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

# Simulation of Ground-Water Flow and Delineation of Areas Contributing Recharge within the Mt. Simon-Hinckley Aquifer to Well Fields in the Prairie Island Indian Community, Minnesota

By J.F. Ruhl

Water-Resources Investigations Report 02-4155

Prepared in cooperation with the Prairie Island Indian Community

**U.S. DEPARTMENT OF THE INTERIOR**

Gale A. Norton, Secretary

**U.S. GEOLOGICAL SURVEY**

Charles G. Groat, Director

Use of trade, product, or firm names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Mounds View, Minnesota, 2002

**For additional information write to:**
**U.S. Geological Survey**
**District Chief**
**2280 Woodale Drive**
**Mounds View, MN 55112**

Copies of this report can be purchased from:

**U.S. Geological Survey**
**Branch of Information Services**
**Box 25286, MS 517**
**Federal Center**
**Denver, CO 80225**

Information regarding the USGS is available on the Internet via the World Wide Web.
You may connect to the USGS Home Page using the Universal Resource Locator (URL) at http://www.rvares.er.usgs.gov

You may also connect to the Minnesota District Home Page at http://mn.water.usgs.gov

For more information on all USGS reports and products (including maps, images, and computerized data), call 1-888-ASK-USGS

Water-Resources Investigations Report 02-4155

# CONTENTS



# ILLUSTRATIONS



# TABLES



# CONVERSION FACTORS

| Multiply: | By: | To obtain: |
|---|---|---|
| meter per day (m/d) | 3.281 | foot per day |
| square meter per day ($m^2$/d) | 10.76 | square foot per day |
| cubic meter per day ($m^3$/d) | 35.3 | cubic foot per day |
| cubic meter per day per kilometer ($m^3$/d/km) | 56.8 | cubic foot per day per mile |
| kilometer (km) | .6215 | mile |

Sea level: Vertical coordinate information is referenced to the North American Vertical Datum of 1988.

# Simulation of Ground-Water Flow and Delineation of Areas Contributing Recharge within the Mt. Simon-Hinckley Aquifer to Well Fields in the Prairie Island Indian Community, Minnesota

By James F. Ruhl


## ABSTRACT

The Prairie Island Indian Community in east-central Minnesota uses ground water from the Mt. Simon-Hinckley aquifer as its source of water supply. Tribal officials implemented a Source Water Protection Program to protect the quality of this water. Areas of contributing recharge were delineated for two community well fields. At well field A are two wells 325 m apart, and at well field B are two wells 25 m apart.

A steady state single layer, two-dimensional ground-water flow model constructed with the computer program MODFLOW, combined with the particle-tracking computer program MODPATH, was used to track water particles (upgradient) from the two well fields. A withdrawal rate of 625 $m^3$/d was simulated for each well field. The ground-water flow paths delineated areas of contributing recharge that are 0.38 and 0.65 $km^2$ based on 10- and 50-year travel times, respectively. The flow paths that define these areas extend for maximum distances of about 350 and 450 m, respectively, from the wells. At well field A the area of contributing recharge was delineated for each well as separate withdrawal points. At well field B the area of contributing recharge was delineated for the two wells as a single withdrawal point. Delineation of areas of contributing recharge to the well fields from land surface would require construction of a multi-layer ground-water flow model.


## INTRODUCTION

The Prairie Island Indian Community (hereinafter referred to as the study area) is located along the Mississippi River in Goodhue County, which is southeast of the seven-county Twin Cities metropolitan area in east-central Minnesota (fig. 1). The community is surrounded by rivers, lakes, and wetlands and is underlain by surficial (water-table) and buried (confined) aquifers. Ground water is the source of water supply in the study area.

Protection of the quality of ground water is an important natural resource issue for community officials. Of particular concern to these officials is potential contamination of sources of ground water to four community wells, two each located in separate well fields. At one of the well fields (identified as A, fig. 1), the wells are about 325 m apart, and at the other well field (identified as B, fig. 1), the wells are about 25 m apart. These wells are open to the Mt. Simon-Hinckley aquifer, a confined sedimentary bedrock aquifer. A priority water-management goal of community officials is delineation of recharge areas around the two well fields for protection against ground-water contamination. Water managers for the community have initiated a SWPP (Source Water Protection Program) to satisfy this goal.

The U.S. Environmental Protection Agency (1987) designed the SWPP to assist State and local agencies and other entities in the development of strategies to protect areas that surround water-supply wells against infiltration, percolation, and transport of leachate to ground water. The general goals of the SWPP are to: (1) delineate sensitive areas around public water-supply wells for protection against potential contamination of source ground water to the wells; (2) identify within these areas potential sources of contamination that may adversely affect the water supply produced by the wells; and (3) identify alternative water supplies for use in the event that current supplies become contaminated (U.S. Environmental Protection Agency, 1987).

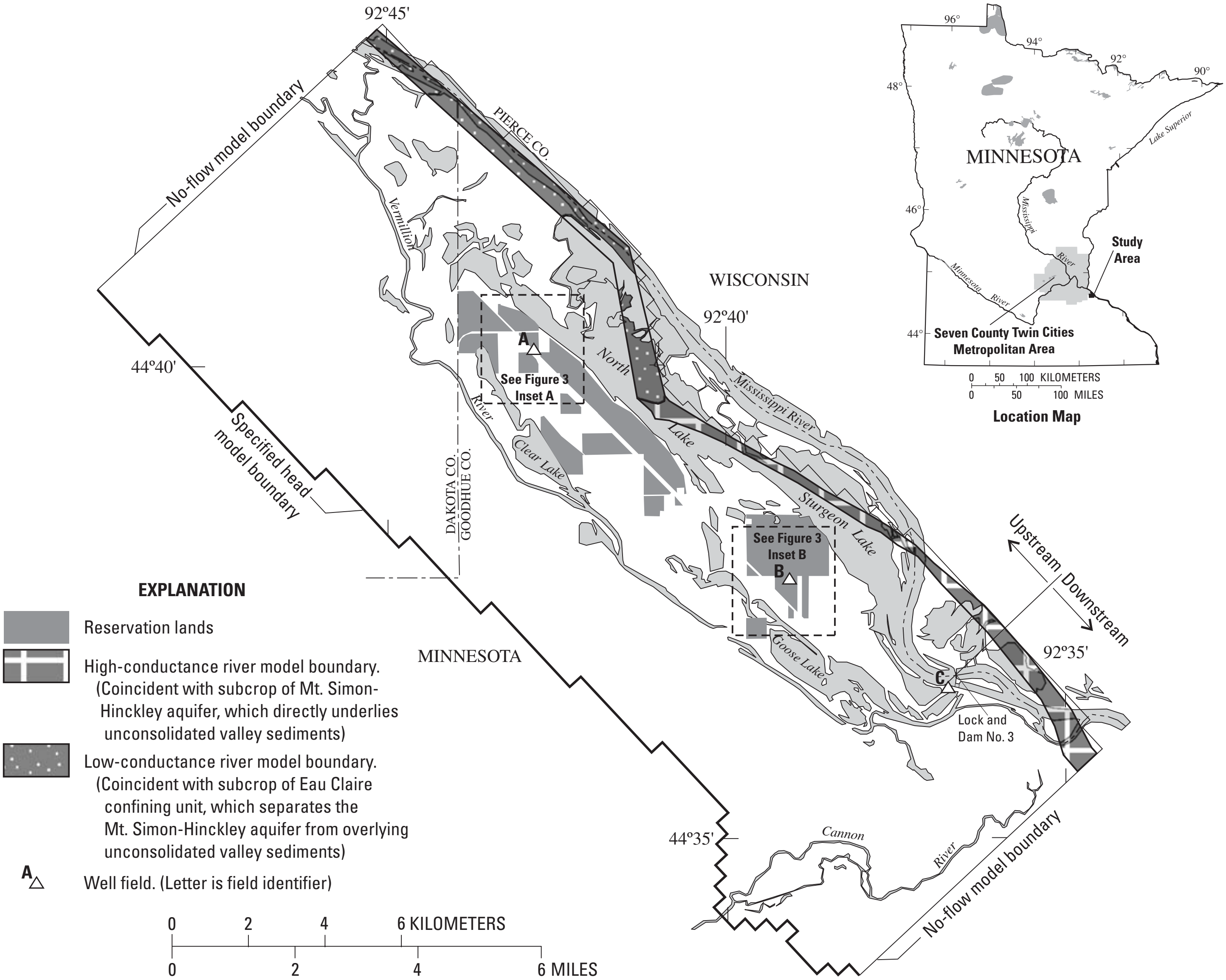


**Figure 1.** Location map, study area model grid boundaries, and two well fields, Prairie Island Indian Community, east-central Minnesota.

The SWPP categorizes sensitive areas around public water-supply wells into the following three types of zones: (1) contribution zones; (2) influence zones; and (3) capture zones (U.S. Environmental Protection Agency, 1987). The contribution zone is the area from where ground-water flow is diverted to a supply well. This area can be thought of as the area bounded by lines of infinite travel time. The influence zone is the area where water levels are perceptibly lowered by withdrawals from a supply well. This area is commonly called the cone of depression. The capture zone is the area around a supply well bounded by lines of equal ground-water travel time. Thus, a capture zone typically is associated with a specified period of years that commonly ranges from 10 to 100 years or greater. In this study capture zones are considered to represent areas of contributing recharge to supply wells.

The methods used to delineate recharge areas around supply wells range from simple techniques, such as specification of a radius around the well of interest, to construction of complex ground-water flow models combined with particle-tracking programs (U.S. Environmental Protection Agency, 1987). Studies for a wide variety of hydrogeologic settings have been done that document approaches to delineation of capture zones around supply wells (Bailey, 1993; Zarriello, 1993; Landmeyer, 1994; Sheets, 1994; Misut and Feldman, 1996; Barlow, 1997; Franke and others, 1998; Masterson and others, 1998; Nicholson and Watt, 1998).

The U.S. Geological Survey (USGS), in cooperation with the Prairie Island Indian Community, delineated areas of contributing recharge within the Mt. Simon-Hinckley aquifer to two well fields based on a ground-water flow model and particle tracking program. Construction of the ground-water flow model improved the understanding of the effects of stresses imposed on the hydrogeologic system of the study area by withdrawals from these well fields.

## PURPOSE AND SCOPE

The purpose of this report is: (1) to describe the development, construction, and application of a ground-water flow model of the Mt. Simon-Hinckley aquifer in the study area (fig. 1); and (2) to use the flow simulation results for delineation of 10- and 50-year areas within the aquifer that contribute recharge to two community well fields. A calibrated numerical ground-water flow model of the Mt. Simon-Hinckley aquifer combined with a particle-tracking program provided the basis for delineation of the recharge areas. The particle tracking program used hydraulic heads and flow-distribution output from the ground-water flow model and assumed pumping conditions based on recent water-use records from one of the well fields (water-use records were not available for the other well field, which was not yet operational).

## PREVIOUS INVESTIGATIONS

Two site-specific studies present water-quality data and describe water resources in the study area. Winterstein (2000) presents water-quality data collected during 1998-99 from the northern portion of the study area. These data were based on water samples collected from 17 wells completed in surficial aquifers. These data included physical and chemical properties such as specific conductance, pH, temperature, dissolved oxygen, alkalinity, and concentrations of chemical constituents such as major ions, nutrients, and iron and manganese. Water from two wells were analyzed for common agricultural pesticides.

Cowdery (1999) described the water resources of the study area based on water-quality data collected from 8 surface-water sites and 22 wells completed in surficial aquifers during 1994-97 and historical data. The data included concentrations of major ions, nutrients, coliform and streptococci bacteria, volatile organic compounds, and triazine herbicides and their degradation products.

## HYDROGEOLOGIC SETTING

Surficial geologic and hydrologic features of the study area include glacial outwash, post-glacial alluvium and terrace deposits, lakes, and wetlands in the Mississippi River Valley (Hobbs and Setterholm, 1998). The Mississippi River Valley in this area generally ranges from 1.5 to 5 km in width. The valley is bounded on each side by bluffs 90-120 m in height that expose flat-lying bedrock formations.

Ground water in the study area is available from unconsolidated alluvium, terrace deposits, and outwash, and from consolidated bedrock units. The alluvium, terrace deposits, and outwash consist primarily of sand and gravel. Cowdery (1999) describes the hydrogeologic characteristics of these deposits in detail. The bedrock units consist of alternating layers of predominantly sandstone and shale, which in descending order are the Paleozoic-age Franconia Formation, Ironton and Galesville Sandstones, Eau Claire Formation, Mt. Simon Sandstone, and Proterozoic-age Hinckley Sandstone. Delin and Woodward (1984) and Mossler and Tipping (2000) describe the hydrogeologic characteristics of these units in detail.

The Franconia Formation (50-53 m thick), which consists primarily of sandstone with lesser amounts of dolostone, siltstone, and shale, is considered to be an aquifer. The Ironton and Galesville Sandstones (15-20 m thick), which consist of very coarse to fine-grained quartzose sandstone, jointly form an aquifer. The Eau Claire Formation (36-43 m thick), which consists of interbedded layers of sandstone, siltstone, and shale, acts as a confining unit. The Mt. Simon Sandstone (as thick as 75 m) consists of coarse-grained quartzose sandstone. The Mt. Simon Sandstone and underlying Hinckley Sandstone comprise the deepest aquifer in the study area.

The Mississippi River Valley along the study area boundary has eroded through the Prairie du Chien-Jordan aquifer, the St. Lawrence confining unit, and about 100 ft into the Franconia aquifer (Cowdery, 1999). Ground-water discharge from the Prairie du Chien-Jordan aquifer, and to a lesser extent from the Franconia aquifer, is from upland areas away from the valley to springs in exposed outcrops along the bluffs of the Mississippi River Valley. Ground-water discharge from the Franconia and underlying aquifers is predominantly upward flow through the unconsolidated valley sediments into the Mississippi River (Cowdery, 1999).

The Mt. Simon-Hinckley aquifer, which is confined by the overlying Eau Claire Formation, discharges into overlying bedrock units and unconsolidated sediments within the Mississippi River Valley. This upward discharge contributes baseflow gain to the Mississippi River (Cowdery, 1999). The Mt. Simon-Hinckley aquifer is a source of ground water for two community well fields (identified as A and B, on fig. 1). (The two wells at well field A are open to only the Mt. Simon Sandstone (Thomas Winterstein, U.S. Geological Survey, oral commun., 2001)).

## SIMULATION OF GROUND-WATER FLOW

The USGS modular, finite-difference computer code, MODFLOW (McDonald and Harbaugh, 1988), was used to simulate ground-water flow in the Mt. Simon-Hinckley aquifer. The governing partial differential ground-water flow equation solved by MODFLOW is:

$$\frac{\partial}{\partial x}\left(Kxx\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(Kyy\frac{\partial h}{\partial y}\right) = 0$$

where;

*Kxx*, and *Kyy* = hydraulic conductivity along x and y coordinate axes, assumed to be parallel to the major axes of hydraulic conductivity (L/T); and

*h* = hydraulic head (L).

The model formulates the equation as sets of simultaneous algebraic equations that are solved by an iterative, finite-difference method of computation. The equations mathematically represent modeled aquifers as a grid of homogeneous blocks or cells with specified hydraulic properties. Boundary conditions are specified for the model grid that are based on the conceptual framework of the hydrologic system.

### MODEL DESIGN AND DISCRETIZATION

Ground-water flow in the Mt. Simon-Hinckley aquifer was simulated as a two-dimensional, steady-state, single-layer, confined system. A variably-spaced model grid was defined for an approximately 135-$km^2$ area that encompasses the study area, including the two community well fields (fig. 2). Orientation of the model grid is such that the rows are parallel to the Mississippi River, which represents the northeast boundary of the modeled area. The dimensions and numbers of rows and columns of the model grid result from the following considerations: (1) adequate representation of aquifer geometry and hydraulic properties and stresses; (2) minimization of computation time; and (3) suitability of the grid spacing for application of the particle-tracking program.

Grid cell dimensions range from about 50 m on a side at each of the two well fields to nearly 300 m on a side along the boundaries of the modeled area farthest from the well fields. Grid cell size increases as distance from the well fields increases because the level of detail in the simulation of ground-water flow for these more distant cells was not needed and the available hydrogeologic data were insufficient to support finer grid spacing.

### MODEL GEOMETRY AND HYDRAULIC PROPERTIES

A thickness of 72 m and a horizontal hydraulic conductivity of 1.35 m/d were specified as model inputs for the Mt. Simon-Hinckley aquifer. Geologic data from well logs and results of an aquifer test conducted at well field site A (fig. 1) provided the basis for these inputs. The aquifer test used two newly installed wells. One of these wells was installed to serve as a community supply well (identified as A-1, fig. 3), and the other well (identified as A-3, fig. 3) was installed as an observation well for the test. Results of the test indicated a transmissivity of 97.2 $m^2$/day (Thomas Winterstein, U.S. Geological Survey, oral commun., 2001).

### MODEL BOUNDARY CONDITIONS

The northeastern side of the model grid, representing the Mississippi River Valley, is a head-dependent flux boundary. This boundary simulates outflow from the model as discharge to the Mississippi River Valley, which, except for withdrawals from wells, is considered to be the only mechanism of discharge from the Mt. Simon-Hinckley aquifer. The southwestern side of the model grid is a specified head boundary (fig. 1). This boundary simulates inflow to the model as lateral flow in the Mt. Simon-Hinckley aquifer from upgradient recharge areas described by Delin and Woodward (1984). The other two sides of the model grid are no-flow boundaries. These boundaries are aligned approximately parallel to regional flow paths through the Mt. Simon-Hinckley aquifer within the study area (Delin and Woodward, 1984).

Riverbed conductance values were specified for the head dependent flux boundaries. These values indicate the effectiveness of the hydraulic connection between the Mississippi River and the Mt. Simon-Hinckley aquifer. A relatively large conductance ($1.5x10^{-4}$/d) was specified for the portion of the head-dependent flux boundary that coincides with the subcrop of the Mt. Simon-Hinckley aquifer (fig. 1), where unconsolidated valley sediments directly overlie the aquifer. A smaller conductance ($1.5 x10^{-6}$/d) was specified for the remaining portion of this boundary, where the Eau Claire confining unit separates the aquifer from the overlying unconsolidated valley sediments.

The river stage specified for the head-dependent flux boundary upstream of the U.S. Army Corps of Engineers Lock and Dam No. 3 (fig. 1) was 205.7 m above sea level. This stage is shown on the Red Wing topographic USGS 1:24,000 quadrangle as the normal pool elevation maintained by the lock and dam. The river stage specified for this boundary downstream of the dam was specified to be 2.4 m lower than the upstream stage (based on the Red Wing topographic USGS 1:24,000 quadrangle).

The initial hydraulic head value of 223 m above sea level used for the specified head boundary was based on

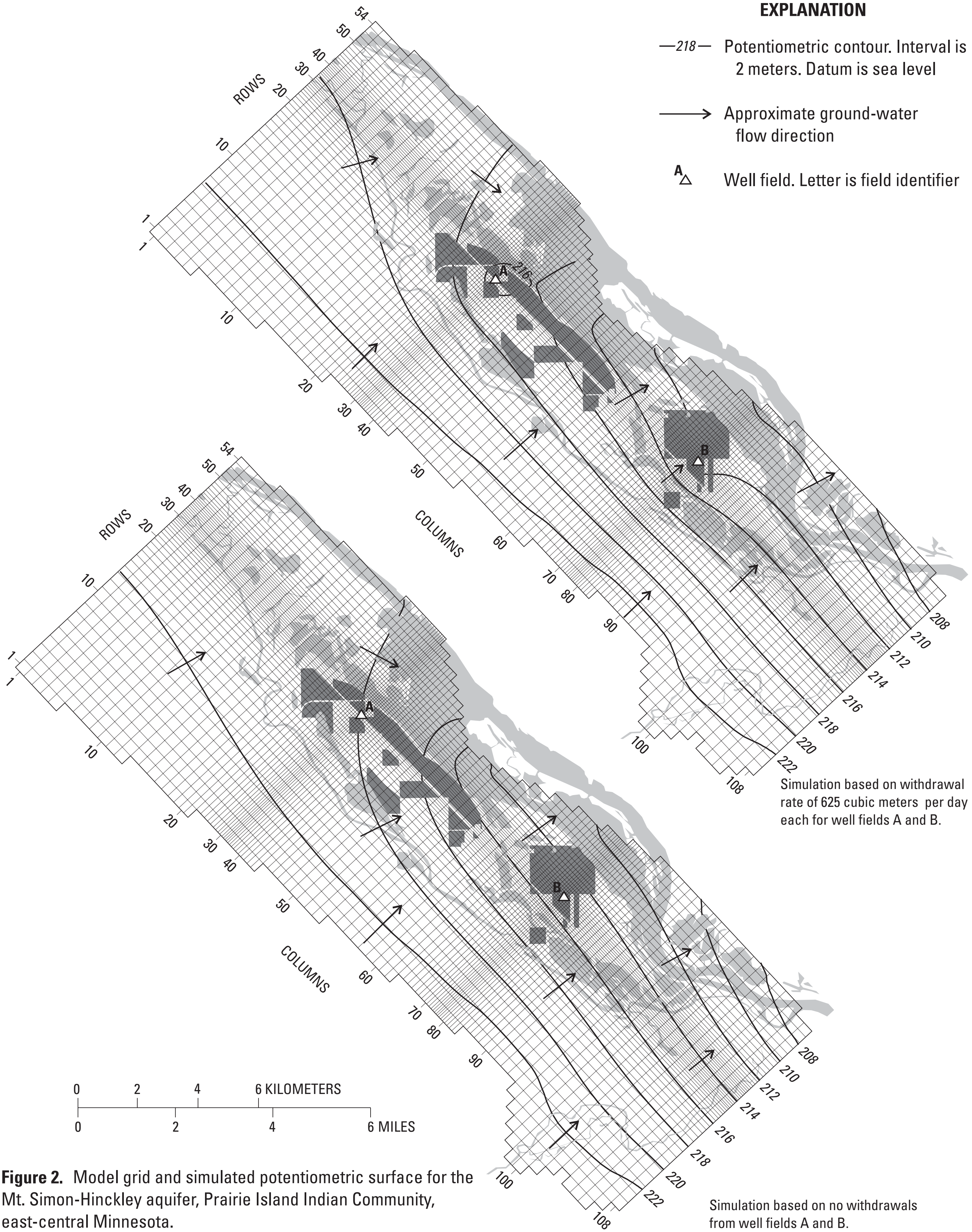


**Figure 2.** Model grid and simulated potentiometric surface for the Mt. Simon-Hinckley aquifer, Prairie Island Indian Community, east-central Minnesota.

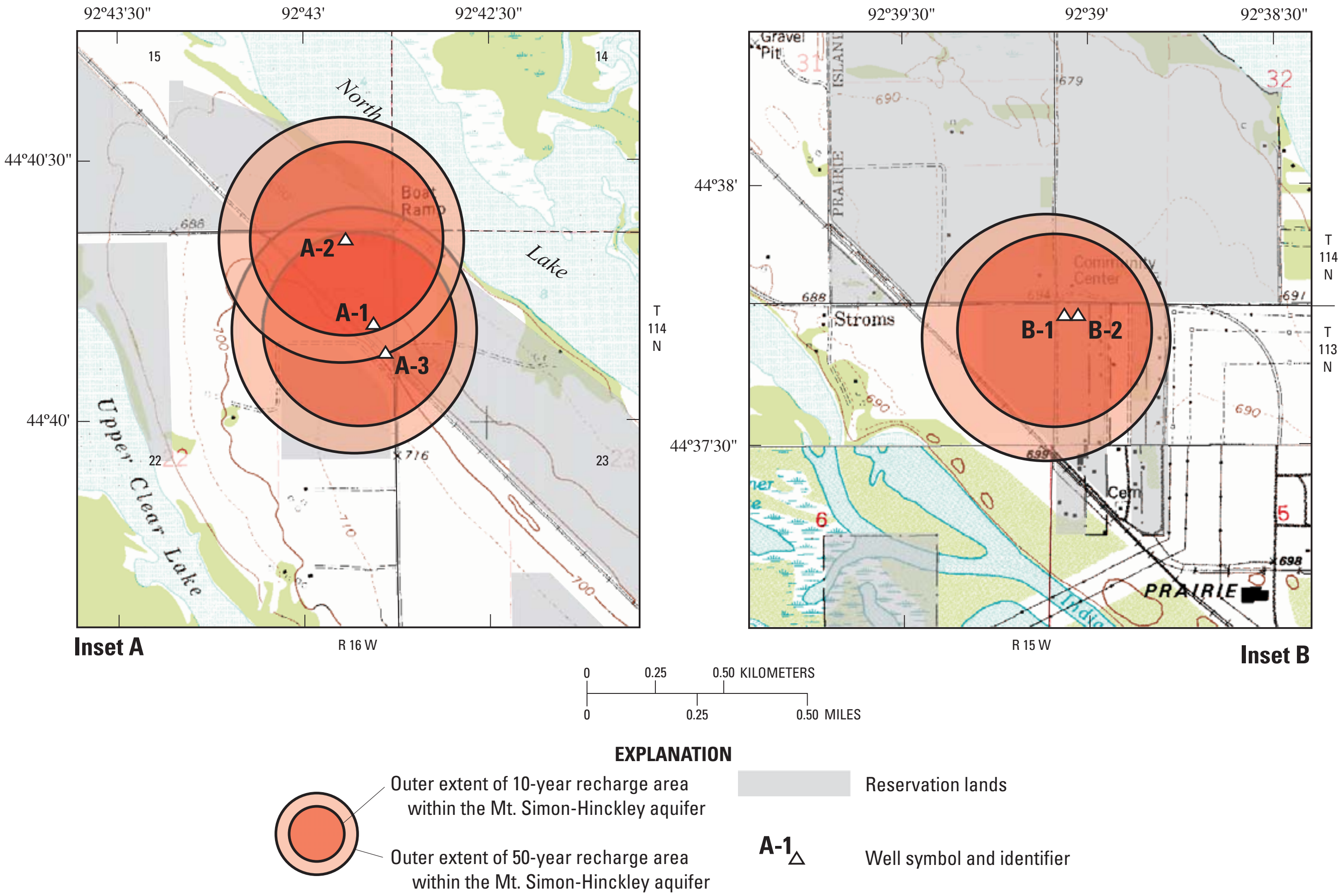


**Figure 3.** Recharge areas within the Mt. Simon-Hinckley aquifer to well fields A and B based on a rate of withdrawal of 625 cubic meters per day for each well field, Prairie Island Indian Community, east-central Minnesota.

the study by Delin and Woodward (1984). That study mapped on a regional scale potentiometric surfaces of aquifers that included the Mt. Simon-Hinckley aquifer.

### Inflows

Under nonpumping conditions, simulated total inflow to the model is 2,609.1 $m^3/d$. The source of nearly all of this inflow is the specified head boundary, which accounts for 99.65 percent of this total (table 1). Areal recharge to the model is the only other source of inflow to the model. This recharge, which represents water that enters the aquifer as leakage through the overlying Eau Claire confining unit, is uniformly distributed to the active cells of the model at a rate of $7.0 \times 10^{-8}$ m/d. This rate is based on estimates of leakage to confined bedrock aquifers in the Twin Cities metropolitan area (Ruhl, 2002). The resulting volumetric rate of recharge to the model is 9.1 $m^3/d$ (table 1). Under pumping conditions, inflows to the model increase to 3,460 $m^3/d$ from the specified head boundary and are assumed to remain the same from recharge (table 1).

### Outflows

Under nonpumping conditions, total simulated outflow (2,610 $m^3/d$) from the model is through the head-dependent flux boundary, and nearly all of that outflow is through the portion of the boundary that coincides with the subcrop of the Mt. Simon-Hinckley aquifer (table 1). Under pumping conditions, 64 percent of outflow from the model is through the head-dependent flux boundary, and the remainder is withdrawals from wells. The simulated withdrawals represent pumpage from the pairs of community wells at well fields A and B (fig. 1). A withdrawal rate of 625 $m^3/d$ was simulated for each well field. This rate of withdrawal is equivalent to the reported combined annual rate of withdrawal during 2000 for the two community wells at well field B (Sara Moore, Prairie Island Indian Community, written commun., 2001).

## MODEL CALIBRATION

Calibration of the model was done primarily by comparison of simulated

Table 1. Simulated volumetric water budget for the steady-state ground-water flow model under nonpumping and pumping conditions for the Prairie Island Indian Community, east-central Minnesota

[flow rates in cubic meters per day; --, no data]

| Nonpumping Conditions | | | | | |
|---|---|---|---|---|---|
| Inflow | | | Outflow | | |
| Source | Rate | Percent | Source | Rate | Percent |
| Specified head boundary | 2,600 | 99.65 | Head-dependent flux boundary (coincident with Eau Claire confining unit subcrop) | 92 | 4 |
| Recharge | 9.1 | 0.35 | Head-dependent flux boundary (coincident with Mt. Simon-Hinckley aquifer subcrop) | 2,518 | 96 |
| -- | -- | -- | Withdrawals from wells | 0 | 0 |
| Total | 2,609.1 | 100 | | 2,610 | 100 |
| **Pumping Conditions** | | | | | |
| Inflow | | | Outflow | | |
| Source | Rate | Percent | Source | Rate | Percent |
| Specifiedhead boundary | 3,460 | 99.74 | Head-dependent flux boundary (coincident with Eau Claire confining unit subcrop) | 76 | 2 |
| Recharge | 9.1 | .26 | Head-dependent flux boundary (coincident with Mt. Simon-Hinckley aquifer subcrop) | 2,143 | 62 |
| -- | -- | -- | Withdrawals from wells | 1,250 | 36 |
| Total | 3,469.1 | 100 | | 3,469 | 100 |

to observed ground-water levels for wells A-3, B-2, and C during the summer of 2001. The observed water levels for these wells are assumed to represent nonpumping, steady-state conditions for the Mt. Simon-Hinckley aquifer. Comparisons also were made of simulated head-dependent boundary outflows to the estimated gain in baseflow in the Mississippi River. Outflow from the head-dependent flux boundary would be expected to represent a significant portion of the gain in baseflow to the Mississippi River (the Franconia-Ironton-Galesville aquifer and unconsolidated valley sediments would also be expected to be sources of baseflow gain). The estimated gain in baseflow was based on a study by Payne (1995) of baseflow gains to the Mississippi River for six subreaches between the headwaters in northern Minnesota and the Twin Cities metropolitan area.

The model was calibrated by adjustment of the hydraulic head value at the specified head boundary and riverbed conductance value at the head-dependent flux boundary. The initial values used for these model inputs were considered to have been less precise estimates of their true values than was the case for the other model inputs, which included horizontal hydraulic conductivity, recharge rate, and river stage of the head-dependent flux boundary.

The model was calibrated to produce residual (observed minus simulated) hydraulic heads of -0.1, 0.0, and 0.1 m for the wells at sites A-3, B-2, and C, respectively. Simulated outflow from the portion of the head-dependent flux boundary where the Eau Claire confining unit separates the Mt. Simon-Hinckley aquifer from overlying unconsolidated valley sediments was 92 $m^3$/d (table 1). Simulated outflow from the portion of the head-dependent flux boundary where the overlying unconsolidated valley sediments directly overlie the Mt. Simon-Hinckley aquifer was 2,518 $m^3$/d (table 1). These outflows—expressed per lineal unit of distance of river—were 13 and 425 $m^3$/d/km, respectively. These outflows are assumed to represent one-half the total gain in baseflow (ground-water discharge) to the Mississippi River (the other one-half from the Wisconsin side of the river).

The total simulated rate of baseflow gain from the Mt. Simon-Hinckley portion of the head-dependent flux boundary would be equivalent to 850 $m^3$/d/km (425 $m^3$/d/km multiplied by 2). This figure is in the lower part of the range (0 - 6,000 $m^3$/d/km) reported by Payne (1995), which would be reasonable for two reasons. First, some of the six subreaches in Payne's study flow through transmissive unconsolidated alluvial sediments similar to those in the study area, where the gain in baseflow would be expected to be similar to that for the study area. In the study area, however, ground-water discharge from the Mt. Simon-Hinckley aquifer to the river must pass through as much as 60 m of unconsolidated valley sediments (Cowdery, 1999), whereas in the upstream reaches studied by Payne (1995) some of the baseflow gain would have been direct discharge from surficial aquifers. Second, a portion of the gain in baseflow would include contributions from the Ironton-Galesville aquifer and the unconsolidated valley sediments, which were not simulated in the model.

Table 2. Sensitivity analysis of calibrated ground-water flow model of the Mt. Simon-Hinckley aquifer in the Prairie Island Indian Community, east-central Minnesota

[$m^3/d$, cubic meters per day]

| Model input tested | Final values used in calibrated model | Multiplication factor used to change value | Change in head-dependent boundary outflow | | Change in simulated hydraulic heads for wells used in model calibration | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Well A-3 | | Well B-2 | | Well C | |
| | | | Percent | Absolute value ($m^3/d$) | Percent | Absolute value (meters) | Percent | Absolute value (meters) | Percent | Absolute value (meters) |
| Specifie head (meters) | 223 | 0.99 | -12 | -310 | -0.8 | -1.7 | -0.5 | -1.1 | -0.4 | -0.8 |
| | | 1.01 | 10 | 268 | 0.8 | 1.7 | 0.5 | 1.1 | 0.4 | 0.8 |
| River stage (meters) | 203.3 below lock and dam; 205.7 above lock and dam | 0.90 | 114 | 3000 | -1.7 | -3.8 | -4.3 | -9.3 | -5.6 | -11.9 |
| | | 0.99 | 10 | 274 | -0.2 | -0.4 | -0.4 | -0.8 | -0.6 | -1.2 |
| | | 1.01 | -12 | -309 | 0.0 | 0.1 | 0.5 | 1.0 | 0.4 | 0.9 |
| | | 1.10 | -113 | -2978 | 0.0 | 0.1 | 0.5 | 1.0 | 0.4 | 0.9 |
| Hydraulic conductivity (meters/day) | 1.35 | 0.10 | -84 | -2210 | -1.5 | -3.4 | -1.8 | -3.8 | -1.6 | -3.4 |
| | | 0.99 | -1 | -17 | 0.0 | -0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| | | 1.01 | 1 | 17 | 0.0 | -0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| | | 10.00 | 153 | 4035 | 1.1 | 2.4 | 2.8 | 5.9 | 3.6 | 7.7 |
| Riverbed conductance (1/days) | 1.5000E-06 no aquifer subcrop; 1.5000E-04 aquifer subcrop | 0.01 | -97 | -2550 | 1.4 | 3.0 | 3.6 | 7.7 | 5.0 | 10.5 |
| | | 0.10 | -75 | -1961 | 1.1 | 2.4 | 2.8 | 5.9 | 3.6 | 7.7 |
| | | 0.99 | 0 | -10 | 0.0 | -0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| | | 1.01 | 0 | 9 | 0.0 | -0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| | | 10.00 | 63 | 1645 | -1.8 | -3.9 | -1.8 | -3.8 | -1.6 | -3.4 |
| | | 100.00 | 102 | 2678 | -3.5 | -7.6 | -2.1 | -4.5 | -1.9 | -4.0 |
| Recharge (meter/day) | 7.00E-08 | 0.01 | -0.9 | -23 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | | 0.10 | -0.9 | -23 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | | 0.99 | 0.0 | 0 | 0.0 | -0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| | | 1.01 | 0.0 | 0 | 0.0 | -0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| | | 10.00 | -0.1 | -2 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| | | 100.00 | 7.0 | 185 | 0.5 | 1.1 | 0.3 | 0.6 | 0.3 | 0.5 |

## MODEL SENSITIVITY

A sensitivity analysis of the calibrated model was done based on changes in model-computed hydraulic heads at three wells identified as A-3, B-2, and C, and the head-dependent boundary outflow. Well A-3 (fig. 3) was used as the observation well for the aquifer test conducted at well field A, well B-2 (fig. 3) is one of two community wells at well field B, and well C (fig. 1) is the drinking-water supply well at the U.S. Army Corps of Engineers Lock and Dam No. 3.

The hydraulic heads and outflow were most sensitive to changes in the specified head boundary and river stage of the head-dependent flux boundary. A change in the specified head and river stage of 1 percent resulted in changes of 10-12 percent in outflow, but considerably smaller changes of less than 1 percent in hydraulic heads (table 2). The model was much less sensitive to horizontal hydraulic conductivity. A change in horizontal hydraulic conductivity of 1 percent resulted in changes of 1 percent in outflow and changes of 0 percent in hydraulic heads. A change in hydraulic conductivity of one order of magnitude resulted in changes of -84 and 153 percent in outflow and changes of -1.8 to 3.6 percent in hydraulic heads. The model was least sensitive to riverbed conductance and recharge. Changes of 1 percent in riverbed conductance and recharge resulted in changes of 0 percent for both head-dependent boundary outflow and hydraulic heads.

## DELINEATION OF RECHARGE AREAS

The USGS developed a particle-tracking program, MODPATH (Pollock, 1989), to simulate ground-water-flow paths for specified advective travel times that may range from one to many years. MODPATH uses the hydraulic heads and flow distribution computed by MODFLOW to determine these flow paths. The flow paths are computed by a semi-analytical particle-tracking scheme based on the assumption that the directional ground-water velocity components within a model vary linearly. The velocity components are based on the intercell flow rates computed by MODFLOW. The particle tracking done by MODPATH assumes that transport is by advection only and that other factors, such as chemical and biological attenuation, solid-phase partitioning, dispersion, and diffusion, are insignificant. MODPATH can track hypothetical particles of water up or down the hydraulic gradient (backward or forward) within the computed flow field. In this study backward tracking from two community well fields was done for advective travel times of 10 and 50 years.

Backward particle tracking from well fields A and B was done to delineate areas within the Mt. Simon-Hinckley aquifer of contributing recharge based on ground-water flow paths determined for 10- and 50-year travel times (fig. 3). A withdrawal rate of 625 $m^3/d$ was simulated for each well field. This daily rate of withdrawal is equivalent to the reported combined annual rate of withdrawal during 2000 for the two community supply wells at well field B (Sara Moore, Prairie Island Indian Community, oral commun., 2001).

At well field A, this rate of withdrawal, combined with backward particle tracking, was simulated as separate withdrawal points for community wells A-1 and A-2 because the distance between them (about 325 m) exceeds the model grid cell dimensions. At well field B, the two community wells were simulated as a single withdrawal point because the distance between them (about 25 m) is only about one-half the distance of the model grid cell dimensions.

The 10- and 50-year recharge areas cover 0.38 and 0.65 $km^2$, respectively (fig. 3). These areas are shown separately for wells A-1 and A-2 because of the simulation as separate withdrawal points. The flow paths that define these areas extend for maximum distances of 350 and 450 m, respectively, from the community supply wells used in the simulations.

## MODEL LIMITATIONS

Only three hydraulic head values were available for model calibration. These hydraulic head values are considered to be accurate to within plus or minus 3 m. Baseflow gains for upstream subreaches of the Mississippi River (Payne, 1995) were used to evaluate the simulated head-dependent boundary outflows. The simulated outflows, however, are only a portion of the total baseflow gain. Precise estimation of the baseflow gain in the study area from the Mt. Simon-Hinckley aquifer would be difficult.

Additional field data would be required to refine the calibration and thereby improve the accuracy of the model. More wells completed in the Mt. Simon-Hinckley aquifer would be needed to obtain additional hydraulic head data for the aquifer. More low-flow streamflow measurements would be needed to estimate the gain in baseflow to the Mississippi River. Ideally, streamflow measurements would be made during low-flow conditions at sites near the upstream and downstream ends of the study area. The downstream site should be upstream of Lock and Dam No. 3 (fig. 1) because of potential effects on baseflow from the dam. Streamflow also would have to be measured in any in-flowing streams between the upstream and downstream measurement sites.

The major limitation of the model is that the Mt. Simon-Hinckley aquifer is simulated as a 1-layer, 2-dimensional system. A multi-layer simulation of the ground-water system would be required to delineate contributing areas of recharge to the well fields from land surface where contaminant sources are likely to occur. Acquisition of additional hydrogeologic data would be needed to construct a more complex multi-layer model. The model at its present stage should be considered useful for estimation of the general effects of changes in hydraulic properties and boundary conditions of the Mt. Simon-Hinckley aquifer on the size of the contributing recharge areas to the well fields within the aquifer.

## SUMMARY

The Prairie Island Indian Community in east-central Minnesota uses ground water from the Mt. Simon-Hinckley aquifer, a confined bedrock aquifer, for community water supply. Tribal officials regard protection of four community supply wells (two wells each in well fields A and B) that are open to this aquifer to be an important natural resource management goal. To satisfy this goal tribal officials implemented a SWPP (Source Water Protection Program), which specifies a strategy formulated by the U.S. Environmental Protection Agency to assist State and local agencies in the delineation of hydrogeologically sensitive areas around water-supply wells. Areas of contributing recharge, which are defined by ground-water flow paths of equal travel time represent these sensitive areas.

A ground-water flow model combined with a particle-tracking program was used to delineate areas of contributing recharge within the Mt. Simon-Hinckley aquifer to the two community well fields. At well field A the two wells are about 325 m apart, and at well field B the two wells are about 25 m apart. The U.S. Geological Survey modular, finite-difference computer program MODFLOW was used to simulate ground-water flow in the Mt. Simon-Hinckley aquifer as a two-dimensional, steady-state, single-layer, confined aquifer system.

A variably-spaced model grid was defined for an approximately a 135-km$^2$ area. The grid was oriented such that the rows are parallel with the Mississippi River, which coincides with the northeast boundary of the grid. This grid boundary was modeled as a head-dependent flux boundary. The southwestern grid boundary was modeled as a specified head boundary. Model-computed hydraulic heads at three wells and outflows from the head-dependent flux boundary were sensitive to changes in the specified head boundary and river stage specified for the head-dependent flux boundary. Calibration of the model was done by adjustment of the hydraulic head value at the specified head boundary and riverbed conductance value at the head-dependent flux boundary.

The U.S. Geological Survey computer program MODPATH was used to track water particles (upgradient) from well fields A and B to delineate areas of contributing recharge based on a withdrawal rate of 625 m$^3$/d for each field. The flow paths defined areas of contributing recharge for the two well fields that are 0.38 and 0.65 km$^2$ in size for 10- and 50-year travel times, respectively. The flow paths that define these areas extend for maximum distances of about 350 and 450 m, respectively. At well field A where the wells are about 325 m apart, the areas of contributing recharge were delineated for each well as separate withdrawal points. At well field B, where the wells are only about 25 m apart, the area of contributing recharge was delineated for both wells as a single withdrawal point.

The major limitation of the model is that delineation of the areas of contributing recharge to the well fields are based on a 2-dimensional, 1-layer simulation within the Mt. Simon-Hinckley aquifer. As a consequence the contributing areas to the well fields are limited to within the Mt. Simon-Hinckley aquifer. A more complex, multi-layer simulation of the ground-water flow system would be required to delineate contributing areas of recharge to the aquifer from land surface. Construction of such a model would require acquisition of additional hydrogeologic data not currently available.

## REFERENCES


Bailey, Z.C., 1993, Hydrology of the Jackson, Tennessee, area and delineation of areas contributing ground water to the Jackson well fields: U.S. Geological Survey Water-Resources Investigations Report 92-4146, 54 p.

Barlow, P.M., 1997, Particle-tracking analysis of contributing areas of public-supply wells in simple and complex flow systems, Cape Cod, Massachusetts: U.S. Geological Survey Water-Supply Paper 2434, 66 p.

Cowdery, T.K., 1999, Water resources of the Prairie Island Indian Reservation, Minnesota, 1994-97: U.S. Geological Survey Water-Resources Investigations Report 99-4069, 36 p.

Delin, G.N., and Woodward, D.G., 1984, Hydrogeologic setting and the potentiometric surfaces of regional aquifers in the Hollandale Embayment, southeastern Minnesota, 1970-80: U.S. Geological Survey Water-Supply Paper 2219, 56 p.

Franke, O.L., Reilly, T.E., Pollock, D.W., and LaBaugh, J.W., 1998, Estimating areas contributing recharge to wells, lessons from previous studies: U.S. Geological Survey Circular 1174, 14 p.

Hobbs, H.C., and Setterholm, D.R., 1998, Geologic Atlas of Goodhue County, Minnesota: Minnesota Geological Survey, County Atlas Series, Map C-12, 6 plates, plate 3--Surficial Geology and Thickness of Quaternary Sediments, scale 1:100,000.

Landmeyer, J.E., 1994, Description and application of capture zone delineation for a wellfield at Hilton Head Island, South Carolina: U.S. Geological Survey Water-Resources Investigations Report 94-4012, 33 p.

Masterson, J.P., Walter, D.A., and LeBlanc, D.R., 1998, Delineation of contributing areas to selected public-supply wells, western Cape Cod, Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 98-4237, 45 p.

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.

Misut, P.E., and Feldman, S.M., 1996, Delineation of areas contributing recharge to wells in central Long Island, New York by particle tracking: U.S. Geological Survey Open-File Report 95-703, 47 p.

Mossler, J.H., and Tipping, R.G., 2000, Bedrock geology and structure of the seven-county Twin Cities metropolitan area, Minnesota: Minnesota Geological Survey, Miscellaneous Map Series M-104, 1 plate, scale 1:125,000

Nicholson, R.S., and Watt, M.K., 1998, Simulation of ground-water-flow patterns and areas contributing recharge to streams and water-supply wells in a valley-fill and carbonate-rock aquifer system, southwestern Morris County, New Jersey: U.S. Geological Survey Water-Resources Investigations Report 97-4216, 40 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.

Pollock, D.W., 1989, Documentation of computer programs to compute and display pathlines using results from the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 89-381, 188 p.

Runkel, A.C., 1998, Geologic Atlas of Goodhue County, Minnesota: Minnesota Geological Survey, County Atlas Series, Map C-12, 6 plates, plate 2--Bedrock Geology, scale 1:100,000.

Ruhl, J.F., 2002, Estimates of 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.

Sheets, R.A., 1994, Contributing recharge areas of water-supply wells at Wright-Patterson Air Force Base, Ohio: U.S. Geological Survey Water-Resources Investigations Report 94-4231, 35 p.

U.S. Environmental Protection Agency, 1987, Guidelines for delineation of wellhead protection areas: U.S. Environmental Protection Agency Office of Ground-Water Protection, Washington, D.C., EPA 440/6-87-010, 189 p.

Winterstein, T.A., 2000, Water-quality data collected on Prairie Island near Welch, Minnesota: U.S. Geological Survey Open-File Report 00-78, 25 p.

Zarriello, P.J., 1993, Determination of the contributing area to six municipal ground-water supplies in the Tug Hill glacial aquifer of northern New York, with emphasis on the Lacona-Sandy Creek well field: U.S. Geological Survey Water-Resources Investigations Report 90-4145, 51 p.