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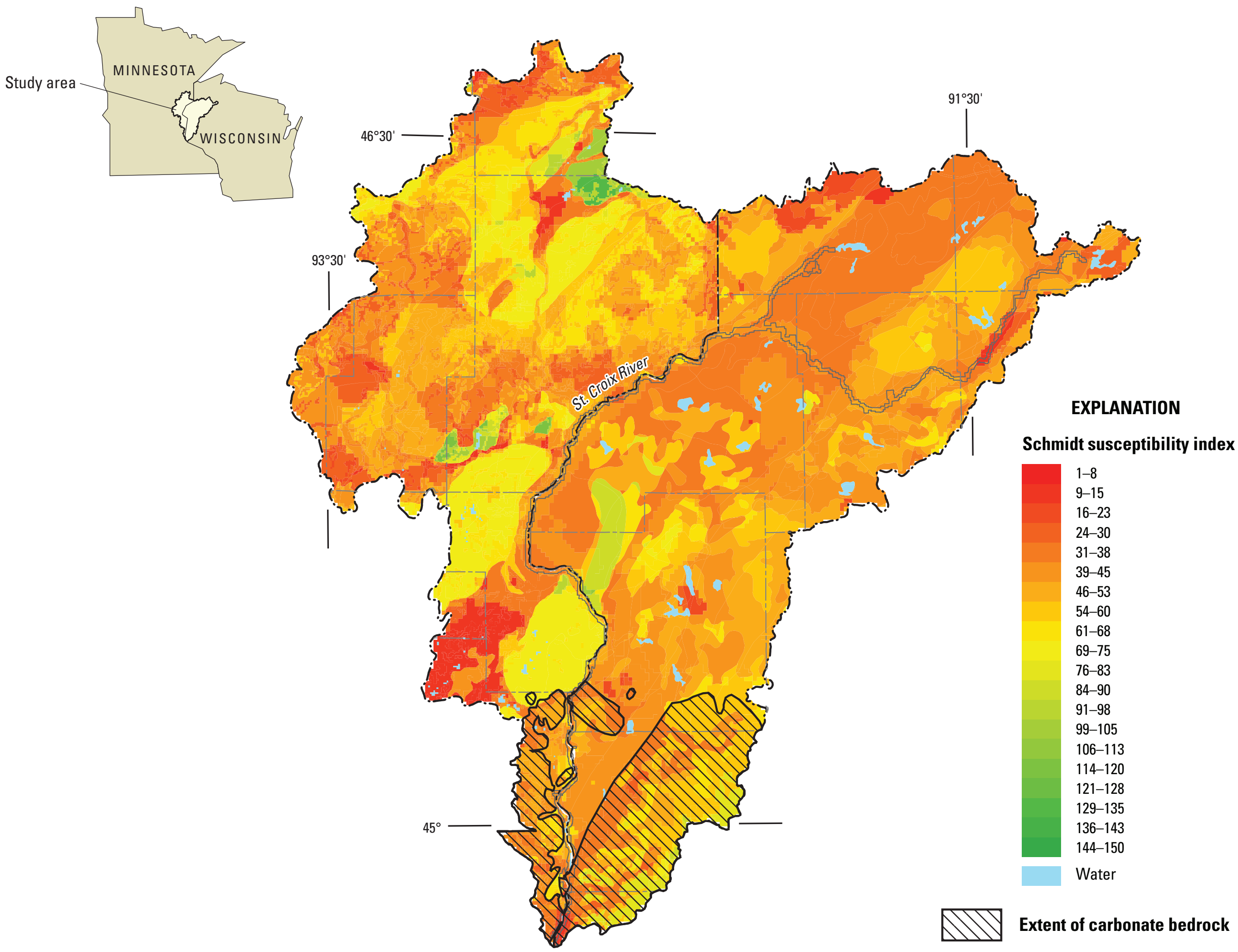
Hydrogeologic Characteristics of the St. Croix River Basin, Minnesota and Wisconsin: Implications for the Susceptibility of Ground Water to Potential Contamination



Scientific Investigations Report 2007–5112

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

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By Paul F. Juckem

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Contents

Figures

Tables

.

Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
kilometer	0.6214	mile (mi)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Hydraulic conductivity*	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity**	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

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

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

*Hydraulic conductivity: the standard unit for hydraulic conductivity is cubic foot per day per square foot of aquifer cross-sectional area ($ft^3/d/ft^2$). In this report, the mathematically reduced form, foot per day (ft/d), is used for convenience.

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

Hydrogeologic Characteristics of the St. Croix River Basin, Minnesota and Wisconsin: Implications for the Susceptibility of Ground Water to Potential Contamination

By Paul F. Juckem

Abstract

Population growth in the St. Croix River Basin in Minnesota and Wisconsin has intensified concerns of county resource managers and the National Park Service, which is charged with protecting the St. Croix National Scenic Riverway, about the potential for ground-water contamination in the basin. This report describes a previously developed method that was adapted to illustrate potential ground-water-contamination susceptibility in the St. Croix River Basin. The report also gives an estimate of ground-water-residence time and surface-water/ground-water interaction as related to natural attenuation and movement of contaminants in five tributary basins.

A ground-water-contamination-susceptibility map was adapted from a state-wide map of Wisconsin to the St. Croix River Basin by use of well-driller construction records and regional maps of aquifer properties in Minnesota and Wisconsin. Measures of various subsurface properties were combined to generate a spatial index of susceptibility. The subjective index method developed for the State of Wisconsin by Schmidt (1987) was not derived from analyses of water-quality data or physical processes. Nonetheless, it was adapted for this report to furnish a seamless map across state boundaries that would be familiar to many resource managers. Following this method, areas most susceptible to contamination appear to have coarse-grained sediments (sands or gravels) and shallow water tables or are underlain by carbonate-bedrock aquifers. The least susceptible areas appear to have fine-grained sediments and deep water tables. If an aquifer becomes contaminated, the ground-water-residence time can affect potential natural attenuation along the ground-water-flow path. Mean basin ground-water-residence times were computed for the Apple, Kettle, Kinnickinnic, Snake and Sunrise River Basins, which are tributary basins to the St. Croix Basin, by use of average aquifer properties of saturated thickness, porosity, and recharge rates. The Apple River Basin had the shortest mean ground-water-residence times (20–120 years), owing largely to the moderate saturated thickness and high recharge rate in the basin. The Kinnickinnic and Sunrise River Basins had the longest mean residence times (60–350 and 70–390 years, respectively) chiefly because of the relatively large saturated thickness of the basins. Owing to limitations of the residence-time calculations, actual ground-water-residence times will vary around the mean values within each basin and may range from days or weeks in karst carbonate aquifers to millennia in deep confined sandstone aquifers.

Areas of relatively short residence time (less than the median residence time in each basin) were identified by use of ground-water-flow models for each of the five tributary basins. Results of simulations show that these areas, in which contaminants may have relatively less time for natural attenuation along the short flow paths, generally occur near streams and rivers where ground water discharges to the surface. Finally, the ground-water-flow models were used to simulate ground-water/surface-water interaction in the five tributary basins. Results of simulations show that some lakes and reservoirs leak surface water into the ground-water-flow system on their downgradient side, where the surface-water outflow has been restricted by a dam or a naturally constricted outlet. These locations are noteworthy because contaminated surface waters could potentially enter the ground-water-flow system at these locations.

Schmidt, R.R., 1987, Groundwater contamination susceptibility map and evaluation: Wisconsin Department of Natural Resources, Wisconsin's Groundwater Management Plan Report 5, PUBL–WR–177–87, 27 p.

Introduction

Many of the values of the St. Croix National Scenic Riverway (fig. 1), including its diverse biota, are related to its good water quality, which is of critical concern to the National Park Service because of its responsibility to manage and protect the riverway. Water quality is also a critical concern for state, county, and local resource managers along the St. Croix River, particularly in watersheds bordering the river that are experiencing rapid population growth and development. Population in the St. Croix River Basin is expected to increase by as much as 39 percent from 2000 to 2020 (Davis, 2004). This growth may increase the potential for ground-water contamination from point sources, such as spills of hazardous materials. The threat from nonpoint sources of contamination, such as those associated with fertilizers, feedlots, and animal-waste disposal, also will likely increase.

Results of hydrologic studies over many years have demonstrated that surface-water and ground-water systems constitute a single resource (Winter and others, 1999); thus, assessments of vulnerability within the St. Croix River Basin should include understanding of how contaminants are transported in both surface water and ground water. Previous work by the U.S. Geological Survey (USGS) in cooperation with the National Park Service provided an integrated understanding of the regional water resource by assembling a series of databases related to the hydrogeology of the basin and by developing a ground-water-flow model that simulates surface-water/ground-water interactions within the basin (Feinstein and others, 2006). This report builds on the work by Feinstein and others (2006) and describes the adaptation of a ground-water-contamination-susceptibility map of Wisconsin to the entire St. Croix River Basin in Wisconsin and Minnesota. The report also describes estimates of potential residence times for contaminants dissolved in ground water, and interactions between potentially contaminated surface water and ground water. The work described in this report was done by the U.S. Geological Survey in cooperation with the National Park Service.

Purpose and Scope

The purpose of this report is to describe the adaptation or development, and evaluation of regional-scale maps and tables designed to illustrate (1) possible susceptibility of ground water to contamination according to a previously developed index method, (2) ground-water-residence times, and (3) areas of surface-water leakage into ground-water-flow systems in the St. Croix River Basin. The scope of the work is regional in scale, yet results could be used as preliminary guidance for design of local and site-scale investigations of ground-water contamination.

Schmidt's (1987) ground-water-contamination susceptibility index map for Wisconsin was adapted to the St. Croix River Basin. This adapted map for the basin is referred to hereafter as the "Schmidt susceptibility index values map." It has been based on readily available digital maps of soil and geologic material, as well as hydrogeologic databases constructed by Feinstein and others (2006). Simulation of ground-water-residence times and ground-water/surface-water interaction in five tributary river basins to the St. Croix River incorporated refinements to the regional ground-water-flow model (referred to herein as the "regional model") developed by Feinstein and others (2006). Maps in this report are presented that show the soil, geologic, and hydrologic characteristics that may affect ground-water susceptibility to contamination according to the index method developed by Schmidt (1987). Maps also show areas of relatively short ground-water-residence times (less than the median time for the tributary basin), and river reaches where surface water enters the ground-water system. Estimates of the mean basin ground-water-residence time in five tributary basins are summarized in a table.

Physical Setting

The St. Croix River (fig. 1) originates near Solon Springs, Wis., and flows approximately 154 mi south to its confluence with the Mississippi River at Prescott, Wis. The St. Croix National Scenic Riverway includes the St. Croix River and the Namekagon River that together amount to 252 river miles for recreational use. The St. Croix River Basin encompasses 7,730 mi^2 in Minnesota and Wisconsin (Lenz and others, 2001) and includes all or part of 19 counties. Land cover is varied, grading from predominantly forest cover upstream in the basin to a mixture of forest, agriculture, and urban land use further downstream. Glacial deposits overlie igneous and sedimentary bedrock in the basin. Feinstein and others (2006) give a detailed description of hydrogeologic properties of the basin.

Figure 1. Location of study area, St. Croix River Basin, Minnesota and Wisconsin.

Methods for Adapting an Existing Ground-Water-Contamination-Susceptibility Map for Wisconsin to the St. Croix River Basin

A map of Ground-Water-Contamination Susceptibility produced by Schmidt (1987) for the State of Wisconsin was adapted for the entire St. Croix River Basin (Minnesota and Wisconsin) by including well-driller construction data in the basin and regional maps of aquifer properties. This Schmidt susceptibility index values map used the same method and numerical ranking scheme (except where indicated below) as Schmidt (1987) to estimate the potential for dissolved chemicals at the land surface to infiltrate through geologic material to the water table. The ranking scheme consists of assigning susceptibility values from 1 to 10 (1 being most susceptible, 10 being least susceptible) to properties identified on four physical resource maps that describe (1) soil material, (2) surficial deposits, (3) bedrock type, and (4) depth to the water table. In addition, a susceptibility multiplier, ranging from 0 to 8, was assigned to a map describing the depth to the uppermost bedrock surface. The susceptibility values assigned to properties of the four resource maps were weighted (multiplied) by values assigned to the depth to bedrock map, because Schmidt (1987) suggested that the depth to bedrock gave an indication of the relative potential for soils and surficial deposits to attenuate contaminants before reaching the water table. Finally, the four weighted resource maps were overlain, and their weighted susceptibility values were added together to produce a composite map reflecting the relative potential for ground water at a particular location to be contaminated by dissolved substances infiltrating with water from the land surface. The following paragraphs give details on each physical resource-map and the weighting scheme.

Soil characteristics of the St. Croix River Basin were derived from the “Soil Atlas of Minnesota” (Minnesota Land Management Information Center, 2004) and a soil-characteristics map of Wisconsin (Schmidt, 1987). For consideration of ground-water-contamination susceptibility, Schmidt (1987) defined soils as the material extending from 0 to 5 ft below the land surface. Schmidt (1987) generated the soil-characteristics map of Wisconsin by grouping soil associations described by Hole and others (1968) into four categories; this map was used without modification for the Wisconsin part of the St. Croix River Basin. The four soil categories were (1) coarse texture/high permeability/sands and gravels, (2) medium-coarse texture/high-medium permeability/sandy, (3) medium texture/medium permeability/loamy, and (4) fine texture/low permeability/clayey. Schmidt (1987) assigned these soil characteristics susceptibility values of 1, 3, 6, and 10, respectively (table 1). To produce a similar soil-characteristics map for the Minnesota part of the St. Croix River Basin, the Soil Landscape Units described in the “Soil Atlas of Minnesota” (Minnesota Land Management Information Center, 2004) were grouped into the same four susceptibility categories on the basis of predominant soil texture described within the first 5 ft of the land surface. Finally, the soil-characteristics maps covering the Wisconsin and Minnesota parts of the basin were joined together (fig. 2).

Surficial deposits, or the unconsolidated deposits that extend from 5 ft below the land surface to the uppermost bedrock, were derived from Goebel and others (1983). Surficial deposits in the St. Croix River Basin were assigned to categories used by Schmidt (1987) in Wisconsin and are described as (1) sand and gravel, (2) sandy, (3) peat, (4) loamy, and (5) clayey (fig. 3). Surficial-deposit susceptibility values matched those used by Schmidt (1987) and are listed in table 1.

Bedrock type was derived from a map of geology and mineral deposits of Minnesota, Wisconsin, and Michigan (Cannon and others, 1997). The geologic units were categorized as (1) carbonates, (2) sandstones, (3) igneous or metamorphic, and (4) shale (fig. 4), and assigned susceptibility values (table 1) according to Schmidt (1987). Carbonate rocks were considered the most susceptible to ground-water contamination because these rocks are prone to fracturing and dissolution, which produces conduits through which water can rapidly infiltrate to the water table. Because of the potential for rapid transport of contaminants through carbonate aquifers (following infiltration to the water table), the extent of carbonate bedrock (regardless of whether it is the uppermost bedrock or is buried beneath sandstone) is identified in figure 4.

Depth to the water table was computed from more than 5,000 measurements reported by drillers at the time of well construction (appendix D in Feinstein and others, 2006). A universal kriging technique was applied to these data so that a grid covering the basin with cells 1 km on each side could be associated with the following depth to water categories: (1) less than 20 ft, (2) 21 to 50 ft, and (3) greater than 50 ft. The categorized grid was assigned susceptibility values according to Schmidt (1987) and filtered to reduce the number of “cell islands,” or locations where a cell of one category was enclosed by cells of another

Table 1. Susceptibility values assigned to the four resource maps used to calculate Schmidt susceptibility index values for the St. Croix River Basin, Minnesota and Wisconsin.

[category descriptions and susceptibility values are derived from Schmidt (1987)]

Resource map	Category	Susceptibility value
Soil characteristics	Coarse texture/high permeability	1
	Medium-coarse texture/high-medium permeability	3
	Medium texture/medium permeability	6
	Fine texture/low permeability	10
Surficial deposits	Sand and gravel	1
	Sandy	2
	Peat	5
	Loamy	6
	Clayey	10
Type of bedrock	Carbonate	1
	Sandstone	5
	Igneous or metamorphic	6
	Shale	10
Depth to water table	0–20 feet	1
	21–50 feet	5
	Greater than 50 feet	10

category. Finally, all adjoining grid cells with the same depth-to-water-table susceptibility value were grouped into a single polygon (fig. 5).

Surface-water features were not incorporated into the interpolation process because of the difficulty involved with differentiating, at the outset, between water bodies that are closely connected with the ground-water-flow system from those that are disconnected, or “perched.” As a result, the depth to the water table for thin areas parallel to large river segments that are well connected with the ground-water-flow system may be less than that depicted in the regional-scale map (fig. 5). Locally, this would cause a slight decrease in the corresponding susceptibility value and the final Schmidt susceptibility index value.

Depth from land surface to bedrock was also calculated from measurements reported by drillers (appendix A in Feinstein and others, 2006), and interpolated to a grid with 1-km by 1-km cells by use of a universal kriging technique. The depth ranges deviated slightly from the categories used by Schmidt (1987) and were grouped into categories that reflect the range in bedrock depth in the St. Croix River Basin. Schmidt (1987) distinguished between areas where bedrock is less than 5 ft below the land surface from areas where bedrock is between 5 and 50 ft below the land surface. Few drillers’ reports indicated bedrock within 5 ft of the land surface in the St. Croix River Basin; therefore, the shallowest depth to bedrock category used to construct the adapted Schmidt susceptibility index values map ranged from 0 to 25 ft. Depth to bedrock was further categorized as 26 to 50 ft, 51 to 100 ft, and greater than 100 ft in accordance with Schmidt (1987). The categorized grid was also filtered to reduce cell islands and then converted to polygons (fig. 6).

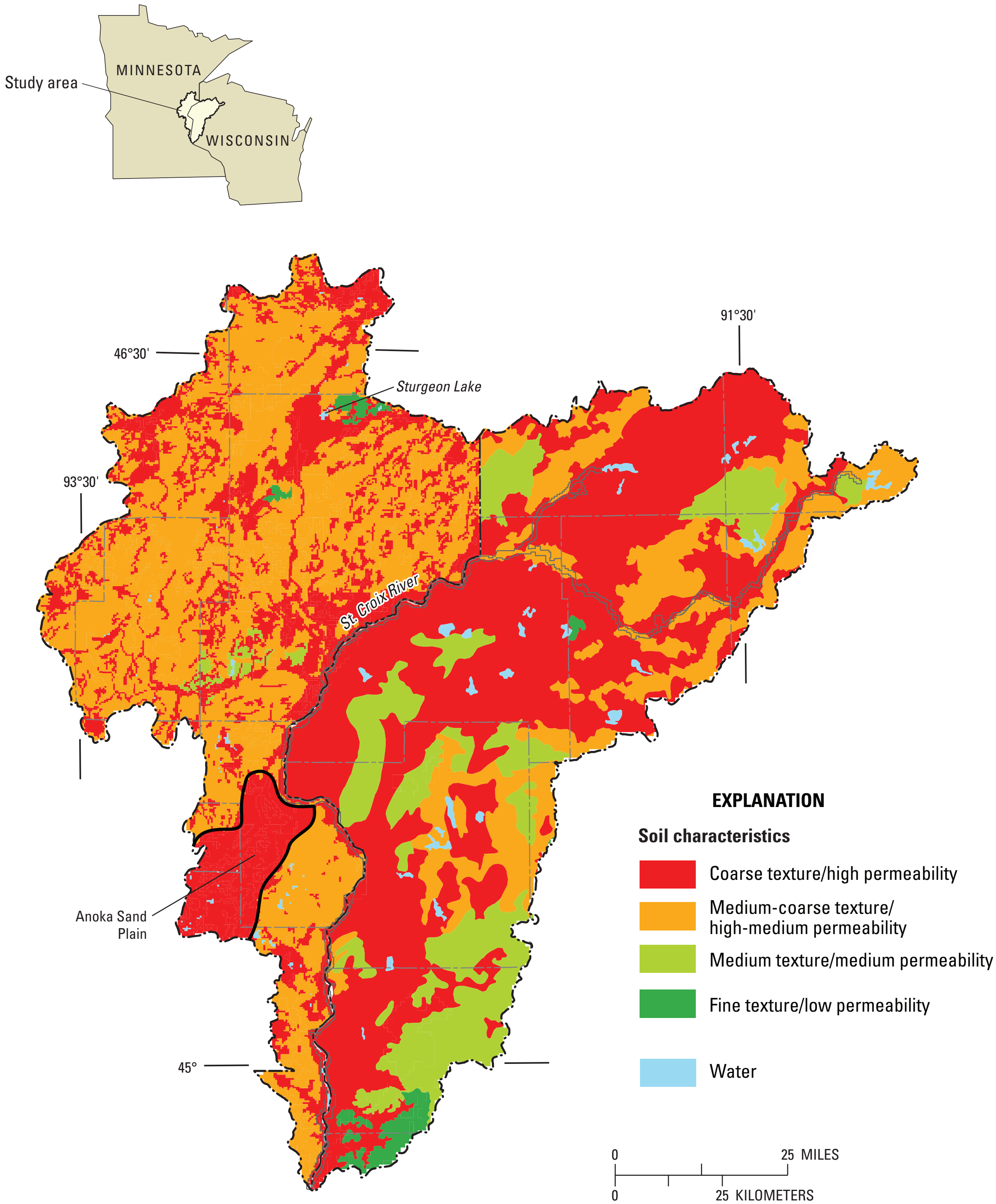

Figure 2. Soil characteristics of the St. Croix River Basin, Minnesota and Wisconsin (modified from Hole and others, 1968; and Minnesota Land Management Information Center, 2004).

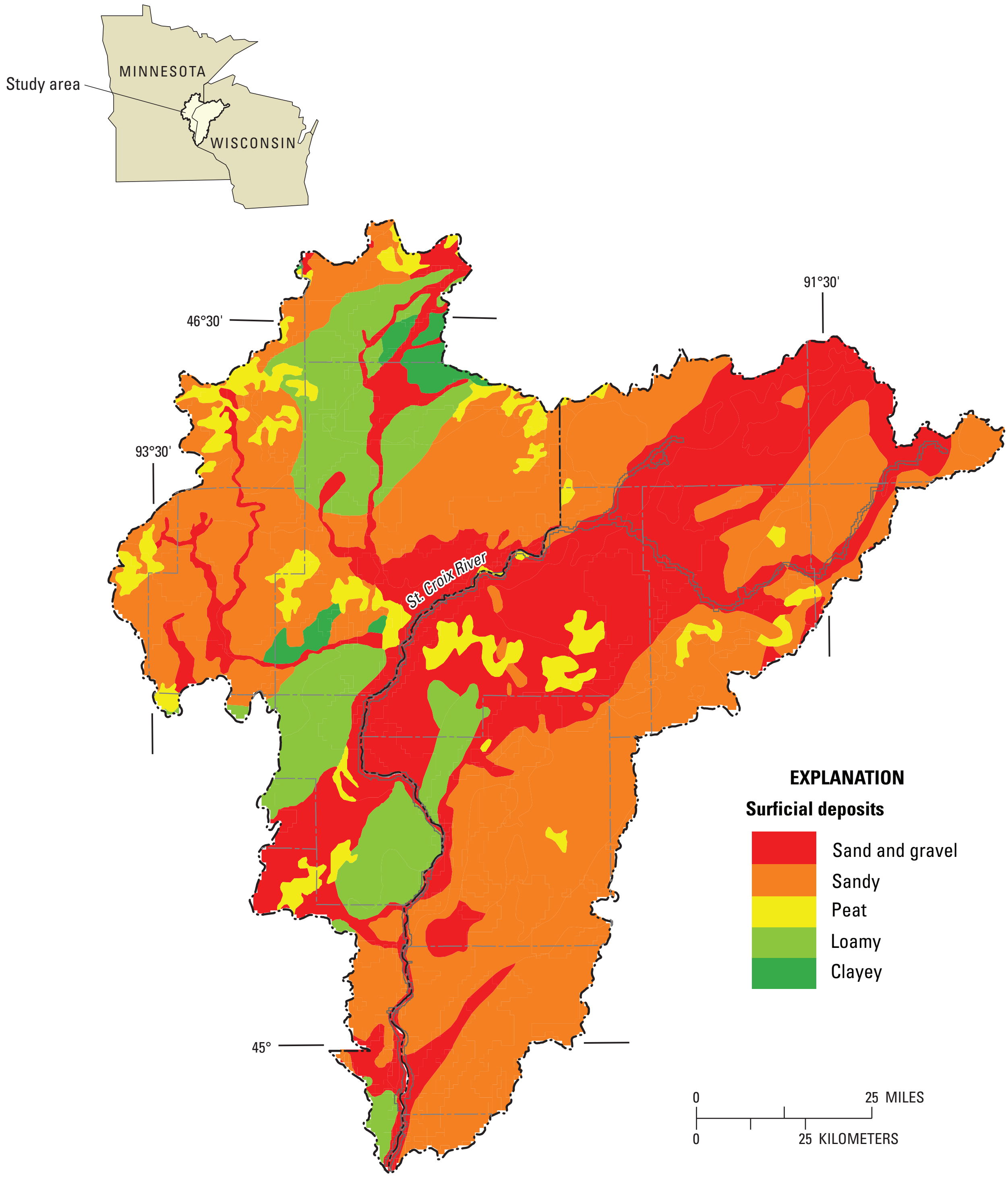

Figure 3. Surficial deposits of the St. Croix River Basin, Minnesota and Wisconsin (modified from Geobel and others, 1983).

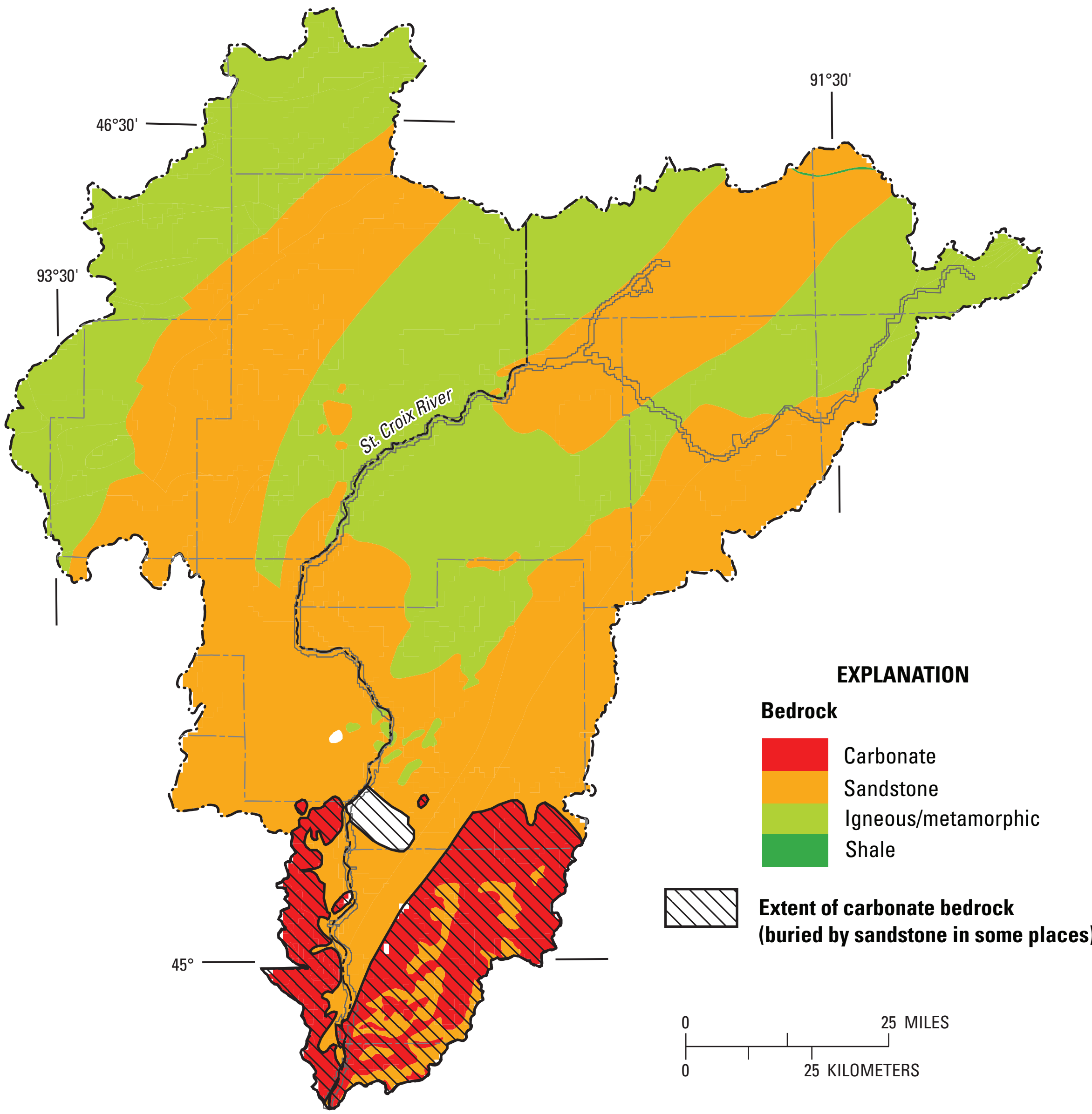

Figure 4. Type of uppermost bedrock in the St. Croix River Basin, Minnesota and Wisconsin (modified from Cannon and others, 1997). Areas where carbonate rocks are present below other rocks may be more susceptible than suggested by the Schmidt susceptibility index method because of the potential for rapid horizontal ground-water flow and contaminant transport from distant points of entry (for example, sinkholes) at the land surface.

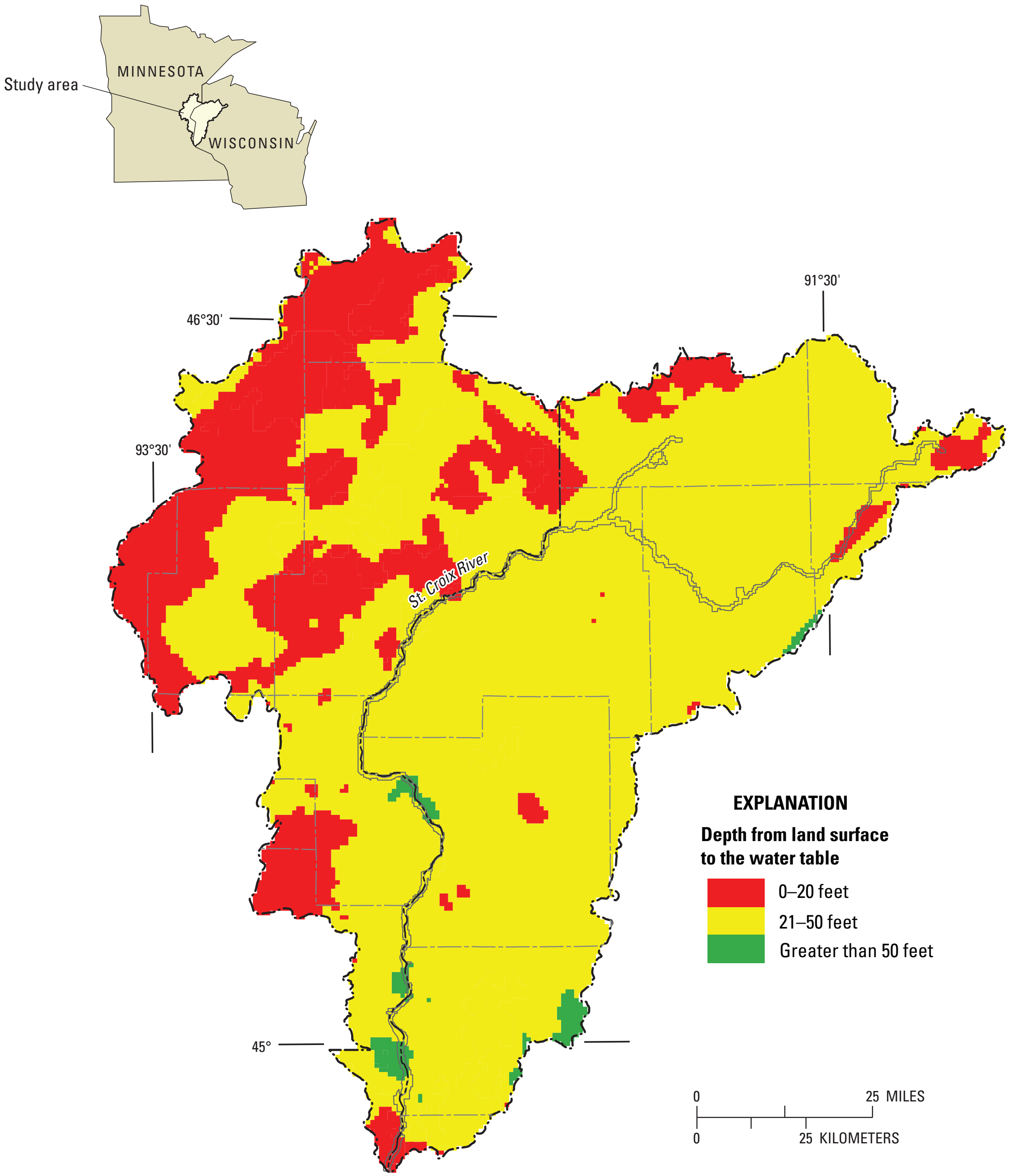

Figure 5. Generalized depth from the land surface to the water table in the St. Croix River Basin, Minnesota and Wisconsin. Locally, the depth to the water table may differ from the categories shown here.

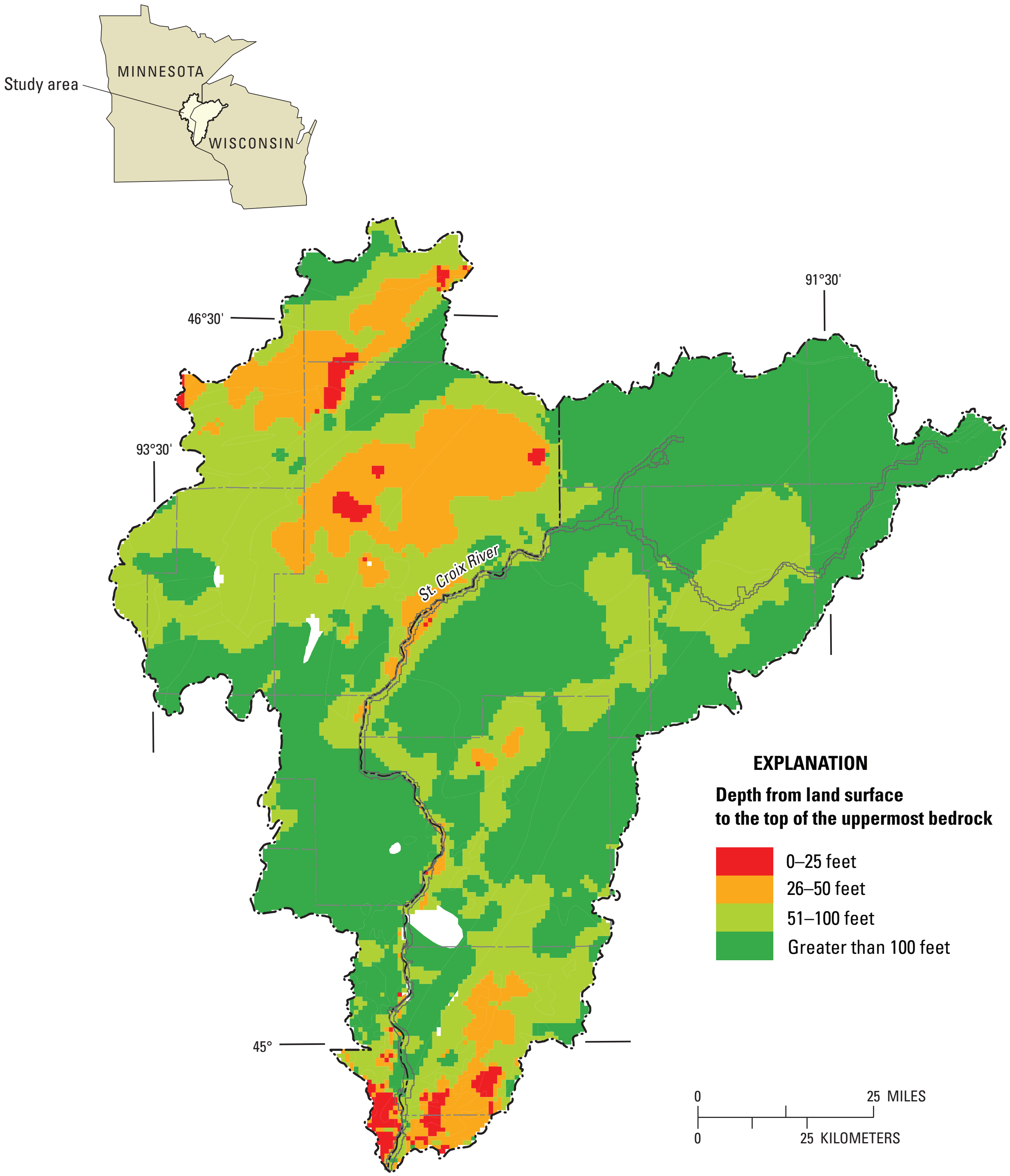

Figure 6. Generalized depth from the land surface to the top of the uppermost bedrock in the St. Croix River Basin, Minnesota and Wisconsin. Locally, the depth to the water table may differ from the categories shown here.

Multiplier values assigned to the depth-to-bedrock map were used to weight susceptibility values of the other four resource maps (table 2). Following the logic of Schmidt (1987), the depth to bedrock indicates the amount of soil and surficial deposits that are present. Where depth to bedrock is great, surficial deposits are thick and, according to Schmidt (1987), are expected to have a greater influence on the infiltration of contaminants to the water table than the type of bedrock beneath the surficial deposits. Conversely, where bedrock is shallow, surficial deposits are thin and Schmidt (1987) expected the bedrock type to influence contamination movement. For example, the type-of-bedrock resource map (fig. 4) was assigned a higher multiplier than any other resource map in areas where bedrock is very shallow (table 2). The depth-to-bedrock multiplier values differed somewhat from those used by Schmidt (1987) because of the difference in how the depth to bedrock map was generated and categorized. For example, the type-of-bedrock resource map was assigned a somewhat smaller multiplier for areas with shallow bedrock depths (0–25 ft) in the St. Croix River Basin compared to areas considered by Schmidt (1987) to have shallow bedrock (0–5 ft).

The individual resource maps were overlain with the depth-to-bedrock map, and the susceptibility values (table 1) were weighted (multiplied) by the depth-to-bedrock multipliers (table 2) for intersecting polygons. The resulting weighted resource maps were then overlain on one another, and the weighted susceptibility values were added together for overlapping polygons to produce a ranked score referred to as the Schmidt susceptibility index (fig. 7). According to the method developed by Schmidt (1987), low values imply relatively higher contamination susceptibility; high values imply relatively lower contamination susceptibility.

Table 2. Multiplier values assigned to the depth-to-bedrock map.

Depth to bedrock range	Soil characteristics	Surficial deposits	Type of bedrock	Depth to water table
0–25 feet	2	3	8	2
26–50 feet	3	4	5	3
51–100 feet	4	5	2	4
Greater than 100 feet	4	7	0	4

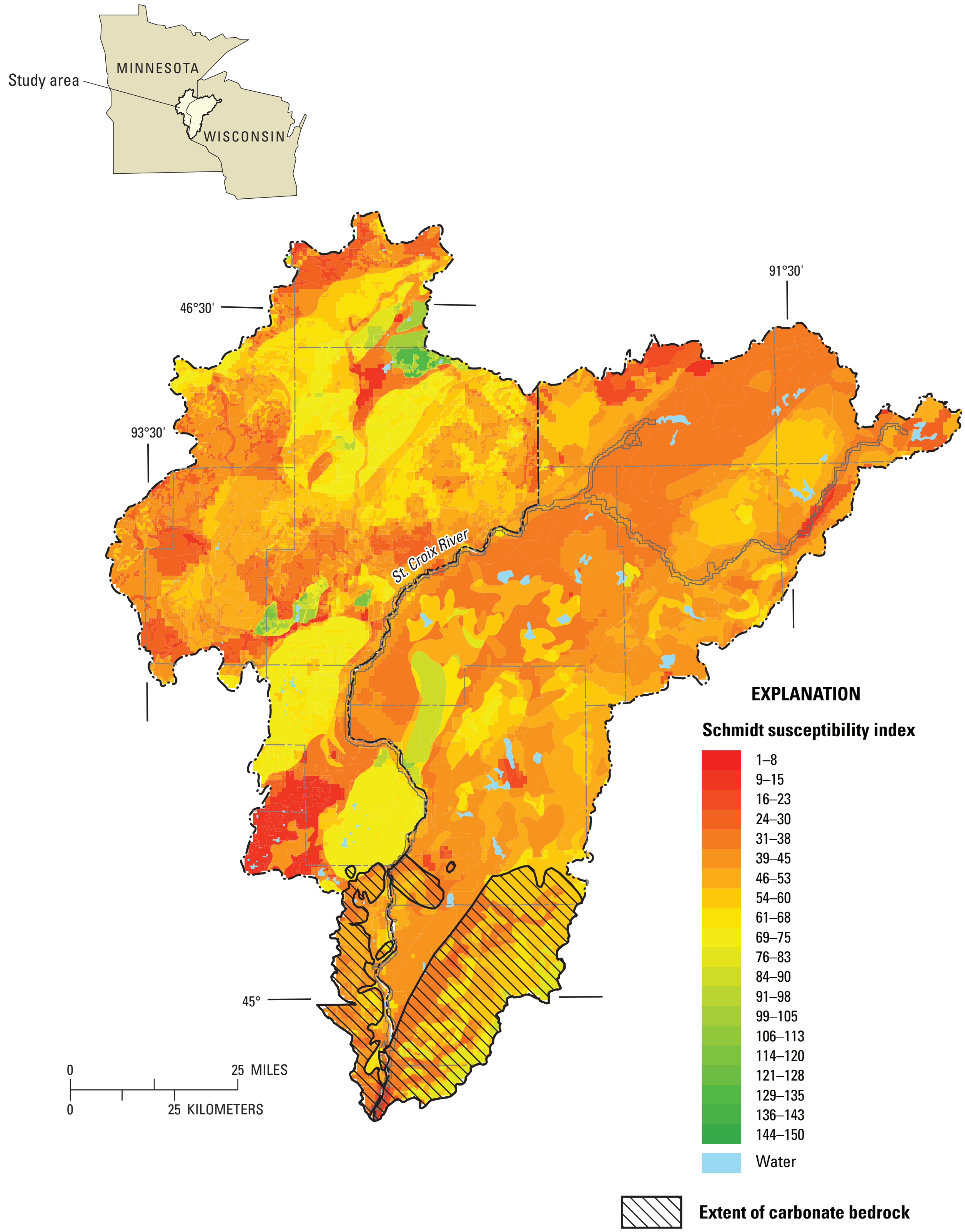

Figure 7. Schmidt susceptibility index (Schmidt, 1987) values for the St. Croix River Basin, Minnesota and Wisconsin. Schmidt susceptibility index is based on a combination of soil, geologic, and hydrogeologic characteristics; lower values imply higher susceptibility. Areas where carbonate rocks are present below other rocks may be more susceptible than suggested by the Schmidt susceptibility index method because of the potential for rapid horizontal ground-water flow and contaminant transport from distant points of entry (for example, sinkholes) at the land surface.

Evaluation of the Schmidt Susceptibility Index Values Map for the St. Croix River Basin

The Schmidt susceptibility index values map for the St. Croix River Basin compares favorably to the map of Wisconsin constructed by Schmidt (1987). For example, a relatively less susceptible area (high index values) in western Burnett and Polk Counties, Wisconsin, occurs adjacent to relatively more susceptible areas to the east in both maps. Likewise, areas underlain by coarse-grained sediments (soil, surficial deposits, and bedrock) with shallow water tables generally appear to be more susceptible to ground-water contamination (low index values) than areas underlain by fine-grained sediments with deep water tables. Ground-water samples containing pesticides and nitrates in a part of the Upper Mississippi River Basin support this generalization (Hanson, 1998). The Anoka Sand Plain, which is in Anoka, Chisago, and Isanti Counties, Minn. (fig. 2), is an example of an area with coarse-grained unconsolidated material and a shallow water table that appears to have a relatively high susceptibility to ground-water contamination (low index values, fig. 7). In contrast, the area northeast of Sturgeon Lake in Minnesota (fig. 2) is underlain by fine-grained unconsolidated material and has a moderately deep water table, which suggests relatively less susceptibility to ground-water contamination according to the method presented by Schmidt (1987).

Ground water in areas underlain by carbonate bedrock may be more susceptible to contamination than indicated by the Schmidt susceptibility index values map (fig. 7). Low-permeability soils (fig. 2) in this area may limit infiltration and enhance overland runoff toward sinkholes and stream sinks (Scott Alexander, University of Minnesota, written commun., 2007). Contaminants in this overland runoff could rapidly infiltrate through sinkholes or desiccation cracks in clay-rich soils and bypass the natural soil-filtration process (Tipping and others, 2001; Tipping, 2002). Further, because of the potential for rapid vertical and horizontal contaminant transport through solution cavities in karst aquifers, contamination could quickly spread to other parts of the aquifer that may be buried below tens or hundreds of feet of surficial deposits or sandstone bedrock. Given the unique susceptibility of karst aquifers to contamination, the extent of carbonate bedrock (regardless of whether it is the uppermost bedrock and near the land surface or is deeply buried beneath sandstone) has been identified in figure 7.

Methods for Determination of Ground-Water-Residence Time and Ground-Water/Surface-Water Interaction

The removal of contaminants from an aquifer is often difficult, and frequently incorporates some level of natural attenuation in which dilution and microbial activity reduce the concentration of the contaminant in the aquifer. The residence time of a contaminant within an aquifer is one factor that can affect the degree of natural attenuation along the ground-water-flow path, and is influenced by physical and chemical properties of both the aquifer and the contaminant itself. Quantifying attenuation and residence time of a specific chemical requires site-specific data. However, a first approximation of ground-water-residence times can be estimated at a regional scale for nonreactive chemicals dissolved in water based on physical properties of the ground-water-flow system. Estimates of ground-water-residence times were evaluated for five tributary basins to the St. Croix River using ground-water-flow models. The models were also used to evaluate locations where surface water likely discharges into the ground-water-flow system. These locations represent a potential avenue for contaminated surface water to enter an aquifer. The methods of construction and application of the ground-water-flow models that were used for these analyses are described below.

Feinstein and others (2006) used the analytic element (AE) code, GFLOW (Haitjema, 1995a) to develop a regional ground-water-flow model of the St. Croix River Basin that described the regional characteristics of the ground-water-flow system. This AE model was the foundation for evaluating ground-water-residence times and surface-water/ground-water interaction at a somewhat smaller scale for five tributary basins, as described in this report. A brief description of AE modeling is included here; more detailed information can be found in Haitjema (1995a). To construct an AE model, features important to ground-water flow (for example, wells) and surface-water features (for example, rivers and lakes) are represented spatially as mathematical elements or strings of elements called line sinks. Each mathematical element is represented by an analytic solution to the equation for ground-water flow. The effects of these individual solutions are added together (“superimposed”) to arrive at a solution for water levels and ground-water flows. In the GFLOW models used here, the analytic elements are two-dimensional and are used to simulate steady-state conditions; that is, ground-water levels represent average conditions of water-table altitude and streamflow, and no consideration is given to variations in time.

For the work described in this report, the regional model was divided into five tributary-basin submodels that were refined (that is, more hydrologic detail was added) to improve (1) estimation of the mean ground-water-residence time in each basin, (2) estimation of areas having relatively short or long ground-water-residence times, and (3) simulation of ground-water/surface-water interaction. The five tributary basins were the Kettle, Snake, and Sunrise River Basins in Minnesota and the Apple and Kinnickinnic River Basins in Wisconsin (fig. 8). Refinements to the tributary-basin submodels included (1) adjusting the base elevation of each model according to crystalline-bedrock elevations, (2) calibrating one or more recharge and hydraulic-conductivity values in each tributary basin, and (3) improving stream-elevation detail along line sinks to improve simulation of ground-water/surface-water interaction.

To simulate ground-water flow using GFLOW, a horizontal base of the ground-water-flow system must be defined at a specified elevation. The crystalline-bedrock elevation at the mouth of each river was used to determine the base of the model for simulating ground-water flow in the Kettle, Snake, and Sunrise River Basins. For simulation of the Kinnickinnic River Basin, the base was assigned to the top elevation of the deepest regional confining unit, the Eau Claire Shale, at the mouth of the basin. The Eau Claire confining unit was used as the model base in order to limit the depth of the simulated ground-water flow system, and thereby improve simulation of tributary-basin-scale ground-water flow and ground-water/surface water interaction in the Kinnickinnic River Basin, which has the thickest sediments and smallest area of the five tributary basins (table 4). The base of the Apple River Basin submodel was varied among three separate zones included in the regional model (fig. 8), each of which was assigned the average crystalline-bedrock elevation within the zone.

Line-sink segments, which represent streams and rivers, were divided into shorter segments in the refined submodels to more precisely match the stream slope and stream geometry. In particular, dam and reservoir outlets were located and line sinks were adjusted such that abrupt changes in stream elevation at these sites were represented in the tributary-basin submodels.

New sets of recharge and hydraulic-conductivity values were estimated by means of a parameter-estimation program (PEST; Doherty, 2004) by matching base flows and water levels within each tributary basin. The primary benefit of using a parameter-estimation program is the capacity to automatically calculate parameter values that result in a quantified best fit between simulated and observed data (for example, ground-water levels and base flow). A subset of the water-level and base-flow targets used by Feinstein and others (2006) that corresponded to the areas within the tributary-basin submodels was used for calibration. The subset of base-flow targets included an estimate of flow near the outlet of each basin, plus a base-flow estimate along the Knife River in the Snake River Basin submodel.

The submodel area for each tributary basin is shown in figure 8, along with zones of differing base elevations and calibrated recharge and hydraulic-conductivity values. In all basins except the Apple River Basin, a single value was used to simulate recharge, hydraulic conductivity, and base elevation. The zones delineated by Feinstein and others (2006) in the Apple River Basin were retained in the refined submodel to simulate changes in the crystalline-bedrock base elevation and potentially related changes in recharge and hydraulic conductivity within these zones.

Calculation of Mean Basin Residence Time

A mean ground-water-residence time in the five tributary basins was calculated by use of the method of Haitjema (1995b). For an idealized ground-water-flow system, the mean basin residence time is the product of the aquifer's saturated thickness and porosity, divided by the basin recharge rate (Haitjema, 1995b). The primary assumptions that characterize an idealized flow system for this calculation are (1) no resistance to vertical ground-water flow (only horizontal flow is considered), (2) no aquifer layering or regionally extensive confining units, and (3) constant saturated thickness and porosity of the aquifer and constant recharge to the aquifer over the entire basin. Assumption 3 is adequate for the regional-scale analyses described in this report. Assumptions 1 and 2 represent limitations of the analysis for parts of all five tributary basins where layered sedimentary rock transmits a substantial proportion of the total ground-water flow through the system. Nonetheless, because this report provides regional estimates and insight to guide regional planning and subsequent local and site-scale investigations, potential violations of assumptions 1 and 2 are ignored for the purpose of calculating basin-wide estimates of the bulk mean basin residence time. The increased range

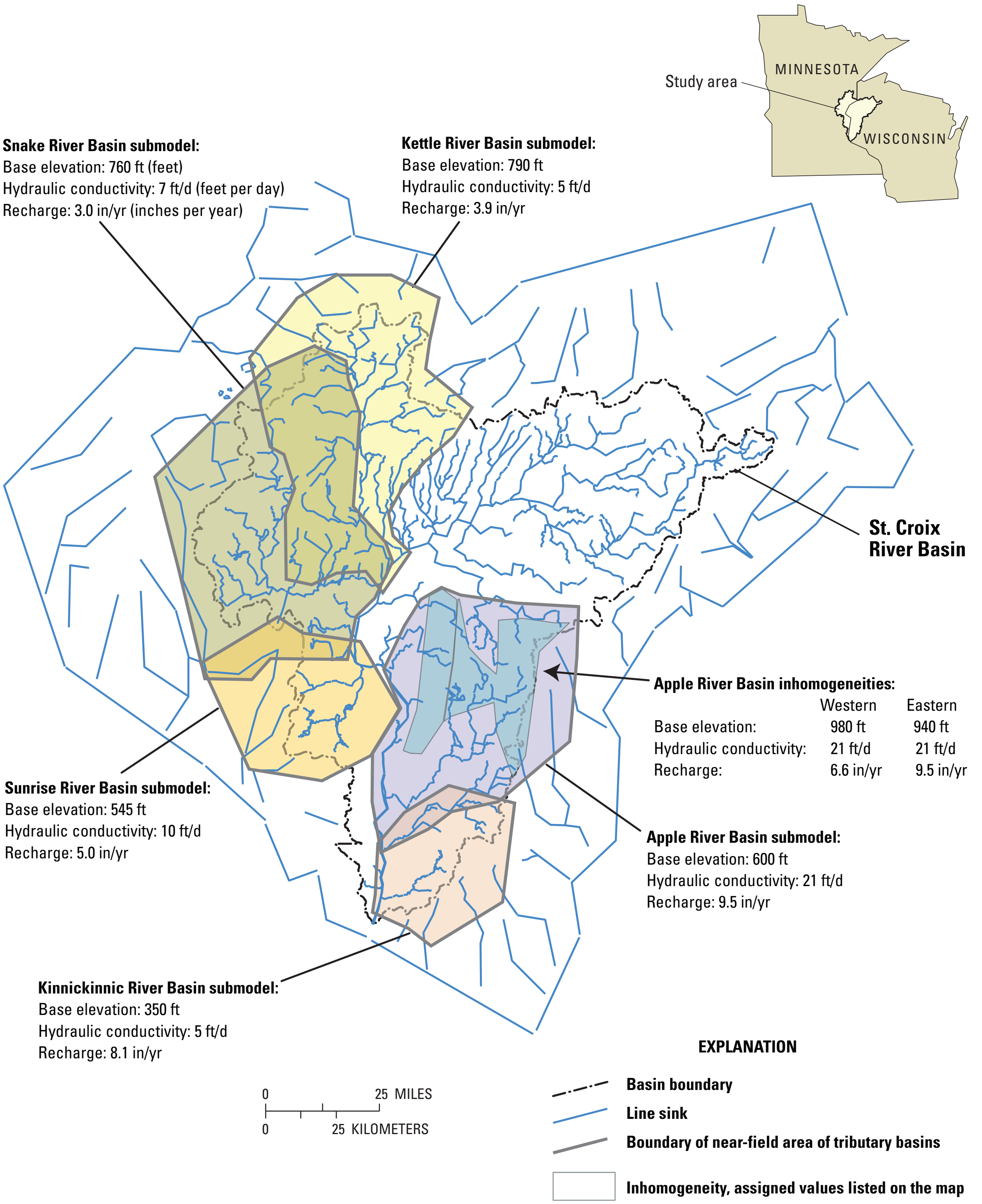

Figure 8. Calibrated hydraulic conductivity, base elevation, and recharge values for tributary-basin models of the Kettle, Snake, and Sunrise River Basins, Minnesota, and of the Apple and Kinnickinnic River Basins, Wisconsin. [ft, feet; ft/d, feet per day; in/yr, inch per year]

in the probable-residence-time estimates associated with these limitations is discussed in the evaluation section of this report.

Values of saturated thickness, porosity, and recharge used to calculate the mean residence times for the five tributary basins were derived from the revised ground-water-flow models and from crystalline-bedrock-elevation information compiled from well-construction reports (appendix A in Feinstein and others, 2006). In areas where the crystalline bedrock is very deep, well-construction data were supplemented with estimates from a contour map of the top elevation of the crystalline bedrock in Minnesota (Mossler, 1983). The crystalline-bedrock elevation was subtracted from water-table elevations simulated by the refined ground-water-flow models to compute an average saturated thickness for each basin. Recharge was derived from calibration of the refined ground-water-flow models. Porosities were based on reported values in the literature (Domenico and Schwartz, 1998), which vary over probable values of 0.05 to 0.3 for mixed glacial sediments and sedimentary bedrock. Thus, a range of mean residence times was calculated for each basin by use of the range of reasonable porosities.

Simulation of Areas With Relatively Short Residence Times

Residence times can be used to estimate the time of arrival of contaminants at a river or lake and to estimate the likelihood that a contaminant will naturally degrade along its travel path. However, residence times can vary, depending upon the location of interest. The five refined ground-water-flow models were used to differentiate areas with relatively short ground-water-residence times from areas having relatively long ground-water-residence times. Simulated particles of water were traced from the water table through the aquifers to a point of discharge such as a river or pumping well. Areas of relatively short residence times were defined as those areas in which the length of time for simulated particles to reach a stream was less than the median traveltime of all simulated particles in the tributary basin. This distinction is used for convenience and does not mean that contaminated water inside the area of relatively short residence time will not undergo any natural attenuation, nor does it mean that contaminated water outside of the marked area will be completely attenuated by natural processes. Rather, contaminated water inside the area of relatively short residence time will, on average, have a shorter residence time and therefore experience less natural attenuation than contaminated water outside of this area. Aquifer porosity was set to 10 percent in each tributary submodel; this was the value used to simulate particle traces in the regional model. The method is subject to the same assumptions of horizontal flow and no aquifer layering as the calculation of mean basin residence time.

Simulation of Stream Leakage Into the Ground-Water System

Chemicals dissolved in surface waters represent a potential source of contamination to ground-water-flow systems. Where the elevation of surface water is higher than the elevation of the water table, surface water can leak through riverbed deposits and recharge the ground-water-flow system. Elevations of surface-water features simulated with line sinks in the regional model were refined in the five tributary-basin submodels to ensure that changes in stream stage were appropriately represented. The largest changes in stream stage typically occurred at outlets of natural lakes and manmade reservoirs. After calibration, line-sink segments were highlighted to identify those river reaches and lake-shoreline segments where the surface waters were losing water to the ground-water-flow system.

Evaluation of Ground-Water-Residence Time and Ground-Water/Surface-Water Interaction

The calibrated recharge values in the refined tributary-basin submodels reflect trends in precipitation and evaporation across the region, as well as differences in infiltration of precipitation to individual aquifers. Recharge generally increases from west to east, following general trends in precipitation and evaporation in southeastern Minnesota and northwestern Wisconsin (Young and Hindall, 1973; Delin and Woodward, 1982; Novitzki, 1982). The exception to this trend is the moderate recharge rate for part of the Apple River Basin underlain by a crystalline-bedrock ridge, where the thin aquifer and near-surface impermeable rock likely limits the amount of precipitation able to infiltrate to and flow through the ground-water system.

Hydraulic conductivity and the model base elevation were treated separately for simulating the five tributary basins. As described previously, base elevations were varied among the tributary-basin submodels to represent crystalline-bedrock elevations. Model refinement included calibration of hydraulic conductivity for each basin so that differences between simulated and observed water levels and base flows were minimized. The pattern of calibrated hydraulic conductivities (fig. 8) matched the general trend in transmissivity estimated by Feinstein and others (2006); that is, in the northern Snake and Kettle River Basins, the base elevation is high with modest hydraulic conductivities of 7 and 5 ft/d, respectively, resulting in relatively lower transmissivities than for the southern basins. Aquifers in the southern Apple, Kinnickinnic, and Sunrise River Basins are generally thicker and have relatively higher hydraulic conductivities, ranging from 5 to 21 ft/d. The low-transmissivity area along the crystalline ridge in the Apple River Basin that was simulated in the regional model is captured in the refined tributary-basin submodel by the high base elevation.

The added flexibility of representing spatial variability in recharge, hydraulic conductivity, and base elevation among the tributary-basin submodels resulted in an improved match to base flow and water-level measurements compared to simulated results from the regional model. Simulated base flows were within 5 percent of all base-flow targets (table 3). Differences between simulated and measured water levels (fig. 9) also were generally improved, with a mean error of 8 ft, a mean absolute error of 20 ft, and a root-mean-square-error of 28 ft for the total of all water-level targets in the five tributary-basin submodels. Simulated results were used to evaluate mean ground-water-residence times (table 4), the spatial distribution of areas with relatively short ground-water-residence times (fig. 10), and the location of river reaches where surface water recharges the ground-water-flow system (fig. 11).

Mean Basin Residence Time Calculations

Conceptually, the mean basin residence time (table 4) is the average amount of time required for a chemical application at any location on the land surface (assuming immediate transportation to the water table) to move through and then exit the aquifer. The calculation averages areas characterized by very short ground-water traveltimes with areas characterized by very long ground-water traveltimes. In addition, aquifer heterogeneity (variability of the aquifer material) and aquifer layering have been ignored. These simplifications tend to reduce the calculated range of residence times, which could vary substantially for individual aquifers; that is, ground-water-residence times are generally shorter in shallow aquifers than in deep confined aquifers because of the additional vertical flow through low-permeability confining units and longer regional flow paths typical of flow in many deep aquifers. Moreover, fractures in shallow carbonate aquifers, such as the karstic Prairie du Chien aquifer, may become enlarged and interconnected by dissolution, thereby increasing preferential flow through these fractures compared to the bulk aquifer thickness. In such karst aquifers, ground-water flow can be very rapid through the conduits (miles per week), yet very slow through the rock matrix. Thus, the actual residence time of a contaminant may be shorter (days or weeks) or longer (millennia) than the range of mean values reported in table 4; a site-specific investigation would be necessary to determine the actual residence time.

Table 3. Estimated and simulated base flow at streamflow-gaging stations in the five tributary basins to the St. Croix River, Minnesota and Wisconsin.

Streamflow-gaging station	Estimated base flow*, in cubic feet per second	Simulated base flow, in cubic feet per second
Apple River	369	369
Kettle River	297	297
Kinnickinnic River	90	90
Snake River	221	222
Knife River (tributary to Snake River)	21	20
Sunrise River	71	71

* Estimated base flow is equivalent to the Q50 flow (streamflow exceeded 50 percent of the time) at the streamflow-gaging station.

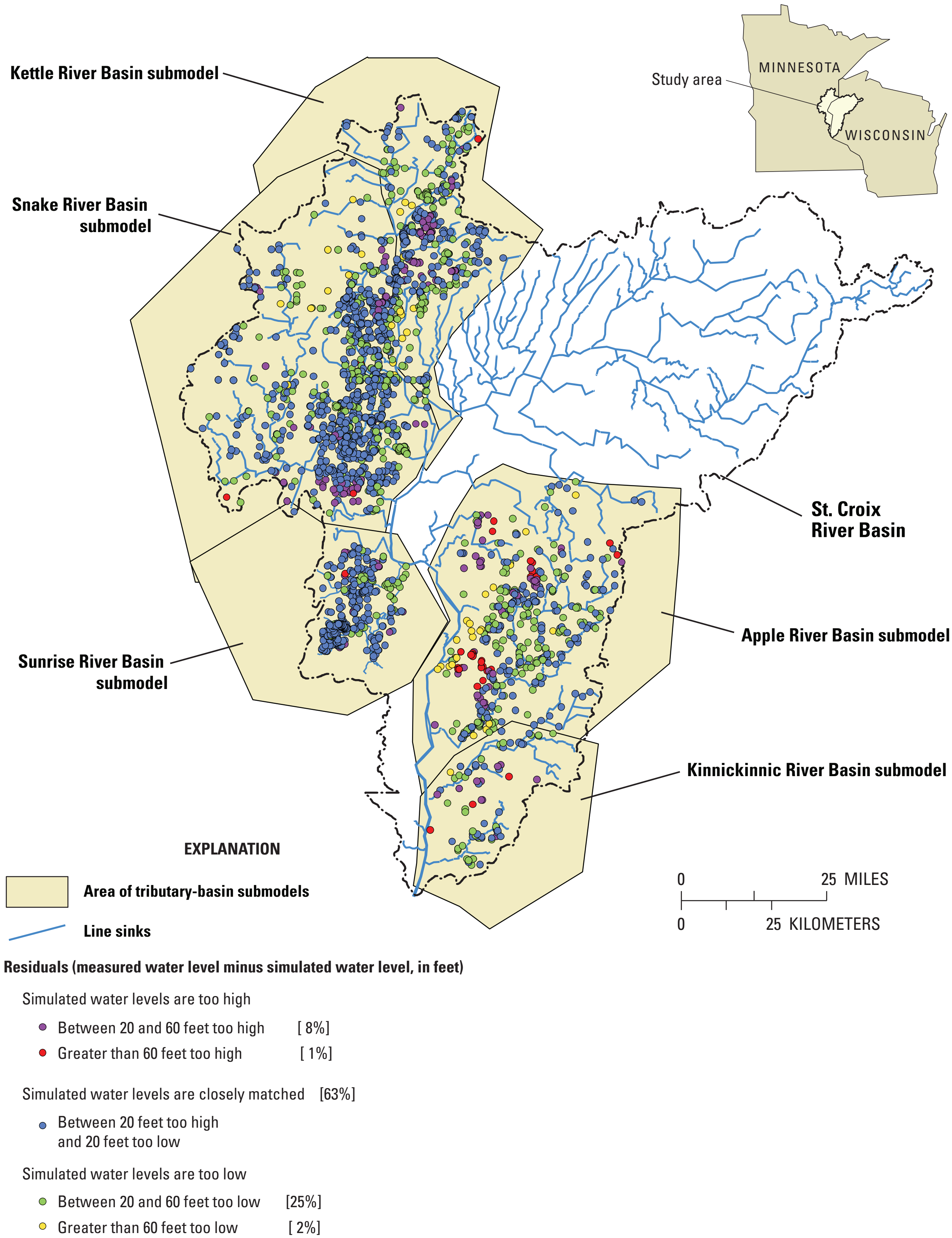

Figure 9. Distribution of water-level residuals for tributary-basin submodels of the Kettle, Snake, and Sunrise River Basins, Minnesota, and of the Apple and Kinnickinnic River Basins, Wisconsin. Percentages may not add to 100 percent because of rounding.

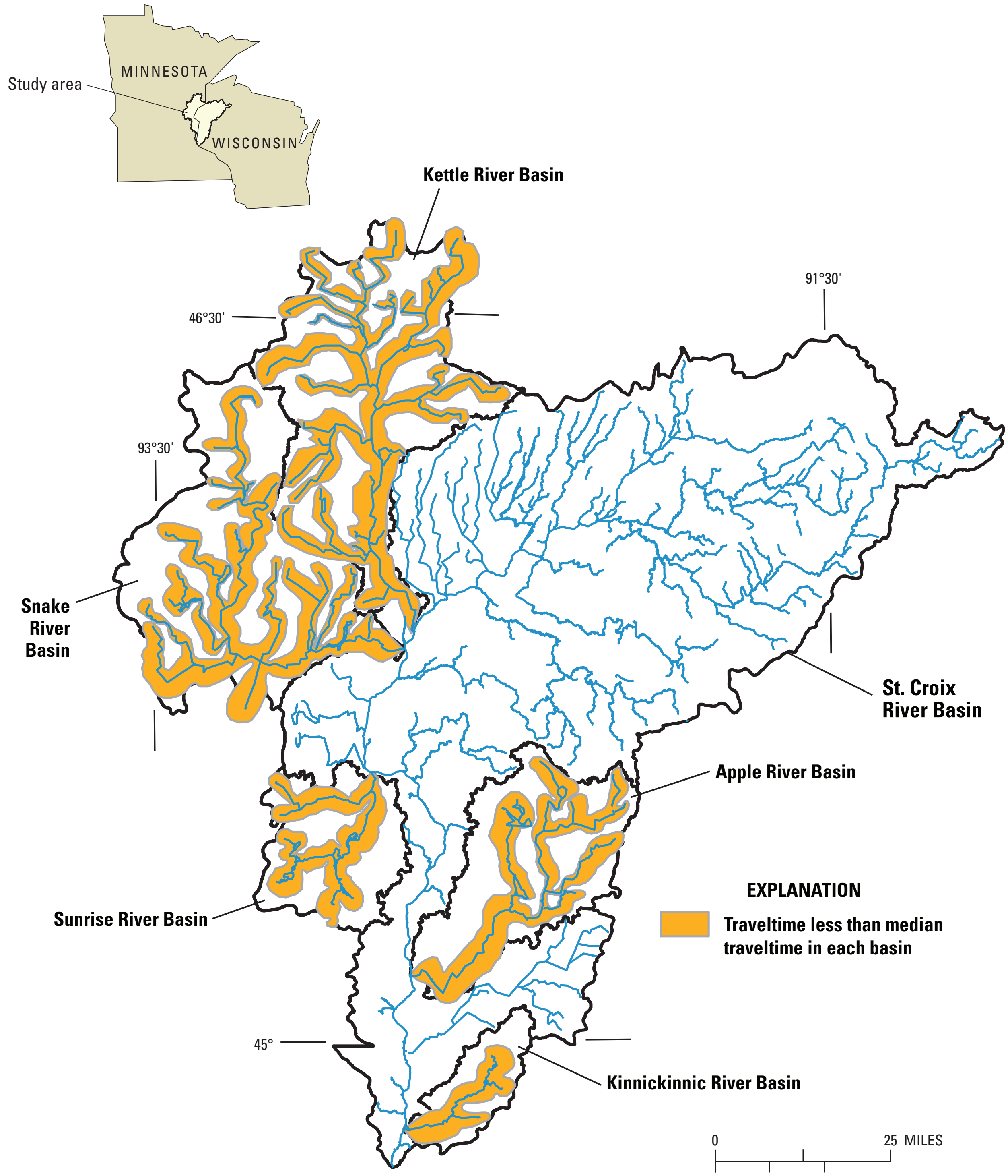

Figure 10. Model-simulated area of relatively short ground-water residence times in the Kettle, Snake, and Sunrise River Basins, Minnesota, and in the Apple and Kinnickinnic River Basins, Wisconsin.

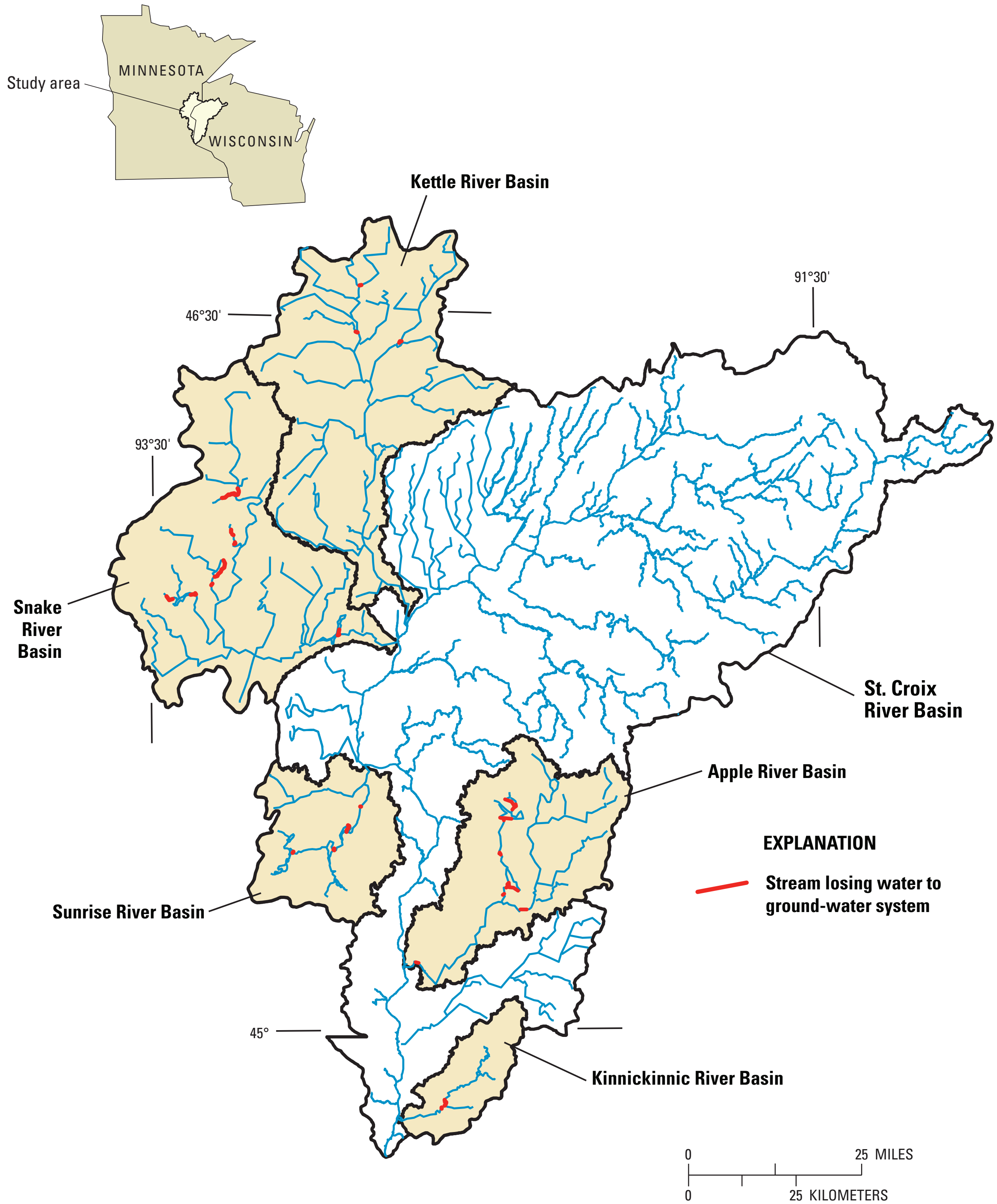

Figure 11. Model-simulated river segments discharging surface water to the ground-water-flow system in the Kettle, Snake, and Sunrise River Basins, Minnesota, and in the Apple and Kinnickinnic River Basins, Wisconsin.

Mean basin residence times are useful for evaluating the bulk response of a ground-water-flow system at a basinwide scale. Several general patterns can be observed from the estimated mean basin residence times (table 4). First, the two basins with the longest residence times, the Kinnickinnic and Sunrise River Basins, are the smallest (areally) of the five basins. Basin size is not a component in the calculation of mean basin residence time. The long residence times in these two relatively small basins can be attributed instead to their relatively large saturated thickness (table 4). Second, the ground-water recharge rate is greater in the Kinnickinnic River Basin than in the Sunrise River Basin and this difference results in a shorter residence time in the Kinnickinnic River Basin. Of the five tributary basins, the shortest mean residence time (20–120 years) was computed for the Apple River Basin, and the longest mean residence time (70–390 years) was computed for the Sunrise River Basin. The approach and results represent a rough guide for resource management that, although not appropriate for site-specific planning, provides an understanding of the processes that influence ground-water-residence time in idealized basins.

Simulated Areas With Relatively Short Residence Times

On the basis of simulated particle traces, areas of relatively short residence time generally occur where ground water discharges to surface-water features (fig. 10). Intuitively, contaminated water infiltrating to the water table near a river or stream has a relatively short distance to flow before discharging to the stream. A similar pattern was identified at the much larger scale of the entire St. Croix River Basin by Feinstein and others (2006). Nonetheless, the scale of investigation can influence the potential to identify areas of relatively short residence times; that is, ground water may move relatively quickly over short distances to seeps, ponds, agricultural tile, or headwater streams in localized areas that were not included in this investigation and therefore not identified.

The residence time of a contaminant in a ground-water-flow system can, among other factors, affect the potential for natural attenuation because of geochemical and biological processes along the flow path. For this reason, delineation of areas with relatively short residence times is useful for resource management and planning. Nonetheless, the degree of actual attenuation will depend upon the type of contaminant, properties of the soil and aquifer, and implementation of any engineered approaches for removing or degrading the contaminant. Response to a specific contamination problem would require site-specific investigation and planning.

Simulated Stream Leakage Into the Ground-Water System

In humid climates such as that of Minnesota and Wisconsin, ground water typically discharges to surface-water features that are in direct connection with the ground-water system. However, surface-water discharge to ground water can occur, and it most commonly occurs where surface waters are naturally or artificially restricted or elevated (fig. 11), such as along the downgradient shoreline of a lake or reservoir where the surface-water level has been elevated by a channel restriction or a dam, or where lakes and ponds are perched above the water table (perched water bodies were not considered in this investigation, however). Surface water can also enter an aquifer where

Table 4. Estimated range of mean ground-water-residence times in the five tributary basins to the St. Croix River, Minnesota and Wisconsin.

Basin	Saturated thickness, in feet	Porosity, in percent	Recharge, in inches per year	Mean residence time, in years
Apple River	310	5–30	9.1*	20–120
Kettle River	190	5–30	3.9	30–170
Kinnickinnic River	780	5–30	8.1	60–350
Snake River	150	5–30	3.0	30–170
Sunrise River	550	5–30	5.0	70–390

* Value is the area-weighted average of calibrated recharge zones in the Apple River tributary-basin submodel.

ground-water-withdrawal wells are near rivers and lakes or along river meanders where local hydraulic gradients can be complex.

Results of simulations illustrate regional ground-water/surface-water interaction along the shoreline of large lakes and reservoirs in the tributary basins (fig. 11). The upgradient (upstream) shorelines of the simulated lakes and reservoirs, like most river segments, are not highlighted and receive ground-water discharge. However, some downgradient shorelines are highlighted (fig. 11), indicating that surface water is discharging into the ground-water-flow system along those segments. Although only large lakes and reservoirs that are well connected to the ground-water system were simulated in the tributary-basin submodels, similar ground-water/surface-water interaction patterns may occur near small lakes and reservoirs. Small perched water bodies may lose water to the ground-water-flow system, with the amount largely dependent upon the permeability of the lakebed sediments. Likewise, the results of simulations illustrate where contaminated surface waters could potentially enter the ground-water system, but local-scale investigations would be needed to determine whether, and to what extent, contaminated surface water was entering the aquifer.

Limitations of the Study

The index method used by Schmidt (1987), and adapted in this report for the St. Croix River Basin, is subjective and includes uncertainties that are difficult to quantify (Focazio and others, 2002). Moreover, subjective methods for estimating ground-water-contamination susceptibility are not scientifically defensible in that categorization of physical resource maps and assignment of susceptibility values to those categories is not derived from analyses of water-quality data or process-based approaches, such as a ground-water-flow simulation. Rather, categorization is determined on the basis of "professional judgment" (Focazio and others, 2002). Nonetheless, the method presented by Schmidt (1987) is familiar to many resource managers in the basin and was adapted for the St. Croix River Basin to furnish a seamless map for resource managers working in both Minnesota and Wisconsin. In addition, the susceptibility patterns estimated by the ground-water-contamination-susceptibility maps for Wisconsin (Schmidt, 1987) and Minnesota (Porcher, 1989) appear to be generally supported by pesticide and nitrate samples from wells in a part of the Upper Mississippi River Basin that includes the St. Croix River Basin (Stark and others, 1996; Hanson, 1998). Regardless, it is important for resource managers to realize the limitations of Schmidt's (1987) method as it relates to the scientific method (Focazio and others, 2002).

The Schmidt susceptibility index values map is not designed for site-specific use because it was derived from regional maps. Instead, the information contained in the map may be useful for regional planning and to help identify areas requiring additional study at a site-specific scale. The method (Schmidt, 1987) is also limited to nonreactive chemicals dissolved in water moving from the land surface to the water table; chemical-specific characteristics (for example, solubility and volatility) were not considered. Similarly, the Schmidt susceptibility index values map does not indicate areas that are or will be contaminated, nor does it identify areas that are not or cannot be contaminated. Whether the water table becomes contaminated at a particular location will depend upon hydrogeologic properties at the site as well as the type and amount of chemical released into the environment. The nature of land use and the intensity of that use will also influence the likelihood of ground-water contamination at a particular location.

The method used to estimate mean basin residence times and areas of relatively short or long residence times incorporated assumptions that characterize idealized flow systems. These assumptions include: (1) no resistance to vertical ground-water flow, (2) no aquifer layering or regionally extensive confining units, and (3) constant saturated thickness and porosity of the aquifer and constant recharge to the aquifer over the entire basin. Idealized flow systems do not occur in nature, and as a result, these assumptions represent limitations of the analysis, especially where layered sedimentary rocks transmit a substantial proportion of the total ground-water flow. The consequence of these limitations is that the mean basin residence times could span a larger range of time than the estimated values reported in table 4 for the five tributary basins. Moreover, the actual residence time of an individual contaminant may be shorter (days or weeks) or longer (millennia) than the range of mean values reported in table 4 depending upon the site specific characteristics of the aquifer, and the physical and chemical characteristics of the contaminant.

Ground-water/surface-water interaction was simulated at a regional scale in the five tributary-basin submodels. Local variations in surface-water elevations, stream meanders, and aquifer heterogeneity, combined with seasonal water-level fluctuations that were not simulated in the steady-state submodels could induce local or temporal changes in the direction of water flow between ground-water and surface-water systems. Similarly, small water bodies were not evaluated in this study, but could locally influence ground-water/surface-water interactions.

Summary

The St. Croix National Scenic Riverway is recognized for its diverse biota and good water quality. In places, the St. Croix River Basin is undergoing rapid development, which may increase the potential for ground-water contamination from point sources such as hazardous-materials spills, in addition to the potential for contamination from nonpoint sources such as those associated with agricultural fertilizers or animal-waste disposal. This study by the U.S. Geological Survey, in cooperation with the National Park Service, was designed to illustrate susceptibility of the ground-water-flow system to potential contamination, estimate ground-water-residence times in five tributary basins to the St. Croix River, and identify river and lake segments in the five tributary basins where surface water could potentially enter the ground-water-flow system. These tributary basins included the Apple, Kettle, Kinnickinnic, Snake, and Sunrise River Basins.

Following the concepts proposed by Schmidt (1987), the susceptibility of ground water to contamination depends in part on the physical properties of the material above the water table. Regionally available maps describing characteristics of soil, surfical deposits, and bedrock were compiled along with information from wells on depth to the water table and depth to bedrock. These data were used to estimate Schmidt susceptibility index values for the St. Croix River Basin. According to Schmidt (1987), these index values indicate relative susceptibility of the ground-water-flow system to contamination at the land surface. Based on this method, areas underlain by coarse-grained sediments and shallow water tables appear to be relatively more susceptible to contamination than areas underlain by fine-grained sediments and a deeper water table. Carbonate bedrock is uniquely susceptible to contamination in areas where karst dissolution cavities may occur (Tipping, 2002). Therefore, the extent of carbonate bedrock is identified on the Schmidt susceptibility index values map.

If a contaminant reaches the water table, its residence time within the aquifer can affect the potential for natural attenuation along the flow path. A method by Haitjema (1995b), using estimates of average saturated thickness, porosity, and recharge, was employed to estimate a range of mean residence times for the five tributary basins. Results were computed as a range of mean residence times due to uncertainty pertaining to the range of possible porosity values. The shortest mean residence time (20–120 years) was computed for the Apple River Basin; the longest mean residence time (70–390 years) was computed for the Sunrise River Basin. Areas of relatively short and relatively long residence times were evaluated by means of refined ground-water-flow submodels that were based on the regional model constructed by Feinstein and others (2006). Relatively short residence time was defined as less than the median residence time of all simulated particles of water in the tributary basin. Results of simulation show that contaminants that enter an aquifer in areas near streams and rivers, where ground water typically discharges from aquifers, will have shorter residence times than contaminants that enter the flow system in areas far from a point of discharge. Contaminants near streams and rivers could have residence times much shorter than the calculated minimum mean basin residence times and could represent a greater threat to aquatic biota because of limited natural attenuation or dilution.

Just as ground-water discharge to streams could contaminate the surface-water system, leakage of contaminated surface water into an aquifer could contaminate the ground-water system. The refined tributary-basin submodels were used to identify areas where average surface-water elevations were above average regional ground-water elevations. These areas, which represent locations where surface water recharges the underlying aquifer, typically occur on the downgradient side of lakes and reservoirs where the surface-water level has been elevated by a channel restriction or a dam.

The results described in this report have limitations. In particular, the Schmidt susceptibility index values map is not designed for site-specific use and includes uncertainties that are difficult to quantify (Focazio and others, 2002) due to the subjective method adapted from Schmidt (1987). Nonetheless, regional patterns of susceptibility index values appear to be generally supported by pesticide and nitrate samples from wells in a part of the Upper Mississippi River Basin that includes the St. Croix River Basin (Stark and others, 1996; Hanson, 1998). Likewise, estimates of contaminant residence times represent a range of basin-wide averages, while the actual residence time of a specific contaminant will vary depending upon its physical and chemical characteristics, the transport process through locally heterogeneous aquifers, and the location at which the contaminant enters the ground-water-flow system. Despite these limitations, the results described in this report provide a regional assessment of ground-water-contamination susceptibility, ground-water-residence times, and ground-water/surface-water interaction, which constitute a foundation for more detailed evaluation at local scales.

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