Regional Ground-Water-Flow Models of Surficial Sand and Gravel Aquifers Along the Mississippi River Between Brainerd and St. Cloud, Central Minnesota

Scientific Investigation Report 2004-5087

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

Regional Ground-Water-Flow Models of Surficial Sand and Gravel Aquifers Along the Mississippi River Between Brainerd and St. Cloud, Central Minnesota

By J.F. Ruhl, and T.K. Cowdery

Prepared in cooperation with the Minnesota Department of Health

Scientific Investigations Report 2004-5087

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

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

U.S. Geological Survey, Reston, Virginia: 2004

For sale by U.S. Geological Survey, Information Services
Box 25286, Denver Federal Center
Denver, CO 80225

For more information about the USGS and its products:
Telephone: 1-888-ASK-USGS
World Wide Web: http://www.usgs.gov/

Suggested citation:
Ruhl, J.F., and Cowdery, T.K., 2004, Regional ground-water-flow models of surficial sand and gravel aquifers along the Mississsippi River between Brainerd and St. Cloud, central Minnesota: U.S. Geological Survey Scientific Investigations Report 2004-5087, 21 p.

Contents

Figures

Tables

Tables--Continued

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow rate	
cubic meter per day (m^3/d)	35.31	cubic foot per day (ft^3/d)
	Hydraulic conductivity	
meter per day (m/d)	3.281	foot per day (ft/d)
	Transmissivity*	
meter squared per day (m^2/d)	10.76	foot squared per day (ft^2/d)

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

$$°F=(1.8\times°C)+32$$

Vertical coordinate information is referenced to the *insert datum name (and abbreviation) here, for instance, "North American Vertical Datum of 1988 (NAVD 88)"*

Horizontal coordinate information is referenced to the *insert datum name (and abbreviation) here, for instance, "North American Datum of 1983 (NAD 83)"*

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

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

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Regional Ground-Water-Flow Models of Surficial Sand and Gravel Aquifers Along the Mississippi River Between Brainerd and St. Cloud, Central Minnesota

By James F. Ruhl, and Timothy K. Cowdery

Abstract

This report documents regional ground-water-flow models constructed by the U.S. Geological Survey in cooperation with the Minnesota Department of Health (MDH) to satisfy the requirements of their Source Water Protection Plan (SWPP). Steady-state single-layer ground-water-flow models were constructed with the computer program MODFLOW to simulate flow in surficial sand and gravel aquifers along the Mississippi River between Brainerd and St. Cloud in central Minnesota. The hydrogeologic data that were used to construct the models were compiled from available sources.

Calibrated values of horizontal hydraulic conductivity and areal recharge for the aquifer in a northern model area were 70 m/d and 3.0×10^{-4} m/d, respectively. This model was sensitive to net areal recharge, vertical hydraulic conductivity of perennial streambed sediments, and horizontal hydraulic conductivity. The major source of net inflow to the model was from edge boundary cells. The major source of net outflow was ground-water discharge to perennial and ephemeral streams.

Calibrated values of horizontal hydraulic conductivity and areal recharge for the aquifer in a southern model area were 70 m/d and 6.0×10^{-4} m/d, respectively. This model was sensitive mostly to horizontal hydraulic conductivity. Net areal recharge and ground-water discharge to perennial streams were the major sources of net inflow and outflow, respectively.

Introduction

The Minnesota Department of Health (MDH) is responsible for implementation of the U.S. Environmental Protection Agency's (USEPA) Source-Water Protection Program (SWPP) in Minnesota. One component of this program is to designate contributing recharge areas that surround public water-supply wells. The USEPA (1987) designed the SWPP to assist state and local agencies and municipalities in the protection of recharge areas that contribute water to public water-supply wells against infiltration, percolation, and transport of contaminants.

The SWPP considers the capture zone of a public water-supply well to be a particularly sensitive area that requires special protection. The capture zone is the area around a supply well bounded by lines of equal ground-water travel time. In this study the capture zone is considered to be the area that contributes recharge to the well for a specific ground-water travel time.

The methods used to delineate capture zones around supply wells range from simple techniques, such as specification of an area of constant radius around the well of interest, to construction of ground-water-flow models combined with particle-tracking programs (U.S. Environmental Protection Agency, 1987). The MDH has adopted the latter, more complex, technique to delineate capture zones around supply wells (Bruce Olsen, Minnesota Department of Health, written commun., 2002). The MDH will use nested, local ground-water-flow models developed within the framework of regional flow models to delineate capture zones around supply wells of interest.

The MDH, in cooperation with the U.S. Geological Survey (USGS), developed regional ground-water-flow models for aquifers in two areas to be used in their SWPP. These models incorporated existing data from the USGS and various state agencies; much of these data were compiled by the MDH. The modeled aquifers consist of surficial sand and gravel deposited by glacial meltwater along the present course of the Mississippi River (fig. 1).

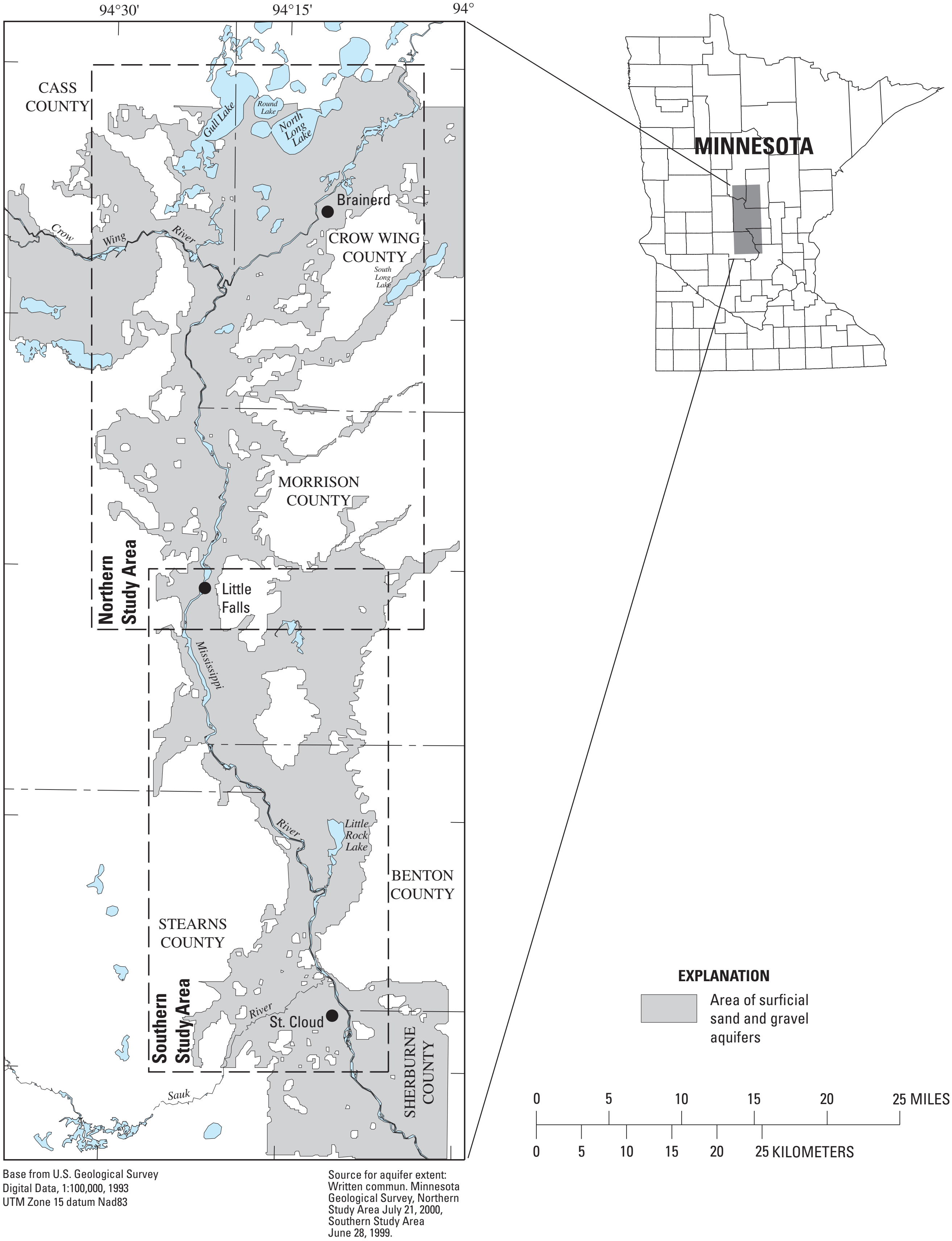

Figure 1. Locations of northern and southern study areas and extent of surficial sand and gravel aquifers along the Mississippi River between Brainerd and St. Cloud in central Minnesota

Purpose and Scope

The purpose of this report is to document regional ground-water-flow models constructed for the MDH to satisfy the requirements of their SWPP. The models were constructed during 2001-02 for surficial sand and gravel aquifers in two areas along the Mississippi River between Brainerd and St. Cloud in central Minnesota. This area was divided into overlapping northern and southern portions, each about 2,000-km^2, for construction of the two models (fig. 1). The two models (hereinafter referred to as the northern and southern models) simulate ground-water flow in the aquifers within these areas as single layer systems under water-table, steady-state conditions. Available hydrologic data were used as model inputs and for model calibration. Ground-water levels measured in wells drilled during the last 50 years and baseflow measurements of the Mississippi River made in 1988 (Payne, 1995) were used for model calibration.

Hydrogeologic Setting

Average monthly temperatures during 1961-90 for St. Cloud, Minnesota, located at the southern end of the study area, ranged from -23.9°C in January to 32.4°C in July (Minnesota State Climatologist, 2002). Average annual precipitation during 1961-90 for St. Cloud was 69.6 cm (Minnesota State Climatologist, 2002). About 80 percent of the annual precipitation occurs during May through October. Estimated mean annual evaporation in the study area is 56 cm (Helgesen and others, 1975).

Unconsolidated glacial deposits from several lobes of the Laurentian Ice Sheet (100,000-10,000 years ago) overlie crystalline bedrock throughout the study area (Wright, 1972). These deposits, which are either stratified (sands and gravels) or unstratified (tills), range from 0 to about 90 m in thickness (Helgesen and others, 1975). The stratified deposits consist of outwash, ice contact, alluvial, and terrace sediments. The alluvial and terrace sediments are glacial deposits reworked by post-glacial streams. The stratified deposits include both extensive surficial sediments and buried sediments of unknown extent lying within unstratified deposits. The locations of most stratified buried sediments and the nature of the hydraulic connections of these deposits to surficial sediments and surface-water bodies are unknown. Based on sediment texture, the hydraulic conductivity of the stratified deposits is 1–6 orders of magnitude greater than the unstratified deposits (Fetter, 1988)

The surficial sand and gravel aquifers in the two study areas consist of stratified glacial deposits adjacent to the Mississippi River. These aquifers are surrounded by unstratified glacial deposits (till). Areal recharge to the aquifers ranges from 1.5×10^{-4} to 8.5×10^{-4} m/d (Helgesen and Lindholm, 1977; Lindholm, 1980; and Ruhl, 2002). The aquifers are recharged from precipitation, including snow melt, and, to a lesser extent, from bank overflow along the Mississippi River during high water and from infiltration along the aquifer edges where the surficial sand and gravel abuts surrounding till. Sources of edge recharge could include overland flow from adjacent till uplands or seepage from ephemeral streams near the aquifer-upland boundary during high-flow periods, and ground-water flow from aquifers buried within surrounding till. The aquifers may also derive recharge from portions of some lakes and wetlands. The aquifers mostly discharge to both perennial (the Mississippi, Sauk, and Crow Wing Rivers) and ephemeral streams and to portions of some lakes and wetlands.

The aquifers are as much as 62 m thick with as much as 44 m of saturation (Lindholm, 1980). The horizontal hydraulic conductivity of these aquifers ranges from 10 to 200 m/d. The transmissivity can be locally as much as 3,700 m^2/d (Lindholm, 1980). Yields from wells completed in the aquifers range from several hundred square meters per day where the saturated thickness is less than 5 m to greater than 5,000 m^3/d (Lindholm, 1980).

Ground-Water Flow Models

Separate models simulated ground-water flow in surficial sand and gravel aquifers for the northern and southern portions of the study area (fig. 1). The conceptual model of the aquifers is based on information in the Hydrogeologic Setting section. Aquifer properties, recharge and discharge characteristics, and aquifer extent and thickness were incorporated into USGS MODFLOW numerical models (McDonald and Harbaugh, 1988) using the U.S. Department of Defense Groundwater Modeling System (GMS) (Environmental Modeling Systems, Incorporated, 2002). MODFLOW is a three-dimensional, finite-difference computer program used to solve the ground-water-flow equation over a modeled area. GMS is a commercial computer program used to prepare input data sets for MODFLOW and to graphically illustrate model input and output. No attempt was made to simulate ground-water flow from or to the unmapped buried sand and gravel aquifers within surrounding till.

Numerical Model Description and Assumptions

Both numerical ground-water models (hereinafter, models) were single-layer, unconfined, two-dimensional (horizontal), and steady-state. The northern model area extends along the Mississippi River from Brainerd to Little Falls (fig. 1). The southern model area extends along the Mississippi River from Little Falls to the confluence of the Mississippi and Sauk Rivers near St. Cloud (fig. 1). The most detailed aquifer geometry data are sand and gravel thickness on a 100-m square gridded array produced by the Minnesota Geological Survey (MGS) (written commun., 1999; 2000). This grid was used as the model grid and is adequate to represent aquifer geometry, hydraulic properties, and boundary conditions in sufficient detail for construction of subsequent nested local models.

Flow of ground water within the surficial sand and gravel aquifers was assumed to be under water-table (unconfined) conditions. Underlying and surrounding tills originally were assumed to represent no-flow boundaries. This assumption proved inaccurate in the first model (southern study area) that was constructed because the edges of the aquifer abutting till were always dry, contrary to actual conditions measured in the aquifers. Consequently, a general head-dependent flux boundary condition was added to the horizontal edges of the northern-study-area model to account for possible runoff infiltration recharge, ephemeral-stream recharge, and recharge from lateral till or buried aquifers.

A general head-dependent flux boundary allows water flow into or out of a cell at a rate proportional to the head gradient between the cell and an external source, and to a proportionality constant that represents the hydraulic conductivity and area of the intervening material. Single values for hydraulic conductivity and area were used for all of the head-dependent flux boundary cells in the model. The original value of hydraulic conductivity was adjusted during the calibration process to produce realistic model output of hydraulic heads and fluxes.

Based on regional water-table maps of the northern and southern ends of each model, ground-water flow was assumed to be perpendicular to the Mississippi, Sauk, and Crow Wing Rivers, the main hydrologic sinks. Therefore, these boundaries were assumed to be no-flow. The southern model terminated at a string of lakes and streams in the northeast part of the model, which also were assumed to be no-flow boundaries.

Net areal recharge, which represents net infiltration of precipitation at land surface (total infiltration minus evapotranspiration), was applied uniformly to each model. Explicit simulation of seasonal evapotranspiration was not attempted in either model because it was beyond the scope of the study.

Surface-water features in each model were simulated as MODFLOW river, general-head, and drain boundaries in the models (figs. 2 and 3). The Mississippi River and smaller perennial streams were modeled as river boundaries; lakes and wetlands were modeled as general-head boundaries; and ephemeral streams (northern study area only) were modeled as drain boundaries. River cells allow leakage through the stream bottom based on the difference in water levels and streambed conductance. A river cell will provide or receive as much water as the model requires to reach a mathematical solution. Drain cells allow leakage only from the aquifer to the drain (ephemeral stream).

Ground-water withdrawals from the aquifer were simulated for 19 and 63 production wells (irrigation and public-supply wells) in the northern and southern models, respectively. Domestic-supply well withdrawals were not simulated because these withdrawals were very small compared to withdrawals from production wells.

Model Input

Input data for both models were prepared as ARC/INFO coverages and shapefiles (Environmental Science Research Institute, 2004), imported into GMS, and edited and converted into MODFLOW input files. Information regarding the original data sets are shown in table 1. The MGS produced a 100-m grid of sand and gravel thickness from existing well stratigraphic logs. These data were modified to produce an aquifer extent and bottom elevation array by subtracting the thickness array from a land-surface digital elevation model (DEM). Model cells with aquifer thickness less than 1m were removed as active cells, resulting in the creation of arrays of aquifer bottom elevation.

The DEM of the land-surface, which is coincident with the MGS sand-and-gravel-thickness array, is interpolated from the USGS 30-m DEM based on the hypsography of 1:24,000-scale USGS quadrangle maps. This DEM, which was assumed to represent the land surface, was used to calculate all elevations

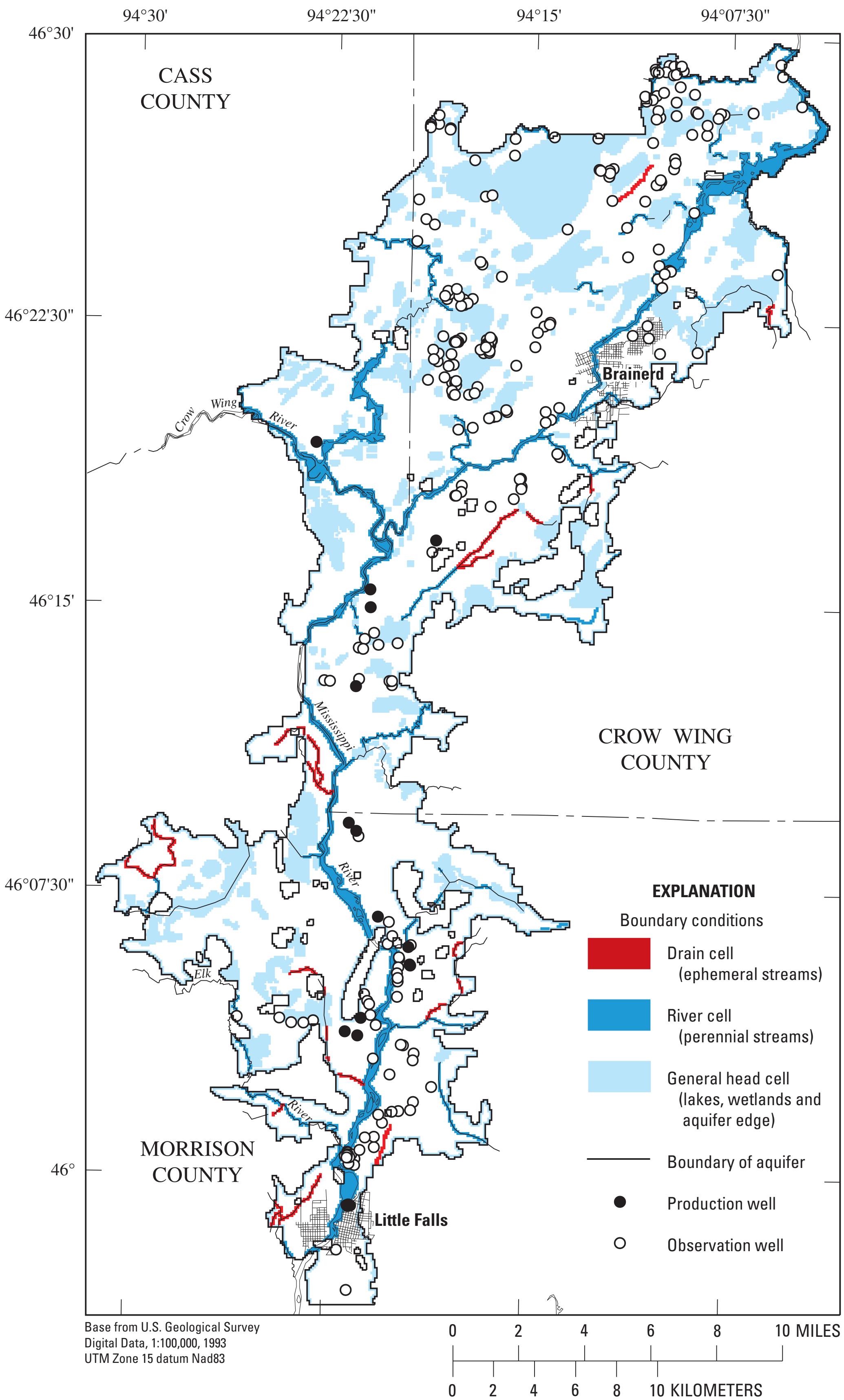

Figure 2. Boundary conditions for the northern model along the Mississippi River between Brainerd and Little Falls in central Minnesota

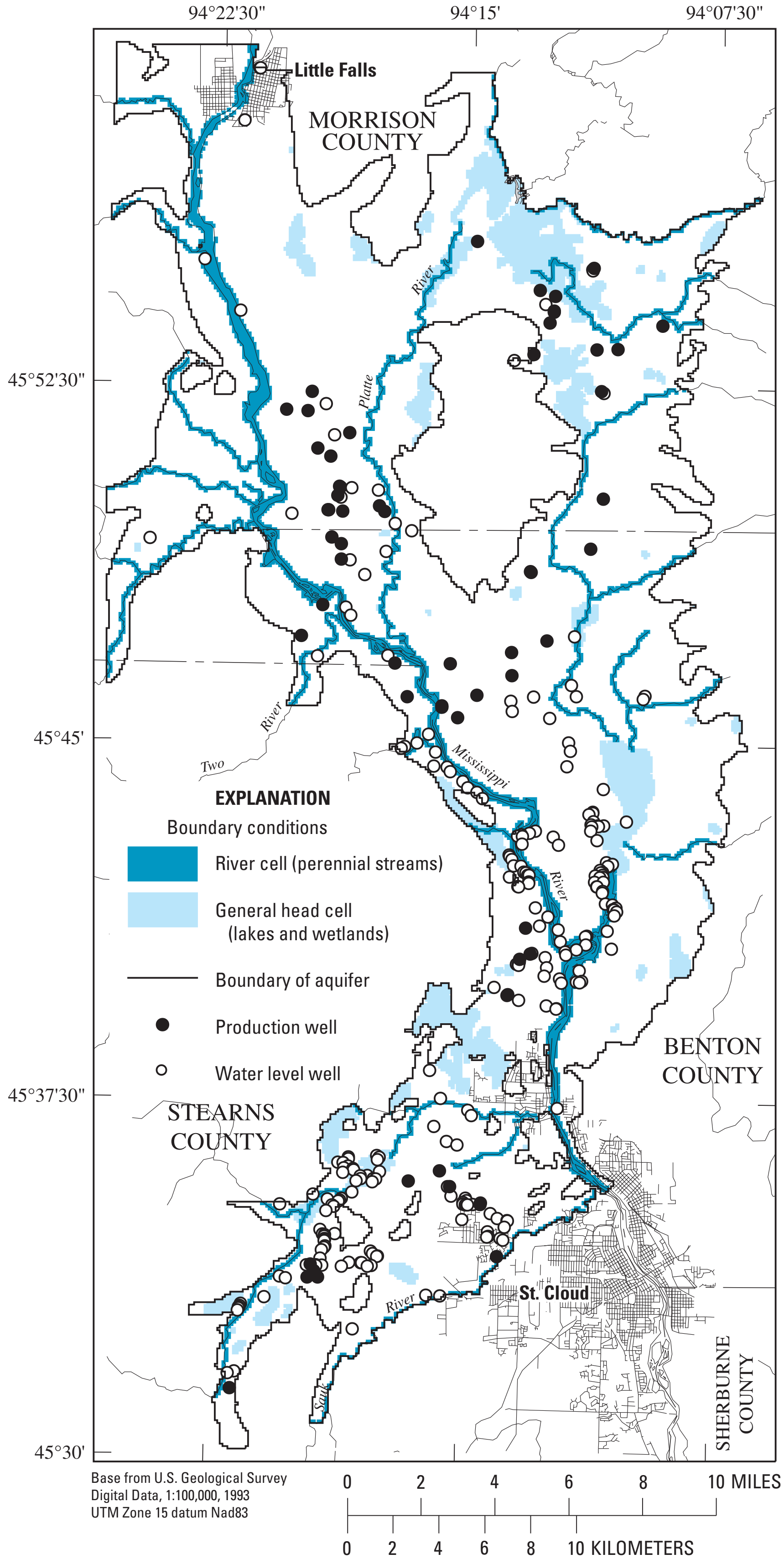

Figure 3. Boundary conditions for the southern model along the Mississippi River betweeen Little Falls and St. Cloud in central Minnesota

Table 1. Data sets used to construct the northern and southern ground-water-flow models between Brainerd and St. Cloud in central Minnesota

[—, not applicable; MGS, Minnesota Geological Survey; CWI, county well index; m, meter; NM, northern model; SM, southern model; USGS, U.S. Geological Survey; DEM, digital elevation model; DLG, digital line graph; PIC, Primary Information Code; GH, general head; RIV, river; DRN, drain; MDH, Minnesota Department of Health; MNDNR, Minnesota Department of Natural Resources; <, less than; >, greater than; m, meter; m/d, meter per day; RCH, recharge; WEL, well]

Model input	Data agency	Data source	Original data set	Scale	Northern model input data set	Southern model input data set	Data modification	MOD-FLOW-stress	Reference
					Aquifer				
Active cells	MGS	CWI well log compilation	sandthk_rev.txt (NM) sandthck.txt (SM)	100-m cells	N-act_aq.shp	modelarea.shp	polygons created from sandthk_rev.txt (NM) or sandthck.txt (SM), including areas >1-m thick		
Cell-top elevation	USGS	1:24,000 quadrangle hypsography	30-m DEM grid	100-m cells	N-dem100m	landsurf	interpolated to 100-m grid		USGS, 1999
Cell-bottom elevation	USGS	1:24,000 quadrangle hypsography	30-m DEM grid	100-m cells	N-aqbottom	sandbott	interpolated to 100-m grid		USGS, 1999
	MGS	CWI well log compilation	sandthk_rev.txt (NM) sandthck.txt (SM)	100-m cells			excluded cell bottom within 1 m of DEM		
Hydraulic Conductivity		Calibrated							
					Hydrography				
Lakes	USGS	quadrangle hydrography	USGS DLG	1:100,000	N-lakes.shp	Lakes.shp	PIC code = 421, removed lakes covering less than 1/4 cell	GH	USGS, 1983
Wetlands	USGS	quadrangle hydrography	USGS DLG	1:100,000	N-wetland_1m.shp	Wetland.shp	PIC code = 109, 111, split polygons into 1-m elevation intervals	GH	USGS, 1983
River areas	USGS	quadrangle hydrography	USGS DLG	1:100,000	N-river_poly.shp	River.shp	split polygons into 1-m elevation intervals (2-m intervals in the northern model)	RIV	USGS, 1983
River lines	USGS	quadrangle hydrography	USGS DLG	1:100,000	N-peren_stream.shp	Streams.shp	PIC code =421, width assumed to be 10 m (SM)	RIV	USGS, 1983
Intermittent river lines	USGS	quadrangle hydrography	USGS DLG	1:100,000	N-inter_stream.shp	—		DRN	USGS, 1983
Hydrographic elevations	USGS	1:24,000 quadrangle hypsography	30-m DEM grid	100-m cells	hydrography shapefiles, N-peren_pts.shp, N-inter_pts.shp	hydrography shapefiles, strnodes.shp	interpolated to 100-m grid, then to hydrographic centroid or endpoint		USGS, 1999

Table 1. Data sets used to construct the northern and southern ground-water-flow models between Brainerd and St. Cloud in central Minnesota—Continued.

[—, not applicable; MGS, Minnesota Geological Survey; CWI, county well index; m, meter; NM, northern model; SM, southern model; USGS, U.S. Geological Survey; DEM, digital elevation model; DLG, digital line graph; PIC, Primary Information Code; GH, general head; RIV, river; DRN, drain; MDH, Minnesota Department of Health; MNDNR, Minnesota Department of Natural Resources; <, less than; >, greater than; m, meter; m/d, meter per day; RCH, recharge; WEL, well]

Model input	Data agency	Data source	Original data set	Scale	Northern model input data set	Southern model input data set	Data modification	MOD-FLOW-stress	Reference
Initial ground-water heads	MDH	CWI well log compilation		100-m cells	N-w_table	wtelev	excluded heads in buried aquifers, above land surface, below aquifer bottom, assumed no stickup of measuring point		
	USGS	quadrangle hydrography	USGS DLG	100-m cells					USGS, 1983
Lake and wetland bed conductance		calibrated			N-lakes.shp, N-wetland_1m.shp	lakes.shp, wetland.shp	initial: 2 m/d (SM)		—
River bed conductance		calibrated			river hydrography shapefiles	river hydrography shapefiles	initial: 20 m/d (SM)		—
Hydrographic bed thickness		assumed			hydrography shapefiles	hydrography shapefiles	2 m for streams, 5 m for wetlands (SM)		—
					Inputs and outputs				
Net areal recharge area	MGS	CWI well log compilation	sandthk_rev.txt (NM) sandthck.txt (SM)	100-m cells	N-act_aq.shp	modelarea.shp	polygons created from sandthk_rev.txt (NM) or sandthck.txt (SM), excluding areas <1-m thick	RCH	—
Net edge recharge area	USGS	constructed	constructed	—	N-edge-points.shp	—	edge cell of model not containing a hydrographic stress	GH	—
Well Withdrawal	MNDNR	Well Water Use	mrcpum.shp (SM)	—		wells.shp	excluded wells screened in buried aquifers, above land surface, below aquifer bottom	WEL	—
Initial net areal recharge rate		calibrated							—
Initial net edge conductivity		calibrated				—	initial value: 0.1 m/d (NM)		—
					Calibration data				
Heads	MDH	CWI retrieval	wells.shp (NM), wells (SM)	—	calibration wells.shp	obwell1.shp	excluded heads in buried aquifers, above land surface, below aquifer bottom, assumed no stickup		—
Flux	USGS	1988 Seepage run	—	—	—	—	compiled from report	—	Payne, 1995

used in the models. The area of hydrologic features (streams, lakes and wetlands, hereinafter referred to as hydrography) originated from the USGS 1:100,000-scale digital line graphs (DLG).

To ease importing the model input data into GMS, the original DLG coverages of the perennial and ephemeral streams, lakes, and wetlands were converted into polygon and arc shapefiles. Polygons less than one-quarter cell in area (2,500 m^2) were excluded from all shapefiles for simplicity. Wetland and river polygons (southern model only) were divided into 100-m-grid sized polygons and assigned a surface elevation from the DEM. These polygons were aggregated into polygons of equal elevation class based on 1-m elevation intervals. River polygons in the northern model were divided into 2-m elevation interval polygons based on DEM elevations along a line tracing the middle of the river. Two-meter intervals were selected to keep the number of river polygons manageable. This choice produces 2-m high waterfalls in the model periodically on the Mississippi River, which do not exist in reality. Modeled ground-water flow near these artificial waterfalls is inaccurate.

The water-table surfaces used to define initial heads in the models are based on the DEM land-surface data for the streams, lakes, wetlands, and on water-table depth data from well logs. The MDH compiled the water-table depth data from the MGS County Well Index data base. These water-level data generally are of poor and variable quality. Most water levels were collected by the well driller, just after well construction. These water levels were affected by drilling and may not be adjusted for the height of the casing above land surface. The water levels were measured during the last 50 years, but most were obtained during the last 30 years. These wells exist throughout the study area, but are spaced more closely near areas of greater population. Average water levels were used at a few sites with multiple measurements.

A water-table surface was needed for initial heads in the model. This surface was generated by interpolating all water-level data using the Inverse-Weighted Distance Method and adjusting the value to 1-m above the aquifer bottom, or to the land surface where the interpolated value was outside those ranges. The measured water-depth data also were used as a water-level calibration data set.

Values of horizontal hydraulic conductivity (table 2) and net areal recharge were applied uniformly throughout the two modeled areas. Net areal recharge was 3 x 10^{-4} and 6 x 10^{-4} m/d for the northern and southern models, respectively. Differences in geology and topography probably cause variation from the uniform values of model input parameters within the study areas. Construction of the models based on the spatial variations of these model input parameters was beyond the scope of the study.

Withdrawals from the aquifer were simulated based on pumping for production wells used for irrigation and municipal water supply reported in Minnesota Department of Natural Resources (DNR) water-use data base. These data were supplied by the MDH in 1999 and reported data for 1998. Pumping amounts have increased over the period during which water levels were measured. However, most water levels used in calibration were measured more recently when the greater pumping was occurring. Pumping during baseflow measurement in 1988 (Payne, 1995) probably was greater than usual because of the drought at

Table 2. Inital values used to define boundary conditions in the ground-water-flow models along the Mississippi River between Brainerd and St. Cloud in central Minnesota

[—, not applicable; GHB, general head boundary package; RIV, river boundary package; DRN, drain boundary package; m, meter; m/d, meter per day]

Model	Surface-water feature	Modeled in MODFLOW as	Feature geometry in model	Bed sediment thickness (m)	River width (m)	Initial hydraulic conductivity (m/d)
Northern	lakes and wetlands	GHB	polygon	2	—	2
	perennial streams	RIV	polygon	2	—	0.2
	perennial streams	RIV	line	2	8	0.2
	ephemeral streams	DRN	line	2	6	20
	edge recharge	GHB	point	—	—	[1]10,000
Southern	lakes	GHB	polygon	2	—	2
	wetland	GHB	polygon	5	—	2
	perennial streams	RIB	polygon	2	—	20
	perennial streams	RIV	line	2	10	20

[1] MODFLOW conductance for the entire 100-m x 100-m cell.

that time. Pumping during 1988 may be comparable to the presumably greater pumping rates of the late 1990's. While the climatological and pumping data for this comparison exist, this analysis was not done for this study. Pumping in the northern and southern model areas ranged from about 9 to 1,000 and from about 2 to 2,000 m^3/d per well, respectively.

Perennial streams were simulated with the MODFLOW river package (RIV), ephemeral streams with the MODFLOW drain package (DRN), and lakes and wetlands with the MODFLOW general-head boundary package (GHB). The packages require user specified values for conductance (a parameter incorporating length, width, and thickness of the connection with the aquifer, and its hydraulic conductivity) and a driving head. Constant values of thickness (and width for line features) and hydraulic conductivity were specified for each connection (table 2). The area (or length for line features) of each connection was derived from the hydrography of USGS 1:100,000 scale digital maps. The dimensions used to define the thicknesses of the bed sediments of streams, lakes, and wetlands are considered to be reasonable estimates of their true values.

The specified conductances are based on estimates of the vertical hydraulic conductivities of the bed sediments. These estimates are considered to be reasonable approximations of their true values based on previously published values of silty, low-permeability unconsolidated materials (Heath, 1983). The conductance specified for the edge recharge cells in the northern model was not chosen on the basis of physical characteristics of the aquifer materials, but rather was adjusted to simulate reasonable ground-water head and flux in the aquifer.

Model Calibration, Sensitivity, and Results

The models were calibrated by varying horizontal hydraulic conductivity, net areal recharge, and conductance for the GHB and RIV packages. Values for these model inputs were selected based on: (1) comparison of the simulated and measured baseflow to the Mississippi River and its tributaries (Payne, 1995); and (2) minimization of the mean errors computed from the differences between measured and simulated hydraulic heads at well locations. In calibration, matching baseflow was given a higher priority than matching heads because of the inaccuracies contained in the head data set.

The baseflows used to calibrate the models were based on a study of baseflow to the reaches of the Mississippi River and tributaries upstream from the Minneapolis-St. Paul area during July 1988 (Payne, 1995). Results of this study were used to estimate tributary and mainstem channel baseflow, which was assumed to be net (ground-water discharge minus possible ground-water recharge) ground-water discharge to the Mississippi River and tributaries in the modeled areas. These measured baseflows were 414,282 and 358,685 m^3/d for the northern and southern models, respectively. These measurements are based on the fractions of the reaches of the Mississippi River within each modeled area relative to the total reach of the Mississippi River analyzed in the study by Payne (1995). The measurements of baseflow to tributaries of the Mississippi River within each modeled area are based on the same approach.

Output from the calibrated models included steady-state hydraulic head values and volumetric inflow and outflow components for the modeled areas. Convergence criteria used to determine solutions for the models were a maximum change in hydraulic head of 0.1 m for any grid cell with a maximum of 250 iterations.

Northern Study Area

Calibrated model inputs for the northern model and the sensitivity of the model to adjustments of these inputs are shown in table 3. The calibrated values of horizontal hydraulic conductivity (70 m/d) and net areal recharge (3.0×10^{-4} m/d) are consistent with previously reported values.

Figure 4 shows the correspondence of measured to simulated hydraulic heads at 236 well locations for the calibrated northern model. The least-squares fit of the measured to simulated hydraulic heads has as an R^2 value of 0.9540. The position of the least-squares line above and to the left of the line of correspondence (fig. 4) indicates a positive bias in the modeled heads. The spatial distribution of these values indicates that the residuals generally are greatest near the periphery of the aquifers distant from the Mississippi River (fig. 5). Steady-state hydraulic heads computed by the model range from about 340 to 370 m above NGVD88.

The mean absolute error for ground-water levels in the sensitivity analysis indicates that the model is most sensitive to net areal recharge and vertical hydraulic conductivity of perennial streambed sediments, and, to a lesser extent, horizontal hydraulic conductivity (table 3). The sensitivity analysis, based on a comparison of the computed as a percent of measured baseflow, produced similar results. This comparison indicates that the model is most sensitive to, in decreasing order, vertical hydraulic conductivity of perennial streambed sediments, horizontal hydraulic conductivity, and net areal recharge (table 3).

The volumetric flow budget of the model indicates that net inflow consists of recharge from edge cells (75 percent) (table 4). The volumetric flow budget also indicates that discharge to perennial streams, lakes, and wetlands accounts for 88 percent of the net outflow, and that discharge to ephemeral streams (11 percent) and to well withdrawals (1 percent) account for the remainder.

Southern Study Area

The southern model was more unstable (less likely to converge to a solution) than the northern model. Thus, calibration and sensitivity analysis of the southern model are based on smaller ranges of model input adjustments. The calibrated model inputs for the southern model and the sensitivity of the model to adjustments of these inputs are tabulated in table 5. The calibrated values of horizontal hydraulic conductivity (70 m/d) and net areal recharge (6.0×10^{-4} m/d) are consistent with previously reported values

Table 3. Sensitivity analysis of the northern ground-water-flow model between Brainerd and Little Falls in central Minnesota.

[The percent discrepancy between total inflow and total outflow for all model runs was within 1.35 percent; m, meter; m/d, meter per day; m^3/d, cubic meter per day]

Calibration variable	Calibrated values (m/d)	Multiplication factor	Computed baseflow as percent of measured baseflow (m^3/d)	Mean absolute error for ground-water levels (m)
Horizontal hydraulic conductivity	70	0.1	31	2.35
		0.2	42	1.97
		0.5	69	1.82
		1.0	100	1.84
		2.0	139	1.94
		5.0	194	2.11
		10.0	232	2.24
Net areal recharge	3.0×10^{-4}	0.1	94	1.70
		0.2	94	1.71
		0.5	97	1.76
		1.0	100	1.84
		2.0	108	1.99
		5.0	131	2.37
		10.0	167	3.04
Vertical hydraulic conductivity of perennial streambed sediments	0.02	0.1	23	2.46
		0.2	39	2.31
		0.5	71	2.03
		1.0	100	1.84
		2.0	133	1.68
		5.0	188	1.58
		10.0	251	1.56
Vertical hydraulic conductivity of lakebed and wetland sediments	2	0.1	107	1.74
		0.2	105	1.76
		0.5	103	1.81
		1.0	100	1.84
		2.0	98	1.86
		5.0	96	1.88
		10.0	95	1.89
Hydraulic conductivity of edge recharge cells	10,000	0.1	98	1.81
		0.2	99	1.82
		0.5	99	1.83
		1.0	100	1.84
		2.0	100	1.84
		5.0	101	1.85
		10.0	101	1.85

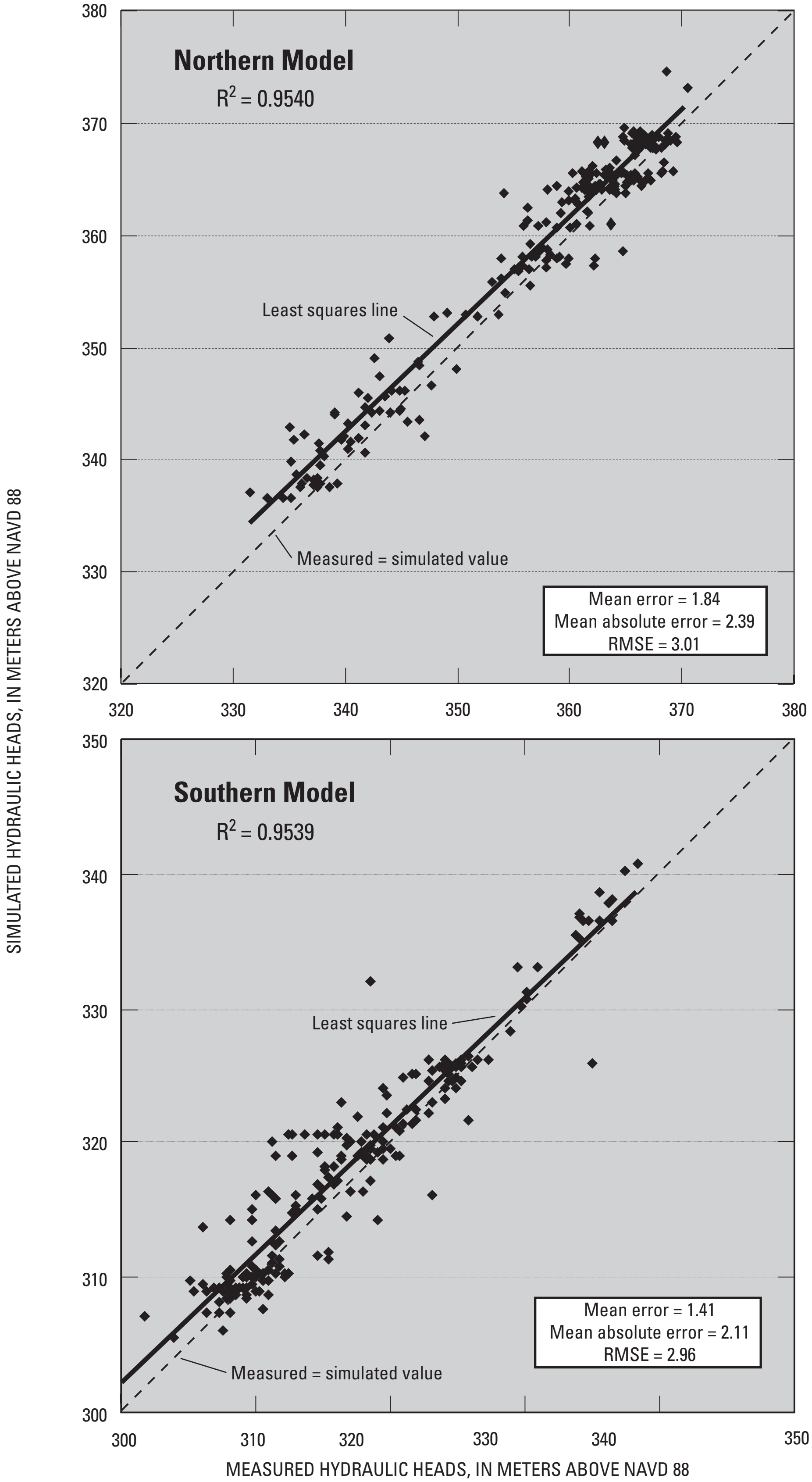

Figure 4. Measured versus simulated water levels in wells for the northern and southern models along the Mississippi River between Brainerd and St. Cloud in central Minnesota [RSME, Root Mean Square Error]

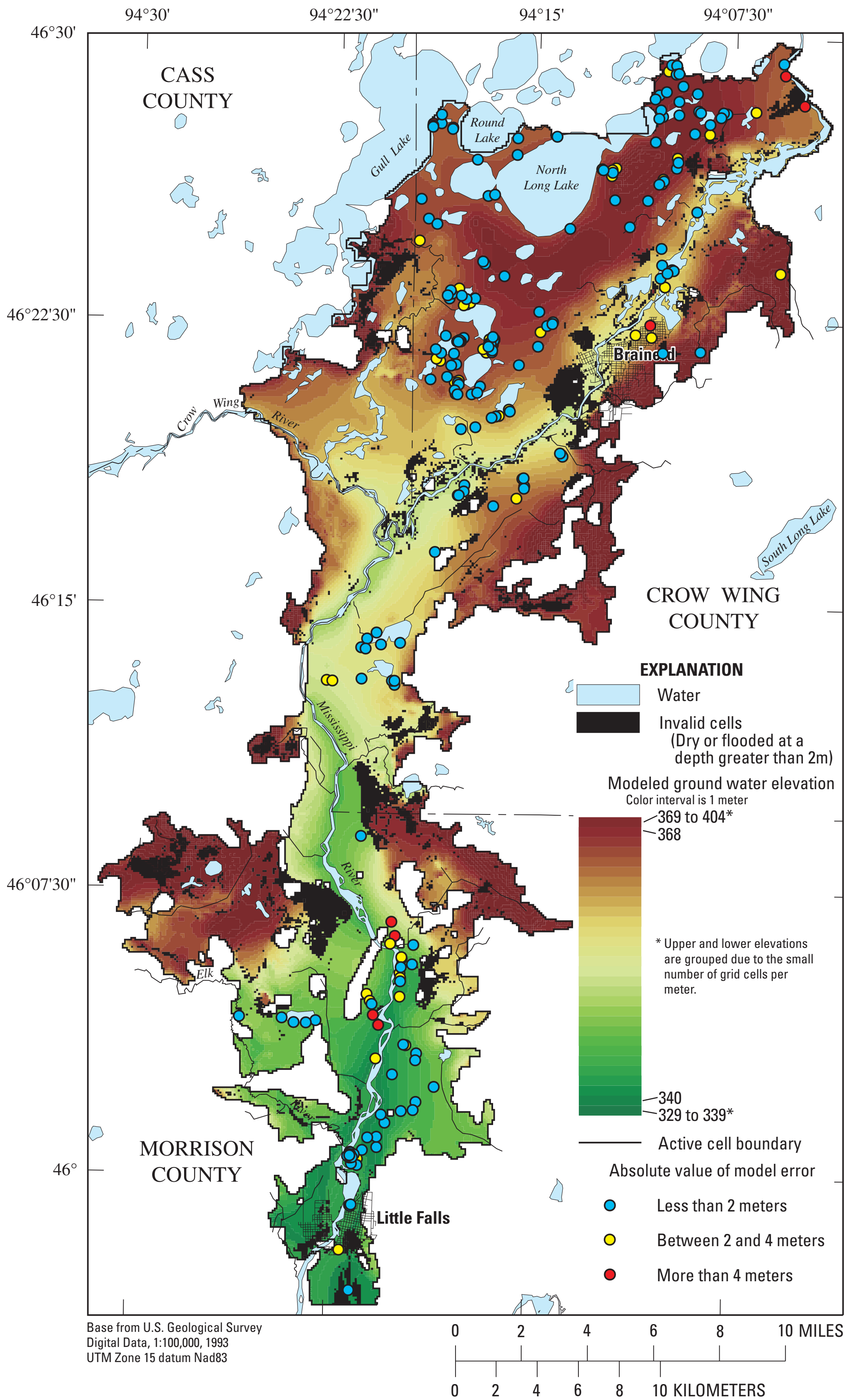

Figure 5. Modeled ground water elevations of the northern model along the Mississsippi River between Brainerd and Little Falls in central Minnesota.

Table 4. Simulated volumetric water budget for the northern ground-water-flow model between Brainerd and Little Falls in central Minnesota

[flow rates in cubic meters per day; —, not applicable; total percentages greater than 100 are due to rounding]

Sources/Sinks	Inflow		Outflow		Net flow (inflow - outflow)		
	Rate	Percent	Rate	Percent	Rate	Percent net inflow	Percent net outflow
Perennial streams	3,846	0	420,298	4	-416,452	—	47
Ephemeral streams	0	0	98,006	1	-98,006	—	11
Lakes and wetlands	9,655,657	82	10,023,679	85	-368,022	—	41
Well withdrawals	0	0	7,126	0	-7,126	—	1
Edge recharge	1,852,970	16	1,238,395	11	614,575	75	—
Net areal recharge	202,539	2	0	0	202,539	25	—
Total	11,715,012	100	11,787,504	101	-72,492	100	100

(Helgesen and Lindholm, 1977; Lindholm, 1980; and Ruhl, 2002).

Figure 4 shows the correspondence of measured to simulated hydraulic heads at 216 well locations for the calibrated southern model. The least-squares fit of the simulated to measured hydraulic heads has an R^2 value of 0.9539. As was the case for the northern model, the position of the least-squares line above and to the left of the line of correspondence (fig. 4) indicates a positive bias in modeled heads. Unlike the northern model, the spatial distribution of these values indicates that the residual water levels generally are greatest within the interior portions of the aquifers distant from the active cell boundary and near to the Mississippi River (fig. 6) However, much of the periphery of the southern model are dry cells, which do not yield residuals. Also, areas with the greatest residuals are near interior areas that have gone dry, demonstrating the inadequacy of the model in these areas. The range of the residuals is less in the southern model than in the northern model. Steady-state hydraulic head computed by the model range from about 305 to 340 m above NGVD88.

The mean absolute error for the ground-water levels in the sensitivity analysis indicates that the model is sensitive to increased horizontal hydraulic conductivity and decreased net areal recharge (table 5). The model was unstable to decreased horizontal hydraulic conductivity and increased areal recharge. The sensitivity of the model to vertical hydraulic conductivity of lakebed sediments was not evaluated because of the instability of the model to changes in this input (table 5). The sensitivity analysis, based on a comparison of the computed as a percent of measured baseflow, indicates that the model was most sensitive to decreased horizontal hydraulic conductivity, and to a lesser extent, increased recharge.

The volumetric-flow budget of the model indicates that net inflow consists of predominantly net areal recharge (88 percent) and to a lesser extent discharge from lakes and wetlands (12 percent) (table 6). The volumetric-flow budget also indicates that discharge to perennial streams accounts for the 96 percent of the net outflow and that well withdrawals account for the remainder.

Model limitations

The ground-water-flow models are numerical simplifications of real aquifer flow systems. Model results are affected by numerical approximations used to solve the ground-water-flow equation, discretization of the modeled area, and the availability and accuracy of hydrogeologic data used to define boundary conditions and model stresses. Another important limitation of calibrated ground-water-flow models is the non-uniqueness of their solutions. Multiple combinations of model input values may result in equally good fits of simulated model outputs to measured data. Limitations of the northern and southern models were evaluated based on the availability and reliability of hydraulic-head and baseflow data used in their calibration.

Hydraulic-head data were available for 236 wells in the northern model and for 216 wells in the southern model. These data are considered accurate to within 2 meters. Comparison of the simulated hydraulic head data to the measured data indicated a positive bias for both the northern and southern models (fig. 4).

Construction of the two models did not address spatial variation of horizontal hydraulic conductiv-

Table 5. Sensitivity analysis of the southern ground-water-flow model between Little Falls and St. Cloud in central Minnesota.

[The percent discrepancy between total inflow and total outflow for all model runs was within 1.14 percent; *, indicates model did not converge to solution; m, meter; m/d, meter per day; m^3/d, cubic meter per day]

Calibration variable	Calibrated values (m/d)	Multiplication factor	Computed baseflow as percent of measured baseflow (m^3/d)	Mean absolute error for water levels (m)
Horizontal hydraulic conductivity	70	0.10	*	*
		0.20	*	*
		0.50	*	*
		1.00	101	1.41
		2.00	142	1.10
		5.00	266	0.96
		10.00	446	0.87
Net areal recharge	6.0x10-4	0.10	*	*
		0.20	50	0.96
		0.50	72	1.07
		1.00	101	1.41
		2.00	*	*
		5.00	*	*
		10.00	*	*
Vertical hydraulic conductivity of perennial streambed sediments	20 for polygons and 100 for line features	0.10	*	*
		0.20	91	1.37
		0.50	89	1.39
		1.00	101	1.41
		2.00	*	*
		5.00	*	*
		10.00	*	*
Vertical hydraulic conductivity of lakebed sediments	2	0.10	*	*
		0.20	*	*
		0.50	*	*
		1.00	101	1.41
		2.00	*	*
		5.00	*	*
		10.00	*	*

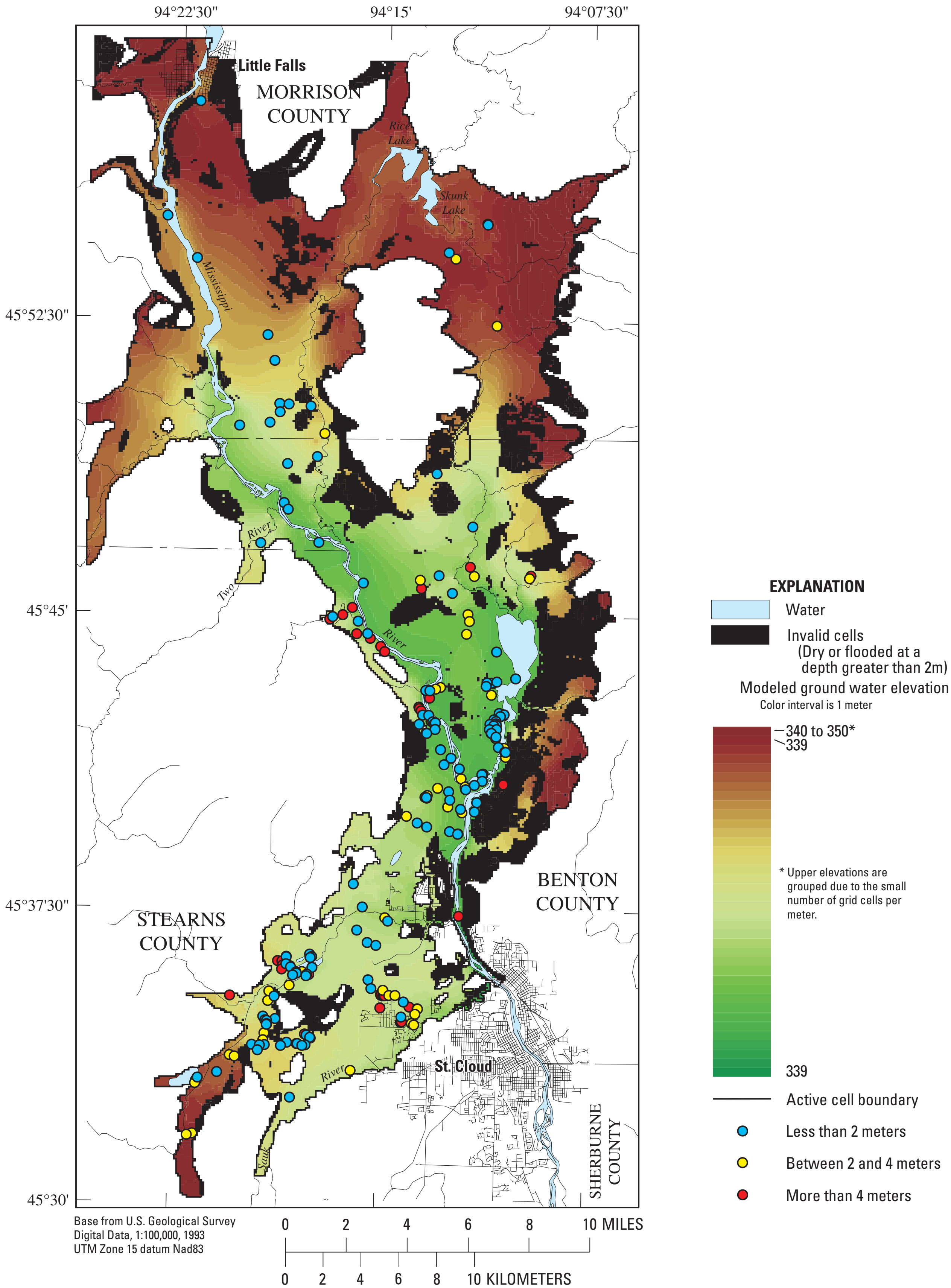

Figure 6. Modeled ground water elevations of the southern model along the Mississippi River between Little Falls and St. Cloud, in central Minnesota

Table 6. Simulated volumetric water budget for the southern ground-water-flow model between Little Falls and St. Cloud in central Minnesota.

[flow rates in cubic meters per day; —, not applicable]

Sources/Sinks	Inflow		Outflow		Net flow (inflow - outflow)		
	Rate	Percent	Rate	Percent	Rate	Percent net inflow	Percent net outflow
Perennial streams	2,529,557	59	2,892,604	67	-363,047	—	96
Lakes and wetlands	1,438,393	34	1,397,947	32	40,446	12	—
Net areal recharge	298,614	7	0	0	298,614	88	—
Well withdrawals	0	0	15,342	1	-15,342	—	4
Total	4,266,564	100	4,305,893	100	-39,329	100	100

ity and recharge. Construction of the models in this manner, which would have required detailed hydrogeologic information from aquifer tests and site-specific studies, was beyond the scope of the study. Therefore, single, uniform values of horizontal hydraulic conductivity and recharge were specified for each model.

Recharge was simulated differently in the two models. These models were developed sequentially. Improvements in model recharge learned while constructing the first model (the southern model area) were incorporated into the second model (the northern model area). Recharge in both models included leakage from rivers, lakes and wetlands, and areal infiltration. The northern model also included lateral recharge from edge grid cells (as a general-head boundary). As a result, the areal recharge rate for the southern model is twice that for the northern model to make up for the lack of edge recharge. Lateral recharge is probably also important in the southern model. Lack of this recharge in the southern model probably explains why so many peripheral cells were dry at steady state. Streambed conductance in the southern model is 5,000 times greater than for the northern model. In the southern model, streambed conductance is greater than aquifer hydraulic conductivity, meaning that the rivers sit within the aquifer material with the river bed material providing no resistance to ground-water flow. This is probably an unrealistic condition and may be related to the lack of edge recharge in the southern model. Future simulations of the southern model area should incorporate edge recharge to address the deficiencies of this model. In the northern model, river bed conductance was decreased to help prevent cells near the river from drying out.

Payne (1995) estimated baseflow to the Mississippi River for subreaches, which were incorporated in the calibration of the two modeled areas. Gunard and others (1988), which indicates that the reported estimated baseflow measurement to be accurate to within 10 percent. The simulated net discharge to the Mississippi River and its tributaries (perennial streams) were calibrated to within 1 percent for both the northern and southern models. Therefore, measurement errors greatly outweigh calibration errors in terms of model flux. Payne's (1995) baseflow measurement was conducted during a period of extreme low flow, and represents a minimum value. Therefore, the flux through, and the recharge to, these models also are minimum values.

Both calibrated models include flooded (simulated water level above land surface) and dry cells. Figures 7 and 8 show cells where the simulated water levels are above land surface by the following two ranges—0.5 to less than 5 m and greater than or equal to 5 m. The elevation of the land surface contains several sources of error. However, one error source is that inherent in the 30-m DEM elevation source, which itself is derived from USGS 1:24,000 scale hypsography. This accuracy is ± 5 ft (1.5 m). The accuracy of the 30-DEM is ± 3 ft (1 m). The land-surface elevation in these models is an interpolation of the 30-DEM to 100 m, which has an unknown accuracy worse than that of the 30-m DEM. Therefore, the true land-surface elevation could vary as much as ±2 m from the surface elevation used in the models. Grid cells with simulated water levels 2 m above the model land surface (flooded cells) may still be hydrologically valid. Grid cells with water levels higher than 2 m above model land surface probably are invalid and model results in or near these areas are not reliable.

The areal extent of dry cells generally was within the interior portion of the northern model and along the periphery of the southern model. The relatively small occurrence of dry cells along the periphery of the northern model compared to the southern model resulted from simulating recharge from till areas using a general head-dependent boundary condition and a large hydraulic conductivity (1,000 m/d).

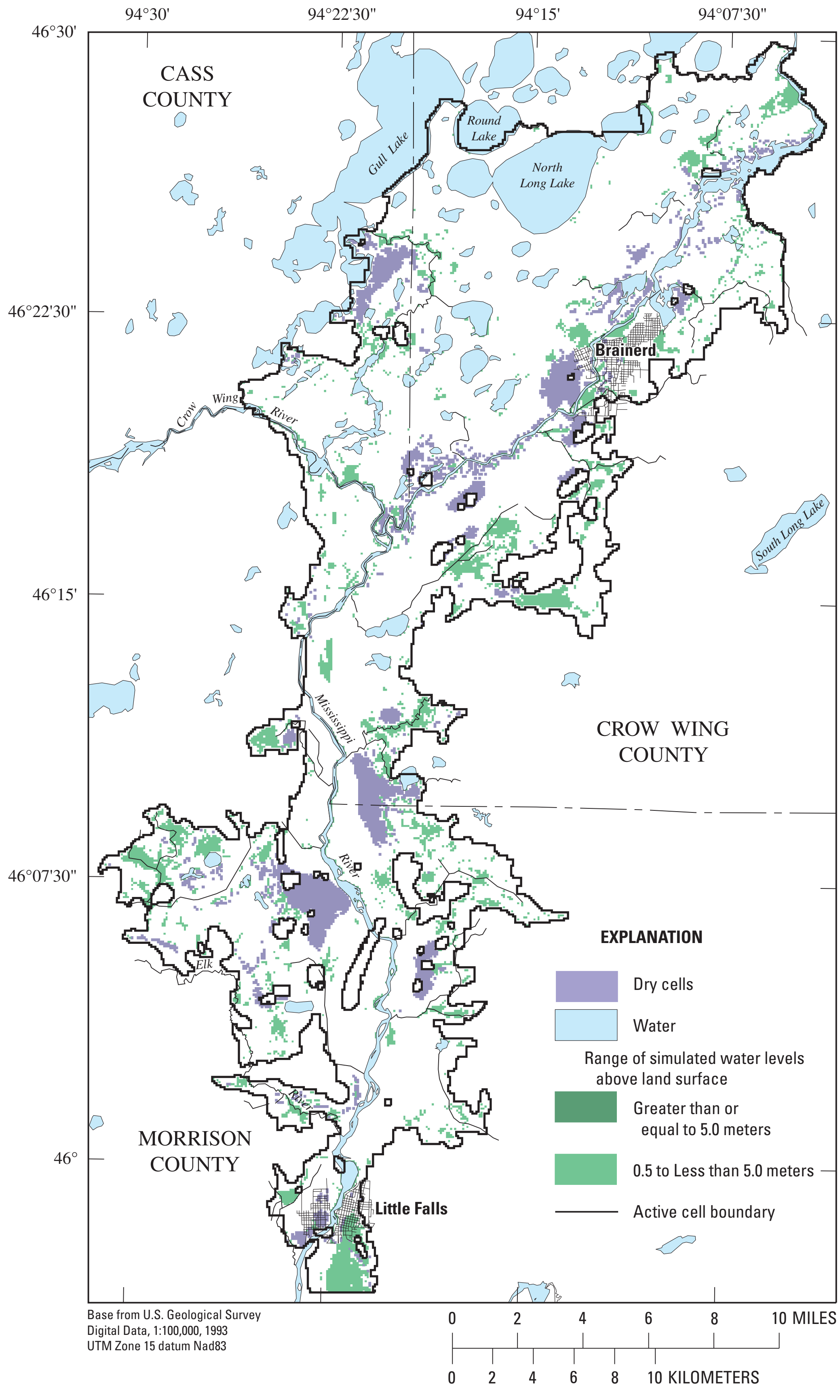

Figure 7. Simulated water levels above land surface and dry cells in the northern model along the Mississippi River between Brainerd and Little Falls in central Minnesota

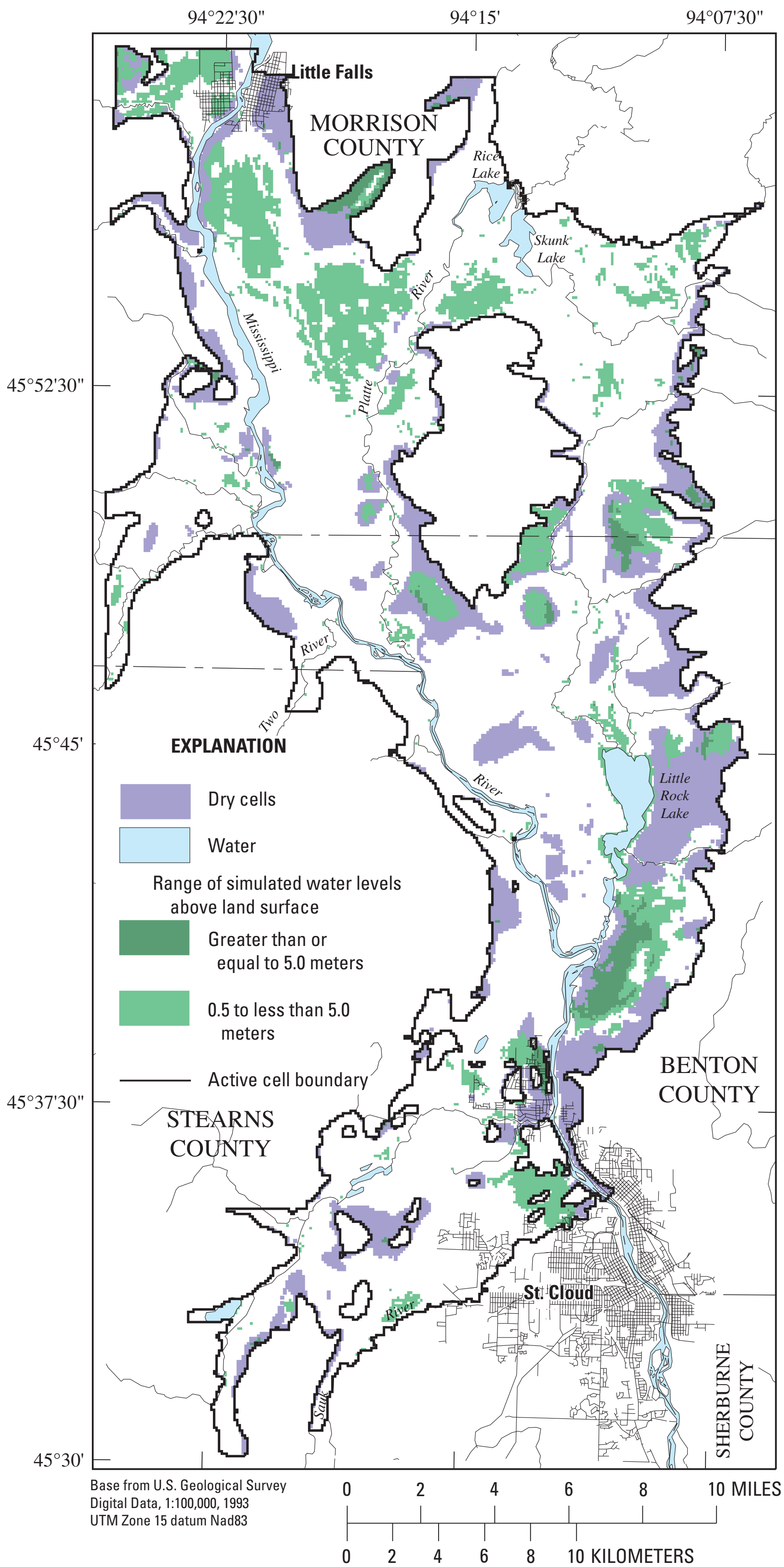

Figure 8. Simulated water levels above land surface and dry cells in the southern model along the Mississippi River between Little Falls and St. Cloud in central Minnesota.

Summary

This report documents regional ground-water-flow models constructed by the U.S. Geological Survey in cooperation with the Minnesota Department of Health (MDH) to satisfy the requirements of their Source Water Protection Plan (SWPP). One component of the SWPP is designation of contributing recharge areas (capture zones) that surround public water-supply wells. The SWPP considers the capture zone of a public water-supply well to be a particularly sensitive area that requires special protection. The MDH will use nested, local ground-water-flow models developed within the framework of these regional flow models for delineation of capture zones around supply wells of interest.

The models were constructed for the surficial sand and gravel aquifers along the Mississippi River between Brainerd and St. Cloud in central Minnesota. A model was constructed in each of the two areas (northern and southern) of about 2,000 km^2. Steady-state, single layer, ground-water-flow models constructed with the computer program MODFLOW simulated flow in the surficial aquifer. The hydrogeologic data used to construct the models were compiled from available sources.

Calibrated values of horizontal hydraulic conductivity and net areal recharge for the northern model were 70 m/d and 3.0×10^{-4} m/d, respectively. This model was sensitive to net areal recharge, vertical hydraulic conductivity of perennial streambed sediments, and horizontal hydraulic conductivity. The major source of net inflow to the model was from edge boundary cells. The major source of net outflow was ground-water discharge to perennial and ephemeral streams.

Calibrated values of horizontal hydraulic conductivity and net areal recharge for the southern model were 70 m/d and 6.0×10^{-4} m/d, respectively. This model was sensitive mostly to horizontal hydraulic conductivity. Net areal recharge and ground-water discharge to perennial streams were the major sources of net inflow and outflow, respectively.

Acknowledgments

The authors thank the people who compiled and mapped hydrogeologic data that were essential to construction of the ground-water-flow model. Bob Tipping and Gary Meyer, geologists, Minnesota Geological Survey, provided surficial sand and gravel thickness data. Steve Robertson, hydrologist, Minnesota Department of Health, provided information about water depth in the surficial aquifer and water use.

References

Environmental Modeling Systems, Incorporated, 2002, The Department of Defense groundwater modeling system online reference manual, accessed December 11, 2002, at URL http://www.ems-i.com/gmshelp/gmsv40help.htm.

Environmental Science Research Institute, 2004, Glossary of GIS terms, accessed April 7, 2004 at URL http://www.esri.com/library/glossary/glossary.html

Fetter, C.W., 1988, Applied hydrogeology: Columbus, Ohio, Merrill Publishing Company, 592 p.

Gunard, K.T., Hess, J.H., Zirbel, J.L., and Cornelius, C.E., 1988, Water-Resources Data, Minnesota water year 1988: U.S. Geological Survey Water-Data Report MN-88-2, 331 p.

Heath, R.C., 1983, Basic ground-water hydrology: U.S. Geological Survey Water Supply Paper 2220, 84 p.

Helgesen, J.O., 1977, Ground-water appraisal of the Pineland Sands Area, central Minnesota: U.S. Geological Survey Water-Resources Investigations 77-102, 49 p.

Helgesen, J.O., Ericson, D.W., and Lindholm, G.E., 1975, Water resources of the Mississippi and Sauk Rivers watershed, central Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA-534, 3 sheets.

Helgesen, J.O., and Lindholm, G.F., 1977, Geology and water-supply potential of the Anoka Sand-Plain aquifer, Minnesota: Minnesota Department of Natural Resources, Division of Waters and the U.S. Department of the Interior, Geological Survey, Technical Paper No. 6, 17 p.

Hobbs, H.C., 2001a, Surficial geology of the Brainerd quadrangle, Crow Wing County, Minnesota: Minnesota Geological Survey, Miscellaneous Map Series M-112, scale 1:24,000.

_____, 2001b, Surficial geology of the Gull Lake quadrangle, Cass and Crow Wing Counties, Minnesota: Minnesota Geological Survey, Miscellaneous Map Series M-113, scale 1:24,000.

Knaeble, A.R., 2001, Surficial geology of the Baxter quadrangle, Cass, Morrison, and Crow Wing Counties, Minnesota: Minnesota Geological Survey, Miscellaneous Map Series M-111, scale 1:24,000.

Lindgren, R.J., 1996, Hydrogeology and ground-water quality of glacial-drift aquifers, Leech Lake Indian Reservation, north-central Minnesota: U.S. Geological Survey Water-Resources Investigations Report 95-4077, 78 p.

Lindholm, G.F., 1980, Ground-water appraisal of sand plains in Benton, Sherburne, Stearns, and Wright Counties, central Minnesota: U.S. Geological Survey Water-Resources Investigations Report 80-1285, 103 p.

Lindholm, G.F., Farrell, D.F., and Helgesen, J.O., 1974, Water resources of the Crow River watershed, south-central Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA-528, 3 sheets.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water-flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 586 p.

Meyer, G.N., and Hobbs, H.C., 1993, Quaternary geologic map of Sherburne County, Minnesota: Minnesota Geological Survey, Miscellaneous Map Series M-77, scale 1:100,000.

Meyer, G.N., Knaeble, A.R., and Ellingson, J.B., 2001, Surficial geology of the St. Cloud 30 x 60 minute quadrangle, central Minnesota: Minnesota Geological Survey, Miscellaneous Map Series M-115, scale 1:100,000.

Miller, R.T., 1982, Appraisal of the Pelican River Sand-Plain aquifer, western Minnesota: U.S. Geological Survey Open-File Report 82-347, 44 p.

Minnesota State Climatologist, 2002, Minnesota State Climatologist, accessed June 10, 2002, at URL: http://climate.umn.edu.

Myette, C.F., 1984, Appraisal of water from surficial-outwash aquifers in Todd County and parts of Cass and Morrison Counties, central Minnesota: U.S. Geological Survey Water-Resources Investigations Report 83-4156, 43 p.

Payne, G.A., 1995, Ground-water baseflow to the Upper Mississippi River upstream of the Minneapolis-St. Paul area, Minnesota during July 1988: U.S. Geological Survey Open-File Report 94-478, 28 p.

Ruhl, J.F., 2002, Recharge to unconfined aquifers and leakage to confined aquifers in the seven-county metropolitan area of Minneapolis-St. Paul, Minnesota: U.S. Geological Survey Water-Resources Investigations Report 02-4092, 32 p.

Stark, J.R., Busch, J.P., and Deters, M.H., 1991, Hydrogeology and water quality of glacial-drift aquifers in the Bemidji-Bagley area, Beltrami, Clearwater, Cass, and Hubbard Counties, Minnesota: U.S. Geological Survey Water-Resources Investigations Report 89-4136, 135 p.

U.S. Environmental Protection Agency, 1987, Guidelines for delineation of wellhead protection areas: U.S. Environmental Protection Agency Office of Ground-Water, EPA 440687101, 207 p.

U.S. Geological Survey, 1983, Digital line graph (DLG) data hydrogaphy and transportation: U.S. Geological Survey USGeoData, area 7, 1:1,000,000 scale.

U.S. Geological Survey, 1999, 30 meter digital elevation model: Minnesota Department of Natural Resources, accessed March 2, 2004, at url: http//www.lmic.state.mn.us/gc/stds/metadata.htm

Wright, H.E., Jr., 1972, Quaternary history of Minnesota, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 515-546.