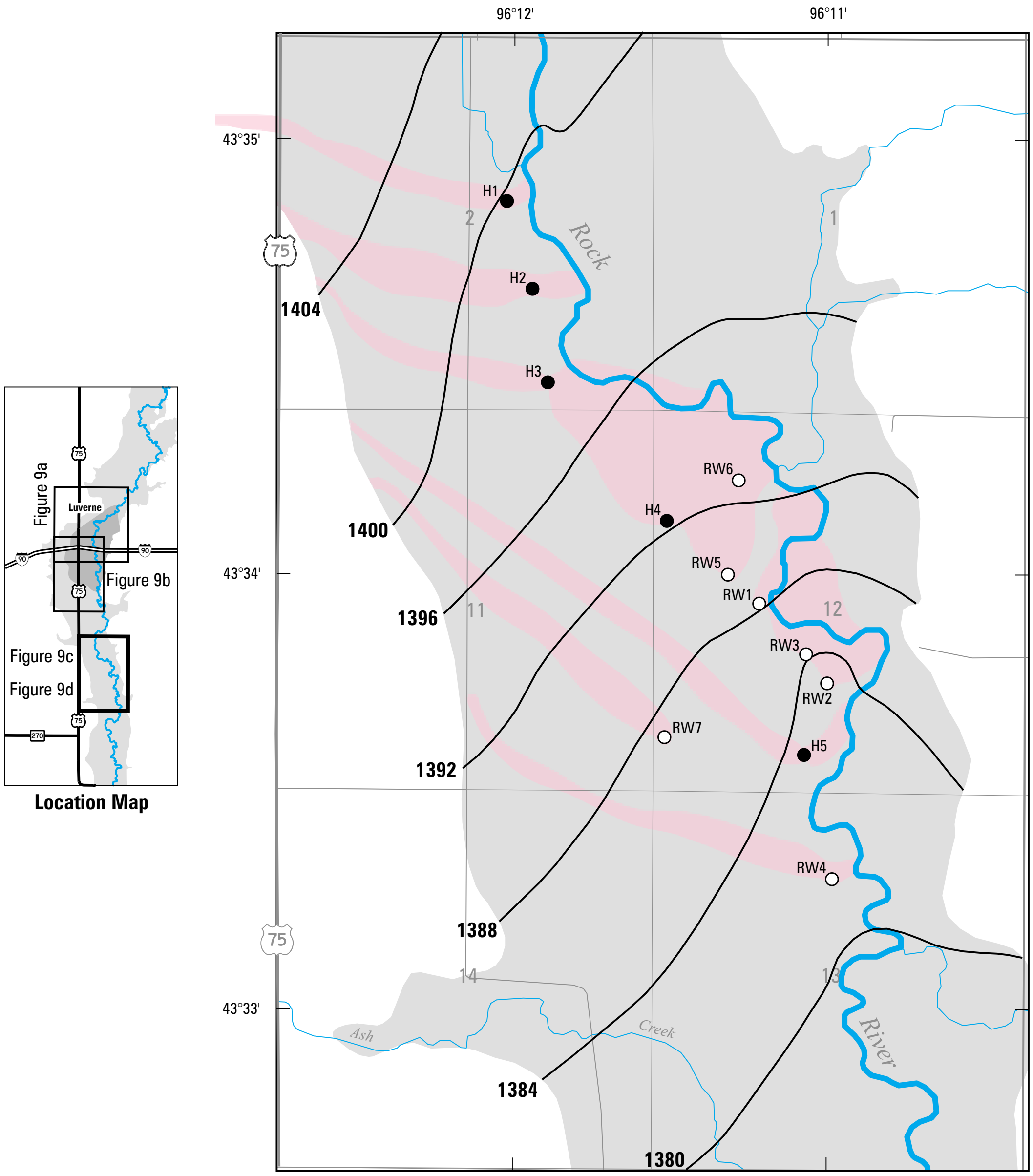
Reduction in the contributing area due to anticipated increased pumping

Expansion in the contributing area due to anticipated increased pumping

1396 Simulated potentiometric contour. For simulation with anticipated increased pumping and normal precipitation. Interval 4 feet. Datum is sea level

RW6 Supply well (with local site identifier)

Figure 9c. Simulated altitude of potentiometric surface, anticipated increased pumping and normal precipitation, and contributing areas of ground-water flow to pumped wells, present pumping and climatic conditions and anticipated increased pumping and normal precipitation, in the Rock County Rural Water well field area with 7 pumped wells, eastern Rock County, Minnesota.



Base from U.S. Geological Survey digital data, 1:100,000, 1973, US Albers Equal Area Projection, standard parallels 29°30′ and 45°35′, central meridian -96°.

T101N R45W

SCALE

0 0.5 1 MILE

0 0.5 1 KILOMETER

EXPLANATION

Area of aquifer

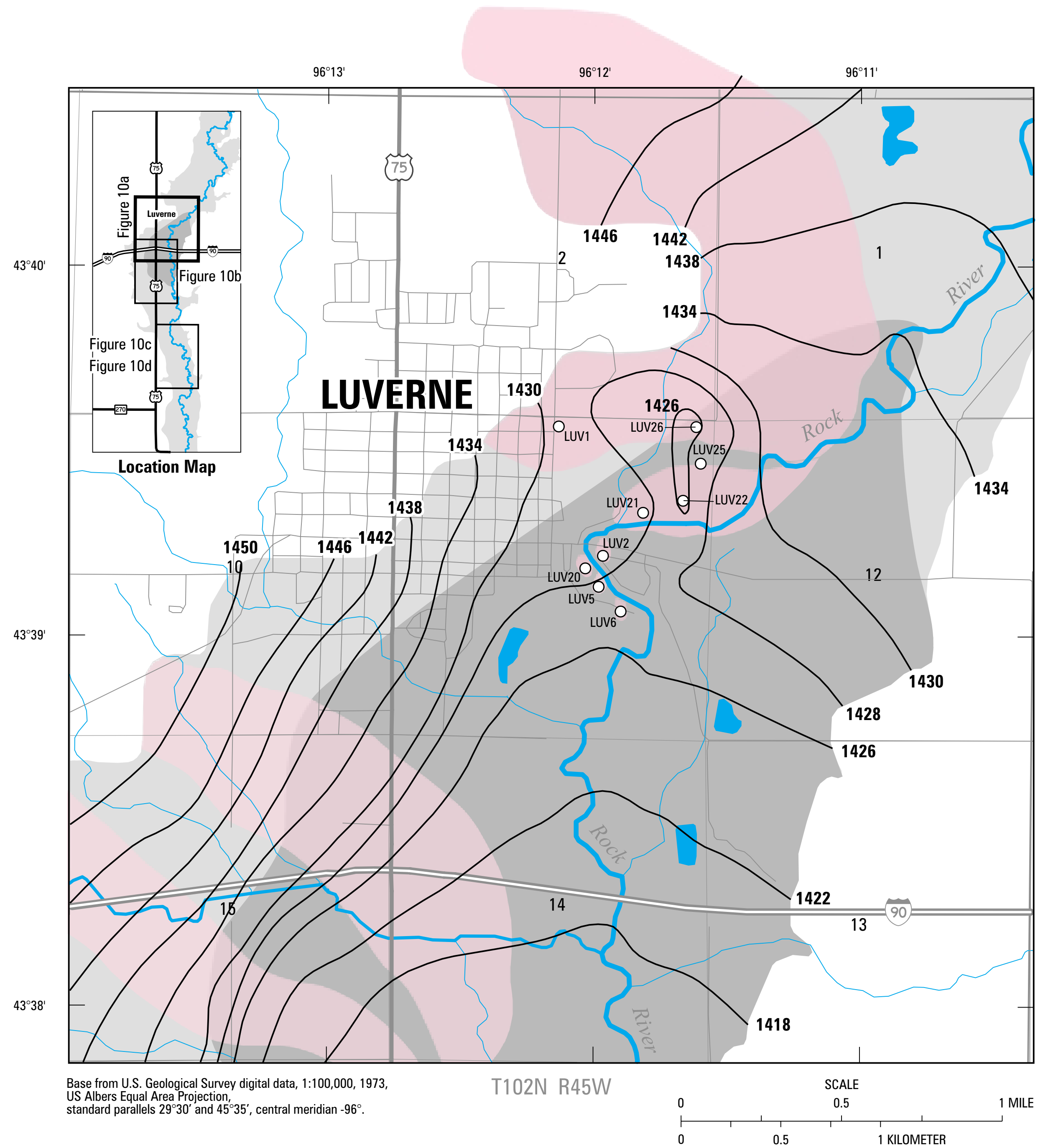
Contributing area of ground-water flow to pumping well

1396 Simulated potentiometric contour. For simulation with anticipated increased pumping and normal precipitation. Interval 4 feet. Datum is sea level

RW7 Supply well (with local site identifier)

H3 Hypothetical well (with local site identifier)

Figure 9d. Simulated altitude of potentiometric surface and contributing areas of ground-water flow to pumped wells, anticipated increased pumping and normal precipitation, in the Rock County Rural Water well field area with 12 pumped wells, eastern Rock County, Minnesota.



EXPLANATION

Area of aquifer

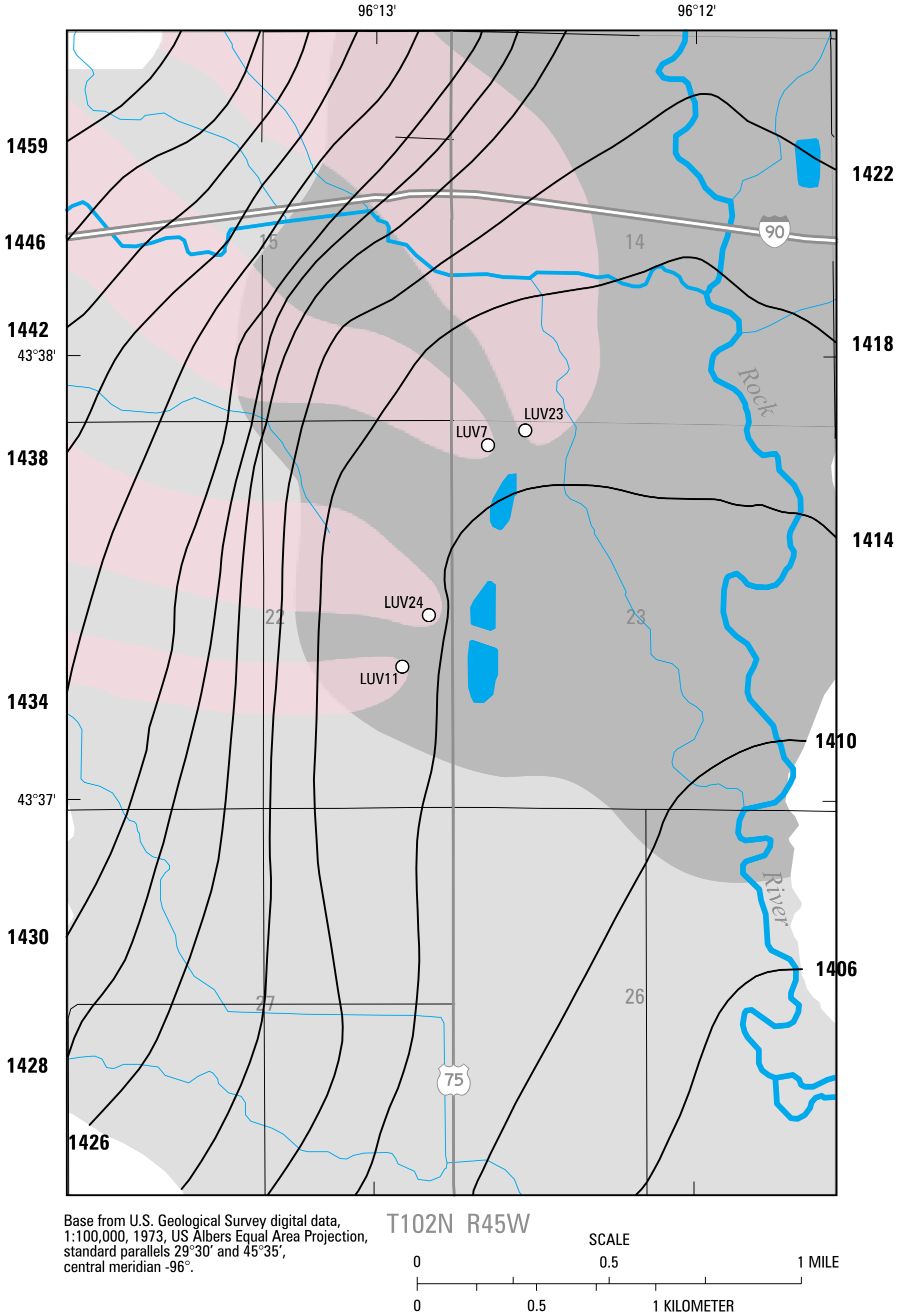
Area where buried unit of aquifer is present

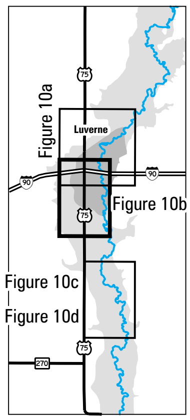
Contributing area of ground-water flow to pumping well

1426 — Simulated potentiometric contour. For simulation with anticipated increased pumping and drought conditions. Interval variable. Datum is sea level

LUV26 ○ Supply well (with local site identifier)

Figure 10a. Simulated altitude of potentiometric surface and contributing areas of ground-water flow to pumped wells, anticipated increased pumping and drought conditions, in the Luverne Municipal well field area, eastern Rock County, Minnesota.





Location Map

EXPLANATION

Area of aquifer

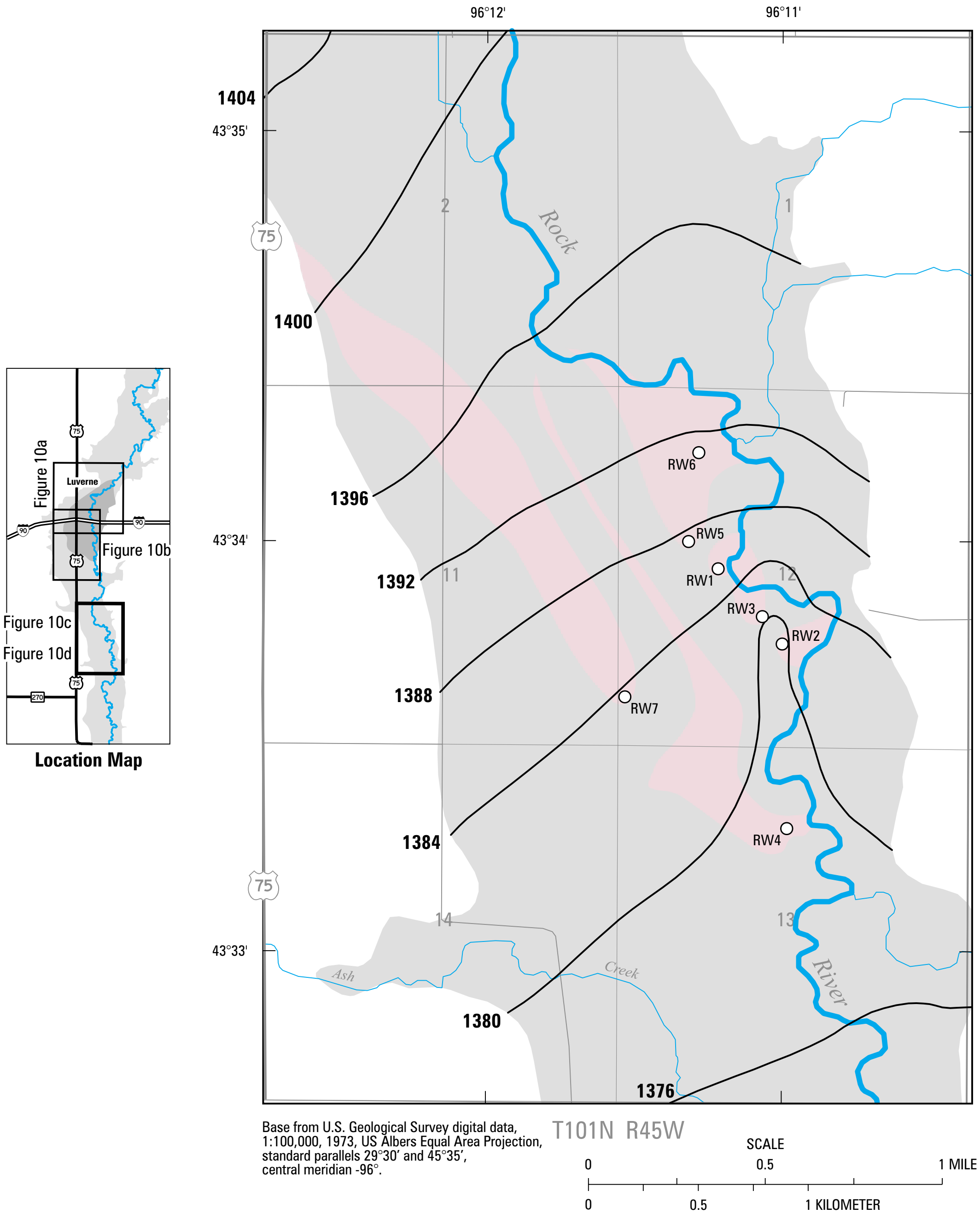
Area where buried unit of aquifer is present

Contributing area of ground-water flow to pumping well

1426 —— Simulated potentiometric contour. For simulation with anticipated increased pumping and drought conditions. Interval variable. Datum is sea level

LUV11 ○ Supply well (with local site identifier)

Figure 10b. Simulated altitude of potentiometric surface and contributing areas of ground-water flow to pumped wells, anticipated increased pumping and drought conditions, in the Luverne Airport well field area, eastern Rock County, Minnesota.



EXPLANATION

Area of aquifer

Contributing area of ground-water flow to pumping well

1384 —— Simulated potentiometric contour. For simulation with anticipated increased pumping and drought conditions. Interval 4 feet. Datum is sea level

RW3 ○ Supply well (with local site identifier)

Figure 10c. Simulated altitude of potentiometric surface and contributing areas of ground-water flow to pumped wells, anticipated increased pumping and drought conditions, in the Rock County Rural Water well field area with 7 pumped wells, eastern Rock County, Minnesota.

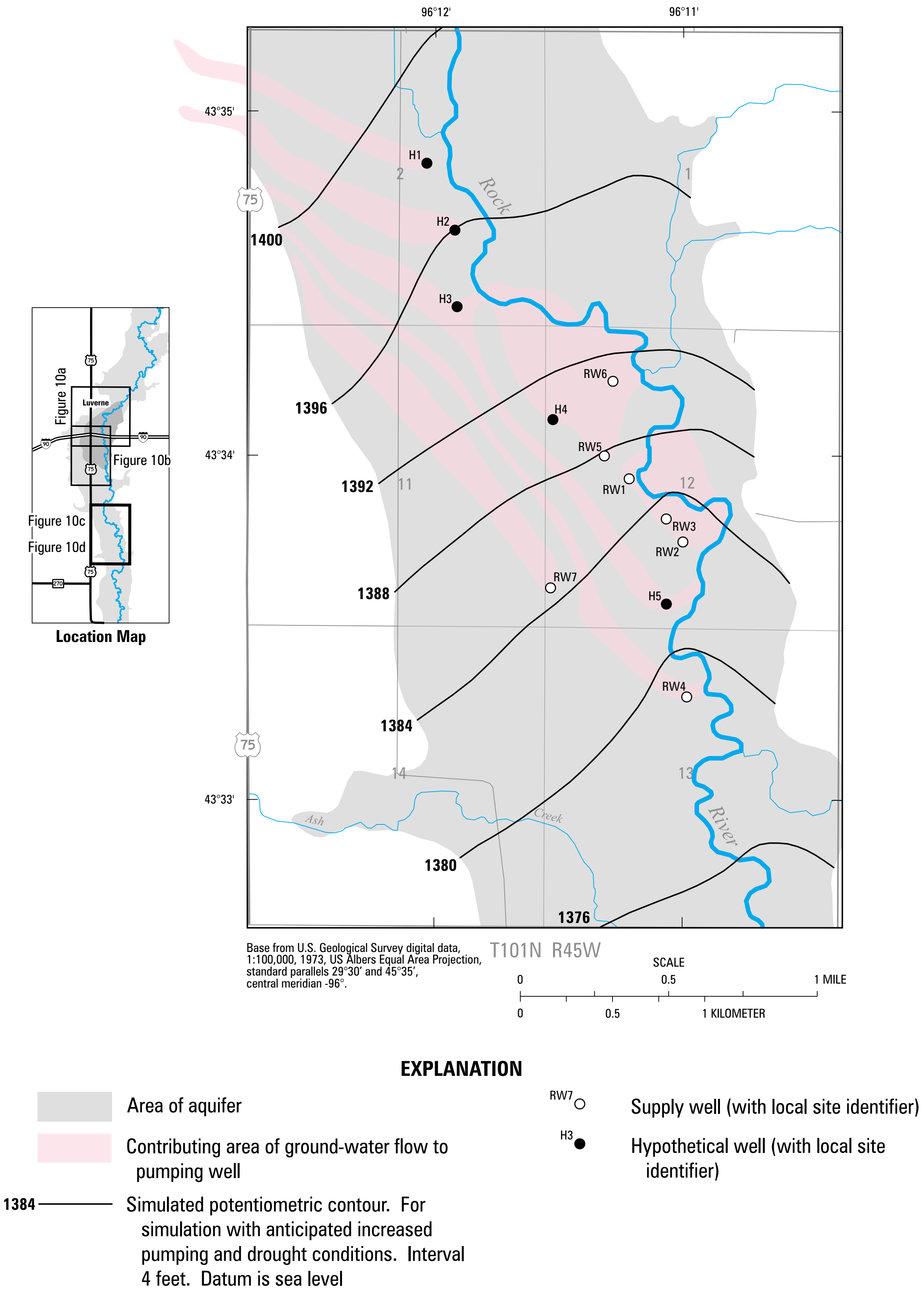


Figure 10d. Simulated altitude of potentiometric surface and contributing areas of ground-water flow to pumped wells, anticipated increased pumping and drought conditions, in the Rock County Rural Water well field area with 12 pumped wells, eastern Rock County, Minnesota.

precipitation observed in most of the hydrographs for the observation wells in the model area. The spring stress period (1995 and 1997) or early summer stress period (1996) areal recharge rate for each year was calculated as the product of 3 ft (the average seasonal water level rise in observation wells) and a specific yield of 0.15. Fall period areal recharge rates were maintained as initially calculated except for fall 1996, which was reduced by 3.2 in./yr. Winter and late summer stress-period areal recharge rates were changed to zero to reflect no net areal recharge to ground water, as indicated by most hydrographs. The revised areal recharge rates (table 7, at the back of the report), in conjunction with a lower specific yield for the surficial unit of the Rock River Valley aquifer, resulted in an improved match between measured and simulated hydraulic heads, particularly during the spring and early summer stress periods. The revised seasonal areal recharge rates, when adjusted to a cumulative annual rate, are within the range of annual recharge rates estimated from the method of hydrograph analysis.

The initial values for stress period maximum ground-water evapotranspiration rates were also revised (table 7, at the back of the report), based on seasonal ratios of evapotranspiration to pan evaporation published by the Southwest Agricultural Experiment Station, University of Minnesota, in southwestern Minnesota (Baker and others, 1979). The seasonal ratios incorporate (1) differences between the pan and soil and plants, and how much solar energy they absorb and (2) variations in available soil water. The ratio varies from about 0.15 in the spring and fall to about 0.90 in July and provides a more accurate estimate of seasonal ground-water evapotranspiration rates than pan-evaporation rates alone. The revised maximum ground-water evapotranspiration rates were calculated as the reported pan-evaporation rate at Sioux Falls, South Dakota, during a stress period, multiplied by 0.3 for the early summer stress periods or multiplied by 0.8 for the late summer stress periods. The revised maximum ground-water evapotranspiration rates resulted in an improved match between measured and simulated hydraulic heads, particularly during the late summer stress period.

The transient simulation for December 1994 through November 1997 acceptably reproduces measured seasonal fluctuations in hydraulic heads in the Rock River Valley aquifer (figs. 6a-6b). Both measured and simulated hydraulic heads and seasonal fluctuations in hydraulic heads near the Rock River are strongly influenced and controlled by stream stages and seasonal changes in stream stages. The differences between measured mean daily streamflows at Luverne and simulated streamflows are all less than or equal to 9 percent of the measured streamflows (table 8, at the back of the report). The simulated streamflows acceptably match the measured streamflows and no changes in hydrogeologic properties of the stream-aquifer system were considered necessary or justified to improve the match.

Model results indicate that there is a net gain to streamflow (net loss from the aquifer) for the model area as a whole for each stress period. There is a general correspondence between the magnitude of streamflow and the magnitude of streamflow gain. The exceptions to this relation occur during the stress periods when areal recharge to the aquifer is simulated—spring 1995 and 1997, early summer 1996, and fall 1995, 1996, and 1997. The largest net gains in streamflow occur during the spring stress periods in 1995 and 1997 and the fall stress periods in 1996 and 1997. Of these 4 stress periods, the only one with a large streamflow is the spring stress period for 1997. This result indicates that the magnitude of simulated gains in streamflow are strongly affected by areal recharge to the aquifer.

Table 4, at the back of the report, gives the values for the hydraulic properties of the hydrogeologic units resulting in the best fit between measured and simulated hydraulic heads for the transient simulation. The values given represent the best estimates for the hydraulic properties of the hydrogeologic units in the study area, based on hydraulic testing conducted for this study, reported values, and the results of the model calibration. The ability of the transient simulation to approximate seasonal fluctuations in hydraulic heads and streamflow during December 1994 through November 1997 indicates that the simulation reasonably represents hydraulic properties of the hydrogeologic units and flows in the stream-aquifer system during the calibration period (tables 4 and 6, at the back of the report). The specified boundary conditions are considered appropriate and areal recharge to the aquifer is within a reasonable expected range. Ground-water withdrawals are known and simulated streamflows in the Rock River at Luverne reasonably match measured values. Estimates of flows in the stream-aquifer system would change with changes in stresses on the system (areal recharge, ground-water evapotranspiration, and ground-water withdrawals) and (or) boundary conditions.

The simulated transient water budget for 1996 is shown in table 6, at the back of the report. Principal sources of water to the Rock River Valley aquifer were as follows: (1) winter, spring, and late summer stress periods—leakage from streams to the aquifer and water released from storage and (2) early summer and fall stress periods—areal recharge and leakage from streams to the aquifer. Areal recharge dominates the water budget during the early summer and fall stress periods, constituting 87.7 and 74.1 percent of the sources of water for these stress periods, respectively. The amount and percentage of water released from storage is greatest during the late summer stress period because no areal recharge occurs to the aquifer and the effects of ground-water withdrawals and ground-water evapotranspiration are greatest during this stress period. The water released from storage is derived predominantly from the surficial unit of the aquifer (model layer 1) (83.4 percent). Only 12 percent of the water released from storage is derived from the buried unit of the aquifer (model layer 3). During stress periods with areal recharge, a greater proportion of the water pumped by wells is derived from the available areal recharge and less release of water from storage is required.

The principle discharges from the Rock River Valley aquifer are: (1) winter and spring stress periods—leakage from the aquifer to streams and ground-water withdrawals, (2) early summer stress period—addition to storage, leakage from the aquifer to streams, and ground-water evapotranspiration, (3) late summer stress period—leakage from the aquifer to streams and ground-water evapotranspiration, and (4) fall stress period—leakage from the aquifer to streams and addition to storage (table 6, at the back of the report). Ground-water withdrawals are a substantial part of the budget during the winter and spring stress periods because the other budget discharge components, other than leakage from the aquifer to streams, are very small. Areal recharge is greater than the sum of the discharges from the aquifer during the early summer and fall stress periods. A portion of the areal recharge is therefore returned to storage in the aquifer. The amount and percentage of addition to storage during the early summer and fall stress periods is much greater than during the other stress periods because areal recharge occurs during these stress periods. More than 80 percent of the addition to storage occurs in the surficial unit of the aquifer (model layer 1).

The net stream-aquifer leakage during each stress period in 1996 was from the Rock River Valley aquifer to the streams for the model area as a whole (table 6, at the back of the report). The net losses from the aquifer to streams during the winter, spring, and late summer stress periods are similar, but the losses during the early summer and fall stress periods are much greater than during the other stress periods. The stress periods with large losses from the aquifer to streams correspond with the stress periods when areal recharge occurs. The results indicate that the magnitude of simulated losses from the aquifer to streams is in direct relation to the amount of areal recharge.

Sensitivity Analysis

A model-sensitivity analysis, wherein a single hydraulic property or flux is varied while all other properties and fluxes are held constant, was done to identify the relative effect of adjustments of hydraulic properties and fluxes on simulated hydraulic heads and streamflows. The degree to which the properties and fluxes were varied was related to the uncertainty associated with each. Variations were kept within reported or plausible ranges of values.

Simulated hydraulic heads for the steady-state simulation were most sensitive to changes in (1) stream stage, (2) areal recharge, (3) ground-water evapotranspiration extinction depth, and (4) aquifer K values of layer 1 (table 9, at the back of the report). For model cells located near river cells, there was nearly an identical correspondence between changes in stream stage and changes in simulated hydraulic heads in the cells. Increasing the K_v values of the confining unit (layer 2) by a factor of 10 or varying K_s of the streams resulted in average changes in hydraulic heads of less than or equal to 0.10 ft.

A model-sensitivity analysis was done for the transient simulation using simulated hydraulic heads and streamflows at the end of the late summer and spring stress periods (table 10, at the back of the report). Simulated hydraulic heads were most sensitive to changes in (1) areal recharge, (2) aquifer specific yields and storage coefficients for layers 1 and 3, and (3) aquifer K values for layers 1 and 3. The changes in simulated hydraulic heads in response to changes in these three factors were greater during the spring stress period than during the late summer stress period because simulated areal recharge to the aquifer occurs during the spring, but not the late summer, stress period. Increasing the K_v values of the confining unit (layer 2) and K_s resulted in average changes in hydraulic heads of less than 0.1 ft.

Variations in stream stage or areal recharge had the greatest effect on simulated streamflows in the Rock River for the steady-state simulation (table 9, at the back of the report).

Variations in areal recharge and aquifer specific yields and storage coefficients for layers 1 and 3 had the greatest effect on simulated streamflows in the Rock River for the transient simulation (table 10, at the back of the report). Changes in simulated streamflows for the spring stress period were generally consistent with, but an order of magnitude greater than, the changes for the late summer stress period because the simulated streamflows for the spring stress period are an order of magnitude greater than for the late summer stress period.

Anticipated Increased Ground-Water Withdrawals

A series of model simulations was done to evaluate the response of the stream-aquifer system in the model area to an anticipated increase in ground-water withdrawals of as much as 0.26 ft^3/s (117 gal/min) from the Luverne well fields and 0.35 ft^3/s (157 gal/min) from the Rock County Rural Water well field. The simulations were done using the projected ground-water withdrawal rates under two different precipitation regimes; the 30-year (1961–90) average annual precipitation, hereinafter termed normal precipitation, and drought-condition precipitation.

The calibrated model was used to simulate the effects of anticipated increased ground-water withdrawals under both steady-state and transient conditions. Recharge-discharge relations change depending on the volume of ground-water withdrawals, location of pumping wells, and natural recharge to and discharge from the aquifer. Ground-water discharge to streams may be diverted to wells because of increased ground-water withdrawals. If ground-water withdrawals continue for a sufficiently long time and do not exceed potential increases in recharge to or potential decreases in discharge from the aquifer, new steady-state hydrologic conditions will occur, new recharge-discharge relations will be established, and the stream-aquifer system will approach a new equilibrium. Under transient conditions, the response of the system to ground-water withdrawals is also dependent on the storage characteristics of the aquifer.

The model simulations with anticipated increased ground-water withdrawals included four hypothetical scenarios for steady-state and transient conditions. The four steady-state simulations with hypothetical scenarios are termed SS1-SS4 (table 11, at the back of the report). The four transient simulations with the same hypothetical scenarios are termed TR1-TR4. The source of the additional water withdrawn due to the anticipated increased ground-water withdrawals under normal- and drought-condition precipitation is discussed in this section. The effects of the anticipated increased ground-water withdrawals on hydraulic heads and streamflow are discussed later in the report in the Effects of Ground-Water Withdrawals section.

Normal Precipitation

Model simulations were done to evaluate the response of hydraulic heads in the Rock River Valley aquifer and streamflow in the Rock River to a combination of increased ground-water withdrawals and normal precipitation. Normal precipitation and the corresponding areal recharge rate were used to represent average climate conditions in the study area.

Steady-state simulations

An 11.5 percent increase in ground-water withdrawals from the Luverne well fields was apportioned uniformly among the 13 municipal wells pumped during 1996. The total pumping rate simulated was 2.28 ft^3/s. A 40 percent increase in ground-water withdrawals for the Rock County Rural Water well field was simulated using two different scenarios. One scenario consisted of ground-water withdrawals from the six existing production wells simulated in the calibrated steady-state simulation and from one well that began pumping in October 1997. The second scenario consisted of ground-water withdrawals from the seven existing wells and from five wells that may be installed in the future (fig. 7a). The distribution of the ground-water withdrawals among the seven wells simulated in the first scenario was based on the distribution among wells during 1997. The distribution of the ground-water withdrawals among the 12 wells simulated in the second scenario was uniform. The total pumping rate simulated from the Rock County Rural Water well field was 1.24 ft^3/s, derived as the average of the pumping rates for 1996 and 1997 adjusted by the projected 40-percent increase in ground-water withdrawals.

The simulated areal recharge rate to the surficial unit of the Rock River Valley aquifer used in the steady-state simulations with increased ground-water withdrawals and normal precipitation was 6.8 in./yr. The areal recharge rate was calculated as the product of (1) the ratio between normal precipitation and precipitation during 1996 (year used to calibrate the steady-state simulation) and (2) the calibrated steady-state recharge rate (7.0 in./yr). An estimated normal precipitation areal recharge rate (6.8 in./yr) was used rather than the calibrated steady-state areal recharge rate (7.0 in./yr) because precipitation during 1996 (28.2 in.), and presumably areal recharge to the aquifer, was somewhat greater than normal (27.4 in.). Also, October 1996 precipitation was about 10 percent above normal. Therefore, a somewhat lower areal recharge rate was considered to better represent average (normal) precipitation conditions and to result in more conservative estimates of probable long-term, steady-state declines in hydraulic heads and changes in stream-aquifer leakage due to anticipated increased ground-water withdrawals. The hydraulic heads used at the general-head boundaries, stream stages and streamflows used in the calibrated steady-state simulation were used in the steady-state simulations with anticipated increased ground-water withdrawals and normal precipitation.

Model results indicate that the additional water withdrawn by the wells due to the anticipated increased ground-water withdrawals was derived from induced infiltration from the Rock River and interception of ground-water flow by the pumped wells. Virtually all of the decrease in net leakage of ground water from the aquifer to the streams occurs to the Rock River in the vicinity of the three well fields. The total ground-water withdrawals in simulations SS1 and SS2 increased by 0.6 ft^3/s, or approximately 20 percent. The net loss from the aquifer by leakage to streams decreased by about 0.7 ft^3/s due to the increased ground-water withdrawals (table 11, at the back of the report, SS1 and SS2). The decrease in net leakage includes both induced infiltration and interception of ground-water flow by pumped wells. The simulated areal recharge to the aquifer was reduced by 0.4 ft^3/s, due to the difference between the normal-precipitation recharge value (6.8 in./yr) and the calibrated steady-state simulation value (7.0 in./yr). Ground-water evapotranspiration decreased by 0.3 ft^3/s, with a net difference between areal recharge and ground-water evapotranspiration (net recharge), therefore, of 0.1 ft^3/s. The total losses to the aquifer for simulations SS1 and SS2 compared to the calibrated steady-state simulation are 0.7 ft^3/s, with 0.6 ft^3/s of the total loss due to increased ground-water withdrawals and 0.1 ft^3/s due to less net recharge. These losses are balanced by a decrease of 0.7 ft^3/s in net leakage of ground water from the aquifer to the streams.

Transient simulations

Transient simulations were made for a hypothetical period of 3 years using the same seasonal stress periods (five per year) as in the calibrated transient simulation. The simulated hydraulic heads at the end of the steady-state simulation were used as the initial hydraulic heads in the 3-year transient simulations. The anticipated increases in ground-water withdrawals from the well fields were apportioned uniformly among the supply wells. The stress-period pumping rates for each well in the Luverne and Rock County Rural Water well fields for 1996 from the calibrated transient simulation were increased by 11.5 percent and 40 percent, respectively. The new stress-period pumping rates were cycled three times for the 3-year transient simulations.

The stress-period areal recharge rates to the surficial unit of the Rock River Valley aquifer used in simulations TR1 and TR2 were similar to those used in the calibrated transient simulation. The rates used were 32.3 in./yr for spring, 4.0 in./yr for fall, and zero for the rest of the stress periods. The rate for spring is the same as that used in the calibrated transient simulation and the rate for fall is nearly the same as that for 1995 and 1997 in the calibrated transient simulation. The new stress-period areal recharge rates were cycled three times for the 3-year transient simulations. The hydraulic heads used at the general-head boundaries were the same as those used for 1996 in the calibrated transient simulation. The general-head boundary hydraulic heads, stream stages, and streamflows used for 1996 in the calibrated transient simulation were cycled three times in the 3-year transient simulations with increased ground-water withdrawals and normal precipitation.

Model results indicate that the additional water withdrawn due to the anticipated increased ground-water withdrawals was derived from induced infiltration from the Rock River and interception of ground-water flow by the pumped wells, as for the steady-state simulations (SS1 and SS2). The net losses from the aquifer by leakage to streams were less than those for the calibrated transient simulation for each stress period due to the increased ground-water withdrawals.

Drought Conditions

Model simulations were done to evaluate the response of hydraulic heads in the Rock River Valley aquifer and streamflow in the Rock River to a combination of increased ground-water withdrawals and drought conditions. The simulated increased ground-water withdrawals were the same as for the simulations with normal precipitation, and do not include increased ground-water withdrawals that may be due to drought conditions, such as increased watering of lawns. The drought conditions simulated were based on climatic conditions in the study area during 1976, the year with the lowest annual precipitation on record at Luverne. Simulated areal recharge was reduced by about 50 percent.

Steady-state simulations

The simulated areal recharge rate to the surficial unit of the Rock River Valley aquifer used in simulations SS3 and SS4 was 3.1 in./yr. The areal recharge rate was calculated as the product of (1) the ratio of precipitation during 1976 (12.1 in.) to precipitation during 1996 (28.2 in.) and (2) the calibrated steady-state areal recharge rate (7.0 in./yr).

In addition to decreasing areal recharge to the aquifer, the following changes were made to simulate drought conditions: (1) all stream stages were lowered by 1.5 ft in the Rock River, (2) streamflow entering the model area at the northern boundary was reduced by 93 percent to 1.5 ft^3/s, and (3) hydraulic heads at the west-central general-head boundary were lowered by 5 ft, based on very limited long-term hydraulic head information in or near the model area. The conditions simulated likely would be even more severe than those experienced during the 1976 drought, because during that drought the extreme stream stage and streamflow conditions were experienced for only a few months. Stream stages were lowered by 1.5 ft in the Rock River; whereas, the streambed altitudes were left unchanged, thereby simulating a depth of water in the river of 0.5 ft. Depth of water in the river during periods of drought is less than during periods of normal precipitation. The recorded low streamflow for the Rock River at SW3 (fig. 2a) was 2.0 ft^3/s in August 1976. The calibrated transient simulation indicated the river segment between the northern model boundary and SW3 is a gaining reach with a gain of about 0.5 ft^3/s at the lower end of a range of streamflows. Tributaries to the Rock River were simulated as dry by assigning zero streamflow for all tributaries.

As for simulations SS1 and SS2, the additional water withdrawn by wells was derived from induced infiltration from the Rock River and interception of ground-water flow by the pumped wells. Areal recharge was decreased by 8.2 ft^3/s and ground-water evapotranspiration decreased by 5.0 ft^3/s. The net recharge compared to the calibrated steady-state simulation was therefore decreased by 3.2 ft^3/s. The simulated net leakage from the aquifer to the streams decreased by 3.8 ft^3/s. Changes in the ground-water flows through the general-head boundaries were less than 0.05 ft^3/s. The losses due to increased ground-water withdrawals (0.6 ft^3/s) and less net recharge (3.2 ft^3/s) were balanced by the simulated decrease in net leakage from the aquifer to the streams (3.8 ft^3/s).

Transient simulations

Simulated stress-period areal recharge rates to the surficial unit of the Rock River Valley aquifer for simulations TR3 and TR4 were 50 percent of the rates for the calibrated transient simulation. This was based on precipitation at Luverne during the 1976 drought, which was approximately one-half the average annual precipitation during 1994–97. In addition to decreasing stress-period areal recharge rates to the aquifer, the following changes were made to simulate drought conditions: (1) 1997 stream stages were lowered by 1.5 ft in the Rock River during the late summer stress period and by 1.0 ft during the early summer and fall stress periods, (2) streamflow entering the model area at the northern boundary was reduced by 93 percent to 1.5 ft^3/s during the late summer stress period, and (3) the hydraulic heads at the west-central general-head boundary were lowered by 5 ft during the late summer stress period. Records indicate that the tributaries to the Rock River in the model area were dry under these extreme low-flow conditions. During the early summer and fall stress periods, 1997 streamflows and stream stages were used. The streamflows and stream stages during these stress periods were the lowest during the 3-year transient calibration period. Streamflows and stages from 1996, representative of average conditions, were used for the winter and spring stress periods.

As for simulations TR1 and TR2, the additional water withdrawn due to the anticipated increased ground-water withdrawals was derived from stream depletion. Net losses from the aquifer by leakage to streams were less than those for the calibrated transient simulation for each stress period.

Numerical Model Limitations and Accuracy of Results

A numerical ground-water-flow model is a practical tool for simulating response of the stream-aquifer system to anticipated areal recharge and stresses (ground-water withdrawals) on the system. A model is a simplification of a complex flow system. The accuracy of the simulations is limited by the accuracy of the data used to describe the properties of the aquifer and the confining unit, areal recharge rates, ground-water withdrawal rates, streambed hydraulic conductivities, and boundary conditions. In addition, a combination of input to the model different from that used in a simulation could produce the same result.

Use of the calibrated model as a management tool is based on the premise that if historical conditions in the aquifer can be simulated, then future similar hydrologic conditions can also be simulated. The variation in recharge and discharge used for the simulation of hypothetical conditions should be similar to that for the calibration simulation. The accuracy of simulation results for hypothetical conditions becomes more uncertain if the variation in recharge and discharge exceeds the range used in calibration.

The accuracy of simulations of hypothetical conditions varies depending on the particular conditions being simulated. Factors affecting the accuracy of the simulations include (1) the duration of the simulation period compared to the duration of the calibration period and (2) the rate of simulated recharge or discharge compared to those used in calibration. Assuming the model calibration is accurate, the most accurate simulations are possible when the duration and hypothetical ground-water withdrawal rate for the simulation are less than, or comparable to, the duration and ground-water withdrawal rate for the calibration simulation. Long simulation periods and high rates of ground-water withdrawal can produce large errors, and special care should be taken in using the results of such simulations.

The duration of the simulation periods for the steady-state and transient simulations of hypothetical conditions done for this study are the same as the duration of the corresponding calibration periods. Also, the rate of simulated ground-water withdrawals for the simulations of hypothetical conditions is similar to the rate of ground-water withdrawals used in calibration simulations. The total annual ground-water withdrawals simulated for hypothetical conditions are only approximately 20 percent greater than the rates simulated in the calibration simulations. The simulated rates of areal recharge and streamflows are also similar in the calibration simulations and the simulations of anticipated increased ground-water withdrawals and normal precipitation. The rates of areal recharge and streamflows in the simulations of anticipated increased ground-water withdrawals and drought conditions, however, are much lower (50 percent for areal recharge) than in the calibration simulations. The results from the simulations of drought conditions, therefore, should be viewed with caution and regarded only as plausible indicators of the hydraulic heads in the Rock River Valley aquifer and streamflows in the Rock River that would occur during periods of drought.

WATER QUALITY

Stream depletion may affect ground-water quality because river water is drawn into the aquifer and to supply wells. Herbicides and nitrate-N have been detected in Rock River water and nearby supply wells in the study area. Other studies have determined that alluvial aquifers can become contaminated with herbicides during the spring flush period (Thurman and others, 1992; Wang and Squillace, 1994). The alluvial aquifers can be affected by bank storage of water from streams containing high concentrations of herbicides and inundation of the flood plain and subsequent recharge by herbicide-contaminated stream water. Water-quality data were used to help assess the interaction between the Rock River and the aquifer and potential degradation of water quality in the aquifer.

Surface Water

Thirteen herbicides or herbicide metabolites were detected in the Rock River at Luverne during May 1989 through May 1995, as part of the USGS Midcontinent Herbicide Study (table 12, at the back of the report). Atrazine plus metabolites, alachlor and alachlor ESA, metolachlor, cyanazine, and acetochlor were detected in the Rock River during the first substantial runoff event in May or June after herbicide application (Scribner and others, 1993; D.A. Goolsby and E.M. Thurman, U.S. Geological Survey, written commun., 1995) (table 17, at the back of the report). The study found that herbicide concentrations generally increased as streamflow peaks increased (Thurman and others, 1991, 1992). Some of the greatest concentrations of atrazine (without metabolites, 10.64 μg/L on June 6, 1994, and 3.52 μg/L on June 19, 1990) and alachlor (2.19 μg/L on June 6, 1994) during spring runoff peaks were temporarily in excess of the USEPA MCLs of 3 μg/L for atrazine and 2 μg/L for alachlor (U.S. Environmental Protection Agency, 1996). The MCLs for atrazine and alachlor are for the parent compounds alone without metabolites. The concentrations of atrazine and alachlor exceeded MCLs in some post-application samples. The other herbicides or metabolites analyzed do not have MCLs, although cyanazine has a health advisory concentration (nonenforceable) of 1 μg/L. Concentrations of herbicides and metabolites in samples collected prior to herbicide application in April or May or in the fall were 0.14 μg/L or less (table 17, at the back of the report) and in many cases were less than the detection limit of 0.05 μg/L, with the exception of alachlor ESA, which had a concentration of 0.69 μg/L on April 4, 1994. Herbicide metabolites, particularly DEA and alachlor ESA, were among the compounds detected most frequently and in the greatest concentrations. The metabolites alachlor OA, acetochlor ESA and OA, metolachlor ESA and OA, and hydroxyatrazine, were not analyzed during the May 1989 through May 1995 sampling because the HPLC analysis procedure was not developed until 1996.

During sampling of the Rock River at Luverne (site SW6, fig. 2b) during November 1995 through August 1997, a total of 17 herbicides or herbicide metabolites were detected (table 12, at the back of the report). Concentrations of atrazine, DEA, DIA, hydroxyatrazine, alachlor ESA, metolachlor, metolachlor ESA, metolachlor OA, acetochlor, and acetochlor ESA were detected in most of the river samples (figs. 11a and 11b, table 17, at the back of the report). Metabolites of alachlor, metolachlor, and acetochlor were consistently present in concentrations greater than the parent compounds (table 17, at the back of the report). In 1997, when metabolites began to be analyzed using the HPLC procedure, metolachlor ESA was detected in the greatest frequency and concentrations (table 17, at the back of the report). The maximum concentrations of all herbicides and metabolites were measured on June 30, 1997, the runoff event with the largest streamflow of any of the May 20 through August 14 post-application runoff events sampled during 1996–97. Similar to the May 1989 through May 1995 sampling, concentrations varied seasonally with generally greater concentrations in post-herbicide application samples collected during May 20 through August 14 than in samples collected prior to herbicide application in the spring or in the late summer or fall (figs. 11a and 11b, and table 17, at the back of the report). However, concentrations of all herbicides and metabolites, with the exception of metribuzin and cyanazine amide, were smaller in post-application runoff samples during 1996–97 than during May 1989–95, which may reflect that streamflow was generally smaller at the time of collection during 1996–97 (table 17, at the back of the report). The only storm runoff event sampled in 1996–97 that had streamflow in the upper range of flows sampled in 1989–95 was the June 30, 1997 event.

The results of sampling the Rock River in the Rock County Rural Water well field (site SW24, fig. 2d) were similar to those at Luverne (site SW6, fig. 2b), except that samples were collected less frequently at SW24 (figs. 11a, 11b, 11d, and 11e; and tables 12 , 13, 17 and 18, at the back of the report). Fewer herbicides and metabolites were detected at SW24 (table 13, at the back of the report) than at SW6 (table 12, at the back of the report) primarily because a sample was not collected at SW24 during the June 30, 1997, storm runoff event and because the site was not sampled during the May 1989 through May 1995 sampling.

Nitrate-N concentrations in the Rock River at Luverne varied between 2.10 and 7.50 mg/L with a median of 4.60 mg/L during November 1995 through August 1997 (table 17, at the back of the report), less than the MCL of 10 mg/L (U.S. Environmental Protection Agency, 1996). These concentrations were slightly greater than those measured during May 1989 through May 1995. Concentrations of nitrate-N did not consistently vary seasonally or in relation to streamflow like herbicide concentrations (figs. 11c and 11f; and table 17, at the back of the report).

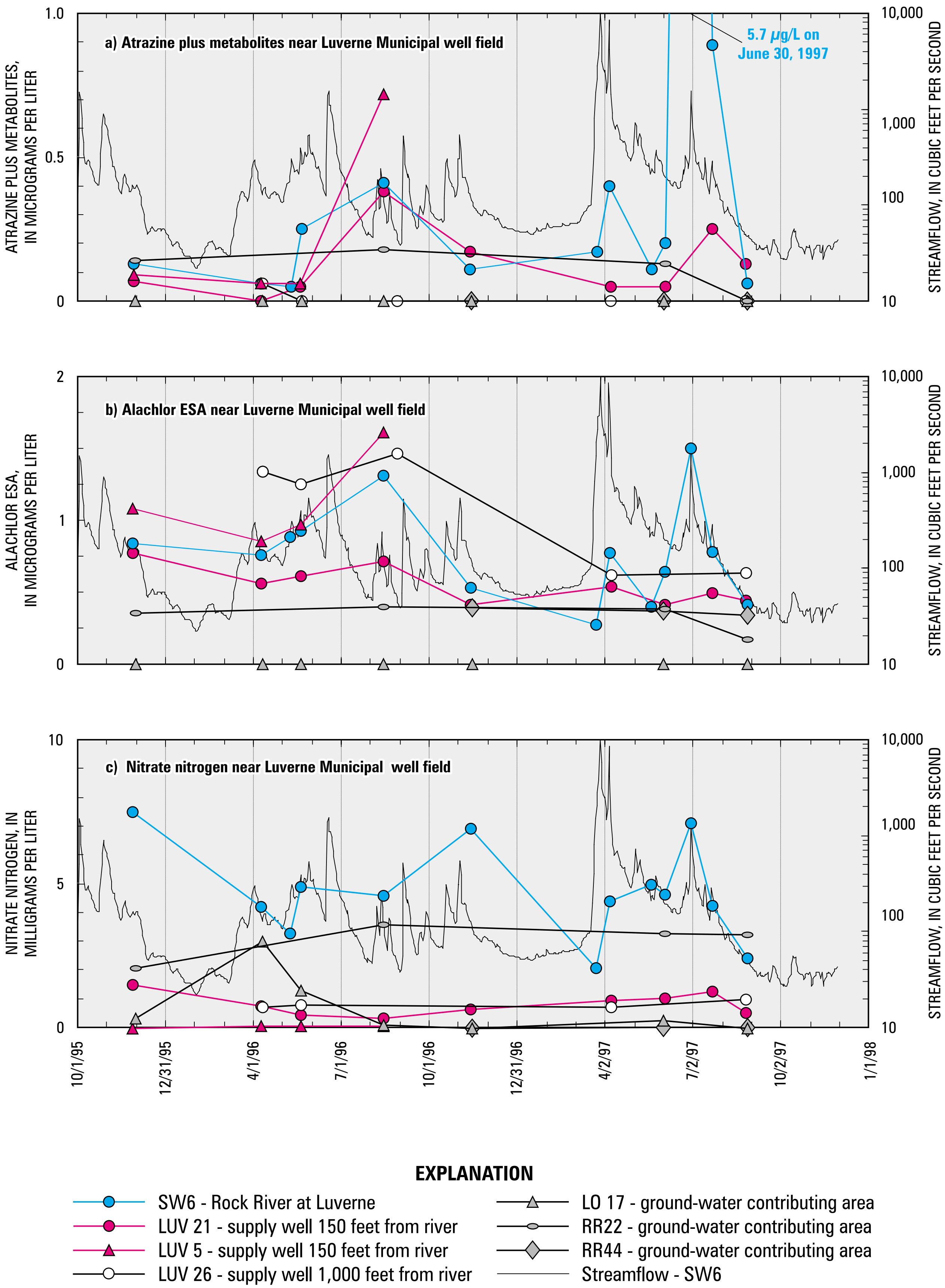
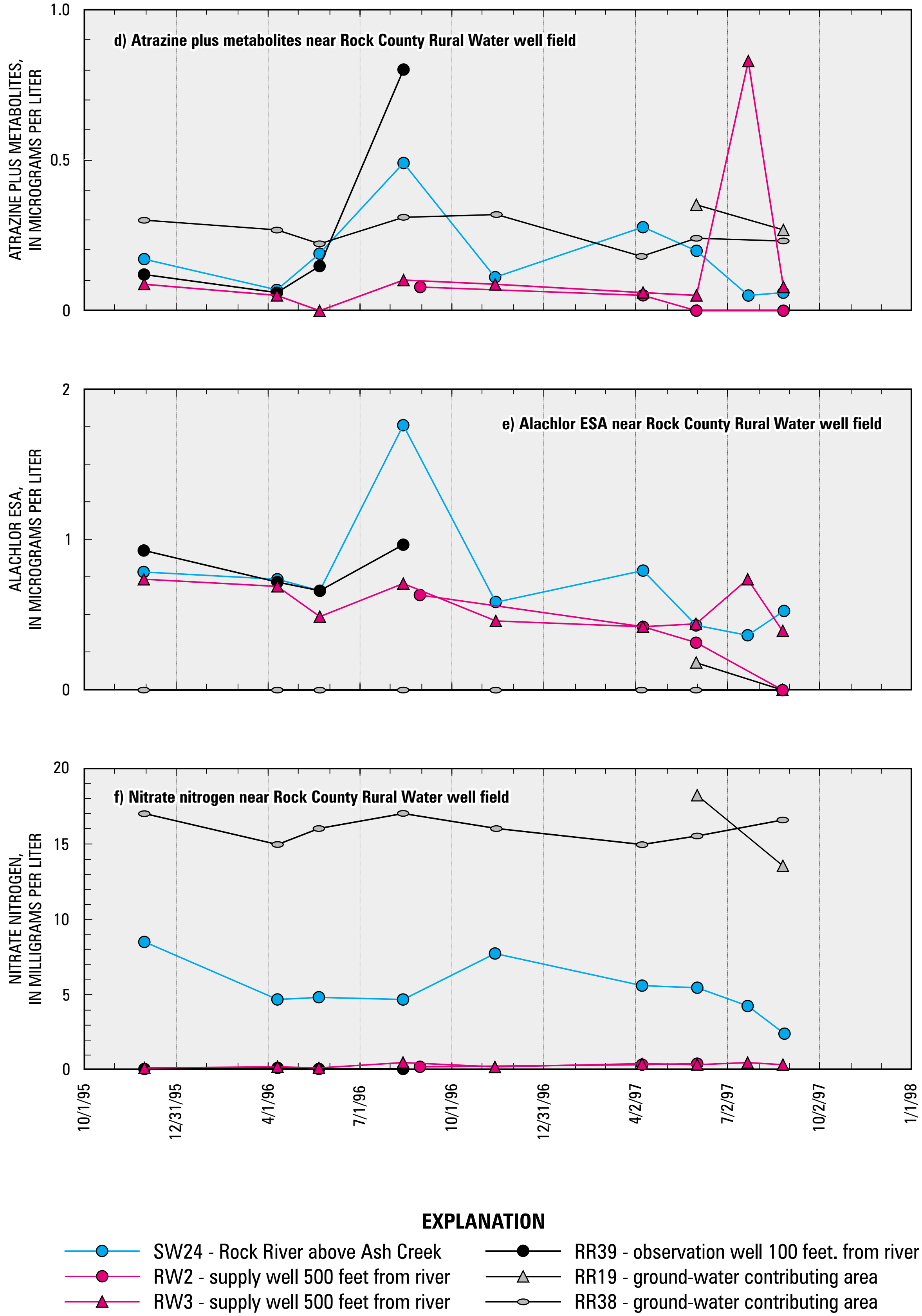


Figure 11. Concentrations of selected water-quality constituents in



surface water and ground water, eastern Rock County, Minnesota, 1995-97.

Ground Water

Comparison of concentrations of herbicides and metabolites in supply wells, the Rock River, and observation wells in the contributing areas of ground-water flow to supply wells indicates that the herbicides and metabolites detected in supply wells originate primarily from induced infiltration of water from the Rock River. A secondary source of some herbicides and metabolites is the ground-water contributing areas to supply wells. The Rock River is the source for all or at least some of the mass of each of the herbicides and metabolites detected in supply wells.

Nine herbicides and metabolites were detected in supply wells located less than 200 feet from the river in the Luverne Municipal well field (table 12, at the back of the report). Metolachlor ESA and alachlor ESA, in order of abundance, were detected in the greatest concentrations and were detected in all samples (table 17, at the back of the report). Atrazine, metolachlor OA, acetochlor ESA, and metolachlor were detected in most samples from supply wells less than 200 feet from the river. DEA, DIA, and acetochlor OA were detected much less frequently. Seasonal changes in concentrations of herbicides and metabolites were generally of smaller magnitude than changes in concentrations in surface water (figs. 11a, 11b, 11d, and 11e; and table 17, at the back of the report).

In the Rock County Rural Water well field, the same nine herbicides and metabolites were detected as in the Luverne Municipal well field, along with hydroxyatrazine (tables 12 and 13, at the back of the report). Metolachlor ESA was detected in the greatest concentrations and frequencies (table 18, at the back of the report). Alachlor ESA, metolachlor OA, atrazine, acetochlor ESA, and hydroxyatrazine were detected in most samples. DEA, DIA, metolachlor, and acetochlor OA were detected much less frequently.

In both the Luverne Municipal and Rock County Rural Water well fields, metolachlor, acetochlor ESA, and acetochlor OA detected in supply wells likely result from induced infiltration of water from the Rock River into the aquifer, considering that concentrations of these herbicides and metabolites in surface water are much greater than those in the ground-water contributing area (tables 17 and 18, at the back of the report). In the Luverne Municipal well field, concentrations of atrazine, DEA, and DIA detected in supply wells less than 200 feet from the river likely primarily reflect the effects of induced infiltration of river water and, in the Rock County Rural Water well field, concentrations of alachlor ESA in supply wells less than 500 feet from the river appear to be derived largely from infiltration of river water. In both cases, concentrations in the river are much greater than concentrations in the ground-water contributing area.

Ground water in the contributing area is a potential source of metolachlor ESA and alachlor ESA, but not other herbicides and metabolites, to supply wells in the Luverne Municipal well field. Metolachlor ESA had median concentrations that were greater than the detection limit (table 17, at the back of the report) and was detected in all three of the wells in the ground-water contributing area (RR22, LO17, and RR44, figs. 2b and 9a) sampled for this metabolite. Alachlor ESA was detected in all samples from wells RR22, RR24, and RR44, but was not detected in wells LO17 or RR25 (fig. 2b). These results indicate that there are sources of alachlor ESA in the contributing area. Atrazine, DEA, DIA, metolachlor, acetochlor ESA, and metolachlor OA were only detected in well RR22, which may not be representative of the general water-quality in the contributing areas.

Eight herbicides and metabolites were detected in observation wells in the Rock County Rural Water well field ground-water contributing area (table 13, at the back of the report). Metolachlor ESA, atrazine, DEA, DIA, and metolachlor OA had median concentrations that were greater than the detection limit (table 18, at the back of the report) and were detected in both of the observation wells (RR38, and RR19, fig. 2d) sampled. Metolachlor ESA was detected in the greatest concentrations. Metolachlor, hydroxyatrazine, and alachlor ESA were each detected once in samples from RR19 but were not detected in RR38.

Atrazine, DEA, alachlor ESA, and metolachlor ESA were detected in supply well LUV23 in the Luverne Airport well field and alachlor ESA was detected in LUV24 (table 17, at the back of the report). Because the contributing areas for these wells do not intersect the river (fig. 9b), the herbicides and metabolites likely reflect sources in the ground-water contributing area rather than in the river.

In both the Luverne Municipal and Rock County Rural Water well fields, metolachlor ESA is likely derived from both induced infiltration of Rock River water and the ground-water contributing area, considering that similarly large concentrations are present in both of these source areas. In the Luverne Municipal well field, alachlor ESA is also likely derived from both induced infiltration of river water and the ground-water contributing area. The correspondence of seasonal variations in concentrations of alachlor ESA in the river and supply wells is suggestive of the river being a source of alachlor ESA (fig. 11b). However, some of the alachlor ESA may be derived from ground-water sources. Concentrations of alachlor ESA in LUV26, which reflect the ground-water contributing area, are similar to those in the river. Concentrations in contributing-area observation wells RR22 and RR44 are similar to the lowest concentrations in LUV21 (fig. 11b). In the Rock County Rural Water well field, concentrations of atrazine plus metabolites were generally greater in the Rock River and the ground-water contributing area than in the supply wells (fig. 11d, table 18, at the back of the report) for unknown reasons. Concentrations of metolachlor OA in the Rock County Rural Water well field were similar in supply wells, the ground-water contributing area, and the river (table 18, at the back of the report). Concentrations of hydroxyatrazine were detected with greater frequency and sometimes at greater concentrations in supply well RW3 than in the ground-water contributing area or the Rock River. Herbicide ratios DAR (DEA/atrazine) and D^2R (DIA/DEA), which have been used by Thurman and others (1992) to evaluate ground-water/surface-water interactions, did not show consistent patterns that indicated relative proportions of atrazine and metabolites derived from ground-water and surface-water sources.

The correspondence of seasonal peaks in concentrations of many herbicides and metabolites in the Rock River and in supply wells is indicative of the linkage between contaminant concentrations in the Rock River and at supply wells (fig. 11a and 11b). In 1996, the greatest concentrations of most herbicides and metabolites at supply wells were detected in mid-August (fig. 11a, 11b, 11d, and 11e). The mid-August 1996 samples were collected near the presumed end of the summer period of relatively large herbicide concentrations in the Rock River following herbicide application in early May. The greatest concentrations of most herbicides and metabolites measured in the Rock River in 1996 were also measured in mid-August 1996. It is possible that greater concentrations of herbicides and metabolites would have been measured during the large runoff event in June 1996 if a sample had been collected, based upon sampling results during other years (fig. 11a). It is likely that the 1996 peak concentrations of herbicides and metabolites in the supply wells in mid-August 1996 reflect relatively large herbicide concentrations in the Rock River during June through August 1996. Similarly, in 1997, peak concentrations of most herbicides and metabolites in supply wells near the Rock River were measured in late July (figs 11a, 11d, and 11e). These 1997 peak concentrations at supply wells likely reflect the effects of the 1997 peak concentrations in the Rock River measured during a large runoff event on June 30, 1997. The exact timing of the greatest concentrations in supply wells near the river depends upon the timing of post-herbicide application storm runoff events and water and herbicide travel times from the river to supply wells.

In addition to being influenced by induced infiltration from the Rock River, the water-quality in the Rock River Valley aquifer can be affected by inundation of the flood plain and subsequent recharge by herbicide-contaminated stream water. Flooding occurred several times during 1996–97. The Rock River overtopped its banks in the vicinity of the Rock County Rural Water well field in May and June 1996 and March, April, and June 1997. The river overtopped its banks in the Luverne Municipal well field during the spring snowmelt runoff of March through April 1997; during this event all of the wells in the well field, with the exception of LUV1, were surrounded by flood waters. These flood events blur the distinction between surface-water and ground-water sources of water and contaminants because the flood waters inundating the floodplain recharge the aquifer and become ground water. Concentrations of herbicides and metabolites in the Rock River increased during the March through April spring flood compared to concentrations measured before and after the flood (figs. 11a and 11b). Thus, although the spring flood preceded herbicide application in 1997, the runoff was apparently great enough that residual herbicide from applications during previous years was mobilized. This event may have resulted in greater movement of herbicides and metabolites to ground water than would have resulted from typical use of these herbicides on cultivated fields in the ground-water contributing area alone. The addition of herbicides and metabolites to ground water from flood events does not change the conclusion that some sources of herbicides and metabolites exist in the ground-water contributing area. Only one of the observation wells sampled (LO17) was a shallow well located in an inundated area; other observation wells sampled either were not inundated (RR38, RR19, RR22, RR25) or were wells screened near the bottom of the aquifer whose water-quality was unlikely to be affected by the flooding (RR44 and RR24). None of the wells in flooded areas were completely submerged.

Concentrations of caffeine were not useful for indicating movement of river water to supply wells in the Rock County Rural Water well field. Caffeine was detected in relatively low concentrations in the Rock River of 0.04 and 0.07 µg/L below the Luverne Wastewater Treatment Plant (site RRWP, fig. 2b) in November 1996 and April 1997, respectively, and 0.04 µg/L at SW24 in November 1996, approximately 9 river mi below the wastewater discharge. Only trace levels of caffeine below the reporting limit (0.04 µg/L) were detected in samples from supply wells RW2 and RW3 and monitoring well RR38, in the Rock County Rural Water well field contributing area and at SW6 and LUV21, upstream of the Luverne Wastewater Treatment Plant; the estimated concentrations were 0.02 µg/L. The trace level detections below the reporting limit may have been related to contamination of the samples during sampling or analysis rather than actual environmental concentrations.

Fecal coliform and fecal streptococcal bacteria were consistently detected in the Rock River during November 1995 through August 1996, in concentrations ranging from 15 to 1,170 colonies per 100 ml and from 93 to 854 colonies per 100 ml, respectively. These bacteria were not detected in supply wells close to the river or in ground-water in the contributing areas to the supply wells, indicating that they are not reaching the supply wells.

In the Luverne Municipal and Rock County Rural Water well fields, concentrations of nitrate-N in supply wells were less than concentrations in the river (figs. 11c and 11f; and tables 17 and 18, at the back of the report,). and were well below the USEPA MCL of 10 mg/L (U.S. Environmental Protection Agency, 1996). Results indicate that the supply wells are not substantially affected by induced infiltration from the river, with respect to nitrate-N.

Concentrations of nitrate-N in the ground-water contributing area to the Luverne Municipal well field do not appear to represent a substantial source of nitrate-N to supply wells. Only wells RR22, with nitrate-N concentrations ranging from 2.1 to 3.6 mg/L, and RR25, which was sampled once and had a concentration of 8.3 mg/L, had concentrations greater than 2 mg/L. Well LUV1, near RR25, is a little used supply well because nitrate-N concentrations have been detected in excess of the USEPA MCL of 10 mg/L (Terry Reisch, City of Luverne, oral commun., 1996). These wells are located on the edge of the aquifer, where it consists of thin layers of poorly sorted silty sand interbedded with clay. The relatively large nitrate-N concentrations in RR25 and LUV1 probably reflect local sources of nitrate-N to these wells.

Relatively large concentrations of nitrate-N in observation wells RR38 and RR19 (14–18 mg/L, fig. 11f ; and table 18, at the back of the report,) imply that the ground-water contributing area is a potential source of nitrate-N to Rock County Rural Water District supply wells. Because these concentrations are substantially greater than those in the Rock County Rural Water District supply wells (fig. 11f), the ground-water contributing area does not appear to be having a substantial effect on concentrations in the supply wells. Because the contributing area for RW6 indicates this well is mostly capturing water from the river, the nitrate-N concentration in this well (20 mg/L) may largely reflect the influence of the river, which had concentrations of nitrate-N ranging from 2.4 to 8.5 mg/L (table 18, at the back of the report). The larger concentration (8.8 mg/L) of nitrate-N in RW4 may reflect both river and ground-water sources of nitrate-N, considering that the contributing area for this well includes areas to the northwest (fig. 9c) that could have similar nitrate-N concentrations to those measured at RR38 and RR19.

The relatively small nitrate-N concentrations in most ground-water samples may be partially the result of biogeochemical conditions in the aquifer that permit denitrification, a biochemical reaction that converts nitrate-N to N_2. The correlation of DO and nitrate-N concentrations has been noted in many previous studies (Korom, 1992). Concentrations of DO in ground-water were less than 0.8 mg/L in samples from nearly all Luverne Municipal supply wells, observation wells in the contributing area to the Luverne Municipal well field, and Rock County Rural Water District supply wells. Wells having greater DO concentrations consistently had greater nitrate-N concentrations (table 14, at the back of the report). Decreased DO and nitrate-N concentrations indicate chemically reduced ground water, following a common sequence of biochemical reactions in ground water (Champ and others, 1979). Results of sampling for dissolved gases at LUV26, LUV23, and RW2 provide additional evidence that denitrification is occurring in the aquifer. In all three samples, concentrations of N_2 were present in excess of what would be expected for water in equilibrium with the atmosphere (table 14, at the back of the report), implying that denitrification is occurring (E. Busenburg, U.S. Geological Survey, oral commun., 1996). Denitrification is likely to be a major mechanism regulating nitrate-N concentrations in the aquifer. However, reduced ground water and denitrification are not occurring everywhere; monitoring wells RR25, RR38, and RR19 had oxic ground-water and nitrate-N concentrations of 8–18 mg/L. Spatial variability of geochemical conditions likely reflects complex interaction between the effects of changing land-use practices, ground-water residence times, and geologic features that affect the distribution of nitrate-N in an aquifer (Böhlke and Denver, 1995).

Stable isotopes of oxygen and hydrogen in water can be used as tracers of water having a unique isotopic value (International Atomic Energy Agency, 1981; Payne, 1988; Coplen, 1993). Values of $\delta^{18}O$ and δD in the Rock River, supply wells, and the ground-water contributing areas were monitored seasonally at selected locations to estimate the proportions of river water in water withdrawn from supply wells. In the absence of evaporative and mixing effects, $\delta^{18}O$ and δD should be unmodified by geochemical processes in a shallow alluvial aquifer system such as the Rock River Valley. Values of $\delta^{18}O$ and δD from surface water and ground water in the study area plotted on the local meteoric water line developed at a research site near Princeton, Minnesota (Landon and others, 1997) indicated that the values were not modified by evaporation, and are conservative tracers of water in the Rock River Valley.

Values of $\delta^{18}O$ (changes in δD values are proportional to those in $\delta^{18}O$ because they are strongly correlated) in the Rock River varied seasonally (table 15, at the back of the report), in a pattern consistent with seasonal precipitation values, which should be isotopically light in winter and isotopically heavy in summer (International Atomic Energy Agency, 1981; Payne, 1988; Coplen, 1993). In contrast, $\delta^{18}O$ values in observation wells in the contributing area to Luverne Municipal supply wells varied relatively little; whereas, values in observation wells in the contributing area to the Rock County Rural Water District supply wells varied slightly more (table 13, at the back of the report). The fluctuations were small compared to those in surface water.

An isotopic contrast between water in the river and ground water made it possible to calculate mixtures of river and contributing area ground-water in the supply wells (table 15, at the back of the report). Values of $\delta^{18}O$ in Luverne Municipal supply wells less than 200 feet from the river were intermediate between seasonal changes in surface-water values and relatively constant contributing area ground-water values. Mass balance mixing calculations using $\delta^{18}O$ and δD values indicated the proportion of river water in Luverne Municipal supply wells LUV21, LUV5, and LUV2 varied from about 15 to 60 percent. The sampling periods of greatest isotopic contrast and most reliable mixing calculations were in April and August 1996 and April, July, and August 1997. Proportions of river water withdrawn varied seasonally for a given well. For example, in LUV21 the proportion of river water withdrawn was about 15 percent in April 1996 and 1997, 40 percent in August 1996, 10–20 percent in July 1997, and 25–50 percent in August 1997. Uncertainties in the mixing proportions reflect uncertainties in river compositions, which can vary over short periods of time, and in travel times of water from the river to the supply well. Well LUV26, about 1,000 feet from the river, had $\delta^{18}O$ from -9.8 to -10.1‰, almost the same as ground water in the contributing area. This result and the lack of seasonal variation in $\delta^{18}O$ suggest that LUV26 draws little or no water from the river; results at LUV25 were similar. Isotopic mixing calculations for the Rock County Rural Water well field were not conclusive as often as in the Luverne Municipal well field. This may reflect that hydraulic gradients are lower in the Rock County Rural Water well field than in the Luverne Municipal well field and thus, travel times from the river to supply wells are expected to be longer. Mixing calculations indicated the proportion of river water withdrawn by RW2 and RW3 varied from 5 to 40 percent (table 15, at the back of the report).

Results of ground-water recharge age dating using CFCs indicates CFC-12 recharge ages of late 1980's for LUV23, and late 1970's or possibly younger for LUV26 and RW2 (table 14, at the back of the report). Older recharge ages were indicated by CFC-11 and CFC-113 than CFC-12; this is consistent with degradation of CFC-11 and CFC-113 under the geochemically reduced ground-water conditions encountered in the Rock River Valley aquifer. CFC-12 is the least readily degraded CFC (Busenberg and Plummer, 1992) and provided the best estimates of recharge age in the samples collected.

The measured tritium concentration for LUV23 of 13.5 TU was consistent with tritium concentrations in precipitation (precipitation tritium data obtained from R.L. Michel, U.S. Geological Survey, written commun., 1996) during the late 1980's and, thus, indicates a recharge age similar to the CFC-12 recharge age. The tritium concentrations for RW2 and LUV26 are slightly low for water recharged in the late 1970's. The somewhat weak match between the CFC-12 recharge ages and the tritium concentrations for RW2 and LUV26 indicates that some CFC-12 degradation may have occurred. Thus, water collected from these wells could have recharged the aquifer more recently than the late 1970's. Degradation of CFC-12 has been shown to occur in some cases under methanogenic conditions, which can occur in highly reduced ground-water (E. Busenberg, U.S. Geological Survey, oral commun., 1996). Despite the uncertainty associated with the CFC recharge ages for water at RW2 and LUV26, the CFC-age dating results indicate that the ground water withdrawn from the supply wells has a residence time in the aquifer of two decades or less.

Water from supply well LUV24, in the Luverne Airport well field, had a tritium value of 15.8 TU, consistent with areal recharge in the 1970's or 1980's, although a more precise estimate of recharge age cannot be determined with tritium alone. Tritium was below the detection limit of 0.8 TU in water from a domestic well (site 434025096124501, fig. 2b) screened in a buried sand layer of unknown thickness in the upland west of the Rock River Valley. This result implies that the water recharged this aquifer prior to the early 1950's (Plummer and others, 1993) and that areal recharge to and water movement in this aquifer is much slower than in the Rock River Valley aquifer. The older age and the fact that specific conductance and concentrations of ammonia nitrogen and sulfate were approximately an order of magnitude greater than concentrations of these constituents in the Rock River Valley aquifer implies that the hydraulic connection with this buried sand unit likely is limited and that discharge from this and other isolated sand units in the upland is a minor source of water to the Rock River Valley aquifer.

EFFECTS OF GROUND-WATER WITHDRAWALS

Analysis of the data collected for this study and the results of numerical ground-water-flow model simulations were used to determine the effects of ground-water withdrawals on streamflow in the Rock River and on ground-water levels and flow. The effects of current ground-water withdrawals and of anticipated increased withdrawals by the three well fields are discussed in this section.

Streamflow

Current Conditions

Results from streamflow measurements during low-flow conditions, comparison of ground-water and surface-water altitudes, hydraulic potentiomanometer measurements, and ground-water-flow model simulations indicate that the Rock River is a gaining stream in most reaches, but is losing water to the aquifer in the vicinity of well fields in close proximity to the river. Simulated steady-state streamflow losses due to induced infiltration of river water into the aquifer in response to ground-water withdrawals in the well fields were approximately 0.5 ft^3/s in both the Luverne Municipal and Rock County Rural Water well fields (figs. 5a and 5c). These well fields are located 150 to 1,500 feet from the Rock River. No induced infiltration in the river reach nearest the Luverne Airport well field occurs because the well field is located 0.5 to 0.75 mi from the Rock River. Steady-state simulated streamflow losses due to interception of ground-water flow that would have discharged into the river without pumped wells were 0.5, 0.3, and 0.3 ft^3/s for the Luverne Municipal, Luverne Airport, and Rock County Rural Water well fields, respectively. Total simulated streamflow losses (induced infiltration plus intercepted subsurface flow) were thus 1.0, 0.3, and 0.8 ft^3/s for the three well fields, respectively, for total streamflow depletions of 2.1 ft^3/s for the study area. Of this streamflow loss, 1.0 ft^3/s resulted from induced infiltration and 1.1 ft^3/s resulted from intercepted subsurface flow.

Total ground-water withdrawal rates of 3.0 ft^3/s in the study area exceed total streamflow depletions of 2.1 ft^3/s. The implication of this result is that the other 0.9 ft^3/s withdrawn from the aquifer is water that was not in the river and would never have discharged to the river. Besides ground-water discharge to streams, the other major discharge component in the natural aquifer system without wells is removal of water from the aquifer due to ground-water evapotranspiration. Therefore (assuming no long-term depletion of storage in the aquifer), the 0.9 ft^3/s, or 30 percent of the water pumped from the aquifer, that does not represent streamflow depletion is water that, in the absence of pumped wells, would have naturally discharged from the aquifer through ground-water evapotranspiration.

Because an average of 1.5 ft^3/s of the water pumped by Luverne is returned to the Rock River as wastewater discharge (approximately 70 percent of the total of 2.1 ft^3/s withdrawn from ground water), the net steady-state simulated streamflow loss for the study area is 0.6 ft^3/s. The return flow approximately counterbalances streamflow losses due to ground-water withdrawals from the Luverne well fields. Thus, streamflow in the study area is slightly less downstream of the Rock County Rural Water well fields than what it would have been without ground-water withdrawals.

The streamflow losses as a result of ground-water withdrawals are insignificant in comparison to typical streamflow and are likely to have a measurable effect on streamflow only during low-flow conditions of less than about 10 ft^3/s. The net steady-state simulated streamflow loss of 0.6 ft^3/s would be detectable above the 5 percent streamflow measurement error only if streamflows were less than 12 ft^3/s. The streamflow losses are unmeasureably small in comparison to a median flow of 110 ft^3/s and average flow of 250 ft^3/s in the Rock River at Luverne during October 1995 through September 1997. Streamflow losses caused by ground-water withdrawals could be more significant in proportion to streamflow than would be suggested by the 1996–97 data alone, however, because lower flows than the lowest measured in the 1996–97 water years are likely to be encountered. The simulated steady-state net streamflow losses of 0.6 ft^3/s are approximately 25 percent of the minimum streamflow measured in the Rock River at Luverne (2.32 ft^3/s). At worst, ground-water withdrawals could measurably diminish streamflow under the lowest 10 percent of streamflows and could diminish flow by at least 25 percent under the most extreme low-flow conditions measured historically.

Anticipated Conditions

The effects of ground-water withdrawals on streamflow in the Rock River were investigated for (1) anticipated increased ground-water withdrawals and normal precipitation (simulations SS1, SS2, TR1, and TR2) and (2) anticipated increased ground-water withdrawals and drought conditions (simulations SS3, SS4, TR3, and TR4).

Normal precipitation

Simulations SS1 and SS2 indicated that the increased ground-water withdrawals resulted in an increase in induced infiltration from the Rock River of 0.1 ft^3/s for the Luverne Municipal well field (SW22 to SW6) and 0.3 ft^3/s for the Rock County Rural Water well field (SW10 to SW20) (table 11, at the back of the report). In simulation SS1, the anticipated increased ground-water withdrawals occur within the current areal extent of the well field and an increase in simulated induced infiltration from the river occurs between SW19 and SW20. In simulation SS2, the area of anticipated increased ground-water withdrawals is expanded to the north of the present well field, with the withdrawal rates from wells in the current well field area actually decreasing due to withdrawals from a greater number of wells. Simulated induced infiltration from the river between SW10 and SW19 increased by 0.4 ft^3/s due to ground-water withdrawals from hypothetical wells H1, H2, and H3, while simulated induced infiltration between SW19 and SW20 decreased by 0.1 ft^3/s (table 11, at the back of the report). The simulated increased interception of ground-water flow between SW6 and SW8 due to the anticipated increased ground-water withdrawals from the Luverne Airport well field was 0.2 ft^3/s. The increases in induced infiltration and interception of ground-water flow for the three well fields due to the anticipated increased ground-water withdrawals represent less than 1 percent of the simulated streamflows.

Simulations TR1 and TR2 indicated minimal changes (4 ft^3/s or less) in simulated seasonal streamflows due to the increased ground-water withdrawals over the 3-year simulation (table 16, at the back of the report). The simulated streamflows ranged from 45.1 to 401 ft^3/s, with the changes constituting about 1 percent or less of the simulated streamflows in the river.

Drought conditions

The steady-state simulations with anticipated increased ground-water withdrawals and drought conditions (SS3 and SS4) used simulated streamflows entering the study area that were an order of magnitude lower than those that were used for the calibrated steady-state simulation and for the simulations with hypothetical normal precipitation. The simulated streamflow losses under drought conditions constitute a greater percentage of the streamflows than do the losses under conditions of normal precipitation.

The anticipated increased ground-water withdrawals under drought conditions resulted in induced infiltration from the Rock River of 0.68 ft^3/s for the Luverne Municipal well field (SW22 to SW6), compared to 0.5 ft^3/s for the calibrated steady-state simulation (table 11, at the back of the report, SS3 and SS4). The simulated streamflow loss constitutes approximately 30 percent of the flow in the river. The simulated gain in streamflow between SW6 and SW8 east of the Luverne Airport well field, as a percentage of flow in the river, decreased by approximately 1.5 percent for simulations SS3 and SS4 (4.8 percent) compared to the calibrated steady-state simulation (6.2 percent).

Simulation SS3 indicated induced infiltration from the Rock River between SW19 and SW20 of 0.92 ft^3/s (table 11, at the back of the report). The simulated streamflow loss is 80 percent greater than the calibrated steady-state loss, and approximately 30 percent greater than for SS1. The simulated induced infiltration constitutes nearly 65 percent of the simulated streamflow in the river at SW20. In simulation SS4, the simulated induced infiltration from the river between SW10 and SW19 approximately doubled compared to the simulations with normal precipitation (SS1 and SS2). The streamflow loss constituted approximately 30 percent of the streamflow in the river at SW19. The induced infiltration between SW19 and SW20 was approximately 0.1 ft^3/s greater than for the calibrated steady-state simulation, and approximately 0.3 ft^3/s less than for simulation SS3.

The transient simulations with anticipated increased ground-water withdrawals and drought conditions indicated simulated reductions in streamflow (as a percentage of streamflow in the Rock River) near the three well fields were least (<1.5 percent) during the spring and early summer stress periods, with streamflows of 120 to 296 ft^3/s (table 14, at the back of the report, TR3 and TR4). The simulated reductions during the late summer stress period, with simulated streamflows of < 10 ft^3/s, were 8 to 10 percent. The simulated induced infiltration from the Rock River to pumped wells during the late summer stress period was approximately 50 percent of the amounts for simulations SS3 and SS4 with comparable low streamflows. The amounts of induced infiltration were less because the travel times of water particles from the river to many of the pumped wells near the river exceed 92 days, the length of the late summer stress period.

Ground-Water Levels and Flow

Historical Ground-Water Withdrawals

The effect of historical ground-water withdrawals from the three public supply well fields on hydraulic heads in the Rock River Valley aquifer and the seasonal effect of ground-water withdrawals were evaluated. This was achieved by removing simulated ground-water withdrawals from the calibrated steady-state and transient simulations. Model results indicate that hydraulic heads have declined 1 to 2 ft in the Luverne Municipal and Rock County Rural Water well fields and 2 to 4 ft in the Luverne Airport well field due to historical ground-water withdrawals. Declines in hydraulic heads were less in the Luverne Municipal and Rock County Rural Water well fields because the Rock River is a source of water by induced infiltration to some wells in these well fields. For transient conditions, declines in hydraulic heads during the late summer stress period were similar to the steady-state differences for wells near the Rock River, but water levels were about 1 ft lower for wells more distant from the river at the Luverne Municipal and Rock County Rural Water well fields. The differences for the Luverne Airport well field were similar to the steady-state differences. The reason for the relatively small differences (about 1 ft or less) between the comparisons of simulations with and without pumped wells for steady-state conditions and for transient conditions during the late summer stress period is that the steady-state simulation was calibrated using hydraulic heads measured during October 1996. Hydraulic heads measured in the aquifer during the fall (fall stress period in the model) are generally similar to hydraulic heads measured in the aquifer during the late summer (late summer stress period in the model) in the study area. Also, the total pumping rates for each well field are similar throughout the year, with only small seasonal differences.

Anticipated Conditions

The effects of increased ground-water withdrawals on ground-water levels and flow were investigated for normal precipitation and drought conditions. The drawdowns cited in the following discussion represent drawdown due to the anticipated increased ground-water withdrawals and simulated precipitation conditions only, not the total drawdown. The drawdowns are calculated as the differences between the model-computed hydraulic heads for the (1) calibrated steady-state simulation and simulations SS1-SS4 and (2) calibrated transient simulation and simulations TR1-TR4. For the transient simulations, model-computed hydraulic heads for the late summer stress period in 1996 for the calibrated transient simulation were compared to model-computed hydraulic heads for the late summer stress period in the third year of simulations TR1-TR4.

Normal precipitation

Simulations SS1 and SS2 indicated maximum drawdowns ranging from 0.5 to 1.4 ft near the three well fields due to the anticipated increased ground-water withdrawals (table 11, at the back of the report). The simulated drawdowns near the Rock River were < 0.1 ft due to the strong influence of stream stage on hydraulic heads near the river. In the vicinity of the Luverne Airport well field, larger drawdowns were simulated north and west of the pumped wells than to the south and east, likely due to the presence of lower-K deposits in those areas. Simulated drawdowns in the Rock County Rural Water well field for simulation SS1 ranged from 0.1 ft near RW6 and RW4 to 1.4 ft near RW2 and RW3. The large simulated drawdowns near wells RW2 and RW3 decreased rapidly to the east toward the Rock River due to the strong influence of stream stage on hydraulic heads near the river. Simulation SS2 indicated both rises and declines in hydraulic heads for the Rock County Rural Water well field (table 11, at the back of the report). Although the total pumping rate for the well field was increased by 40 percent compared to the calibrated steady-state simulation, the addition of five hypothetical wells resulted in lower pumping rates per well for this simulation. The simulated rises in hydraulic heads near wells RW2, RW3, and RW4 were due to the lower pumping rates for the wells compared to the rates for the calibrated steady-state simulation. Simulated drawdowns near hypothetical wells H1, H2, and H3 ranged from 0.2 ft at the Rock River to 1.0 ft near the middle well of the three wells (H2).

Simulations TR1 and TR2 indicated maximum seasonal drawdowns ranging from 0.5 to 1.7 ft near the three well fields due to the anticipated increased ground-water withdrawals (table 14, at the back of the report). The simulated drawdowns in the Luverne Municipal well field ranged from 0.1 ft or less near the Rock River to 0.6 ft distant from the river. Simulated seasonal drawdowns in the Rock County Rural Water well field with seven pumped wells (TR1) ranged from 0.1 to 0.9 ft, with the largest drawdowns occurring near wells RW2 and RW3, and the smallest near well RW1. The simulated seasonal drawdowns with 12 pumped wells (TR2) ranged from 1.1 to 1.7 ft near the three northern hypothetical wells (H1, H2, and H3). The drawdowns for the late summer stress period are similar to those for steady-state conditions (varying by < 0.5 ft) because the steady-state hydraulic heads represent the heads observed each year during the fall and winter seasons. The hydrographs of observation wells in the study area indicate that hydraulic heads during the late summer (late summer stress period) are similar to hydraulic heads during the fall and winter seasons. The simulated hydraulic heads in the vicinity of the three well fields were similar during each stress period from year to year, with no annual decline in heads during the 3-year simulation period. The results indicate that the anticipated increased ground-water withdrawals likely would not appreciably alter hydraulic heads and the existing steady-state conditions near the existing well fields during periods of normal precipitation.

Results also indicated that the contributing areas for wells in the Luverne Municipal well field would not be appreciably affected by the increased ground-water withdrawals (fig. 9a), with only a small expansion of the contributing area for well LUV26 to the southwest. The contributing area for well LUV23 in the Luverne Airport well field was enlarged due to the simulated increased ground-water withdrawals (fig. 9b) and extends farther to the north and northeast than for the calibrated steady-state simulation. The anticipated increased ground-water withdrawals and addition of well RW7 resulted in shifting of the simulated contributing areas for two (wells RW4 and RW5) of the six original wells in the Rock County Rural Water well field (fig. 9c). The orientation of the contributing area for well RW5 was shifted to the east and ends at the Rock River due to changes in the potentiometric surface caused by the increased ground-water withdrawals. The contributing area for well RW7 extends from the well northwestward to the western model boundary. The effect of ground-water withdrawals from well RW7 on the simulated contributing area for well RW4 is to shift the western part of the contributing area to the south. Simulation TR2 indicated that the contributing areas of most of the wells in the Rock County Rural Water well field are affected by ground-water withdrawals by nearby wells (fig. 9d). The relatively close spacing of the 12 wells within the relatively narrow river valley results in much overlapping of contributing areas. The simulated contributing areas for the three northern hypothetical wells (H1, H2, and H3) extend eastward to the Rock River and westward to the western model boundary. An analysis of the 5-year and 10-year capture zones for the pumped wells in all three well fields indicated that the increased ground-water withdrawals resulted in a more rapid expansion of the capture zones for each well compared to current pumping rate capture zones, although the long-term (steady-state) contributing areas are not significantly changed.

Drought conditions

Simulations SS3 and SS4 indicated maximum drawdowns ranging from 3.8 to 7.0 ft near the three well fields (table 11, at the back of the report). Simulated drawdowns near the six wells closest to the Rock River in the Luverne Municipal well field were between 1.5 and 1.8 ft, similar to changes in stream stage. The largest drawdowns in the vicinity of the Luverne Airport well field occurred near a zone of low K northwest of the wells (fig. 7c) that is the major source area for pumped wells LUV7 and LUV23. For simulation SS3, drawdowns in the Rock County Rural Water well field were 1.0 to 2.5 ft greater near well RW7 than elsewhere. The influence of the river on drawdowns is indicated by the lesser simulated drawdowns near the wells located closer to the river than RW7. Simulated drawdowns near wells RW2, RW3, and RW7 in the Rock County Rural Water well field were 1 to 2 ft less for simulation SS4 than for simulation SS3 because the total ground-water withdrawals were evenly distributed among a greater number of wells. Simulated drawdowns near hypothetical wells H1, H2, and H3 ranged from 2.5 to 3.0 ft. for simulation SS4.

Simulations TR3 and TR4 indicated increases in maximum seasonal drawdowns during the late summer stress period in the third year of the simulations of from 1.5 to 2.5 ft near the three well fields (table 14, at the back of the report). The increases in simulated drawdowns in the Luverne Municipal well field area were greatest (1.5 ft) near the wells farthest from the river (LUV1 and LUV26), and least (0.1 to 0.3 ft) near the wells closest to the Rock River. The increases in simulated drawdowns northwest of the two southern wells in the Luverne Airport well field, near the contact between the low- and high-K aquifer materials, were approximately 1.6 ft. Simulation TR3 indicated increases in simulated drawdowns for the Rock County Rural Water well field ranging from 0.3 ft near well RW1 to 1.8 ft near well RW7. Simulation TR4 indicated that increases in simulated drawdowns near hypothetical wells H4 and H5 were approximately 1.0 ft, and near wells H1, H2, and H3 were from 2.0 to 2.5 ft.

Results from simulations TR3 and TR4 indicated no annual decline in hydraulic heads near the Rock River, due to the strong influence of stream stage on hydraulic heads in the aquifer. Annual declines in hydraulic heads would occur with the simulated drought conditions in areas distant from the river, however. The simulations indicated declines in hydraulic heads ranging from 0.2 to 0.4 ft/yr in the vicinity of the three well fields and from 0.3 to 0.8 ft/yr near the west-central aquifer boundary. Simulated declines near well RR19 were approximately 0.6 ft greater at the end of simulation TR4 than for simulation TR3. Simulated declines in hydraulic heads near well RR38 were about 0.8 ft greater at the end of simulation TR3 than for simulation TR4. The anticipated increased ground-water withdrawals would result in annual declines in hydraulic heads as long as drought conditions persisted or until new recharge-discharge relations are established and the stream-aquifer system approaches a new equilibrium condition.

The simulated drawdowns with increased ground-water withdrawals and drought conditions (simulations TR3 and TR4) are two to three times greater than with normal precipitation (simulations TR1 and TR2) at the end of the 3-year simulation period. These drawdowns, however, are much less than for the steady-state simulation with drought conditions because an equilibrium condition had not been reached and water levels were still declining.

Simulations SS3 and SS4 indicated the expansion of simulated contributing areas for pumped wells that are distant from the Rock River. The simulated contributing area for well LUV26 in the Luverne Municipal well field expanded by approximately 0.25 miles to the southwest, east, northeast, and north compared to steady-state conditions (figs. 9a and 10a). The simulated contributing areas for the northern wells (LUV7 and LUV23) in the Luverne Airport well field expanded by as much as 0.25 miles compared to steady-state conditions (figs. 9b and 10b). The simulated contributing areas for the southern pumped wells (LUV11 and LUV24) also increased in size, but to a lesser degree than for the northern wells. Changes in the simulated potentiometric surface for simulations SS3 and SS4 resulted in a reduction in the size of the contributing area for some of the pumped wells near the Rock River in the Luverne Municipal well field. The potentiometric surface for these simulations indicates a greater north-south component of ground-water flow near the Rock River and wells LUV2 and LUV20 than the potentiometric surfaces for the calibrated steady-state and increased ground-water withdrawals and normal precipitation simulations (simulations SS1 and SS2), resulting in the elimination of the western parts of the contributing areas for these wells.

The anticipated increased ground-water withdrawals and drought conditions caused a greater north-south component of ground-water flow in the vicinity of the Rock County Rural Water well field and changes in the contributing areas of the wells (figs. 10c and 10d). The contributing area for well RW7 in simulation SS3 increased in width by as much as 0.25 miles and increased in length to the northwest nearly 0.5 miles compared to simulation SS1 (figs. 9c and 10c). The contributing area for well RW4 in this simulation (SS3) extends to the north rather than to the west, as it did in the calibrated steady-state and SS1 simulations (fig. 10c). In simulation SS4, the result of the greater north-south orientation of the contributing areas of the wells and the presence of the two southern hypothetical wells (H4 and H5) is a constriction or narrowing of the contributing areas for many of the pumped wells due to the effects of nearby wells (fig. 10d). Much of the area from the Rock River to the western aquifer boundary between well H1 and well H5 constitutes a probable contributing area for one or more of the pumped wells. The simulated contributing areas for the three northern hypothetical wells are slightly larger in areal extent for drought conditions (simulation SS4) than for normal precipitation (simulation SS2).

Ground-Water Quality

The results of water-quality sampling are consistent with field measurements of surface-water/ground-water interactions and simulation results in indicating that water and some contaminants move from the Rock River to supply wells less than 500 ft from the river. Comparison of concentrations of herbicides and metabolites in samples from supply wells, the Rock River, and monitoring wells in the contributing areas of ground-water flow to supply wells indicates that the herbicides and metabolites detected at supply wells originate primarily from induced infiltration of water from the Rock River, but that sources of some herbicides and metabolites also occur in the ground-water contributing areas to supply wells. While some of the relatively low nitrate-N concentrations at supply wells could be the result of induced infiltration from the river, nitrate-N concentrations at supply wells did not indicate substantial effects from induced infiltration. Other contaminants or tracers that were detected in the river, such as fecal coliform and fecal streptococcal bacteria and caffeine, were not detected at supply wells near the river. These results indicate that only some contaminants that are present in relatively large concentrations and are not controlled by biochemical processes occurring in the aquifer are reaching the supply wells near the river.

SUMMARY

Increased demand for ground water in southwestern Minnesota has resulted in increased withdrawals from surficial aquifers. The Rock River Valley aquifer is currently the only viable water source for the City of Luverne and the Rock County Rural Water District. Ground-water flow in the aquifer is integrally linked to flow in the Rock River. Three public supply well fields in Rock County are located near the Rock River and have the potential to interact with the river. The Rock River Valley aquifer consists of a surficial sand and gravel unit that underlies the entire Rock River Valley and a buried sand and gravel unit that is present only in the vicinity of the Luverne Municipal and Airport well fields. The surficial and buried units of the aquifer are separated by a clay and till layer ranging in thickness from 1 to 38 ft. The confining unit is generally less than 10 ft thick, and in many cases less than 3 ft thick. The combined maximum saturated thickness of the aquifer is 52 ft, with a median of 22 ft. The thickness of the buried unit ranges from 3 to 17 ft and is generally composed of coarser material and is thicker underlying the Luverne Airport well field than it is underlying the Luverne Municipal well field.

Recharge to the Rock River Valley aquifer occurs primarily by infiltration of precipitation to the saturated zone (areal recharge) and by induced infiltration from the Rock River due to withdrawals by supply wells near the river. Discharge from the aquifer occurs as leakage to streams, ground-water evapotranspiration, and ground-water withdrawals by wells. Water levels in wells completed in the aquifer generally fluctuate 3–5 ft annually in response to seasonal variations in recharge and discharge. Areal recharge to the aquifer ranged from 6.9 to 8.1 in., with an average of 7.2 in., during 1995 and from 2.9 to 8.2 in. with an average of 4.8 in., during 1996, based on hydrograph analysis.

The regional directions of ground-water flow in the Rock River Valley aquifer are from the aquifer margins toward the Rock River and from north to south. The Rock River is the major discharge area within the stream-aquifer system. The horizontal hydraulic gradient in the aquifer ranges from 5 to 20 ft/mi. The Rock River is a gaining stream in most reaches, but is losing water to the aquifer in the vicinity of well fields in close proximity to the river.

A numerical model of ground-water flow was constructed based on knowledge of the hydrogeologic setting, aquifer characteristics, distribution and amount of recharge and discharge, and aquifer boundaries. The simulated water budget for the calibrated steady-state simulation indicated that areal recharge accounts for 38 percent of the

sources of water to the Rock River Valley aquifer and leakage from streams to the aquifer contributes 58.7 percent. The largest discharge from the aquifer is leakage from the aquifer to streams (71.1 percent). The other major discharges from the aquifer are ground-water evapotranspiration (20.3 percent) and withdrawals by wells (8 percent). The net stream-aquifer leakage is approximately 5 ft^3/s from the aquifer to the streams, indicating that the Rock River is a gaining stream overall in the model area. The simulated contributing areas for the wells in the three well fields extend to the aquifer boundaries on the west and are generally truncated at the Rock River. The simulated contributing areas for the Luverne Municipal well field also extend approximately 1 mi to the north of the well field.

The simulated transient water budget for 1996 indicated that the principal sources of water to the Rock River Valley aquifer were as follows: (1) winter, spring, and late summer stress periods—leakage from streams to the aquifer and water released from storage and (2) early summer and fall stress periods—areal recharge and leakage from streams to the aquifer. The amount and percentage of water released from storage is greatest during the late summer stress period. The principal discharges from the aquifer are: (1) winter and spring stress periods—leakage from the aquifer to streams and ground-water withdrawals, (2) early summer stress period—addition to storage, leakage from the aquifer to streams, and ground-water evapotranspiration, (3) late summer stress period—leakage from the aquifer to streams and ground-water evapotranspiration, and (4) fall stress period—leakage from the aquifer to streams and addition to storage. The amount and percentage of addition to storage during the early summer and fall stress periods is much greater than during the other stress periods.

The herbicides atrazine, alachlor, metolachlor, acetachlor, and cyanazine, and metabolites of these herbicides occurred in concentrations of 0.05 to 11.5 µg/L in the Rock River at Luverne during major runoff events following application of herbicides in the spring. Concentrations of herbicides and metabolites in samples collected prior to herbicide application in the spring or in the fall were generally smaller. Atrazine and metabolites, alachlor ESA (a metabolite of alachlor), metolachlor and metabolites metolachlor ESA and metolachlor OA, and acetochlor metabolites acetochlor ESA and acetochlor OA were detected at concentrations of 0.05 to 2.8 µg/L in municipal supply wells less than 500 ft from the river during November 1995 through August 1997. Herbicides and metabolites detected in supply wells originate primarily from induced infiltration of water from the Rock River, but sources of some herbicides and metabolites also occur in the ground-water contributing areas. Ten herbicides or metabolites were detected in supply wells located near the Rock River in the Luverne Municipal and Rock County Rural Water well fields: atrazine, deethylatrazine, deisopropylatrazine, hydroxyatrazine, alachlor ESA, metolachlor, metolachlor ESA, metolachlor OA, acetochlor ESA, and acetochlor OA. Alachlor ESA and metolachlor ESA detected in supply wells in the Luverne Municipal well field are likely derived both from the Rock River and ground water in the contributing area to the supply wells. Atrazine, deethylatrazine, deisopropylatrazine, hydroxyatrazine, metolachlor ESA, and metolachlor OA detected in supply wells in the Rock County Rural Water well field are likely derived both from the Rock River and ground water in the contributing area to the supply wells. Nitrate-Nconcentrations in supply wells and in the ground-water contributing area to the Luverne Municipal well field were generally less than 1.5 mg/L. Nitrate-N concentrations of 2.4–8.5 mg/L in the Rock River in the Rock County Rural Water well field and 14–18 mg/L in the ground-water contributing area to the Rock County Rural Water supply wells are not having a substantial affect on nitrate-N nitrogen concentrations in most supply wells. Isotopic mixing calculations indicate that proportions of river water withdrawn from supply wells less than 500 ft from the river range from 5 to 60 percent of total withdrawals.

Simulated steady-state streamflow losses due to induced infiltration of river water into the aquifer in response to ground-water pumping in the well fields were approximately 0.5 ft^3/s in both the Luverne Municipal and Rock County Rural Water well fields; no induced infiltration in the river reach nearest the Luverne Airport well field occurs. Simulated streamflow losses due to interception of ground-water flow that would have discharged into the river without pumping wells (intercepted subsurface flow) were 0.5, 0.3, and 0.3 ft^3/s for the Luverne Municipal, Luverne Airport, and Rock County Rural Water well fields, respectively. Total simulated streamflow losses were thus 2.1 ft^3/s. Because an average of 1.5 ft^3/s of the water pumped by Luverne is returned to the Rock River as wastewater discharge, the net steady-state simulated streamflow loss for the study area is 0.6 ft^3/s. The streamflow loss as a result of ground-water withdrawals is insignificant in comparison to typical streamflow (median streamflow at Luverne during 1996–97 was 110 ft^3/s) and is likely to have a measurable effect on streamflow only during low-flow conditions of less than about 10 ft^3/s.

A series of hypothetical model simulations was done to evaluate the response of the stream-aquifer system in the model area to anticipated increases in ground-water withdrawals from the Luverne and Rock County Rural Water well fields. The precipitation regimes simulated were the 30-year (1961–90) average (normal) annual precipitation and drought-condition precipitation levels. The additional losses to the ground-water system for the simulations with anticipated increased ground-water withdrawals and normal precipitation compared to the calibrated steady-state simulation were 0.7 ft^3/s, with 0.6 ft^3/s of the total loss due to increased ground-water withdrawals and 0.1 ft^3/s due to less net recharge. These losses were balanced by a decrease of 0.7 ft^3/s in net leakage of ground water from the aquifer to the streams. For the steady-state simulations with anticipated increased ground-water withdrawals and drought conditions, the additional losses were 3.8 ft^3/s, also balanced by the simulated decrease in net leakage from the aquifer to the streams.

The steady-state simulations with anticipated increased ground-water withdrawals and normal precipitation indicated that the increased withdrawals resulted in an increase in induced infiltration from the Rock River of 0.1 ft^3/s for the Luverne Municipal well field and 0.3 ft^3/s for the Rock County Rural Water well field. The simulated increased interception of ground-water flow east of the Luverne Airport well field was 0.2 ft^3/s. The increases in induced infiltration and interception of ground-water flow for the three well fields represented less than 1 percent of the simulated streamflows. The steady-state simulations with drought conditions resulted in induced infiltration from the Rock River of 0.68 ft^3/s for the Luverne Municipal well field, constituting approximately 30 percent of the flow in the river. The anticipated increased ground-water withdrawals under drought conditions with a 7-well scenario for the Rock County Rural Water well field resulted in a simulated streamflow loss constituting nearly 65 percent of the simulated streamflow in the river. In the simulation with a 12-well scenario for the Rock County Rural Water well field, the streamflow loss constituted approximately 30 percent of the streamflow in the river. The transient simulations with anticipated increased ground-water withdrawals and drought conditions indicated simulated reductions in streamflow (as a percentage of streamflow in the Rock River) near the three well fields were least (<1.5 percent) during the spring and early summer stress periods, with streamflows of approximately 100 to 300 ft^3/s. The simulated reductions were greatest (8 to 10 percent) during the late summer stress period, with simulated streamflows of less than 10 ft^3/s.

The steady-state simulations with anticipated increased ground-water withdrawals and normal precipitation indicated maximum drawdowns ranging from 0.5 to 1.4 ft near the three well fields. The simulated drawdowns near the wells closest to the Rock River were less than 0.1 ft due to the strong influence of stream stage on hydraulic heads near the river. The steady-state simulation with anticipated increased ground-water withdrawals, normal precipitation, and 12 pumped wells for the Rock County Rural Water well field indicated both rises and declines in hydraulic heads. The transient simulations with anticipated increased ground-water withdrawals and normal precipitation indicated maximum seasonal drawdowns ranging from 0.5 to 1.7 ft near the three well fields, with no annual decline in hydraulic heads during the 3-year simulation period. The steady-state simulations with drought conditions indicated maximum drawdowns ranging from 3.8 to 7.0 ft near the three well fields. The transient simulations with drought conditions indicated declines in hydraulic heads ranging from about 0.2 to 0.4 ft/yr in the vicinity of the three well fields, except for near the Rock River.

The simulations with anticipated increased ground-water withdrawals and normal precipitation indicated no appreciable changes in contributing areas for wells in the Luverne Municipal well field. The contributing area for well LUV23 in the Luverne Airport well field was somewhat enlarged due to the increased withdrawals. The simulations with drought conditions indicated the expansion of simulated contributing areas by as much as 0.25 mi for pumped wells that are distant from the Rock River. In the simulation with 12 pumped wells in the Rock County Rural Water well field, much of the area from the Rock River to the western aquifer boundary and between the northernmost and southernmost wells constituted a probable contributing area for one or more of the pumped wells.

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Supplemental Information

Table 1. Aquifer hydraulic properties measured during 1996–97, eastern Rock County, Minnesota

[K, horizontal hydraulic conductivity; ft, feet; d, day; S, storage coefficient; Sy, specific yield; --, not determined; high, at least one estimated value for horizontal hydraulic conductivity is greater than 40 feet per day; medium, all estimated values for horizontal hydraulic conductivity are less than 40 feet per day and at least one estimated value is greater than 10 feet per day; low, all estimated values for horizontal hydraulic conductivity are less than 10 feet per day; ft/d, feet per day, wells shown in figures 2a-2d]

		K (ft/d)				S or Sy	
	K categorization	Single-well aquifer test, Theis recovery[1]	Single-well aquifer test, Hurr & Worthington[2]	Slug test, Bouwer & Rice[3]	Multi-well aquifer test	Multi-well aquifer test	Well depth (ft below land surface)
Multi-well Aquifer Test							
LUV23 - pumped well							32.0
RR32 - observation well							12.5
Analysis method - of pumping or recovery phase - of observation or pumped well							
Theis - pumping - observation well[4]					384	0.050	
Cooper-Jacob - pumping - observation well[5]					379	0.047	
Neuman - pumping - observation well[6]					399	0.045	
Theis - recovery - observation well[1]					354	0.026	
Theis - pumping - pumped well[4]					379	--	
Cooper-Jacob - pumping - pumped well[5]					379	--	
Single-Well Aquifer Tests							
LO17	high	19	76	28			16.0
RR13	high	598	250	55			18.0
RR17	high	528	43	16			20.0
RR19	high	54	125				14.0
RR27	high	25	128				34.0
RR32	high	35	44	40			12.5
RR35	high	386	120				17.0
RR36	high	691	175				13.0
RR38	high	368	121	14			19.0
RR39	high	11	29	53			17.0
RR4	high	51	12				13.9
RR44	high		199				33.0
RR46	high		87				43.0
RR48	high		44				20.0
RR50	high		274				17.0
RR51	high		99				38.0
RR52	high		117				41.0
RR9	high	342	168	105			20.0
RR6	medium			14			20.0
DNR-67006	medium			22			15.5
RR21	medium	6.7	16				20.0
RR29	medium	2.8	8.6	31			14.0
RR30	medium	1.4	1.9	11			14.0
RR2	medium	4.7	13				11.1
RR3	low	3.3	1.5				14.0
RR1	low			0.2			19.1
RR12	low			1.3			12.0
RR22	low	0.7	0.7				13.0
RR23	low			3.1			14.0
RR24	low	0.9	2.9				30.5
RR25	low			8.7			18.5
RR31	low	0.6	2.7	3.3			15.0
RR33	low			0.3			9.5
RR37	low			0.2			23.0
RR43	low			0.1			20.5
RR5	low			0.6			17.0
RR7	low			0.04			17.1
RR45	low[7]						31.0
RR8	low[7]						20.0
RR49	low[7]						30.0

Table 1. Aquifer hydraulic properties measured during 1996–97, eastern Rock County, Minnesota (Continued)

[K, horizontal hydraulic conductivity; ft, feet; d, day; S, storage coefficient; Sy, specific yield; --, not determined; high, at least one estimated value for horizontal hydraulic conductivity is greater than 40 feet per day; medium, all estimated values for horizontal hydraulic conductivity are less than 40 feet per day and at least one estimated value is greater than 10 feet per day; low, all estimated values for horizontal hydraulic conductivity are less than 10 feet per day; ft/d, feet per day, wells shown in figures 2a-2d]

	K (ft/d)			
	Single-well aquifer test, Theis recovery[1]	Single-well aquifer test, Hurr & Worthington[2]	Slug test, Bower & Rice[3]	Well depth (ft below land surface)
Statistics				
All Single-Well Test Sites				
maximum	691	274	105	43.0
90th percentile	535	187	53	33.2
75th percentile	349	124	28	20.0
median	22	60	11	17.1
25th percentile	3.2	12	0.6	14.0
10th percentile	0.88	2.3	0.20	12.9
minimum	0.6	0.7	0.04	9.5
average	156	83	19	19.9
standard deviation	233	80	26	8.3
number of sites	20	26	21	39
High K Sites				
maximum	691	274	105	43.0
90th percentile	591	214	75	38.9
75th percentile	422	158	54	29.8
median	198	119	40	18.5
25th percentile	33	52	22	16.3
10th percentile	20	39	15	13.6
minimum	11	12	14	12.5
average	259	117	44	22.6
standard deviation	256	74	31	10.2
number of sites	12	18	7	18
Medium K Sites				
maximum	6.7	16	31	20.0
90th percentile	5.9	15	28	20.0
75th percentile	4.7	13	24	17.8
median	3.3	8.6	18	14.0
25th percentile	2.8	1.9	13	14.0
10th percentile	2.0	1.7	12	12.8
minimum	1.4	1.5	11	11.1
average	3.8	8.2	20	15.5
standard deviation	2.0	6.5	9	3.3
number of sites	5	5	4	7
Low K Sites				
maximum	0.9	2.9	8.7	31.0
90th percentile	0.86	2.9	3.8	28.3
75th percentile	0.8	2.8	2.7	20.4
median	0.7	2.7	0.45	17.8
25th percentile	0.65	1.7	0.2	14.3
10th percentile	0.62	1.1	0.09	12.3
minimum	0.6	0.7	0.04	9.5
average	0.73	2.1	1.8	18.6
standard deviation	0.15	1.2	2.7	6.3
number of sites	3	3	10	14

[1] Kruseman and deRidder, 1990, p. 232-233.

[2] Kruseman and de Ridder, 1990, p. 226-229.

[3] Bouwer and Rice, 1976.

[4] Theis, 1935

[5] Cooper and Jacob, 1946

[6] Neuman, 1974.

[7]Based upon very slow well response, not possible to calculate value

Table 2. Streambed hydraulic conductivity determined using field constant-head permeameter tests, eastern Rock County, Minnesota

[K_s, streambed hydraulic conductivity; ft, feet; d, day; REW, right edge of water when facing downstream; <0.01, K_s too small to measure by permeameter method]

Site (Shown in figures 2a-2d)	Date measured	Permeameter location from REW (ft)	Depth of streambed tested (ft)	Average K_s at measurement location (ft/d)	Stream width (ft)	Median K_s for stream section (ft/d)
Rock River sites (arranged in upstream to downstream order)						
SW3	7/30/96	10	0.79	0.20	70	40
SW3	7/30/96	40	0.98	14		
SW3	7/30/96	50	0.88	66		
SW3	7/30/96	60	1.28	115		
SW21	7/31/96	5	0.58	45	44	27
SW21	7/31/96	15	0.81	27		
SW21	7/31/96	25	0.59	36		
SW21	7/31/96	35	0.64	20		
SW21	7/31/96	40	0.50	6.5		
SW22	7/30/96	10	0.99	48	62	68
SW22	7/30/96	20	0.94	88		
SW22	7/30/96	30	0.90	126		
SW22	7/30/96	44	1.01	21		
SW6	7/31/96	30	1.03	62	60	38
SW6	7/31/96	40	1.10	6.7		
SW6	7/31/96	50	1.11	38		
SW6D	7/31/96	2	0.93	36	50	25
SW6D	7/31/96	10	1.14	69		
SW6D	7/31/96	20	0.73	14		
SW6D	7/31/96	30	0.94	6.4		
SW7	8/8/96	7	1.01	86	92	43
SW7	8/8/96	27	0.99	61		
SW7	8/8/96	47	0.81	43		
SW7	8/8/96	67	0.78	2.0		
SW7	8/8/96	87	0.61	0.48		
SW8	8/1/96	10	0.97	3.4	100	26
SW8	8/1/96	30	1.07	26		
SW8	8/1/96	50	0.98	18		
SW8	8/1/96	70	1.12	27		
SW8	8/1/96	90	1.21	300		
SW10	8/1/96	10	1.17	4.9	70	5.3
SW10	8/1/96	20	1.07	1.4		
SW10	8/1/96	30	1.01	5.6		
SW10	8/1/96	40	0.92	14		
SW19	8/7/96	8	0.61	3.3	56	40
SW19	8/7/96	18	0.91	40		
SW19	8/7/96	28	1.15	189		
SW19	8/7/96	38	0.99	52		
SW19	8/7/96	48	1.00	11		
SW24	8/7/96	5	0.93	16	60	10
SW24	8/7/96	15	0.77	37		
SW24	8/7/96	25	0.96	4.0		
SW24	8/7/96	35	0.93	2.2		
SW20	8/7/96	4	0.91	26	40	49
SW20	8/7/96	12	0.98	34		
SW20	8/7/96	20	1.24	282		
SW20	8/7/96	28	1.04	49		
SW20	8/7/96	36	0.99	109		
SW12	8/2/96	5	0.99	167	50	163
SW12	8/2/96	15	0.83	163		

Table 2. Streambed hydraulic conductivity determined using field constant-head permeameter tests, eastern Rock County, Minnesota (Continued)

[K_s, streambed hydraulic conductivity; ft, feet; d, day; REW, right edge of water when facing downstream; <0.01, K_s too small to measure by permeameter method]

Site (Shown in figures 2a-2d)	Date measured	Permeameter location from REW (ft)	Depth of streambed tested (ft)	Average K_s at measurement location (ft/d)	Stream width (ft)	Median K_s for stream section (ft/d)
SW12	8/2/96	25	0.67	115		
SW12	8/2/96	35	0.99	163		
SW12	8/2/96	45	1.06	136		
SW13	8/1/96	5	0.95	0.32	51	197
SW13	8/1/96	15	0.89	185		
SW13	8/1/96	25	1.03	197		
SW13	8/1/96	35	0.99	401		
SW13	8/1/96	45	1.09	305		
Statistics for Rock River sites						
maximum			1.28	401	100	197
90th percentile			1.13	186	88	144
75th percentile			1.03	104	70	49
median			0.98	37	60	40
25th percentile			0.88	12	50	26
10th percentile			0.66	3.0	45	13
minimum			0.50	0.20	40	5.3
number of measurements			58	58	13	13
average			0.94	71	62	56
standard deviation			0.17	89	18	58
Rock River tributary sites (arranged in upstream to downstream order)						
SW4	7/30/96	10	0.89	226	50	140
SW4	7/30/96	25	1.23	140		
SW4	7/30/96	33	1.00	13		
SW5	7/30/96	5	1.00	<0.01	8	<0.01
SW26	6/19/96	5	1.15	0.09	10	0.09
SW27	8/1/96	5	1.00	<0.01	10	<0.01
SW28	8/1/96	3	0.89	0.15	6	0.15
SW9	7/31/96	17	0.82	33	40	40
SW9	7/31/96	37	1.12	47		
SW11	8/6/96	5	0.48	<0.01	10	<0.01
Statistics for Rock River tributary sites						
maximum			1.23	226	50	140
90th percentile			1.16	148	44	80
75th percentile			1.09	43	25	20
median			1.00	6.7	10	0.09
25th percentile			0.89	0.02	9	<0.01
10th percentile			0.79	<0.01	7	<0.01
minimum			0.48	<0.01	6	<0.01
number of measurements			10	10	7	7
average			0.96	46	19	26
standard deviation			0.21	77	18	52

Table 3. Stream discharge and estimated stream-aquifer leakage under low-flow conditions during 1995–97, eastern Rock County, Minnesota

[--, no measurement; ft^3/s, cubic feet per second; $ft^3/s/mi$, cubic feet per second per mile; R., River; LMWF, reach affected by Luverne Municipal Well Field; LAWF, reach affected by Luverne Airport Well Field; RWWF, reach affected by Rural Water Well Field; red numbers indicate reaches with streamflow losses that are greater than discharge measurement uncertainty of 5 percent; blue numbers indicate reaches with streamflow gains that are greater than discharge measurement uncertainty of 5 percent. Measurement sites are shown on fig. 2a, 2b, 2c, and 2d]

				October 6-8, 1997				January 22-25, 1996				July 29-August 1, 1996			
Rock River site (Shown in figures 2a-2d)	Tributary site	Distance from last site on Rock R. (river miles)	Cumulative distance from SW3 (river miles)	Rock River discharge (ft^3/s)	Tributary discharge (ft^3/s)	River reach gain (+) or loss (-)[1] (ft^3/s)	River reach gain (+) or loss (-) ($ft^3/s/mi$)	Rock River discharge (ft^3/s)	Tributary discharge (ft^3/s)	River reach gain (+) or loss (-)[1] (ft^3/s)	River reach gain (+) or loss (-) ($ft^3/s/mi$)	Rock River discharge (ft^3/s)	Tributary discharge (ft^3/s)	River reach gain (+) or loss (-)[1] (ft^3/s)	River reach gain (+) or loss (-) ($ft^3/s/mi$)
SW3			0	23.3 ± 0.6				24.8 ± 0.6				33.3 ± 0.8			
	SW4				2.60 ± 0.1				2.43 ± 0.1				9.70 ± 0.2		
	SW5				0.89 ± 0.0				1.46 ± 0.0				1.81 ± 0.0		
SW21		5.95	5.95	26.0 ± 0.7		-0.79	-0.13	28.5 ± 0.7		-0.19	-0.03	49.1 ± 1.2		4.29	0.72
SW22		2.58	8.53	28.6 ± 0.7		2.60	1.01	35.4 ± 0.9		6.90	2.67	51.2 ± 1.3		2.10	0.81
	SW26				0.04 ± 0.0				---				0.20 ± 0.0		
SW6	LMWF	1.15	9.68	26.6 ± 0.7		-2.04	-1.77	28.6 ± 0.7		-6.80	-5.91	51.0 ± 1.3		-0.40	-0.35
	Luverne Wastewater Plant Discharge				1.03				1.50				1.75		
	SW27				0				trace				trace		
SW7		1.09	10.77	--				31.1 ± 0.8		1.00	0.92	55.9 ± 1.4		3.15	2.89
	SW28				0.09 ± 0.0				---				0.21 ± 0.0		
SW8	LAWF	2.09	12.86	28.7 ± 0.7		0.98	0.31	35.5 ± 0.9		4.40	2.11	52.8 ± 1.3		-3.31	-1.58
	SW9				1.90 ± 0.0				2.22 ± 0.1				7.61 ± 0.2		
SW10		3.33	16.19	34.6 ± 0.9		4.00	1.20	32.0 ± 0.8		-5.72	-1.72	58.6 ± 1.5		-1.81	-0.54
SW19	RWWF	1.77	17.96	31.2 ± 0.8		-3.40	-1.92	36.9 ± 0.9		4.90	2.77	61.7 ± 1.5		3.10	1.75
SW24	RWWF	1.10		35.3 ± 0.9		4.10	3.73	---				---			
SW20	RWWF	1.07	19.03	35.9 ± 0.9		0.60	0.56	32.8 ± 0.8		-4.10	-1.89	61.1 ± 1.5		-0.60	-0.28
SW12		1.34	20.37	35.2 ± 0.9		-0.70	-0.52	31.7 ± 0.8		-1.10	-0.82	65.2 ± 1.6		4.10	3.06
	SW11				0.04 ± 0.0				---				1.64 ± 0.0		
SW13		5.41	25.78	38.6 ± 1.0		3.36	0.62	38.6 ± 1.0		6.90	1.28	67.9 ± 1.7		1.06	0.20
Total for study area					6.59	8.71			7.61	6.19			22.92	11.68	
Change from SW3 to S13				15.3				13.8				34.6			
Average							0.34				0.24				0.45

[1]After correction for tributary inflow

Table 4. Initial and final (best-match) calibration values of hydraulic properties and fluxes in numerical model of Rock River Valley aquifer, eastern Rock County, Minnesota

[ft, feet; ft/d, feet per day; in./yr, inches per year]

Hydraulic property or flux and hydrogeologic unit	Initial value	Final calibration value
Areal recharge to aquifer (in./yr) (Steady-state simulation)	6.0	7.0
Horizontal hydraulic conductivity (ft/d)		
Surficial unit of aquifer		
Main area	190	100
Margins	190	50
Confining units		
Main area	1.0	1.0
Luverne well fields area	1.0	1.5
Buried unit of aquifer		
Main area	190	100
Luverne Airport well field area	380	350
Northwest boundary area	100	50
Vertical hydraulic conductivity (ft/d)		
Surficial unit of aquifer		
Main area	19	10
Margins	19	5
Confining units		
Main area	0.001	0.001
Luverne well fields area	0.015	0.15
Buried unit of aquifer		
Main area	19	10
Luverne Airport well field area	38	35
Northwest boundary area	10	5
Hydraulic conductivity of streambed (ft/d)		
Rock River and Champepadan Creek	30	30
Elk Creek	3.0	3.0
Mound and Ash Creeks	0.1	0.1
Minor drainages	0.01	0.01
Specific yield for surficial unit of aquifer		
Main area	0.15	0.10
Margins	0.10	0.10
Storage coefficient		
Confining units		
Main area	0.00001	0.00001
Luverne well fields area	0.00001	0.0005
Buried unit of aquifer		
Main area	0.01	0.01
Luverne Airport well field area	0.05	0.05
Northwest boundary area	0.005	0.005
Maximum ground-water evapotranspiration rate (in./yr)	30.8	30.8
Ground-water evapotranspiration extinction depth (ft)	7	5

Table 5. Measured and model-computed streamflows in the Rock River and leakage between the Rock River Valley aquifer and the Rock River for the steady-state simulation, eastern Rock County, Minnesota

[All values are in cubic feet per second; positive number for stream-aquifer leakage indicates a gain in streamflow and a loss from the aquifer; negative number for stream-aquifer leakage indicates a reduction in streamflow and a gain to the aquifer]

	Measured		Model-computed	
Surface-water site (shown in figures 2a-2d)	Streamflow	Stream-aquifer leakage[1]	Streamflow	Stream-aquifer leakage[1]
SW3	23.3	-0.79	23.6	1.5
SW21	26.0	2.60	27.9	1.1
SW22	28.6	-2.04	29.0	-0.5
SW6	26.6	0.98	28.5	0.9
SW8	28.7	4.00	30.4	0.8
SW10	34.6	-3.40	32.8	-0.3
SW19	31.2	4.10	32.5	-0.5
SW24	35.3	0.60	32.0	0.0
SW20	35.9	-0.70	32.0	-0.6
SW12	35.2	3.36	31.4	3.1
SW13	38.6		34.5	
Total net leakage		8.71		5.5

[1]Computation of stream-aquifer leakage accounts for tributary inflow

Table 6. Simulated water budget for steady-state simulation and for transient simulation by stress period, for 1996, eastern Rock County, Minnesota

[Numbers in parentheses are percentages of total sources or of total discharges; --, not applicable; ft^3/s, cubic feet per second; <, less than]

Budget component	Steady-state simulation	Transient simulation: Source (ft^3/s), Stress period				
		Winter (December-February)	Spring (March-April)	Early summer (May-June)	Late summer (July-September)	Fall (October-November)
Areal recharge from precipitation (to layer 1)	14.89 (38.0)	0	0	68.72 (87.7)	0	20.37 (74.1)
Lateral subsurface inflow (layer 1)						
Northern boundary	0.22 (0.6)					
Champepadan Creek boundary	0.20 (0.5)					
West-central boundary	0.86 (2.2)					
Subtotal	1.28 (3.3)	2.85 (20.7)	2.67 (18.9)	2.61 (3.3)	2.69 (11.2)	2.55 (9.3)
Stream-aquifer leakage (layer 1)	22.99 (58.7)	6.16 (44.9)	6.76 (47.8)	7.05 (9.0)	7.96 (33.2)	4.58 (16.7)
Release from storage						
Layer 1	--	4.17	4.03	0.002	11.12 (83.4)	0.0002
Layer 2	--	0.08	0.10	<0.0001	0.62 (4.6)	0.0001
Layer 3	--	0.47	0.57	<0.0001	1.60 (12.0)	0.0003
Subtotal	--	4.72 (34.4)	4.70 (33.3)	0.002 (.003)	13.34 (55.6)	0.0006 (.002)
Total	39.16	13.73	14.13	78.38	23.99	27.50
Leakage between model layers						
Layer 1	1.14					
Layer 2						
Layer 1	2.28					
Layer 3	1.04					
Subtotal	3.32					
Layer 3	2.18					
Total	6.64					

Table 6. Simulated water budget for steady-state simulation and for transient simulation by stress period, for 1996, eastern Rock County, Minnesota (Continued)

[Numbers in parentheses are percentages of total sources or of total discharges; --, not applicable; ft^3/s, cubic feet per second; <, less than]

Budget component	Steady-state simulation	Transient simulation: Discharge (ft^3/s): Stress period: Winter (December-February)	Spring (March-April)	Early summer (May-June)	Late summer (July-September)	Fall (October-November)
Pumpage						
Layer 1	2.02 (5.1)	1.64	1.64	1.88	1.94	1.71
Layer 2	0.0004 (<0.1)	0.05	0.04	0.04	0.05	0.06
Layer 3	1.13 (2.9)	1.19	1.17	1.00	1.19	1.10
Subtotal	3.15 (8.0)	2.88 (21.1)	2.85 (20.2)	2.92 (3.7)	3.18 (13.3)	2.87 (10.4)
Ground-water evapotranspiration (layer 1)	7.94 (20.3)	0	0	11.25 (14.4)	8.92 (37.2)	0
Lateral subsurface outflow (layer 1)						
Southern boundary	0.22 (0.6)	0.21 (1.5)	0.19 (1.3)	0.22 (0.3)	0.22 (0.9)	0.22 (0.8)
Stream-aquifer leakage (layer 1)	27.85 (71.1)	9.62 (70.4)	10.35 (73.3)	27.08 (34.6)	11.67 (48.6)	15.75 (57.1)
Addition to storage						
Layer 1	--	0.56	0.42	30.93	0.00004	7.18
Layer 2	--	0.20	0.18	1.49	0.00000	0.46
Layer 3	--	0.19	0.14	4.36	0.00000	1.12
Subtotal	--	0.95 (7.0)	0.74 (5.2)	36.78 (47.0)	0.00004 (0.00)	8.76 (31.7)
Total	39.16	13.66	14.13	78.25	23.99	27.60
Net loss from aquifer due to stream-aquifer leakage	4.86	3.46	3.59	20.03	3.71	11.17
Difference: Sources - discharges	0.00	0.07	0.00	0.13	0.00	-0.10
Leakage between model layers						
Layer 1	2.28					
Layer 2						
Layer 1	1.14					
Layer 3	2.18					
Subtotal	3.32					
Layer 3	1.04					
Total	6.64					

Table 7. Initial and final (best-match) calibration values of areal recharge and ground-water evapotranspiration for transient simulation, eastern Rock County, Minnesota

[All values are in inches per year]

Stress period	Recharge		Ground-water evapotranspiration	
	Initial value	Final calibration value	Initial value	Final calibration value
Winter 1995	0.69	0.00	0.00	0.00
Spring 1995	14.36	32.31	0.0	0.0
Early summer 1995	10.77	0.0	53.02	22.72
Late summer 1995	10.83	0.0	56.24	64.27
Fall 1995	4.44	4.44	0.0	0.0
Winter 1996	2.73	0.0	0.0	0.0
Spring 1996	1.10	0.0	0.0	0.0
Early summer 1996	14.05	32.31	57.92	24.82
Late summer 1996	8.21	0.0	52.41	59.90
Fall 1996	12.78	9.58	0.0	0.0
Winter 1997	4.91	0.0	0.0	0.0
Spring 1997	3.71	32.31	0.0	0.0
Early summer 1997	12.65	0.0	58.62	25.12
Late summer 1997	4.96	0.0	62.35	71.25
Fall 1997	3.53	3.53	0.0	0.0

Table 8. Measured and model-computed streamflow at Luverne for transient simulation, eastern Rock county, Minnesota

[ft^3/s, cubic feet per second]

Stress period	Measured streamflow at Luverne (ft^3/s)	Model-computed streamflow at Luverne (ft^3/s)	Difference (percent)
[1]Winter 1995	49	45	8.2
[2]Spring 1995	125	123	1.6
[3]Early summer 1995	367	343	6.5
[4]Late summer 1995	111	101	9.0
[5]Fall 1995	336	314	6.5
Winter 1996	49	45	8.2
Spring 1996	125	117	6.4
Early summer 1996	367	339	7.6
Late summer 1996	111	104	6.3
Fall 1996	141	135	4.3
Winter 1997	60	56	6.8
Spring 1997	1162	1090	6.2
Early summer 1997	288	268	6.9
Late summer 1997	124	115	7.3
Fall 1997	45	44	2.2

[1]Winter stress period is from December through February
[2]Spring stress period is from March through April
[3]Early summer stress period is from May through June
[4]Late summer stress period is from July through September
[5]Fall stress period is from October through November

Table 9. Sensitivity of simulated hydraulic heads in the Rock River Valley aquifer and simulated streamflows in the Rock River to changes in values of hydrologic properties or conditions in steady-state simulation, eastern Rock County, Minnesota

[ft, feet; ft/d, feet per day; in/yr, inches per year; ft^3/s, cubic feet per second. Mean deviations of hydraulic heads are deviations from values calculated by best-match simulation]

		Hydraulic head (ft)			Streamflow (ft^3/s)		
Hydrologic property or condition	Multiplied by factor of (or other specified variation)	Algebraic value of mean deviation	Absolute value of mean deviation	Range	SW6	SW8	SW20
Areal recharge to layer 1	1.5	0.97	0.97	0.00 to 3.35	30.4	32.9	35.4
Areal recharge to layer 1	0.5	-1.32	1.32	-5.91 to 0.00	26.4	27.6	28.3
Aquifer horizontal hydraulic conductivities of layer 1	2.0	-0.91	0.99	-5.51 to 0.72	29.1	31.5	33.5
Aquifer horizontal hydraulic conductivities of layer 1	0.5	0.67	0.86	-1.16 to 4.78	27.8	29.3	30.7
Aquifer horizontal hydraulic conductivities of layer 3	2.0	-0.20	0.29	-2.84 to 1.23	28.4	30.5	32.2
Aquifer horizontal hydraulic conductivities of layer 3	0.5	0.13	0.26	-2.17 to 2.13	28.5	30.2	31.9
Vertical hydraulic conductivities of confining unit (layer 2)	10	-0.03	0.04	-0.84 to 0.05	28.5	30.4	32.0
Vertical hydraulic conductivities of confining unit (layer 2)	0.1	0.14	0.25	-1.23 to 2.94	28.5	30.3	31.9
Maximum ground-water evapotranspiration rate	[1]44 in./yr	-0.22	0.22	-0.77 to 0.00	27.7	29.3	30.2
Maximum ground-water evapotranspiration rate	[2]22 in./yr	0.22	0.22	0.00 to 0.66	29.1	31.2	33.4
Ground-water evapotranspiration extinction depth	[3]10 ft	-1.30	1.30	-3.03 to 0.00	24.9	25.6	25.5
Ground-water evapotranspiration extinction depth	[4]3 ft	0.47	0.47	0.00 to 1.11	29.5	31.7	34.1
Streambed hydraulic conductivity	2.0	0.00	0.00	-0.03 to 0.02	28.5	30.1	32.0
Streambed hydraulic conductivity	[5]1.0 ft/d	-0.02	0.10	-0.58 to 0.28	28.8	30.9	32.4
Stream stage	[6]plus 3.0 ft	1.65	1.65	0.00 to 3.00	25.0	25.7	25.4
Stream stage	[7]minus 3.0 ft	-1.76	1.76	-3.00 to 0.00	30.4	32.9	36.1
Calibration streamflows					28.5	30.4	32.0

[1]Represents pan evaporation rate

[2]Represents pan evaporation rate times 0.5

[3]Represents plausible maximum rooting depth

[4]Represents plausible minimum rooting depth

[5]Represents plausible lower limit

[6]Indicates all stream stage altitudes were increased by 3.0 ft

[7]Indicates all stream state altitudes were decreased by 3.0 ft

Table 10. Sensitivity of simulated hydraulic heads in the Rock River Valley aquifer and simulated streamflows in the Rock River to changes in values of hydrologic properties or conditions in transient simulation, late summer and spring stress periods, eastern Rock County, Minnesota

[ft, feet; ft/d, feet per day; ft^3/s, cubic feet per second; LS, late summer stress period; SP, spring stress period. Mean deviations of hydraulic heads are deviations from values calculated by best-match simulation]

		Hydraulic head (ft)						Streamflow (ft^3/s)					
		LS			SP			SW6		SW8		SW20	
Hydrologic property or condition	Multiplied by factor of (or other specified variations)	Algebraic value of mean deviation	Absolute value of mean deviation	Range	Algebraic value of mean deviation	Absolute value of mean deviation	Range	LS	SP	LS	SP	LS	SP
Aquifer horizontal hydraulic conductivities of layers 1 and 3	2.0	-0.51	0.79	-4.27 to 2.31	-0.76	0.98	-4.77 to 1.94	102	1100	105	1110	121	1310
	0.5	0.48	0.86	-3.40 to 3.65	0.74	1.13	-3.66 to 4.23	101	1100	102	1110	118	1300
Vertical hydraulic conductivities of confining unit (layer 2)	10	0.00	0.07	-0.41 to 0.85	-0.07	0.09	-0.76 to 0.29	101	1100	103	1110	119	1310
	0.1	-0.02	0.20	-2.47 to 1.50	0.19	0.39	-1.74 to 2.87	101	1100	103	1110	119	1310
Aquifer specific yields and storage cefficients for layers 1 and 3	2.0	0.05	0.25	-1.30 to 0.79	-0.92	0.92	-2.47 to 0.00	102	1090	104	1100	120	1300
	[1]0.2, 0.5	-0.14	0.28	-0.89 to 0.56	1.40	1.40	0.00 to 3.55	100	1100	102	1110	117	1310
Confining unit storage coefficients (layer 2)	10	-0.20	0.26	-5.78 to 0.41	-0.55	0.55	-8.75 to 0.00	102	1100	104	1100	120	1300
	0.1	-0.03	0.06	-0.42 to 0.36	0.24	0.24	0.00 to 3.15	101	1100	103	1110	118	1310
Streambed hydraulic conductivity	2.0	0.05	0.05	-0.01 to 0.71	0.06	0.07	-0.06 to 1.14	101	1100	103	1110	119	1300
	[2]1.0 ft/d	-0.24	0.29	-2.21 to 0.18	-0.27	0.41	-3.62 to 0.66	102	1100	105	1110	120	1300
Areal recharge to layer 1	1.5	0.59	0.59	0.00 to 2.64	1.55	1.55	0.00 to 4.53	102	1110	104	1120	120	1320
	0.5	-0.69	0.69	-3.13 to 0.00	-1.67	1.67	-5.09 to 0.00	100	1090	102	1100	117	1290
Calibration streamflows								101	1100	103	1110	119	1310

[1]Storage coefficient of high (350 ft/d) horizontal hydraulic conductivity area of layer 3 underlying Luverne Airport well field multiplied by factor of 0.2; all other aquifer specific yields and storage coefficients multiplied by 0.5

[2]Represents plausible lower limit5

Table 11. Simulated drawdowns and streamflows for steady-state simulations with anticipated increased ground-water withdrawals and hypothetical climatic conditions, eastern Rock County, Minnesota

[<, less than; NA, well is not simulated for hypothetical scenario. Maximum is maximum drawdown simulated in vicinity of well field. A positive value for stream-aquifer leakage indicates a gain in streamflow and a loss to the aquifer. A negative value for stream-aquifer leakage indicates a reduction in streamflow and a gain to the aquifer]

	Drawdown near well (feet)			
	Hypothetical scenario[1]			
Well field and well	SS1	SS2	SS3	SS4
Luverne Municipal				
Maximum	0.5	0.5	3.8	3.8
LUV25	0.4	0.4	2.6	2.6
LUV20	<0.1	<0.1	1.8	1.8
LUV21	0.1	0.1	1.9	1.9
Luverne Airport				
Maximum	0.6	0.6	7.0	7.0
LUV23	0.45	0.5	4.3	4.3
LUV9	0.5	0.5	5.0	5.0
Rock County Rural Water				
Maximum	1.4	1.0	4.5	4.0
RW2	1.4	0.8(+)	3.4	1.0
RW6	0.1	0.1	1.6	1.6
RW7	1.0	0.5	4.5	3.5
H2	NA	1.0	NA	2.5

Streamflow and stream-aquifer leakage rates (cubic feet per second)

			Hypothetical scenario[1]							
	Calibration rates		SS1		SS2		SS3		SS4	
Surface-water site	Flow	Leakage	Flow	Leak-age	Flow	Leak-age	Flow	Leak-age	Flow	Leak-age
SW3	23.6		23.6		23.6		1.82		1.82	
		4.3		4.2		4.2		0.23		0.23
SW21	27.9		27.8		27.8		2.05		2.05	
		1.1		1.1		1.1		0.80		0.80
SW22	29.0		28.9		28.9		2.85		2.85	
		-0.5		-0.6		-0.6		-0.68		-0.68
SW6	28.5		28.3		28.3		2.17		2.17	
		1.9		1.7		1.7		0.11		0.11
SW8	30.4		30.0		30.0		2.28		2.28	
		2.4		2.5		2.5		0.42		0.42
SW10	32.8		32.5		32.5		2.70		2.70	
		-0.3		-0.4		-0.7		-0.35		-0.64
SW19	32.5		32.1		31.8		2.35		2.06	
		-0.5		-0.6		-0.5		-0.64		-0.53
SW24	32.0		31.5		31.3		1.71		1.53	
		0.0		-0.1		0.1		-0.28		-0.10
SW20	32.0		31.4		31.4		1.43		1.43	
		-0.6		-0.7		-0.7		0.22		0.25
SW12	31.4		30.7		30.7		1.65		1.68	
		3.1		3.0		3.1		0.90		0.91
SW13	34.5		33.7		33.8		2.55		2.59	

[1]Hypothetical scenario:

SS1: Anticipated increased ground-water withdrawals, normal precipitation, 7 wells in Rock County Rural Water well field.

SS2: Anticipated increased ground-water withdrawals, normal precipitation, 12 wells in Rock County Rural Water well field.

SS3: Anticipated increased ground-water withdrawals, drought conditions, 7 wells in Rock County Rural Water well field.

SS4: Anticipated increased ground-water withdrawals, drought conditions, 12 wells in Rock County Rural Water well field.54

Table 12. Herbicides and metabolites detected in the Rock River, supply wells less than 200 feet from the Rock River, and the ground-water contributing area to supply wells, Luverne Municipal well field, and sources of the herbicides and metabolites detected in supply wells, eastern Rock County, Minnesota

[Blue, indicates that the probable source of the herbicides and metabolites in supply wells is the Rock River; Red, indicates that the probable source of the herbicides and metabolites in supply wells is the ground-water contributing area; BlueRed, indicates that both the Rock River and the ground-water contributing area are probable sources for the herbicides and metabolites detected in supply wells]

Rock River	Supply wells less than 200 feet from river	Ground-water contributing area
Atrazine[1,2]	Atrazine	Atrazine
De-ethylatrazine[1,2]	De-ethylatrazine	De-ethylatrazine
De-isopropylatrazine[1,2]	De-isopropylatrazine	De-isopropylatrazine
Hydroxyatrazine[3]		
Alachlor[1,2]		
Alachlor ESA[1,2]	Alachlor ESA	Alachlor ESA
Alachlor OA[3]		
Metolachlor[1,2]	Metolachlor	Metolachlor
Metolachlor ESA[3]	Metolachlor ESA	Metolachlor ESA
Metolachlor OA[3]	Metolachlor OA	Metolachlor OA
Acetochlor[1,2]		
Acetochlor ESA[3]	Acetochlor ESA	Acetochlor ESA
Acetochlor OA[3]	Acetochlor OA	
Cyanazine[1,2]		
Cyanazine amide[1,2]		
Metribuzin[1,2]		
Propazine[1,2]		
Propalachlor[1]		
Simazine[1]		
Prometon[4]		
Not detected: prometryn, ametryn, terbutryn		

[1]Herbicide or metabolite detected in the Rock River during May 1989 - May 1995 sampling

[2]Herbicide or metabolite detected in the Rock River during November 1995-August 1997 sampling

[3]Metabolite only analyzed in 1997

[4]Detected in LUV23 (Luverne Airport well field). May be related to waste soil from nearby abandoned railroad bed

Table 13. Herbicides and metabolites detected in the Rock River, supply wells less than 500 feet from the Rock River, and the ground-water contributing area to supply wells, Rock County Rural Water well field, and sources of the herbicides and metabolites detected in supply wells, eastern Rock County, Minnesota

[Blue, indicates that the probable source of the herbicides and metabolites in supply wells is the Rock River; Red, indicates that the probable source of the herbicides and metabolites in supply wells is the ground-water contributing area; BlueRed, indicates that both the Rock River and the ground-water contributing area are probable sources for the herbicides and metabolites detected in supply wells

Rock River	Supply wells less than 500 feet from river	Ground-water contributing area
Atrazine	Atrazine	Atrazine
De-ethylatrazine	De-ethylatrazine	De-ethylatrazine
De-isopropylatrazine	De-isopropylatrazine	De-isopropylatrazine
Hydroxyatrazine	Hydroxyatrazine	Hydroxyatrazine
Alachlor ESA	Alachlor ESA	Alachlor ESA
Metolachlor	Metolachlor	Metolachlor
Metolachlor ESA	Metolachlor ESA	Metolachlor ESA
Metolachlor OA	Metolachlor OA	Metolachlor OA
Acetochlor		
Acetochlor ESA	Acetochlor ESA	
Acetochlor OA	Acetochlor OA	
Not detected: alachlor, cyanazine, cyanazine amide, metribuzin, propazine, propalchlor, simazine, prometryn, ametryn, terbutryn, alachlor OA		

Table 14. Selected water-quality, age-dating, and dissolved-gas data for supply wells in the Rock River Valley aquifer, eastern Rock County, Minnesota

[°C, degrees Celsius; mS/cm @ 25°C, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; µg/L, micrograms per liter; N_2, nitrogen gas; Ar, argon gas; O_2, oxygen gas; CO_2, carbon dioxide gas; CH_4, methane gas; N_20, nitrous oxide; excess N_2, concentration of N_2 greater than that in equilibrium with atmosphere at recharge temperature; CFC, chlorofluorocarbon]

Well name (shown in figures 2a-2d)	LUV 26	LUV 23	RW2
MN Unique #	513016	149192	149159
USGS site ID	433932096113701	433750096123201	433345096110001
Sample date	8/29/96	8/30/96	8/30/96
Sample time	1600	900	1030
Water temperature (°C)	12.3	10.3	12.6
Dissolved oxygen (mg/L)	0.5	1.9	0.6
Nitrogen, nitrate (mg/L as N)	1.0	5.0	0.20
Nitrogen, nitrite (mg/L as N)	<0.005	<0.005	<0.005
Dissolved gases			
N_2 (mg/L)	29.05	25.03	24.60
Ar (mg/L)	0.76	0.72	0.71
O_2 (mg/L)	0.22	0.00	0.00
CO_2 (mg/L)	30.19	43.55	30.60
CH_4 (mg/L)	0.0006	<0.0001	0.0031
Excess N_2 (mg/L)	5	4	4
Estimated recharge temperature (°C)	10.8	9.7	10.5
Excess air (mg/L)	12.1	7.6	7.5
Tritium			
Tritium (tritium units)	12.4	13.5	12.6
Tritium +/- (tritium units)	1.0	1.1	1.0
CFC recharge ages			
CFC-12 - median	1980	1988	1978
Replicate - 1	1980	1988	1978
Replicate - 2	1981	1988	1978
Replicate - 3	1980	1990	1978
CFC-11 - median	1963	1973	1960
Replicate - 1	1963	1973	1961
Replicate - 2	1963	1973	1960
Replicate - 3	1963	1974	1960
CFC-113 - median	1971	1980	1955
Replicate - 1	1972	1980	1955
Replicate - 2	1971	1980	1955
Replicate - 3	1955	1979	1969
Laboratory comments - CFC's	Some N_2O Late 1970's	Some N_2O Late 1980's	Trace methane Late 1970's
CFC/Geochemical interpretation			
Reduced ground water?	Yes	No	Yes
Excess N_2 (indicating denitrification)?	Yes	Yes	Yes
Methanogenic ground water?	No	No	Yes
CFC matches tritium?	Probably	Yes	Probably
CFC degradation?			
CFC-12	Possibly	No	Possibly
CFC-113	Yes	Yes	Yes
CFC-11	Yes	Yes	Yes

Table 14. Selected water-quality, age-dating, and dissolved-gas data for supply wells in the Rock River Valley aquifer, eastern Rock County, Minnesota (Continued)

[°C, degrees Celsius; mS/cm @ 25°C, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; µg/L, micrograms per liter; N_2, nitrogen gas; Ar, argon gas; O_2, oxygen gas; CO_2, carbon dioxide gas; CH_4, methane gas; N_20, nitrous oxide; excess N_2, concentration of N_2 greater than that in equilibrium with atmosphere at recharge temperature; CFC, chlorofluorocarbon]

Mixing effects (long screen) on ages?	No	No	No
Interpreted ground-water recharge age:	Late 70’s or younger	Later 80’s	Late 70’s or younger
Explanation:	Degradation of CFC-11 and CFC-113. CFC-12, late 70’s. Tritium is lower than would be expected for late 70’s water but is within the range of possibility. Some degradation of CFC-12 may have occurred.	CFC-12 and tritium are consistent. CFC-113 and CFC-11 are degraded.	Degradation of CFC-11 and CFC-113. CFC-12, late 70’s. Tritium is lower than would be expected for late 70’s water but is within the range of possibility. Some degradation of CFC-12 may have occurred.
Well/aquifer description			
Casing depth (feet)	23	26	22
Well depth (feet)	33	32	32
Screen length (feet)	10	6	10
Aquifer saturated thickness (feet)	26	24	28
Bottom of aquifer (feet)	33	40	33
Percent of aquifer in screen	38	25	36
Water level below land surface (feet)	5	7	8
Aquifer	surficial sand & gravel	surficial sand & gravel	surficial sand & gravel

Table 15. Stable-isotopic data and estimated proportions of river water in supply wells near the Rock River using stable-isotopic mixing calculations, eastern Rock County, Minnesota

[‰, per mil; %, percent; % river water, percent of water withdrawn from supply well that comes from the Rock River; invalid, isotopic mixing calculations were unsuccessful because supply-well isotopic composition was not between that of river and ground-water contributing area]

				River - 1st choice value for mixing calculations			River - 2nd choice value for mixing calculations			River - 1st choice value for mixing calculations		River - 2nd choice value for mixing calculations		
Supply well (shown in figures 2a-2d)	Supply well sampling date	Supply well δD (‰)	Supply well $\delta^{18}O$ (‰)	River sampling date	River δD (‰)	River $\delta^{18}O$ (‰)	River sampling date	River δD (‰)	River $\delta^{18}O$ (‰)	% river water based on δD	% river water based on $\delta^{18}O$	% river water based on δD	% river water based on $\delta^{18}O$	Summary notes (best estimate):
Luverne Municipal well field														
Ground-water contributing area average: δD (‰) = -68.5 $\delta^{18}O$ (‰) = -9.9														
LUV21	11/28/95	-62.9	-9.1	11/28/95	-65.4	-9.4				invalid	invalid			little isotopic contrast
LUV5	11/28/95	-62.4	-8.9	11/28/95	-65.4	-9.4				invalid	invalid			little isotopic contrast
LUV21	4/9/96	-71.8	-10.4	3/30/96	-92.8	-13.2	4/9/96	-66.4	-9.8	14	14	invalid	invalid	15%
LUV5	4/9/96	-77.2	-11.2	3/30/96	-92.8	-13.2	4/9/96	-66.4	-9.8	36	38	invalid	invalid	40%
LUV5	8/14/96	-62.3	-9.0	8/14/96	-52.1	-7.7				38	40			40%
LUV21	8/15/96	-62.6	-8.9	8/14/96	-52.1	-7.7				36	44			40%
LUV21	11/13/96	-62.4	-8.9	11/13/96	-62.7	-8.9				invalid	95			little isotopic contrast
LUV21	4/8/97	-73.9	-10.6	3/24/97	-108.5	-15.3	4/7/97	-89.8	-12.5	14	13	25	27	15-25%
LUV21	6/3/97	-70.6	-10.0	5/20/97	-64.0	-9.1	6/3/97	-62.8	-9.0	invalid	invalid	invalid	invalid	little isotopic contrast
LUV21	7/23/97	-65.6	-9.4	6/30/97	-35.0	-6.2	7/23/97	-49.2	-7.4	9	15	15	21	10-20%
LUV21	8/27/97	-63.5	-9.2	8/28/97	-58.6	-8.3	7/23/97	-49.2	-7.4	51	43	26	27	25-50%
LUV22	8/27/97	-71.5	-10.2	8/28/97	-58.6	-8.3	7/23/97	-49.2	-7.4	invalid	invalid	invalid	invalid	little isotopic contrast
LUV22	8/28/97	-62.5	-9.0	8/28/97	-58.6	-8.3	7/23/97	-49.2	-7.4	61	56	31	36	30-60%

Table 15. Stable-isotopic data and estimated proportions of river water in supply wells near the Rock River using stable-isotopic mixing calculations, eastern Rock County, Minnesota (Continued)

[‰, per mil; %, percent; % river water, percent of water withdrawn from supply well that comes from the Rock River; invalid, isotopic mixing calculations were unsuccessful because supply-well isotopic composition was not between that of river and ground-water contributing area]

				River - 1st choice value for mixing calculations			River - 2nd choice value for mixing calculations			River - 1st choice value for mixing calculations		River - 2nd choice value for mixing calculations		
Supply well (shown in figures 2a-2d)	Supply well sampling date	Supply well δD (‰)	Supply well $\delta^{18}O$ (‰)	River sampling date	River δD (‰)	River $\delta^{18}O$ (‰)	River sampling date	River δD (‰)	River $\delta^{18}O$ (‰)	% river water based on δD	% river water based on $\delta^{18}O$	% river water based on δD	% river water based on $\delta^{18}O$	Summary notes (best estimate):
Rock County Rural Water well field														
Ground-water contributing area average: δD (‰) = -67.9; $\delta^{18}O$ (‰) = -9.8														
RW3	11/29/95	-63.4	-8.92	11/28/95	-65.4	-9.42				invalid	invalid			little isotopic contrast
RW3	4/10/96	-66.3	-9.62	3/30/96	-92.8	-13.21	4/9/96	-66.4	-9.82	invalid	invalid	invalid	invalid	
RW3	8/13/96	-65.1	-9.24	8/14/96	-52.1	-7.65				18	26			20-25%
RW2	8/30/96	-65.9	-9.5	8/14/96	-52.1	-7.65				13	14			15%
RW3	11/13/96	-63	-8.82	11/13/96	-62.7	-8.88				unreason-able	invalid			little isotopic contrast
RW3	4/9/97	-66.7	-9.74	3/24/97	-108.5	-15.26	4/7/97	-89.8	-12.53	invalid	invalid	invalid	invalid	
RW2	4/9/97	-71	-10.13	3/24/97	-108.5	-15.26	4/7/97	-89.8	-12.53	8	6	14	12	5-15%
RW3	6/2/97	-73.5	-10.34	5/20/97	-64	-9.11	6/3/97	-62.8	-8.95	invalid	invalid	invalid	invalid	little isotopic contrast
RW2	6/2/97	-66.3	-9.62	5/20/97	-64	-9.11	6/3/97	-62.8	-8.95	41	26	31	21	little isotopic contrast
RW3	7/23/97	-68.4	-9.84	6/30/97	-35	-6.21	7/23/97	-49.2	-7.36	invalid	invalid	invalid	invalid	
RW3	8/27/97	-64.1	-9.23	8/28/97	-58.6	-8.28	7/23/97	-49.2	-7.36	41	38	20	23	20-40%

Table 16. Simulated drawdowns and streamflows for transient simulations with anticipated increased ground-water withdrawals and hypothetical climatic conditions, eastern Rock County, Minnesota

[<, less than; NA, well is not simulated for hypothetical scenario. Maximum is maximum drawdown simulated in vicinity of well field. Simulated drawdowns are at end of late summer stress period in third year of 3-year simulation. (+) indicates a simulated rise in hydraulic head. A positive value for stream-aquifer leakage indicates a gain in streamflow and a loss to the aquifer. A negative value for stream-aquifer leakage indicates a reduction in streamflow and a gain to the aquifer]

Well field and well site (shown on figures 2a-2d)	Drawdown near well (feet)			
	Hypothetical scenario[1]			
	TR1	TR2	TR3	TR4
Luverne Municipal				
Maximum	0.6	0.6	1.5	1.5
LUV25	0.5	0.5	1.0	1.0
LUV20	0.1	0.1	0.2	0.2
LUV21	0.1	0.1	0.3	0.3
Luverne Airport				
Maximum	0.5	0.5	1.6	1.6
LUV23	0.4	0.4	0.8	0.8
LUV9	0.3	0.3	1.0	1.0
Rock County Rural Water				
Maximum	0.9	1.7	1.8	2.5
RW2	0.9	1.1 (+)	1.5	0.2 (+)
RW6	0.3	0.5	0.6	0.9
RW7	0.8	0.3	1.8	1.0
H2	NA	1.7	NA	2.5

Stress period and surface-water site	Simulated streamflows (cubic feet per second)				
		Hypothetical scenario[1]			
	Calibration flows	TR1	TR2	TR3	TR4
Winter					
SW6	44.8	45.1	45.1	42.8	42.8
SW8	46.4	46.8	46.8	43.7	43.7
SW19	52.7	53.4	53.2	49.5	49.3
SW24	52.1	53.1	52.9	49.1	48.9
SW20	52.0	53.0	52.8	48.8	48.8
Spring					
SW6	117	117	117	120	120
SW8	119	119	119	123	123
SW19	140	140	139	146	145
SW24	140	140	139	146	145
SW20	140	140	138	145	145
Early summer					
SW6	339	339	339	252	252
SW8	341	341	341	252	252
SW19	401	401	401	296	296
SW24	400	400	400	295	295
SW20	400	400	400	295	295

Table 16. Simulated drawdowns and streamflows for transient simulations with anticipated increased ground-water withdrawals and hypothetical climatic conditions, eastern Rock County, Minnesota (Continued)

[<, less than; NA, well is not simulated for hypothetical scenario. Maximum is maximum drawdown simulated in vicinity of well field. Simulated drawdowns are at end of late summer stress period in third year of 3-year simulation. (+) indicates a simulated rise in hydraulic head. A positive value for stream-aquifer leakage indicates a gain in streamflow and a loss to the aquifer. A negative value for stream-aquifer leakage indicates a reduction in streamflow and a gain to the aquifer]

Stress period and surface-water site	Simulated streamflows (cubic feet per second)				
		Hypothetical scenario[1]			
	Calibration flows	TR1	TR2	TR3	TR4
Late summer					
SW6	104	104	104	5.26	5.26
SW8	105	105	105	7.33	7.33
SW19	123	123	122	9.28	9.03
SW24	122	122	121	8.74	8.59
SW20	122	122	121	8.81	8.81
Fall					
SW6	135	133	133	42.0	42.0
SW8	138	135	135	43.7	43.7
SW19	161	158	157	50.0	49.7
SW24	161	158	157	49.4	49.2
SW20	160	157	156	48.9	48.8

[1]Hypothetical scenario:

TR1:Anticipated increased ground-water withdrawals, normal precipitation, 7 wells in Rock County Rural Water well field

TR2:Anticipated increased ground-water withdrawals, normal precipitation, 12 wells in Rock County Rural Water well field

TR3:Anticipated increased ground-water withdrawals, drought conditions, 7 wells in Rock County Rural Water well field

TR4:Anticipated increased ground-water withdrawals, drought conditions, 12 wells in Rock County Rural Water well field

Table 17. Statistical summary of concentrations of selected water-quality constituents in the Rock River during May 1989-May 1995 and November 1995-August 1997, supply wells, and the ground-water contributing area, Luverne Municipal well field, and supply wells, Luverne Airport well field, eastern Rock County, Minnesota

[Nov., November, Aug., August; Oct., October; <, less than; --, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; detection percentage, percent of samples in which specified herbicide was detected; ft^3/s, cubic feet per second]

	Nov. 1995-Aug. 1997 River	Nov. 1995-Aug. 1997 Luverne Municipal supply well <200 feet from river	Nov. 1995-Aug. 1997 Luverne Municipal supply well 200-1,000 feet from river	Nov. 1995-Aug. 1997 Ground-water contributing area to supply well	Nov. 1995-Aug. 1997 Luverne Airport supply wells	May 1989-May 1995 River; all samples	May 1989-May 1995 River May-June post-application runoff events	May 1989-May 1995 River April-May pre-application or Oct.	Nov. 1995-Aug. 1997 River May 20-Aug. 14 post-application runoff events	Nov. 1995-Aug. 1997 River Aug. 28-May 10 pre-application, late summer, or post-growing season
Dissolved oxygen (mg/L)										
Maximum	14	0.80	0.7	6.2	1.9	--	--	--	14	11
Median	9.8	0.18	0.3	0.13	1.7	--	--	--	12	8.6
Minimum	5.5	0.10	0.11	0.07	0.14	--	--	--	9.1	5.5
Number of samples	12	15	7	16	3	0	0	0	6	6
Number of sites	1	4	2	5	2				1	1
Nitrate nitrogen (mg/L)										
Maximum	7.50	1.50	2.20	8.33	4.95	6.10	6.10	5.30	7.11	7.5
Median	4.60	0.48	0.99	0.31	4.66	3.05	4.85	1.45	4.78	4.2
Minimum	2.10	<0.01	0.72	<0.01	0.27	0.60	2.10	0.60	4.24	2.1
Number of samples	13	15	7	16	3	8	4	4	6	7
Number of sites	1	4	2	5	2	1	1	1	1	1
Atrazine + metabolites de-ethylatrazine and de-isopropylatrazine (µg/L)										
Maximum	5.70	0.72	0.06	0.18	0.21	11.90	11.90	0.14	5.70	0.40
Median	0.17	0.06	<0.05	<0.05	0.21	1.50	4.05	0.08	0.33	0.11
Minimum	0.05	<0.05	<0.05	<0.05	<0.05	0.06	1.50	0.06	0.11	0.05
Number of samples	13	15	7	16	3	7	4	3	6	7

Table 17. Statistical summary of concentrations of selected water-quality constituents in the Rock River during May 1989-May 1995 and November 1995-August 1997, supply wells, and the ground-water contributing area, Luverne Municipal well field, and supply wells, Luverne Airport well field, eastern Rock County, Minnesota (Continued)

[Nov., November, Aug., August; Oct., October; <, less than; --, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; detection percentage, percent of samples in which specified herbicide was detected;

	Nov. 1995-Aug. 1997 River	Nov. 1995-Aug. 1997 Luverne Municipal supply well <200 feet from river	Nov. 1995-Aug. 1997 Luverne Municipal supply well 200-1,000 feet from river	Nov. 1995-Aug. 1997 Ground-water contributing area to supply well	Nov. 1995-Aug. 1997 Luverne Airport supply wells	May 1989-May 1995 River; all samples	May 1989-May 1995 River May-June post-application runoff events	May 1989-May 1995 River April-May pre-application or Oct.	Nov. 1995-Aug. 1997 River May 20-Aug. 14 post-application runoff events	Nov. 1995-Aug. 1997 River Aug. 28-May 10 pre-application, late summer, or post-growing season
Number of sites	1	4	2	5	2	1	1	1	1	1
Detection percentage	100	87	14	19	67	100	100	100	100	100
Atrazine (µg/L)										
Maximum	4.98	0.56	0.06	0.08	0.11	10.64	10.64	0.08	4.98	0.23
Median	0.07	0.07	<0.05	<0.05	0.06	1.23	3.21	0.08	0.06	0.06
Minimum	0.05	<0.05	<0.05	<0.05	<0.05	0.06	1.23	0.06	0.06	0.05
Number of samples	13	15	7	16	3	7	4	3	6	7
Number of sites	1	4	2	5	2	1	1	1	1	1
Detection percentage	100	87	14	19	67	100	100	100	100	100
De-ethylatrazine (µg/L)										
Maximum	0.52	0.10	<0.05	0.07	0.10	0.91	0.91	0.06	0.52	0.12
Median	0.06	<0.05	<0.05	<0.05	0.07	0.17	0.46	<0.05	0.08	<0.05
Minimum	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.17	<0.05	0.07	<0.05
Number of samples	13	15	7	16	3	7	4	3	6	7
Number of sites	1	4	2	5	2	1	1	1	1	1
Detection percentage	62	20	0	19	67	71	100	33	100	29
De-isopropylatrazine (µg/L)										
Maximum	0.20	0.06	<0.05	0.05	<0.05	0.47	0.47	<0.05	0.20	0.08

Table 17. Statistical summary of concentrations of selected water-quality constituents in the Rock River during May 1989-May 1995 and November 1995-August 1997, supply wells, and the ground-water contributing area, Luverne Municipal well field, and supply wells, Luverne Airport well field, eastern Rock County, Minnesota (Continued)

[Nov., November, Aug., August; Oct., October; <, less than; --, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; detection percentage, percent of samples in which specified herbicide was detected;

	Nov. 1995-Aug. 1997 River	Nov. 1995-Aug. 1997 Luverne Municipal supply well <200 feet from river	Nov. 1995-Aug. 1997 Luverne Municipal supply well 200-1,000 feet from river	Nov. 1995-Aug. 1997 Ground-water contributing area to supply well	Nov. 1995-Aug. 1997 Luverne Airport supply wells	May 1989-May 1995 River; all samples	May 1989-May 1995 River May-June post-application runoff events	May 1989-May 1995 River April-May pre-application or Oct.	Nov. 1995-Aug. 1997 River May 20-Aug. 14 post-application runoff events	Nov. 1995-Aug. 1997 River Aug. 28-May 10 pre-application, late summer, or post-growing season
Median	0.05	<0.05	<0.05	<0.05	<0.05	0.10	0.33	<0.05	0.08	<0.05
Minimum	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.10	<0.05	<0.05	<0.05
Number of samples	13	15	7	16	3	7	4	3	6	7
Number of sites	1	4	2	5	2	1	1	1	1	1
Detection percentage	62	13	0	6	0	57	100	0	83	43
Alachlor ESA (µg/L)										
Maximum	1.50	1.61	1.46	0.52	0.21	5.40	5.40	0.69	1.50	0.88
Median	0.77	0.56	0.77	<0.10	0.17	1.01	3.21	0.69	0.86	0.76
Minimum	0.27	0.35	0.62	<0.10	0.13	0.69	1.01	0.69	0.40	0.27
Number of samples	13	15	7	16	3	3	2	1	6	7
Number of sites	1	4	2	5	2	1	1	1	1	1
Detection percentage	100	100	100	50	100	100	100	100	100	100
Metolachlor (µg/L)										
Maximum	3.44	0.11	<0.05	0.06	<0.05	11.47	11.47	0.10	3.44	0.99
Median	0.09	0.06	<0.05	<0.05	<0.05	1.30	4.29	0.09	0.25	0.06
Minimum	<0.05	<0.05	<0.05	<0.05	<0.05	0.05	1.30	0.05	0.07	<0.05
Number of samples	13	15	7	16	3	7	4	3	6	7
Number of sites	1	4	2	5	2	1	1	1	1	1

Table 17. Statistical summary of concentrations of selected water-quality constituents in the Rock River during May 1989-May 1995 and November 1995-August 1997, supply wells, and the ground-water contributing area, Luverne Municipal well field, and supply wells, Luverne Airport well field, eastern Rock County, Minnesota (Continued)

[Nov., November, Aug., August; Oct., October; <, less than; --, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; detection percentage, percent of samples in which specified herbicide was detected;

	Nov. 1995-Aug. 1997 River	Nov. 1995-Aug. 1997 Luverne Municipal supply well <200 feet from river	Nov. 1995-Aug. 1997 Luverne Municipal supply well 200-1,000 feet from river	Nov. 1995-Aug. 1997 Ground-water contributing area to supply well	Nov. 1995-Aug. 1997 Luverne Airport supply wells	May 1989-May 1995 River; all samples	May 1989-May 1995 River May-June post-application runoff events	May 1989-May 1995 River April-May pre-application or Oct.	Nov. 1995-Aug. 1997 River May 20-Aug. 14 post-application runoff events	Nov. 1995-Aug. 1997 River Aug. 28-May 10 pre-application, late summer, or post-growing season
Detection percentage	77	20	0	6	0	100	100	100	100	57
Metolachlor ESA (µg/L)										
Maximum	6.29	2.48	1.24	2.85	0.69	--	--	--	6.29	3.16
Median	3.76	1.91	0.84	0.74	0.69	--	--	--	3.67	2.95
Minimum	1.16	1.28	0.80	0.33	0.69	--	--	--	3.26	1.16
Number of samples	7	4	3	4	1	0	0	0	4	3
Number of sites	1	1	2	3	1				1	1
Detection percentage	100	100	100	100	100				100	100
Metolachlor OA (µg/L)										
Maximum	4.51	0.43	<0.20	0.32	<0.20	--	--	--	4.51	1.38
Median	0.52	0.29	<0.20	<0.20	<0.20	--	--	--	0.73	0.35
Minimum	0.28	0.23	<0.20	<0.20	<0.20	--	--	--	0.47	0.28
Number of samples	7	4	3	4	1	0	0	0	4	3
Number of sites	1	1	2	3	1				1	1
Detection percentage	100	100	0	25	0				100	100
Acetochlor ESA (µg/L)										
Maximum	4.13	0.38	<0.20	0.21	<0.20	--	--	--	4.13	1.03
Median	0.50	0.14	<0.20	<0.20	<0.20	--	--	--	0.59	0.25

Table 17. Statistical summary of concentrations of selected water-quality constituents in the Rock River during May 1989-May 1995 and November 1995-August 1997, supply wells, and the ground-water contributing area, Luverne Municipal well field, and supply wells, Luverne Airport well field, eastern Rock County, Minnesota (Continued)

[Nov., November, Aug., August; Oct., October; <, less than; --, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; detection percentage, percent of samples in which specified herbicide was detected;

	Nov. 1995-Aug. 1997 River	Nov. 1995-Aug. 1997 Luverne Municipal supply well <200 feet from river	Nov. 1995-Aug. 1997 Luverne Municipal supply well 200-1,000 feet from river	Nov. 1995-Aug. 1997 Ground-water contributing area to supply well	Nov. 1995-Aug. 1997 Luverne Airport supply wells	May 1989-May 1995 River; all samples	May 1989-May 1995 River May-June post-application runoff events	May 1989-May 1995 River April-May pre-application or Oct.	Nov. 1995-Aug. 1997 River May 20-Aug. 14 post-application runoff events	Nov. 1995-Aug. 1997 River Aug. 28-May 10 pre-application, late summer, or post-growing season
Minimum	<0.20	<0.20	<0.20	<0.20	<0.20	--	--	--	0.26	<0.20
Number of samples	7	4	3	4	1	0	0	0	4	3
Number of sites	1	1	2	3	1				1	1
Detection percentage	86	50	0	25	0				100	67
Acetochlor OA (µg/L)										
Maximum	6.73	0.53	<0.20	<0.20	<0.20	--	--	--	6.73	0.67
Median	<0.20	<0.20	<0.20	<0.20	<0.20	--	--	--	0.33	<0.20
Minimum	<0.20	<0.20	<0.20	<0.20	<0.20	--	--	--	<0.20	<0.20
Number of samples	7	4	3	4	1	0	0	0	4	3
Number of sites	1	1	2	3	1				1	1
Detection percentage	43	25	0	0	0				50	33
Acetochlor (µg/L)										
Maximum	0.81	<0.05	<0.05	<0.05	<0.05	5.63	5.63	--	0.81	0.10
Median	0.07	<0.05	<0.05	<0.05	<0.05	5.63	5.63	--	0.10	<0.05
Minimum	<0.05	<0.05	<0.05	<0.05	<0.05	5.63	5.63	--	<0.05	<0.05
Number of samples	13	15	7	16	3	1	1	0	6	7
Number of sites	1	4	2	5	2	1	1		1	1
Detection percentage	54	0	0	0	0	100	100		83	29

Table 17. Statistical summary of concentrations of selected water-quality constituents in the Rock River during May 1989-May 1995 and November 1995-August 1997, supply wells, and the ground-water contributing area, Luverne Municipal well field, and supply wells, Luverne Airport well field, eastern Rock County, Minnesota (Continued)

[Nov., November, Aug., August; Oct., October; <, less than; --, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; detection percentage, percent of samples in which specified herbicide was detected;

	Nov. 1995-Aug. 1997 River	Nov. 1995-Aug. 1997 Luverne Municipal supply well <200 feet from river	Nov. 1995-Aug. 1997 Luverne Municipal supply well 200-1,000 feet from river	Nov. 1995-Aug. 1997 Ground-water contributing area to supply well	Nov. 1995-Aug. 1997 Luverne Airport supply wells	May 1989-May 1995 River; all samples	May 1989-May 1995 River May-June post-application runoff events	May 1989-May 1995 River April-May pre-application or Oct.	Nov. 1995-Aug. 1997 River May 20-Aug. 14 post-application runoff events	Nov. 1995-Aug. 1997 River Aug. 28-May 10 pre-application, late summer, or post-growing season
Alachlor OA (µg/L)										
Maximum	1.25	<0.20	<0.20	<0.20	<0.20	--	--	--	1.25	<0.20
Median	<0.20	<0.20	<0.20	<0.20	<0.20	--	--	--	<0.20	<0.20
Minimum	<0.20	<0.20	<0.20	<0.20	<0.20	--	--	--	<0.20	<0.20
Number of samples	7	4	3	4	1	0	0	0	4	3
Number of sites	1	1	2	3	1				1	1
Detection percentage	14	0	0	0	0				25	0
Hydroxyatrazine (µg/L)										
Maximum	2.40	<0.20	<0.20	<0.20	<0.20	--	--	--	2.40	0.78
Median	0.23	<0.20	<0.20	<0.20	<0.20	--	--	--	0.12	0.26
Minimum	<0.20	<0.20	<0.20	<0.20	<0.20	--	--	--	<0.20	<0.20
Number of samples	7	4	3	4	1	0	0	0	4	3
Number of sites	1	1	2	3	1				1	1
Detection percentage	57	0	0	0	0				50	67
Alachlor (µg/L)										
Maximum	0.10	<0.05	<0.05	<0.05	<0.05	2.19	2.19	<0.05	0.10	<0.05
Median	<0.05	<0.05	<0.05	<0.05	<0.05	0.10	0.59	<0.05	<0.05	<0.05
Minimum	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.10	<0.05	<0.05	<0.05

Table 17. Statistical summary of concentrations of selected water-quality constituents in the Rock River during May 1989-May 1995 and November 1995-August 1997, supply wells, and the ground-water contributing area, Luverne Municipal well field, and supply wells, Luverne Airport well field, eastern Rock County, Minnesota (Continued)

[Nov., November, Aug., August; Oct., October; <, less than; --, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; detection percentage, percent of samples in which specified herbicide was detected;

	Nov. 1995-Aug. 1997 River	Nov. 1995-Aug. 1997 Luverne Municipal supply well <200 feet from river	Nov. 1995-Aug. 1997 Luverne Municipal supply well 200-1,000 feet from river	Nov. 1995-Aug. 1997 Ground-water contributing area to supply well	Nov. 1995-Aug. 1997 Luverne Airport supply wells	May 1989-May 1995 River; all samples	May 1989-May 1995 River May-June post-application runoff events	May 1989-May 1995 River April-May pre-application or Oct.	Nov. 1995-Aug. 1997 River May 20-Aug. 14 post-application runoff events	Nov. 1995-Aug. 1997 River Aug. 28-May 10 pre-application, late summer, or post-growing season
Number of samples	13	15	7	16	3	7	4	3	6	7
Number of sites	1	4	2	5	2	1	1	1	1	1
Detection percentage	8	0	0	0	0	57	100	0	17	0
Cyanazine (µg/L)										
Maximum	0.53	<0.05	<0.05	<0.05	<0.05	4.23	4.23	<0.05	0.53	<0.05
Median	<0.05	<0.05	<0.05	<0.05	<0.05	2.05	3.09	<0.05	<0.05	<0.05
Minimum	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	2.05	<0.05	<0.05	<0.05
Number of samples	13	15	7	16	3	7	4	3	6	7
Number of sites	1	4	2	5	2	1	1	1	1	1
Detection percentage	15	0	0	0	0	57	100	0	33	0
Cyanazine amide (µg/L)										
Maximum	0.32	<0.05	<0.05	<0.05	<0.05	0.17	0.17	--	0.32	<0.05
Median	<0.05	<0.05	<0.05	<0.05	<0.05	0.17	0.17	--	<0.05	<0.05
Minimum	<0.05	<0.05	<0.05	<0.05	<0.05	0.17	0.17	--	<0.05	<0.05
Number of samples	13	15	7	16	3	1	1	0	6	7
Number of sites	1	4	2	5	2	1	1		1	1
Detection percentage	8	0	0	0	0	100	100		17	0

Table 17. Statistical summary of concentrations of selected water-quality constituents in the Rock River during May 1989-May 1995 and November 1995-August 1997, supply wells, and the ground-water contributing area, Luverne Municipal well field, and supply wells, Luverne Airport well field, eastern Rock County, Minnesota (Continued)

[Nov., November, Aug., August; Oct., October; <, less than; --, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; detection percentage, percent of samples in which specified herbicide was detected;

	Nov. 1995-Aug. 1997 River	Nov. 1995-Aug. 1997 Luverne Municipal supply well <200 feet from river	Nov. 1995-Aug. 1997 Luverne Municipal supply well 200-1,000 feet from river	Nov. 1995-Aug. 1997 Ground-water contributing area to supply well	Nov. 1995-Aug. 1997 Luverne Airport supply wells	May 1989-May 1995 River; all samples	May 1989-May 1995 River May-June post-application runoff events	May 1989-May 1995 River April-May pre-application or Oct.	Nov. 1995-Aug. 1997 River May 20-Aug. 14 post-application runoff events	Nov. 1995-Aug. 1997 River Aug. 28-May 10 pre-application, late summer, or post-growing season
Metribuzin (µg/L)										
Maximum	0.28	<0.05	<0.05	<0.05	<0.05	0.24	0.24	<0.05	0.28	<0.05
Median	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.12	<0.05	<0.05	<0.05
Minimum	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Number of samples	13	15	7	16	3	7	4	3	6	7
Number of sites	1	4	2	5	2	1	1	1	1	1
Detection percentage	8	0	0	0	0	29	50	0	17	0
Propazine (µg/L)										
Maximum	0.06	<0.05	<0.05	<0.05	<0.05	0.13	0.13	<0.05	0.06	<0.05
Median	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.03	<0.05	<0.05	<0.05
Minimum	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Number of samples	13	15	7	16	3	7	4	3	6	7
Number of sites	1	4	2	5	2	1	1	1	1	1
Detection percentage	8	0	0	0	0	29	50	0	17	0
Streamflow at time of sample collection (ft^3/s)										
Maximum	4180					2000	2000	168	1550	4180
Median	231					184	491	62	233	155
Minimum	47					12	200	12	132	47
Number of samples	13					8	4	4	6	7
Number of sites						1	1	1	1	1

Table 18. Statistical summary of concentrations of selected water-quality constituents in the Rock River, supply wells, and the ground-water contributing area to supply wells, Rock County Rural Water well field, eastern Rock County, Minnesota

[--, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; detection percentage, percent of samples in which specified herbicide was detected; <, less than]

	River	Supply well 360-500 feet from river	Ground-water contributing area to supply wells	River May 20-Aug 14 Post-application runoff events	River Aug. 28-May 10 Pre-application, late summer, or post-growing season
Dissolved oxygen (mg/L)					
Maximum	14	1.5	7.2	8.2	14
Median	9.9	0.36	5.5	7.7	13
Minimum	6.6	0.14	4.8	6.6	9.9
Number of samples	9	9	10	4	5
Number of sites	1	1	1	1	1
Nitrate nitrogen (mg/L)					
Maximum	8.5	8.8	18	5.5	8.5
Median	4.8	0.37	16	4.8	5.6
Minimum	2.4	0.15	14	4.2	2.4
Number of samples	9	14	10	4	5
Number of sites	1	4	2	1	1
Atrazine + metabolites de-ethylatrazine and de-isopropylatrazine (µg/L)					
Maximum	0.49	0.83	0.35	0.49	0.28
Median	0.17	0.06	0.27	0.20	0.11
Minimum	0.05	<0.05	0.18	0.05	0.06
Number of samples	9	14	10	4	5
Number of sites	1	4	2	1	1
Detection percentage	100	71	100	100	100
Atrazine (µg/L)					
Maximum	0.32	0.56	0.13	0.32	0.13
Median	0.07	0.06	0.09	0.10	0.06
Minimum	0.05	<0.05	0.07	0.05	0.05
Number of samples	9	14	10	4	5
Number of sites	1	4	2	1	1
Detection percentage	100	71	100	100	100
De-ethylatrazine (µg/L)					
Maximum	0.17	0.17	0.13	0.17	0.09
Median	0.05	<0.05	0.09	0.07	<0.05
Minimum	<0.05	<0.05	0.05	<0.05	<0.05
Number of samples	9	14	10	4	5
Number of sites	1	4	2	1	1
Detection percentage	55	7	100	75	40

Table 18. Statistical summary of concentrations of selected water-quality constituents in the Rock River, supply wells, and the ground-water contributing area to supply wells, Rock County Rural Water well field, eastern Rock County, Minnesota (Continued)

[--, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; detection percentage, percent of samples in which specified herbicide was detected; <, less than]

	River	Supply well 360-500 feet from river	Ground-water contributing area to supply wells	River May 20-Aug 14 Post-application runoff events	River Aug. 28-May 10 Pre-application, late summer, or post-growing season
De-isopropylatrazine (µg/L)					
Maximum	0.07	0.10	0.12	0.06	0.07
Median	<0.05	<0.05	0.09	<0.05	0.05
Minimum	<0.05	<0.05	0.05	<0.05	<0.05
Number of samples	9	14	10	4	5
Number of sites	1	4	2	1	1
Detection percentage	44	7	100	25	60
Alachlor ESA (µg/L)					
Maximum	1.76	0.74	0.18	1.76	0.79
Median	0.66	0.45	<0.05	0.55	0.74
Minimum	0.36	<0.05	<0.05	0.36	0.53
Number of samples	9	14	10	4	5
Number of sites	1	4	2	1	1
Detection percentage	100	86	10	100	100
Metolachlor (µg/L)					
Maximum	0.42	0.28	0.07	0.42	0.32
Median	0.14	<0.05	<0.05	0.18	0.13
Minimum	0.05	<0.05	<0.05	0.05	0.05
Number of samples	9	14	10	4	5
Number of sites	1	4	2	1	1
Detection percentage	100	50	10	100	100
Metolachlor ESA (µg/L)					
Maximum	2.82	3.21	3.36	2.82	2.38
Median	2.46	2.28	1.30	2.68	2.115
Minimum	1.85	1.45	0.24	2.53	1.85
Number of samples	4	6	5	2	2
Number of sites	1	2	2	1	1
Detection percentage	100	100	100	100	100
Metolachlor OA (µg/L)					
Maximum	0.64	0.76	0.48	0.56	0.64
Median	0.50	0.41	0.32	0.50	0.42
Minimum	0.20	0.26	<0.20	0.44	0.20
Number of samples	4	6	5	2	2
Number of sites	1	2	2	1	1
Detection percentage	100	100	60	100	100

Table 18. Statistical summary of concentrations of selected water-quality constituents in the Rock River, supply wells, and the ground-water contributing area to supply wells, Rock County Rural Water well field, eastern Rock County, Minnesota (Continued)

[--, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; detection percentage, percent of samples in which specified herbicide was detected; <, less than]

	River	Supply well 360-500 feet from river	Ground-water contributing area to supply wells	River May 20-Aug 14 Post-application runoff events	River Aug. 28-May 10 Pre-application, late summer, or post-growing season
Acetochlor ESA (µg/L)					
Maximum	0.39	0.71	<0.20	0.37	0.39
Median	0.32	<0.20	<0.20	0.32	<0.20
Minimum	<0.20	<0.20	<0.20	0.27	<0.20
Number of samples	4	6	5	2	2
Number of sites	1	2	2	1	1
Detection percentage	75	50	0	100	50
Acetochlor OA (µg/L)					
Maximum	0.31	0.67	<0.20	0.31	0.26
Median	<0.20	<0.20	<0.20	<0.20	<0.20
Minimum	<0.20	<0.20	<0.20	<0.20	<0.20
Number of samples	4	6	5	2	2
Number of sites	1	2	2	1	1
Detection percentage	50	17	0	50	50
Acetochlor (µg/L)					
Maximum	0.29	<0.05	<0.05	0.29	0.13
Median	0.06	<0.05	<0.05	0.07	<0.05
Minimum	<0.05	<0.05	<0.05	<0.05	<0.05
Number of samples	9	14	10	4	5
Number of sites	1	4	2	1	1
Detection percentage	55	0	0	55	40
Alachlor OA (µg/L)					
Maximum	<0.20	<0.20	<0.20	<0.20	<0.20
Median	<0.20	<0.20	<0.20	<0.20	<0.20
Minimum	<0.20	<0.20	<0.20	<0.20	<0.20
Number of samples	4	6	5	2	2
Number of sites	1	2	2	1	1
Detection percentage	0	0	0	0	0
Hydroxyatrazine (µg/L)					
Maximum	0.24	1.04	0.24	<0.20	0.24
Median	<0.20	<0.20	<0.20	<0.20	<0.20
Minimum	<0.20	<0.20	<0.20	<0.20	<0.20
Number of samples	4	6	5	2	2
Number of sites	1	2	2	1	1
Detection percentage	25	50	20	0	50

Table 18. Statistical summary of concentrations of selected water-quality constituents in the Rock River, supply wells, and the ground-water contributing area to supply wells, Rock County Rural Water well field, eastern Rock County, Minnesota (Continued)

[--, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; detection percentage, percent of samples in which specified herbicide was detected; <, less than]

	River	Supply well 360-500 feet from river	Ground-water contributing area to supply wells	River May 20-Aug 14 Post-application runoff events	River Aug. 28-May 10 Pre-application, late summer, or post-growing season
Alachlor (µg/L)					
Maximum	<0.05	<0.05	<0.05	<0.05	<0.05
Median	<0.05	<0.05	<0.05	<0.05	<0.05
Minimum	<0.05	<0.05	<0.05	<0.05	<0.05
Number of samples	9	14	10	4	5
Number of sites	1	4	2	1	1
Detection percentage	0	0	0	0	0
Cyanazine (µg/L)					
Maximum	<0.05	<0.05	<0.05	<0.05	<0.05
Median	<0.05	<0.05	<0.05	<0.05	<0.05
Minimum	<0.05	<0.05	<0.05	<0.05	<0.05
Number of samples	9	14	10	4	5
Number of sites	1	4	2	1	1
Detection percentage	0	0	0	0	0
Cyanazine amide (µg/L)					
Maximum	<0.05	<0.05	<0.05	<0.05	<0.05
Median	<0.05	<0.05	<0.05	<0.05	<0.05
Minimum	<0.05	<0.05	<0.05	<0.05	<0.05
Number of samples	9	14	10	4	5
Number of sites	1	4	2	1	1
Detection percentage	0	0	0	0	0
Metribuzin (µg/L)					
Maximum	<0.05	<0.05	<0.05	<0.05	<0.05
Median	<0.05	<0.05	<0.05	<0.05	<0.05
Minimum	<0.05	<0.05	<0.05	<0.05	<0.05
Number of samples	9	14	10	4	5
Number of sites	1	4	2	1	1
Detection percentage	0	0	0	0	0
Propazine (µg/L)					
Maximum	<0.05	<0.05	<0.05	<0.05	<0.05
Median	<0.05	<0.05	<0.05	<0.05	<0.05
Minimum	<0.05	<0.05	<0.05	<0.05	<0.05
Number of samples	9	14	10	4	5
Number of sites	1	4	2	1	1
Detection percentage	0	0	0	0	0