Characterization of Ground-Water Flow Between the Canisteo Mine Pit and Surrounding Aquifers, Mesabi Iron Range, Minnesota

By Perry M. Jones

Water-Resources Investigations Report 02-4198

Prepared in cooperation with the Minnesota Department of Natural Resources

U.S. DEPARTMENT OF THE INTERIOR

Gale A. Norton, Secretary

U.S. GEOLOGICAL SURVEY

Charles G. Groat, Director

Mound 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 02-4198

Contents

Illustrations

Tables

Tables—Continued

Conversion Factors, Abbreviations, and Sea Level Datum,

Multiply	By	To obtain
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
acre	4,047	square meter
square mile (mi^2)	2.590	square kilometer
square foot per day (ft^2/day)	0.09290	square meter per day
cubic foot (ft^3)	0.02832	cubic meter
gallon (gal)	0.003785	cubic meter
acre-foot (acre-ft)	1,233	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
degrees Fahrenheit	°C = (°F – 32) / 1.8	degrees Celsius

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

Water year: The water year is October 1 through September 30 and is named for the calendar year in which it ends.

Characterization of Ground-Water Flow Between the Canisteo Mine Pit and Surrounding Aquifers, Mesabi Iron Range, Minnesota

By Perry M. Jones

ABSTRACT

The U.S. Geological Survey, in cooperation with the Minnesota Department of Natural Resources, conducted a study to characterize ground-water flow conditions between the Canisteo Mine Pit, Bovey, Minnesota, and surrounding aquifers following mine abandonment. The objective of the study was to estimate the amount of steady-state, ground-water flow between the Canisteo Mine Pit and surrounding aquifers at pit water-level altitudes below the level at which surface-water discharge from the pit may occur. Single-well hydraulic tests and stream-hydrograph analyses were conducted to estimate horizontal hydraulic conductivities and ground-water recharge rates, respectively, for glacial aquifers surrounding the mine pit. Average hydraulic conductivity values ranged from 0.05 to 5.0 ft/day for sands and clays and from 0.01 to 121 ft/day for coarse sands, gravels, and boulders. The 15-year averages for the estimated annual recharge using the winter records and the entire years of record for defining baseflow recession rates were 7.07 and 7.58 in., respectively. These recharge estimates accounted for 25 and 27 percent, respectively, of the average annual precipitation for the 1968-82 streamflow monitoring period. Ground-water flow rates into and out of the mine pit were estimated using a calibrated steady-state, ground-water flow model simulating an area of approximately 75 mi^2 surrounding the mine pit. The model residuals, or difference between simulated and measured water levels, for 15 monitoring wells adjacent to the mine pit varied between +28.65 and –3.78 ft. The best-match simulated water levels were within 4 ft of measured water levels for 9 of the 15 wells, and within 2 ft for 4 of the wells. The simulated net ground-water flow into the Canisteo Mine Pit was +1.34 ft^3/s, and the net ground-water flow calculated from pit water levels measured between July 5, 1999 and February 25, 2001 was +5.4 ft^3/s. Simulated water levels and ground-water flow to and from the mine pit for the calibrated steady-state simulation were most sensitive to changes in horizontal hydraulic conductivity, suggesting that this characteristic is the predominant parameter controlling steady-state water-level and flow conditions. A series of 14 steady-state simulations at constant pit water-level altitudes between 1,300 and 1,324 ft was completed with the calibrated model to assess the effect of current and potential future pit water-level altitudes on ground-water inflow to and outflow from the mine pit. Total simulated ground-water inflow to the mine pit at a constant pit water-level altitude of 1,300 ft was 1.40 ft^3/s, with a total simulated ground-water outflow of 0.06 ft^3/s discharging from the mine pit to local aquifers. Steady-state simulations indicate that total simulated ground-water inflow will decrease from 1.40 to 1.00 ft^3/s and total simulated ground-water outflow will increase from 0.06 to 0.91 ft^3/s as the pit water-level altitude rises from 1,300 to 1,324 ft. When the pit water-level altitude is 1,324 ft^3/s, the lowest pit-rim altitude, the simulated net ground-water inflow is 0.09 ft^3/s. At pit water-level altitudes between 1,302 and 1,306 ft, all but a small rate (less than 0.01 ft^3/s) of the total simulated ground-water outflow from the pit occurs in the Trout Lake area. At pit water-level altitudes between 1,308 and 1,324 ft, simulated outflow occurs in three outflow locations: the Trout Lake, the Prairie River, and Holman Lake areas.

INTRODUCTION

Rising water level in the Canisteo Mine Pit (fig. 1) and other mine pits on the Mesabi Iron Range, Minnesota is a concern of downgradient communities, land owners, and the Minnesota Department of Natural Resources (MNDNR). Concern exists that as the pit water-level altitude continues to rise, mine water may eventually discharge from the pit over land surface, resulting in undesirable downgradient erosion and localized flooding. Since mine adandonment in 1985, water level in the Canisteo Mine Pit has risen nearly 300 ft. Since November 1994, the water level has risen at an

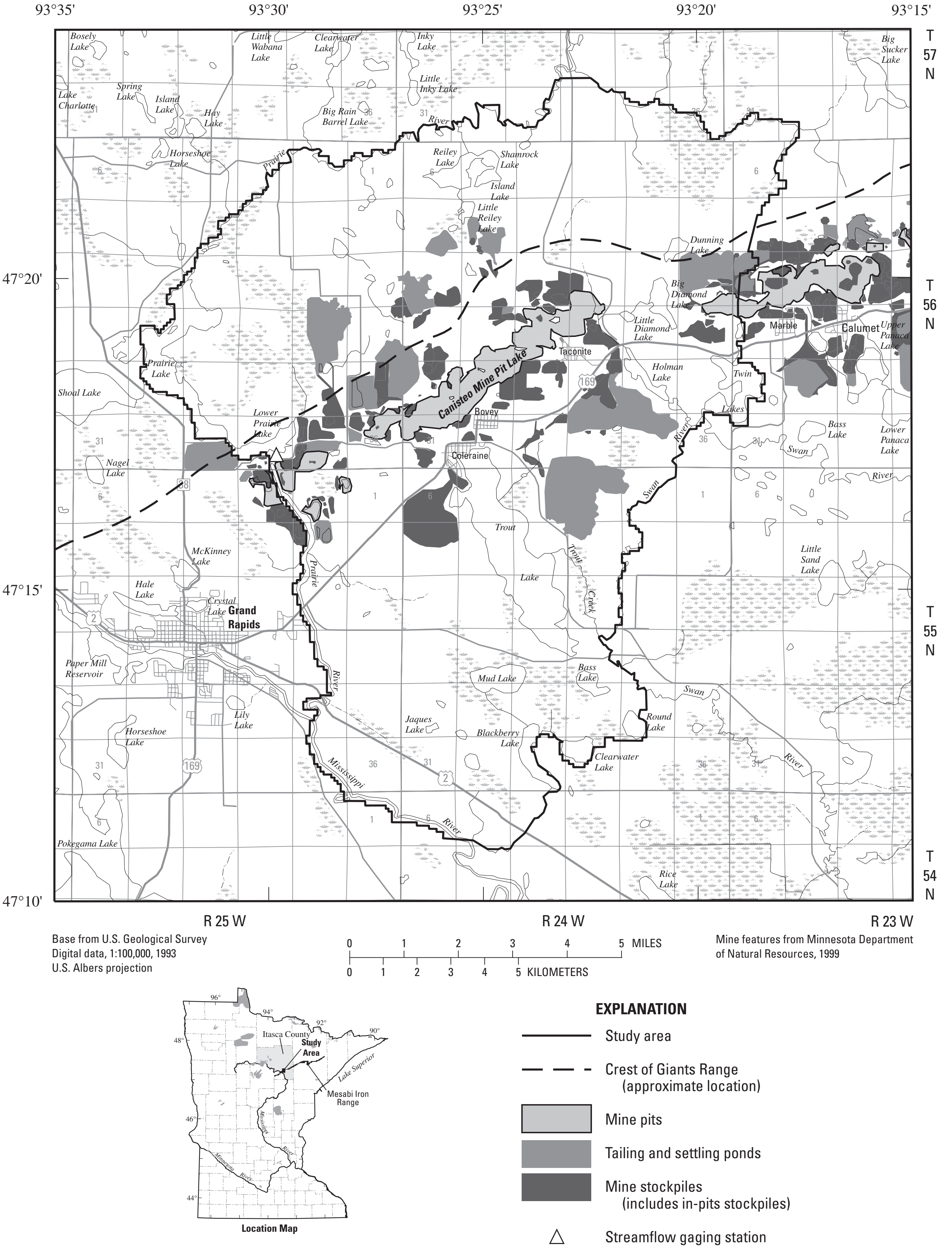

Figure 1. Location of Canisteo Mine Pit study area, mining features, and Prairie River near Taconite, Minnesota streamflow gaging station, Bovey, Minnesota.

average rate of 2.5 to 5 ft/yr (fig. 2) (John Adams and Joe Maki, Minnesota Department of Natural Resources, oral commun., 1999). During May 2001, the water-level altitude in the Canisteo Mine Pit was 1,301 ft. The lowest pit wall altitude is 1,324 ft.

The development and abandonment of large, open-pit mines has a substantial effect on local water resources. Dewatering activities at large taconite (iron ore) pits form huge hydrologic sinks during mining, capturing surface and ground water from multiple watersheds. About 12 billion gallons (36,800 acre-ft) of water is currently pumped annually from Mesabi Iron Range taconite pits, with many pits dewatering several thousand gallons of water per minute (Adams, 1994). Dewatering ceases with mine abandonment, but surface and ground waters continue to flow into the mine. The pit water level rises until a relatively steady-state hydrologic condition is achieved. Prior to achieving this steady-state condition, the pit water level could rise above the lowest pit-rim altitude, resulting in surface discharge of water. The outflow from the mine pits may result in flooding and water quality and erosion problems (Adams, 1994).

In general, components of the water balance for an abandoned mine pit include direct precipitation to the pit, evaporation from the pit, surface-water flow to and from the pit, and ground-water flow to and from the pit. For mine pits on the Mesabi Iron Range, surface-water flow can include overland flow and inflowing water from streams and other surface conveyances. Ground-water flow to and from pits occurs in bedrock aquifers, glacial aquifers, surrounding overburden, and tailings piles.

Often the most important and difficult dependent variable to estimate in an abandoned mine pit water balance prediction is the amount of ground-water inflow and outflow. During the initial stage of water-level recovery following mine abandonment, ground-water inflow is often the main water-balance component controlling pit water-level rise. Other water-balance components usually become important as a steady-state water balance becomes established. Mine pit water-level data collected by the MNDNR suggest that ground-water inflow currently is the largest and most significant water-balance component of the Canisteo Mine Pit (John Adams, Minnesota Department of Natural Resources, oral commun.,

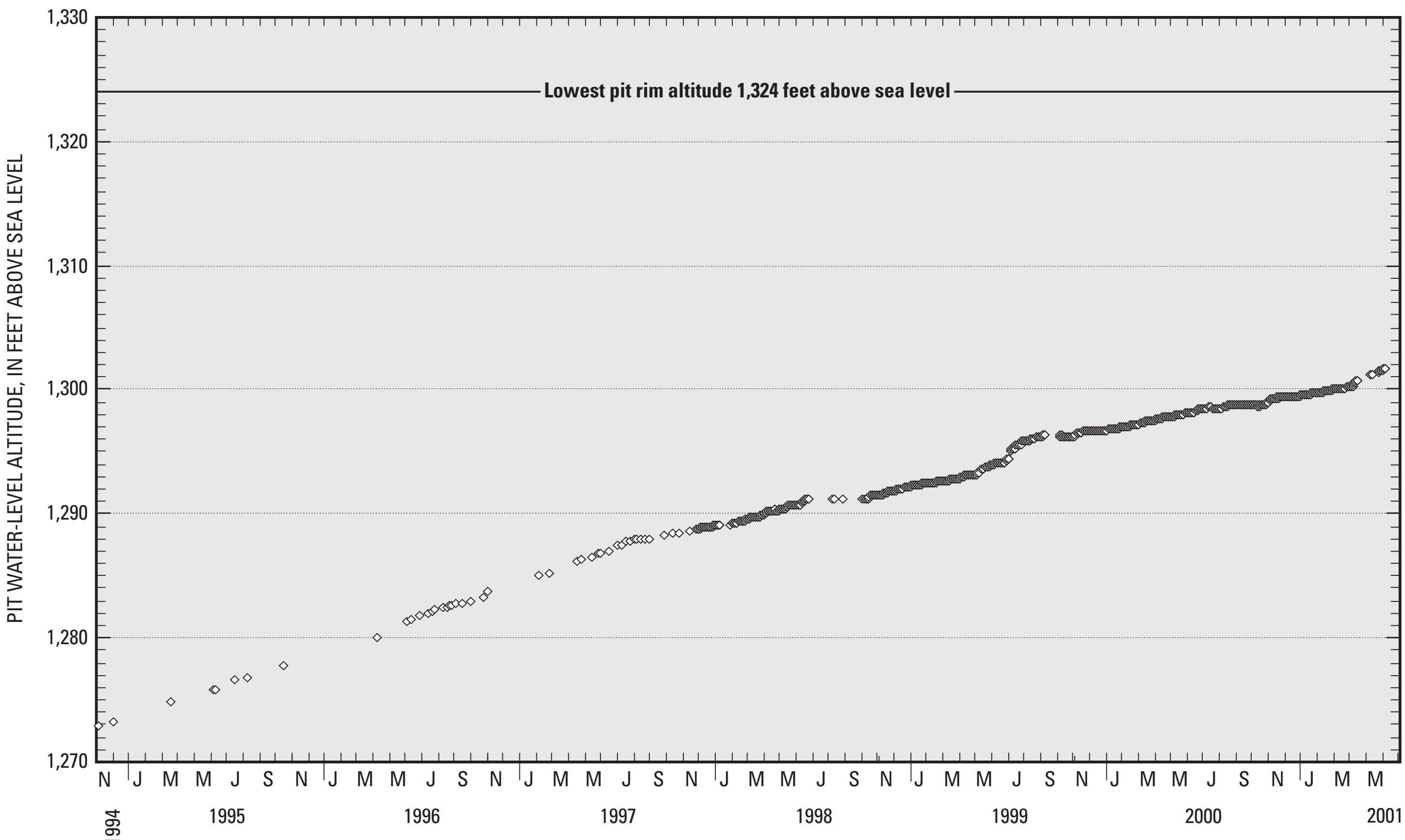

Figure 2. Water-level altitude in the Canisteo Mine Pit, Bovey, Minnesota, November 1994-June 2001.

1998). Prediction of ground-water inflow and outflow rates of the Mesabi Iron Range mine pits is often difficult due to a lack of water-level data for glacial and bedrock aquifers surrounding the mines, and the complexity of the glacial and fractured bedrock aquifers. Also, large surface mining operations often crosscut surface- and ground-water divides, further complicating the hydrologic balance of the mine setting.

The U.S. Geological Survey (USGS), in cooperation with the MNDNR, conducted a study to characterize ground-water flow conditions between the Canisteo Mine Pit and surrounding aquifers following mine abandonment. The main objective of the study was to estimate the amount of ground-water flow between the Canisteo Mine Pit and surrounding aquifers at pit water-level altitudes below the level at which surface-water discharge from the pit may occur. This study was part of a more comprehensive water-balance study of the Canisteo Mine Pit conducted by the MNDNR and supported by the State of Minnesota under the recommendation of the Legislative Commission on Minnesota Resources (LCMR). Ground-water flow estimates from this study will be used by MNDNR to predict the pit's probable steady-state water-level altitude and possible surface outflow locations and rates (Minnesota Department of Natural Resources, 1999). This report presents results of the study and includes descriptions of single-well hydraulic tests, stream-hydrograph analyses, and ground-water flow simulations of aquifers surrounding the Canisteo Mine.

ACKNOWLEDGMENTS

The author gratefully thanks the Minnesota Department of Natural Resources and the Legislative Commission on Minnesota Resources for providing assistance needed to complete this study. Mr. Robert T. Leibfried, Mr. John L. Adams, Mr. Joseph R. Maki, Mr. Carl F. Rundberg, and Mr. John Z. Mackiewicz of the Minnesota Department of Natural Resources provided much assistance during the course of this study. Mr. Dave Lorenz, Mr. Chris Sanocki, and Mr. Brian Fischer of the U.S. Geological Survey provided assistance in geographic information systems (GIS) work needed for conducting flow simulations. Mr. Tim Cowdery, Mr. Geoff Delin, and Mr. Brain Chaplin of the U.S. Geological Survey provided assistance in the development of the GMS and MODFLOW files. Mr. Fred Baker of Baker Consultants, Inc. provided the code and assistance with the PITLAKE Package for the MODFLOW-96 Model. Attempts were made to simulate the mine pit using the PITLAKE package developed by Baker Consultants, Inc. (Baker Consultants, Inc., 2000). However, incompatibility between the PITLAKE code and the version of MODFLOW-96 used with the GMS interface could not be overcome.

PHYSICAL SETTING OF CANISTEO MINE PIT STUDY AREA

The study area is approximately 75 mi^2 surrounding the Canisteo Mine Pit (fig. 1). The Canisteo Mine Pit is a complex of abandoned natural ore pits located on the Mesabi Iron Range, Itasca County, north-central Minnesota, north of the cities of Coleraine, Bovey, and Taconite (fig. 1). The mine pit is approximately 4.8 miles in length and has an average width of approximately 0.5 miles (Bob Leibfried, Minnesota Department of Natural Resources, written commun., 2001). At a surface-water altitude of 1,301 ft, the pit holds approximately 140,000 acre-ft of water. Mining of iron and associated dewatering from the pit ceased in 1984. The pit's watershed is approximately 4,536 acres (7.09 mi^2) and is part of the upper Mississippi River Basin, hydrologic unit 07010103 (U.S. Geological Survey, 1974). No active iron-ore mining has occurred in the study area since 1985.

Climate in the watershed is continental: cold winters and hot summers. The mean annual temperature (1961-90) at Grand Rapids, Minnesota is 38.6 °F, and the mean annual precipitation is 27.54 in. (Minnesota State Climatologist, 2001). January is the coldest month and July is the warmest month. February is the driest month and June is the wettest month. Mean January temperature is 3.8 °F, and mean July temperature is 67.4 °F. Mean February precipitation is 0.54 in., and mean June precipitation is 4.11 in.

Land-surface altitude in the study area ranges from 1,260 ft along the Mississippi River in the southern portion to 1,550 ft along the Giants Range. The Giants Range is a linear ridge composed of Precambrian granitic and undifferentiated metasedimentary rocks that trend northeast to southwest, north of the Canisteo Mine Pit (fig. 1). This range is the major topographic high, with land-surface altitude along its' crest varying from 1,400 to 1,550 ft in the study area.

Local topography and hydrology of the Iron Range have been affected by previous mining activities. Twenty-two percent of the land cover of the study area has been directly or indirectly affected by mining, with most of the open mine pits, tailings, and stockpiles present in the central mining region of the study area (fig. 1) (Minnesota Department of Natural Resources, 2001b). Tailings and stockpiles are as high as 170 ft above the land surface and extend over an area of several square miles. Since no active iron ore mining is present in the study area, the heights and extents of these piles are relatively static. In addition to pits and excavations, tailings and settling ponds used previously for the treatment of mine waters exist throughout the mining region (fig. 1).

Vegetative land cover in the study area consists of a mix of northern hardwood forest and grasslands. Thirty-eight percent of the study area consists of forest, with 61 percent of the forest cover being deciduous forest, 24 percent being mixed-wood forest, and 15 percent being young forest (Minnesota Department of Natural Resources, 2001b). Grasslands cover 11 percent of the study area.

Twenty-two percent of the land cover of the study area is open water or wetlands (Minnesota Department of Natural Resources, 2001b). Many natural lakes and six abandoned mine pit lakes, including the Canisteo Mine Pit Lake, are present within the study area (fig. 1). Lakes in minor excavations and natural ore pits are found throughout the central portion of the study area. With the exception of the Canisteo Mine Pit Lake, relatively steady-state water levels exist in all of the mine pits. The remaining 7 percent of the land cover consists of urban and residential areas.

Surface drainage and ground-water flow through the study area is generally to the north-northwest, north of the crest of the Giants Range and to the south-southeast, south of the Giants Range crest (Oakes, 1970). Surface drainage north of the crest flows to the Prairie River, which enters the study area from the north. The Prairie River flows west-southwest along the western edge of the study area and into the Prairie Lake-Lower Prairie Lake System, a system formed by the damming of the river south of the Lower Prairie Lake (fig. 1). Downstream of the Lower Prairie Lake, the Prairie River flows to the Mississippi River. The Mississippi River flows from Grand Rapids to the southeast out of the study area.

South of the Canisteo Mine Pit, drainage is to the south and is divided into three watersheds: Trout Lake, Holman Lake, and Prairie River (fig. 1). Trout Lake is one of the largest lakes in the study area, with an area of 3.0 mi^2 (1,890 acres). Discharge from the lake is to the east through Trout Creek, which flows east-southeast into Swan River. The Swan River flows southeast out of the study area. Water from Dunning Lake, Big Diamond Lake, Little Diamond Lake, wetlands, and tributaries north of the Holman Lake flows into Holman Lake from the northwest during portions of the year. The area of Holman Lake is 0.2 mi^2 (146 acres). Water entering Holman Lake discharges into the Swan River upgradient of the Trout Creek/Swan River confluence.

Glacial drift covers much of the study area, with the exception of bedrock outcrops along the Giants Range. Three major morainal till units and associated glaciofluvial outwash deposits exist, formed during the Wisconsin glaciation ice advances from the north and west of the study area (Winter, 1971). Total drift thicknesses range from zero along portions of the Giants Range to more than 300 ft in the southern part of the study area and in bedrock valleys. The stratigraphically lowest till unit, the basal till, is a dark-greenish and brownish-gray till that is sandy, silty, clayey, and calcareous (Winter, 1971). The basal till is found mainly in the southern portion of the study area. The middle boulder and upper surficial till units are found throughout the study area. The boulder till ranges widely in color from gray to yellow, and consists of sands and silts, with abundant cobbles and boulders (Winter, 1971). This till tends to be the thickest unit in the study area. The surficial till is brown in color; sandy, silty, and calcareous; and is generally less than 30 ft thick in the study area.

Glaciofluvial outwash deposits lie stratigraphically between surficial and boulder tills, and often lie between the boulder and basal till or bedrock (Winter, 1973a). These outwash deposits consist largely of sands, gravels, and boulders. Glaciofluvial outwash deposits between the surficial and boulder tills are the thickest and most continuous outwash deposits in the study area, often greater than 50 ft thick and sometimes greater than 100 ft in portions of buried valleys (Winter, 1973a). These outwash deposits consist of fine–grained sands throughout much of the study area, but are highly transmissive, coarse-grained sands, gravels, and boulders in buried valleys, and at other locations where the bedrock surface is low. The glaciofluvial sediments found below the boulder till are fairly continuous south of the Canisteo Mine Pit. These sediments are poorly sorted and are generally less than 50 ft thick, but are greater than 100 ft thick locally in buried bedrock valleys and in the vicinity of Trout Lake (Winter, 1973a). Clays, silts, and sands reworked and redeposited by Glacial Lake Aitkin overlie surficial tills near Trout Lake, and in the western and southern portion of the study area (Winter 1973a).

Iron ore was extracted from the Canisteo Mine and other mines from a narrow belt of iron-rich bedrock strata known as the Biwabik Iron Formation, which trends to the northeast for approximately 120 miles across northeast Minnesota (Morey, 1972). The Biwabik Iron Formation is overlain and bounded to the south by the Virginia Formation. The Virginia Formation consists of argillites, siltstones, and graywackes, and is underlain and bounded to the north by the Pokegama Quartzite. The Precambrian granitic rocks that form the Giants Range underlie the Pokegama Quartzite. Cretaceous sandstones, iron formation, and shales overlie the Precambrian rocks in portions of the study area. Bedrock valleys have been identified in the study area (Bruce A. Bloomgren, Minnesota Geological Survey, oral commun., 2001), but the extent and depth of these valleys is poorly defined due to the insufficient spacing of wells and boreholes.

Present ground-water withdrawals are mainly from glaciofluvial aquifers through municipal, small industrial, and domestic wells. In 1999, the city of Coleraine (population 1,110) (U.S. Census Bureau, 2002) withdrew 51.1 million gallons of water from two wells screened in buried glacial sands and gravels (Minnesota Department of Natural Resources, 2001c) (fig. 3). The city of Bovey (population 662) (U.S. Census Bureau, 2002) withdrew 32 million gallons of water from a well screened in buried glacial sands and gravels (Minnesota Department of Natural Resources, 2001c) (fig. 3). The city of Taconite (population 315) (U.S. Census Bureau, 2002) withdrew 11.7 million gallons of water from two wells completed in the Biwabik Iron Formation and other Precambrian bedrock (Minnesota Department of Natural Resources, 2001c) (fig. 3). Domestic wells in the study area extract water mostly from glaciofluvial aquifers, with few households using the Biwabik Iron Formation for a source of water.

METHODS OF INVESTIGATION

Ground-water flow rates into and out of the Canisteo Mine Pit were estimated by a steady-state, numerical, ground-water flow model. Once the steady-state model was calibrated to water levels measured in 15 monitoring wells, it was used to examine ground-water flow rates into and out of the mine pit at various potential future pit water-level altitudes. Single-well hydraulic tests and stream-hydrograph analyses were used to estimate hydraulic conductivities and ground-water recharge rates, respectively, for glacial aquifers surrounding the mine pit. These estimates were used as initial input values for the model.

SINGLE-WELL HYDRAULIC TESTS

Single-well hydraulic tests and slug tests were performed during 1999-2000 in 14 of the 18 monitoring wells surrounding the mine pit (fig. 3). The MNDNR installed 16 of these 18 monitoring wells to monitor ground-water levels, characterize the surficial geology, and assess hydraulic properties of glacial aquifers surrounding the mine pit. A total of 21 pumping tests and 20 slug tests were performed in the 14 wells. A Grundfos Redi-Flo2 submersible pump with a check valve was used to lower water levels during the pumping tests, whereas a PVC-cased, sand-filled slug was placed in the wells to displace water during the slug tests. A Druck PDCR 830 (0-10 psi) pressure transducer with a Campbell Scientific CR-10 data logger and/or a Solinst Levelogger pressure transducer/data logger system were used to record water levels during the pumping and slug tests. The length of these tests varied from less than one minute to 17 hours.

Water-level data from the pumping and slug tests were analyzed using the AQTESOLV for Windows, version 2.16, program (Duffield, 1995). Transmissivity values were obtained from analysis of water levels during the pumping tests using the Theis (1935) and Cooper and Jacob (1946) curve-matching methods. The recovery periods during the pumping tests were only analyzed if the check valve in the pump prevented water in the pump's hose from flushing down into the well after the pump was shut off. The Bouwer and Rice (1976) method was used to determine hydraulic conductivity values from the water-level recovery data during both the pumping and slug tests.

STREAM-HYDROGRAPH ANALYSES

Daily stream discharge records during 1968-82 for the Prairie River near Taconite, Minnesota streamflow gaging station were used in stream-hydrograph analyses to determine ground-water recharge estimates for surficial aquifers in the study area (fig. 1). This discontinued gage is the only stream gage located in or near the study area, and therefore offered the best opportunity to assess ground-water recharge rates using daily streamflow records with stream-hydrograph analysis methods.

Discharge records were analyzed using the USGS RECESS and RORA Programs (Rutledge, 1998). The RECESS Program was used to select periods of time in the discharge record when streamflow was considered to be solely from ground-water discharge, and use these portions of the record to determine a best-fit equation for the rate of recession as a function of the logarithm of flow. Because the recession rate values can be affected by ground-water evapotranspiration (Rutledge, 2000), best-fit recession equations were determined for winter records, when most of the streamflow record is considered to be solely from ground-water recharge, and for the entire annual streamflow record. Coefficients of these best-fit equations were used to derive a master recession curve of streamflow recession. The RORA Program uses the derived master recession curve with the recession-curve-displacement method to estimate the ground-water recharge for each streamflow peak (Rutledge, 1998). Annual and quarterly estimates of the mean rates of ground-water recharge were calcu-

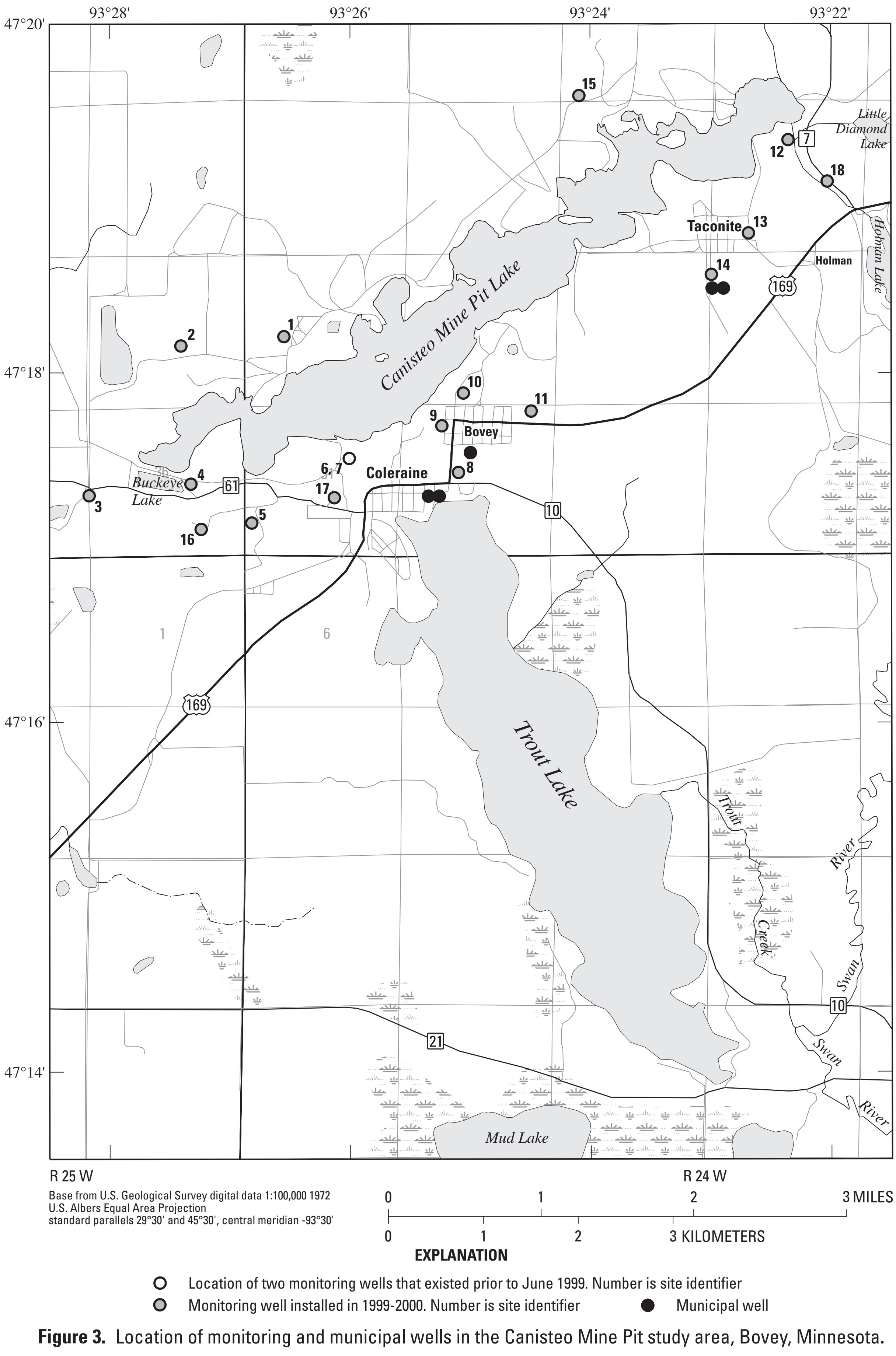

Figure 3. Location of monitoring and municipal wells in the Canisteo Mine Pit study area, Bovey, Minnesota.

lated using both the winter and entire annual records in RORA for each year of the 1968-82 record.

GROUND-WATER FLOW MODEL OF THE CANISTEO MINE PIT STUDY AREA

A three-dimensional, numerical ground-water flow model was developed, incorporating an area of approximately 75 mi^2 surrounding the Canisteo Mine Pit (fig. 4). The USGS Modular Ground-Water Flow Model, commonly referred to as MODFLOW-96, was used to simulate ground-water flow conditions surrounding the mine site. MODFLOW-96 is a modular, three-dimensional, finite-difference, ground-water-flow model that simulates ground-water flow in multiple aquifers (Harbaugh and McDonald, 1996). The steady-state representation of the study area was done using the BASIC, BCF, General-Head, River, Well, Drain, Recharge, and Preconditioned Conjugate Gradient (PCG2) Solver modules of MODFLOW-96. The MODFLOW-96 simulations were developed, run, and analyzed using a graphic-user interface called the Groundwater Modeling System (GMS) (U.S. Department of Defense, 1998). The USGS MODPATH, Version 3 particle-tracking, post-processing package (Pollock, 1994) was used to compute ground-water flow paths originating from the pit at pit water-level altitudes of 1,300 and 1,320 ft based on water-level outputs from the MODFLOW simulations at these two pit water levels.

Simulation of ground-water flow conditions surrounding the Canisteo Mine Pit was undertaken using a five-step approach: (1) compile existing hydrologic and geologic data needed to construct the model; (2) discretize the compiled data; (3) calibrate the model through the comparison of simulated and measured ground-water levels and flow rates; (4) perform sensitivity analyses on the calibrated model, assessing the effect of ground-water recharge and hydraulic conductivity on ground-water levels and flow rates; and (5) run predictive simulations of future ground-water levels under potential future elevated pit water levels.

Data Sets Used

A variety of data sources were used to represent various hydrologic features in the model. The properties needed in the model to represent these features include the extent and thickness of aquifers and confining units; the boundaries, water-level altitudes, and depths of surface-water bodies that affect ground-water flow, and well withdrawal rates from aquifers. Table 1 is a list of data sources used in the construction of the model. This data consisted of geologic logs, GIS data sets, water-level altitudes, mine pit dimensions, and municipal well pumping records.

Geologic logs from existing municipal, domestic and monitoring wells and previously drilled auger holes, were used to develop representations of glacial and bedrock units in the model. The well logs were obtained from water-well records in the Minnesota Geological Survey’s (MGS) County Well Index (table 1). Existing auger-hole data were collected from the USGS Ground-Water data base and MNDNR existing records. Geologic logs were entered into GMS, where the layering of the simulated aquifers were constructed through interpolation between the logs. Interpolation was done referencing geologic maps and publications by Oakes (1970), and Winter (1971, 1973a, and 1973b), and bedrock-depth maps developed by MNDNR using collected borehole data and results from seismic surveys conducted in the study area (Petersen and Berg, 2000). Based on this geologic interpolation method, a three-dimensional model representing the geology of the study area was created.

A series of GIS data sets were used to identify and represent hydrologic features and processes occurring in the study area (table 1). Data sets for perennial wetlands, lakes, and rivers were obtained from the National Wetland Inventory data base (U.S. Fish & Wildlife Service, 1994). Included were natural and man-made lakes, such as tailings ponds, settling ponds, and mine pits. Water-level altitude data for the perennial wetlands, rivers, and most of the lakes used in the model were obtained directly from these data sets. Water-level altitude data for 15 lakes, including 4 mine pits, were obtained from MNDNR hydrologists and the MNDNR Lake-Level data base (Minnesota Department of Natural Resources, 2001a) (table 1). Dimensions for the Canisteo Mine Pit were obtained from GIS data sets developed by the MNDNR from altitude data obtained in the Mesabi elevation project (Minnesota Department of Natural Resources, 1999). Pumping records for municipal wells in the study area were obtained from the MNDNR Water-Appropriation-Permit data base (Minnesota Department of Natural Resources, 2001c). A data set representing areal recharge to the surficial layer of the model was developed using USGS recharge rate data obtained from stream-hydrograph analysis (table 1).

Discretization of the Model

A three-dimensional, numerical ground-water flow model was constructed based on a conceptual model of hydrogeology in the study area. The conceptual model was created based on a knowledge of the hydrogeologic setting, aquifer characteristics, distributions and amounts of ground-water recharge and discharge, and aquifer boundaries.

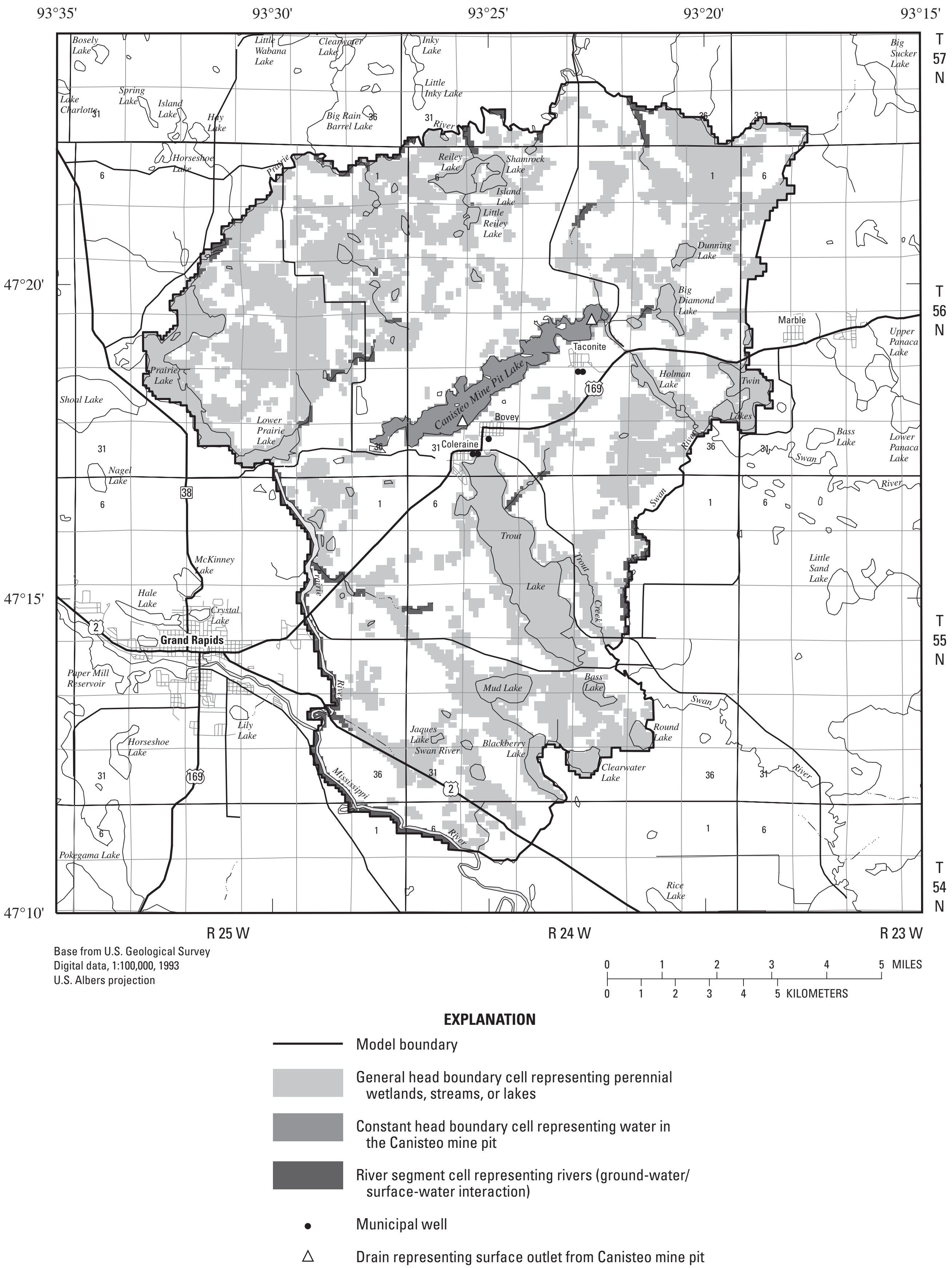

Figure 4. Model segmentation for MODFLOW simulation of aquifers surrounding the Canisteo Mine Pit, Bovey, Minnesota.

Table 1. Data sources used in the MODFLOW steady-state simulations of aquifers surrounding the Canisteo Mine Pit, Bovey, Minnesota

Data	Type of data	Source of data	Type of information	Date compiled
Wells and auger holes	Geologic logs (interpolated geology)	Minnesota Geological Survey's County Well Index, U.S. Geological Survey Ground-Water data base, Minnesota Department of Natural Resources, Divisions of Minerals and Waters records	Location, geologic description, stratigraphy	November 2000
Wetlands	GIS data sets	U.S. Fish & Wildlife Service, National Wetlands Inventory data base	Location, area, water-level altitude	January 2001
Lakes	GIS data sets	U.S. Fish & Wildlife Service, National Wetlands Inventory data base	Location, area, water-level altitude	January 2001
Rivers (polygons)	GIS data sets	U.S. Fish & Wildlife Service, National Wetlands Inventory data base	Location, area, water-level altitude, stage	January 2001
Rivers (Arc and Node)	GIS data sets	U.S. Fish & Wildlife Service, National Wetlands Inventory data base	Location, area, water-level altitude, stage	January 2001
Lake	Water-level altitude	Minnesota Department of Natural Resources, Division of Waters, Lake Level data base	Altitude for eleven lakes	June 1999
Canisteo Mine Pit	Dimensions	Minnesota Department of Natural Resources, Division of Minerals records	Location, area, altitude	January 2001
Areal Recharge	GIS data sets	Developed from U.S. Geological Survey data	Location, recharge rate	January 2001
Municipal wells of Taconite, Bovey, and Coleraine	Pumping records	Minnesota Department of Natural Resources, Division of Waters, Water-Appropriations-Permit data base	Annual pumping rates	January 2001

A "true-layer" approach was undertaken to define layering represented by the model, explicitly defining altitudes and aquifer hydraulic properties of cells in each layer based on the three-dimensional model. The study area was discretized into rectangular finite-difference grid cells within which the hydrogeologic properties were homogeneous and isotropic. Ground-water flow within the aquifers was simulated using a block-centered approach, where flow was calculated between discretized cells based on head conditions at the cell's central nodes (McDonald and Harbaugh, 1988). Hydrogeologic properties and stresses were applied to model cells assuming that the assigned properties and stresses represent average conditions within the cells. Starting hydraulic head values in the cells were set at 1,324 ft in each of the layers, and were later modified to reflect head values calculated by early iterations of the model.

The three-dimensional, finite-difference grid used in the model representation of the study area was evenly spaced, consisting of 222 rows and 200 columns. The dimensions of the grid cells were 328 ft (100 m) along rows and along columns. The model was divided vertically into seven layers, based generally on the hydrogeologic units and depth of the Canisteo Mine Pit. All of the layers were represented as either confined or unconfined, with their transmissivities varying with saturated thicknesses. Simulation of flow between the cells and the layers was dependent on the cellular dimensions, thicknesses, and hydraulic conductivities between adjacent cells and layers. A detailed discussion of flow between cells and layers in the model can be found in McDonald and Harbaugh (1988).

The horizontal boundaries of the model were, for the most part, imposed along a series of perennial rivers, streams, lakes, and wetlands, that were located a sufficient distance from the Canisteo Mine Pit to have minimal effect on ground-water flow to and from the mine pit (fig. 4). The boundaries were present in each of the seven layers in the model, and were no-flow boundaries. Cells outside of the model boundary were inactive. The model area was bounded to the north and northwest by the Prairie River, and bounded to the west by the MacDougal Bay-Prairie Lake-Lower Prairie Lake System and the Prairie River. The southwestern portion of the model was bounded by the Mississippi River. The southeastern boundary of the model consisted of perennial wetlands and three lakes; Blackberry, Clearwater, and Round Lakes. The model was bounded to the east by the Swan River, Twin Lakes, and a series of lakes and perennial wetlands. Sucker Brook was the northeast boundary of the model. The bottom of the lowest layer in the model was simulated as a no-flow, vertical boundary. The amount of vertical flow across the bottom of the lowest layer in the model was assumed to be small relative to the amount of horizontal flow.

The hydrogeology of the study area was represented in the model by three hydrogeologic units: (1) glaciofluvial sediments (sands, gravels and boulders) present in two layers of the model; (2) glacial clays and tills (mixture of clays, fine sands, gravels and boulders) present in three layers of the model; and (3) bedrock, including Biwabik Iron Formation, Virginia Formation, Pokegama Quartzite, Precambrian granitic, and Cretaceous sandstones, iron formation, and shales present in two layers of the model. Initial hydraulic conductivities were specified for each of three hydrogeologic units based on pumping and slug test analyses conducted during this study, and hydraulic conductivity values published by Winter (1973a).

All lakes and perennial wetlands were represented in the model as general-head boundaries (fig. 4), using the general-head module in MODFLOW-96. Lakes and perennial wetlands were segmented to individual cells in the finite-difference grid. A total of 11,654 general-head boundary cells were specified in the model. With general-head boundaries, flow into and out of a cell is portioned based on the hydraulic-head difference between the head in the cell and the assigned general head, and on a conductance term (McDonald and Harbaugh, 1988). In each of the model cells specified as a general-head boundary, the conductance for the boundary is defined as the hydraulic conductivity of the bed material divided by the vertical thickness of the lake or wetland bed material, multiplied by the area of the lake or wetland in the cell. A hydraulic conductivity of 0.07 ft/day and a vertical thickness of 3.28 ft were used in calculating the conductance term in each of the general-head boundary cells. Both hydraulic conductivity and vertical thickness of lake and wetland bed material can be highly variable for lakes and wetlands. The selected hydraulic conductivity value represents a low value for the range of hydraulic conductivity values for glacial tills obtained from single-well hydraulic tests in this study and for hydraulic conductivity values determined for lake-bed material of Shingobee Lake, Minnesota (Kishel and Gerla, 2002). Many of the lakes and wetlands in the study area lie above glacial till, so a hydraulic conductivity value for the glacial till was used for the lake-bed material. An assumed value of 3.28 ft was used to represent an average thickness for the bed material for lakes and wetlands in the area. Lake and wetland areas and altitudes from the National Wetland Inventory GIS data sets were used for the areas and head values, respectively, for the general head boundaries representing the lake and perennial wetlands segments.

Selected streams and rivers not simulated as part of wetlands were simulated using the river module of MODFLOW-96. The river module is used to simulate flow between the surface-water features and ground-water systems (McDonald and Harbaugh, 1988). Streams and rivers were segmented into reaches, with each reach corresponding to individual cells in the finite-difference grid (fig. 4). A total of 791 river cells were specified in the model. Flow between the river reaches and the ground-water flow systems was calculated for each cell based on a conductance term and the head difference between the river altitude and the aquifer (McDonald and Harbaugh, 1988). In the river module, the conductance term is defined as the hydraulic conductivity divided by the vertical thickness of the river-bed materials, multiplied by the surficial area of the river bed in that cell (McDonald and Harbaugh, 1988). A hydraulic conductivity of 0.07 ft/day and a vertical thickness of 3.28 ft were used for the river-bed hydraulic conductivity and vertical thickness, respectively. Many of the streams and rivers in the study area lie above glacial till, so a hydraulic conductivity value for the glacial till was used. An assumed value of 3.28 ft was used to represent an average thickness for the bed material for streams and rivers in the area. Surficial areas and altitudes for the river segments were obtained from the National Wetland Inventory GIS data sets. River stage values were assumed to be 6.56 ft above the altitude of the riverbed. The stage of rivers varies seasonally with precipitation rates, and therefore, the chosen river stages were assumed to represent average stage values for the rivers.

A specified-flux boundary was used to represent areal recharge to the surficial layer of the model using the recharge module in MODFLOW-96. Areal recharge to the surficial layer represents the net difference between precipitation and evapotranspiration losses occurring above the water table. Initial recharge rates were proportioned based on results from stream hydrograph analyses and geology in the surficial layer of the model (table 2). The largest recharge rates were simulated where glaciofluvial sediments were present on the land surface, and the smallest recharge rates were simulated where glacial clays and tills and bedrock were present at the land surface.

Pumping from the five municipal wells in the study area was simulated in the model using the well module in MODFLOW-96 (fig. 4). Water withdrawals from municipal wells for the cities of Taconite, Bovey, and Coleraine were simulated. In the simulation for each well, water was withdrawn from the aquifer at a specified rate during the simulation, where the rate was independent of the cell area and head (McDonald and Harbaugh, 1988). Flow rates for the simulated wells were based on an average of annual pumping rates for 1984-99. Annual pumping rates for the municipal wells were obtained from the MNDNR Water Appropriations Permit data base (Minnesota Department of Natural Resources, 2001c). The two municipal wells for the city of Taconite were simulated as two separate wells pumping 2,190 ft^3/day each

Table 2. Ground-water recharge and hydraulic conductivity values for the best-fit calibration of the MODFLOW steady-state simulations of aquifers surrounding the Canisteo Mine Pit, Bovey, Minnesota

[All values are in feet per day]

Type of simulated cell	Ground-water recharge		Hydraulic conductivity	
	Initial	Final	Inital	Final
Glaciofluvial sediments	1.6×10^{-3}	1.1×10^{-3}	6.6	13.1, 32.8
Glacial tills	1.6×10^{-4}	3.9×10^{-6}	7.0×10^{-2}	7.0×10^{-2}
Bedrock	1.6×10^{-4}	2.3×10^{-4}	7.0×10^{-3}	7.0×10^{-3}
Pit	1.4×10^{-3}	1.4×10^{-3}	3.28×10^{3}	3.28×10^{4}

from bedrock in the lowest two layers in the model. Pumping from the Bovey municipal well was simulated as a single well pumping a total of 13,738 ft^3/day from sand in two layers of the model. The two municipal wells for the city of Coleraine were simulated as a single well in a single model cell, since little is known about what proportion of the city's water is being pumped from each well. A total pumping rate of 26,839 ft^3/day was used for the simulated Coleraine well, pumping water from glaciofluvial sediments in two layers of the model.

The Canisteo Mine Pit was represented in the model as a series of highly conductive, constant-head cells. This approach has been used by researchers in simulations of several other mine pits and has been shown to be valid (Chung and Anderson, 1998). An initial hydraulic conductivity value of 3,280 ft/day was used for the pit constant-head cells (table 2). This initial value was used because this large value allows water levels in the pit cells to be relatively consistent and to respond similar to a lake. During calibration, a constant-head value of 1,300 ft, representing the pit water-level altitude on January 4, 2001, was used for each of the pit cells. A rate of 0.0014 ft/day was used to represent the recharge (amount of precipitation minus evaporation) entering the pit (table 2).

The drain module of MODFLOW-96 was used in two mine pit cells to simulate surface outflow from the pit above the lowest pit-rim altitude (fig. 4). Each simulated drain removed water from the pit cell at a rate based on a specified conductivity value and the difference between the head in the pit cell and a specified-fixed head. A fixed head of 1,324 ft, representing the lowest pit-rim altitude, was applied to the drains. A hydraulic conductivity of 32,800 ft/day was used for both of the drains.

Within the model boundaries, model cells were allowed to wet and rewet, using the following linear equation with a wetting factor of 1.0 and a wetting iteration interval of 1:

$$h = BOT + WETFCT\ (h_n - BOT)$$

where

h is the head at a cell,

BOT is the altitude of the aquifer bottom,

WETFCT is the wetting factor, a factor that is initially established at a cell when it is converted from dry to wet, and

h_n is the head at the neighboring cell that causes the cell to wet (McDonald and others, 1991).

This equation is a simplification of flow through the vadose zone because the model does not simulate the effects of the capillary fringe. The Preconditioned Conjugate Gradient (PCG2) solver module was used with the modified incomplete Cholesky preconditioning option (relaxation parameter = 1.0) to solve the matrix equations produced by the model (Hill, 1990). This module was selected because the preconditioned conjugate-gradient method has been shown to be an efficient iterative method for solving difficult modeling problems (Meijerink and van der Vorst, 1977).

Model Calibration, Sensitivity Analyses, and Simulations

Model calibration involved adjusting initial estimates of aquifer properties and boundary conditions by trial-and-error until simulated steady-state water levels and flows acceptably match measured values. For this study, recharge rates and hydraulic conductivities were the only inputs adjusted during calibration. Storage terms were not included in the simulations. Once the model was calibrated, a sensitivity analysis was performed using the model to determine the effects of changes in hydraulic conductivity and ground-water recharge on simulated water levels and flows and identify important parameters governing water levels and flows in the system. Finally, a series of 14 steady-state simulations were run to determine ground-water inflow and outflow rates from the Canisteo Mine Pit to the surrounding aquifers.

Model calibration was accomplished by visually and statistically matching simulated hydraulic heads to measured water levels measured on January 4, 2001 in 15 monitoring wells surrounding the mine pit and comparing simulated and calculated flow rates to the mine pit. Water levels on January 4, 2001 were chosen because they appeared to be the most stable. Therefore, they were assumed to most accurately represent steady-state conditions. Water levels in the monitoring wells were recorded between July 1999 and May 2001 (fig. 5). Water levels in most of the wells tended to follow seasonal fluc-

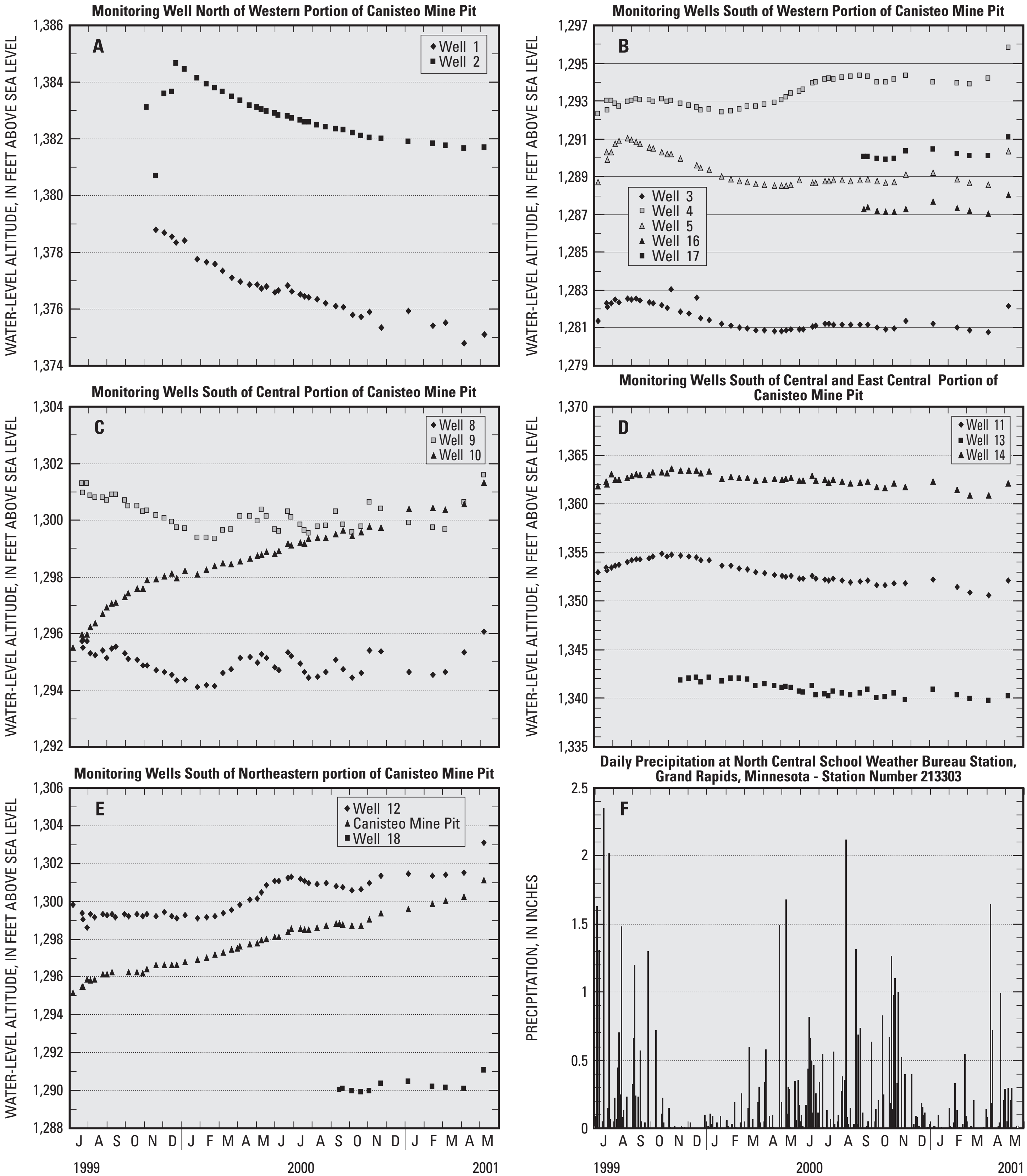

Figure 5. Water-level altitudes in monitoring wells surrounding the Canisteo Mine Pit, Bovey, Minnesota, water-level altitudes in the Canisteo Mine Pit, and daily precipitation at North Central School Weather Bureau Station, Grand Rapids, Minnesota - Station Number 213303, July 1999-May 2001 (Well numbers shown in figure 3).

tuations in response to precipitation and snowmelt, with the level of response varying with well depth (table 3) and aquifer properties. For example, water levels in wells 1 and 2 declined, whereas water levels in well 10 rose during the monitoring period (fig. 5). The water-level rise in well 10 seemed to correlate with the water-level rise in the mine pit, indicating a strong hydraulic connection. In general, water levels in the monitoring wells were stable between December 2000 and February 2001 during the 1999-2001 monitoring period.

Prior to installation of the MNDNR monitoring wells, little other ground-water level data existed in the study area. Only two monitoring wells (6 and 7, fig. 3), were located in the vicinity of the Canisteo Mine Pit prior to the installation of the 15 monitoring wells. These wells were only 20 ft deep (table 3), and little water-level data were available. Water levels for domestic wells recorded during installation were available for water wells in the MGS County Well Index data base. However, the data base did not contain temporal water-level data**.** A piezometric contour map published by Oakes (1970) was used as a reference for generally assessing the simulated water-table contours.

During calibration, the simulated net ground-water flow rate into the Canisteo Mine Pit, at a pit water-level altitude of 1,300 ft, was compared to a net flow rate determined from water-level altitudes measured between July 5, 1999 and February 25, 2001. Water-level altitudes in the mine pit rose from 1,295 ft to 1,300 ft for this period with a net water-volume change of 6,459 acre-ft in the mine over a 600-day period (fig. 2). The net flow rate for this 600-day period was 5.4 ft^3/s. This method of calibration of flow is only an approximate calibration because the match is between transient flow data and steady-state simulated flow data.

Once the model was calibrated, 15 simulations were performed to assess the sensitivity of the model to changes in ground-water recharge rates and hydraulic conductivity. The purpose of these sensitivity analyses is to provide an understanding of the importance of various parameters on simulation results and how data limitations related to these parameters may affect modeling results. Four of the 15 simulations were conducted under various ground-water recharge rates, varying the recharge rates by factors of 0.5, 0.75, 1.25, and 1.5 times the rates of the calibrated model. This range in recharge rates approximates the range in annual ground-water recharge estimates produced using stream-hydrograph methods (table 4). In the other 11 simulations, horizontal hydraulic conductivity values were varied by factors of 0.2, 0.5, 2, 5 and 10 times the values of the calibrated model, and vertical hydraulic conductivity values were varied by factors of 0.1, 0.2, 0.5, 2, 5 and 10 times the values of the calibrated model. Sensitivity analysis runs were compared to the calibrated model by observing changes in water levels in the monitoring wells and total ground-water flow rates into and out of the Canisteo Mine Pit.

Fourteen steady-state simulations were conducted to assess the effect of current and potential future pit water-level altitudes on ground-water inflow to and outflow from the Canisteo Mine Pit. Simulations were run at various constant values for the mine pit water-level altitude. These constant-head values were varied by1 or 2 ft increments from 1,300 to 1,324 ft. Ground-water inflow rates were determined for the entire mine pit through summation of inflows to model pit cells along the simulated pit-aquifer boundary. Outflow rates were determined for the entire mine pit and for three areas along the south pit-aquifer boundary: the Holman Lake area, the Prairie River area, and the Trout Lake area. GMS was used to generate the simulated altitude of potentiometric surface for the MODFLOW simulation at the pit water-level altitude of 1,300 ft.

The USGS MODPATH package was used to compute ground-water flow paths originating from the mine at pit water-level altitudes of 1,300 and 1,320 ft for MODFLOW simulations. MODPATH computes the position of water particles at points in time and total travel time for each particle. Using MODPATH and pit water-level altitudes of 1,300 and 1,320 ft, starting locations for hypothetical water particles were placed along the boundary of the simulated mine pit in each of the model layers. The particles were then tracked forward in time through the flow field until they reached a sink (discharge point). Sinks included lakes, pumped wells, and wetlands.

Model Limitations and Accuracy

The numerical ground-water flow model is a simplification of a complex glaciated terrain and flow system located in a fractured bedrock, mining region. The accuracy of the simulations is limited to the accuracy, amount, and distribution of the data used to describe the hydrologic parameters of the flow system. These parameters include the hydraulic properties of the aquifers and confining units, areal recharge rates, and hydrologic boundary conditions. Parameters determined for the model during calibration are not unique. Due to parameter correlation, different combinations of model input could produce similar results.

The hydraulic conductivity, ground-water level, and flow data used in model calibration were measured in glacial drift in the vicinity of the Canisteo Mine Pit. Therefore, the

Table 3. Monitoring well data and single-well aquifer hydraulic properties measured during 1999-2000 for aquifers surrounding the Canisteo Mine Pit, Bovey, Minnesota

[ft^2/day, square feet per day; ft/day, feet per day; ---, no value]

Monitoring well number (figure 3)	Number of pumping tests	Number of slug tests	Well depth (feet below land surface)	Geology at well screen	Average transmissivity (ft^2/day)		Average hydraulic conductivity (ft/day)		
					Single-well pumping test (Theis,1935)	Single-well pumping test (Cooper-Jacob, 1946)	Single-well pumping test recovery (Bouwer & Rice, 1976)	Slug test, recovery following slug insertion (Bouwer & Rice, 1976)	Slug test, recovery following slug removal (Bouwer & Rice, 1976)
1	6	3	50	Coarse sand and gravel, iron formation	98	107	58	52	51
2	0	0	69	Clay and coarse sand, iron formation	---	---	---	---	---
3	2	1	82	Large boulders, sand, gravel	183	182	40	2.2	12
4	0	3	82	Coarse sand and gravel, iron formation	---	---	---	2.7	1.6
5	0	2	46	Coarse sand, gravel, boulders	---	---	---	[1]0.01	---
6	0	0	20	Sand	---	---	---	---	---
7	0	0	20	Sand	---	---	---	---	---
8	1	1	30	Blue clay	21	22	---	5.0	4.8
9	2	2	35	Gray sand	8.6	8.5	---	2.5	1.6
10	4	1	85	Sandy gravel	236	224	50	62	62
11	0	2	80	Gray sandy clay and rocks	---	---	---	0.06	0.08
12	4	2	50	Coarse sand and gravel	258	252	121	120	121
13	0	1	62	Sandy clay and boulders, slate	---	---	---	0.05	---
14	0	2	77	Fine to medium gray sandy clay, medium gray sand, boulders	---	---	---	0.23	0.23
15	0	0	28	Granite	---	---	---	---	---
16	0	1	70	Gray clay, fine to medium sand	---	---	---	0.23	---
17	1	0	80	Boulders, some iron formation	222	214	21	---	---
18	1	0	70	Coarse sand and gray clay	247	300	68	---	---

[1]Only partial recovery during slug test.

Table 4. Quarterly and annual estimates of ground-water recharge from stream-hydrograph analyses of 1968-82 discharge records for the Prairie River near Taconite, Minnesota gage using the U.S. Geological Survey's Programs RORA and PART (Rutledge, 1998), and annual precipitation data from 1968-82 for the Grand Rapids Forestry Laboratory/North Central School (1961-1990)

[All values are inches, except values in parentheses which are recharge as a percent of annual precipitation; normal, 27.54 inches]

Year	Ground-water recharge estimates (using the best-fit equation obtained from winter records for estimating baseflow recession rates)					Ground-water recharge estimates (using the best-fit equation obtained from the entire records for estimating baseflow recession rates)					Annual precipitation - Grand Rapids
	January-March	April-June	July - September	October - December	Annual	January-March	April-June	July - September	October - December	Annual	
1968	0.23	6.12	0.62	0.94	7.91 (27)	0.18	4.36	1.65	1.57	7.76 (26)	29.62
1969	0.85	5.78	0.29	1.56	8.48 (32)	0.76	6.78	0.74	1.39	9.67 (36)	26.81
1970	0.55	5.72	-1.43	1.42	6.26 (25)	0.57	4.94	0.04	0.86	6.41 (26)	24.87
1971	0.64	5.61	-1.00	3.39	8.64 (28)	0.50	5.95	0.09	2.36	8.90 (29)	31.12
1972	-0.35	4.19	2.05	0.44	6.33 (25)	0.39	4.11	1.96	0.60	7.06 (28)	24.87
1973	1.79	1.80	0.95	2.19	6.73 (24)	1.10	2.37	0.91	2.99	7.37 (26)	28.33
1974	0.36	7.83	-0.97	1.10	8.32 (30)	0.20	8.35	0.33	0.86	9.74 (35)	27.63
1975	1.15	5.32	0.89	0.84	8.20 (28)	0.89	5.04	2.82	0.68	9.43 (33)	29.00
1976	0.37	1.77	0.26	0.12	2.52 (14)	0.24	2.14	0.58	0.11	3.07 (17)	17.98
1977	0.49	0.74	3.06	2.22	6.51 (17)	0.32	0.67	1.99	3.27	6.25 (16)	38.00
1978	0.08	5.32	2.07	0.03	7.50 (25)	0.17	4.78	2.95	0.22	8.12 (27)	30.46
1979	0.98	7.36	-0.26	1.44	9.52 (39)	0.84	6.02	2.09	0.79	9.74 (40)	24.57
1980	0.40	1.27	1.78	0.43	3.88 (18)	0.33	1.40	1.43	0.74	3.90 (18)	21.62
1981	0.32	3.42	0.56	1.48	5.78 (20)	0.23	2.90	1.32	1.61	6.06 (21)	29.42
1982	0.65	5.54	0.61	2.69	9.49 (28)	0.64	6.25	1.11	2.37	10.37 (31)	33.94
15-year average	0.57	4.52	0.63	1.35	7.07 (25)	0.49	4.40	1.33	1.36	7.58 (27)	27.88

accuracy of the simulations could decrease farther away from the simulated mine pit. The accuracy of the model in the bedrock aquifers is unknown because water-level data were not available for the bedrock formations.

The calibrated, steady-state model is believed to be a reasonable tool for water-resources management based on the premise that future hydrologic conditions will be similar to historical conditions. Furthermore, it is assumed that variations in annual recharge and discharge for the simulations of steady-state conditions will be similar to those simulated in the calibrated model. The accuracy of the simulations of steady-state conditions becomes more uncertain if the variation in annual recharge or discharge exceeds the range used in the calibrated model. Because the model was calibrated under the assumption of steady-state flow conditions, the model will most accurately reflect the effects of annual or multiple-year stresses, and not short-term transient stresses, on the flow system.

SINGLE-WELL HYDRAULIC TEST

Average transmissivity and hydraulic conductivity values obtained from the single-well hydraulic tests are listed in table 3. Average transmissivity values ranged from 8.5 to 300 ft^2/day, with little variations seen between values obtained from Theis and Cooper-Jacob analyses for all of the wells, with the exception of well 18. The lowest values were obtained from tests conducted in wells completed in sand or clay, while the higher values were obtained from tests conducted in wells completed in coarse sands, gravels, and boulders (table 3). Average hydraulic conductivity values ranged from 0.01 to 121 ft/day. Hydraulic conductivity values for wells completed in sands and clays ranged from 0.05 to 5.0 ft/day. The lower values of this range were the best available values for representing the hydraulic conductivity of glacial tills in the area, and therefore, an initial hydraulic conductivity value of 0.07 ft/day was used in the model (table 2). Hydraulic conductivity values for coarse sands, gravels, and boulders ranged from 0.01 to 121 ft/day. The lowest values, ranging from 0.01 to 2.7 ft/day, were obtained from wells with a completion interval of less than 1 ft, and therefore, may not accurately represent the actual hydraulic conductivity of the geology around the well. An average value of 6.6 ft/day obtained from initial single-well tests conducted in wells completed in coarse sands and gravels was used as an initial value for simulated glaciofluvial sediments (table 2). Hydraulic conductivity values obtained from analyses of pumping test recovery, slug insertion, and slug removal tests conducted in four individual wells (wells 1, 3, 10, and 12) varied little, with the exception of well 3 (table 3).

STREAM-HYDROGRAPH ANALYSES

Quarterly and annual estimates of ground-water recharge based on stream-hydrograph analyses of the Prairie River and annual precipitation values for the Grand Rapids Forestry Laboratory/North Central School are listed in table 4. Quarterly estimates of recharge for the 1968-82 record ranged from –1.43 to 7.83 in. using the best-fit equation obtained from winter streamflow records, and ranged from 0.04 to 8.35 in. using the best-fit equation obtained from the annual streamflow records (table 4). During most years, the greater values tended to occur in the spring (April-June) and the lower values occurred in the winter (January-March).

Annual estimates of recharge during 1968-82 ranged from 2.52 to 9.52 in. using the best-fit equation obtained from the winter streamflow records, and ranged from 3.07 to 10.37 in. using the best-fit equation obtained from the annual streamflow records (table 4). Annual estimates between 1962-82 using either solely the winter record or the entire record for base-flow recession analysis accounted for between 14 to 40 percent of annual precipitation. The 15-year average for the annual recharge estimate was 7.07 in. using the winter streamflow records and 7.58 in. using annual streamflow records, accounting for 25 and 27 percent, respectively, of the average annual precipitation for 1968-82 (table 4).

A value of 7 in./yr (1.6×10^{-3} ft/day), similar to the 15-year average for the annual recharge values using winter streamflow records, was used in the model to represent ground-water recharge to surficial glaciofluvial sediments. An initial value of 0.7 in./yr (1.6×10^{-4} ft/day) was used in the model to represent ground-water recharge rates to surficial glacial tills and bedrock. Delin (1988) computed average recharge rates of 0.61 and 10.7 in./yr through glacial tills and surficial sands, respectively, in the Brooten-Belgrade area, west-central Minnesota.

CALIBRATION OF THE MODFLOW-96 GROUND-WATER FLOW MODEL

The final calibration values for the hydraulic conductivity and ground-water recharge rates are listed in table 2. The match between simulated and measured water levels was improved by (1) increasing the hydraulic conductivity for the glaciofluvial sediments from 6.6 to 32.8 ft/day southwest of the mine pit, (2) increasing the hydraulic conductivity for the glaciofluvial sediments from 6.6 to

13.1 ft/day in the rest of the model, (3) decreasing ground-water recharge rates for glaciofluvial sediments from 1.6 x 10^{-3} to 1.1x 10^{-3} ft/day and for glacial tills from 1.6 x 10^{-4} to 3.9 x 10^{-6} ft/day, and (4) increasing ground-water recharge rates for bedrock from 1.6 x $10^{-4}$to 2.3 x 10^{-4} ft/day. The above changes are considered to be acceptable because they are all within ranges of values calculated or measured in the field for this study or reported in previous studies.

Simulated an measured water levels for 15 of the 18 monitoring wells and the simulated minus measured water-level difference for the 15 wells are presented in table 5. The difference between simulated and measured water levels varied between +28.65 and –3.78 ft (table 5). The best-match simulated water levels were within 2 ft of measured water levels for 4 of the 15 wells, and within 4 ft for 9 of the wells. These 9 wells were located north of the Canisteo Mine Pit and south of the mine pit in the Trout Lake and Holman Lake areas (figure 3 and table 5). The mean absolute difference between simulated and measured water levels, computed as the sum of the absolute values of the differences divided by the number of wells, for the 15 wells is +7.25 ft. The mean algebraic difference between simulated and measured water levels, computed as the algebraic sum of the differences divided by the number of wells, for the 15 wells is +4.25 ft, indicating the positive differences were not balanced by the negative differences. Positive water-level differences greater than 6.6 ft were found in five monitoring wells located southwest of the mine pit and northwest of Trout Lake, and for one well (18) located near Holman Lake (figure 3 and table 5). The root mean squared error, or the average of the squared differences in simulated and measured heads, was +10.28 ft.

A plot of measured versus best-fit simulated water levels for the monitoring wells is shown in figure 6. Most of the measured values lie close to the 1:1 linear relation, except for water levels for the six monitoring wells with a positive water-level difference greater than 6.6 ft. Topographically, these six monitoring wells are located at relatively low altitudes near the mine pit. Water-level altitudes for five of the six wells are less than 1,300 ft (figure 6).

The positive water-level differences found in five monitoring wells located southwest of the mine pit may, in part, be explained by the presence of unidentified zones of greater hydraulic conductivity in the glaciofluvial sediments or vertical leakage to bedrock aquifers. The lack of monitoring wells completed in bedrock in the vicinity of the Canisteo Mine Pit makes it impossible to determine directly if vertical leakage is occurring to bedrock aquifers.

The simulated net ground-water flow into the Canisteo Mine Pit was +1.34 ft^3/s, and the net ground-water flow calculated from pit water-level altitudes measured between July 5, 1999 and February 25, 2001 was +5.4 ft^3/s. Several reasons can be given for explaining why the calculated value is higher than the simulated value. Greater than normal precipitation in

Table 5. Measured and simulated water-level altitudes in monitoring wells for the best-fit calibrations of the MODFLOW steady-state simulations surrounding the Canisteo Mine Pit, Bovey, Minnesota

[ft, feet; ---, no value]

Monitoring well number	Water-level altitudes in monitoring wells (ft)		Simulated - measured (ft)
	Simulated	Measured on 1/4/01	
1	1,372.77	1,375.94	-3.17
2	1,378.12	1,381.90	-3.78
3	1,309.88	1,281.23	+28.65
4	1,300.69	1,294.00	+6.69
5	1,301.02	1,289.21	+11.81
8	1,293.08	1,294.65	-1.57
9	1,298.46	1,299.89	-1.43
10	1,299.15	1,300.41	-1.26
11	1,348.72	1,352.19	-3.47
12	1,302.03	1,301.45	+0.58
13	1,343.93	1,340.93	+3.00
14	1,359.22	1,362.32	-3.10
16	1,304.00	1,287.66	+16.34
17	1,297.18	1,290.46	+6.72
18	1,325.92	1,316.22	+9.70
Mean absolute difference	---	---	+7.25
Mean algebraic difference	---	---	+4.25
Root mean squared error	---	---	+10.28

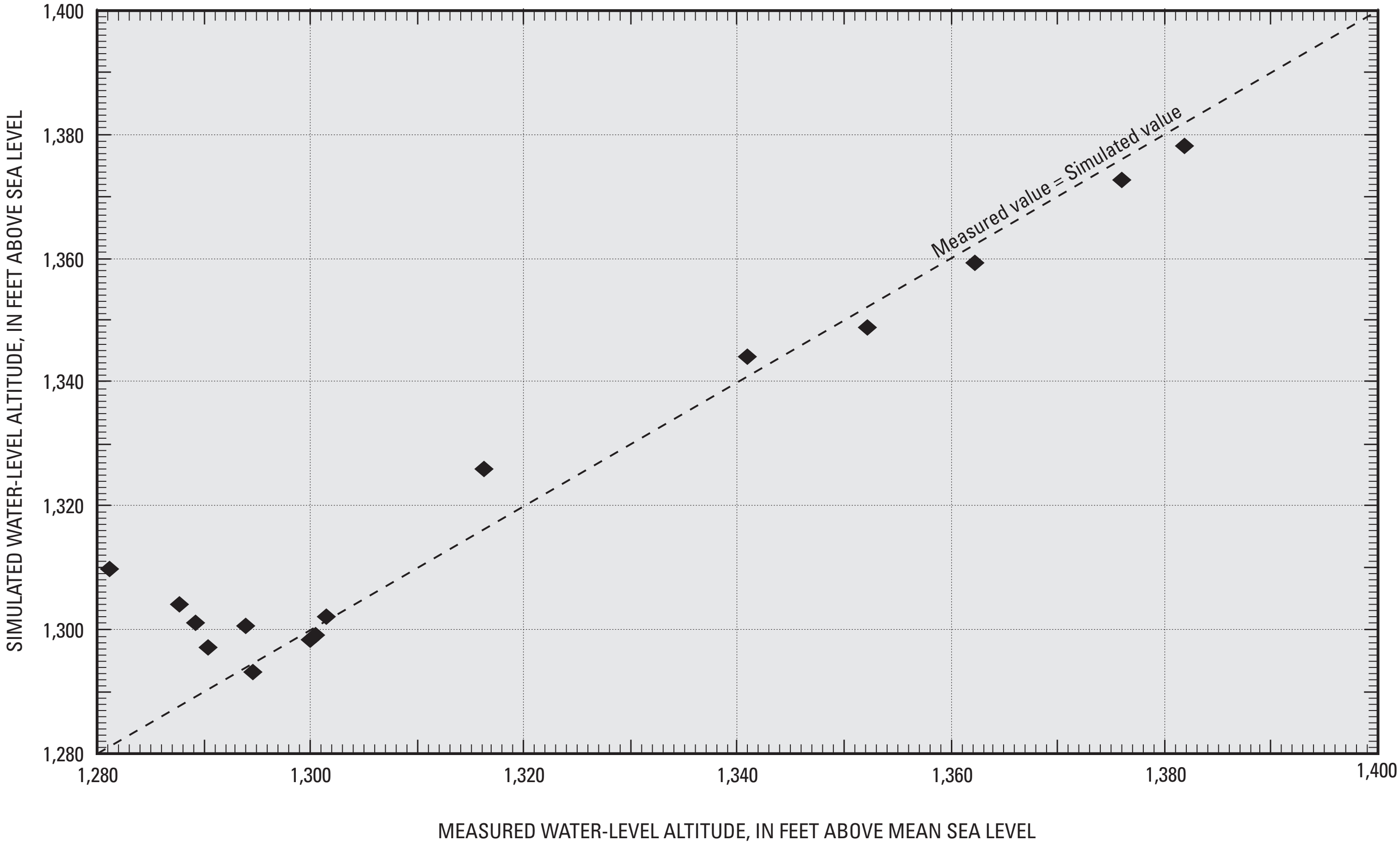

Figure 6. Measured versus simulated water-level altitude in monitoring wells at a constant pit water-level altitude of 1,300 feet above sea level (see table 5).

the modeling area during the three years prior to January 4, 2001 could have resulted in a temporal increase in flow rates to the mine pit. Annual precipitation at Grand Rapids, Minnesota for 1998, 1999, and 2000 was greater than the normal mean-annual precipitation by 1.16, 7.26, and 1.76 in., respectively. The use of temporal data to determine the calculated value may also explain the greater value. The calculated value was an average of transient, rising water levels, and the simulated value was obtained from the steady-state model. Head gradients around the mine pit during rising pit water-level conditions were greater than gradients during the simulated steady-state condition. Since flow rates to the mine are directly related to the surrounding head gradients, transient flow rates would be greater. In all of the model simulations, no flow occurred out of either of the drains.

MODEL SENSITIVITY TO GROUND-WATER RECHARGE AND HYDRAULIC CONDUCTIVITY

Simulated water levels and ground-water flow to and from the Canisteo Mine Pit were most sensitive to changes in horizontal hydraulic conductivity, suggesting that this characteristic is the predominant parameter controlling steady-state water-level and flow conditions. Table 6 lists simulated water levels in 15 monitoring wells and total ground-water flow into and out of the Canisteo Mine Pit for simulations at various multiples of the calibrated horizontal hydraulic conductivity. Maximum water-level differences from the calibrated model varied between –21.13 and +59.91 ft for the monitoring wells under various multiples (table 6). Simulated ground-water inflow to the mine pit varied from 0.47 to 6.79 ft^3/s and simulated ground-water outflow from the mine pit varied from 0.01 to 0.63 ft^3/s under various multiples of the calibrated horizontal hydraulic conductivity values (table 6).

Water levels and ground-water flow rates were less sensitive under various multiples of the calibrated vertical hydraulic conductivity values compared to the horizontal hydraulic conductivity values. Maximum water-level differences from the calibrated model for each well varied between –17.29 and +21.69 ft for the

Table 6. Simulated water-level altitudes in monitoring wells and simulated ground-water flow rates into and out of the Canisteo Mine Pit, Bovey, Minnesota for MODFLOW steady-state simulations at various mulitples of the calibrated horizontal hydraulic conductivity values

[values in parentheses are water-level or flow differences from calibrated model values; ft, feet above sea level; ft^3/s, cubic feet per second]

Monitoring wells	Water-level altitudes in monitoring wells (ft)					
	Calibrated model	0.2 times the calibrated horizontal hydraulic conductivity values	0.5 times the calibrated horizontal hydraulic conductivity values	2 times the calibrated horizontal hydraulic conductivity values	5 times the calibrated horizontal hydraulic conductivity values	10 times the calibrated horizontal hydraulic conductivity values
1	1,372.77	1,432.68 (59.91)	1,409.71 (36.94)	1,359.12 (-13.65)	1,359.12 (-13.65)	1,359.12 (-13.65)
2	1,378.12	1,378.12 (0.00)	1,378.12 (0.00)	1,378.12 (0.00)	1,378.12 (0.00)	1,378.12 (0.00)
3	1,309.88	1,310.93 (1.05)	1,310.20 (0.32)	1,309.51 (-0.37)	1,308.43 (1.45)	1,306.92 (2.96)
4	1,300.69	1,300.85 (0.16)	1,300.72 (0.03)	1,300.59 (-0.10)	1,300.49 (-0.20)	1,300.39 (-0.30)
5	1,301.02	1,301.80 (0.78)	1,301.35 (0.33)	1,300.72 (0.30)	1,300.33 (-0.69)	1,300.07 (-0.95)
8	1,293.08	1,289.34 (-3.74)	1,288.58 (4.50)	1,295.05 (1.97)	1,296.13 (3.05)	1,296.62 (3.54)
9	1,298.46	1,306.56 (8.10)	1,296.26 (-2.20)	1,299.11 (0.65)	1,299.28 (0.82)	1,299.31 (0.85)
10	1,299.15	1,307.78 (8.63)	1,300.10 (0.95)	1,298.00 (-1.15)	1,297.05 (-2.10)	1,296.69 (-2.46)
11	1,348.72	1,373.26 (24.54)	1,356.14 (7.42)	1,341.04 (-7.68)	1,331.82 (-16.90)	1,327.59 (-21.13)
12	1,302.03	1,302.13 (0.10)	1,302.07 (0.04)	1,302.07 (- 0.04)	1,302.03 (0.00)	1,301.97 (-0.06)
13	1,343.93	1,339.86 (-4.07)	1,344.26 (0.33)	1,342.75 (-1.18)	1,337.57 (-6.36)	1,333.66 (-10.27)
14	1,359.22	1,343.14 (-16.08)	1,356.99 (-2.23)	1,355.97 (-3.25)	1,359.35 (0.13)	1,346.75 (-12.47)
16	1,304.00	1,305.12 (1.12)	1,304.46 (0.46)	1,303.51 (-0.49)	1,304.17 (0.17)	1,302.00 (-2.00)
17	1,297.18	1,297.21 (0.03)	1,297.11 (-0.07)	1,297.4 (0.06)	1,297.21 (0.03)	1,297.57 (0.39)
18	1,325.92	1,320.70 (-5.22)	1,323.95 (-1.97)	1,327.66 (1.74)	1,326.02 (0.10)	1,327.36 (1.44)

Type of flow	Total ground-water flow - Canisteo Mine Pit (ft^3/s)					
	Calibrated model	0.2 times the calibrated horizontal hydraulic conductivity values	0.5 times the calibrated horizontal hydraulic conductivity values	2 times the calibrated horizontal hydraulic conductivity values	5 times the calibrated horizontal hydraulic conductivity values	10 times the calibrated horizontal hydraulic conductivity values
Inflow	1.40	0.47	0.86	2.26	4.36	6.79
Outflow	0.06	0.01	0.03	0.13	0.33	0.63
Net	1.34	0.46	0.83	2.13	4.03	6.16

monitoring wells (table 7). Simulated ground-water inflow to the mine pit varied from 1.10 to 1.52 ft^3/s and simulated ground-water outflow from the mine pit varied from 0.04 to 0.11 ft^3/s under various multiples of the calibrated vertical hydraulic conductivity values (table 7).

Water levels and ground-water flow rates were the least sensitive under various multiples of the calibrated ground-water recharge rates compared to the hydraulic conductivity values. Maximum water-level differences from the calibrated model for each well varied between –10.93 and +9.28 ft for the monitoring wells (table 8). Simulated ground-water inflow to the mine pit varied from 1.31 to 1.47 ft^3/s and simulated ground-water outflow from the mine pit varied from 0.06 to 0.07 ft^3/s under various multiples of the calibrated ground-water recharge rates (table 8).

SIMULATIONS CHARACTERIZING CURRENT AND POTENTIAL FUTURE GROUND-WATER FLOW CONDITIONS NEAR THE MINE PIT

Simulated ground-water flow conditions obtained from the calibrated model for January 4, 2001 (constant pit water-level altitude of 1,300 ft) indicate that estimated total ground-water inflow to the Canisteo Mine Pit was 1.40 ft^3/s, with only 0.06 ft^3/s discharging to local aquifers (table 6). The potentiometric surface of the simulated ground-water flow indicates that ground water was flowing into the mine pit along most of the pit boundary, with ground-water outflow occurring from the pit to the Trout Lake area (fig. 7, and table 9). Most ground-water inflow originates less than one mile from the pit boundary. Ground-water inflow occurs along the north side of the pit and near Taconite, and from the south north of U.S. Highway 169 (fig. 7). Steep hydraulic gradients in the potentiometric surface that exist near the north and southeast pit boundaries are in part due to the presence of poorly conductive glacial

Table 7. Simulated water-level altitudes in monitoring wells and simulated ground-water flow rates into and out of the Canisteo Mine Pit, Bovey, Minnesota for MODFLOW steady-state simulations at various mulitples of the calibrated vertical hydraulic conductivity values

[values in parentheses are water-level or flow differences from calibrated model value; ft, feet above sea level; ft^3/s, cubic feet per second]

Monitoring well numbers	Water-level altitudes in monitoring wells (ft)						
	Calibrated model	0.1 times the calibrated vertical hydraulic conductivity values	0.2 times the calibrated vertical hydraulic conductivity values	0.5 times the calibrated vertical hydraulic conductivity values	2 times the calibrated vertical hydraulic conductivity values	5 times the calibrated vertical hydraulic conductivity values	10 times the calibrated vertical hydraulic conductivity values
1	1,372.77	1,359.12 (-13.65)	1,359.12 (-13.65)	1,365.12 (-7.65)	1,394.42 (21.65)	1,394.46 (21.69)	1,384.84 (12.07)
2	1,378.12	1,378.12 (0.00)	1,378.12 (0.00)	1,378.12 (0.00)	1,378.12 (0.00)	1,378.12 (0.00)	1,378.12 (0.00)
3	1,309.88	1,310.07 (0.19)	1,310.01 (0.13)	1,309.91 (0.03)	1,309.84 (-0.04)	1,309.84 (-0.04)	1,309.84 (-0.04)
4	1,300.69	1,300.92 (0.23)	1,300.85 (0.16)	1,300.69 (0.00)	1,300.66 (-0.03)	1,300.66 (-0.03)	1,300.66 (-0.03)
5	1,301.02	1,300.95 (-0.07)	1,301.12 (0.10)	1,300.95 (0.07)	1,301.08 (0.06)	1,301.08 (0.06)	1,301.08 (0.06)
8	1,293.08	1,291.34 (-1.74)	1,292.91 (-0.17)	1,291.96 (-1.12)	1,293.90 (0.82)	1,294.69 (1.61)	1,294.13 (1.05)
9	1,298.46	1,295.51 (-2.95)	1,296.92 (-1.54)	1,297.44 (-1.02)	1,299.34 (0.88)	1,300.26 (1.80)	1,299.54 (1.08)
10	1,299.15	1,297.44 (-1.71)	1,297.87 (-1.28)	1,298.39 (-0.76)	1,299.90 (0.75)	1,300.85 (1.70)	1,299.90 (0.75)
11	1,348.72	1,338.91 (-9.81)	1,342.06 (-6.66)	1,346.29 (-2.43)	1,350.82 (2.10)	1,353.18 (4.46)	1,351.90 (3.18)
12	1,302.03	1,302.07 (0.04)	1,302.03 (0.00)	1,302.03 (0.00)	1,302.07 (0.04)	1,302.07 (0.04)	1,302.07 (0.04)
13	1,343.93	1,326.64 (-17.29)	1,327.33 (-16.60)	1,342.68 (-1.25)	1,345.05 (1.12)	1,345.51 (1.58)	1,345.80 (1.87)
14	1,359.22	1,350.82 (-8.40)	1,355.68 (-3.54)	1,356.76 (-2.46)	1,359.02 (-0.20)	1,363.75 (4.53)	1,363.45 (4.23)
16	1,304.00	1,304.13 (0.13)	1,304.53 (0.53)	1,303.94 (0.06)	1,304.00 (0.00)	1,304.00 (0.00)	1,304.00 (0.00)
17	1,297.18	1,297.41 (0.23)	1,297.47 (0.29)	1,297.08 (-0.10)	1,297.24 (0.06)	1,297.28 (0.10)	1,297.28 (0.10)
18	1,325.92	1,328.71 (2.79)	1,327.95 (2.03)	1,326.71 (0.79)	1,325.16 (-0.76)	1,324.44 (-1.48)	1,324.15 (-1.77)

Type of flow	Total ground-water flow - Canisteo Mine Pit (ft^3/s)						
	Calibrated model	0.1 times the calibrated vertical hydraulic conductivity values	0.2 times the calibrated vertical hydraulic conductivity values	0.5 times the calibrated vertical hydraulic conductivity values	2 times the calibrated vertical hydraulic conductivity values	5 times the calibrated vertical hydraulic conductivity values	10 times the calibrated vertical hydraulic conductivity values
Inflow	1.40	1.10	1.21	1.35	1.45	1.50	1.52
Outflow	0.06	0.11	0.06	0.07	0.05	0.04	0.04
Net	1.34	0.99	1.15	1.28	1.40	1.46	1.48

Table 8. Simulated water-level altitudes in monitoring wells and simulated ground-water flow rates into and out of the Canisteo Mine Pit, Bovey, Minnesota for MODFLOW steady-state simulations at various mulitples of the calibrated ground-water recharge rates

[values in parentheses are water-level or flow differences from calibrated model value; ft, feet above sea level; ft^3/s, cubic fee per second]

Monitoring well numbers	Water-level altitudes in monitoring wells (ft)				
	Calibrated model	0.5 times the calibrated ground-water recharge rates	0.75 times the calibrated ground-water recharge rates	1.25 times the calibrated ground-water recharge rates	1.5 times the calibrated ground-water recharge rates
1	1,372.77	1,361.84 (-10.93)	1,365.22 (-7.55)	1,371.98 (-0.79)	1,382.05 (9.28)
2	1,378.12	1,378.12 (0.00)	1,378.12 (0.00)	1,378.12 (0.00)	1,378.12 (0.00)
3	1,309.88	1,309.38 (-0.50)	1,309.65 (-0.23)	1,310.14 (0.26)	1,310.37 (0.49)
4	1,300.69	1,300.62 (-0.07)	1,300.66 (-0.03)	1,300.69 (0.00)	1,300.69 (0.00)
5	1,301.02	1,300.92 (-0.10)	1,300.98 (-0.04)	1,301.08 (0.06)	1,301.12 (0.10)
8	1,293.08	1,292.72 (-0.36)	1,292.88 (-0.20)	1,293.24 (0.16)	1,293.43 (0.35)
9	1,298.46	1,298.03 (-0.43)	1,298.26 (-0.20)	1,298.69 (0.23)	1,298.88 (0.42)
10	1,299.15	1,298.62 (-0.53)	1,298.88 (-0.27)	1,299.41 (0.26)	1,299.67 (0.52)
11	1,348.72	1,345.90 (-2.82)	1,347.31 (-1.41)	1,350.10 (1.38)	1,351.41 (2.69)
12	1,302.03	1,302.03 (0.00)	1,302.03 (0.00)	1,302.07 (0.04)	1,302.07 (0.04)
13	1,343.93	1,343.96 (0.03)	1,344.09 (0.16)	1,344.13 (0.20)	1,344.13 (0.20)
14	1,359.22	1,359.02 (-0.20)	1,359.19 (-0.03)	1,359.28 (0.06)	1,359.35 (0.13)
16	1,304.00	1,303.84 (-0.16)	1,303.94 (-0.06)	1,304.07 (0.07)	1,304.17 (0.17)
17	1,297.18	1,297.11 (-0.07)	1,297.15 (-0.03)	1,297.21 (0.03)	1,297.21 (0.03)
18	1,325.92	1,325.79 (-0.13)	1,325.85 (-0.07)	1,325.98 (0.06)	1,326.02 (0.10)

Type of flow	Total ground-water flow - Canisteo Mine Pit (ft^3/s)				
	Calibrated model	0.5 times the calibrated ground-water recharge rates	0.75 times the calibrated ground-water recharge rates	1.25 times the calibrated ground-water recharge rates	1.5 times the calibrated ground-water recharge rates
Inflow	1.40	1.31	1.36	1.43	1.47
Outflow	0.06	0.07	0.06	0.06	0.06
Net	1.34	1.24	1.30	1.37	1.41

tills and mine tailings surrounding the mine pit (fig. 7). MODPATH simulations of water flowing from the pit to local aquifers at the constant pit water-level altitude of 1,300 ft indicate that water from the pit was flowing to Trout Lake or the municipal wells of Bovey or Coleraine on January 4, 2001 (figure 8a).

A water budget is an accounting of inflow to, outflow from, and storage change in the simulated aquifer. For the steady-state model, inflow (sources of water) to the aquifer equals outflow (discharges) from the aquifer. General head-dependent boundaries at simulated wetlands and lakes accounted for 80.1 percent and areal recharge to the aquifers contributed 18.3 percent of the sources of water to aquifers in the calibrated model for January 4, 2001 (constant pit water-level altitude of 1,300 ft) (table 10). The remaining 1.6 percent comes from rivers and the Canisteo Mine Pit. Discharge from general head-dependent boundaries accounted for 90.6 percent of the total discharge from the aquifer (table 10). Discharge from rivers, the Canisteo Mine Pit, and municipal wells accounted for 9.4 percent of the total discharge.

Model simulations indicate that as water levels continue to rise in the Canisteo Mine Pit, total ground-water inflow rates will decrease and total ground-water outflow rates will increase until a steady-state balance is reached, or surface outflow occurs. Simulations of steady-state conditions at various constant pit water levels indicate that total ground-water inflow will decrease from 1.40 to 1.00 ft^3/s and total ground-water outflow will increase from 0.06 to 0.91 ft^3/s as the pit water-level altitude rises from 1,300 to 1,324 ft (table 9). Over the same pit water level rise, the net ground-water inflow will decrease from 1.34 to 0.09 ft^3/s. At the highest pit water-level altitude (1,324 ft), model results indicate a net ground-water inflow rate of 0.09 ft^3/s, which will likely result in discharge to land surface at the location of the lowest pit-rim altitude.

Total ground-water inflow and total net ground-water flow decreases nearly linear with increasing pit water-level altitudes (figs. 9a and 9b), while the total ground-water flow out of the mine pit (total ground-water outflow) increase occurs nearly curvilinear as a power function (figure 9c). A Mann-Kendall test (Helsel and Hirsch, 1992) on the total ground-water

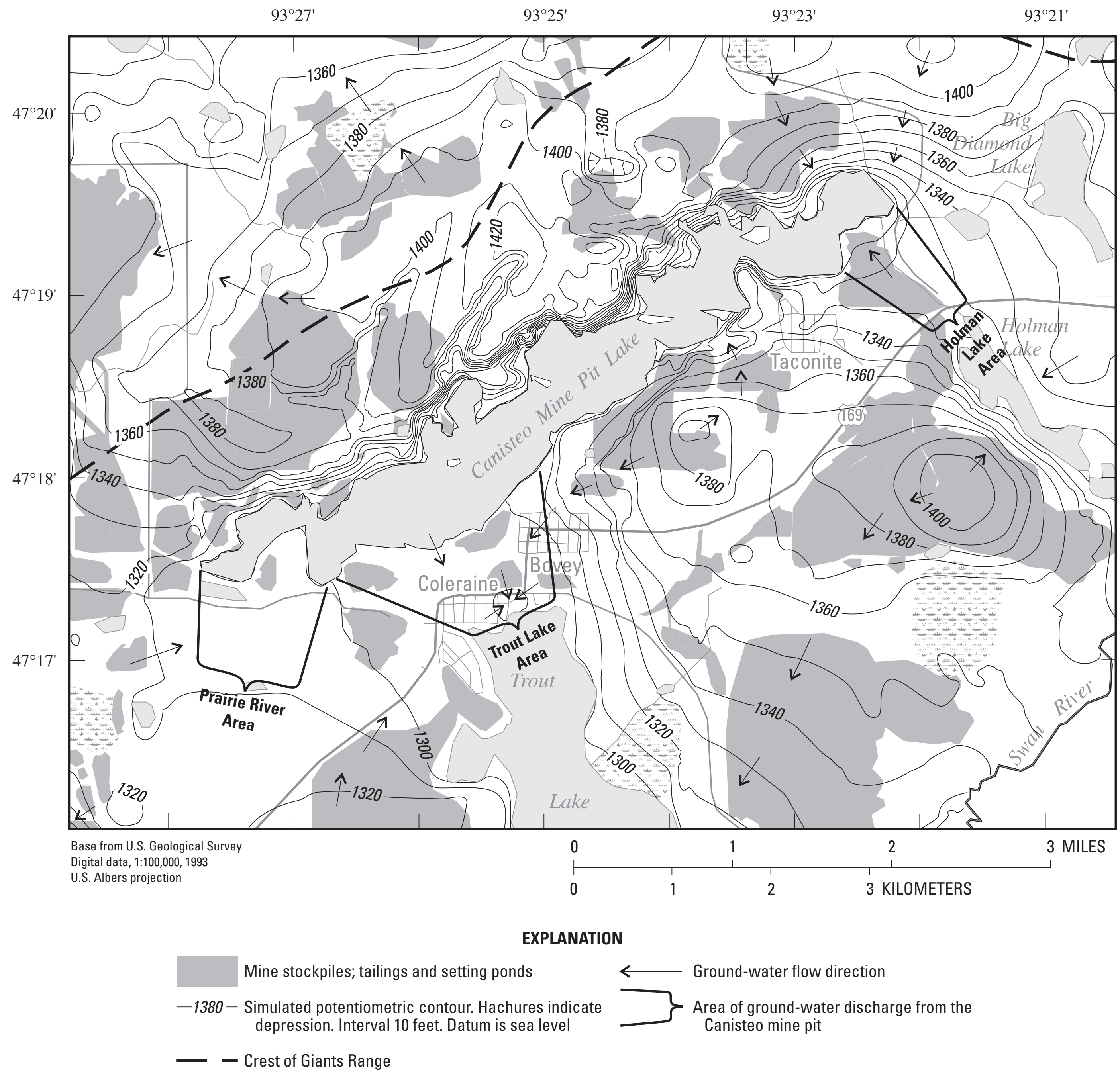

Figure 7. Simulated steady-state altitude of potentiometric surface of ground-water flow and ground-water flow direction in the vicinity of the Canisteo Mine Pit, Bovey, Minnesota (Constant pit water-level altitude of 1,300 feet above sea level).

inflow at the various constant pit water levels (fig. 9a) has a median slope of -0.02. This slope represents the rate of ground-water inflow decrease per foot of change in pit water-level rise. A Mann-Kendall test (Helsel and Hirsch, 1992) on the total net ground-water flow at the various constant pit water-level altitudes (fig. 9b) has a median slope of -0.05. This slope represents the rate of net ground-water flow decrease per foot of change in pit water-level rise.

Model results also indicate that the location of ground-water flow from the mine pit (ground-water outflow) will vary as the pit water level rises. At the constant pit water-level altitude of 1,300 ft, all ground-water outflow occurred in the Trout Lake area. At pit water-level altitudes between 1,302 and 1,306 ft, all but a small rate (less than 0.01 ft^3/s) of the total ground-water outflow occurred in the Trout

Table 9. Simulated ground-water flow rates into and out of the Canisteo Mine Pit, Bovey, Minnesota for MODFLOW steady-state simulations at various constant pit water levels

[ft^3/s, cubic feet per second; values in parentheses are percent of total pit ground-water outflow]

Constant pit water levels (ft)	Total ground-water inflow (ft^3/s)	Ground-water outflow (ft^3/s)				Net ground-water flow (total inflow - total outflow) (ft^3/s)
		Total	Prairie River area	Trout Lake area	Holman Lake area	
1300	1.40	0.06	0 (0)	0.06 (100)	0 (0)	1.34
1302	1.38	0.10	0 (0)	0.10 (99)	< 0.01 (1)	1.28
1304	1.32	0.13	0 (0)	0.13 (99)	< 0.01 (1)	1.19
1305	1.30	0.15	0 (0)	0.15 (99)	< 0.01 (1)	1.15
1306	1.26	0.17	0 (0)	0.17 (99)	< 0.01 (1)	1.09
1308	1.24	0.22	0.01 (4)	0.21 (94)	< 0.01 (2)	1.02
1310	1.21	0.29	0.03 (11)	0.25 (86)	0.01 (3)	0.92
1312	1.16	0.36	0.06 (17)	0.29 (80)	0.01 (3)	0.80
1314	1.12	0.44	0.09 (21)	0.34 (77)	0.01 (2)	0.68
1315	1.12	0.47	0.11 (23)	0.35 (75)	0.01 (2)	0.65
1316	1.09	0.52	0.13 (25)	0.38 (73)	0.01 (2)	0.57
1318	1.04	0.60	0.18 (30)	0.41 (68)	0.01 (2)	0.44
1320	1.04	0.70	0.22 (31)	0.46 (65)	0.03 (4)	0.34
1322	1.03	0.80	0.26 (33)	0.50 (62)	0.04 (5)	0.23
1324	1.00	0.91	0.31 (34)	0.54 (59)	0.06 (7)	0.09

Lake area. This small amount of ground-water outflow occurs in the Holman Lake area (fig. 7, table 9). At pit water-level altitudes between 1,308 and 1,324 ft, model results indicate that ground-water outflow will occur in three locations: the Trout Lake, Prairie River, and Holman Lake areas (fig. 7). Model-computed ground-water outflow in the Prairie River area increases from 0.01 to 0.31 ft^3/s between pit water-level altitudes of 1,308 and 1,324 ft, accounting for 4 and 34 percent of the total ground-water outflow, respectively (table 9). This water will eventually discharge to wetlands southwest of the mine pit in the direction of the Prairie River (figure 8b). Between pit water-level altitudes of 1,308 and 1,324 ft, simulated ground-water outflow in the Trout Lake area increases from 0.21 to 0.54 ft^3/s, accounting for 94 and 59 percent of the total simulated ground-water outflow, respectively. Similar to simulated ground-water outflow at the pit water-level altitude of 1,300 ft, this simulated ground-water outflow in the Trout Lake area will either eventually end up in Trout Lake or the municipal wells of Bovey or Coleraine (fig. 8b). Simulated ground-water outflows are much lower in the Holman Lake area, increasing from 0.01 to 0.06 ft^3/s between pit water-level altitudes of 1,308 and 1,324 ft, respectively (fig. 9d, table 9). This simulated ground-water outflow remains within 0.1 mi of the pit wall under steady-state conditions (figure 8b).

Simulated ground-water outflow in the Trout Lake and Prairie River areas increases nearly linear with increasing pit water levels (figs. 9e and 9f), while the simulated ground-water outflow in the Holman Lake area increases nearly curvilinear as a power function for outflow values below 0.01 ft^3/s (figure 9d). Mann-Kendall tests (Helsel and Hirsch, 1992) on the simulated ground-water outflow in the Trout Lake area (fig. 9e) and in the Prairie River area (fig. 9f) at the various constant pit water levels have median slopes of 0.02. The slopes in these relations represent the rate of simulated ground-water outflow increase in the Trout Lake and Prairie River area, per foot of change in pit water-level rise.

Water budgets for the model simulations at various pit water levels are listed in table 10. Total inflow to (sources) and outflow (discharges) from the modeled area tend to gradually increase with increasing constant pit water levels. Simulated inflows to the modeled area increase from 59.85 to 60.38 ft^3/s and simulated outflows increase from 59.85 to 60.40 ft^3/s from the 1,300 ft simulation to the 1,324 ft simulation, respectively (table 10). Inflow from the simulated mine pit increases with higher pit water levels, and were somewhat offset by decreases in simulated inflow from wetlands and streams, represented by general head-dependent boundaries. Outflow to the aquifer from the simulated mine pit decreases with higher pit water levels, and were offset by increases in simulated outflow from the wetlands and streams (table 10). Simulated recharge and inflow from rivers did not vary between the various constant pit water-level simulations, as did simulated ground-water outflow from rivers and municipal wells.

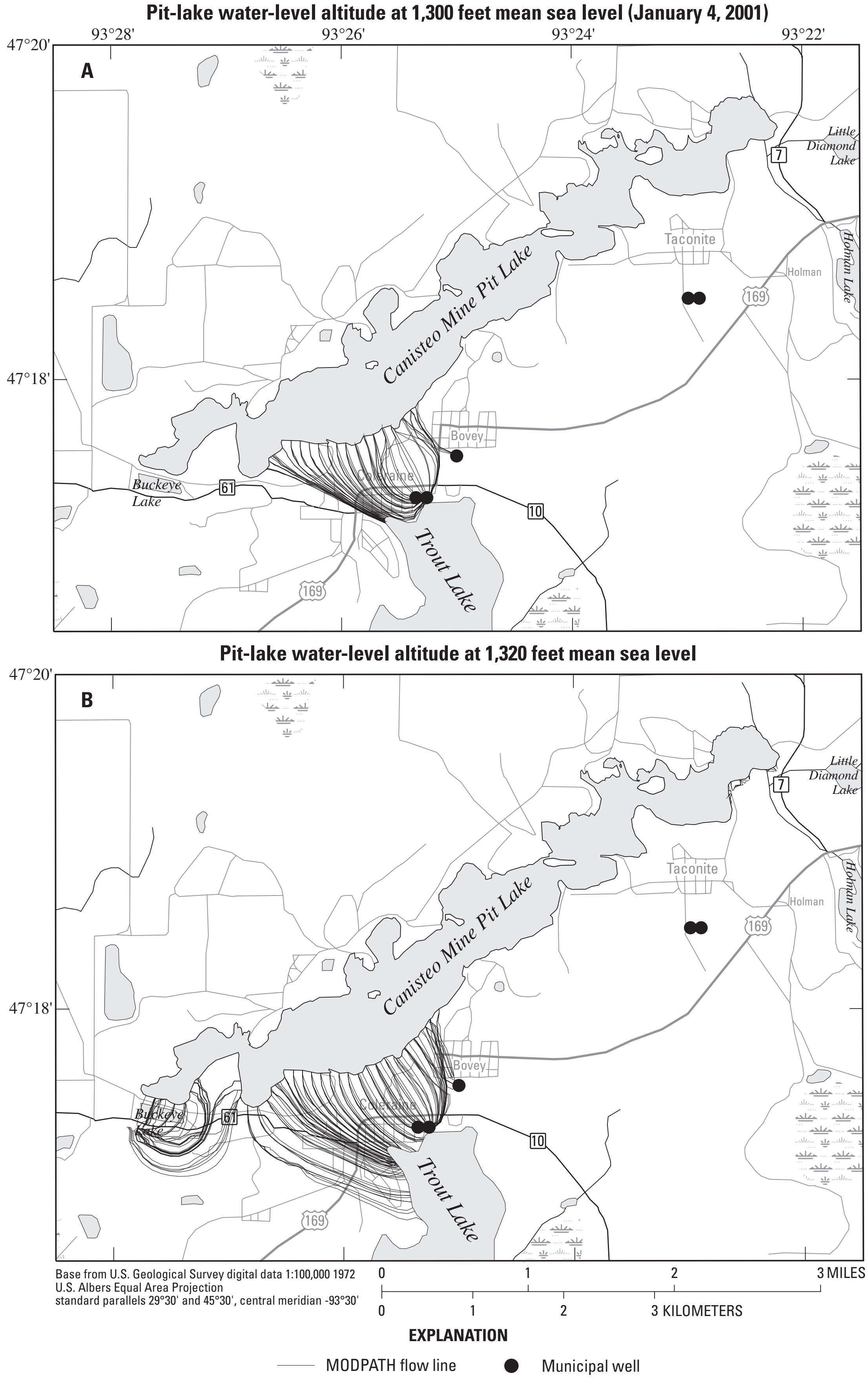

Figure 8. MODPATH flow lines for ground-water outflow from Canisteo Mine Pit at pit water-level altitude of: A.) 1,300 and B.) 1,320 feet above mean sea level, Bovey, Minnesota.

Table 10. Simulated water budgets for steady-state MODFLOW simulations for aquifers surrounding the Canisteo Mine Pit, Bovey, Minnesota.

[all values are in cubic feet per second; ft, feet above sea level]

Budget component	Discharge														
	Pit water-level altitudes (ft)														
	[1]1,300	1,302	1,304	1,305	1,306	1,308	1,310	1,312	1,314	1,315	1,316	1,318	1,320	1,322	1,324
In															
Constant head - Canisteo Mine Pit	0.06	0.10	0.13	0.15	0.17	0.22	0.29	0.36	0.44	0.47	0.52	0.60	0.70	0.80	0.91
Rivers	0.88	0.88	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
Recharge	10.97	10.97	10.97	10.97	10.97	10.97	10.97	10.97	10.97	10.97	10.97	10.97	10.97	10.97	10.97
Head-dependent Boundaries	47.94	47.92	47.88	47.86	47.85	47.83	47.80	47.82	47.72	47.73	47.71	47.68	47.68	47.67	47.63
Total in	59.85	59.87	59.85	59.85	59.86	59.89	59.93	60.02	60.00	60.04	60.07	60.12	60.22	60.31	60.38
Out															
Constant head - Canisteo Mine Pit	1.40	1.38	1.32	1.30	1.26	1.24	1.21	1.16	1.12	1.12	1.09	1.04	1.04	1.03	1.00
Rivers	3.69	3.69	3.69	3.69	3.69	3.69	3.69	3.69	3.69	3.69	3.69	3.69	3.69	3.70	3.70
Head-dependent boundaries	54.22	54.26	54.32	54.35	54.38	54.43	54.50	54.58	54.66	54.70	54.75	54.85	54.95	55.05	55.16
Municipal wells	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
Total out	59.85	59.87	59.87	59.88	59.87	59.90	59.94	59.97	60.01	60.05	60.07	60.12	60.22	60.32	60.40
Total in - out	0.00	0.00	-0.02	-0.03	-0.01	-0.01	-0.01	0.05	-0.01	-0.01	0.00	0.00	0.00	-0.01	-0.02

[1]The pit water level of 1,300 ft represents the calibrated steady-state model, which was calibrated to water levels measured on January 4, 2001.

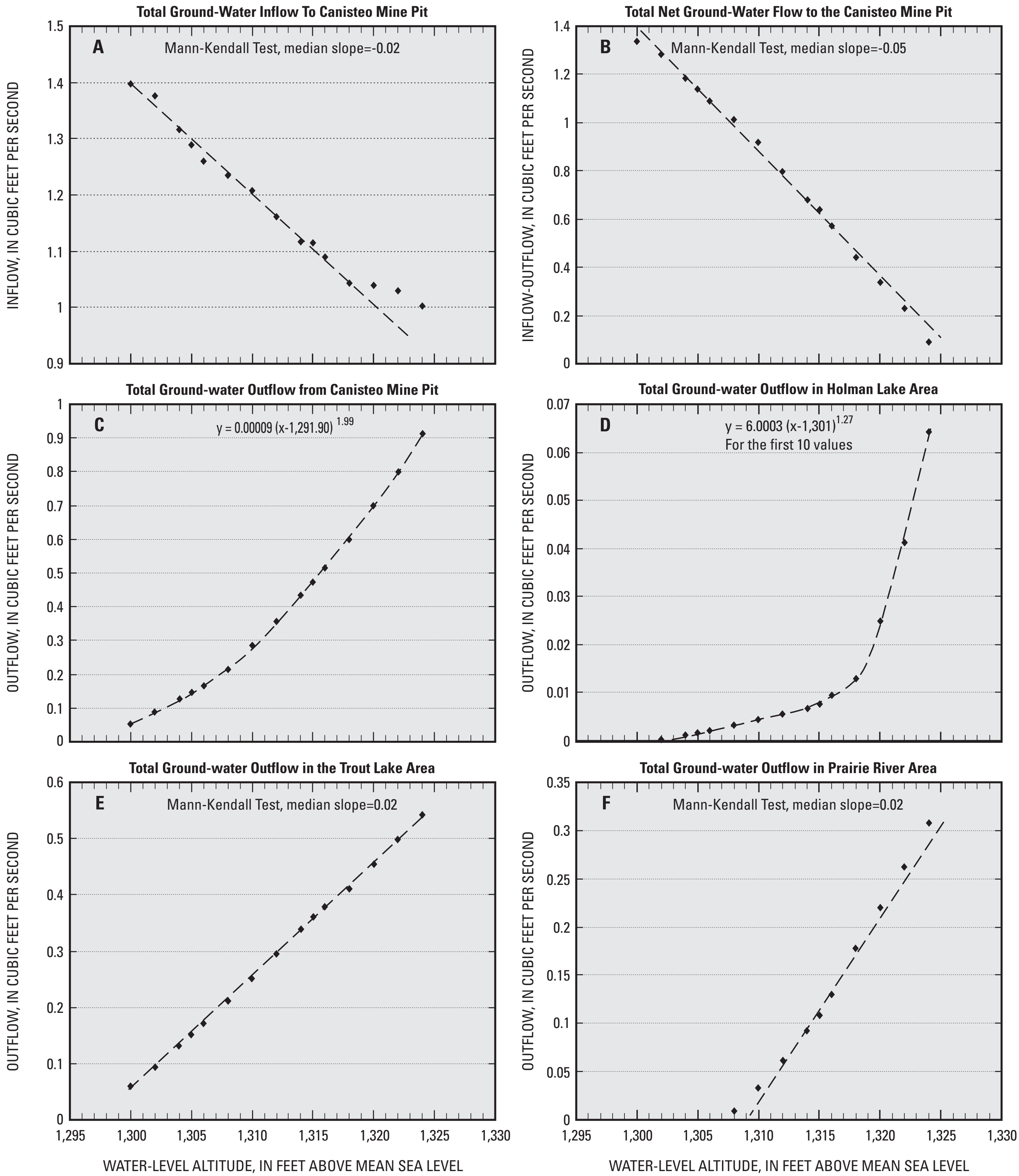

Figure 9. Simulated (A) total ground-water inflow, (B) total net ground-water inflow, outflow (C) total ground-water outflow rates from the entire pit, (D) ground-water outflow from the pit in the Holman Lake area, (E) the Trout Lake area, and (F) the Prairie River area at various constant pit-lake water-level altitudes for the Canisteo Mine Pit, Bovey, Minnesota.

SUMMARY AND CONCLUSIONS

The U.S. Geological Survey, in cooperation with the Minnesota Department of Natural Resources, conducted a study to characterize ground-water flow conditions between the Canisteo Mine Pit, Bovey, Minnesota, and surrounding aquifers following mine abandonment. The objective of the study was to estimate the amount of steady-state, ground-water flow between the mine and surrounding aquifers at pit water-level altitudes below the level at which surface-water discharge from the pit may occur.

Single-well hydraulic tests and stream-hydrograph analyses were conducted to estimate horizontal hydraulic conductivities and ground-water recharge rates, respectively, for glacial aquifers around the mine pit. Average hydraulic conductivity values ranged from 0.05 to 5.0 ft/day for sands and clays and from 0.01 to 121 ft/day for coarse sands, gravels, and boulders. The 15-year averages for the estimated annual recharge using the winter records and the entire years of record for defining baseflow recession rates were 7.07 and 7.58 in., respectively. These recharge estimates accounted for 25 and 27 percent, respectively, of the average annual precipitation for the 1968-82 streamflow monitoring period.

Ground-water flow rates into and out of the Canisteo Mine Pit were estimated using a calibrated steady-state, ground-water flow model. The U.S. Geological Survey's MODFLOW-96 code was used to simulate an area of approximately 75 mi^2 surrounding the mine pit. The model residuals, or difference between simulated and measured water levels, for 15 monitoring wells adjacent to the Canisteo Mine Pit varied between +28.65 and –3.78 ft. The best-match simulated water levels were within 4 ft of measured water levels for 9 of the 15 wells, and within 2 ft for 4 of the wells. The simulated net ground-water flow into the Canisteo Mine Pit was +1.34 ft^3/s, and the net ground-water flow calculated from pit water-level altitudes measured between July 5, 1999 and February 25, 2001 was +5.4 ft^3/s. Simulated water levels and ground-water flow to and from the Canisteo Mine Pit for the calibrated steady-state simulation were most sensitive to changes in horizontal hydraulic conductivity, suggesting that this characteristic is the predominant parameter controlling steady-state water-level and flow conditions.

A series of 14 steady-state simulations at constant pit water-level altitudes between 1,300 and 1,324 ft was completed to assess the effect of current and potential future pit water levels on ground-water inflow and outflow from the Canisteo Mine Pit. Simulated ground-water flow conditions obtained from the calibrated model indicate that total simulated ground-water inflow to the Canisteo Mine Pit was 1.40 ft^3/s, with only 0.06 ft^3/s discharging to local aquifers, at a constant pit water-level altitude of 1,300 ft. Simulations of steady-state conditions at various constant pit water-level altitudes indicate that total simulated ground-water inflow will decrease from 1.40 to 1.00 ft^3/s and total simulated ground-water outflow will increase from 0.06 to 0.91 ft^3/s as the pit water-level altitude rises from 1,300 to 1,324 ft. At the lowest pit-rim altitude of 1,324 ft, model results indicate a net simulated ground-water flow of 0.09 ft^3/s into the mine pit, and it is likely that surface discharge to land surface will occur at the location of the lowest pit-rim altitude. At pit water-level altitudes between 1,302 and 1,306 ft, all but a small rate (less than 0.01 ft^3/s) of the total simulated outflow occurs in the Trout Lake area. At pit water-level altitudes between 1,308 and 1,324 ft, simulated outflow occurs in three locations: the Trout Lake, the Prairie River, and Holman Lake areas.

REFERENCES

Adams, J.L, 1994, The water balance of abandoned mine pits: Minnesota Ground Water Association, v. 13, no. 1, p. 4-9.

Baker Consultants, Inc., 2000, User's documentation for the PITLAKE package for the MODFLOW-96 model: Version 2.1, 38 p.

Bouwer, H. and Rice, R.C., 1976, A slug test method for determining hydraulic conductivity of unconfined aquifers with completely or partially penetration wells: Water Resources Research, v. 12, no. 3, p. 423-428.

Chung, K.P. and Anderson, M.P., 1998, Simulation of lake levels—Comparison between MODFLOW's lake package and the use of high conductivity zones: Proceedings of MODFLOW98 Conference, v. 1, Golden, Colorado, October 4-8, 1998, p. 339-344.

Cooper, H.H. and Jacob, C.E., 1946, A generalized graphic method for evaluating formation constants and summarizing well field history: American Geophysical Union Transactions, v. 27, p. 526-534.

Delin, G.N., 1988, Geohydrology and water quality of confined-drift aquifers in the Brooten-Belgrade area, west-central Minnesota: U.S. Geological Survey Water-Resources Investigations Report 88-4124, 138 p.

Duffield, G.M., 1995, AQTESOLV Aquifer Test Solver: Reston, Virginia, Geraghty & Miller, Inc., 132 p.

Harbaugh, A.W., and McDonald, M.G., 1996, User's documentation for MODFLOW-96, an update to the U.S. Geological Survey Modular Finite-Difference Ground-

Water Flow Model: U.S. Geological Survey Open-File Report 96-485, 63 p.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: New York, Elsevier Science Publishers, 522 p.

Hill, M.C., 1990, Preconditioned conjugate-gradient 2 (PCG2)—A computer program for solving ground-water flow equations: U.S. Geological Survey Water-Resources Investigations Report 90-4048, 43 p.

Kishel, H.F., and Gerla, P.J., 2002, Effects of small-scale hydraulic variation on ground-water discharge to Shingobee Lake, Minnesota: The University of North Dakota, Department of Geology web page, accessed April 23, 2002, at URL http://www.geology.und.nodak.edu/gerla/home/cur_res.html

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. A-1, p. 2-1 – 2-35.

McDonald, M.G., Harbaugh, A.W., Orr, B.R., and Ackerman, D.J., 1991, A method of converting no-flow cells to variable-head cells for the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 91-536, 99 p.

Meijerink, J.A., and van der Vorst, H.A., 1977, An iterative solution method for linear systems of which the coefficient matrix is a symmetric M-Matrix: Mathematics of Computation, v. 31, no. 137, p. 148-162.

Minnesota Department of Natural Resources, 1999, Mesabi Elevation Project, Arc/Info export files and shape files of surface elevation contour lines and spot elevation: CD-ROM data.

——-2001a, Lake finder, 1996: accessed January 11, 2000, at URL http://www.dnr.state.mn.us/lakefind/index.html.

———2001b, LandSat-based land use-land cover (Raster), 1995 (Minnesota): Minnesota Department of Natural Resources online metadata, accessed July 11, 2001, at URL http://deli.dnr.state.mn.us/metadata/full/lusatra3.html

———2001c, Minnesota Water Use Information (Raster), 1996 (Minnesota): Minnesota Department of Natural Resources online metadata, accessed January 23, 2001, at URL http://www.dnr.state.mn.us/waters/programs/water_mgt_section/appropriations/wateruse.html

Minnesota State Climatologist, 2001, Normal precipitation and temperature data: accessed July 11, 2001, at URL http://climate.umn.edu/doc/historical/normals.htm

Morey, G.B., 1972, Mesabi Range, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota—A Centennial Volume: Minnesota Geological Survey, p. 204-217.

Oakes, E.L., 1970, Geology and ground-water resources of the Grand Rapids area, north-central Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas, HA-322, scale 1:48,000.

Petersen, T., and Berg, J., 2000, Seismic refraction surveys for Canisteo water balance project: Minnesota Department of Natural Resources, Division of Waters, Internal Report, November, 2000, 6 p.

Pollock, D.P., 1994, User's guide for MODPATH/MODPATH-PLOT, Version 3—A particle tracking post-processing package for MODFLOW, the U. S. Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94-464, 120 p.

Rutledge, A.T., 1998, Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow records—update: U.S. Geological Survey Water Resources Investigations Report 98-4148, 43 p.

———2000, Considerations for use of the RORA Program to estimate ground-water recharge from streamflow records: U.S. Geological Survey Open-File Report 00-156, 44 p.

Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage: American Geophysical Union Transactions, v. 16, p. 519-524.

Winter, T.C., 1971, Sequence of glaciation in the Mesabi-Vermilion Iron Range area, northeastern Minnesota: U.S. Geological Survey Professional Paper 750-C, p. C82-C88.

———1973a, Hydrogeology of glacial drift, Mesabi Iron Range, northeastern Minnesota: U.S. Geological Survey Water Supply Paper 2029-A, 23 p.

———1973b, Petrography and stratigraphy of glacial drift, Mesabi-Vermilion Iron Range area, northeastern Minnesota: U.S. Geological Survey Bulletin 1331-C, 41 p.

U.S. Census Bureau, 2002, Population data: accessed February 6, 2002, at URL http://factfinder.census.gov/servlet/BasicFactsServlet

U.S. Department of Defense, 1998, Groundwater modeling system, user's manual, Brigham Young University, 620 p.

U.S. Fish & Wildlife Service, 1994, National wetlands inventory digital data: October 1991 to 1994, at URL http://www.nwi.fws.gov

U.S. Geological Survey, 1974, Hydrologic unit map—1974 State of Minnesota: U.S. Geological Survey, 1 pl.