Prepared in cooperation with the Minnesota Ojibwe Bands

Simulation of the Regional Groundwater-Flow System in the St. Louis River Basin, Minnesota

Scientific Investigations Report 2019–5033

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

Cover. St. Louis River at Jay Cooke State Park, Minnesota. Photograph by Megan Haserodt, U.S. Geological Survey.

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Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83), Zone 15N.

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

Abbreviations

DF	Dupuit-Forchheimer (approximation)
lidar	light detection and ranging
MDNR	Minnesota Department of Natural Resources
MPCA	Minnesota Pollution Control Agency
NWI	National Wetlands Inventory
NWIS	National Water Information System
SLRB	St. Louis River Basin
SSURGO	Soil Survey Geographic (database)
SWB	soil-water-balance
USGS	U.S. Geological Survey

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Abstract

The St. Louis River Basin (SLRB) covers 3,600 square miles in northeastern Minnesota, with headwaters in the Mesabi Range and extensive wetlands and lakes throughout the basin. To better understand the regional groundwater system in the SLRB, a two-dimensional, steady-state groundwater-flow model of the SLRB was developed by the U.S. Geological Survey, in cooperation with the Minnesota Ojibwe Bands, using the analytic-element computer code GFLOW. The parameter-estimation software suite PEST was used to obtain a best fit of the modeled to measured groundwater levels and streamflows. The calibrated regional model was locally refined to create a smaller version of the model, the central SLRB model, that was used to evaluate hydrologic effects from extensive ditching in wetlands of the central SLRB. The refinements included adding ditches that were not represented in the regional model and modifying the aquifer base elevation to be more representative of the localized area. The central SLRB model was recalibrated to better match the distribution of mapped wetlands. Two scenarios were run of the central SLRB model: one with ditches and one without ditches. The model results were compared between the two scenarios to assess the effect of ditching on the groundwater system and potential changes to hydrologic conditions that support wetlands.

Calibration of the regional SRLB model resulted in average horizontal hydraulic conductivity values of 6–39 feet per day for the glacial deposits and 3–4 feet per day for the uppermost fractured bedrock in the Biwabik Iron-Formation on the Mesabi Range. Average recharge across the calibrated model was 5.9 inches per year. Linesink resistance for the routed stream network was calibrated by using resistance categories based on the mapped soil hydrologic groups. The modeled regional groundwater-flow direction was generally to the south near the Mesabi Range topographic high and south or southwest across the rest of the basin.

The updated calibration of the central SLRB model resulted in average horizontal hydraulic conductivity values of 5–36 feet per day for the glacial deposits and 3 feet per day for the uppermost fractured Biwabik Iron-Formation of the Mesabi Range. Average recharge across the ditch scenarios was 4.1 inches per year. Comparison of the preditch and postditch model scenarios showed that ditching reduced the area where the modeled water table was within 1 foot of the land surface (a wetland hydrology indicator) in as much as 40,000 acres, or 37 percent, of mapped permanent wetlands in the SLRB. An increase in the depth to the water table in wetland areas has the potential to degrade wetland persistence or function.

Introduction

The St. Louis River Basin (SLRB) drains over 3,600 square miles in northeastern Minnesota (fig. 1). Its headwaters are in the Mesabi Range (hereafter “Iron Range”), where iron ore has been mined extensively for over a century. In addition to iron ore resources, the SLRB contains vast tracts of wetlands and numerous lakes.

The shallow groundwater system in this region is in unconsolidated glacial deposits and the upper, fractured crystalline bedrock. To assess the regional groundwater-flow system in the SLRB and the local effects of ditching in the central wetlands of the basin (near Meadowlands and Floodwood, Minnesota; fig. 1), a modeling study was conducted by the U.S. Geological Survey (USGS) in cooperation with the Minnesota Ojibwe Bands. The objective of the SLRB regional model is to provide an understanding of the regional groundwater-flow system from which defensible model boundary conditions for local finite-difference models can be extracted. The regional model covers the entire SLRB but is most detailed in the area near the Iron Range. The regional model was refined and reduced in the central SLRB to create a model (subsequently referred to as the “central SLRB model”) that was used to evaluate ditching effects, including a lower water table and possible loss of wetland persistence and function. The regional and central SLRB models can be downloaded from the Haserodt and others (2019) model archive.

This report presents the results of an investigation of the shallow groundwater system (in the unconsolidated material and upper fractured bedrock) in the SLRB and includes a more detailed analysis of the interactions between surface water and groundwater in the extensive ditches in the central wetlands of the SLRB.

The report includes (1) an overview of the hydrologic setting and conceptual model, (2) discussion of modeling

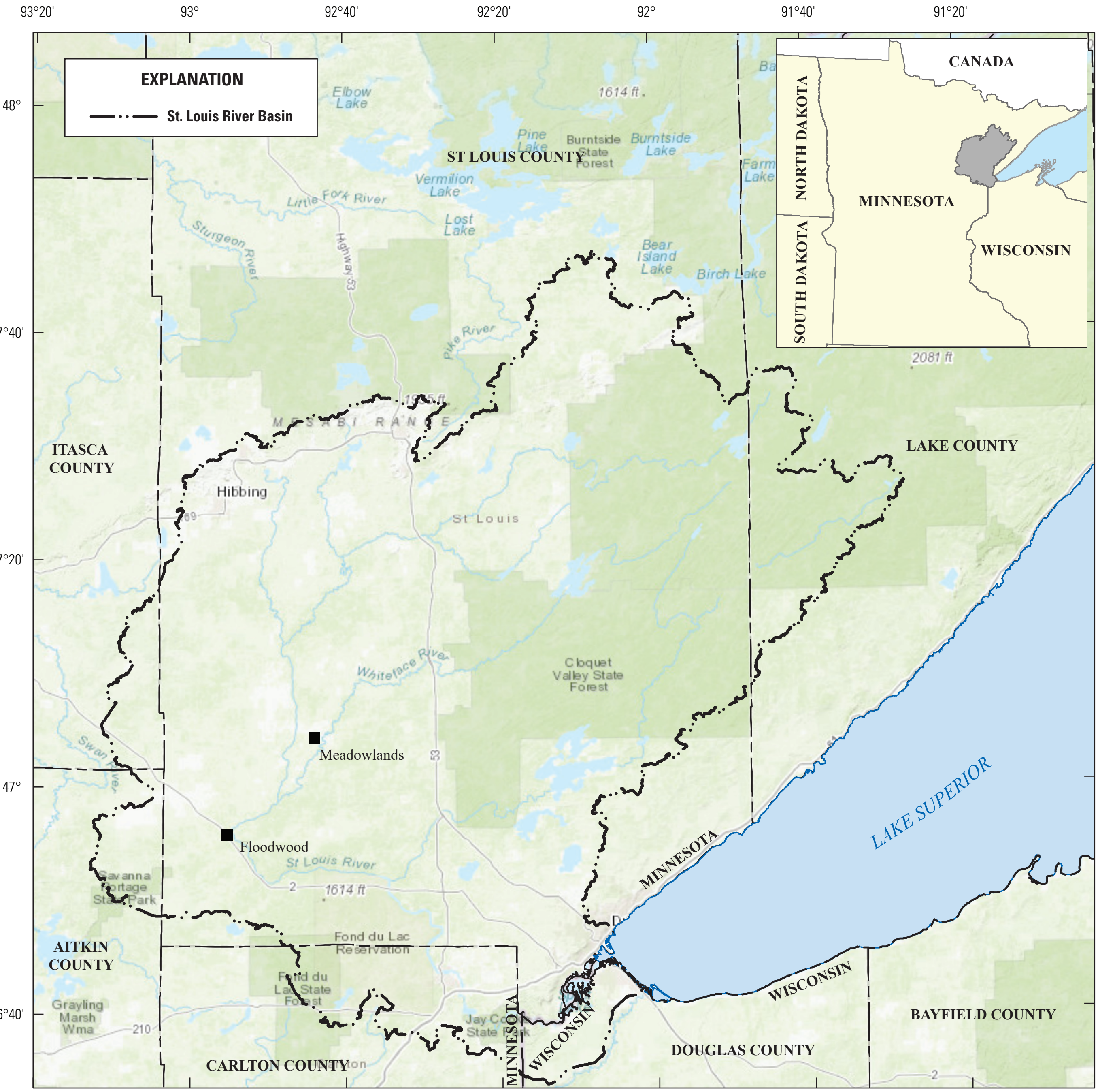


Figure 1. Location of the St. Louis River Basin, northeastern Minnesota.

methods, (3) development and calibration of the regional groundwater model, (4) discussion of model assumptions and limitations, (5) development and application of the locally refined model with two ditch scenarios, and (6) a summary section.

Hydrogeologic Setting and Conceptual Model of the Flow System

The SLRB (fig. 1) is 82 miles long at its widest point and drains over 3,600 square miles in northeastern Minnesota. The surface-water basin consists of a main St. Louis River stem and two major tributaries: the Whiteface River and the Cloquet River (fig. 2). From north to south, minor tributaries to the St. Louis River include the Partridge River, the Embarrass River, Mud Hen Creek, the East and West Two Rivers, the East and West Swan Rivers, the Floodwood River, the East Savanna River, the Artichoke River, Stoney Brook, the Pine River, the Midway River, and Miller Creek. At its northern reach, the St. Louis River flows west and south. At its southern reach, the St. Louis River flows south and east into Lake Superior. The St. Louis River Basin topography is generally steep along the Iron Range at the northern boundary, relatively flat in the glacial lake plain in southwest and central parts of the basin, hummocky to the east where southwestward-trending glacial drumlins are numerous, and steep near the outlet along the shores of Lake Superior (Lindholm and others, 1979). The headwater drainage network of the northern basin has been substantially modified and continues to be modified by human activities along the Iron Range, including numerous open pit mines, tailings disposal, and ditching. Mining in the basin may increase if proposed copper-nickel mines are developed (Mining Minnesota, 2019).

The basin is in a humid, continental climate characterized by appreciable precipitation, hot summers, and cold winters (Pidwirny, 2006). Regionally, groundwater is present in the unconsolidated deposits and in fractures in the upper bedrock (Siegel and Ericson, 1980). The conceptual model of the study area was derived from existing geologic information about the Quaternary deposits (Minnesota Geological Survey, 2013), bedrock lithology (Jirsa and others, 2011), and existing hydrologic studies in the region (Cotter and others, 1965; Oakes, 1970; Stark, 1977; Olcott and others, 1978; Lindholm and others, 1979; Siegel and Ericson, 1980; Jones, 2002; Tetra Tech, 2014; Barr Engineering Company [Barr], 2014, 2015).

For regional modeling purposes, the hydrostratigraphy of the SLRB was simplified as follows (from land surface):

- a thin, sometimes absent, unconsolidated sand and gravel and sandy till aquifer that is Quaternary in age;
- an upper fractured bedrock aquifer that is hydraulically connected to the unconsolidated aquifer with hydraulic properties that may vary across the basin as a result of different dipping igneous and metasedimentary bedrock units; and
- a low-permeability, less fractured, lower bedrock basement (which is represented with an impermeable base in the regional model).

Unconsolidated Quaternary deposits (fig. 3) range in thickness (fig. 4) from over 500 feet near the mouth of the St. Louis River to absent in parts of the Iron Range along the northern boundary of the basin and the eastern edge of the basin where bedrock outcrops (Minnesota Geological Survey, 2013). Unconsolidated material is generally thicker in the western half of the basin than the east. Unconsolidated deposits include (1) calcareous ground-moraine, end-moraine, and lake-modified till from the Des Moines Lobe (western SLRB); (2) noncalcareous ground- and end-moraine till from the Rainy and Superior Lobes (northern, eastern, and southern SLRB); (3) coarse glaciofluvial deposits and lake sediment (sand and gravel with some silt); (4) fine glacial lake sediment (clay and silt); and (5) peat. Till from the Rainy and Superior Lobes is predominately sandy, whereas till from the Des Moines Lobe is predominately clayey (Hobbs and Goebel, 1982).

The bedrock geology is complex across the basin, particularly in the east (fig. 5). Bedrock is primarily Precambrian basement rock (Cotter and others, 1965) and is extensively intruded by igneous dikes and sills, especially to the south along Lake Superior (Olcott and others, 1978). South of the Iron Range, bedrock units generally dip toward the southeast (Jirsa and others, 2011). The crystalline bedrock has little primary porosity, and most permeability is from fractures. Locally, secondary porosity via leaching in the Biwabik Iron-Formation has increased the permeability of this unit by up to 50 percent (Siegel and Ericson, 1980). Only a simplified representation of the uppermost bedrock was considered for purposes of the regional model.

Existing literature and completion depths of water supply wells in the area suggest two bedrock hydrostratigraphic units: a more permeable, upper fractured bedrock aquifer and an underlying, less fractured bedrock unit (Cotter and others, 1965; Siegel and Ericson, 1980; Barr, 2014). There is an evidence of an aquitard between the unconsolidated aquifer and upper fractured bedrock aquifer, and therefore these units are assumed to be hydraulically connected to the unconsolidated deposits (Siegel and Ericson, 1980). The thickness of the upper fractured bedrock hydrostratigraphic unit is not well characterized in the field and is reported to average around 200–300 feet (Siegel and Ericson, 1980; Barr, 2014). A study of wells completed in the crystalline bedrock aquifers of northeastern Minnesota found the average well depth to be 175 feet in the Proterozoic (late Precambrian) metasedimentary aquifer that includes the Thompson Formation, 150 feet in the volcanic units along Lake Superior that include the North Shore Volcanic Group, 438 feet in the Biwabik Iron-Formation, and 143 feet in the Precambrian bedrock aquifer that includes the Duluth Complex (fig. 5) (Anderson, 1986). Bedrock well depths suggest that the fractured bedrock aquifer thickness is

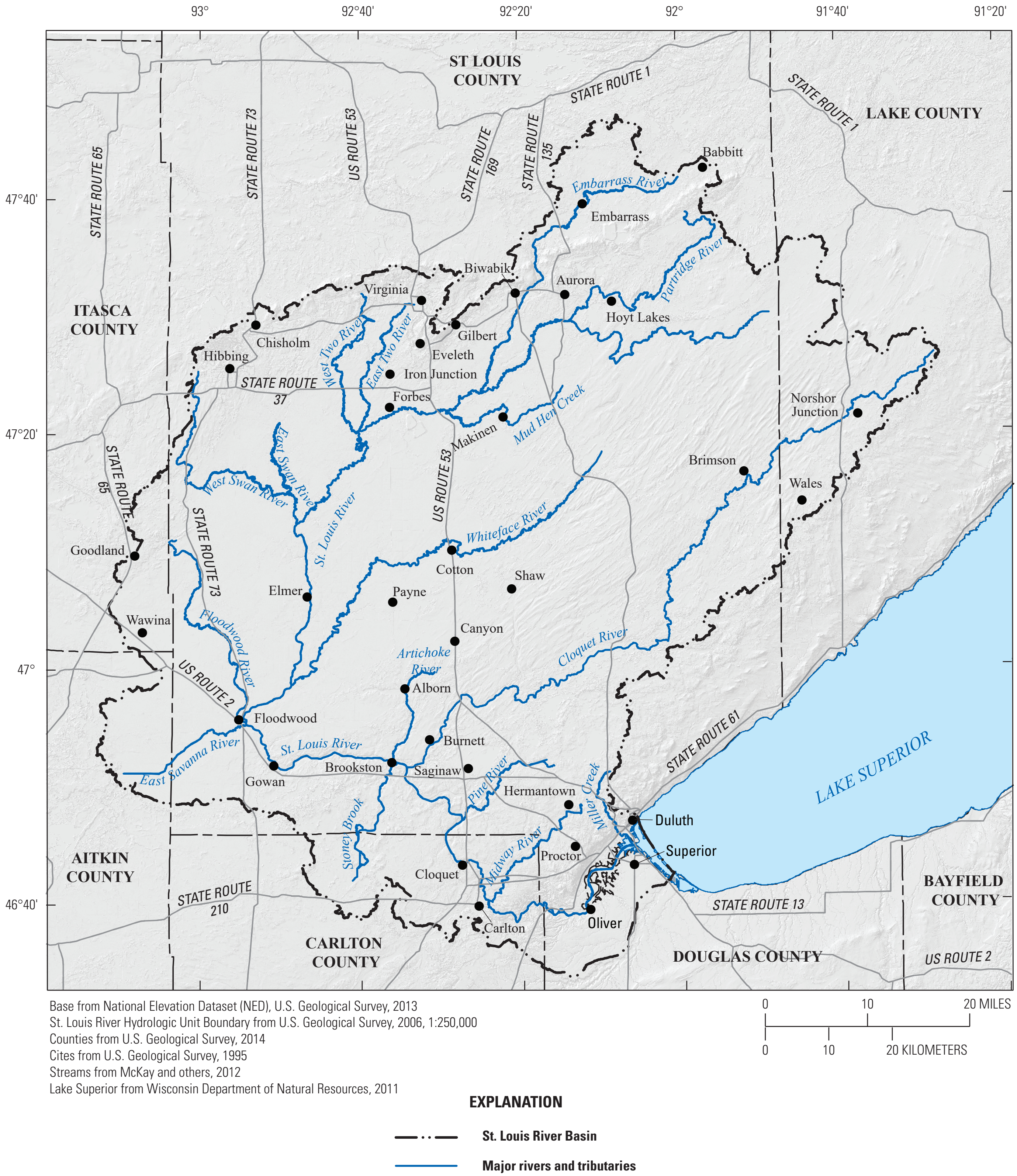


Figure 2. Major streams in the St. Louis River Basin, northeastern Minnesota.

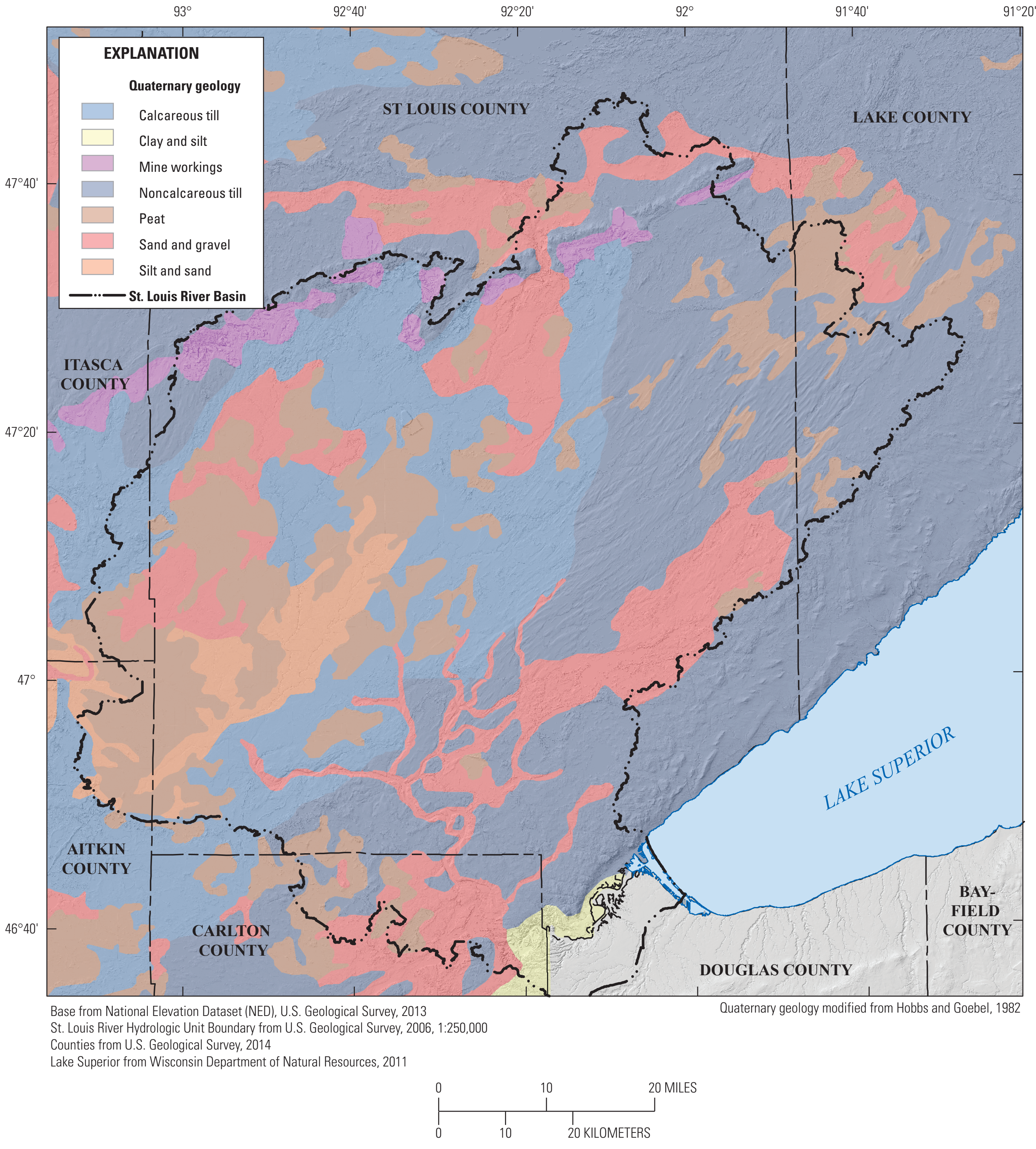


Figure 3. Quaternary deposits in the St. Louis River Basin, northeastern Minnesota.

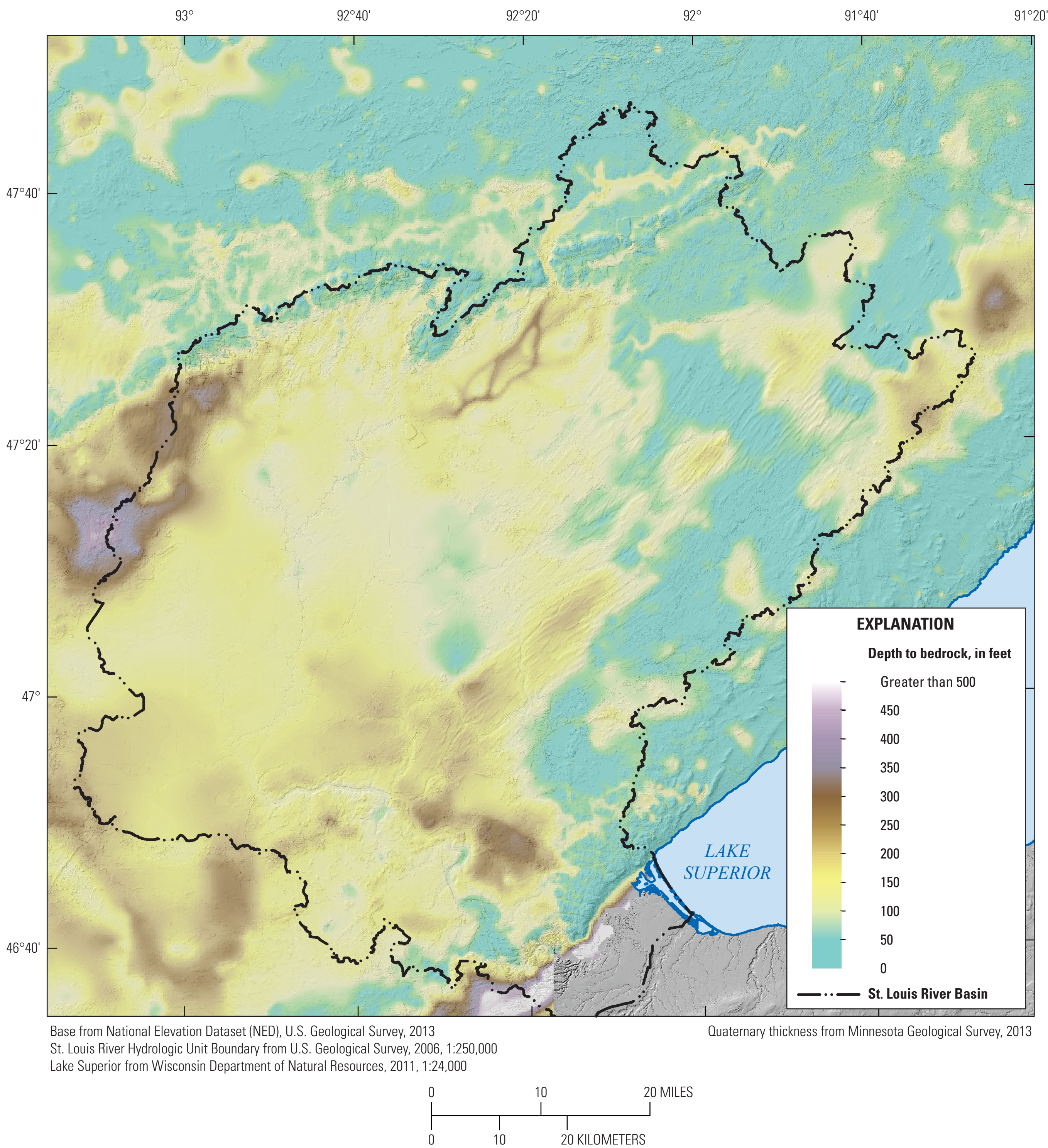


Figure 4. Thickness of Quaternary deposits in the St. Louis River Basin, northeastern Minnesota.

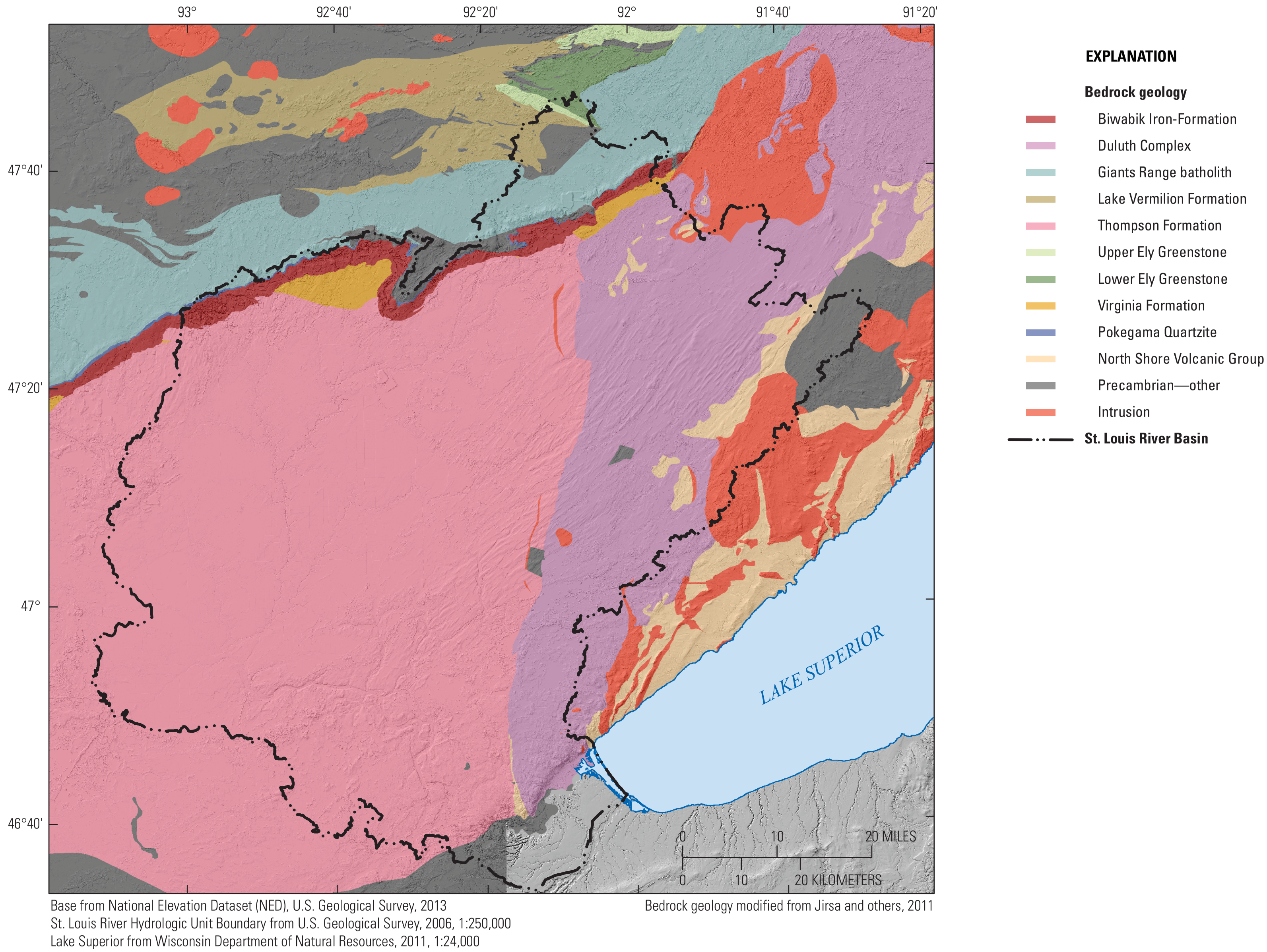


Figure 5. Simplified bedrock geology in the St. Louis River Basin, northeastern Minnesota.

generally on the order of a few hundred feet across much of the basin, and permeable zones in the Biwabik Iron-Formation are over 400 feet thick. A summary of published hydraulic conductivity values for the region is provided in table 1. For the purpose of this model, a thickness of 150 feet was assumed for the upper fractured bedrock.

Given the humid continental climate, much of the basin area provides groundwater recharge for the SLRB regional aquifer, except where the aquifer discharges to streams, wetlands, and mine pits within the SLRB (Lindholm and others, 1979). Where groundwater is used as a water supply source, 25 percent comes from the bedrock aquifer and the rest from the unconsolidated Quaternary aquifer (Lindholm and others, 1979). Where used, the bedrock aquifer can be locally productive, with well yields in bedrock wells completed in fractured zones that can equal or exceed that those of wells in the unconsolidated sediment (Lindholm and others, 1979). Wells completed in the Biwabik Iron-Formation have reported yields of up to 1,000 gallons per minute (Cotter and others, 1965).

Analytic-Element Methods of Hydrologic Modeling

An analytic-element screening model based on the program GFLOW (Haitjema, 1995) was used to simulate regional groundwater flow in the SLRB to provide a starting point for future modeling efforts in the SLRB. Analytic-element methods were pioneered in Minnesota by Otto Strack

Table 1. Summary of literature hydraulic conductivity values for the St. Louis River Basin, northeastern Minnesota.

[In the exponential notation used, 2.1E−05 represents 2.1×10^{-5}. Barr, Barr Engineering Company; --, no data]

***A.* Unconsolidated deposits**

Estimated hydraulic conductivity, in feet per day	Unit	Source
0.4 to 362	Sand and gravel	Stark (1977)
0.004 to 15.5	Sand and gravel	Siegel and Ericson (1980)
0.01 to 121	Coarse sand and gravel	Jones (2002)
0.04 to 6.7	Rainy Lobe till	Stark (1977)
2.1E−05 to 0.13	Rainy Lobe till	Siegel and Ericson (1980)
1E−05 to 0.01	Des Moines Lobe till	Siegel and Ericson (1980)
0.05 to 5.0	Sand and clay	Jones (2002)
0.012 to 31	Sand and clay	Barr (2006a)
0.001 to 0.1	Peat	Siegel and Ericson (1980)

***B.* Fractured bedrock**

Estimated hydraulic conductivity, in feet per day	Depth, in feet	Source
	Duluth Complex	
0.05 to 0.4	<400	Stark (1977), reported in Barr (2014)
3E−3 to 2E−2	<300	Siegel and Ericson (1980), reported in Barr (2014)
3E−3 to 1E−2	<450	Barr (2006a), reported in Barr (2014)
4E−4 to 1E−2	0 to >1,000	Stark (1977), reported in Barr (2014)
3E−4 to 8E−4	0 to >1,000	Barr (2006a), reported in Barr (2014)
	Virginia Formation	
0.05 to 0.7	<300	Barr (2006b), reported in Barr (2014)
2E−3 to 0.6	0 to <700	Barr (2006b), reported in Barr (2014)
	Giants Range batholith	
42	<47	Barr (2015)
[1]4E−3 to 2	<100	Barr (2014)
4	<100	Barr (2014)
3.E−02	<200	Barr (2014)
	Biwabik Iron-Formation	
0.2 to 16	--	Barr (2011)

[1]Some zones produced no water during packer test.

and his students (for example, Strack, 1989). An analytic-element model is ideally suited for use as a screening model that provides a simplified version of a hydrologic system and can be completed ahead of a more complex modeling effort. Screening models (Hunt and others, 1998) are fast to construct but carry less system detail than more complex models (for example, a screening model might simulate only areal two-dimensional flow). The analytic-element method is well suited for screening models because it assumes an infinite aquifer extent and, therefore, does not require the construction of a model grid with finite perimeter boundaries. Instead, the nearfield area of interest is represented with internal boundary conditions typically consisting of surface-water bodies and other hydrologic features represented with greater detail than the surrounding area. These boundary conditions are digitized into the model as analytic elements, and analytic solutions for each element are added to obtain an overall solution for groundwater flow that is continuous across the domain. Typically, more detail is specified for the analytic elements representing the area of interest than for areas distant from the area of interest.

Being gridless, analytic-element screening models are easily modified, and surface-water features can be refined anywhere within the model domain, and the model domain itself can be easily expanded or contracted by adding or removing elements. This flexibility allows for quick simulations of future areas of interest within the model domain. Moreover, the ability to represent a large model domain efficiently facilitates representative regional models because the interaction with distant hydraulic boundaries (for example, distant large rivers and lakes) can be accounted for by direct simulation rather than assuming hydrologic effects which then must be translated to specified perimeter boundary conditions. Detailed mathematical descriptions of the analytic-element method can be found in Strack (1989, 2017) and Haitjema (1995), and a review of groundwater applications of analytic-element methods is given by Hunt (2006). The following sections describe in greater detail the two models developed for this work: the regional model and the central SLRB model. Development, calibration, and results for each model are discussed independently. The “Summary and Conclusions” section combines results and findings from both modeling efforts.

Development of the Regional GFLOW Model

The surface-water network for the regional SLRB model consists of two domains—hereafter called the nearfield and the farfield (Anderson and others, 2015, chapter 9). The nearfield is the area of interest where greater linesink (analytic element) detail is used, which for this study is the Iron Range and its immediately adjacent drainage basins. The farfield is the area surrounding the nearfield that contains hydrologic features that control the large-scale groundwater flow toward or away from the nearfield. In our regional model, the function of the farfield is to simulate representative and scientifically defensible groundwater divides surrounding the Iron Range area of interest.

The approximate east-west extent of the regional model’s farfield domain is from the Swan River near Blackberry, Minn., to Lake Superior, near Little Marais, Minn. In the north-south direction, the model extends from near Ely, Minn., south to the mouth of the St. Louis River at Duluth, Minn. (fig. 6). This domain represents an area on the order of 7,700 square miles. Surface-water features were digitized into the model as strings of linesink elements with heads specified based on elevations in the National Hydrography Dataset (NHDPlus v2; McKay and others, 2012) and a high-resolution (approx. 1 meter in the horizontal direction and a few centimeters in the vertical direction) light detection and ranging (lidar) elevation dataset (MDNR, 2011). In the nearfield area, streams were represented with stream elements (Mitchell-Bruker and Haitjema, 1996), which are a specialized case of a head-dependent-flux boundary condition that routes streamflow along a linesink network while limiting the potential amount of water lost from the stream to that captured upstream. Nearfield elements were represented with greater linesink resolution and included streambed resistance (streambed thickness divided by its vertical hydraulic conductivity).

Streambed resistance values were obtained by using hydrologic groups of soil adjacent to the stream. Soil data came primarily from the Soil Survey Geographic Database (SSURGO; Natural Resources Conservation Service, 2014); data from the State Soil Geographic database (STATSGO; Schwarz and Alexander, 1995) were used to fill gaps where no SSURGO data were available. Soil hydrologic groups were mapped to the midpoint of the linesink string; within each soil hydrologic group, a single resistance value was then applied throughout the model domain. Soil hydrologic groups are lettered by infiltration capacity, with “A” soils having the highest infiltration capacity and “D” soils having the lowest infiltration capacity. Locations mapped as “A/D,” “B/D,” and “C/D”—where the first letter is the drained soil condition and the second is the natural soil condition—were included in the “D” group. The distribution of resulting streambed resistance based on soil hydrologic groups along the linesinks is presented in figure 6.

The streamflow routing functionality of GFLOW’s stream elements was used to simulate the accumulation of base flow along consecutive linesinks. Streams in the farfield were represented, with coarser resolution than nearfield streams, as specified-head boundaries, without routing or streambed resistance. Lakes were simulated with stream linesinks around their perimeter and were routed to downstream surface-water features if an outlet existed. For regional model purposes, mine pits where active dewatering was apparent (as identified by using pit water-level elevations estimated from lidar data from MDNR, 2011) were represented as specified-head linesinks where the stage was set to 100 feet below the average land-surface elevation at the edge of the pit. An elevation of

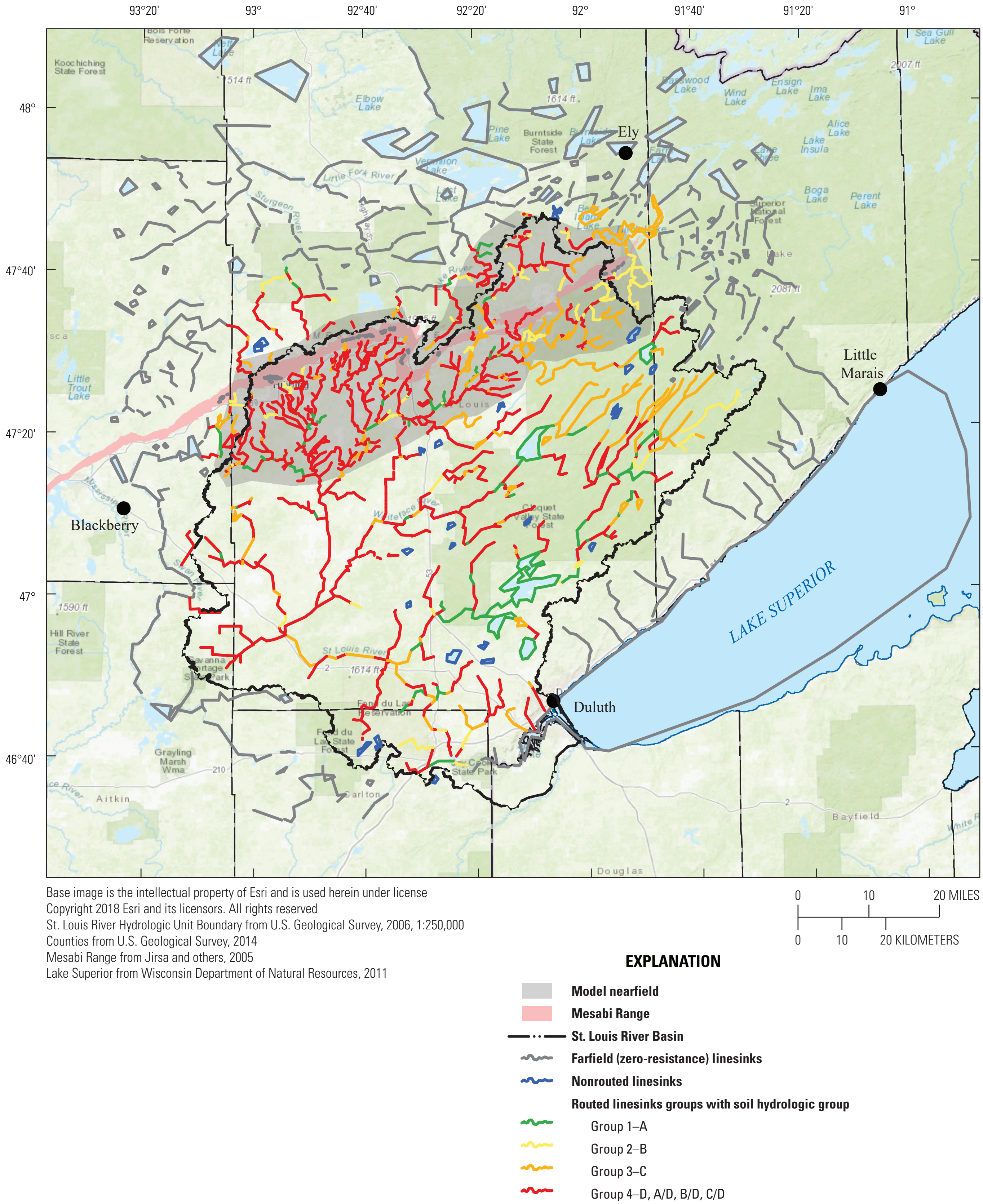


Figure 6. Regional GFLOW model domain with linesinks, northeastern Minnesota.

100 feet below land surface was selected as best representing dewatering to the base of the more permeable, upper fractured bedrock aquifer. The sensitivity of the groundwater-flow solution to depths of 50, 200, and 300 feet below land surface was also tested during the calibration process.

The two-dimensional areal regional model simulates aquifer properties in terms of aquifer transmissivity (horizontal hydraulic conductivity multiplied by the saturated aquifer thickness). Inhomogeneity elements were constructed to represent variability in transmissivity and were placed by using changes in hydraulic conductivity due both to the lithology of the unconsolidated material and the Iron Range and to changes in aquifer thickness across the modeled area (fig. 7). Areas beyond the inhomogeneities were assigned a background till hydraulic conductivity value (“Till—medium thickness” parameter). A uniform model base elevation of 500 feet was used across the model domain and was not adjusted during calibration. Aquifer thickness was set to 2,000 feet, well above the highest water levels simulated, to ensure simulation of unconfined flow (where aquifer saturated thickness is dependent on the simulated water levels).

Recharge (fig. 8) came from a combined dataset of the Smith (2017) St. Louis Basin soil-water-balance (SWB) model and the statewide SWB model (Smith and Westenbroek, 2015), both representing average conditions from 1996 to 2010. The recharge was resampled to a 500-meter raster and applied as a variable grid across the model domain. Two recharge grid multipliers were used during calibration to adjust the SWB recharge over the model domain; one multiplier was applied to areas with high (>50 percent) wetland density (from the National Wetlands Inventory [NWI] wetland coverage), where SWB may overestimate recharge values, and a second multiplier was used for nonwetland areas. Average SWB recharge in the model domain based on these SWB estimates was 6.2 inches per year, which is slightly lower than the constant recharge rate used by Tetra Tech (2014) of 7.8 inches per year for a GFLOW model focused on the central Iron Range.

Calibration of the Regional GFLOW Model

The regional model was calibrated by using the PEST parameter-estimation software suite (Doherty, 2016). Parameterization can be considered an automated form of trial-and-error calibration (Anderson and others, 2015), where model inputs are systematically adjusted to minimize the misfit between the observed field data and the model-simulated equivalent data. This fit is represented numerically by an objective function, which is the unitless sum of squared, weighted residuals between model outputs and their equivalent “observed” values (the calibration targets). Model inputs adjusted during calibration included hydraulic conductivity for each inhomogeneity (fig. 7), a background hydraulic conductivity for areas beyond the inhomogeneities (“Till—medium thickness”), the two recharge grid multipliers (wetland and nonwetland), and streambed resistance parameters for each of the four soil hydrologic groups. For the four streambed resistance parameters, an order was enforced by setting tiered minimum and maximum allowable bounds such that the minimum bound of one group was the maximum bound for the next group, according to the relative ranking of associated soil groups. The hydraulic conductivities of the two Iron Range inhomogeneities were tied (enforced ratio between hydraulic conductivities in these two inhomogeneities) during parameter estimation so that the hydrologic properties were similar. During calibration, a total of 20 parameters were adjusted; there were 21 total parameters, but the hydrologic conductivities of the Iron Range inhomogeneities were tied, so they were adjusted as a single parameter during calibration.

A calibration dataset of groundwater elevation (head) and streamflow (flux) was developed to compare steady-state model outputs with field measurements of the system. Historical water-level measurements from 1891 to 2017 were obtained from the Minnesota Well Index (https://www.health.state.mn.us/communities/environment/water/mwi/index.html), Minnesota Department of Natural Resources lake-level records from 1899 to 2016 (http://www.dnr.state.mn.us/lakefind/index.html), flooded mine-pit elevations from the 2011 lidar (MDNR, 2011), and head targets used in the Barr (2015) groundwater-flow model. Where present, multiple measurements of head were averaged to develop a single, steady-state value representing average conditions. Streamflows were obtained from the USGS National Water Information System (NWIS—https://waterdata.usgs.gov/nwis) and the Minnesota Department of Natural Resources (MDNR)/Minnesota Pollution Control Agency (MPCA) Cooperative Stream Gaging database (http://www.dnr.state.mn.us/waters/csg/index.html). In addition to head targets, a summed flooding parameter (the amount to which modeled heads exceeded the land surface) across the grid from which GFLOW extracts a groundwater head solution was used during the calibration process to penalize excessive flooding.

Average annual base flows were computed from continuous records by using the Institute of Hydrology Base Flow Index (BFI) method (Institute of Hydrology, 1980; Wahl and Wahl, 1988). NWIS calibration data were from 2010 to 2017, and MPCA data were from 2008 to 2017, with the exception of streamgage 3084001 where historical flow data from the 1950s appeared consistent with modern data and were included in the base-flow separation. Following the methodology of Gebert, Radloff, and others (2007) and Gebert, Walker, and Kennedy (2011), partial records of miscellaneous NWIS flow measurements from 1950 to 2017 were converted to an equivalent average annual base flow by using relation lines with data from a nearby continuous-record site. For each partial record, multiple nearby records were compared to identify the best relation line. This adjustment is necessary to help ensure that a single or a small number of measurements are representative of longer term conditions.

The overall goal of the calibration-target weighting process is to increase the signal-to-noise ratio of the observation set to maximize the transfer of information from

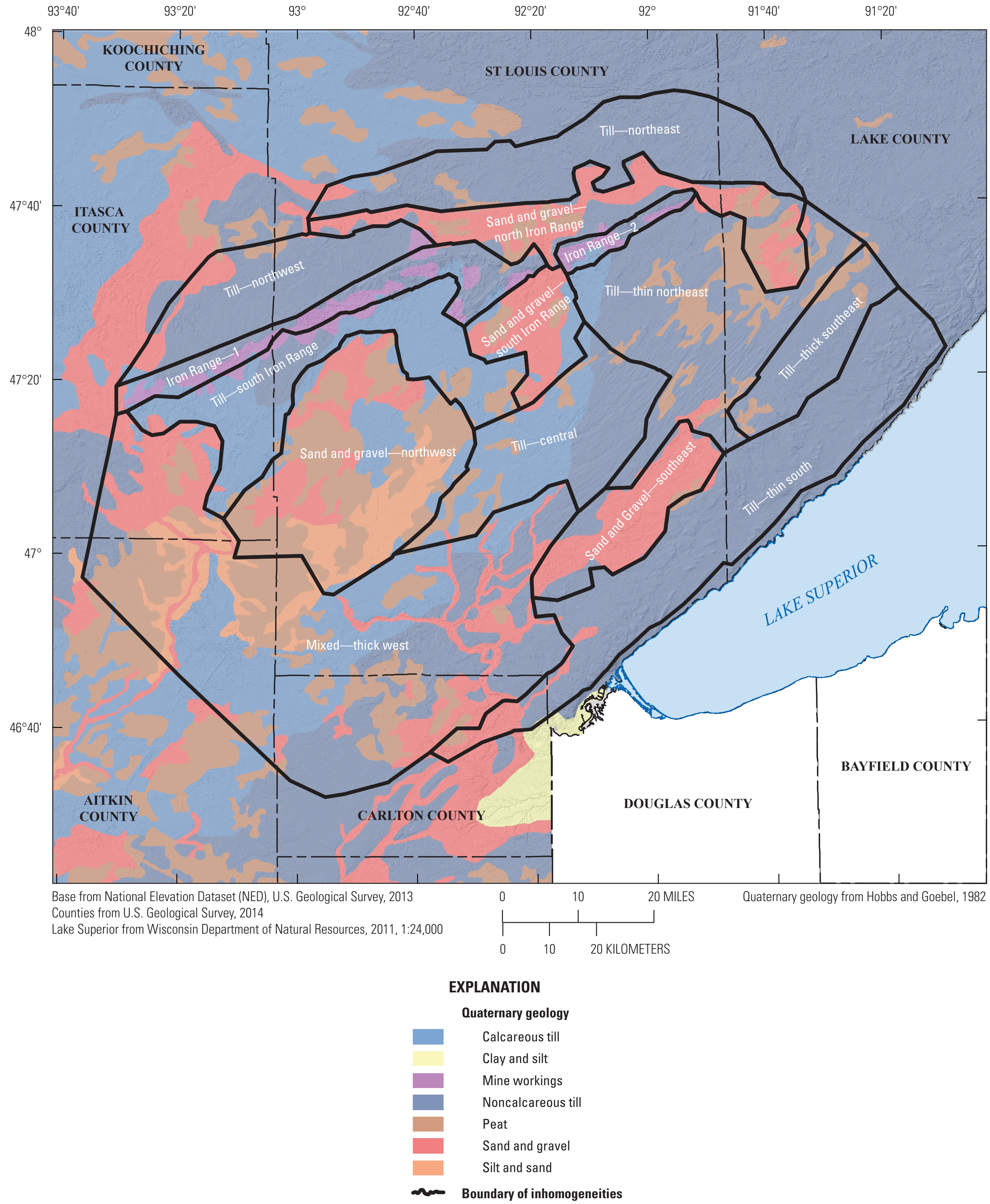
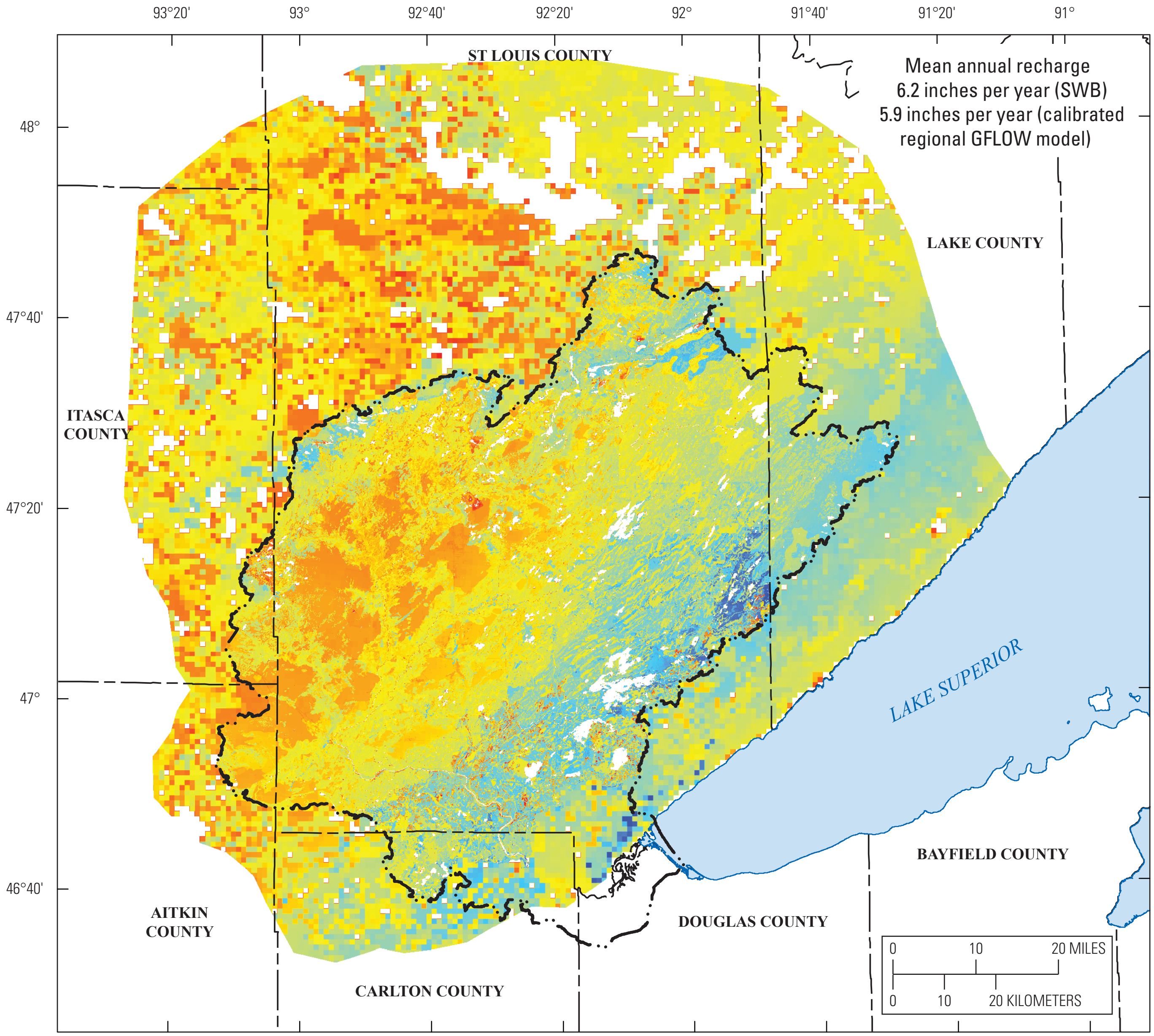


Figure 7. Inhomogeneities in the regional GFLOW model of the St. Louis River Basin, northeastern Minnesota.



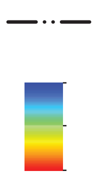
Base from U.S. Geological Survey and Wisconsin Department of Natural Resources digital data
St. Louis River Hydrologic Unit Boundary from U.S. Geological Survey, 2006, 1:250,000
Counties from U.S. Geological Survey, 2014
Lake Superior from Wisconsin Department of Natural Resources, 2011, 1:24,000

Recharge for areas outside the St. Louis River Basin from Smith and Westenbroek, 2015
Recharge for areas inside the St. Louis River Basin from Smith, 2017

EXPLANATION

St. Louis River Basin

Estimated groundwater recharge from SWB, in inches per year



High : 16.6

Low : 0

Figure 8. Soil-water-balance (SWB) recharge distribution in the domain of the regional GFLOW model of the St. Louis River Basin, northeastern Minnesota.

the observations to the estimated parameters (for example, Doherty and Hunt, 2010). SLRB observations were variably weighted to address differences in data quality, applicability for model objectives, information content, proximity to the Iron Range (where mining may produce highly transient target data that may poorly reflect the steady-state period), proximity to the bluff along Lake Superior, location uncertainty, and temporal variability (for example, Anderson and others, 2015, p. 400–401). Additional weight was added to large flux observations from downstream gages to better constrain the recharge multiplier. Weighting was also used to prevent a single group or target type from dominating the objective function. In general, targets that were farther from the nearfield area of interest were assigned lower weights; targets in the farfield were used to better constrain the area surrounding the Iron Range area of interest. A total of 9,672 weighted observations (9,631 head observations, 40 flow measurements, and 1 composite flooding parameter) were included in the calibration process; weighting for the observation groups is given in table 2. A full set of calibration targets is provided in the ancillary directory of the accompanying model archive for this report (Haserodt and others, 2019).

Table 2. Summary of target groups and weighting for the regional GFLOW model of groundwater flow in the St. Louis River Basin, northeastern Minnesota.

[In the exponential notation used, 2.0E−02 represents 2.0×10^{-2}. MDNR, Minnesota Department of Natural Resources; MPCA, Minnesota Pollution Control Agency; USGS, U.S. Geological Survey; lidar, light detection and ranging]

Observation group	Weight	Explanation
lakes_ff	1.0E−01	Farfield lake observations from the MDNR lake-level records (http://www.dnr.state.mn.us/lakefind/index.html)
lakes_nf	1.0E−01	Nearfield lake observations from the MDNR lake-level records (http://www.dnr.state.mn.us/lakefind/index.html)
lakes_ir	2.0E−02	Lake observations from the MDNR lake level records near mining features (http://www.dnr.state.mn.us/lakefind/index.html) within a 0.5-mile buffer of mining features
mn_flux	Varies with streamflow rate	Flux observations for smaller rivers from the MDNR/MPCA Cooperative Stream Gaging database (http://www.dnr.state.mn.us/waters/csg/index.html)
mn_flux_lg	Varies with streamflow rate	Flux observations for large rivers from the MDNR/MPCA Cooperative Stream Gaging database (http://www.dnr.state.mn.us/waters/csg/index.html)
mnhead_ff	3.0E−02	Farfield head observations from the Minnesota Well Index (https://www.health.state.mn.us/communities/environment/water/mwi/index.html)
mnhead_nf	5.0E−02	Nearfield head observations from the Minnesota Well Index (https://www.health.state.mn.us/communities/environment/water/mwi/index.html)
mnhead_ir	1.0E−02	Nearfield head observations from the Minnesota Well Index (https://www.health.state.mn.us/communities/environment/water/mwi/index.html) within 0.5-mile buffer of mining features
mnheadff_blf	1.0E−01	Head observations from the Minnesota Well Index (https://www.health.state.mn.us/communities/environment/water/mwi/index.html) near the Lake Superior shoreline
nws_dv	Varies with streamflow rate	Flux observations from smaller river USGS streamgages with daily streamflow values (https://waterdata.usgs.gov/nwis)
nwis_dv_lg	Varies with streamflow rate	Flux observations large river USGS streamgages with daily streamflow values (https://waterdata.usgs.gov/nwis)
nwisdv_ir	Varies with streamflow rate	Flux observations from smaller river USGS streamgages (https://waterdata.usgs.gov/nwis) within 0.5-mile buffer of mining features
nwis_rel	Varies with streamflow rate	Flux observations using relation lines and data from USGS partial-record stations (https://waterdata.usgs.gov/nwis)
pits	1.0E−02	Head observations for inactive mine pits using water elevations from the 2011 lidar (MDNR, 2011)
barr	2.0E−01	Head targets from the Barr groundwater model (Barr Engineering Company, 2015)
fld_red	2.6E−03	Composite flood-reduction target using head values calculated at the GFLOW extract grid

The model was calibrated to the weighted observations by automated adjustment of model inputs until a satisfactory level of fit between the model outputs and field observations was obtained (Anderson and others, 2015, p. 402–409). Once parameters that gave the best fit were determined, they were evaluated for reasonableness given what is known about the model area. Once both reasonable parameters and a best fit were obtained, the model was deemed calibrated.

Calibration Results and Discussion for the Regional GFLOW Model

The results of fitting between the measured targets and the model results are shown spatially (figs. 9 and 10) and as observed-to-simulated 1:1 plots (figs. 11 and 12); observed heads and base flows were generally well simulated by the regional model. The simplification of the natural system and the lower weight of farfield targets resulted in some spatial bias in the model's ability to fit the farfield measured data, however. For example, head residuals showed some spatial bias with low simulated heads in the southern region of the model (fig. 9); bias in this area was deemed acceptable because it is considered part of the model farfield and is distant from the model nearfield centered on the Iron Range. Near the Iron Range, observations may not be well simulated because mining operations were not expressly simulated in the regional model.

Parameter identifiability (Doherty and Hunt, 2009) was also calculated (fig. 13) for the 20 regional model parameters. In figure 13, dark bars represent calibration data providing high support for estimation of the parameter shown on the x-axis. For example, estimation of the tied hydraulic conductivities in the Iron Range ("Iron Range 1 and 2" in fig. 13*A*) is well constrained by the observations; the "Linesink resistance—group 1" is not constrained by the observation data used for calibration (no color or bar is associated with parameter "Linesink resistance—group 1" in fig. 13*B*). In general, forecasts that depend on parameters with low identifiability (light-colored bars) will have high uncertainty.

Simulated water table elevations from the steady-state (long-term average) model are shown in figure 14. Groundwater flows from high groundwater heads to lower heads, and flow direction is approximately perpendicular to the equal-elevation contour lines. Groundwater flow is generally south from the Iron Range and southwest across the rest of the SLRB. The results show groundwater recharge throughout the basin as well as along the Iron Range, except for pumped mine pits. Groundwater discharges to rivers and wetlands within the SLRB and to Lake Superior. A map of simulated flooding (fig. 10), where modeled groundwater elevation is above the land surface, generally corresponds with mapped wetlands and suggests groundwater discharge to these wetland features. Flooding where there are no mapped wetlands, particularly along the western edge of the model and parts of the Iron Range, is likely caused by the farfield simplifications such as a lack of linesink features that would lower the head solution in these regions. Nonrepresentative model results for farfield areas such as the western edge of the regional model domain were deemed acceptable because the farfield was not a primary objective of model calibration. A cross section (fig. 15) from the southeastern edge of the model to the northwest (cross-section trace shown in fig. 10), shows that the simulated water table is generally at or below land surface. The section in figure 15 with zero vertical exaggeration demonstrates that the thickness of the unconsolidated aquifer is negligible compared to the horizontal extent of the aquifer, supporting use of the Dupuit-Forchheimer (DF) approximation used by the analytic-element regional model (discussed in the "Assumptions and Limitations of the Regional GFLOW Model" section).

Because a two-dimensional, areal model of groundwater flow simulates aquifer transmissivity, an equivalent horizontal hydraulic conductivity was calculated from the optimal model transmissivity by using average saturated thickness within an inhomogeneity (fig. 16). The saturated thickness used represented an average thickness of the unconsolidated deposits within an inhomogeneity plus the upper 150 feet of bedrock, assumed to be connected via fractures; therefore, calculated horizontal hydraulic conductivities reported represent a bulk property for the combined upper fractured bedrock and unconsolidated aquifer. Inhomogeneities representing sand and gravel deposits tended to have relatively high hydraulic conductivity values (11–39 feet per day) (fig. 16). Calibrated horizontal hydraulic conductivity values for areas characterized as having more till were generally lower than for areas with sand and gravel deposits but were higher than might be expected (6–27 feet per day) from regional till literature values (table 1). Although the inhomogeneity boundaries (fig. 7) were based on predominant grain size (coarser sand/gravel versus till within the inhomogeneity), the small number of piecewise-constant inhomogeneities covering such large areas could not capture the detail of the local lithologic units, including small-scale, high-conductivity units within the till inhomogeneities. In addition, a predominately sandy lithology was reported for till associated with the Rainy and Superior Lobes and may suggest that these tills have higher than typical hydraulic conductivity values for a till (Minnesota Geological Survey, 2013). In the Iron Range area of interest, the calibrated equivalent hydraulic conductivity values were similar to the average calibrated horizontal hydraulic conductivity in Barr (2015) of 19.2 feet per day for upland areas and 23.7 feet per day for wetland areas. Average calibrated values (3 and 4 feet per day) for the two Iron Range bedrock units were also within the range of hydraulic conductivity estimates (0.2–16 feet per day) presented in Barr (2011) for the Biwabik Iron-Formation.

Average recharge across the calibrated model was 5.9 inches per year (fig. 8). Recharge occurs across the model domain as terrestrial recharge originating as rain and snowmelt.

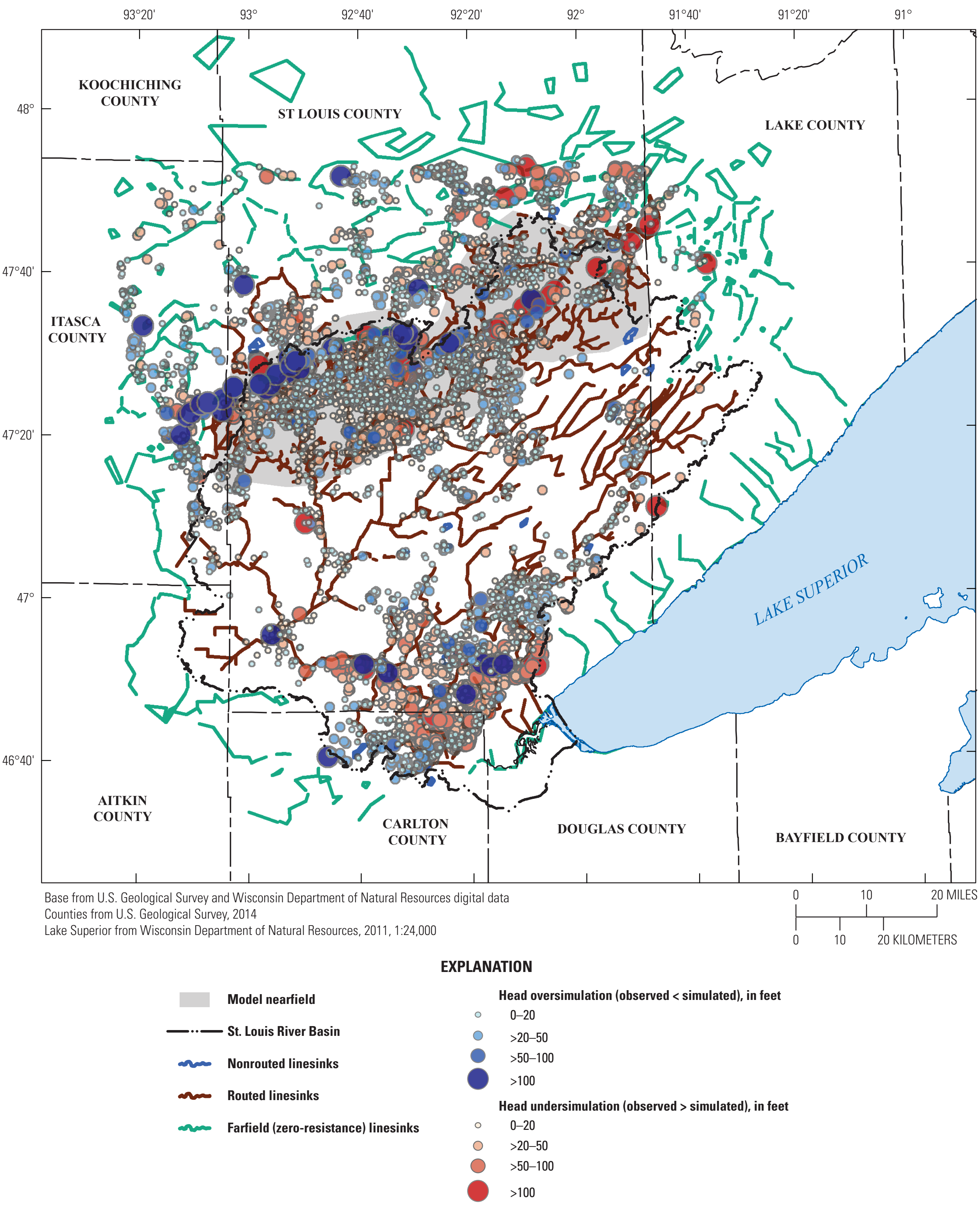


Figure 9. Spatial distribution of head target residuals, where symbol size is scaled to residual magnitude, for the regional GFLOW model of the St. Louis River Basin, northeastern Minnesota.

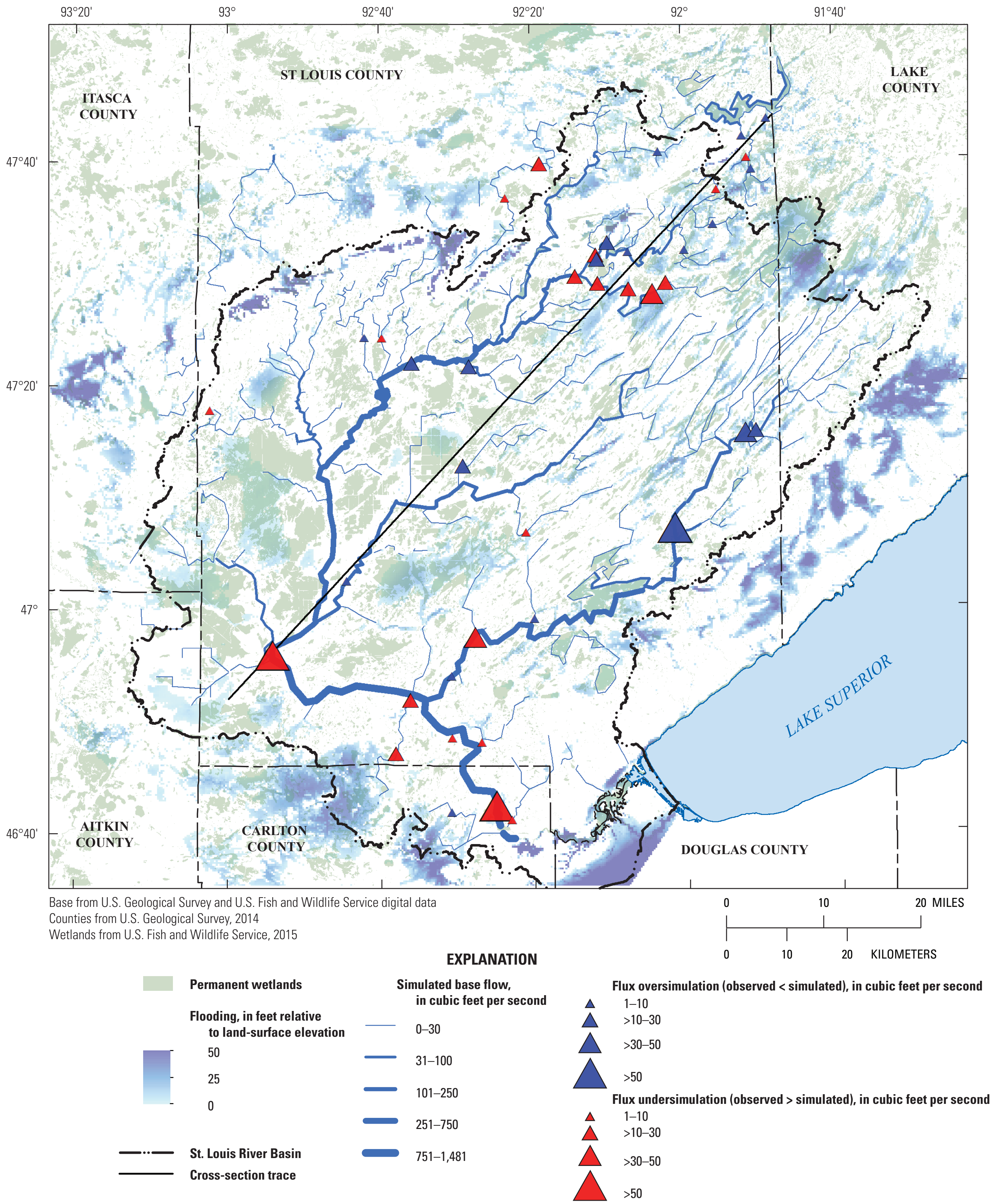


Figure 10. Spatial distribution of flux target residuals, where symbol size is scaled to residual magnitude, and locations of flooding where modeled heads exceed the land surface for the regional GFLOW model of the St. Louis River Basin, northeastern Minnesota. A cross-section trace is provided for the cross section presented in figure 15.

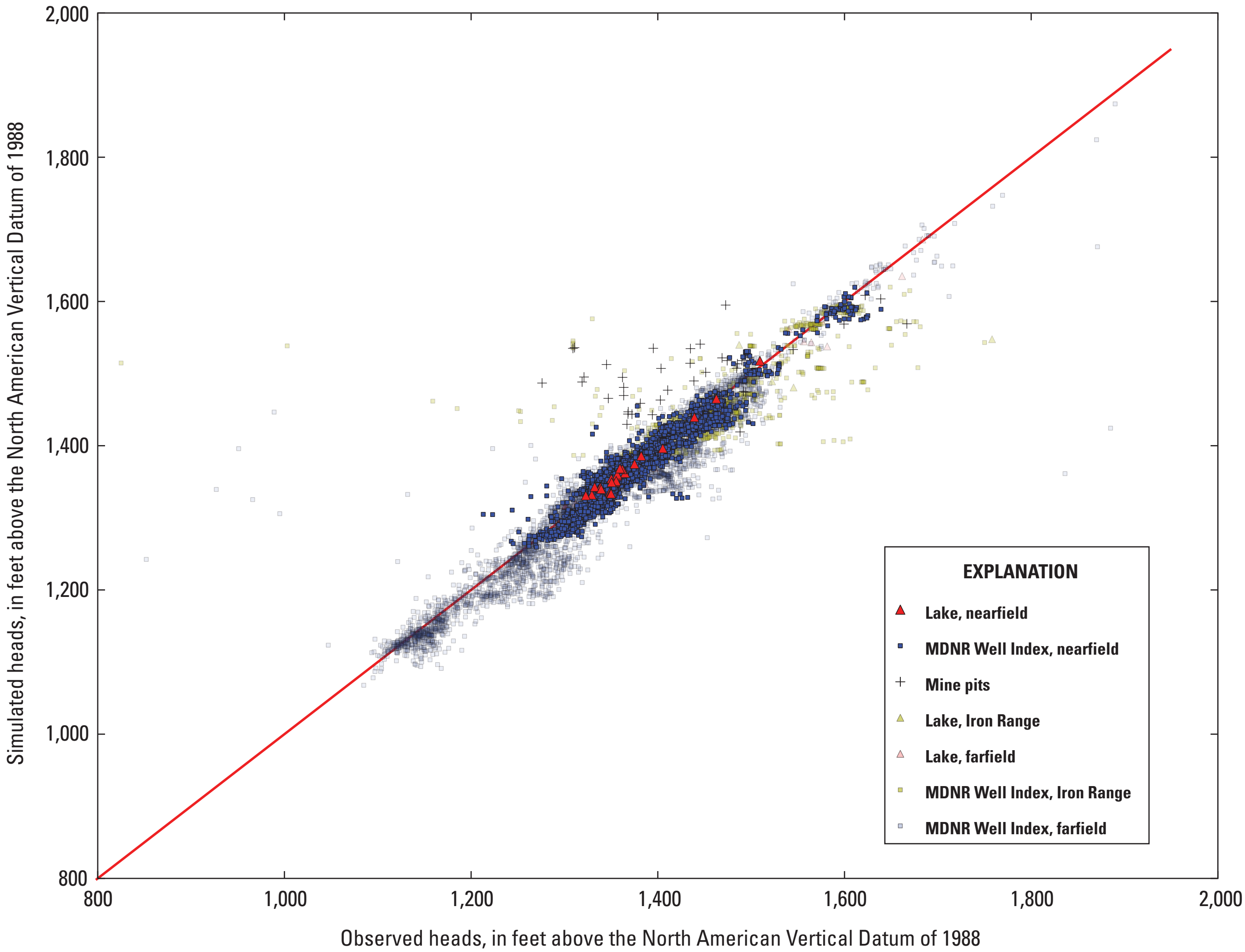


Figure 11. Comparison of simulated and observed heads for the regional GFLOW model of the St. Louis River Basin, northeastern Minnesota. Diagonal red 1:1 line indicates perfect fit. MDNR, Minnesota Department of Natural Resources.

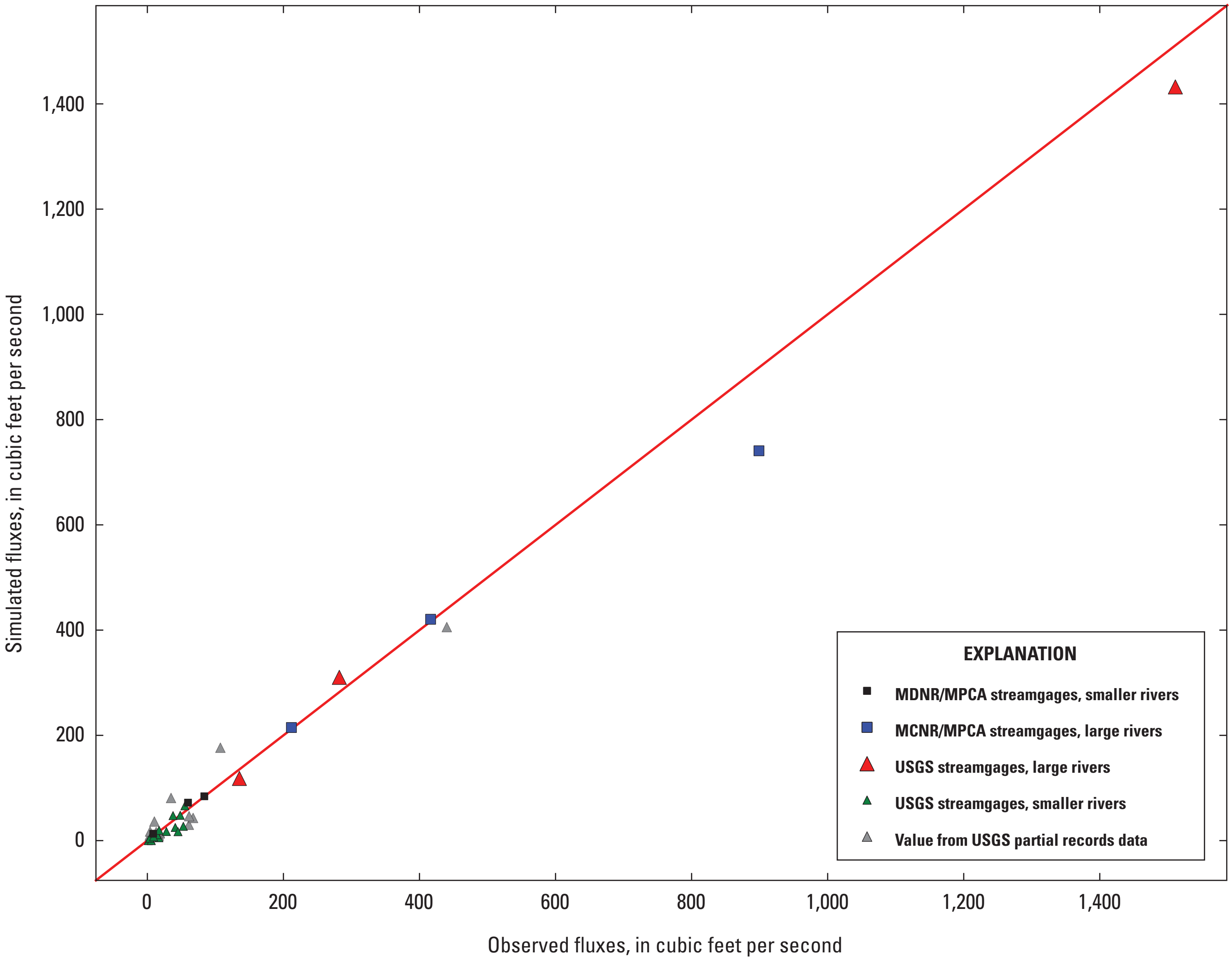


Figure 12. Comparison of simulated and observed fluxes for the regional GFLOW model of the St. Louis River Basin, northeastern Minnesota. Diagonal red 1:1 line indicates perfect fit. MDNR, Minnesota Department of Natural Resources; MPCA, Minnesota Pollution Control Agency; USGS, U.S. Geological Survey.

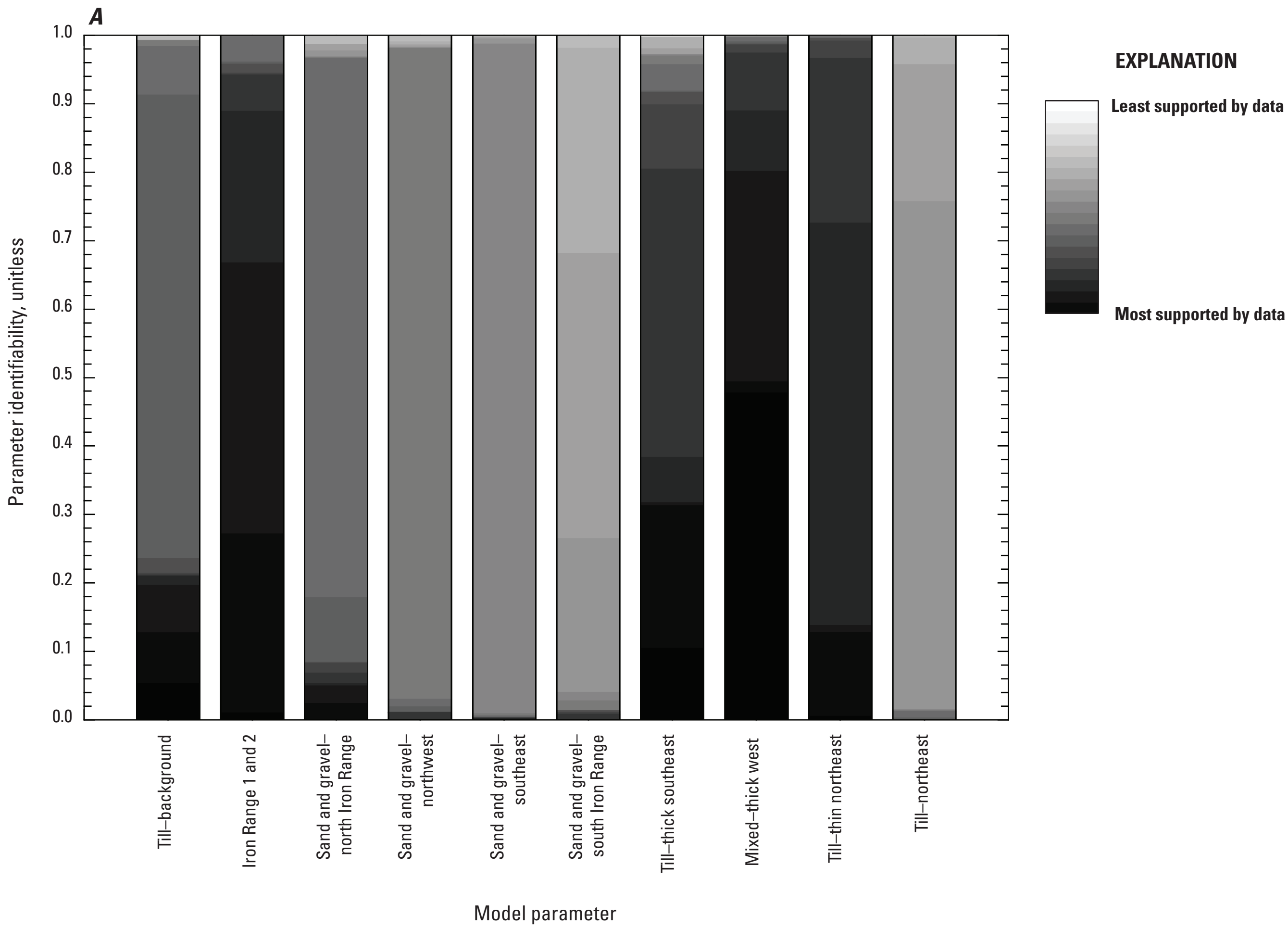


Figure 13. *A* and *B*, Parameter identifiability for the regional GFLOW model of the St. Louis River Basin, northeastern Minnesota.

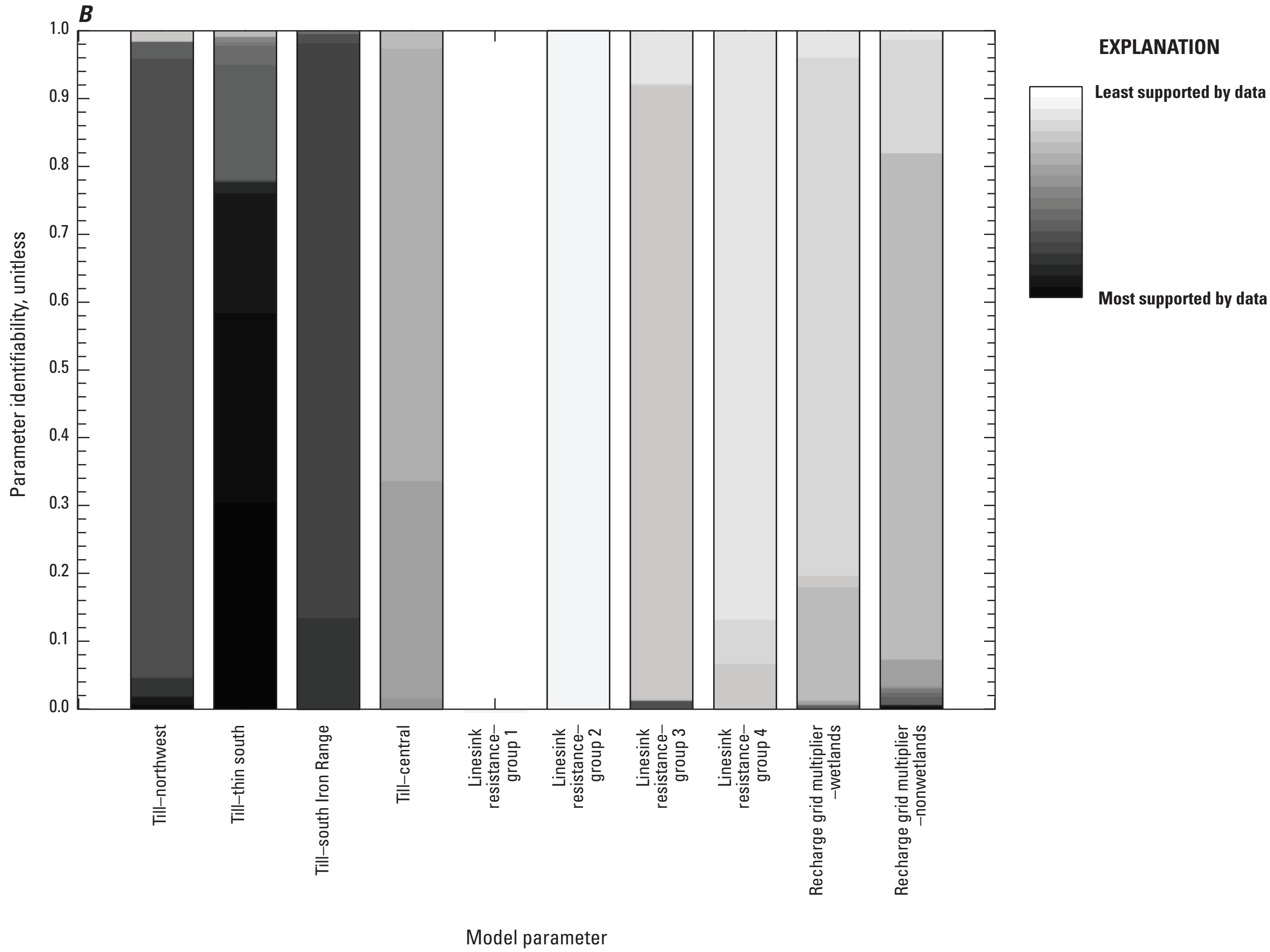


Figure 13. *A* and *B*, Parameter identifiability for the regional GFLOW model of the St. Louis River Basin, northeastern Minnesota.—Continued

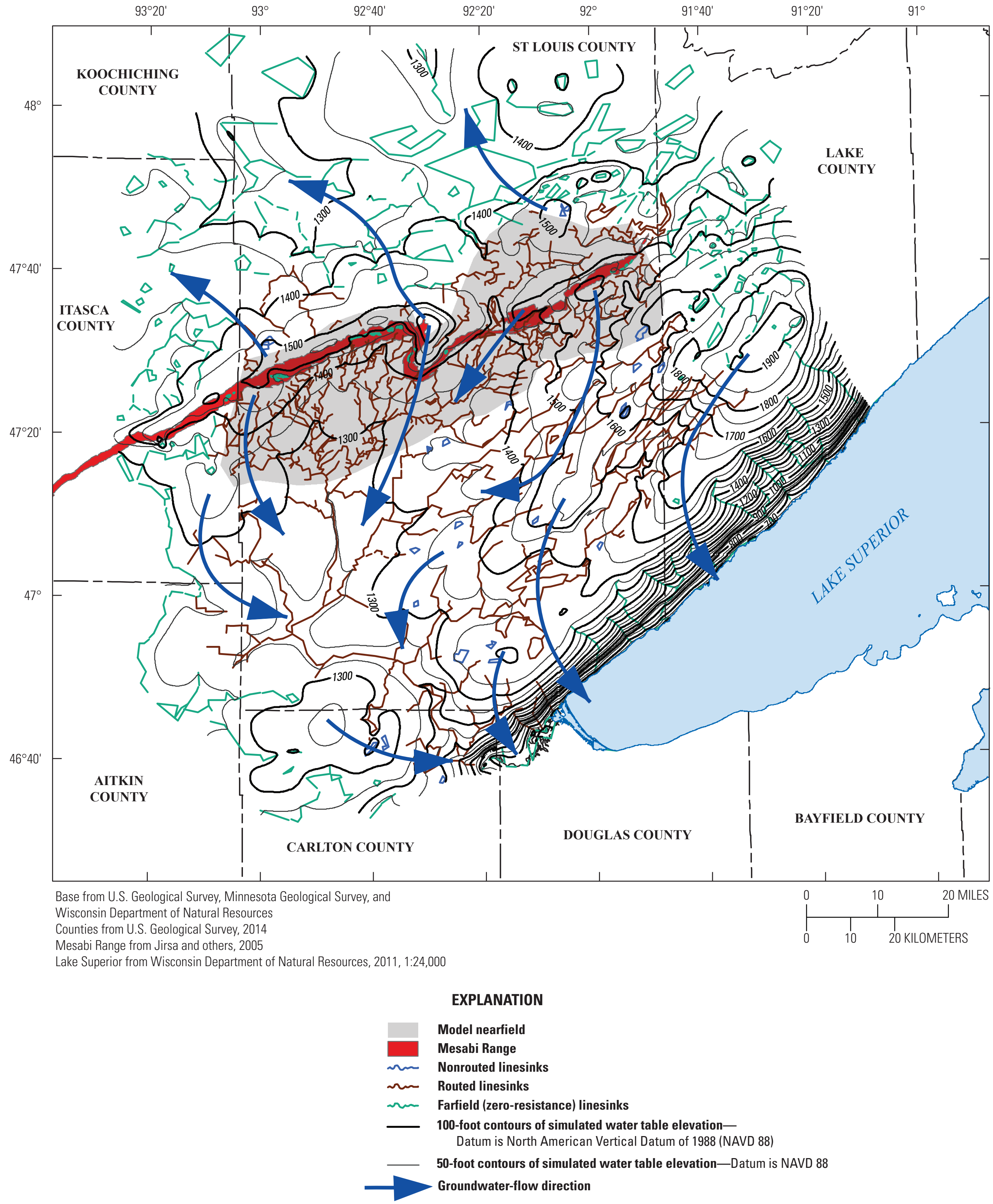


Figure 14. Modeled water table elevation across the domain of the regional GFLOW model of the St. Louis River Basin, northeastern Minnesota.

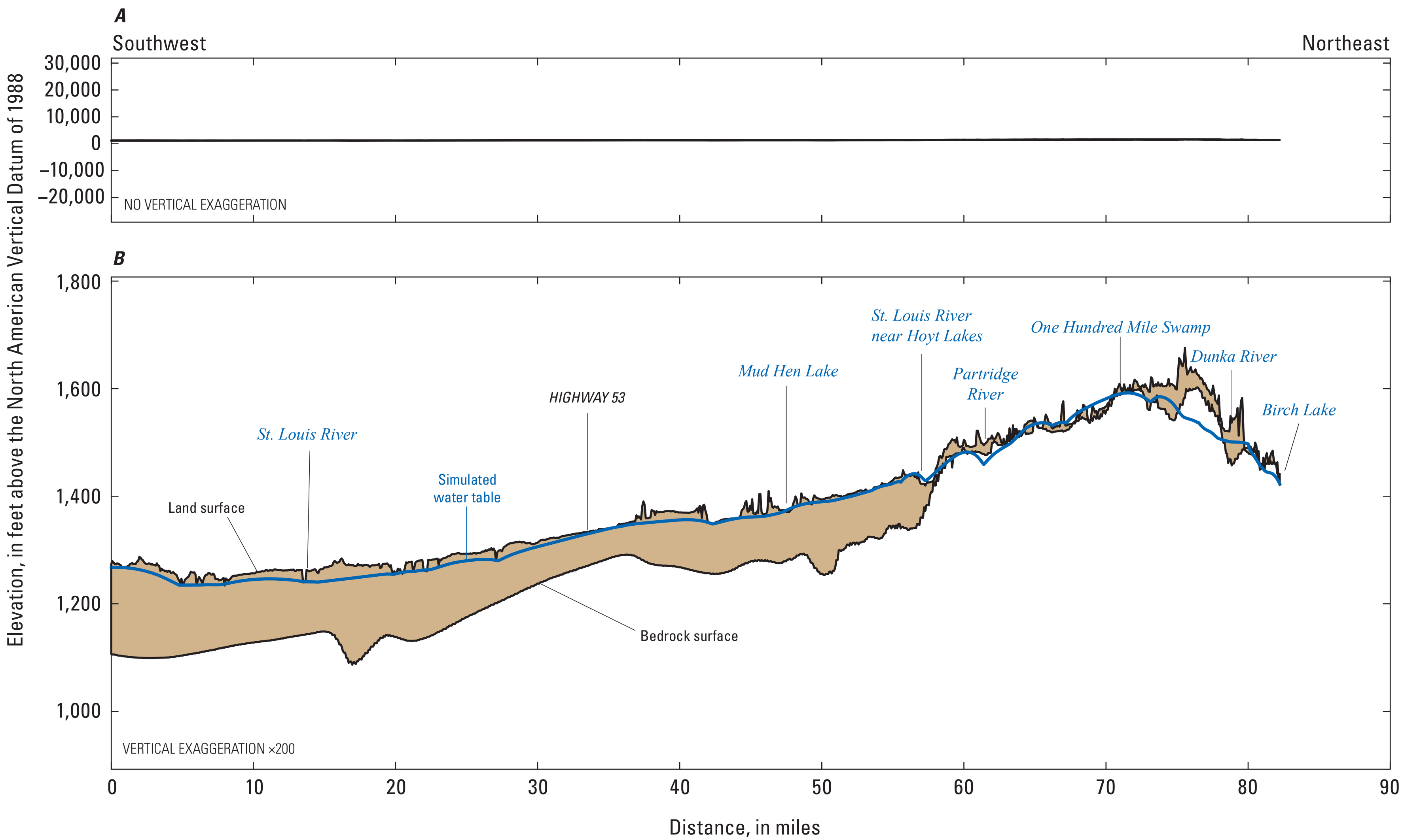
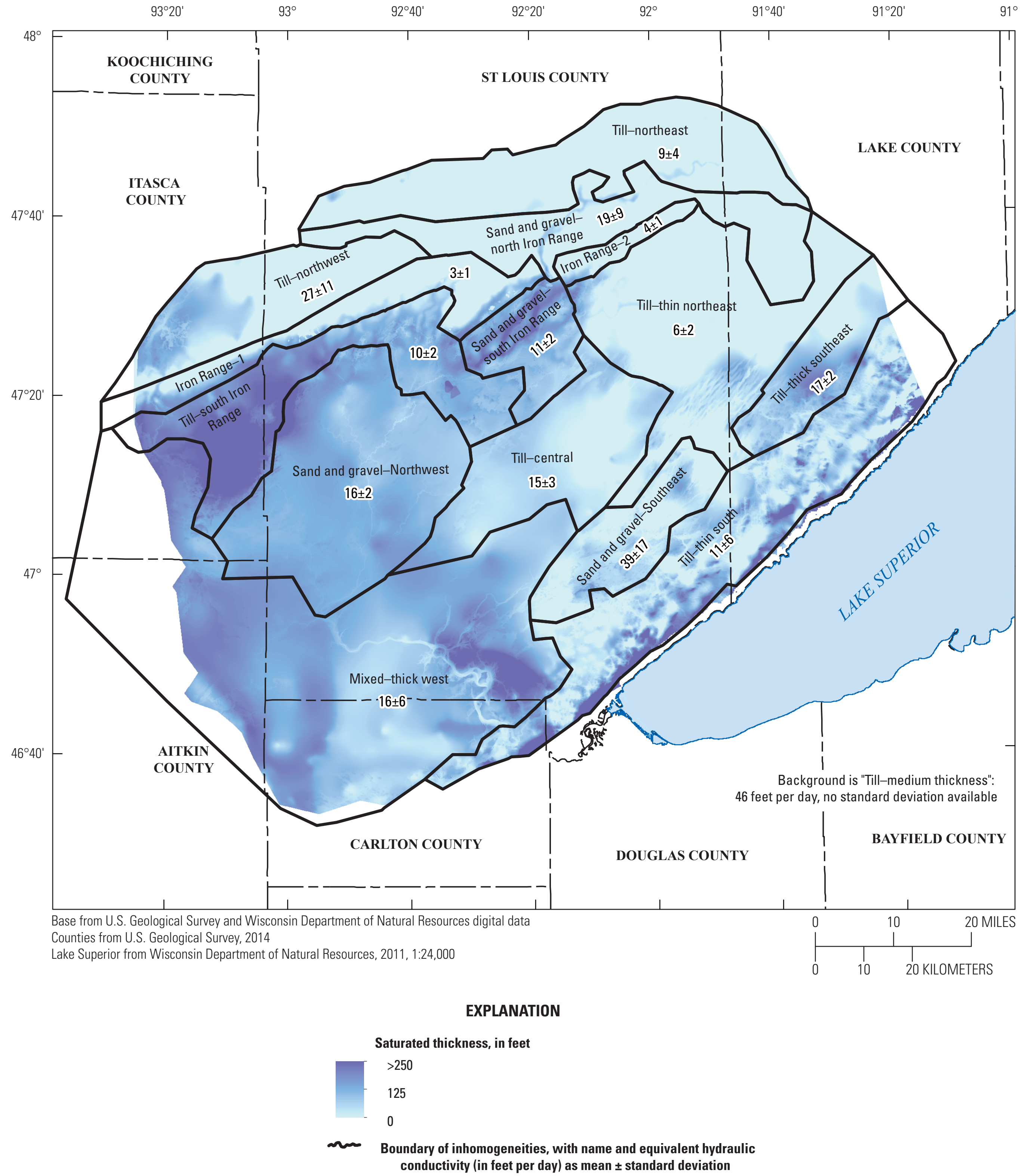


Figure 15. Unconsolidated deposit thickness and water table elevation along trace shown in figure 10, St. Louis River Basin, northeastern Minnesota. Cross section is shown with both *A*, 0× and *B*, 200× vertical exaggeration.



Base from U.S. Geological Survey and Wisconsin Department of Natural Resources digital data
Counties from U.S. Geological Survey, 2014
Lake Superior from Wisconsin Department of Natural Resources, 2011, 1:24,000

Figure 16. Modeled saturated thickness in the unconsolidated aquifer and equivalent hydraulic conductivity for the inhomogeneities in the regional GFLOW model of the St. Louis River Basin, northeastern Minnesota. The equivalent hydraulic conductivity for areas outside the inhomogeneities (Till—medium thickness parameter) is presented as a note on bottom right of the figure.

Assumptions and Limitations of the Regional GFLOW Model

The SLRB regional model, like all models, is a simplification of a natural system of unknowable complexity. Local complexities, such as wetlands, hydrostratigraphy, irregular bedrock topography, and hydrologic changes resulting from mining operations were not explicitly simulated in the regional model. The representativeness of the simulation is also limited in areas where measured data were scarce. Regional properties are less affected by local complexities, and thus regional models such as the SLRB model can provide a useful quantitative framework for investigating large-scale questions related to the regional flow system and provide perimeter boundary conditions for inset models within the nearfield.

More specifically, the SLRB regional model documented here has the following simplifying assumptions:

- In the analytic-element model, the Dupuit-Forchheimer (DF) approximation used in two-dimensional areal groundwater flow is assumed to be appropriate. An areal two-dimensional groundwater-flow model was deemed to be appropriate because the aquifer is relatively thin and areally extensive (fig. 15)—the SLRB aquifer is on the order of hundreds of feet thick but extends several miles. The DF approximation is also supported by the relatively high hydraulic conductivity of the aquifer, relatively high groundwater-recharge rate, and presence of perennial streams (see Haitjema and Mitchell-Bruker, 2005). It should be noted that two-dimensional areal flow approximations do not mean that only horizontal flow can be simulated; vertical dimensions of flow in the regional model are solved by mass balance rather than Darcy's law (see Strack, 1989).
- The groundwater and surface-water systems are assumed to be in close hydrologic connection in the study area. As a result, elevations of surface-water features are assumed to approximate heads in the underlying groundwater system.
- Hydraulic conductivity and aquifer thickness parameters together are adequately represented with piecewise-constant zones (inhomogeneities) that extend over contiguous areas.
- A single value for the aquifer bottom elevation was assumed for the entire model. Because GFLOW simulates areal two-dimensional groundwater flow, aquifer transmissivities (hydraulic conductivity multiplied by aquifer thickness) are ultimately used to solve the groundwater-flow governing equation.
- The geometries of surface-water bodies are sufficiently represented for regional groundwater flow by strings of linesink elements.
- The areal distribution of recharge from the soil-water balance approach is representative for the SLRB. This assumption may be violated in wetlands and other areas where the water table is shallow and SWB may be overestimating recharge.
- Simulated conditions in the SLRB are assumed to be at steady state (that is, the simulation represents long-term average conditions where heads do not change over time, and thus water stored in the system does not change). As a result, all input stresses to the model, including recharge rates, stream stages, and mine-pit elevations represent long-term average values. This assumption may not be well suited for representing local groundwater flow influenced by dynamic mine-pit operation.
- The construction and calibration of the model are focused on capturing behavior in the shallow part of the groundwater-flow system in the Iron Range area. This focus limits the use of the model to represent groundwater flow in local groundwater-flow systems in deeper bedrock, or areas distant from the nearfield area of interest.
- Future analyses of particle tracking and travel time with this model may be limited by the single aquifer base applied across the domain and the application of gridded recharge, which is applied by GLFOW to the bottom of the model. Furthermore, particle-tracking analyses should include a more in-depth assessment of aquifer porosity, which was outside the focus of this project.

Because of these simplifying assumptions, the regional model may not be suitable for simulating flow at smaller site scales, where local variations in aquifer properties and vertical gradients are potentially important. The single, flat base elevation of the aquifer is also not well suited for parts of the SLRB where aquifer thickness, upper bedrock properties, and bottom topography change greatly over short distances. In particular, some areas of the model domain, such as nearfield areas adjacent to pits on the Iron Range, have poor simulation to local water-level targets. Such areas are better simulated with a more heterogeneous three-dimensional inset model. Lastly, the model should not be used for particle-tracking applications because of how gridded recharge is applied by GFLOW.

Development of the Central St. Louis River Basin Model

The regional model was refined to focus on local ditching in the central SLRB, a wetland-rich area to the south of the Iron Range and centered on Floodwood, Minn. The purpose of the central SLRB model was to determine whether the extensive ditching in this area has affected hydraulic head and subsequent wetland extent and persistence in the basin. The effect of ditching was simulated by comparing two separate central SLRB model scenarios—one with the ditch network represented as linesinks and a “preditch” scenario with ditch linesinks removed. The central SLRB model was constructed by defining a new nearfield area of interest around the ditched areas and eliminating linesinks representing hydrologic features in distant areas of the SLRB to reduce model run time. Linesinks that existed in the regional model were refined by giving them greater density and detail, and additional linesinks were added to represent the ditch network by using data from the National Hydrography Dataset (NHDPlus v2; McKay and others, 2012). Ditch elevations were assigned by using 1-meter lidar data (MDNR, 2011) and were checked to ensure that the hydraulic heads decreased in the downstream direction. Ditches were given resistance values that were adjusted during local model calibration. Aquifer inhomogeneities beyond the new model farfield were removed; eight inhomogeneities remained and retained the geometry used in the regional model, with the exception of minor updates to obtain model solution stability where ditch linesinks crossed inhomogeneity boundaries. Because the steep bluff down to Lake Superior was eliminated from the domain, the aquifer base elevation was increased to 1,175 feet in the model to approximately match the aquifer base for the central SLRB model area (fig. 17). To reduce model run time, the northeastern part of the regional model was removed, as well as detail to the southeast, including Lake Superior. The new model farfield includes a reduced version of the original linesink geometry.

Central St. Louis River Basin Model Calibration

The central SLRB model, which was a local refinement of the regional model, was recalibrated to improve model performance in the central wetlands area of interest. The most downstream flux target with a complete basin in the ditch scenarios was the MDNR Whiteface River near Meadowlands Gage, no. 03055001 (approximately 2 miles downstream of the Meadowlands marker in fig. 17); the Meadowlands streamgage was the only flux target used in the recalibration. Head targets near the ditched wetlands are sparser than the density available for the regional model. Historical wetland hydrology that produced hydric soils that are persisting in the ditched areas was considered in the central SLRB model calibration. Therefore, the model calibration included two conditions: (1) a condition representative of present-day hydrology similar to the regional model that used current heads and fluxes as targets; and (2) a condition representative of the hydrology before ditching, where targets consisted of heads near land surface in the areas mapped as wetland. The former used the ditch scenario and had 3,784 head targets and one flux target from the State databases; calibration targets for the latter condition were developed by using a grid of 1,427 synthetic wetland head targets with a distribution defined by mapped wetlands in the National Wetlands Inventory (MDNR, 2009), where each target consisted of a head value equal to the land-surface elevation. Synthetic wetland targets were used in the preditch scenario. During the model calibration, both model scenarios (ditch and preditch) were run simultaneously using the same parameter values in each scenario, and the goodness-of-fit was calculated from the combined residuals of present-day heads and flows reflecting ditched conditions and preditch high-water levels in mapped wetland areas.

Ditch Scenario Results and Discussion

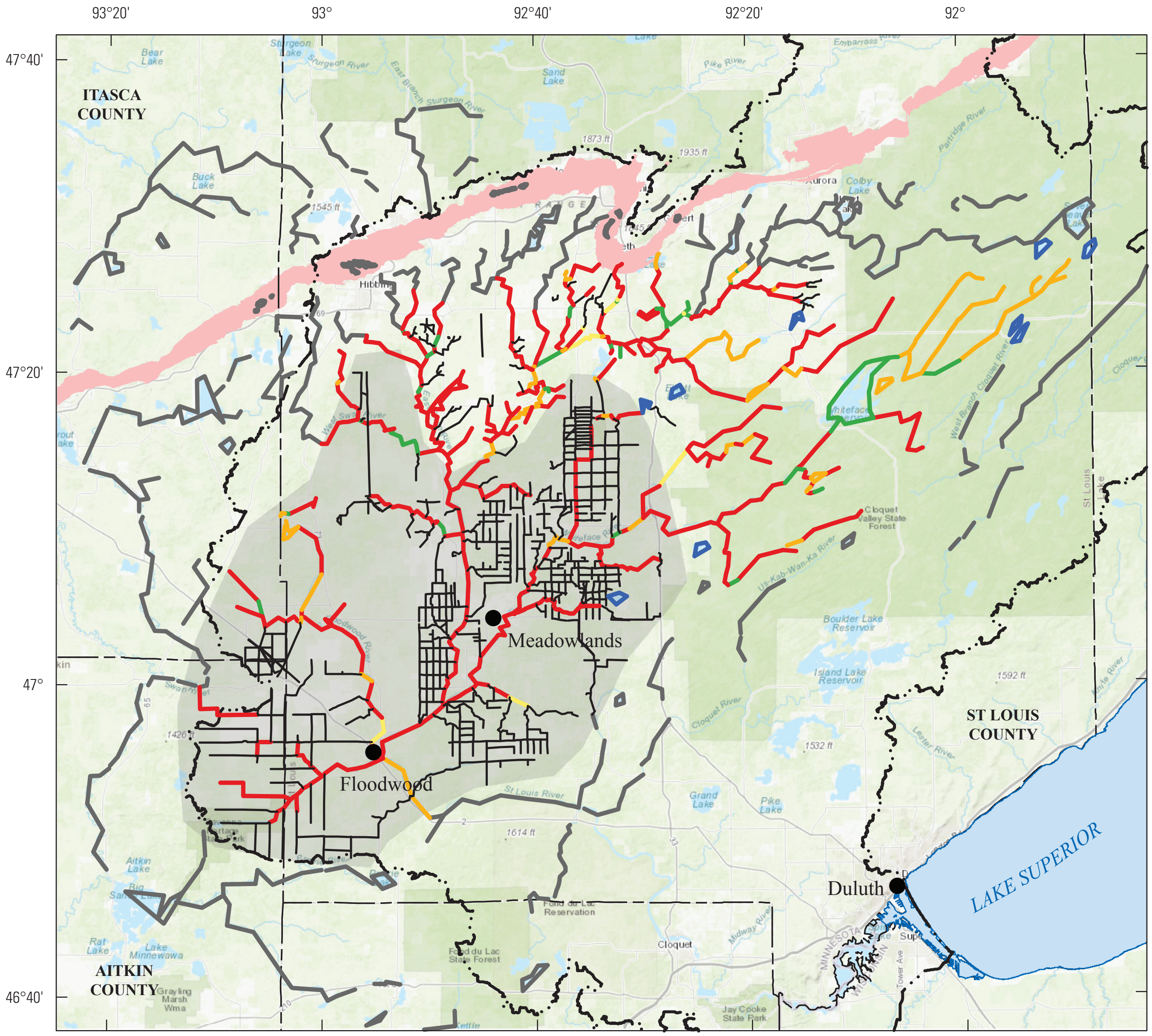
The approach of using both scenarios in the central SLRB model calibration improved the head solution (fig. 18) compared to the regional model in the central SLRB wetlands and had better agreement with the NWI wetland distribution (fig. 19). Appendix 1 presents more discussion of the calibration results. Even with the local refinement and calibration, modeled heads in some wetland areas were still undersimulated, most notably where mapped wetlands were adjacent to incised river valleys.

This undersimulation of heads may be the result of not modeling fine wetland materials, like peat, or any fine material supporting wetland conditions. Most of the ditched wetlands are within the “Sand and gravel—northwest” regional model inhomogeneity, which represents predominately sand and gravel Quaternary material. Local-scale heterogeneity in the glacial deposits was not represented in the local model but is likely a major factor in wetland distribution where fine material or extensive peat deposits with low hydraulic conductivity would support a higher water table. These local factors are not captured in the central SLRB model scenarios, which inherited the larger scale geologic units of the regional model. This lack of heterogeneity represents a limitation of the modeling process and available data (Hunt and others, 2007). However, compared to the regional model, the local model provides a more representative simulation of groundwater-wetland-ditch interaction in the central wetlands of the SLRB.

The updated calibration of the central SLRB model resulted in average horizontal hydraulic conductivity values of 5–36 feet per day for the glacial deposits and 3 feet per day for the uppermost fractured Iron Range bedrock. Average recharge across the ditch scenarios was 4.1 inches per year.

Assessment of Hydrologic Changes Due to Ditching

To assess the effect of ditching on wetland persistence and function, the extent of areas where the water table was 1 foot below the land surface or less (a wetland hydrology indicator; U.S. Army Corps of Engineers, 2010, p. 75), including areas with a modeled water table above land surface, was compared between the preditch and ditch scenarios. The 1-foot criterion was arbitrarily chosen as being representative of areas with a high enough modeled water table to potentially



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St. Louis River Hydrologic Unit Boundary from U.S. Geological Survey, 2006, 1:250,000
Counties from U.S. Geological Survey, 2014
Mesabi Range from Jirsa and others, 2005
Lake Superior from Wisconsin Department of Natural Resources, 2011

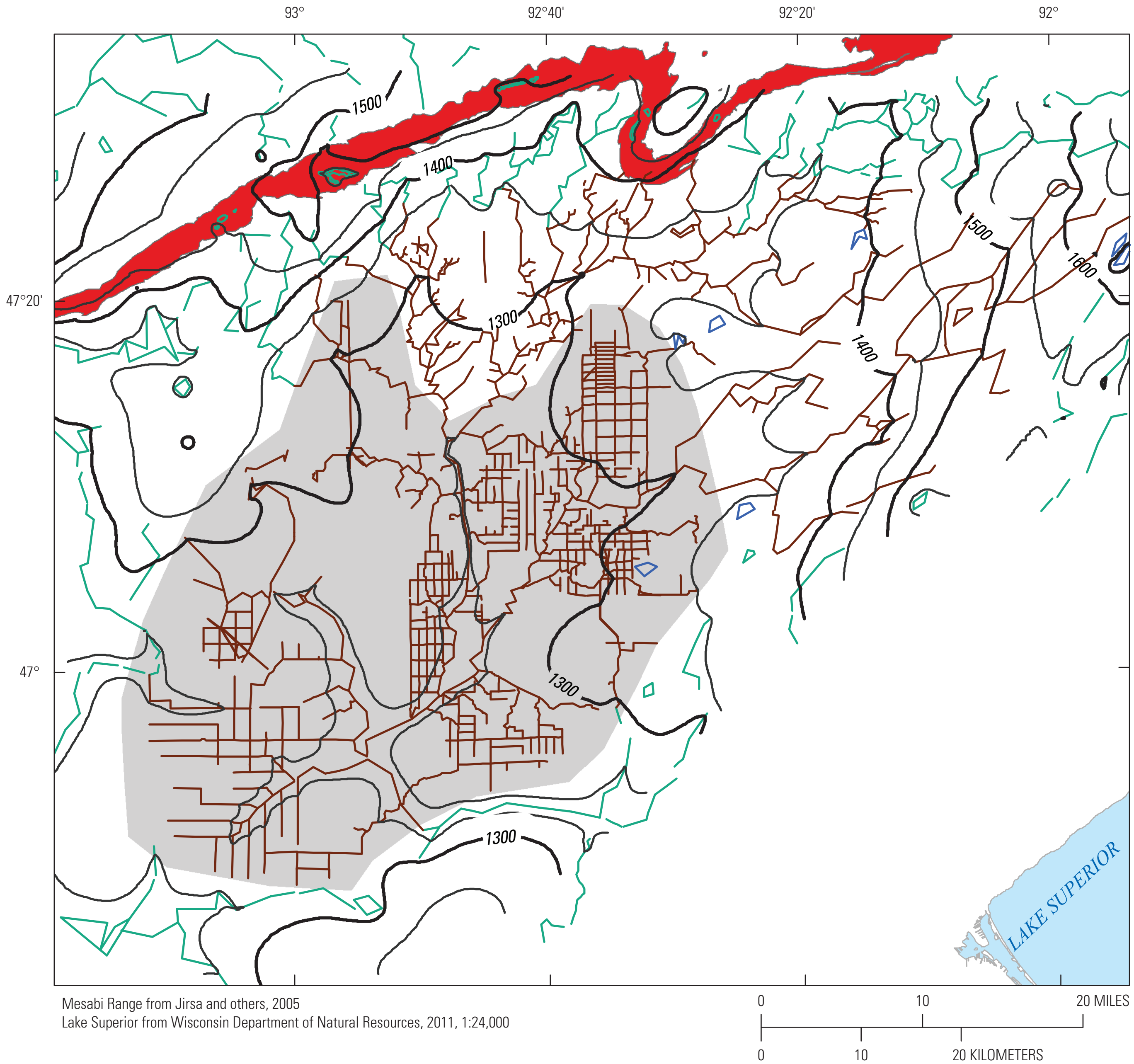
0 10 20 MILES
0 10 20 KILOMETERS

EXPLANATION

Mesabi Range
Model nearfield
Farfield (zero-resistance) linesinks
Nonrouted linesinks
St. Louis River Basin

Routed linesinks groups with soil hydrologic group
Ditch
Group 1–A
Group 2–B
Group 3–C
Group 4–D, A/D, B/D, C/D

Figure 17. Ditching scenario with linesinks in the central St. Louis River Basin model of groundwater flow, northeastern Minnesota.



EXPLANATION

- **Model nearfield**
- **Mesabi Range**
- **100-foot groundwater elevation contours, with labels**—Datum is North American Vertical Datum of 1988 (NAVD 88)
- **50-foot groundwater elevation contours**—Datum is NAVD 88
- **Nonrouted linesinks**
- **Routed linesinks**
- **Farfield (zero-resistance) linesinks**

Figure 18. Head solution from the ditch scenario of the central St. Louis River Basin model of groundwater flow, northeastern Minnesota.

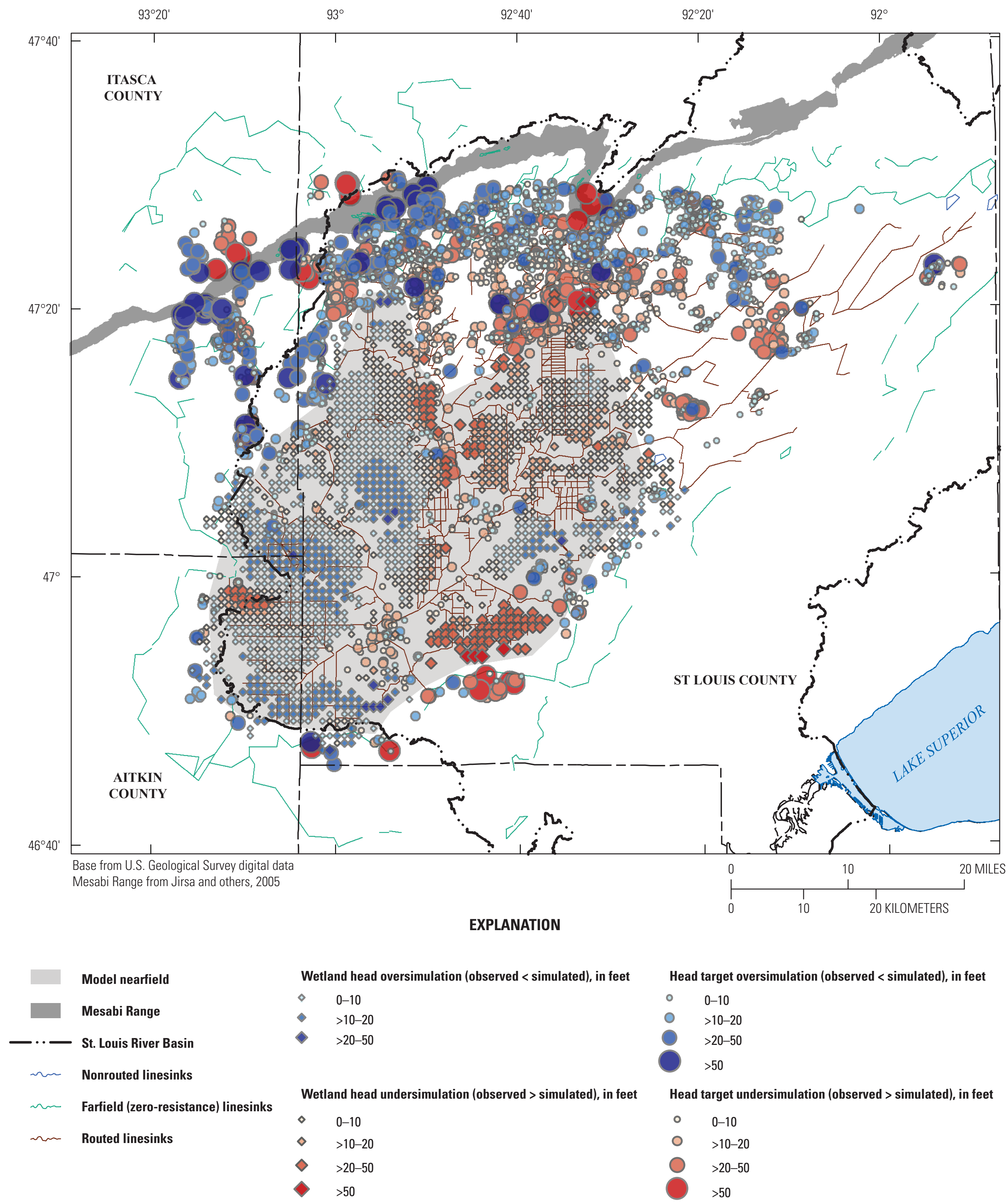


Figure 19. Spatial distribution of head target residuals from the ditch scenario of the central St. Louis River Basin model of groundwater flow, northeastern Minnesota, where symbol size is scaled to residual magnitude.

support permanent wetlands and is referred to in this report as “areas with a shallow water table.” Nearfield areas with a shallow water table in the preditch scenario of the central SLRB model correspond reasonably well (fig. 20) to the NWI wetland coverage filtered to represent permanent wetlands; this includes wetlands with water regime types F (semipermanently flooded), G (intermittently exposed), H (permanently flooded), and select B (saturated) type wetlands that correspond to peatlands (U.S. Fish and Wildlife Service, 2015).

The total area with a shallow water table was compared between the preditch and ditch scenarios to assess how much area of mapped wetlands potentially had changes in water table elevation due to ditching. For this assessment, only areas with a shallow water table that were also mapped as permanent wetlands (MDNR, 2014, 2017; Kloiber, 2017) were included, and model areas with a shallow water table and no mapped wetlands were excluded. The estimate of potentially affected wetlands is likely low if the wetlands experienced enough hydrologic changes to no longer be mapped as permanent wetlands in the wetland survey. Overall, the ditch scenario of the central SLRB model has less mapped wetland area that has a modeled water table within 1 foot of land surface than the preditch scenario (fig. 21). The change in area with a shallow water table suggests that the ditches are effective at routing water away from some parts of the central wetlands of the SLRB. Using the criterion of a water table within 1 foot of land surface and only considering changes in areas of mapped permanent wetlands, comparison of the total shallow water table area in the preditch and ditch scenarios suggests that ditching potentially affects wetland persistence or function in as much as 40,000 acres, or 37 percent, of mapped permanent wetlands in the central SLRB (fig. 21). If the evaluation were not restricted to areas presently mapped as wetlands, then as much as 100,000 acres, or 41 percent of areas with a simulated water table within 1 foot of the land surface in the model without ditches, may have been affected. The number of wetland acres potentially affected by ditching is a somewhat qualitative assessment of where hydrologic changes may have occurred; a more quantitative assessment of changes to wetland areas would benefit from more detailed modeling focused on wetland hydrology as well as from ground-truthing the model results using, for example, historical aerial photographs and measurements of present-day water levels in the wetlands.

Assumptions and Limitations of the Central St. Louis River Basin Model Scenarios

In addition to the assumptions and limitations of the regional model, the following assumptions were made for the central SLRB model scenarios:

- The heterogeneity reflected by the regional model inhomogeneities was sufficient to capture the major hydrologic processes driving the distribution of wetlands.
- The system represented by the regional model inhomogeneities and recharge grid was sufficient to capture the primary hydrologic processes in the area of the ditches.
- The two-dimensional simulation that results from the Dupuit-Forchheimer approximation is sufficient for representing the large-scale groundwater and surface-water interaction between the aquifer and ditches.

While the distribution of modeled heads at or near the land surface matched many of the mapped wetlands, some wetlands were not well represented by the model results. There are likely wetland processes, vertical flow, and small-scale heterogeneity that are not being captured by the ditch scenarios, which maintained heterogeneity in the surficial deposits that was mappable at the scale of the regional model. A detailed, MODFLOW (Langevin and others, 2017) modeling effort focused on the wetlands may provide a better assessment of changes in wetland hydrology.

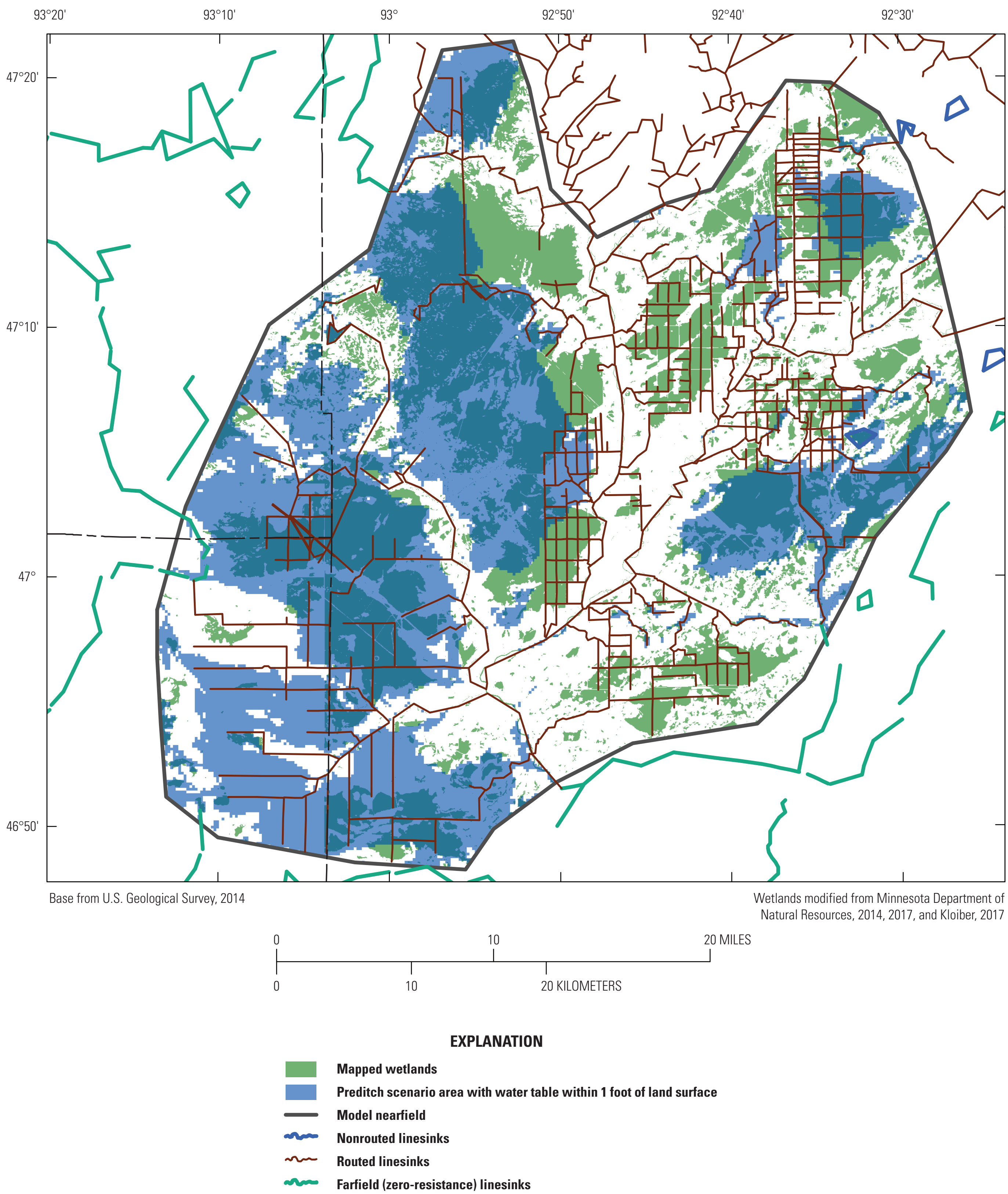


Figure 20. Comparison of permanent wetlands as mapped by the National Wetland Inventory to flooded areas of the preditch scenario head solution in the central St. Louis River Basin model of groundwater flow, northeastern Minnesota.

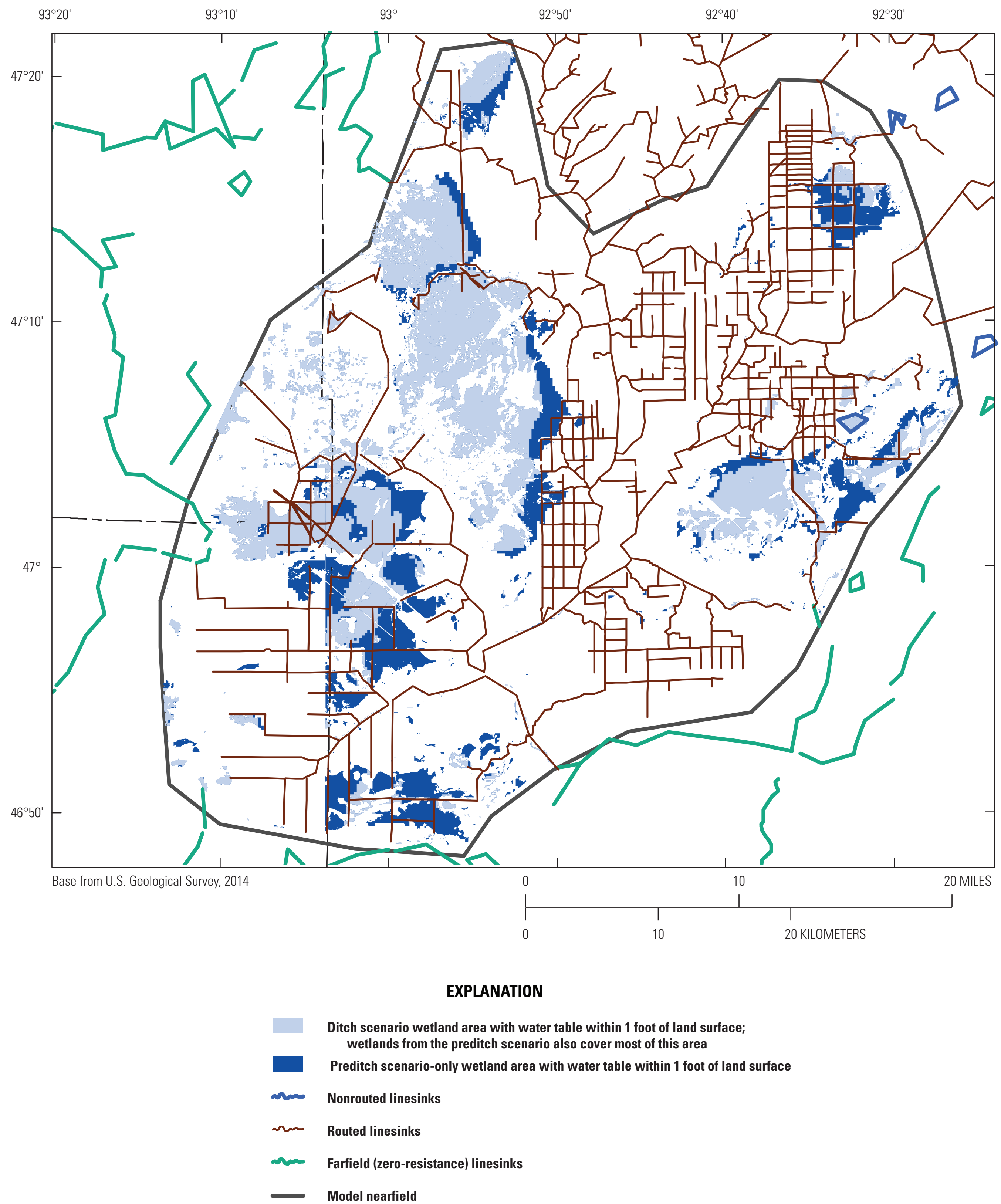


Figure 21. Comparison of flooded areas (wetlands) from head solution of preditch to ditch scenarios in the central St. Louis River Basin model of groundwater flow, northeastern Minnesota.

Summary and Conclusions

The U.S. Geological Survey, in cooperation with the Minnesota Ojibwe Bands, developed a two-dimensional, steady-state, analytic-element groundwater-flow model of the St. Louis River Basin (SLRB) in northeastern Minnesota by using the computer code GFLOW and calibrating with the parameter-estimation software suite PEST. The model was calibrated to water levels measured in 9,631 wells, lakes, and mine pits and base-flow measurements at 40 locations along streams and rivers. The regional model was locally refined in the area near the central SLRB wetlands and recalibrated to better represent the wetlands. Calibration of the regional SRLB model resulted in average horizontal hydraulic conductivity values of 6–39 feet per day for the glacial deposits and 3–4 feet per day for the uppermost fractured bedrock of the Biwabik Iron-Formation of the Mesabi Range. Average recharge across the calibrated model was 5.9 inches per year. The updated calibration of the central SLRB model resulted in average horizontal hydraulic conductivity values of 5–36 feet per day for the glacial deposits and 3 feet per day for the uppermost fractured Mesabi Range bedrock. Average recharge across the ditch scenarios was 4.1 inches per year.

The calibrated regional model was used to improve understanding of the shallow groundwater-flow system in the SLRB and evaluate the effects of ditching in the wetlands in the central SLRB. Key findings are as follows:

- Groundwater recharge occurs across the basin as terrestrial recharge originating as rain and snowmelt.
- Groundwater naturally discharges to surface waters, including the St. Louis River, wetlands, and Lake Superior.
- The regional groundwater-flow direction is generally south and southwest.
- The spatial extent of shallow modeled depth to groundwater in the preditch scenario corresponds well to permanent wetlands coverage from the National Wetlands Inventory.
- Comparison of preditch and ditch model scenarios of the central SLRB model suggests that ditching was effective at removing water near the ditches and may have altered wetland persistence or function in as much as 40,000 acres of mapped permanent wetlands in the central SLRB.

In addition to assessing effects from ditching with the central SLRB model that was derived from the regional model, the regional model provides a framework for the development of future models in the SLRB and offers a case study for effective use of a screening model to improve understanding of a regional flow system.

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Appendix 1

Appendix 1. Central St. Louis River Basin Model Calibration Results

The central St. Louis River Basin model was calibrated with 5,211 head targets and 1 flux target with the goal of reducing undersimulated heads in the central wetlands area while not compromising a reasonable head solution in the surrounding area. Head targets near the ditched wetlands are sparser than the density available for the regional model. Historical wetland hydrology that produced hydric soils that are persisting in the ditched areas was considered in the central St. Louis River Basin model calibration. Therefore, the model calibration included two conditions: (1) a condition of present-day hydrology that used current heads and flux targets and was similar to the regional model and (2) a condition of hydrology before ditching that used synthetic wetland head targets with heads set at land surface in the areas mapped as wetland. The former had 3,784 head targets and 1 flux target from the State databases; calibration targets for the latter were developed by using a grid of 1,427 synthetic wetland head targets with a distribution defined by mapped wetlands in the National Wetlands Inventory (Minnesota Department of Natural Resources, 2009), where each target consisted of a head value equal to the land-surface elevation. Target weighting is summarized in table 1.1; weights were assigned with the goal of providing greater weight to targets in and near the ditched area while not overwhelming the objective function with a single target group or type. The objective function is the unitless sum of squared, weighted residuals between model outputs and their equivalent "observed" values (the calibration targets). A full set of calibration targets is provided in the ancillary directory of the accompanying model archive (Haserodt and others, 2019).

The results of fitting between the measured targets and the model simulation are shown spatially (fig. 19) and as an observed-to-simulated 1:1 plot (fig. 1.1). The modeled heads were generally within 10 feet of the measured or synthetic heads in the wetlands, and the largest differences were near river valleys. The head residuals are spatially biased, with some wetland areas entirely oversimulated and others undersimulated. This spatial bias was deemed acceptable given the level of complexity available with the existing inhomogeneities and the regional focus of the modeling effort. The flux target at the Meadowlands streamgage (approximately 2 miles downstream of the Meadowlands marker in figure 17) was matched within 1 cubic foot per second.

Parameter identifiability (Doherty and Hunt, 2009) was also calculated (fig. 1.2) for the 16 model parameters in the ditch scenario. In figure 1.2, dark bars represent calibration data providing high support for estimation of the parameter shown on the x-axis. In general, forecasts that depend on parameters with low identifiability (light-colored bars) will have high uncertainty. The most identifiable parameters were the hydraulic conductivity values for the "Sand and gravel—northwest," "Mixed—thick west," and "Till—central" inhomogeneities, where most of the ditching is and where the synthetic wetland head targets were added.

Because a two-dimensional, areal model of groundwater flow simulates aquifer transmissivity, an equivalent horizontal hydraulic conductivity was calculated from the optimal model transmissivity by using average saturated thickness within each inhomogeneity (fig. 1.3). The saturated thickness represented an average thickness of the unconsolidated deposits within an inhomogeneity plus the upper 150 feet of bedrock that was assumed to transmit water via fractures; therefore, calculated horizontal hydraulic conductivities represent a bulk property for the combined upper fractured bedrock and unconsolidated aquifer. Overall, the equivalent hydraulic conductivities in the model nearfield were lower in the ditch scenario than in the regional model. Inhomogeneities representing sand and gravel deposits had values that ranged from 8 to 13 feet per day, and till values ranged from 5 to 36 feet per day. The higher till values are in the farfield of the ditch scenario, where heads were weighted lower.

The average recharge from the ditch scenario was 4.1 inches per year, compared to 5.9 inches per year from the calibrated regional model. The calibrated ditch scenario showed a minor reduction in the wetland recharge multiplier and a larger reduction in the upland recharge multiplier.

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Table 1.1. Summary of target groups and weighting for the central St. Louis River Basin model of groundwater flow, northeastern Minnesota.

[In the exponential notation used, 1.64E−05 represents 1.64×10^{-5}. MDNR, Minnesota Department of Natural Resources; MPCA, Minnesota Pollution Control Agency; NWI, National Wetlands Inventory]

Observation group	Weight	Explanation
mn_flux_lg	1.64E−05	Flux observations for large rivers from the MDNR/MPCA Cooperative Stream Gaging database (http://www.dnr.state.mn.us/waters/csg/index.html).
mnhead_ff	3.00E−03	Farfield head observations from the Minnesota Well Index (https://www.health.state.mn.us/communities/environment/water/mwi/index.html)
ditch_nf	4.80E−02	Nearfield head observations from the Minnesota Well Index (https://www.health.state.mn.us/communities/environment/water/mwi/index.html)
wtld	1.40E−02	Synthetic wetland head observations with a distribution from mapped wetlands in NWI and heads set at land-surface elevation.

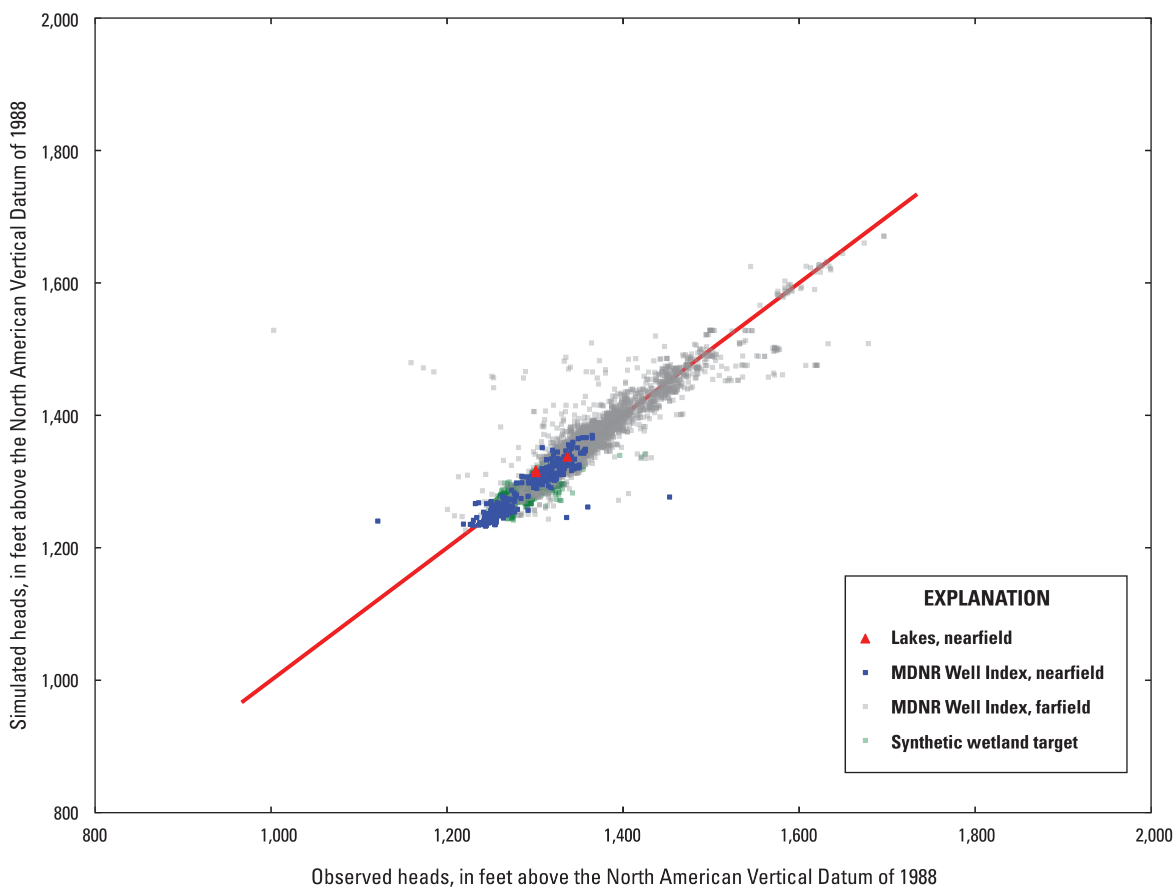

Figure 1.1. Comparison of simulated and observed heads in the central St. Louis River Basin model of groundwater flow, northeastern Minnesota. Diagonal red 1:1 line indicates perfect fit. MDNR, Minnesota Department of Natural Resources.

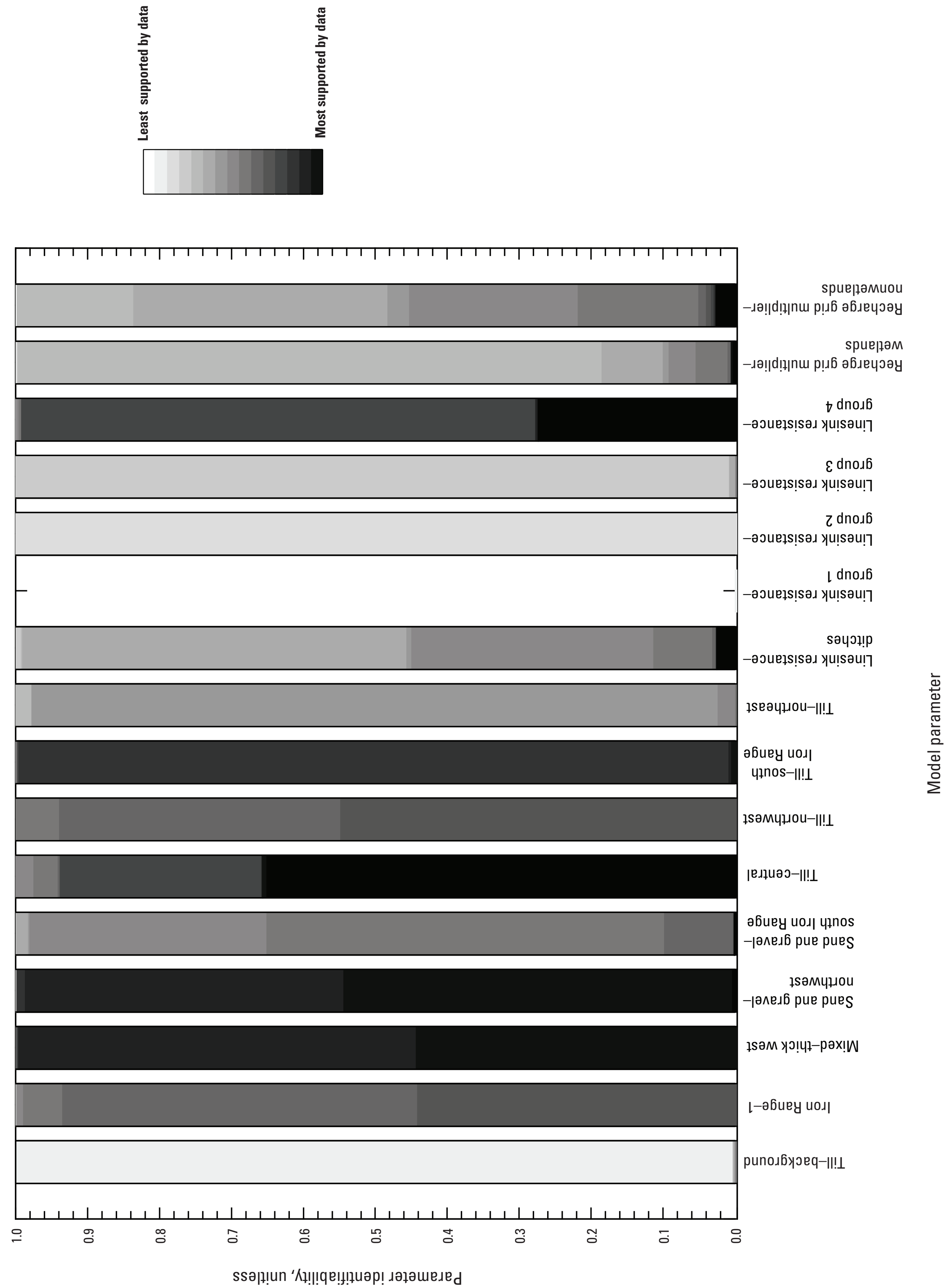

Figure 1.2. Parameter identifiability from the ditch scenario calibration for the central St. Louis River Basin model of groundwater flow, northeastern Minnesota.

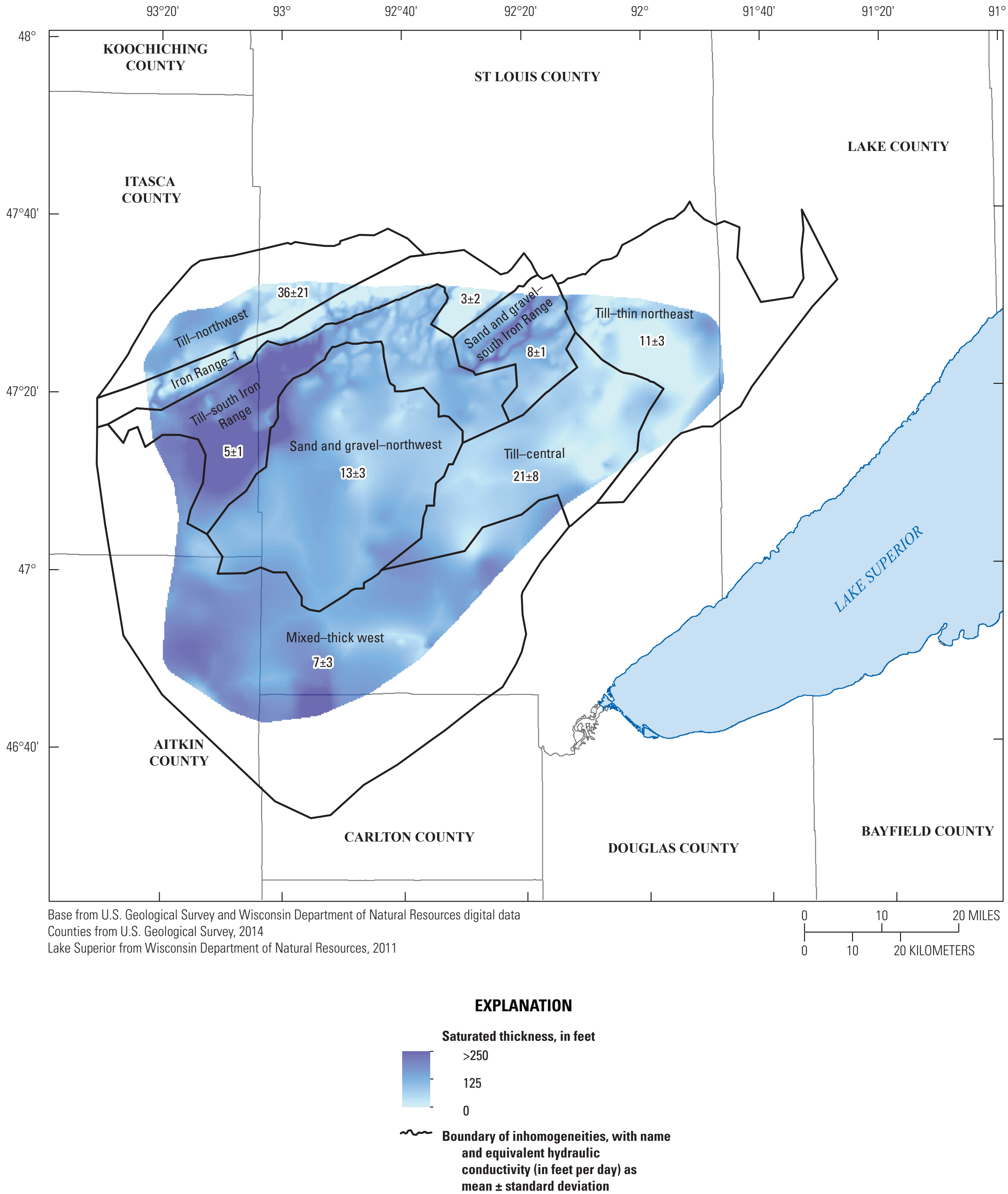

Figure 1.3. Modeled saturated thickness in the unconsolidated aquifer and equivalent hydraulic conductivity for the model inhomogeneities for the central St. Louis River Basin model of groundwater flow, northeastern Minnesota.

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