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Groundwater Simulation Modeling and Potentiometric Surface Mapping, McHenry County, Illinois

Scott C. Meyer, Yu-Feng Lin, Daniel B. Abrams, George S. Roadcap

ILLINOIS

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Scott C. Meyer, M.S., P.G.
Illinois State Water Survey

Yu-Feng Lin, Ph.D.
Illinois State Geological Survey

Daniel B. Abrams, Ph.D.
Illinois State Water Survey

George S. Roadcap, Ph.D., P.G.
Illinois State Water Survey

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Abstract

Illinois State Water Survey researchers conducted two studies to support water resources planning in McHenry County, Illinois. The first was an investigation to map heads in the shallow aquifers of McHenry County, and the second was a project to develop and use a computer model to simulate groundwater flow in the aquifers supplying the county. This report summarizes the hydrogeology of McHenry County and the surrounding region, discusses historical and future groundwater pumping, describes the methods employed to measure and map shallow heads in McHenry County, presents and discusses the potentiometric surface maps developed from the measured heads, summarizes the methods and datasets used to develop the groundwater flow model, and presents and discusses groundwater flow model results.

We mapped 329 water levels measured in 2011 in wells finished in 5 shallow aquifers in McHenry County, including sand and gravel aquifers and the underlying Shallow Bedrock Aquifer. The water levels are strongly influenced by connections between the aquifers, which equalize heads between aquifers, and between the aquifers and surface waters, which equalize surface water elevation and head in the connected aquifer. The shallowest of these aquifers are completely desaturated in areas of dissected topography and in elevated areas adjacent to steep slopes, where any water entering the unit from above can readily drain out. The measured water levels suggest that heads in the shallow aquifers were about 2 feet higher in 2011 than in 1994, suggesting that changes in pumping rates and distribution, climate, land use, land cover, and other factors have not resulted in a countywide decline in shallow aquifer heads during the period from 1994 to 2011.

A groundwater flow model was developed to provide planners and researchers with an understanding of the consequences in McHenry County of groundwater development in the county and surrounding areas of Wisconsin and Illinois. The 2.9-million cell MODFLOW model simulates groundwater flow under transient conditions in all major aquifers underlying McHenry County and represents pumping from over 8700 wells in the McHenry County region. The hydrogeology of the region is represented with 26 layers. The model is used to quantify drawdown and reduction in natural groundwater discharge to surface waters resulting from historical pumping from 1864 to 2009 and estimated pumping, under three plausible scenarios of groundwater development, from 2010 to 2050.

Simulations show that the impermeable upper bedrock materials underlying the Shallow Bedrock Aquifer and overlying the Ancell Unit aquifer strongly influence groundwater circulation in the aquifers underlying McHenry County. The impermeable upper bedrock greatly limits leakage into the deep aquifers underlying it, which include sandstones of the Ancell, Ironton-Galesville, Eau Claire, and Mt. Simon Units. The comparatively low transmissivity of these deep aquifers also limits eastward movement of water from north-central Illinois and south-central Wisconsin, where the impermeable upper bedrock is generally absent, toward cones of depression in heavily pumped areas of northeastern Illinois and southeastern Wisconsin. Model simulations reflect the influence of these factors, showing that drawdown in the deep aquifers increases from west to east across McHenry County, exceeding 400 feet in the southeastern part of the county in 2009. Drawdown under scenarios of future pumping increases to 2050, and model simulations show that, for the simulated annualized pumping rates, Ancell head decreases to within 50 feet of the top of the Ancell Unit within McHenry County by 2050 under the most extreme pumping scenario.

The shallow aquifers overlying the impermeable upper bedrock materials, which include the Shallow Bedrock Aquifer and unconsolidated sand and gravel aquifers contained within the overlying Quaternary materials, are affected by significantly less drawdown than the deep aquifers, although this drawdown could still cause well failures in affected areas. The largest cones of depression surround public water system wells and commercial/industrial wells in and near Woodstock, Algonquin, Carpentersville, Cary, and Crystal Lake. Less drawdown affects the shallow aquifers because they receive replacement water at significantly greater rates than do the deep aquifers. Since this replacement water originates as captured surface water, however, withdrawals from the shallow aquifers, although they result in less drawdown, cause reductions in natural groundwater discharge, and these reductions may affect base flows in streams and water levels in lakes and wetlands. Model simulations show that natural groundwater discharge in the McHenry County area has been reduced by about 11.5 percent by pumping of groundwater. Watersheds that have experienced the greatest reductions are those of the Crystal Lake Outlet and the City of Woodstock (Silver Creek). Although these streams and many others in McHenry County receive discharges of treated effluent from wastewater treatment plants at rates that compensate in quantity for these reductions in natural groundwater discharge, the effluent differs in quality from natural groundwater, and it is discharged at point locations rather than by diffuse seepage along stream channels.

Recommendations for further work include efforts to refine the model as well as modeling studies to simulate alternative scenarios of groundwater development in McHenry County. Such simulations can provide planners with guidance to minimize and/or distribute unwelcome impacts from pumping.

1 Introduction

McHenry County (Figure 1, Figure 2, Figure 3) is entirely dependent on groundwater for farm and rural domestic water supplies, public water systems, self-supplied commercial and industrial water supply, and self-supplied irrigation. Although the Fox River passes through the county, the river and other surface waters are not currently used for water supplies in the county. Sustaining the water supply for McHenry County requires sound planning and management decisions regarding groundwater availability and use within the county. The purpose of this report is to provide a rational basis for such decisions by providing and discussing observations and computer-model output pertinent to the groundwater resources of the county and their present and future use. For readers who are not familiar with groundwater science, Appendix A discusses basic concepts in the field, and Section 7 is a glossary of technical terms employed in this report. Supplemental information on the contents of this report, including data files, technical aspects of the groundwater flow modeling, animations of model output, and updated model output, are available at http://www.isws.illinois.edu/docs/pubs/iswscr2013-06/.

1.1 Previous Investigations

The geology and groundwater resources of McHenry County have been described in many reports by the Illinois State Geological Survey (ISGS), Illinois State Water Survey (ISWS), and other agencies.

Curry et al. (1997) and Thomason and Keefer (2013) list several investigations by the ISGS that discuss the geology of McHenry County. These include reports and mapping projects that address limited aspects of the county geology as well as more comprehensive geology for planning investigations. Curry et al. (1997) mapped Quaternary lithostratigraphic units in McHenry County and constructed derivative maps, including a soil drainage map and an aquifer sensitivity map. Thomason and Keefer (2013) created a three-dimensional model of the Quaternary materials in McHenry County that was employed as the conceptual model for the groundwater flow model developed for the present study.

Groundwater studies in McHenry County began with the work of Sasman (1957), who measured shallow groundwater levels to determine the cause of water level fluctuations of Crystal Lake in southeastern McHenry County. Suter et al. (1959) discussed the groundwater resources of McHenry County as part of a summary of the groundwater resources of the Chicago region. Csallany and Walton (1963) conducted statistical analyses of specific capacity data derived from pumping tests of shallow bedrock wells in northern Illinois, including McHenry County, and estimated probable ranges in yields of these wells in a variety of geographic and hydrogeological settings. Prickett et al. (1964) estimated the practical sustained yield of the existing municipal well fields serving Woodstock, and Walton (1965), as part of a statewide assessment, estimated groundwater recharge in the Woodstock area. Woller and Sanderson (1976) described the public groundwater supplies in McHenry County. Schicht et al. (1976) summarized the availability, quality, and cost of water in northeastern Illinois and estimated areas of future groundwater shortfall. Nicholas and Krohelski (1984) measured water levels in wells finished in the glacial drift in McHenry County and combined the data to generate a composite potentiometric surface map for all of the glacial drift aquifers in the county. Meyer (1998) measured water levels and used the measurements to map potentiometric surfaces of glacial drift aquifers in the county.

Meyer et al. (2012), building on groundwater flow modeling developed for Kane County by Meyer et al. (2009), developed a groundwater flow model to quantify impacts of estimated future pumping on groundwater flow in (1) deep aquifers throughout northeastern Illinois (including McHenry County), and (2) shallow aquifers in the Illinois portion of the Fox River watershed (which includes eastern McHenry County). The modeling of Meyer et al. (2012) suggested that drawdown had exceeded 400 feet (ft) in the Ancell Unit (the shallowest of the deep aquifers in the region) throughout eastern McHenry County as of 2005, a corroboration of region-wide water level measurements (Suter et al., 1959; Walton et al., 1960; Sasman et al., 1961; Sasman et al., 1962; Sasman et al., 1967; Sasman et al., 1973; Sasman et al., 1977; Sasman et al., 1982; Visocky et al., 1985; Sasman et al., 1986; Visocky, 1993; 1997; Burch, 2002; 2008). Drawdown in the deep aquifers is a consequence of pumping not only in McHenry County, but also throughout the Chicago-Milwaukee region. Drawdown in the shallow aquifers is more localized than in the deep aquifers because it is moderated by connections with surface water and by higher rates of recharge than that which affects the deep aquifers. However, the modeling of Meyer et al. (2012) showed that 2005 drawdown in the shallow Quaternary aquifers exceeded 5 ft in central McHenry County, around Woodstock, and in southeastern McHenry County. Although the magnitudes of these drawdowns are much less than those in the deep aquifers, readers should be aware that they have the potential to affect wells because pumps in shallow wells are set much nearer the static water level than in deep wells. The modeling by Meyer et al. (2012) showed that natural groundwater discharge to watersheds overlapping McHenry County (and within the Fox watershed) had declined as of 2005 by 3 to 35 percent as a consequence of groundwater pumping, the largest reduction occurring in the southeastern McHenry County watershed of the Crystal Lake Outlet.

1.2 Acknowledgments

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Several ISWS researchers and support staff contributed to this project. Sandie Osterbur assisted in the assembly of private water well records for water level measurement. Kevin Rennels assisted with field work. Tim Bryant assembled groundwater withdrawal data and municipal well information from the ISWS Illinois Water Inventory Program database. Karen Bridges developed GIS graphics for inclusion in the final report. Stephen Burch (retired) provided historical pumping data for northeastern Illinois covering the period 1864–1963.

Finally, we thank the many private well owners and community operators who allowed measurement of the water level in their wells, and we thank the McHenry County Defenders for

assisting us in arranging permission to measure water levels in many private wells in McHenry County.

1.3 How Much Groundwater is Available in McHenry County?

How much groundwater is available to users in McHenry County long-term—that is, the sustainable pumping rate—depends on how groundwater withdrawals affect the environment and what the public considers to be acceptable environmental impacts (Bredehoeft, 2002; Devlin and Sophocleus, 2005). Moreover, impacts from groundwater withdrawals change constantly as the hydrologic cycle adjusts to climate variability and change, as new wells are put into service and old wells are taken out of service, and pumping rates at operating wells rise and fall to meet demands, not only in McHenry County, but also in adjacent parts of Illinois and Wisconsin. For example, although the deep bedrock Mt. Simon unit could potentially provide additional groundwater to McHenry County, groundwater in all but the uppermost part of the unit is highly saline. The demand for this water, however, is currently not high enough to justify the high costs of desalination. Predicting future groundwater availability is complicated by the fact that the cost of providing water is constantly changing under the influence of new technologies, a changing economy, and other factors.

Groundwater withdrawals cause the subsurface water pressure (head) in source aquifers to decline. These head declines (drawdown) can in turn lead to a variety of economic, biological, physical, and geochemical impacts that introduce considerable complexity to the problem of computing water availability. If large enough, drawdown may cause water levels in wells to decline to such a degree that pumping expenses increase and/or well yields decrease. Head declines may also result in decreased groundwater discharge to streams (base flow), possibly leading to reduced streamflow during periods of low precipitation, reduced water levels in lakes, reduced saturated conditions in wetlands, and changes in aquatic habitats and vegetation. In some settings, reduced heads can result in decreased groundwater quality, requiring expensive treatment. Where do scientists, and more importantly the public, draw the line as to what is or is not an acceptable impact?

In this study, instead of generating single-value estimates of groundwater availability, a groundwater flow model was employed to simulate the impacts of plausible future pumping conditions. If impacts suggested by the models are considered by stakeholders to be unacceptable or too uncertain, they may recommend adopting policies and targeted monitoring and water management strategies to track and mitigate impacts regionally or in specific affected areas, or conducting additional studies to reduce uncertainty. The model developed for this project can be used for future analysis of other scenarios to test effects of alternative management strategies. Northeastern Illinois is a subject of ongoing research by the ISWS and other researchers, and supplemental information, including updates to the model, will be made available at http://www.isws.illinois.edu/docs/pubs/iswscr2013-06/.

1.4 Pertinent Geographic Areas

Figure 1 illustrates three geographic areas referenced throughout this report. The first of these, *McHenry County*, corresponds to the political entity of McHenry County. We define *northeastern Illinois* as an 11-county region that includes Boone, Cook, Du Page, De Kalb, Grundy, Kane, Kankakee, Kendall, Lake, McHenry, and Will Counties. This definition is consistent with the usage of Dziegielewski and Chowdhury (2008) and Meyer et al. (2012). Our *regional study area* encompasses a multistate area that includes large portions of Illinois, Indiana, Michigan, Wisconsin, and Lake Michigan. The regional study area corresponds to the geographic extent of the groundwater flow model, discussed in Section 4, which is the basis for much of the analysis included in this report.

1.5 Hydrogeological Framework

Paleozoic sedimentary rocks overlie the crystalline Precambrian basement throughout northeastern Illinois. The Paleozoic rocks of McHenry County, which are about 2000 to 3600 ft thick, were deposited in marine environments during the Cambrian, Ordovician, and Silurian Periods, about 400 to 550 million years before the present.

The Paleozoic sedimentary rocks are overlain by unconsolidated materials—mostly gravel, sand, silt, and clay—that were deposited much more recently, during the Quaternary Period. The Quaternary Period encompasses the most recent 2.6 million years of earth history and was marked by repeated glaciation of northeastern Illinois. Quaternary materials range in thickness from less than 50 ft in many areas of western McHenry County to more than 500 ft in the northwestern corner of the county (Figure 4).

The Paleozoic bedrock surface underlying the Quaternary materials (Figure 5) is composed of rocks ranging in age from the Ordovician to Silurian Periods and deposited roughly 400 to 500 million years before the present. The bedrock surface, which generally slopes downward from west to east, preserves some preglacial topographic features, notably a network of bedrock valleys incised into the bedrock through stream erosion prior to glaciation. The bedrock valleys were largely filled with sediment during Quaternary glaciation of the region, deposits that sometimes include thick intervals of permeable sand and gravel that today, because they are buried and saturated with water, function as aquifers. The most significant bedrock valley in the McHenry County area is the Troy Bedrock Valley, which crosses the northwestern corner of the county and contains about 500 ft of Quaternary sediment. Unnamed bedrock valleys, which are in some places coincident with locations of modern streams, occur in west-central and northeastern McHenry County.

The hydrologic character of the Quaternary materials and underlying bedrock, and their three-dimensional orientation, together define the hydrogeological framework of the McHenry County region. This framework exerts significant control on groundwater flow and availability.

This report employs customized hydrostratigraphic nomenclature both to simulate groundwater flow in McHenry County and to facilitate discussion. *Hydrostratigraphic units* are defined on the basis of the gross hydrologic characteristics of earth materials and frequently represent aggregations of *lithostratigraphic units* (defined on the basis of material characteristics), which are commonly used by geologists. The hydrostratigraphic nomenclature used in this report describes earth materials present in a large area of Illinois, Wisconsin, Michigan, Indiana, and Lake Michigan. Unit thicknesses vary considerably. Some units may not be present or have a limited distribution in McHenry County, but the presence of these units within the region may affect local groundwater flow within the county. Although the units are hydrologically heterogeneous at high resolution, they are assumed to be composed of a continuous flow medium. Because the model simulations are at a regional scale, hence the representative elementary volume is large, this assumption is valid.

1.5.1 Bedrock Hydrostratigraphy

The following paragraphs summarize the bedrock hydrostratigraphic nomenclature (Figure 6) and hydrologic character of these bedrock units in northeastern Illinois. Quaternary materials

(Section 1.5.5) overlie the Paleozoic rocks in almost all of McHenry County. More detailed discussions of the Paleozoic rocks are widely cited (Willman et al., 1975; Visocky et al., 1985).

1.5.1.1 Precambrian Unit

The Precambrian rocks underlying the Paleozoic sedimentary rocks of northeastern Illinois, which are 3000 to 5000 ft below the land surface, are typically interpreted to be relatively impermeable metamorphic and plutonic igneous rocks (McGinnis, 1966; Nicholas et al., 1987; Catacosinos et al., 1990; Catacosinos and Daniels, 1991; Cannon et al., 1997). The Precambrian rocks are aggregated as the Precambrian Unit in this report.

1.5.1.2 Mt. Simon Unit

The lowermost water-yielding rocks in northeastern Illinois—the Mt. Simon Sandstone and, directly overlying the Mt. Simon, the Elmhurst Sandstone Member of the Eau Claire Formation—are grouped as the Mt. Simon Unit. Use of these Cambrian sandstones for water supply is limited in northeastern Illinois by high salinity (Visocky et al., 1985). The Mt. Simon Unit ranges in thickness from 1200 to 2100 ft in McHenry County, thickening southeastward.

1.5.1.3 Eau Claire Unit

We group as the Eau Claire Unit the upper two members of the Cambrian Eau Claire Formation, the Lombard Dolomite Member and the overlying Proviso Siltstone Member. Lithologically and hydrologically, the Eau Claire Unit transitions between an aquitard and an aquifer in northeastern Illinois. The Eau Claire Unit consists of shale, siltstone, and dolomite in the southern part of northeastern Illinois, but it grades northward across the region to sandstone (Buschbach, 1964; Willman et al., 1975), which functions as an aquifer. Young and Siegel (1992) noted that the effectiveness of the Lombard and Proviso Members as a confining unit is directly dependent on the proportion of relatively impermeable shale, siltstone, and dolomite within the interval—a proportion that increases to the south. In southeastern Wisconsin, the Eau Claire Unit is an aquifer consisting of sandstone with local beds of green to black shale and dolomite. It is aggregated with equivalents of the underlying Mt. Simon Unit and overlying Ironton-Galesville Unit as the Lower Sandstone Aquifer by the Southeastern Wisconsin Regional Planning Commission and Wisconsin Geological and Natural History Survey (2002). In McHenry County, the Eau Claire Unit ranges from 150 to 410 ft thick and thickens southward.

1.5.1.4 Ironton-Galesville Unit

The Ironton-Galesville Unit, consisting of the Cambrian Ironton and Galesville Sandstones, overlies the Eau Clare Unit and is continuous throughout northeastern Illinois (Visocky et al., 1985). This unit is typically 150 to 225 ft thick and is thickest in the southeast portion of northeastern Illinois. In McHenry County, the unit is 90 to 180 ft thick and is thickest in the southwest. The Ironton-Galesville is a laterally persistent, consistently permeable aquifer throughout northeastern Illinois (Visocky et al., 1985). Wells are often screened through both the Ironton-Galesville and overlying Ancell Group sandstones, referred to in this report as the Ancell Unit.

1.5.1.5 Potosi-Franconia and Prairie du Chien-Eminence Units

The Potosi-Franconia Unit (Franconia Formation and overlying Potosi Dolomite, both Cambrian) and the Prairie du Chien-Eminence Unit (Cambrian Eminence Formation and overlying Ordovician Prairie du Chien Group) sequentially overly the Ironton-Galesville Unit. Both units consist predominantly of fine-grained siliciclastic sediments and dolomite with lenses of sandstone. Generally, these units function as an aquitard, but sandstones contained within them sometimes function as aquifers. Where these rocks subcrop the Quaternary materials and form the bedrock surface, as occurs to the northwest of McHenry County, in Wisconsin, and to the southwest near the Sandwich Fault Zone, secondary porosity permits small groundwater supplies to be obtained from them. The combined thickness of the Potosi-Franconia and Prairie du Chien-Eminence Units ranges from 10 to 200 ft in McHenry County, increasing southward.

1.5.1.6 Ancell Unit

The Ancell Unit of this report consists of the Ordovician Ancell Group. In northeastern Illinois, the Ancell Unit consists of the Glenwood Formation (sandstone, dolomite, and shale) and the St. Peter Sandstone. Where the St. Peter Sandstone is present in northern Illinois, it is an important aquifer that can supply high-capacity municipal wells; it is often screened in combination with the Ironton-Galesville Unit. In McHenry County, the Ancell Unit ranges from 130 to 320 ft in thickness, its thickness increasing southwestward.

1.5.1.7 Galena-Platteville and Maquoketa Units

The Galena-Platteville Unit, consisting of the Ordovician Platteville and Galena Groups, is predominantly pure limestone and dolomite, while the Maquoketa Unit consists of dolomitic shale, argillaceous dolomite, and limestone assigned to the Ordovician Maquoketa Group. Where present within about 25 to 125 ft of the bedrock surface, weathering and dissolution of the carbonate rocks (limestone and dolomite) of the Galena-Platteville and Maquoketa Units has resulted in enough secondary porosity and permeability that part or all of the units may be included in the Shallow Bedrock Aquifer (Section 1.5.2). In most of northeastern Illinois, however, the Galena-Platteville and Maquoketa Units function as an aquitard. The combined thickness of the Galena-Platteville and Maquoketa Units ranges from 100 to 610 ft in McHenry County, increasing eastward.

1.5.1.8 Silurian-Devonian Carbonate Unit

Carbonate rocks deposited during the Silurian and Lower to Middle Devonian Periods are included in the Silurian-Devonian Carbonate Unit. The Silurian System consists largely of dolomite, but lesser amounts of shale are present, and the dolomites may be argillaceous, silty, or clean. Lower and Middle Devonian limestone and dolomite, although present elsewhere within the regional study area, do not extend into northeastern Illinois, where the Silurian-Devonian Carbonate Unit is composed entirely of Silurian dolomites. Within about 25 to 125 ft of the bedrock surface, the Silurian-Devonian Carbonate Unit incorporates secondary porosity and permeability and is included in the Shallow Bedrock Aquifer (Section 1.5.2). Where it is overlain by younger rocks of the impermeable Upper Bedrock Unit, weathering and dissolution of the Silurian-Devonian Carbonate Unit has been minimal, and the Silurian-Devonian Carbonate Unit is most accurately characterized as an aquitard. In McHenry County, the Silurian-Devonian Carbonate Unit is laterally discontinuous, having been removed by erosion in much of the county. Where present, it is generally less than 100 ft thick.

1.5.1.9 Upper Bedrock Unit

The Upper Bedrock Unit contains Upper Devonian to Cretaceous rocks of variable lithology. This unit is absent from all of northeastern Illinois except southwestern Will County and southern Grundy County. Although this sequence includes both aquifers and confining units in areas remote from northeastern Illinois, the overall hydrologic effect of the sequence for the underlying units is one of an aquitard owing to the presence of widespread, relatively impermeable fine siliciclastic materials within it.

1.5.2 Shallow Bedrock Aquifer

Where the impermeable Upper Bedrock Unit is absent, the uppermost 25 to 125 ft of bedrock (Zeizel et al., 1962; Bergeron, 1981; Graese et al., 1988; Visocky and Schulmeister, 1988; Kay and Kraske, 1996)—where the bedrock consists of rocks of the Silurian-Devonian Carbonate Unit, Maquoketa Unit, and Galena-Platteville Unit—forms the Shallow Bedrock Aquifer (Csallany and Walton, 1963) (Figure 6). This aquifer, also called the *dolomite aquifer* or *shallow dolomite aquifer*, is defined by secondary porosity and permeability that formed through weathering and dissolution of the carbonate rock, principally along fractures and bedding planes, with subsequent burial by Quaternary materials and saturation by groundwater. The Shallow Bedrock Aquifer is a common target of domestic supply wells in McHenry County, but well yields are variable, a product of the size, number, and degree of connection of fractures and bedding planes intersected by the well bore.

Because the bedrock units dip gently from west to east, and because they have been beveled to a roughly horizontal surface largely through preglacial erosion, the hydrostratigraphic units affected by weathering and dissolution—and therefore included in the Shallow Bedrock Aquifer—differ with geography. In eastern parts of northeastern Illinois, the Shallow Bedrock Aquifer is included entirely within the Silurian-Devonian Carbonate Unit. Westward, as the Silurian-Devonian Carbonate Unit thins, the Shallow Bedrock Aquifer includes, together with the remaining thin edge of the Silurian-Devonian Carbonate Unit, parts or all of the Maquoketa Unit and, even farther west, the Galena-Platteville Unit.

1.5.3 Bedrock Structure

Figure 7 illustrates the generalized bedrock geology of the regional study area. Paleozoic rocks underlying northeastern Illinois dip gently off the combined Wisconsin and Kankakee Arches into the Michigan Basin to the northeast (as shown in Figure 8, a west-to-east cross section through McHenry County) and the Illinois Basin to the south (as shown in Figure 9, a north-to-south cross section). However, the Sandwich Fault Zone (Figure 9) displaces the Paleozoic rocks in Kendall and southern De Kalb counties.

1.5.4 Bedrock Surface

Prior to glaciation, the upper surface of the bedrock was eroded to a roughly planar surface interrupted by subtle bedrock topographic highs and topographically low bedrock valleys. The resulting bedrock surface is composed of progressively younger rocks to the east and south, toward the centers of the Michigan and Illinois Basins. In McHenry County, this general pattern holds, with the Silurian-Devonian Carbonate Unit comprising the bedrock surface in eastern and central parts of the county, and Maquoketa and Galena-Platteville Units forming the bedrock surface farther west (Figure 10).

1.5.5 Quaternary Hydrostratigraphy

The Quaternary Period was marked by repeated glacial advances into northeastern Illinois, and most of the Quaternary materials in the region were deposited directly by melting glaciers or by glacial meltwater. Geologists group these glaciations into two major episodes, the earlier Illinois Episode and the later Wisconsin Episode.

On the basis of geological modeling by Thomason and Keefer (2013), we subdivide the Quaternary materials into 9 hydrostratigraphic units (Figure 6). This hydrostratigraphic nomenclature is not intended to convey the genesis of these Quaternary units, but the origin of the units is relevant to understanding groundwater circulation in McHenry County, and some features of the distribution of the Quaternary hydrostratigraphic units reflect this origin. Section 1.5.6 therefore summarizes the origin of the Quaternary materials, and thickness maps (Figure 11 to Figure 18) and cross sections (Figure 19 to Figure 28) show their distribution, as hydrostratigraphic units, in McHenry County. Figure 29 diagrammatically illustrates the stratigraphic relationships of the Wisconsin Episode lithostratigraphic units in the McHenry County area, which, in the nomenclature of this report, are assigned to the Ashmore Unit (which also contains limited Illinois Episode materials), Tiskilwa Unit, Yorkville-Batestown Unit, Haeger-Beverly Unit, and Wadsworth Unit. Figure 29 does not illustrate the stratigraphic relationships of the Illinois Episode materials, which in this report are assigned to the Lower Glasford Sand Unit, Lower Glasford Unit, Upper Glasford Sand Unit, Winnebago-Upper Glasford Unit, and Ashmore Unit (which mostly contains Wisconsin Episode materials). Thomason and Keefer (2013) discuss the origin and distribution of the Quaternary materials in McHenry County in greater detail.

1.5.5.1 Lower Glasford Sand Unit

The Lower Glasford Sand Unit (Figure 11) consists of sand and gravel underlying undifferentiated fine-grained materials of the lower Glasford Formation (Section 1.5.5.2) that cannot be assigned to the Oregon Member of the Glasford (Section 1.5.5.4). This unit is widespread in McHenry County, exceeding 100 ft in thickness in bedrock valleys in the western part of the county, and it is commonly employed as a source aquifer for both small and large groundwater supplies. Where present, the unit rests on the bedrock surface and is in hydraulic connection with the Shallow Bedrock Aquifer (Section 1.5.2).

1.5.5.2 Lower Glasford Unit

Undifferentiated fine-grained materials of the lower Glasford Formation, principally diamicton that cannot be assigned to the Oregon Member of the Glasford (Section 1.5.5.4), are included in the Lower Glasford Unit (Figure 12). The Lower Glasford Unit is present mainly in western McHenry County, where its thickness sometimes exceeds 100 ft in bedrock valleys. The unit functions as an aquitard.

1.5.5.3 Upper Glasford Sand Unit

Sand and gravel underlying the Oregon Member of the Glasford Formation (Section 1.5.5.4) and overlying undifferentiated fine-grained materials of the lower Glasford (Section 1.5.5.2) is assigned to the Upper Glasford Sand Unit (Figure 13). The Upper Glasford Formation functions as an aquifer, but it is less commonly exploited for water supplies in McHenry County than other Lower Quaternary aquifers (i.e., the Lower Glasford Sand Unit and Ashmore Unit) because of its limited distribution and thickness.

1.5.5.4 Winnebago-Upper Glasford Unit

The Winnebago-Upper Glasford Unit (Figure 14) consists principally of fine-grained materials of the Oregon Member of the Glasford Formation and the overlying Winnebago Formation. The unit is a widespread aquitard in McHenry County that exceeds 200 ft in thickness in the Troy Bedrock Valley in the northwestern part of the county.

1.5.5.5 Ashmore Unit

The Ashmore Unit (Figure 15) consists of sand and gravel of the Ashmore Tongue of the Henry Formation (Mason Group). The Henry Formation is a lithostratigraphic unit consisting of sand and gravel deposited in fluvial meltwater environments during Wisconsin Episode glaciations of northeastern Illinois. The Henry Formation, together with intertonguing fine-grained lacustrine deposits of the Equality Formation, is laterally equivalent to the Wedron Formation, which is chiefly diamicton (nonsorted materials deposited directly by melting ice) (Figure 29). Although Henry Formation sand and gravel is exposed at the surface in parts of McHenry County, the Henry Formation intertongues with the Wedron Formation. The Ashmore Tongue is a lateral extension of the Henry Formation that occurs beneath the Tiskilwa Formation (Wedron Group), a thick and widespread layer of diamicton that we represent as the Tiskilwa Unit (Section 1.5.5.6). The Ashmore Unit is laterally extensive in McHenry County, with thicknesses up to about 100 ft. It is widely used for domestic water supplies and for some public, industrial, and commercial supplies.

1.5.5.6 Tiskilwa Unit

The Tiskilwa Unit (Figure 16), which includes diamicton of the Tiskilwa Formation (Wedron Group) (Figure 29), is widespread in McHenry County. Its thickness exceeds 250 ft along Marengo Ridge, which is a terminal moraine marking the maximum westward advance of the glacier that deposited it. The Tiskilwa Formation functions as an important aquitard in northeastern Illinois.

1.5.5.7 Yorkville-Batestown Unit

The Yorkville-Batestown Unit (Figure 17) includes diamicton of the Batestown and Yorkville Members (Lemont Formation, Wedron Group) together with unnamed tongues of Henry Formation sand and gravel that occur beneath each diamicton tongue (Figure 29). Individually, these lithostratigraphic units are thin, laterally discontinuous, and limited in total distribution. The Yorkville-Batestown Unit occurs in south-central and southeastern McHenry County, where it extends up to about 130 ft thick. It functions as both an aquifer and an aquitard because it contains sand and gravel as well as diamicton, but it is used as an aquifer comparatively little because the unnamed sand and gravel tongues within it are shallow, thin, and sporadic and limited in distribution.

1.5.5.8 Haeger-Beverly Unit

The Haeger Member (Lemont Formation, Wedron Group) and Beverly Tongue (Henry Formation, Mason Group), together with the surficial Henry Formation (Figure 29), are grouped as the Haeger-Beverly Unit (Figure 18). The Haeger Member is a sandy diamicton with abundant beds of sand and gravel and thin beds of silt and clay. The Beverly Tongue and surficial Henry Formation consist predominantly of coarse sand and gravel. The Haeger-Beverly Unit extends up to about 200 ft thick in McHenry County. Where saturated with water, as in valley-fill deposits, the Haeger-Beverly Unit functions as an aquifer that can provide large groundwater supplies, but at higher elevations it is commonly not saturated or only partially saturated. Its shallow occurrence also renders the Haeger-Beverly Unit vulnerable to drought and to contamination from surface sources.

1.5.5.9 Wadsworth Unit

In the hydrostratigraphic nomenclature of this report, the uppermost Quaternary materials in the McHenry County area—diamicton of the Wadsworth Formation—is referred to as the Wadsworth Unit. The Wadsworth Unit, an aquitard, does not occur in McHenry County, but it extends westward within Lake County nearly to the eastern boundary of McHenry County. Its thickness exceeds 100 ft in morainal deposits in western Lake County.

1.5.6 Origin and Distribution of Quaternary Materials

In general, the Illinois Episode deposits—including the Lower Glasford Sand Unit (Figure 11), the Lower Glasford Unit (Figure 12), the Upper Glasford Sand Unit (Figure 13), and the Winnebago-Upper Glasford Unit (Figure 14)—thicken westward within McHenry County, with some units absent from large areas of central and eastern McHenry County. The Illinois Episode glacial history of northeastern Illinois is more poorly understood than the Wisconsin Episode history because the Illinois Episode materials are buried and more heavily eroded than the younger Wisconsin Episode materials, which are commonly exposed at the surface in this region.

Overlying deposits—the Ashmore Unit (Figure 15), Tiskilwa Unit (Figure 16), Yorkville-Batestown Unit (Figure 17), Haeger-Beverly Unit (Figure 18), and Wadsworth Unit—were mostly deposited in conjunction with Wisconsin Episode glaciers, although the lower Ashmore Unit contains some materials that were deposited or that formed as soils during the Illinois Episode or during the period of warmer climate that prevailed between the Illinois and Wisconsin Episodes. The Wisconsin Episode glaciers advanced westward across McHenry County from the Lake Michigan basin (Hansel and Johnson, 1996).

The materials deposited during each glacial advance were in most areas partly eroded by meltwater and ice associated with subsequent glaciations. The last glaciation affecting the McHenry County area resulted in deposition of the Wadsworth Unit. The Wadsworth Unit is not present within McHenry County, though it is present in Lake County not far from the McHenry County border.

Quaternary aquifers consist of sporadically distributed sand and gravel layers deposited by glacial meltwater. These materials commonly represent proglacial deposits—those that were deposited by meltwater to the west of the margin of each westward-advancing glacier. These are commonly preserved at the base of a diamicton unit deposited as the glacier advanced over its own meltwater deposits. For example, much of the Ashmore Unit, an important sand and gravel aquifer in McHenry County, represents material deposited in advance of the westward-advancing glacier that deposited the Tiskilwa Unit above it.

The cross sections of Quaternary materials shown in Figure 19 to Figure 28 graphically synthesize the information discussed above and illustrated in the thickness maps (Figure 11 to Figure 18).

West-to-east cross-section C-C' (Figure 21), transecting central McHenry County, displays many features representative of the Quaternary hydrostratigraphic sequence throughout McHenry County. The highest bedrock surface elevations along this line of section occur in west-central McHenry County. From this point eastward, the bedrock surface declines gently to the eastern boundary of the county, but to the west it declines more steeply into an unnamed bedrock valley (also see Figure 5). The unnamed bedrock valley is filled with over 300 ft of sub-Ashmore Unit glacial drift. In western McHenry County, Figure 21 shows that the sub-Ashmore deposits extend to land surface, but to the east, they are buried beneath a generally eastward-thickening wedge of younger materials. Taken as a whole, the sub-Ashmore deposits are much thinner eastward from west-central McHenry County, where they were extensively eroded prior to deposition of the younger materials. Their greater thickness in western McHenry County is a consequence of preservation within bedrock valleys.

The Illinois Episode hydrostratigraphic sequence displayed in the other west-to-east cross sections (Figure 19, Figure 20, Figure 22, Figure 23) is similar to that displayed in Figure 21. Cross-section A-A' (Figure 19), transecting McHenry County along its northern boundary, crosses the Troy Bedrock Valley in northwestern McHenry County (Figure 5). The Troy Bedrock Valley is filled with over 400 ft of sub-Ashmore materials in McHenry County. The thickness of the Lower Glasford Sand Unit, an aquifer, exceeds 100 ft along the valley axis (also see Figure 11). Cross-section B-B' (Figure 20), which crosses north-central McHenry County, transects a broad, shallow bedrock valley, which is unnamed, in northwestern McHenry County that contains nearly 100 ft of the Lower Glasford Unit, an aquitard (also see Figure 13). Cross-section D-D' (Figure 22), crossing south-central McHenry County, transects, in southwestern McHenry County, an unnamed bedrock valley system containing all of the sub-Ashmore units discussed in this report, but cross-section E-E' (Figure 23), along the southern boundary of McHenry County, does not encounter bedrock valleys as do the other west-to-east cross sections (also see Figure 5, Figure 11, Figure 12, Figure 13, Figure 14).

The west-to-east cross sections show that, in western McHenry County, the uppermost unit in the county, the Haeger-Beverly Unit, is present as a discontinuous sheet that, where present, is draped over all underlying units, although it frequently thins to a zero edge east of the western boundary of McHenry County. The Haeger-Beverly Unit generally thickens and becomes more continuous eastward within McHenry County, but, as shown in cross-section D-D' (Figure 22) and Figure 18, it is also thick along the Kishwaukee River valley of west-central McHenry County.

Marengo Ridge, a moraine that consists primarily of Tiskilwa Unit diamicton, marks the principal western terminus of deposition of the Ashmore and Tiskilwa Units, although outliers of Ashmore and Tiskilwa Unit materials occur west of Marengo Ridge, most notably in northwestern McHenry County (Figure 15, Figure 16). Marengo Ridge is dissected by valleys and is poorly developed along cross-section C-C' (Figure 21), but it is more recognizable in the other west-to-east cross sections (Figure 19, Figure 20, Figure 22, Figure 23), in which it appears as a prominent topographic feature that is principally an expression of an underlying ridge of Tiskilwa Unit diamicton (Figure 16); in some places Marengo Ridge is underlain by more than 250 ft of Tiskilwa Unit material (e.g., Figure 19). The Ashmore Unit, an aquifer, is present as a discontinuous sheet in McHenry County east of Marengo Ridge (Figure 15), while the Tiskilwa Unit, an aquitard, forms a more continuous sheet, its maximum thickness at Marengo Ridge.

The Yorkville-Batestown Unit is restricted in occurrence to south-central McHenry County, where its thickness rarely exceeds 100 ft (Figure 17). In the southern portion of its distribution, the Yorkville-Batestown Unit extends to land surface, but it is overlapped to the east, west, and north by coarse-grained sediments of the Haeger-Beverly Unit (Figure 21, Figure 22, Figure 23).

North-to-south cross-section H-H' (Figure 26), which transects central McHenry County, shows that in central McHenry County, near the center of the cross section, most of the Quaternary hydrostratigraphic units are present. The sub-Ashmore units that are present, which total less than 100 ft in thickness, include the sporadically occurring Lower Glasford Sand Unit and a more continuous sheet of Winnebago-Upper Glasford Unit (also see Figure 11 and Figure 14). The Lower Glasford Unit appears at the northern and southern ends of the line of section, but the Upper Glasford Sand Unit is very thin and, at the resolution of the cross section, is only apparent at its northern end (also see Figure 13). The Ashmore Unit is widespread along the line of section and exceeds 50 ft in thickness in some areas, although it is absent in south-central McHenry County, and it is very thin in other areas (also see Figure 15). The thickness of the overlying Tiskilwa Unit exceeds 100 ft in central and south-central parts of the county, but the Tiskilwa is absent in a limited area of north-central McHenry County (also see Figure 16), juxtaposing aquifer materials of the Haeger-Beverly Unit, Ashmore Unit, and (because all sub-Ashmore units in the area are also absent), the Shallow Bedrock Aquifer. Such hydrologic connections facilitate the exchange of water between aquifers and, in potentiometric surface maps, are reflected by coincidence in heads among the connected aquifers. The Yorkville-Batestown Unit occurs in the upper Quaternary in the southern portion of Figure 26 and is overlain northward by the Haeger-Beverly Unit. The Haeger-Beverly Unit is present along much of the line of section, but it is particularly thick in north-central McHenry County, where its thickness exceeds 50 ft (also see Figure 18).

As discussed in the following paragraphs, the Quaternary materials shown in the other north-to-south cross sections, considered in comparison with cross-section H-H' (Figure 26), reflect the west-to-east trends discussed previously (page 12).

Cross-section F-F' (Figure 24) shows that, on the western edge of McHenry County, the Quaternary is composed entirely of a thick sequence of sub-Ashmore materials that are overlain sporadically by coarse materials of the Haeger-Beverly Unit, most significantly in the Kishwaukee River valley of southwestern McHenry County (also see Figure 18). Total Quaternary thickness exceeds 400 ft in northwestern McHenry County (also see Figure 4). This great thickness partially reflects preservation in western McHenry County of sub-Ashmore materials within comparatively steep-walled bedrock valleys, most notably the Troy bedrock valley (Figure 5). Figure 24 shows that the Lower Glasford Sand Unit and Upper Glasford Sand Unit are thicker and more extensive aquifers in western McHenry County than elsewhere in the county, although the Lower Glasford Sand Unit is restricted in distribution to the axes of buried bedrock valleys (also see Figure 11 and Figure 13). North-to-south cross-section G-G' (Figure 25), transecting west-central McHenry County, trends roughly parallel to the axis of Marengo Ridge, and as a result, it shows a great thickness of Tiskilwa Unit diamicton. The Tiskilwa Unit in Figure 25 is in some places greater than 200 ft thick (also see Figure 16). Sand and gravel of the Ashmore Unit sporadically underlies the Tiskilwa Unit along the line of section, but where present, it is comparatively thin (also see Figure 15). The total thickness of the sub-Ashmore materials is intermediate between cross sections F-F' and H-H' (Figure 24, Figure 26), generally 50 to 100 ft, but thicker within the unnamed bedrock valley underlying the modern Kishwaukee River valley. Sands and gravels of the Lower and Upper Glasford Sand Units are sporadically present, although the Lower Glasford Sand Unit is restricted in occurrence (also see Figure 11), and the Upper Glasford Sand Unit, although more widely distributed, is thin (also see Figure 13). The Haeger-Beverly Unit is sporadically present as the uppermost unit in the Quaternary sequence and, in Figure 25, reaches its greatest thickness in the Kishwaukee River valley of southwestern McHenry County.

Transecting the Quaternary units along the eastern boundary of McHenry County, north-to-south cross section J-J' (Figure 28) shows the Haeger-Beverly Unit to be continuously present and generally thick (commonly exceeding 100 ft) in eastern McHenry County (Figure 18). In the east-central part of the county, Figure 28 shows this sheet of Haeger-Beverly Unit to overlie heavily eroded remnants of all older units; at some locations, the Haeger-Beverly Unit extends from land surface to the bedrock surface, all previously deposited Quaternary materials having been removed by erosion. The juxtaposition through this erosional surface between the coarse-grained Haeger-Beverly deposits and other shallow aquifers likely facilitates hydrologic connection between these aquifers and with local surface waters. In northeastern McHenry County, the units underlying the Haeger-Beverly are substantially less eroded, and indeed greater than 100 ft of sub-Ashmore materials are present along the line of section of Figure 28. Likewise, in southeastern McHenry County, erosion has removed less of the sub-Haeger-Beverly section. Sands and gravels of the Ashmore Unit are comparatively widespread along the line of cross section J-J' and are frequently 10 to 50 ft thick, and the deeper Lower Glasford Sand Unit is sporadically present. North-to-south cross section I-I' (Figure 27) displays Quaternary erosional and depositional patterns that are intermediate between cross sections H-H' and J-J' (Figure 25, Figure 27). Less erosion of the sub-Haeger-Beverly Quaternary units has occurred than to the east, and substantially more Tiskilwa Unit and Yorkville-Batestown Unit materials are present (also see Figure 16 and Figure 17). Ashmore Unit sand and gravels are thin, but widespread (also see Figure 15), and some Lower Glasford Sand Unit material is present at the bedrock surface, though this material is comparatively thin (also see Figure 11). Thick, coarse-grained Haeger-Beverly Unit sediment is draped over the older materials along most of this line of section (also see Figure 18).

The distribution of the Quaternary materials in McHenry County is complicated by lateral thickness variations that reflect bedrock surface configuration, differential erosion of underlying (pre-existing) materials, and lateral differences in rates of deposition of individual units. The earlier and deeper units (Lower Glasford Sand Unit, Lower Glasford Unit, Upper Glasford Unit, and Winnebago-Upper Glasford Unit) are, in general, present in western McHenry County or throughout McHenry County. Where absent in central and eastern McHenry County, these units were eroded prior to deposition of younger units. The greatest thicknesses of these units mostly occur within bedrock valleys that formed prior to the onset of Quaternary glaciation. The Ashmore Unit and Tiskilwa Unit are widely distributed throughout central and eastern McHenry County, the Tiskilwa Unit being, in general, the thickest of the Quaternary Units, exceeding 200 ft in thickness along Marengo Ridge. The Yorkville-Batestown Unit is restricted to south-central and southeastern McHenry County. Coarse-grained materials of the Haeger-Beverly Unit are draped over underlying deposits in many parts of McHenry County and are thickest in eastern McHenry County and in the Kishwaukee River valley of southwestern McHenry County. The Wadsworth Unit is present in Lake County, just east of McHenry County, but it is not present within McHenry County.

Figure 1 Regional index map showing locations and areas discussed in text

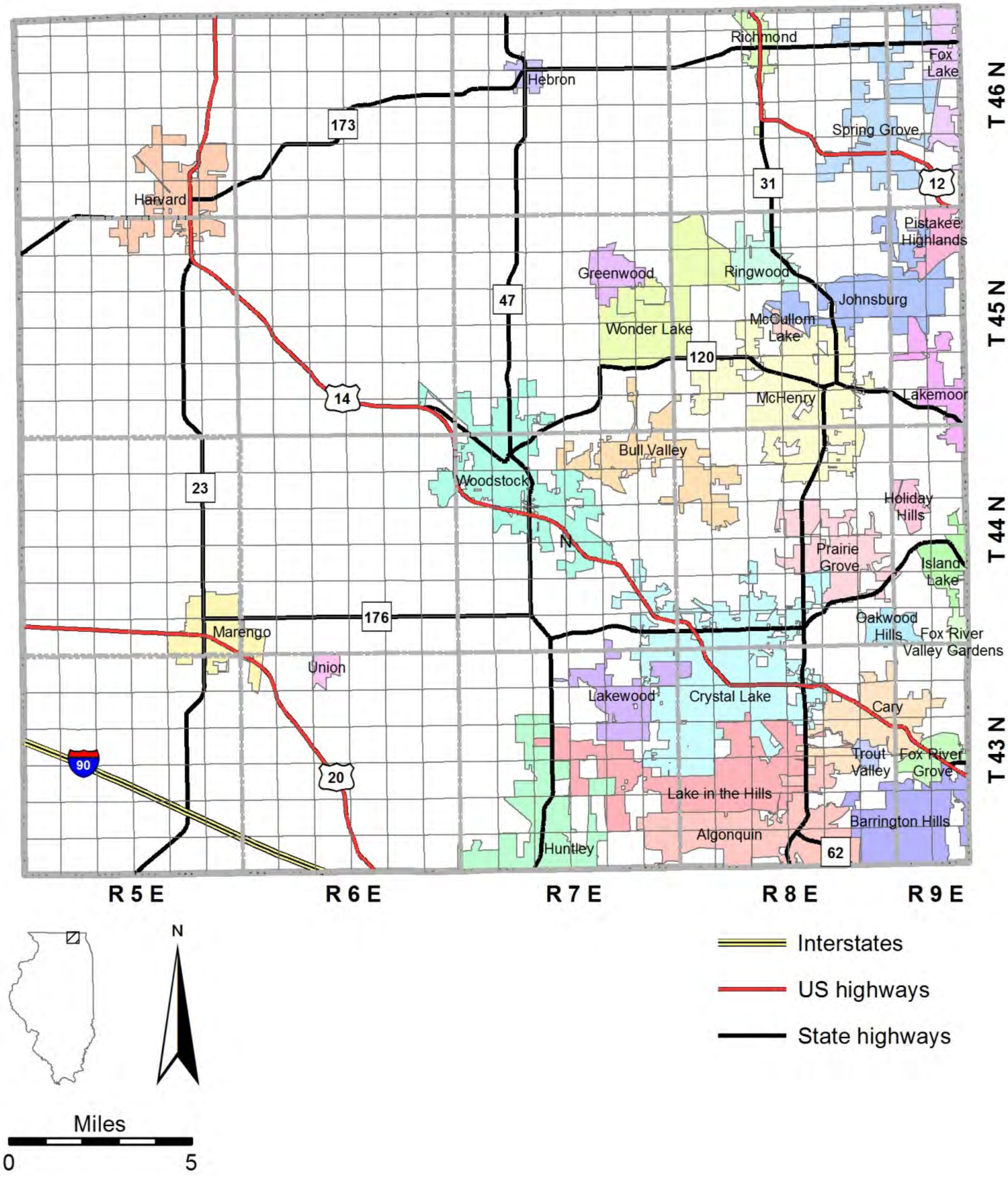

Figure 2 Index map showing municipalities and highways in McHenry County

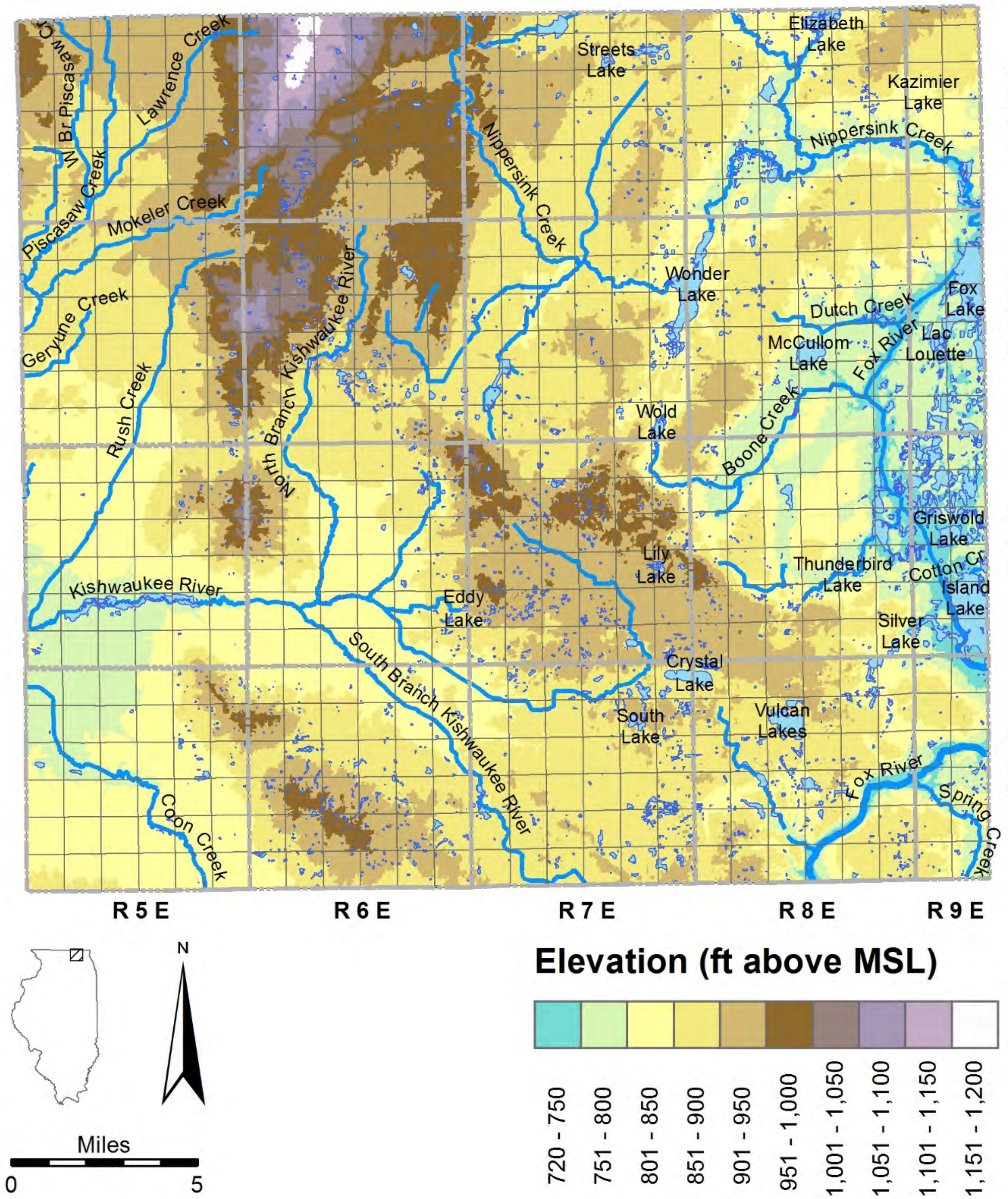

Figure 3 Index map showing hydrography and topography of McHenry County

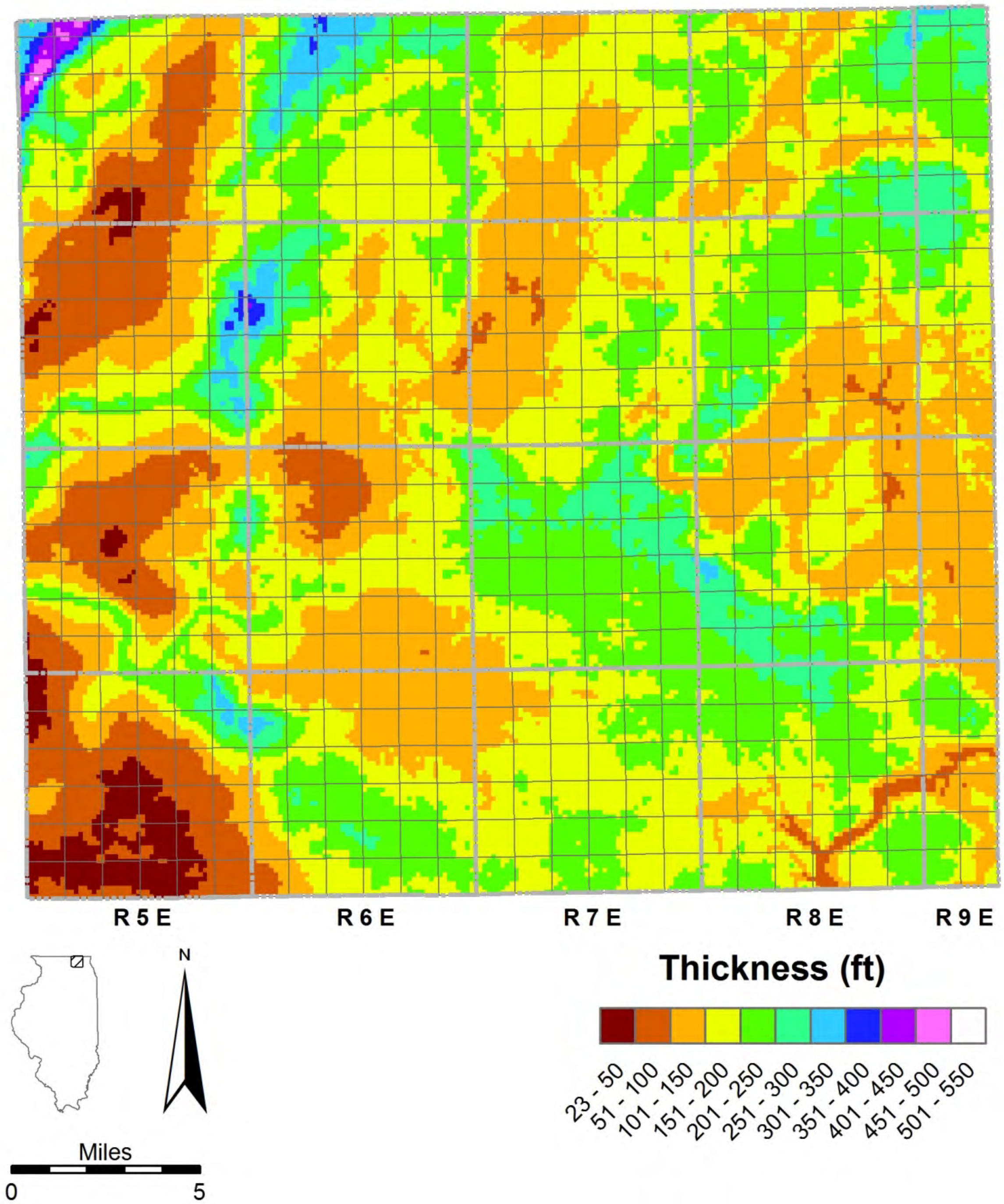

Figure 4 Glacial drift thickness in McHenry County

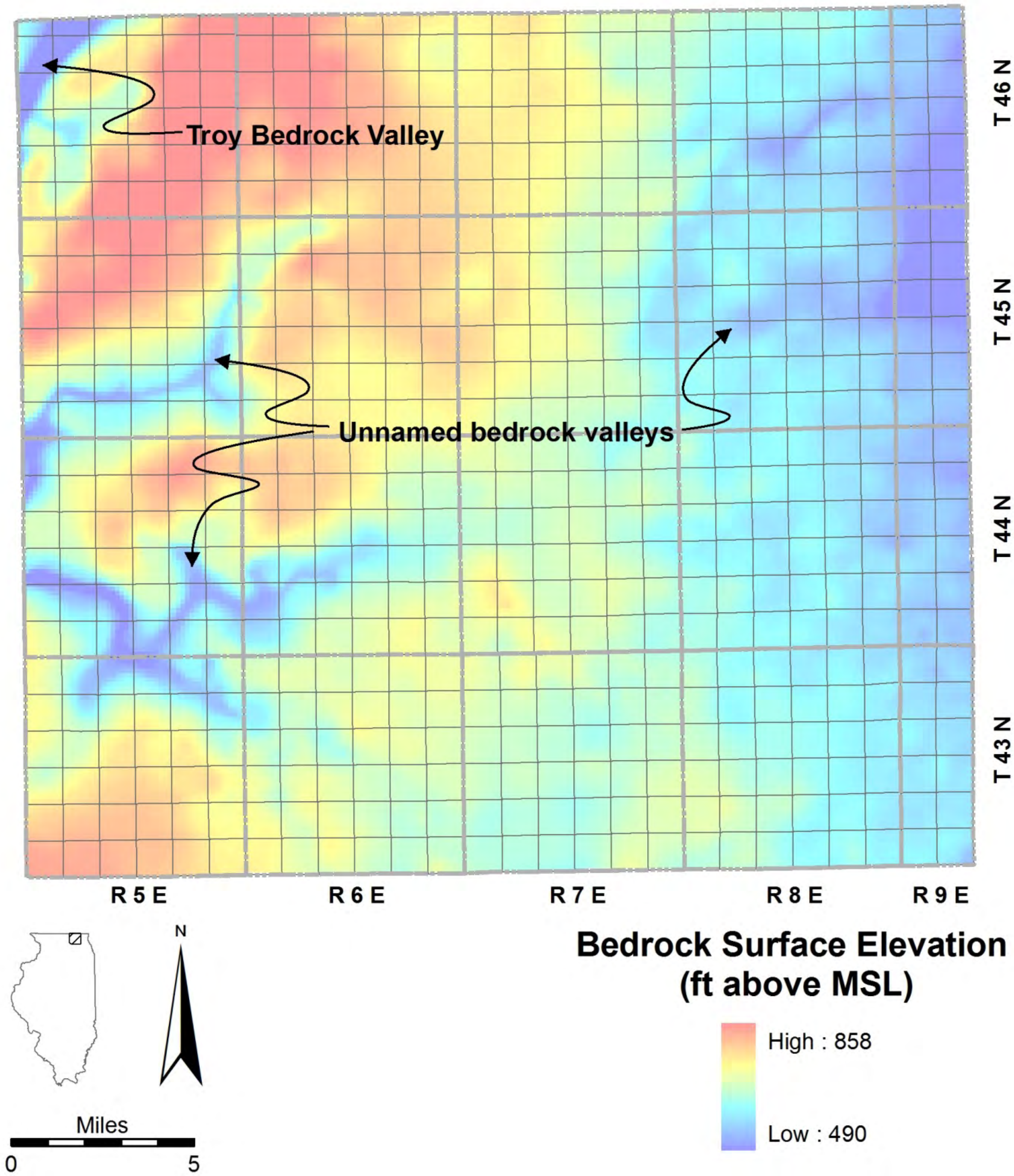

Figure 5 Bedrock surface topography of McHenry County

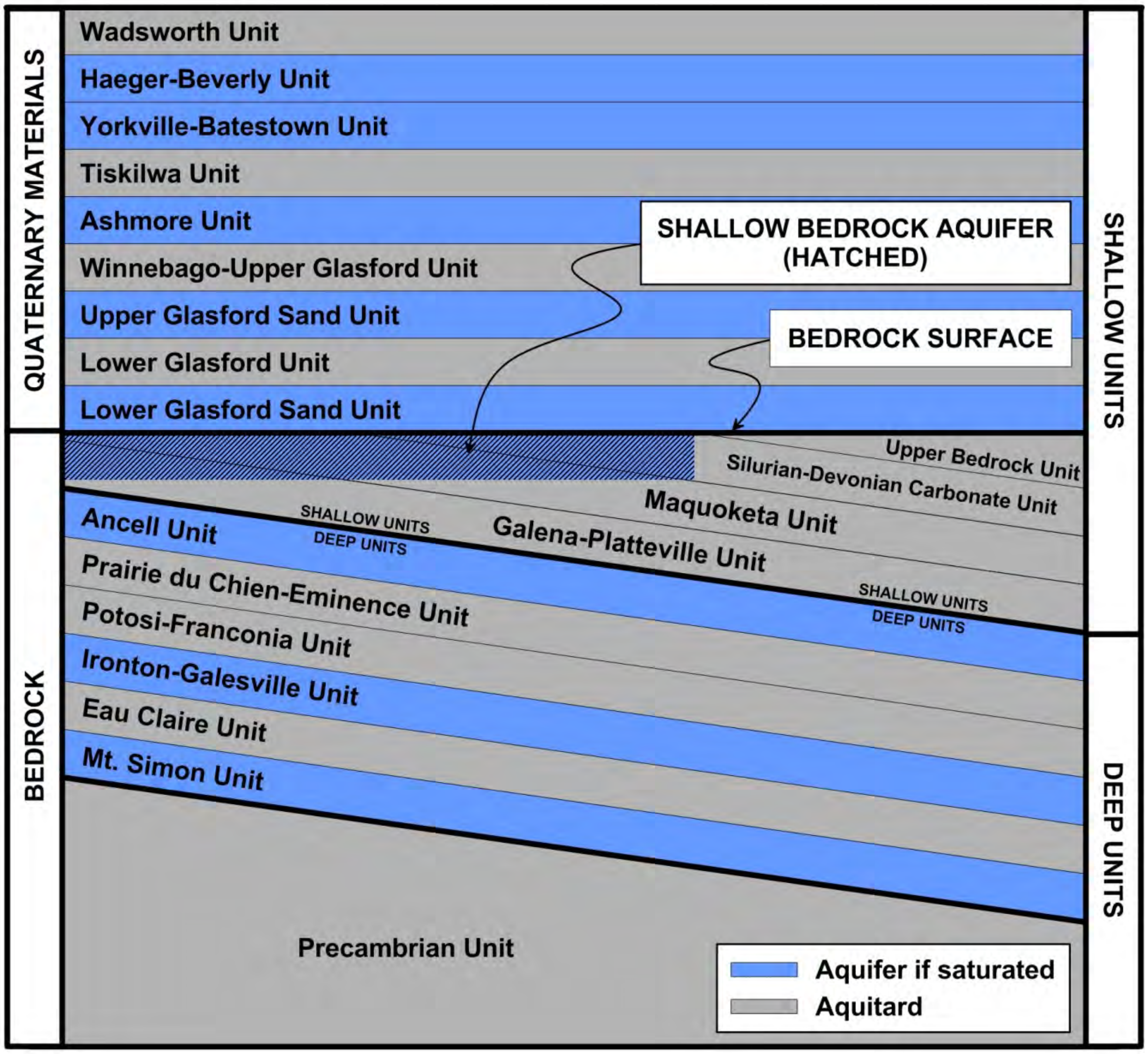

Figure 6 Diagrammatic cross section showing hydrostratigraphic units discussed in the text. Tilting bedrock units reflect actual west (left)-to-east (right) dip of bedrock units underlying McHenry County.

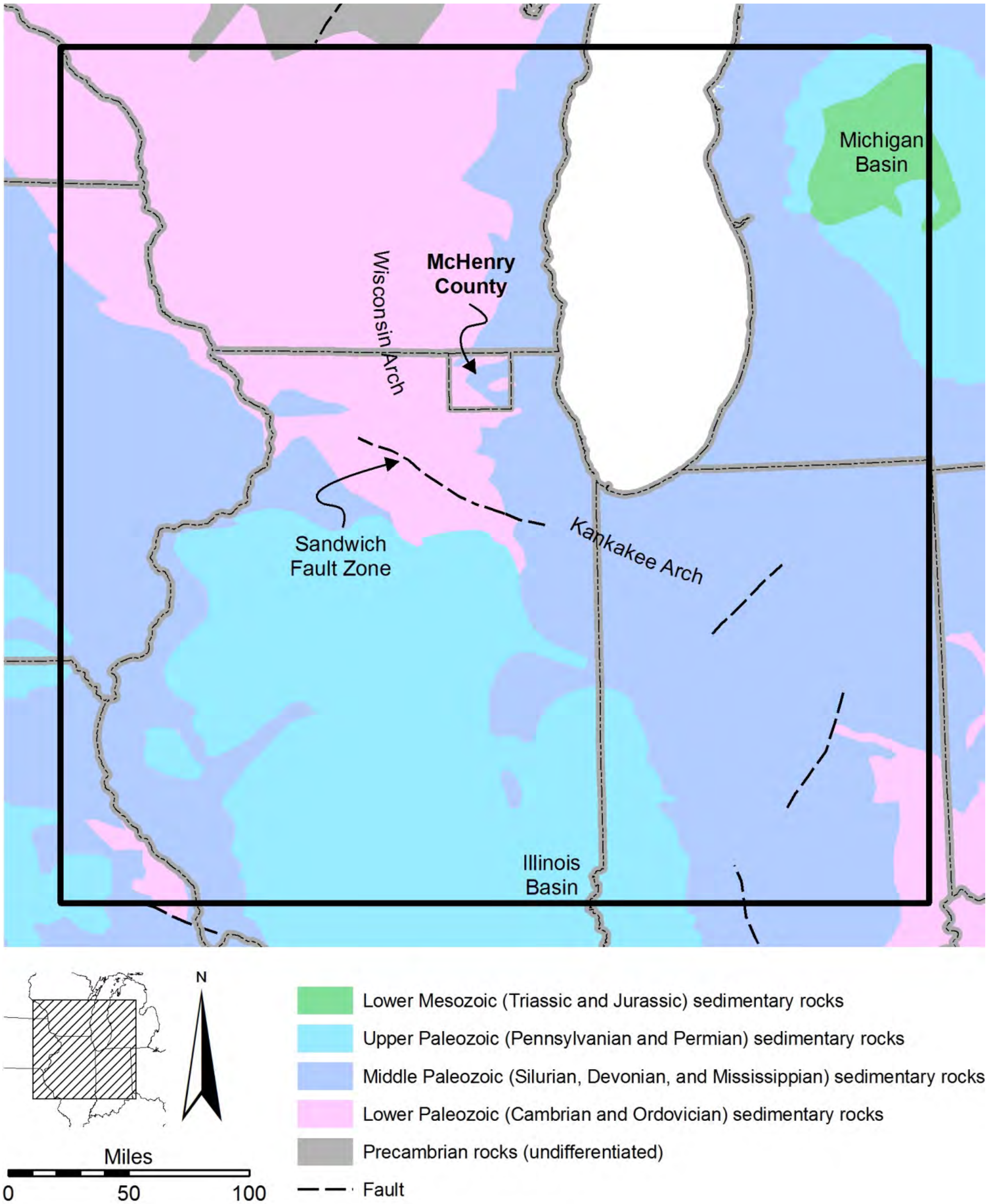

Figure 7 Generalized regional bedrock geology (Reed and Bush, 2005)

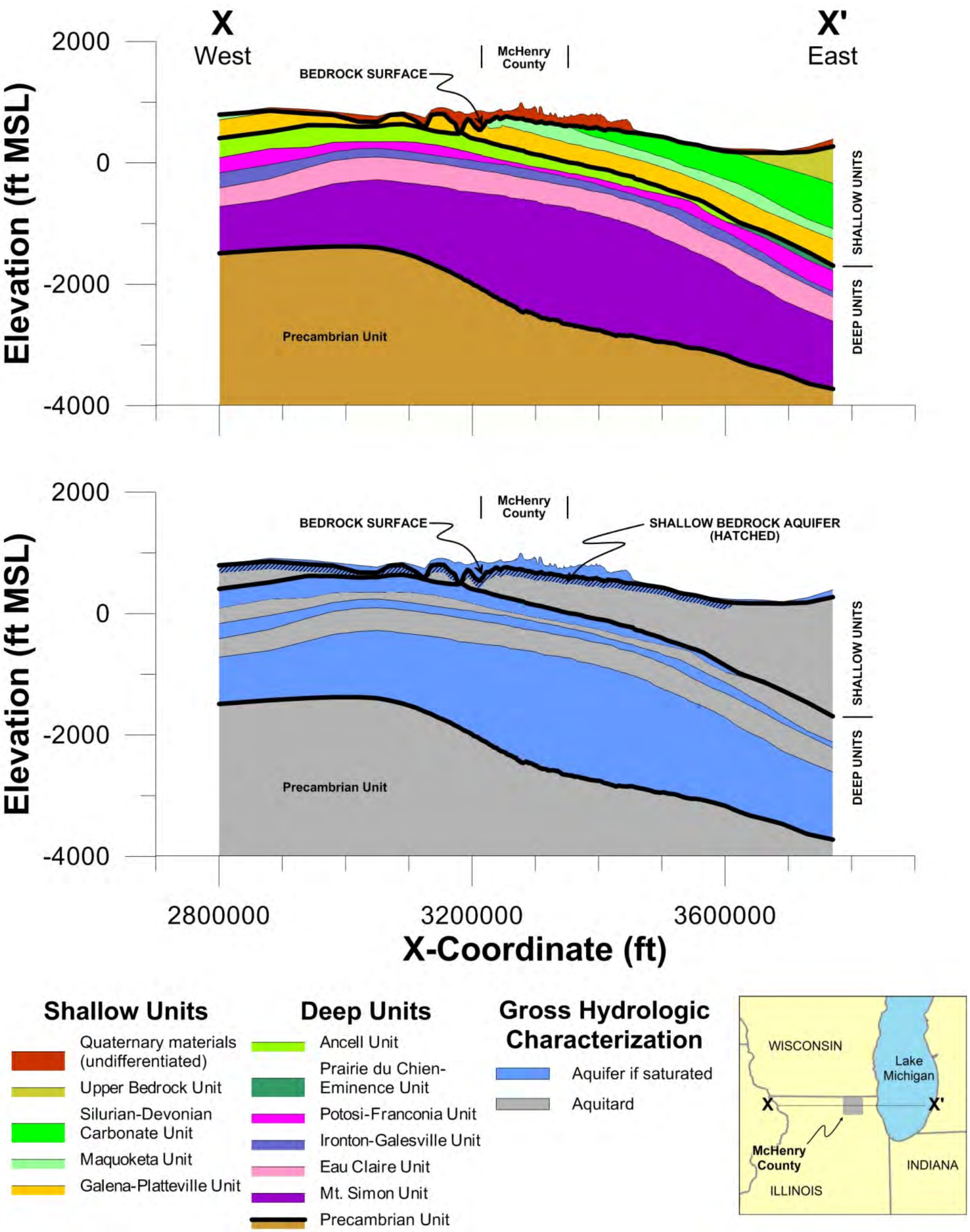

Figure 8 West-to-east regional cross section through McHenry County showing all hydrostratigraphic units (top) and aquifer units (bottom) discussed in the text

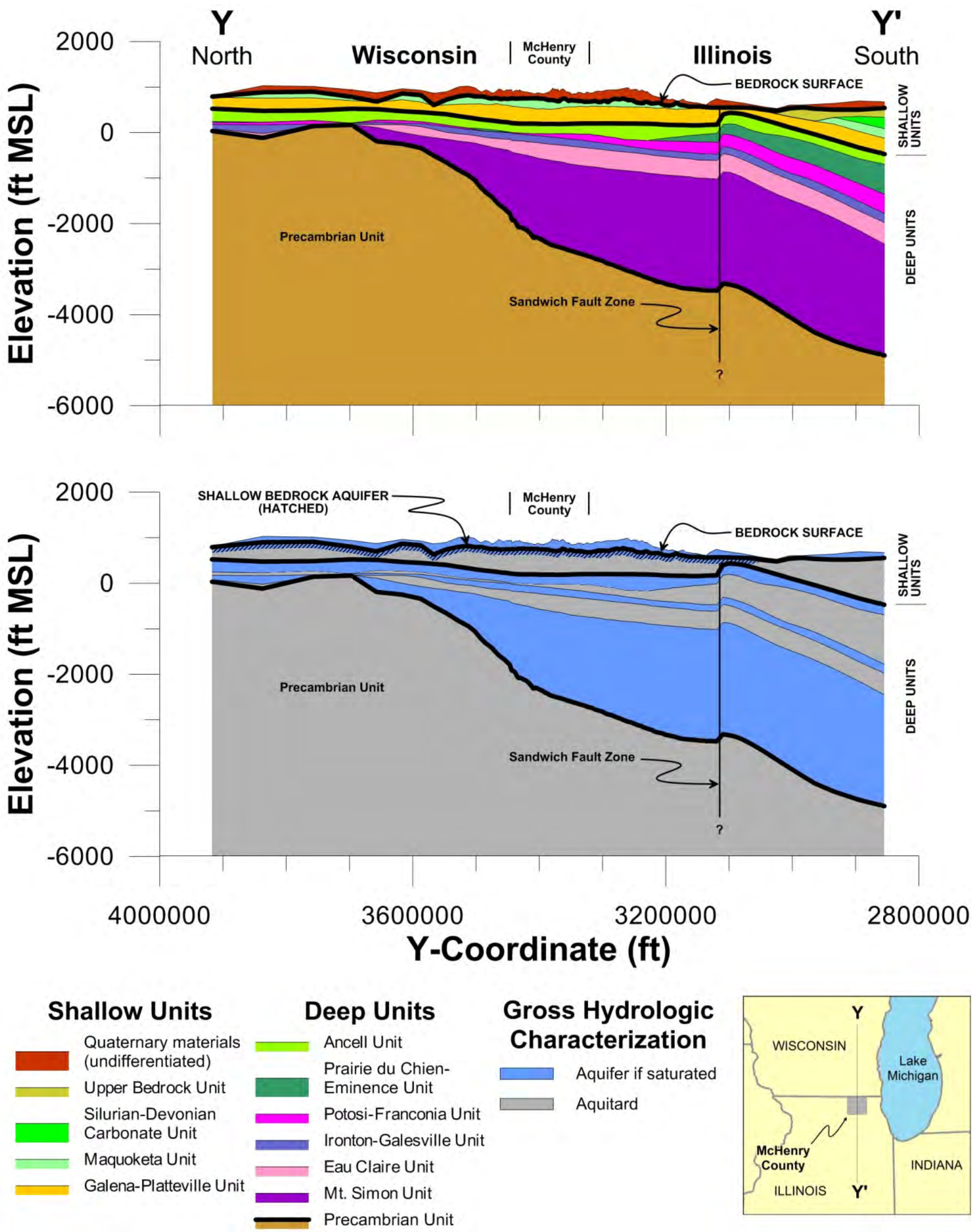

Figure 9 North-to-south regional cross section through McHenry County showing all hydrostratigraphic units (top) and aquifer units (bottom) discussed in the text

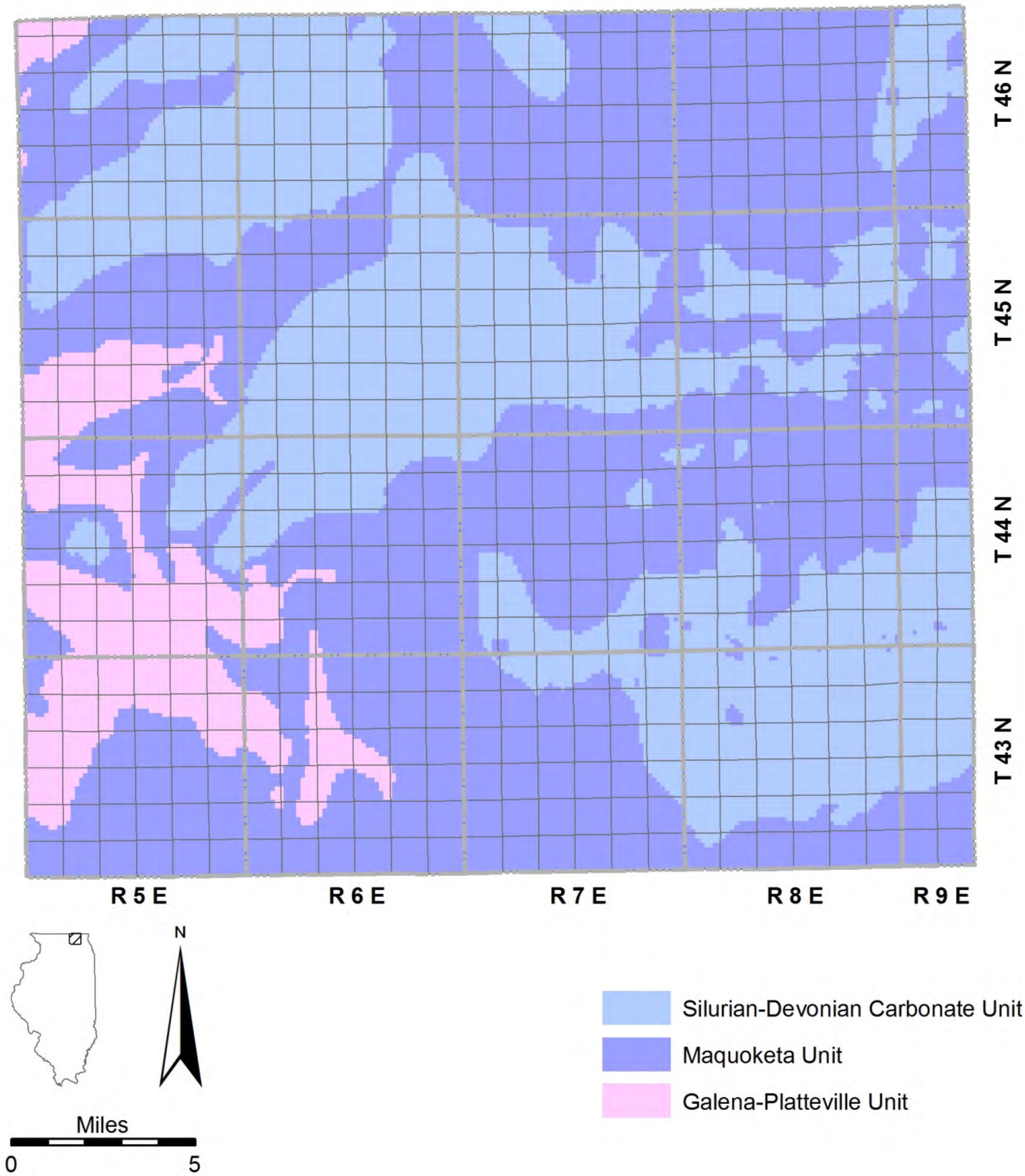

Figure 10 McHenry County bedrock surface hydrogeology

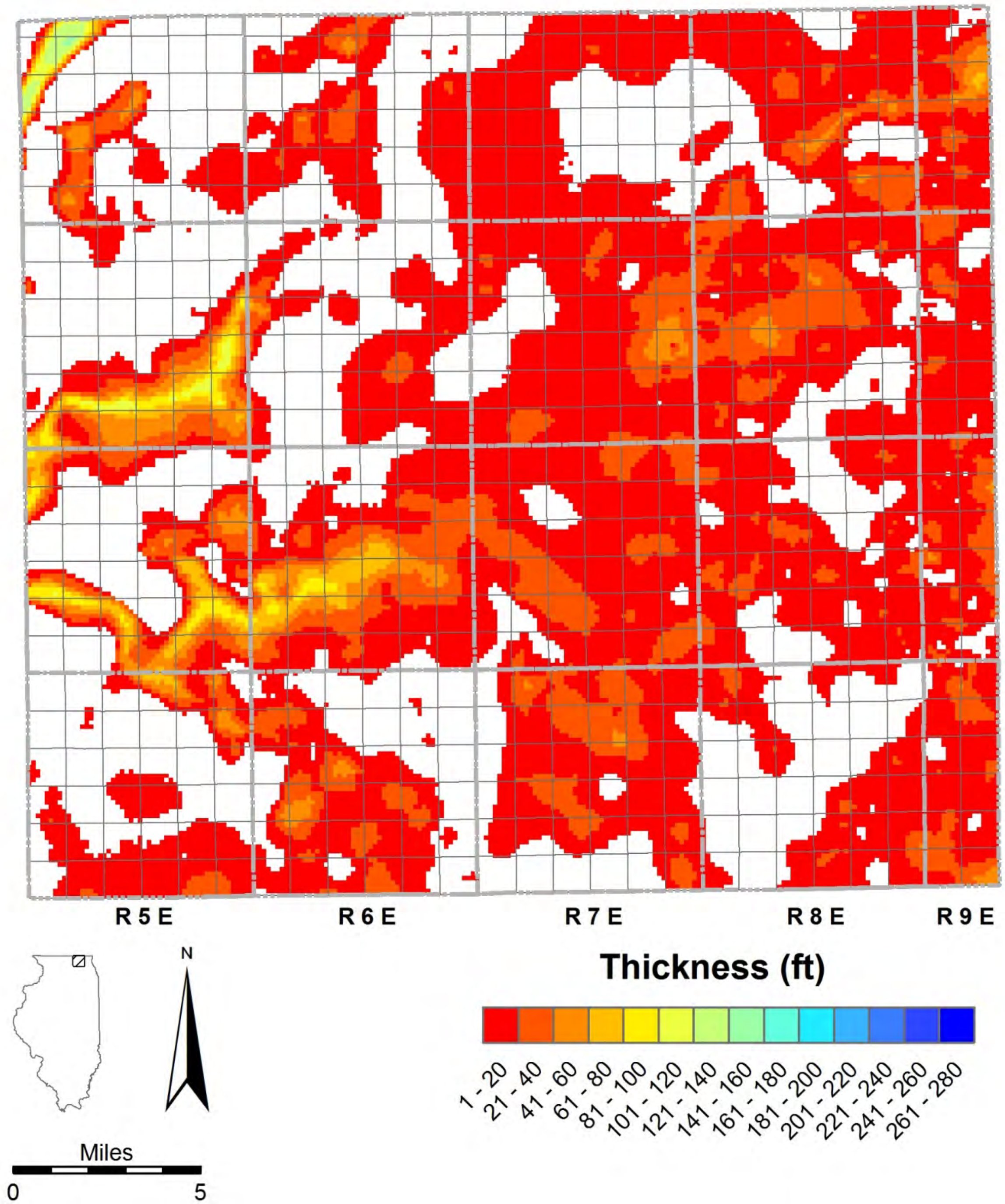

Figure 11 Thickness of Lower Glasford Sand Unit in McHenry County

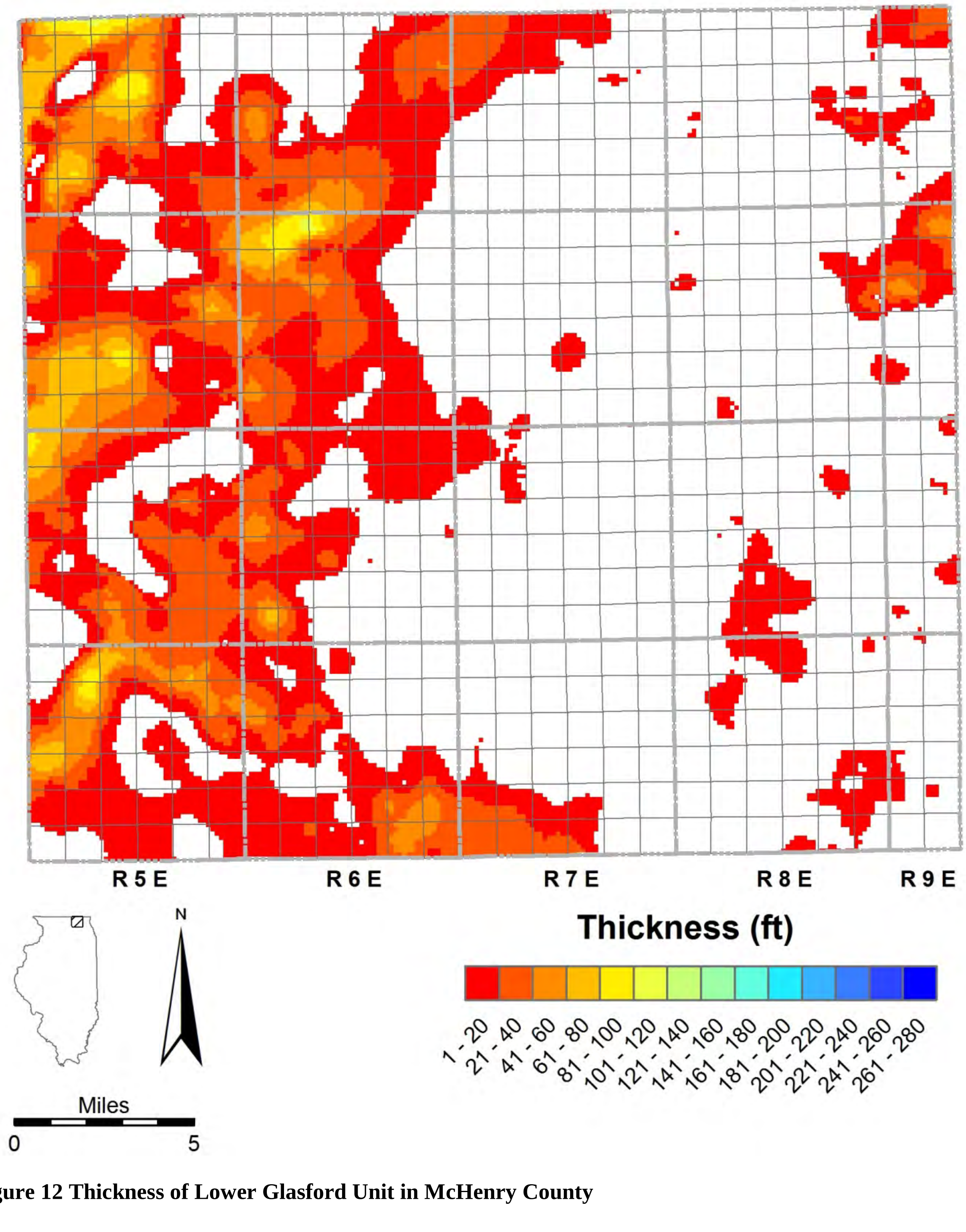

Figure 12 Thickness of Lower Glasford Unit in McHenry County

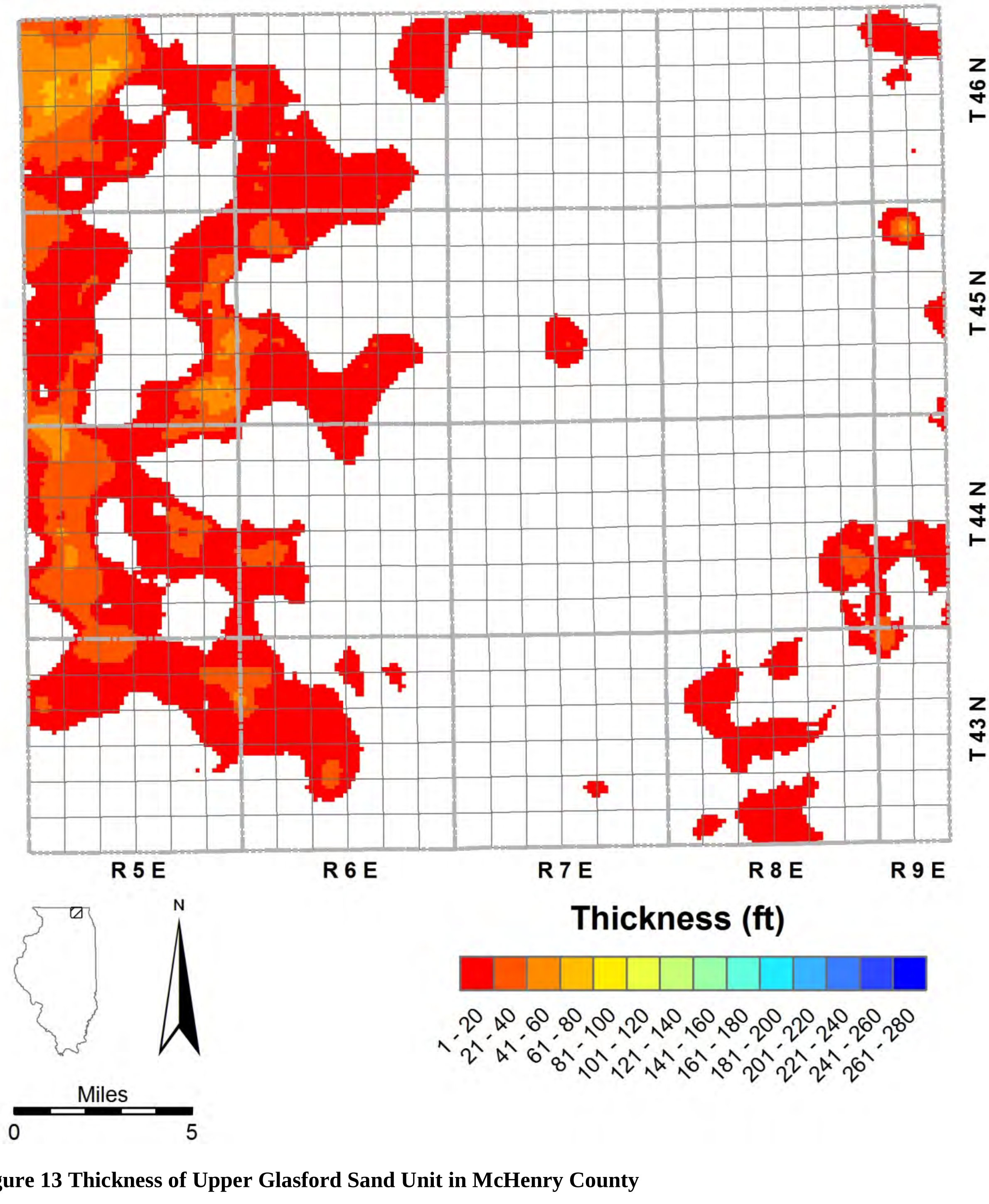

Figure 13 Thickness of Upper Glasford Sand Unit in McHenry County

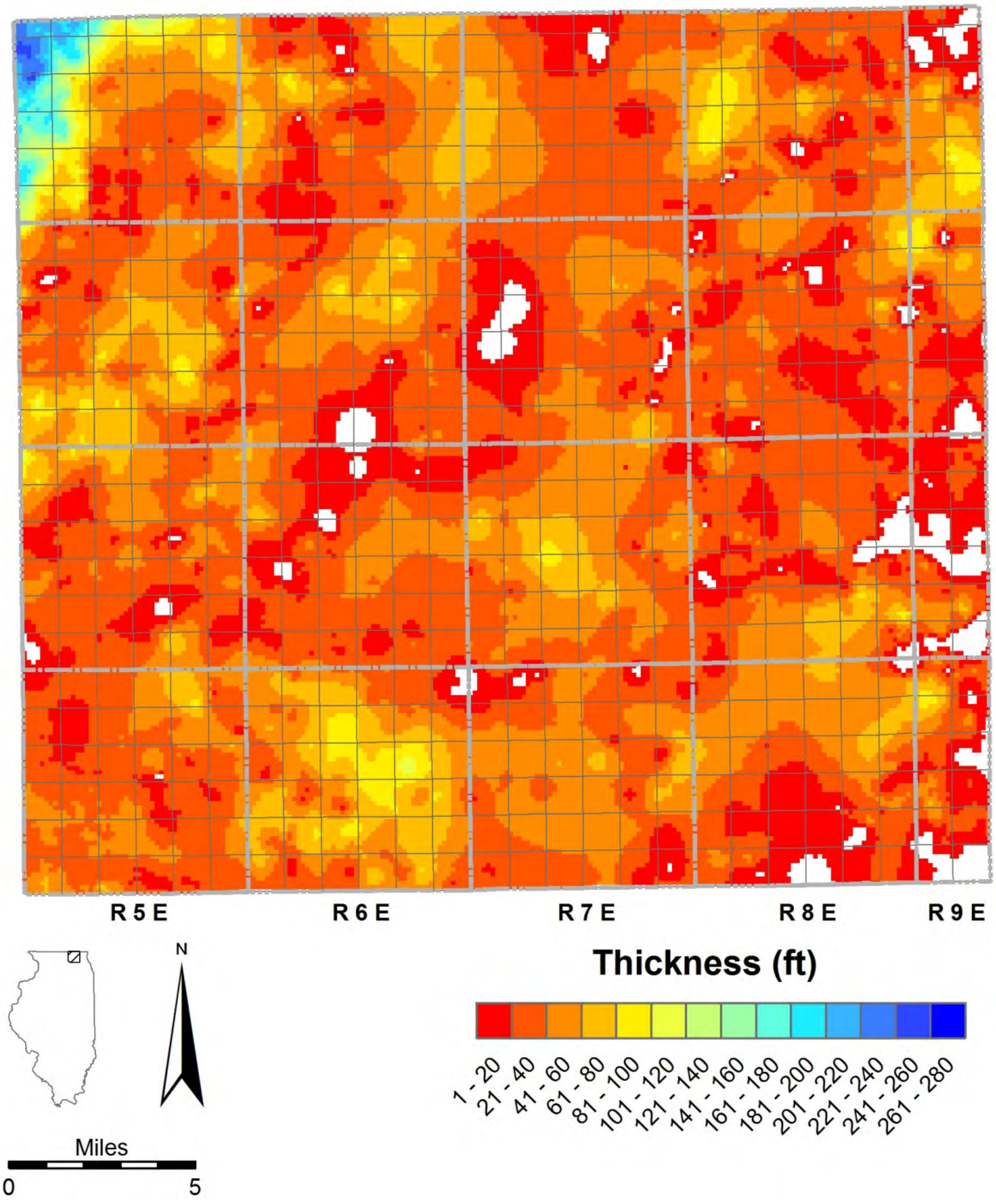

Figure 14 Thickness of Winnebago-Upper Glasford Unit in McHenry County

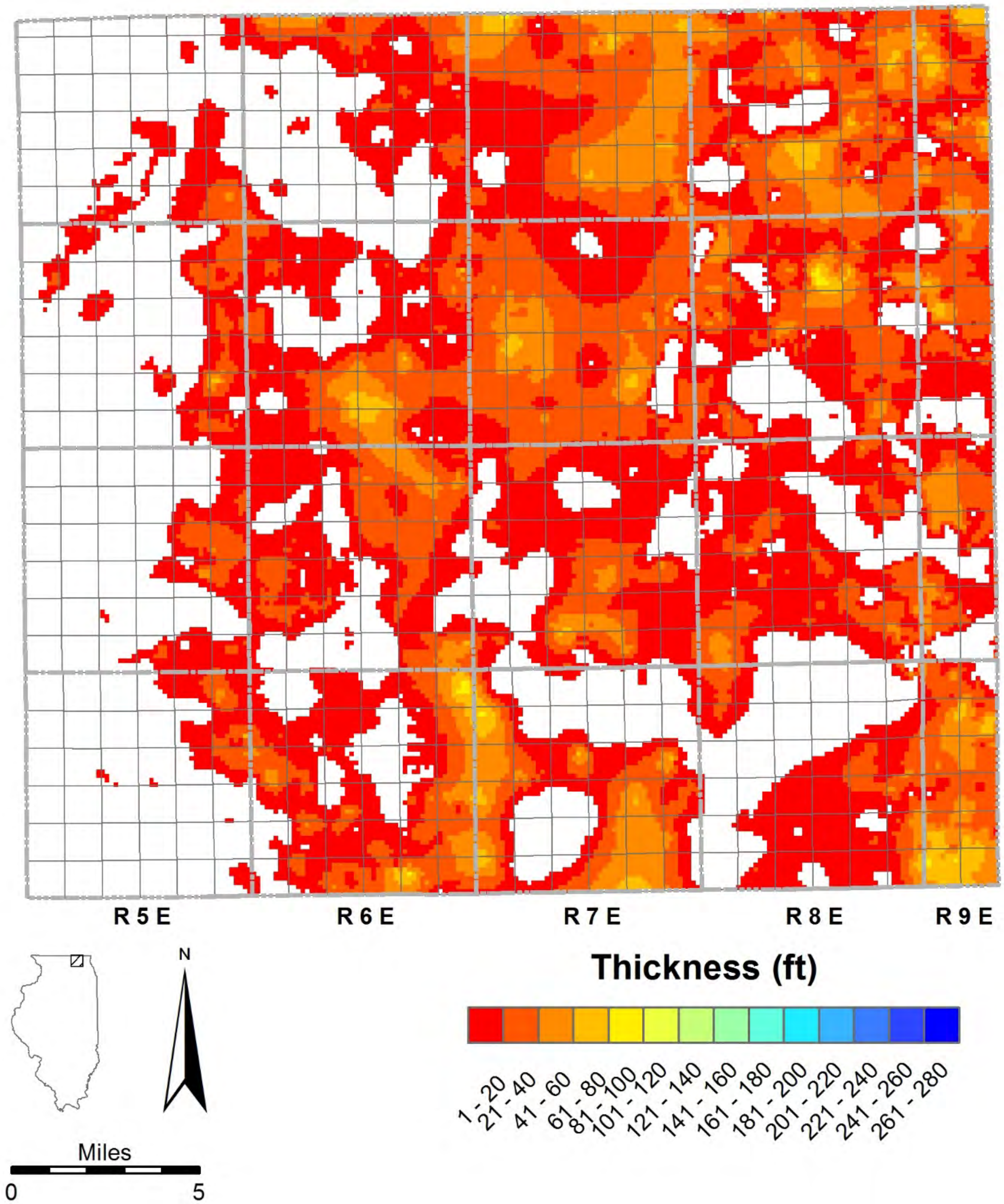

Figure 15 Thickness of Ashmore Unit in McHenry County

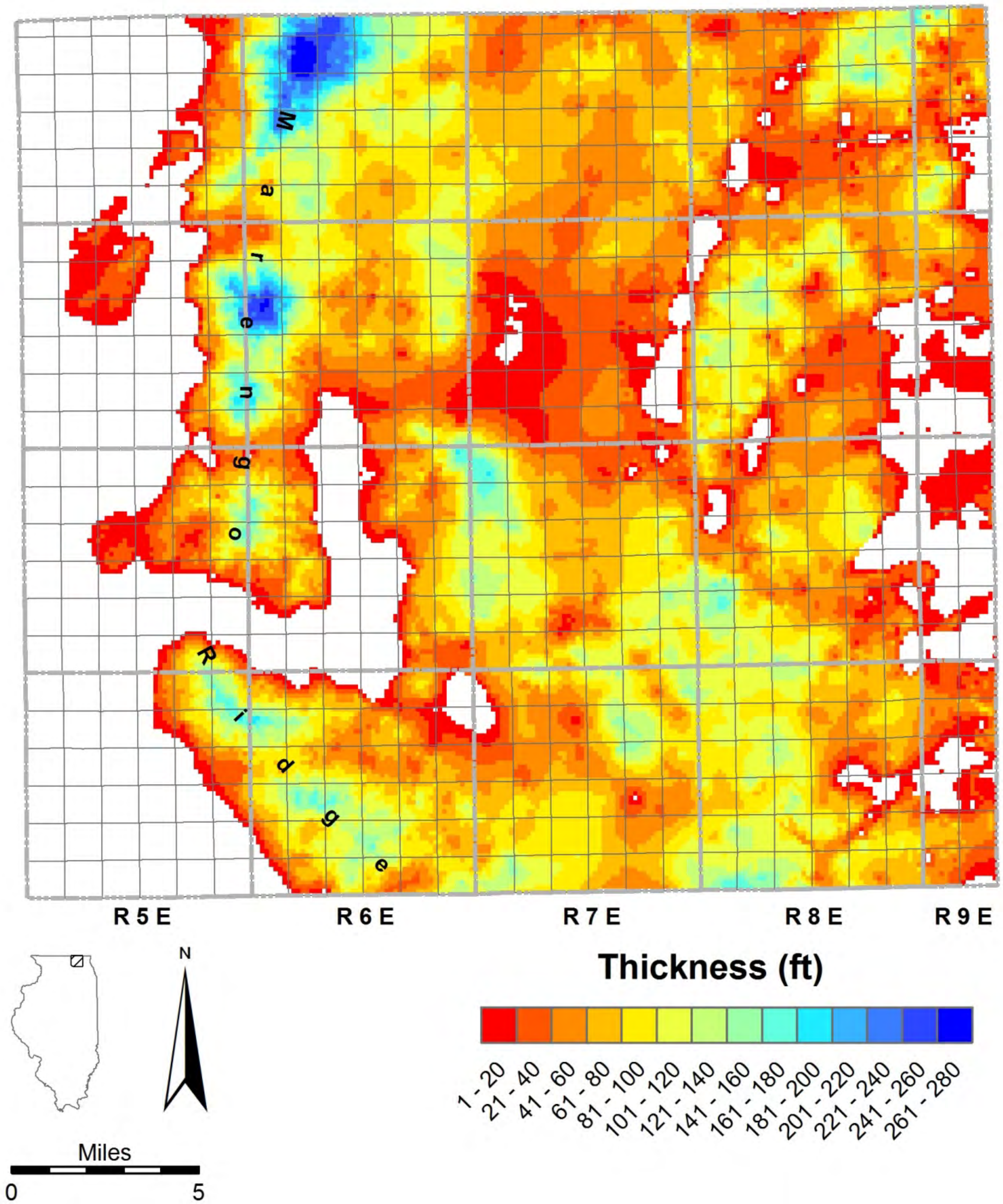

Figure 16 Thickness of Tiskilwa Unit in McHenry County

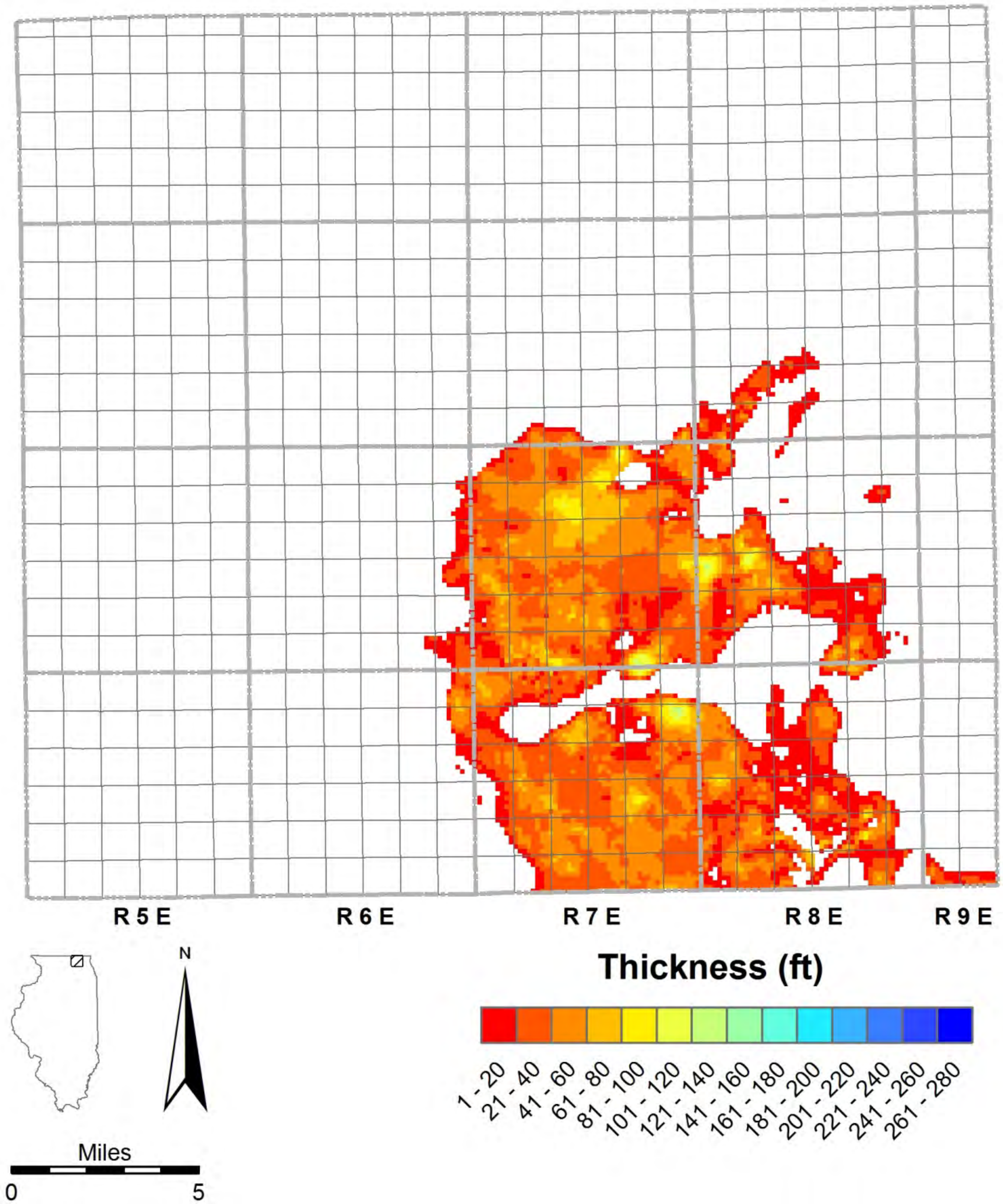

Figure 17 Thickness of Yorkville-Batestown Unit in McHenry County

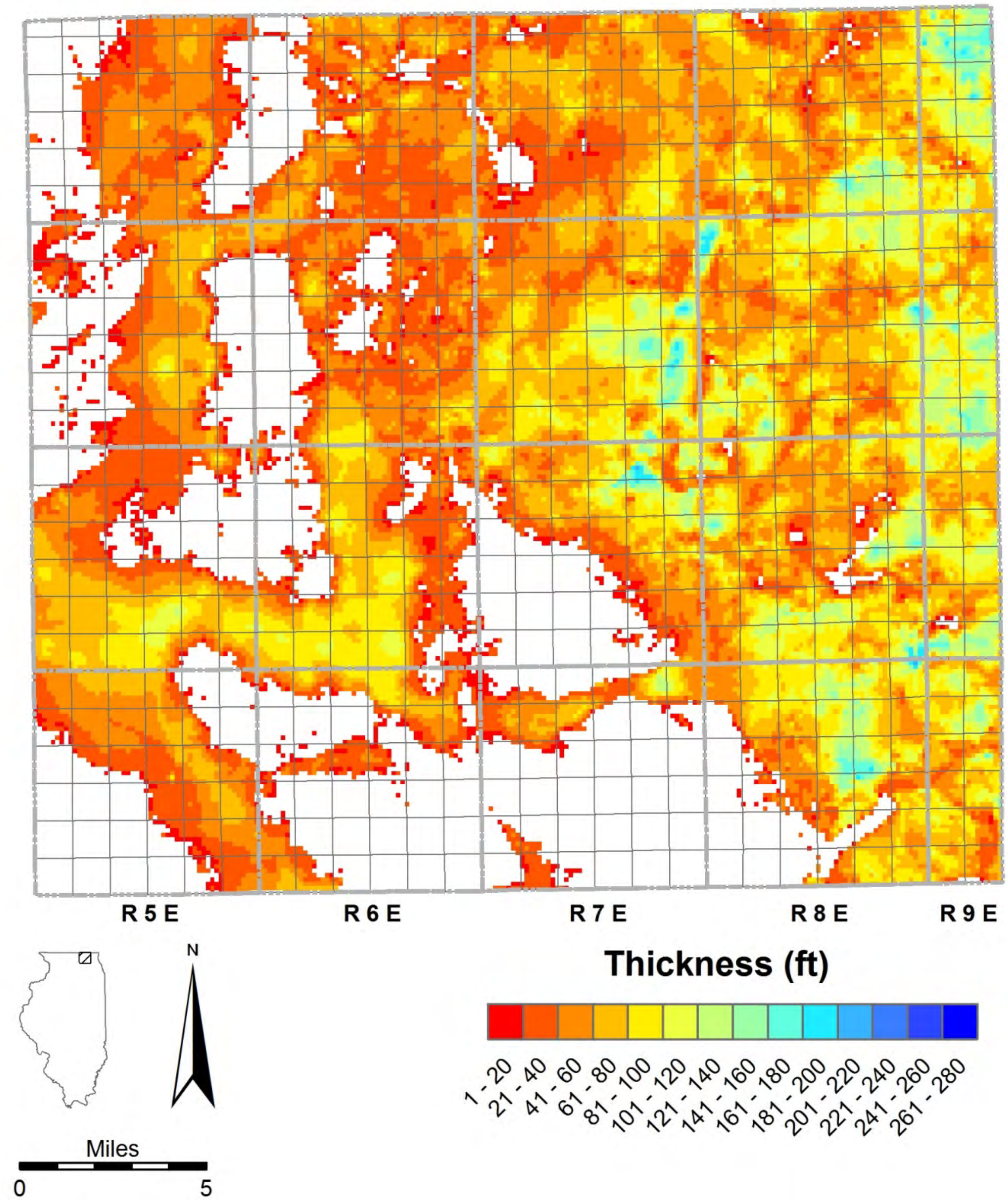

Figure 18 Thickness of Haeger-Beverly Unit in McHenry County

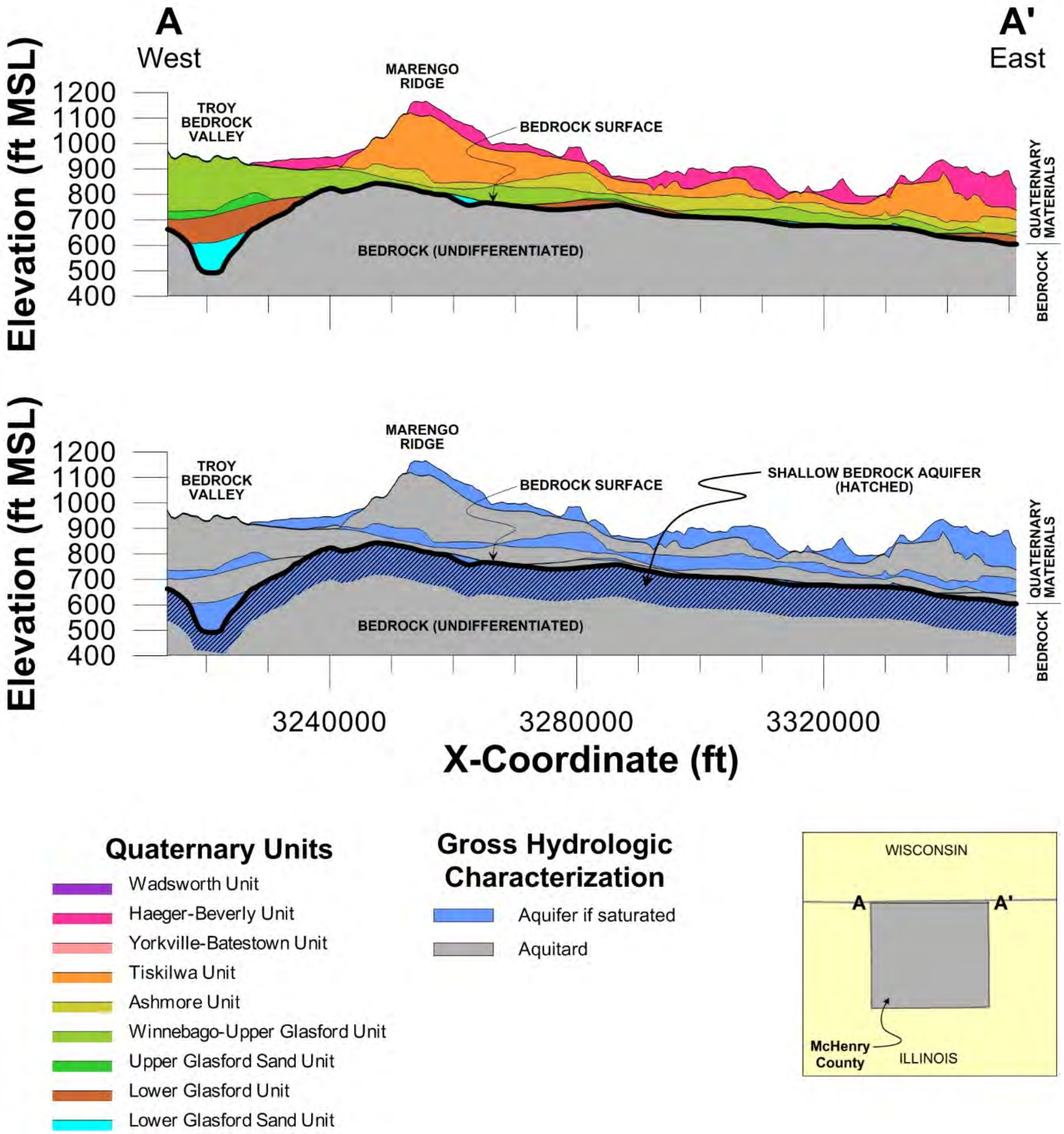

Figure 19 West-to-east cross section along northern edge of McHenry County showing shallow hydrostratigraphic units (top) and aquifer units (bottom) discussed in the text

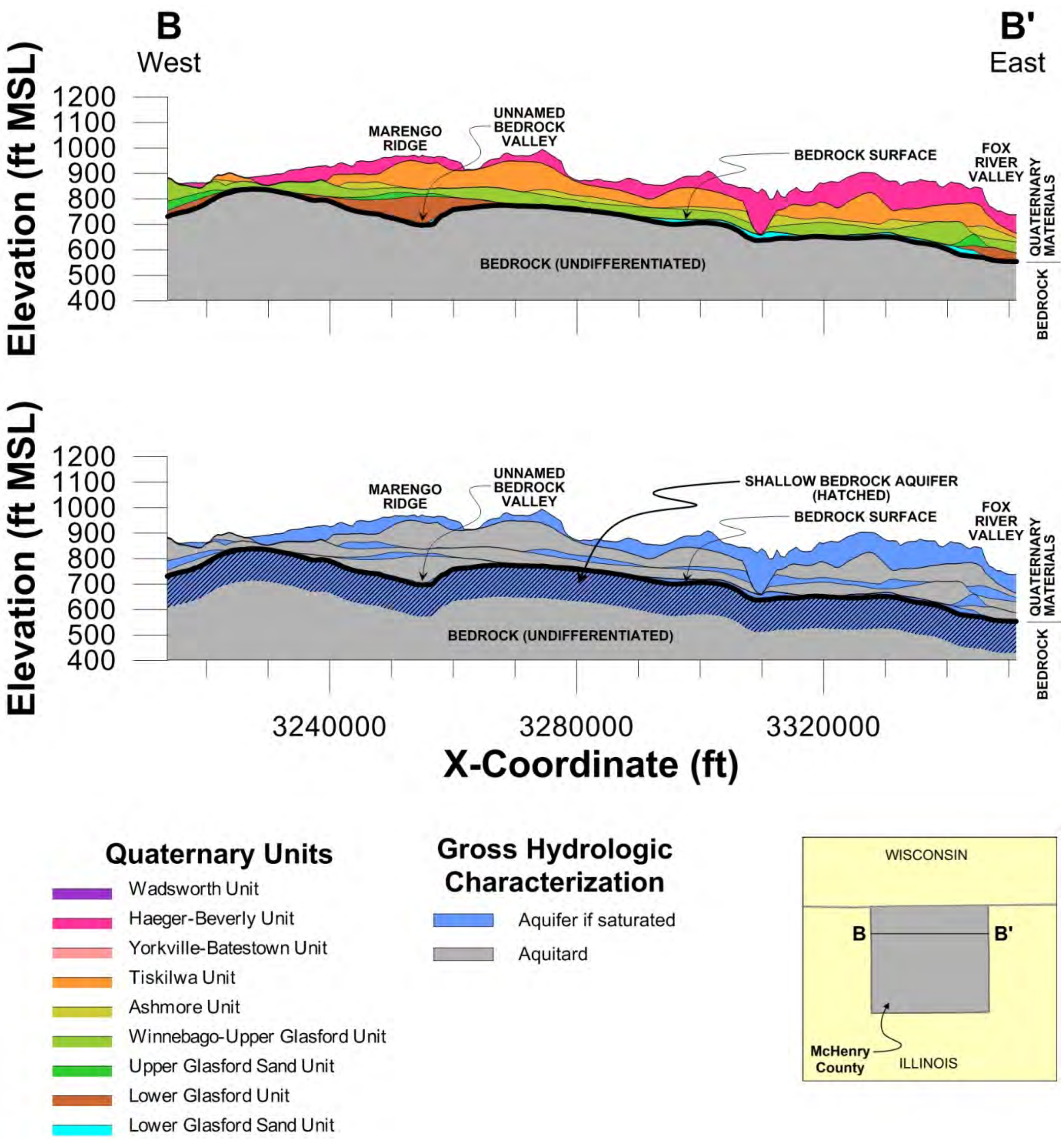

Figure 20 West-to-east cross section through north-central McHenry County showing shallow hydrostratigraphic units (top) and aquifer units (bottom) discussed in the text

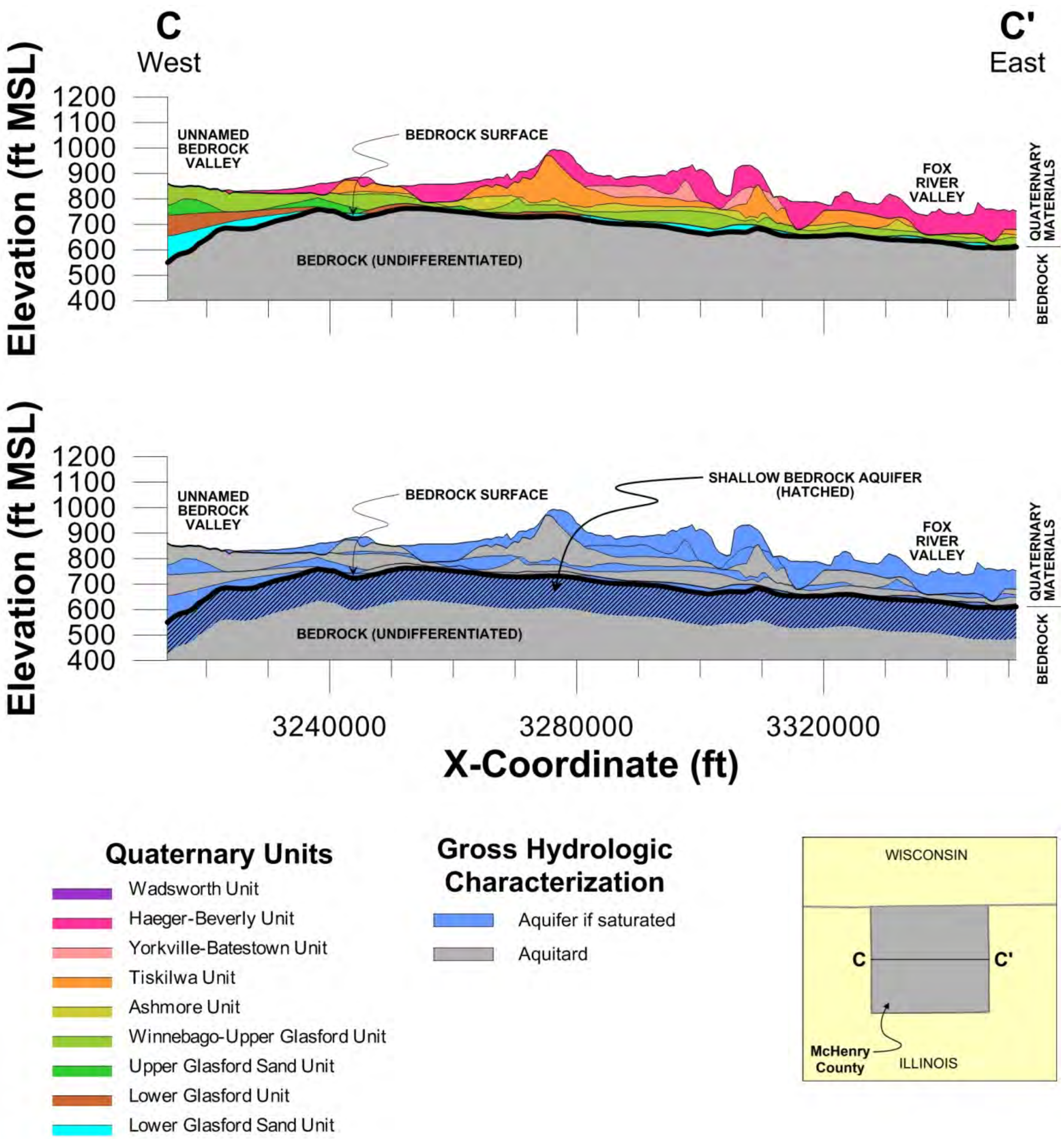

Figure 21 West-to-east cross section through central McHenry County showing shallow hydrostratigraphic units (top) and aquifer units (bottom) discussed in the text

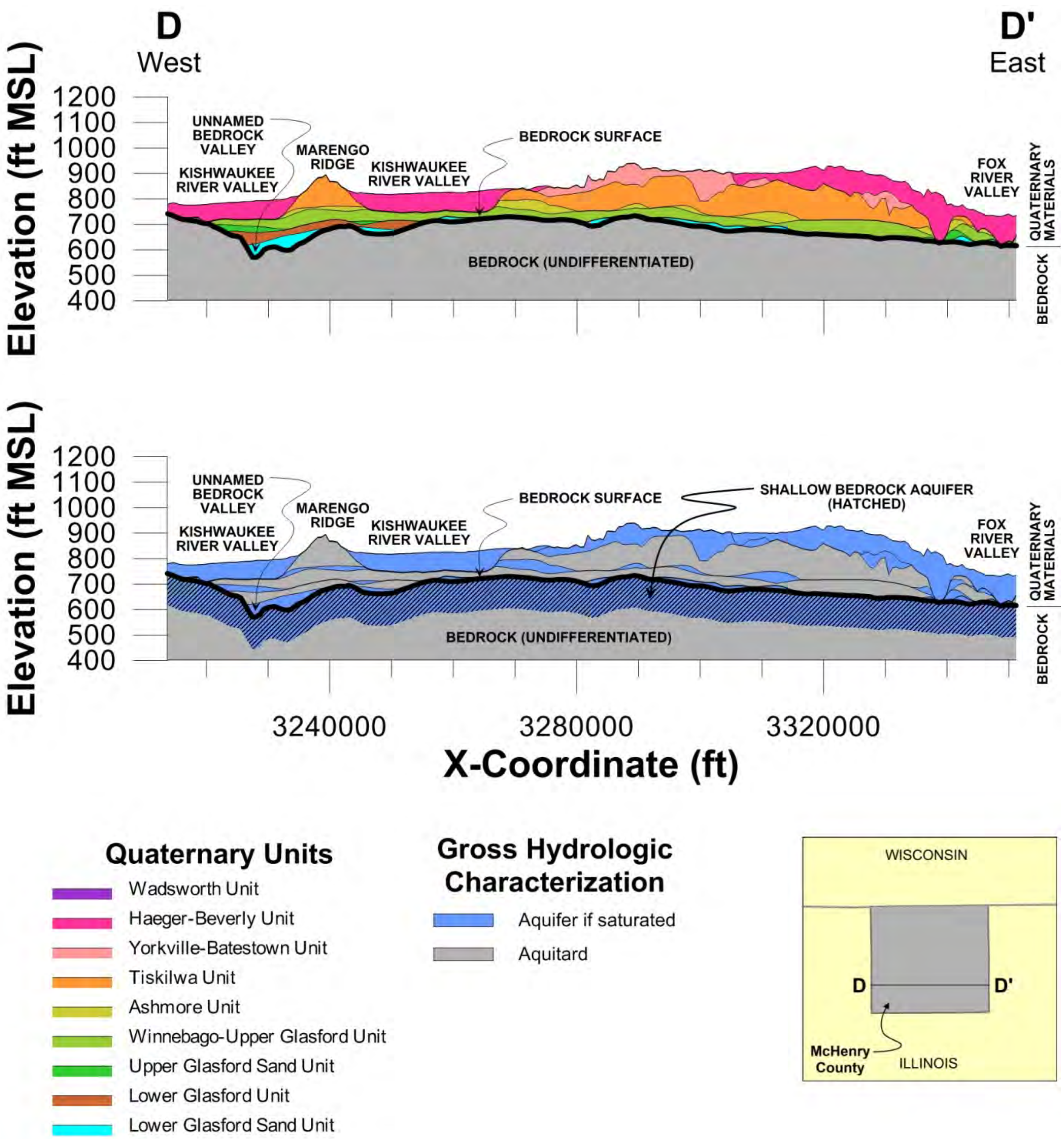

Figure 22 West-to-east cross section through south-central McHenry County showing shallow hydrostratigraphic units (top) and aquifer units (bottom) discussed in the text

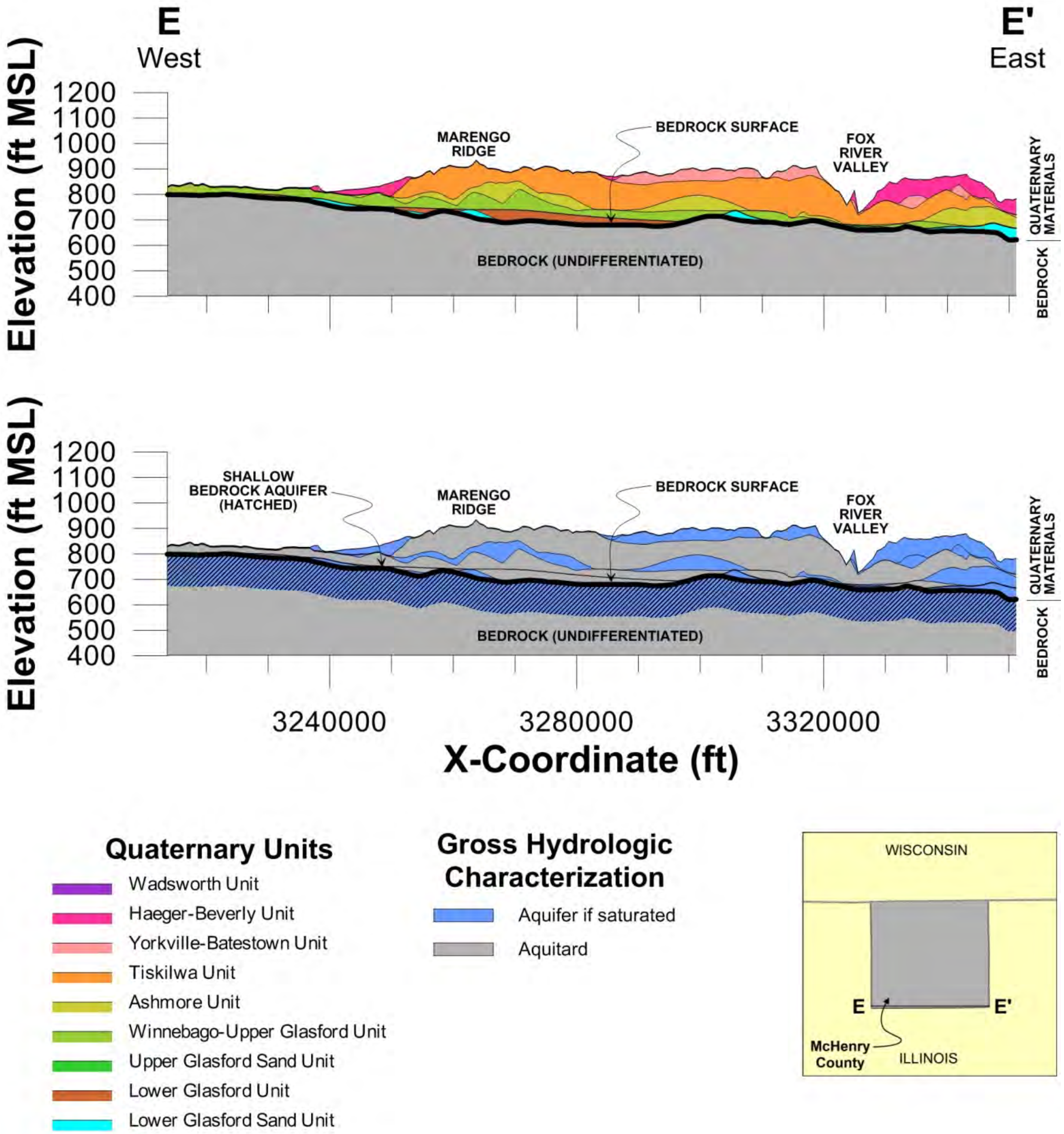

Figure 23 West-to-east cross section along southern edge of McHenry County showing shallow hydrostratigraphic units (top) and aquifer units (bottom) discussed in the text

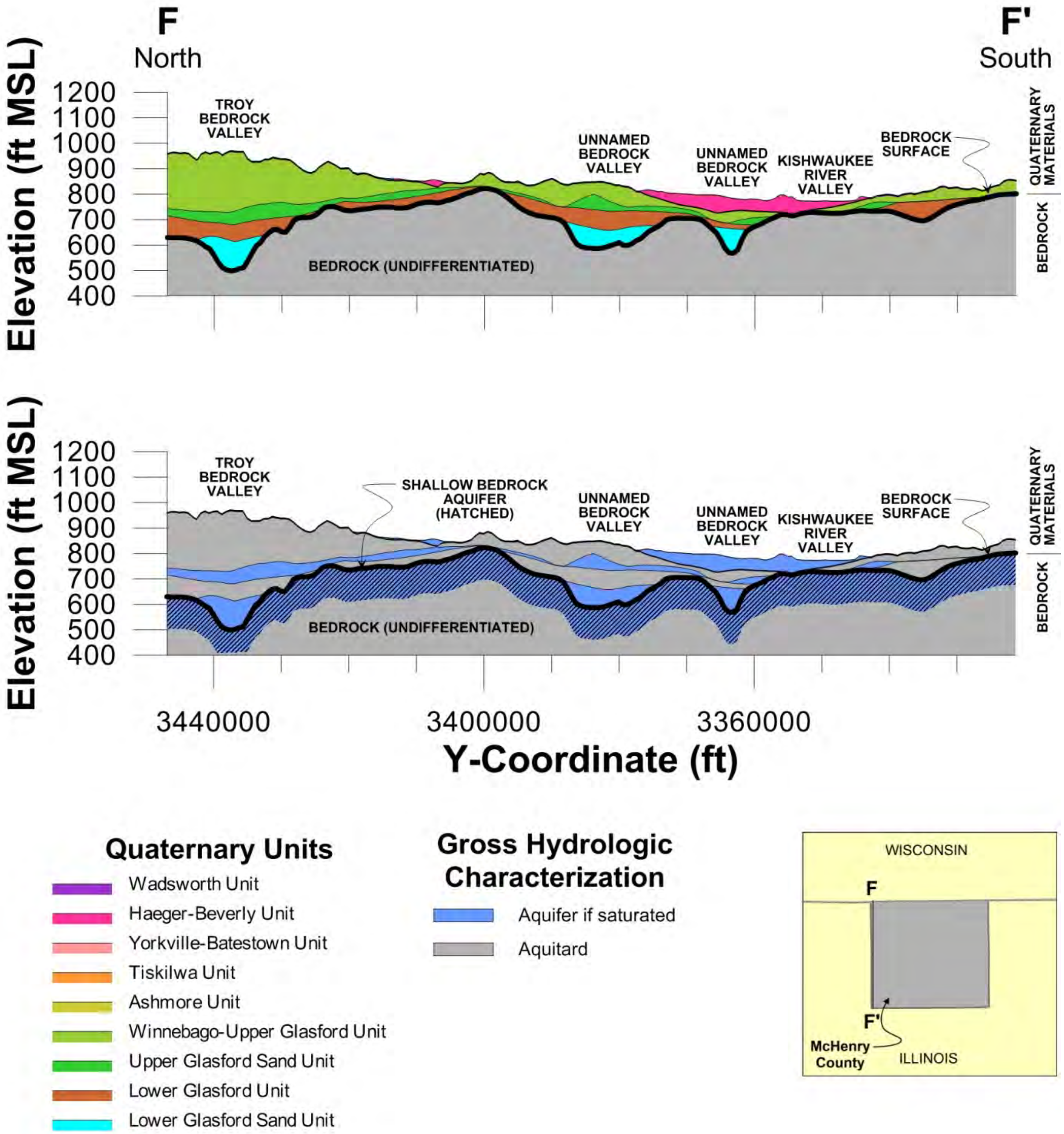

Figure 24 North-to-south cross section along western edge of McHenry County showing shallow hydrostratigraphic units (top) and aquifer units (bottom) discussed in the text

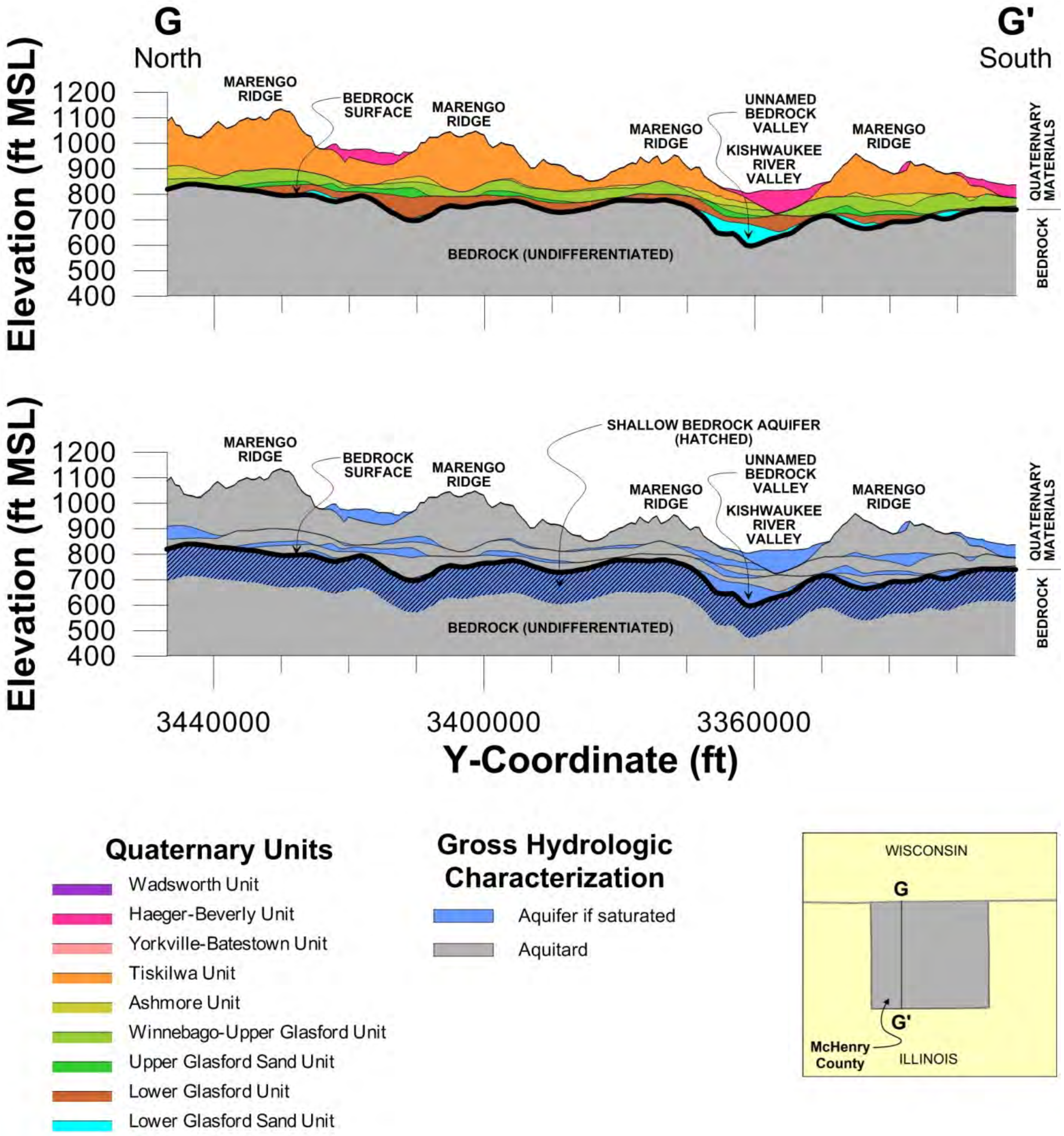

Figure 25 North-to-south cross section through west-central McHenry County showing shallow hydrostratigraphic units (top) and aquifer units (bottom) discussed in the text

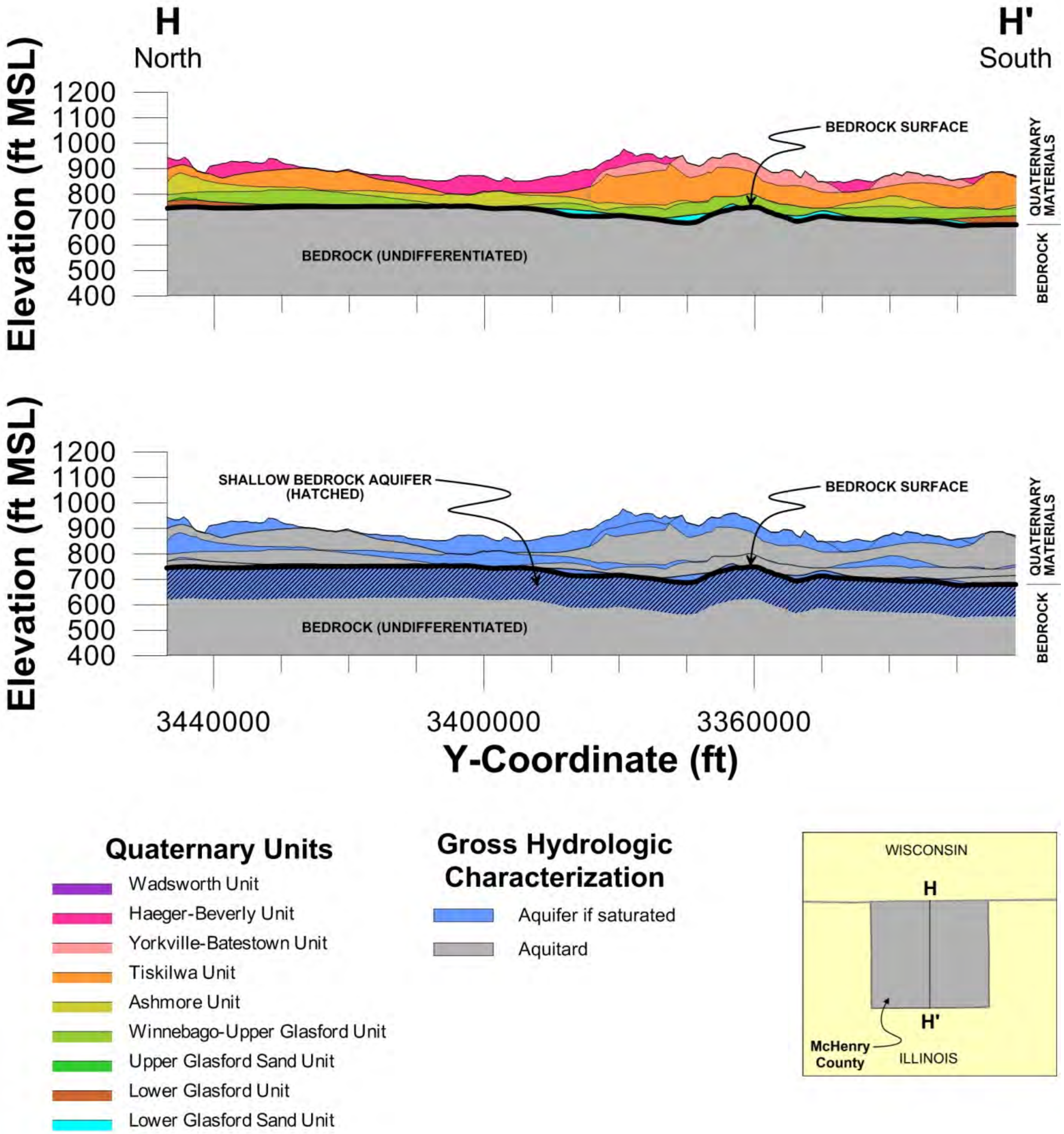

Figure 26 North-to-south cross section through central McHenry County showing shallow hydrostratigraphic units (top) and aquifer units (bottom) discussed in the text

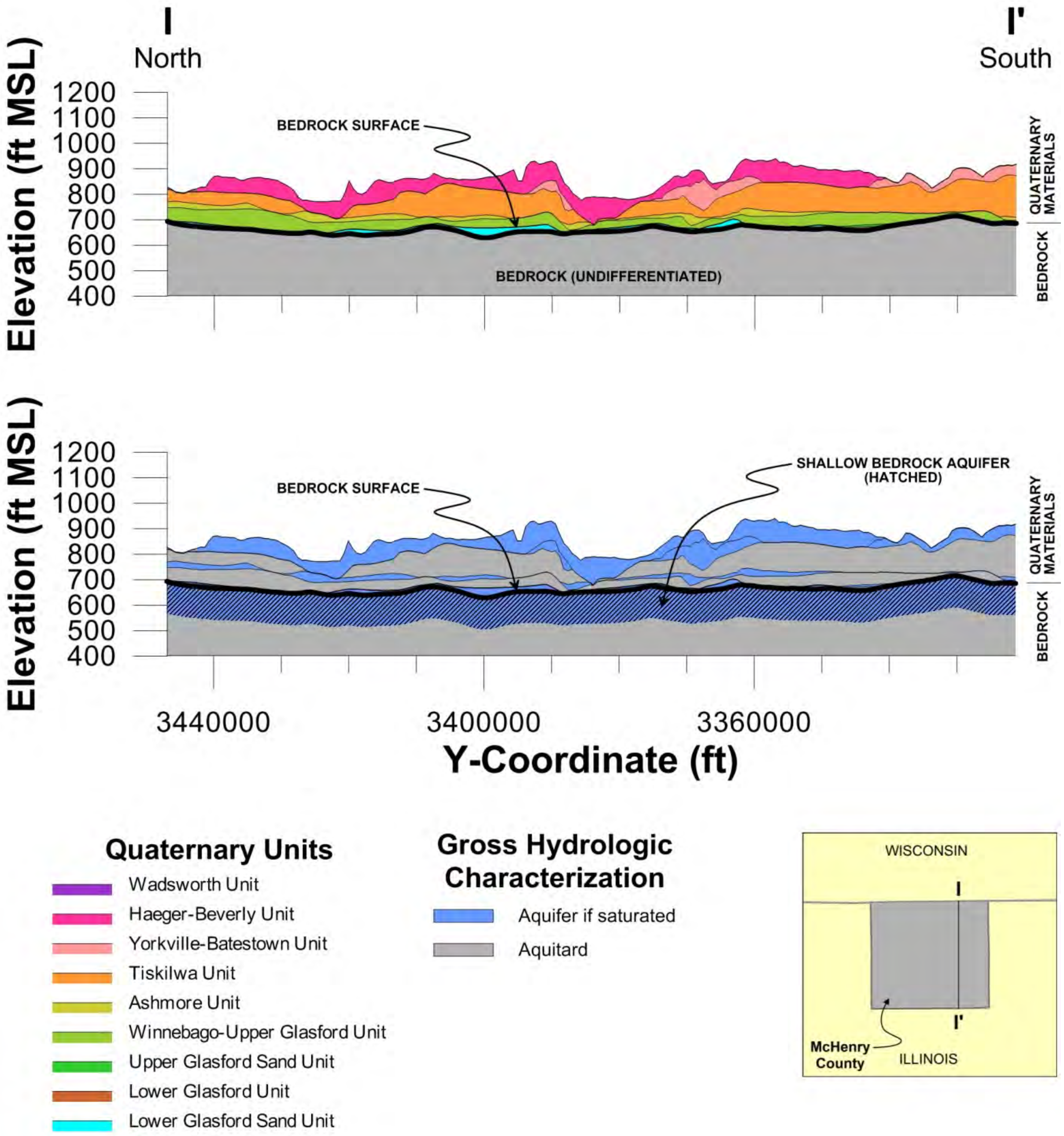

Figure 27 North-to-south cross section through east-central McHenry County showing shallow hydrostratigraphic units (top) and aquifer units (bottom) discussed in the text

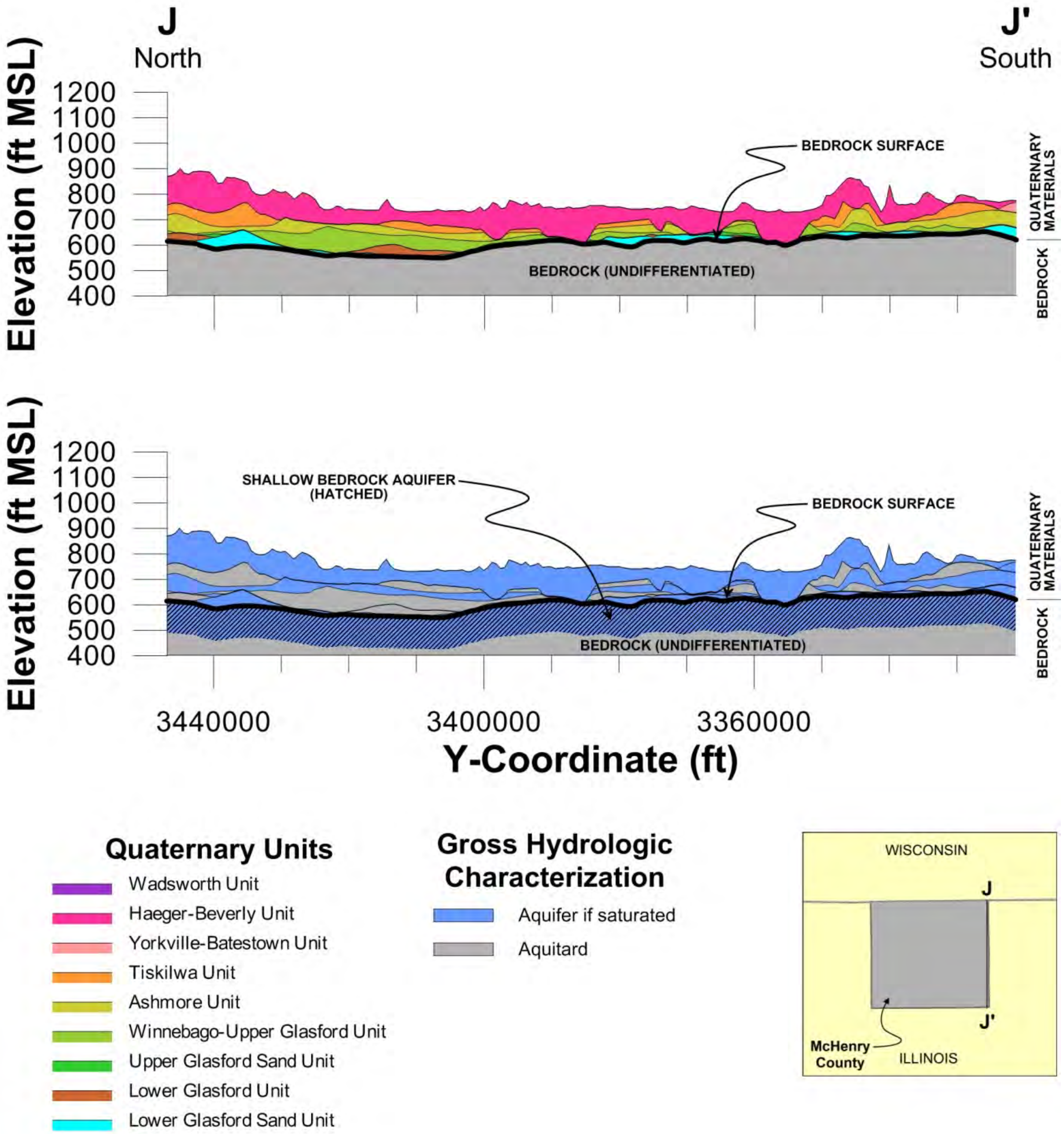

Figure 28 North-to-south cross section along eastern edge of McHenry County showing shallow hydrostratigraphic units (top) and aquifer units (bottom) discussed in the text

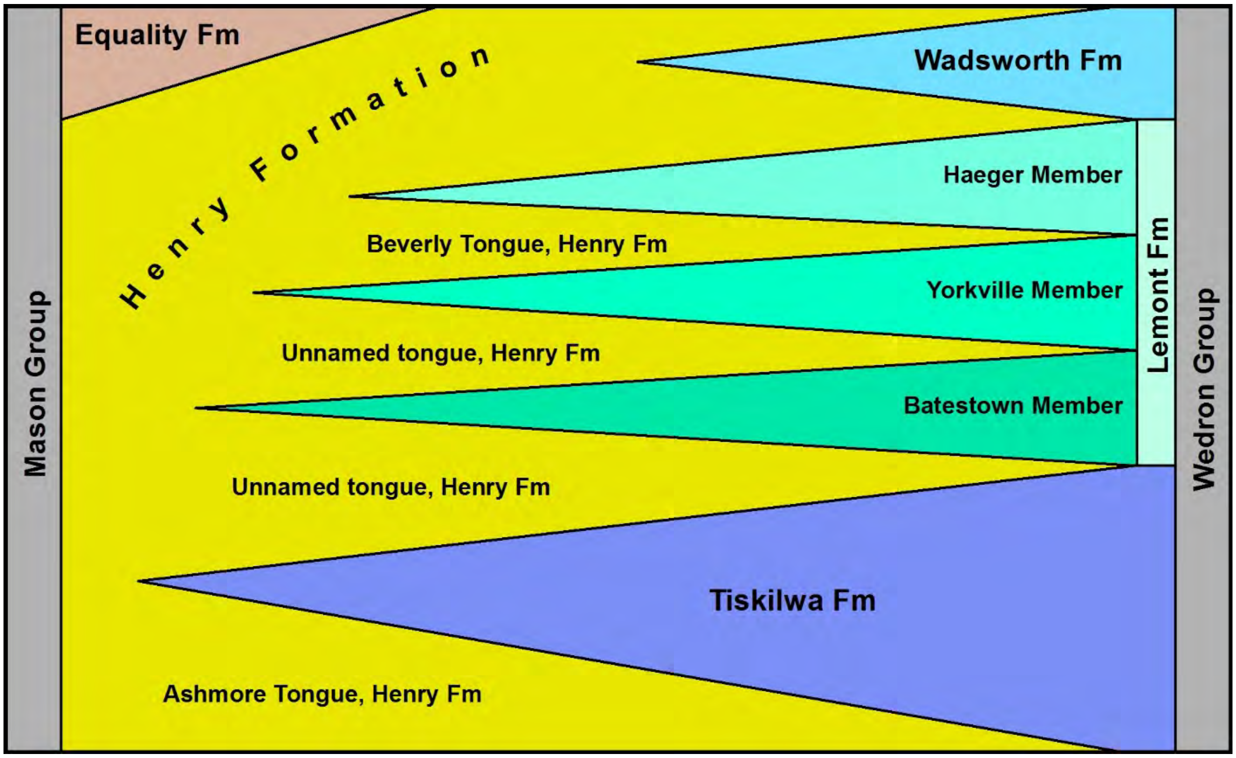

Figure 29 Stratigraphic relationships of Wisconsin Episode lithostratigraphic units in the McHenry County area (Dey et al., 2007)

1.6 Convention for Denoting Deep and Shallow Units, Aquifers, and Wells

For convenience in discussing groundwater in the northeastern Illinois region, we employ nomenclature to consistently distinguish between *shallow units* and *deep units*, between *shallow aquifers* and *deep aquifers*, and between *shallow wells* and *deep wells*. The *shallow units* are hydrostratigraphic units overlying the Ancell Unit, and the *deep units* are the Ancell Unit and units underlying the Ancell (Figure 6 to Figure 9). While this nomenclature is subjective, it is descriptive for the local study area of McHenry County. It is not descriptive in portions of the regional study area (principally in southern Wisconsin and near the Sandwich Fault Zone in Illinois) where the Upper Bedrock, Silurian-Devonian, Maquoketa, and Galena-Platteville Units are absent (Figure 30). In these areas, the Ancell Unit, or an underlying unit, may be present at a relatively shallow depth.

The *deep aquifers* are aquifer units within the sequence of deep units. The deep aquifers include the Cambrian and Ordovician Mt. Simon Unit, Eau Claire Unit, Ironton-Galesville Unit, and Ancell Unit, consisting principally of sandstone. In northeastern Illinois, the Mt. Simon Unit is used far less than the Ancell and Ironton-Galesville Units because of the expense of drilling to it and because deeper portions of the Mt. Simon contain water that is too salty for most uses. The Eau Claire Unit is transitional from an aquitard in the southern part of northeastern Illinois to an aquifer at the Wisconsin border. The deep aquifers are separated from one another in most areas by comparatively impermeable aquitards (confining units) that include the Eau Claire Unit (in the southern part of northeastern Illinois), Potosi-Franconia Unit, and Prairie du Chien-Eminence Unit. Impermeable Precambrian rocks underlie the Mt. Simon Unit and comprise the lowermost of the deep units.

The *shallow aquifers* are aquifers within the sequence of shallow units (Figure 6). They include the Shallow Bedrock Aquifer and discontinuous layers of unconsolidated sand and gravel contained in the Quaternary materials overlying the bedrock. In general, the most transmissive sand and gravel aquifers (and potentially the most productive) reside within the stratigraphically lower portion of the Quaternary sequence and include the Lower Glasford Sand Unit, Winnebago-Upper Glasford Sand Unit, and Ashmore Unit. Sand and gravel comprises the entirety of each of these units, and where sufficiently thick and sufficiently saturated with groundwater, wells open to these units can yield groundwater in quantities useful to public water systems. The upper Quaternary includes other sand and gravel layers that are less transmissive owing to lower permeability, reduced thickness, and/or incomplete saturation. These include the Yorkville-Batestown and Haeger-Beverly Units. In contrast to the Lower Glasford, Winnebago-Upper Glasford, and Ashmore Units, the Yorkville-Batestown and Haeger-Beverly Units are not everywhere composed completely of sand and gravel, but may include comparatively impermeable materials, predominantly diamicton. The Yorkville-Batestown and Haeger-Beverly Units each contain sand and gravel, as well, but these aquifers are much less commonly employed for water supply both because they are comparatively thin, and therefore only marginally productive, and because their shallow position leaves them vulnerable to drought and contamination from surface sources. The shallow depth of the Yorkville-Batestown and Haeger-Beverly Units has made these units attractive targets for mining, particularly in eastern McHenry County.

In most of northeastern Illinois, the shallow and deep aquifers are separated by a laterally extensive, relatively impermeable interval underlying the Shallow Bedrock Aquifer. Because this interval limits vertical leakage of water between the shallow and deep aquifers, it is called a *confining unit*. This impermeable interval is present throughout McHenry County, but in the areas outside McHenry County where the Ancell Unit (or deeper) is the uppermost bedrock unit, this confining unit has been weathered away.

In practice, withdrawals from the shallow units are distributed among the Quaternary aquifers and the Shallow Bedrock Aquifer. Wells drilled into deep units are sometimes left open to all overlying units, so withdrawals from deep wells can also include withdrawals from shallow units. For purposes of this study, shallow wells are those open *only* to the shallow units. Deep wells are open to the deep units but also may be open to the shallow units. Withdrawals from deep wells open to the shallow aquifers in the 11-county northeastern Illinois area have generally declined since 1964. In 2005, withdrawals from these wells constituted only about 3 percent of total groundwater withdrawals in the region (Meyer et al., 2012).

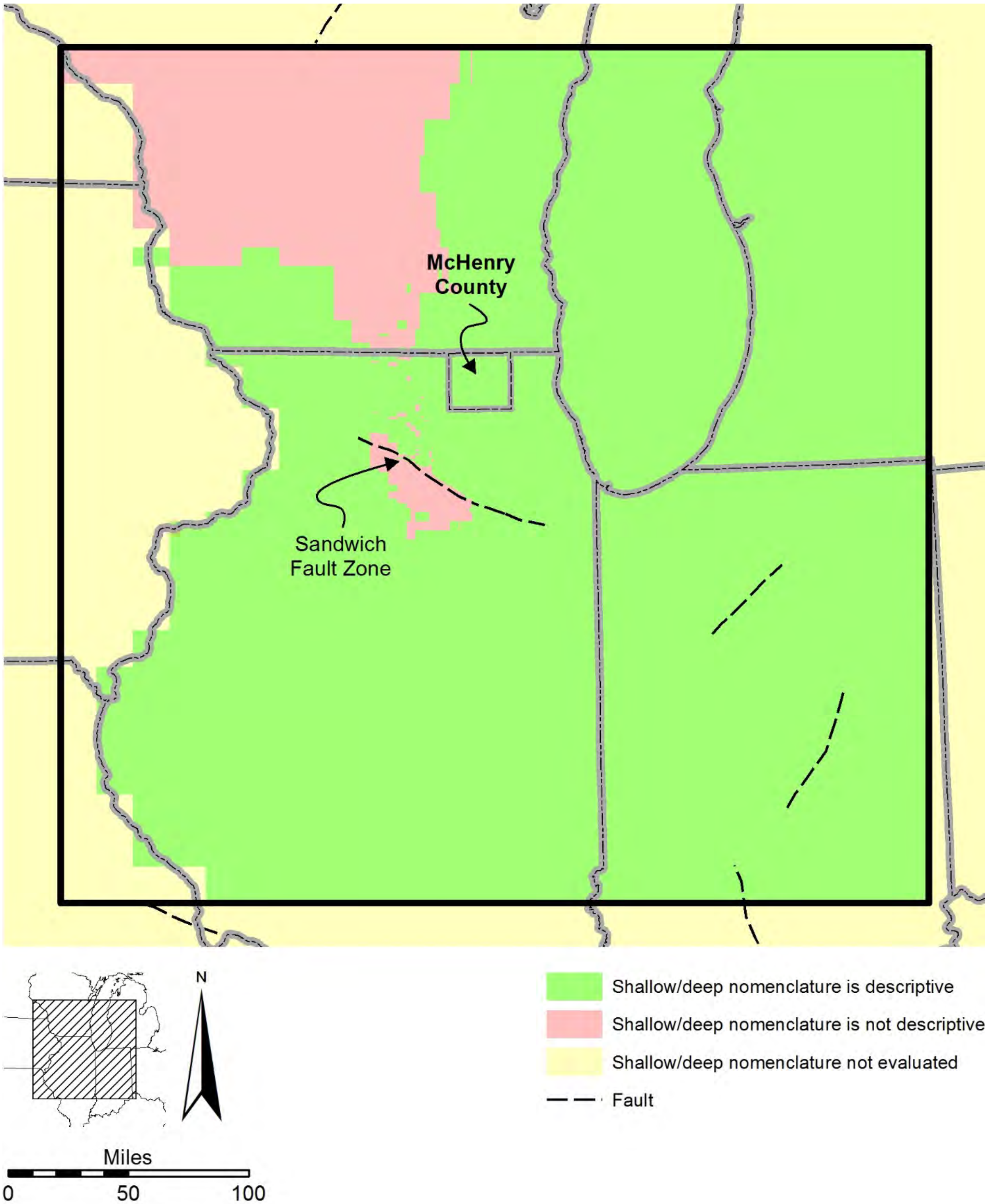

Figure 30 Areas where shallow/deep nomenclature used in this report is descriptive

2 Groundwater Withdrawals in 2009 and Future Withdrawals to 2050

2.1 Introduction

This chapter summarizes historical groundwater withdrawals, emphasizing pumping in 2009 (the most recent year for which complete data were available at the time of project execution), and estimates of future groundwater withdrawals developed for this study, but based on estimates by Dziegielewski and Chowdhury (2008). We discuss model-simulated impacts of withdrawing water at the estimated rates in Chapter 4.

Like Dziegielewski and Chowdhury (2008), we discuss water use by five major groups of potential water users in McHenry County:

- Self-supplied domiciles;
- Public water systems;
- Self-supplied commerce and industry;
- Self-supplied irrigation and agriculture; and
- Self-supplied electric power generation.

2.2 Historical Withdrawals

In this section we summarize historical groundwater withdrawals from 1964 to 2009, emphasizing the distribution of withdrawals among sectors, locations, and sources in 2009. The discussion focuses on withdrawals that are reported to the ISWS (i.e., those by public water systems, self-supplied commercial and industrial facilities, and self-supplied irrigation operations), but ISWS researchers believe these reported values to be a comprehensive and accurate representation of most of the water withdrawn in McHenry County. We note, however, that in 2005, about 55,000 people in McHenry County used about 4.9 million gallons per day (Mgd) of groundwater obtained from household wells rather than from public water supply systems (Dziegielewski and Chowdhury, 2008) (Table 1). These withdrawals constitute the self-supplied domestic sector discussed in Section 2.1; estimates for this sector are not available for later years. Assuming that the 2005 estimate of self-supplied domestic groundwater withdrawals is approximately correct for 2009, about 17 percent of groundwater withdrawn in McHenry County was withdrawn by the self-supplied domestic sector.

Available pumping data show that, during the period 1964–2009, McHenry County was entirely dependent on groundwater for public supply, self-supplied industrial and commercial facilities, and self-supplied irrigation. In 2009, withdrawals of groundwater by these sectors averaged 24.7 Mgd, approximately triple the 1964 average, the earliest year for which the ISWS maintains reliable withdrawal records (Figure 31). Average annual withdrawals have increased fairly steadily since 1964. About 67 percent of the groundwater withdrawn in McHenry County in 2009 was withdrawn by public water systems (Table 1). Public water systems include public and private facilities that provide water for residential, commercial, industrial, and other purposes. In 2009, pumping by public water systems in McHenry County averaged 19.9 Mgd. In northeastern Illinois, most water for commerce and industry, electric power generation, and irrigation and agriculture is self-supplied (i.e., facilities operate their own wells and intakes instead of purchasing water from public water supplies). In 2009, self-supplied groundwater withdrawals in McHenry County for commercial and industrial uses averaged 4.4 Mgd, and those for irrigation and agriculture (including irrigation of golf courses) averaged 0.5 Mgd. There were no recorded withdrawals of groundwater for thermoelectric power generation in 2009 in McHenry County, nor were there in 2005 (Dziegielewski and Chowdhury, 2008).

Most of the groundwater withdrawn for public supply, self-supplied industrial and commercial facilities, and self-supplied irrigation in McHenry County has historically been pumped from shallow wells (Figure 31). This predominance reflects the widespread and productive character of the shallow aquifers in the county, which makes expenditures for drilling deep wells unnecessary in many areas. In 2009, about 72 percent of these withdrawals were obtained from shallow wells. The most heavily pumped wells are mostly those operated by public water systems, most notably those of Crystal Lake, McHenry, and Woodstock. Deep wells are fewer in number than shallow wells but include the most heavily pumped wells in the county, Crystal Lake wells 7 and 8 (Figure 32, Figure 33). Shallow wells are more widespread, but, like the deep wells, are more densely distributed in the eastern part of McHenry County, which is more heavily populated.

Groundwater withdrawals in northeastern Illinois have declined since the 1980s, largely as a consequence of public water systems in Cook, Du Page, and Lake Counties shifting from groundwater to Lake Michigan as a water source, but also because of conservation, improvements in efficiency, reduction of leakage, and deindustrialization (Figure 34). The largest annual declines in total groundwater withdrawals occurred in the early 1990s, when many groundwater-using public systems in Du Page County shifted to Lake Michigan water. Declines in withdrawals from deep wells have been greater than those from shallow wells, primarily because many public water systems that switched to Lake Michigan relied heavily on deep wells. The overall spatial effect of the shift to a Lake Michigan source by inner suburban public water systems has been to push the band of groundwater withdrawals farther west and south as pipelines deliver Lake Michigan water to inland areas at progressively greater distances from the lake. Withdrawals from the shallow units in 2009 are concentrated within a corridor extending from the Indiana boundary in Will County northwestward through the Fox River Valley of Kane County and extreme northwestern Cook County and northward into McHenry County (Figure 35). In the southern part of the corridor, the source of these shallow withdrawals is predominantly the shallow bedrock aquifer (Will, southern Cook, and Du Page Counties), but large amounts of groundwater are withdrawn from Quaternary sand and gravel aquifers in the northern part of the corridor (east-central and northeastern Kane County and McHenry County). Principal areas of withdrawals from the deep units in 2009 are (1) the industrial corridor along the Chicago Sanitary and Ship Canal and Des Plaines River, (2) the Fox River Valley area of southeastern Kane County, and (3) southeastern McHenry County (Figure 36).

Table 1 Estimated Groundwater Withdrawals by Water Supply Sector, McHenry County (2009)

Water Supply Sector	***Withdrawals (Mgd)***	***Proportion***
Self-supplied domiciles*	4.9	17%
Public water systems	19.9	67%
Self-supplied commerce and industry	4.4	15%
Self-supplied irrigation and agriculture	0.5	2%
Self-supplied electric power generation	0.0	0%
TOTAL	29.6	100%

*Estimated for 2005 (Dziegielewski and Chowdhury, 2008) and assumed accurate for 2009 by the authors

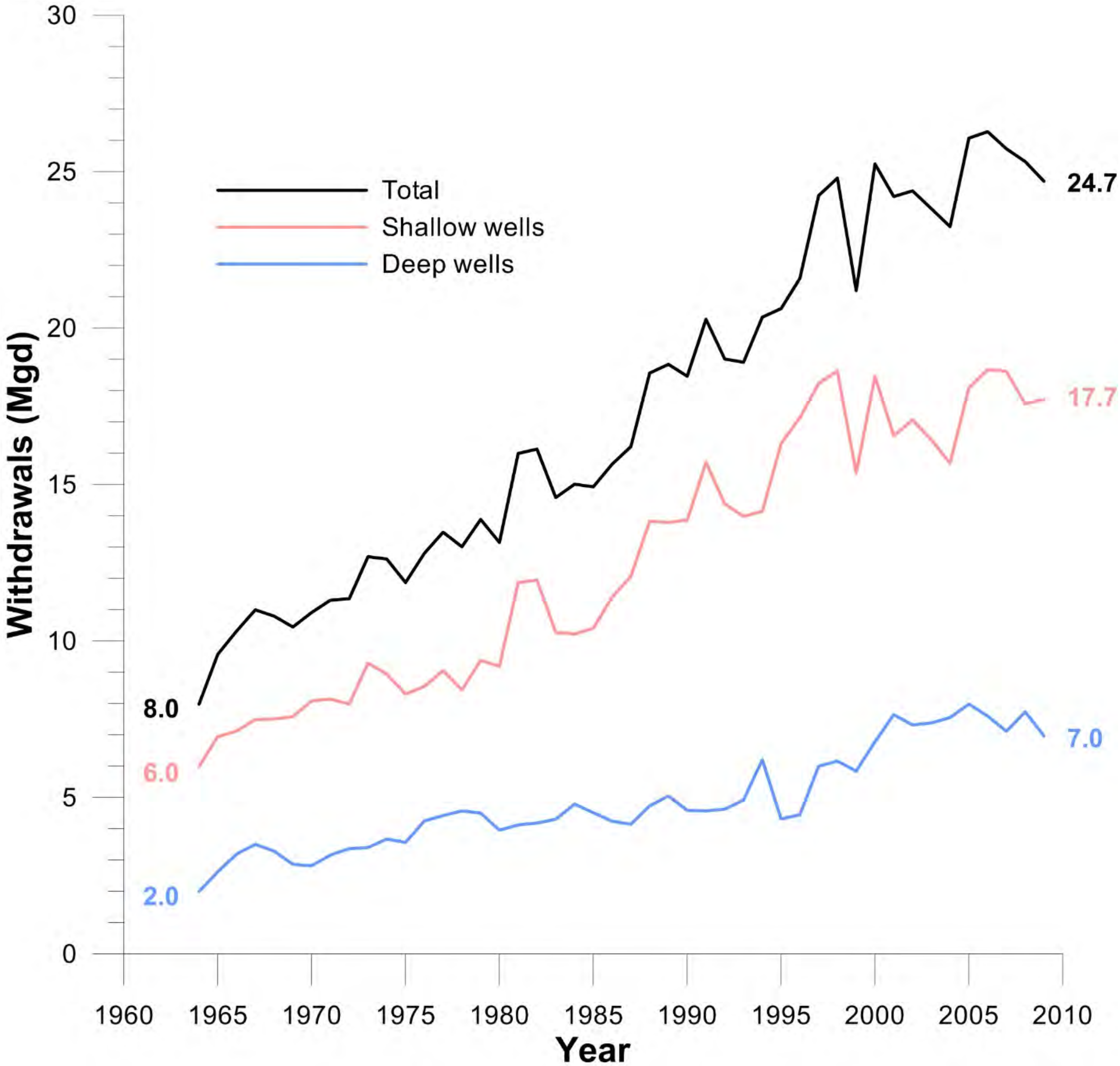

Figure 31 Water withdrawals by public water systems, by self-supplied commercial and industrial facilities, and for self-supplied irrigation in McHenry County (1964-2009). All withdrawals are derived from groundwater sources.

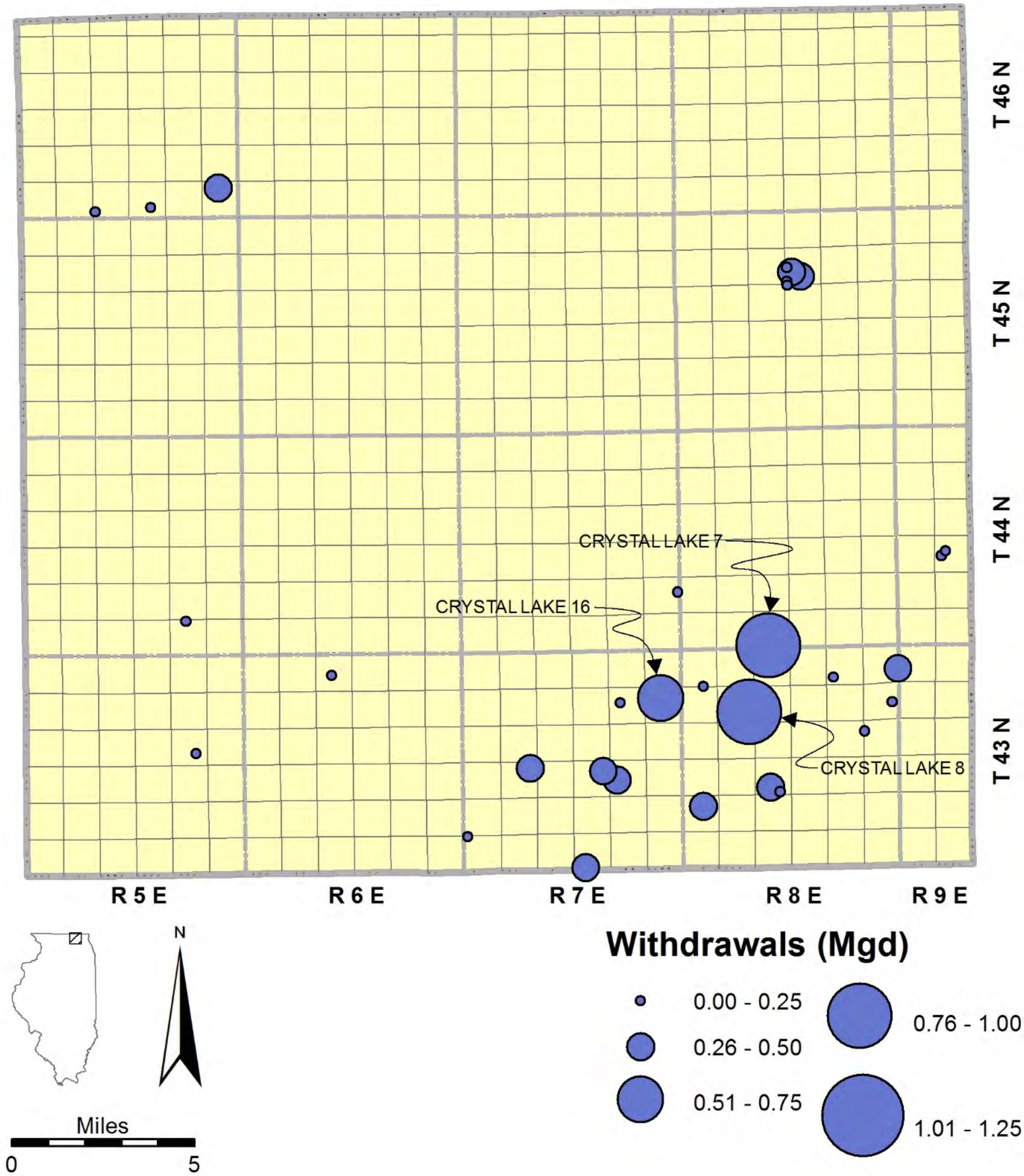

Figure 32 Withdrawals from deep wells for public supply, self-supplied commercial and industrial facilities, and self-supplied irrigation and agriculture in McHenry County (2009). Wells pumped at average rates greater than 0.5 Mgd are labeled.

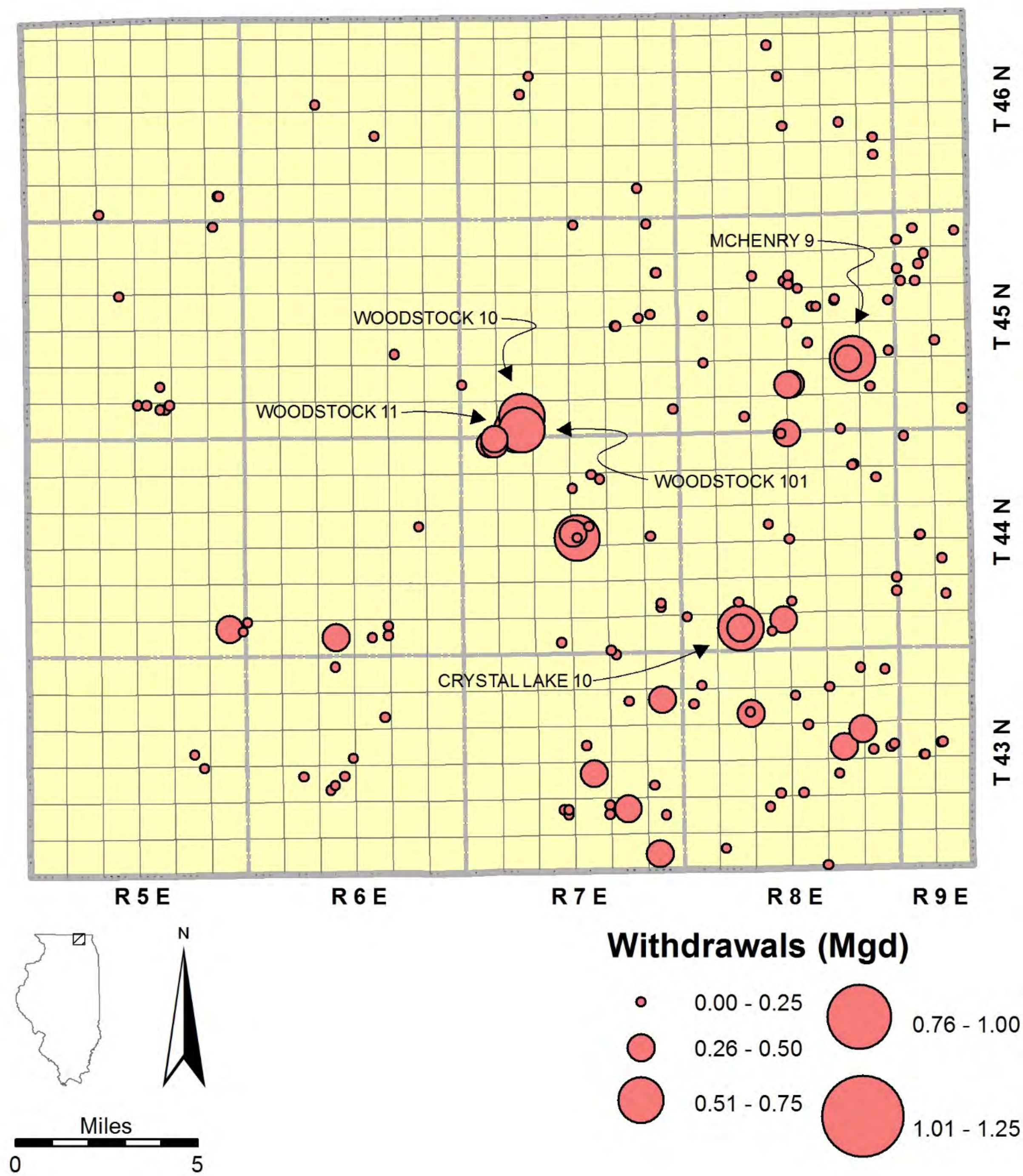

Figure 33 Withdrawals from shallow wells for public supply, self-supplied industrial and commercial facilities, and self-supplied irrigation and agriculture in McHenry County (2009). Public supply wells pumped at average rates greater than 0.5 Mgd are labeled.

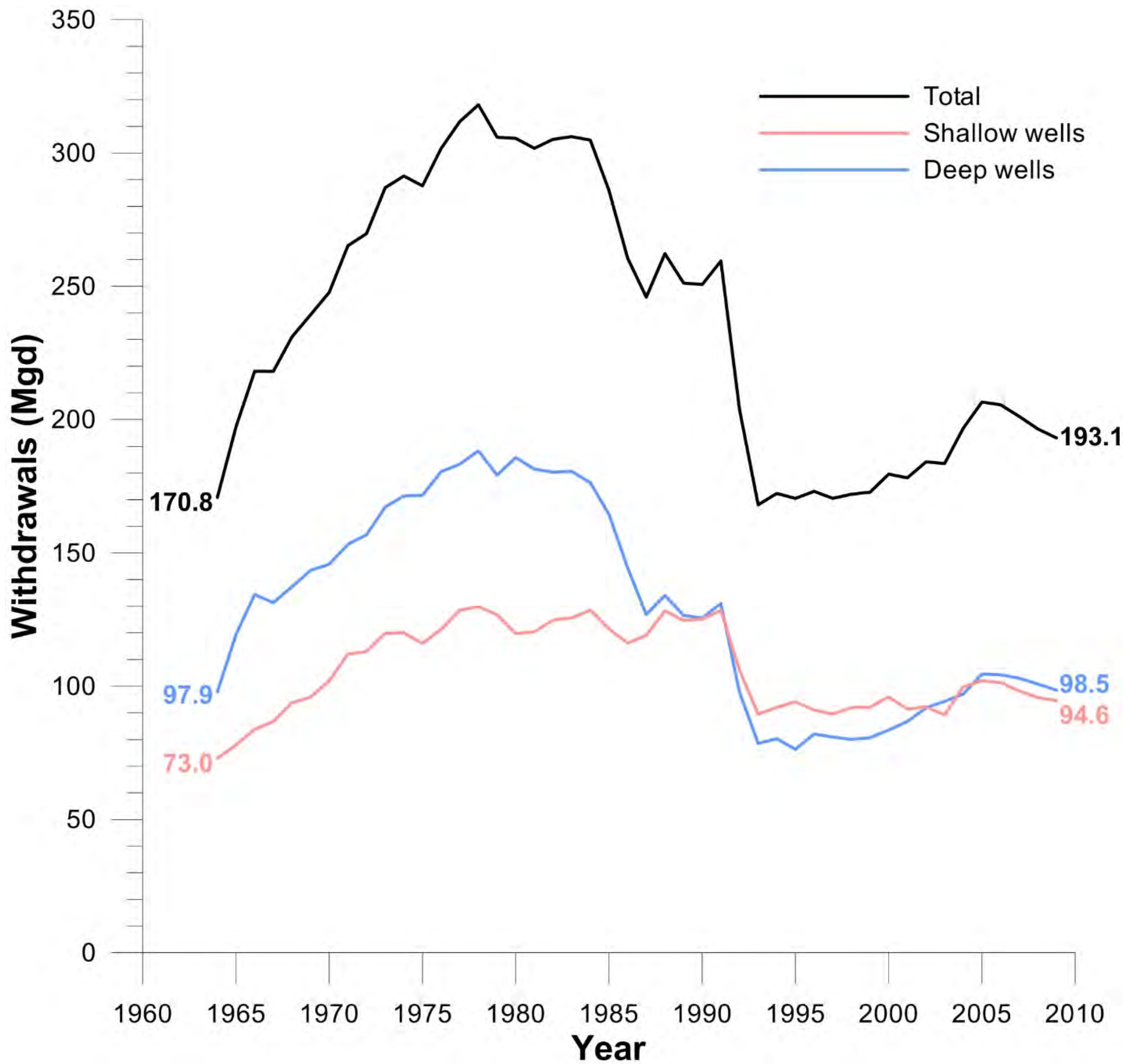

Figure 34 Groundwater withdrawals by public water systems, by self-supplied commercial and industrial facilities, and for self-supplied irrigation in northeastern Illinois (1964-2009)

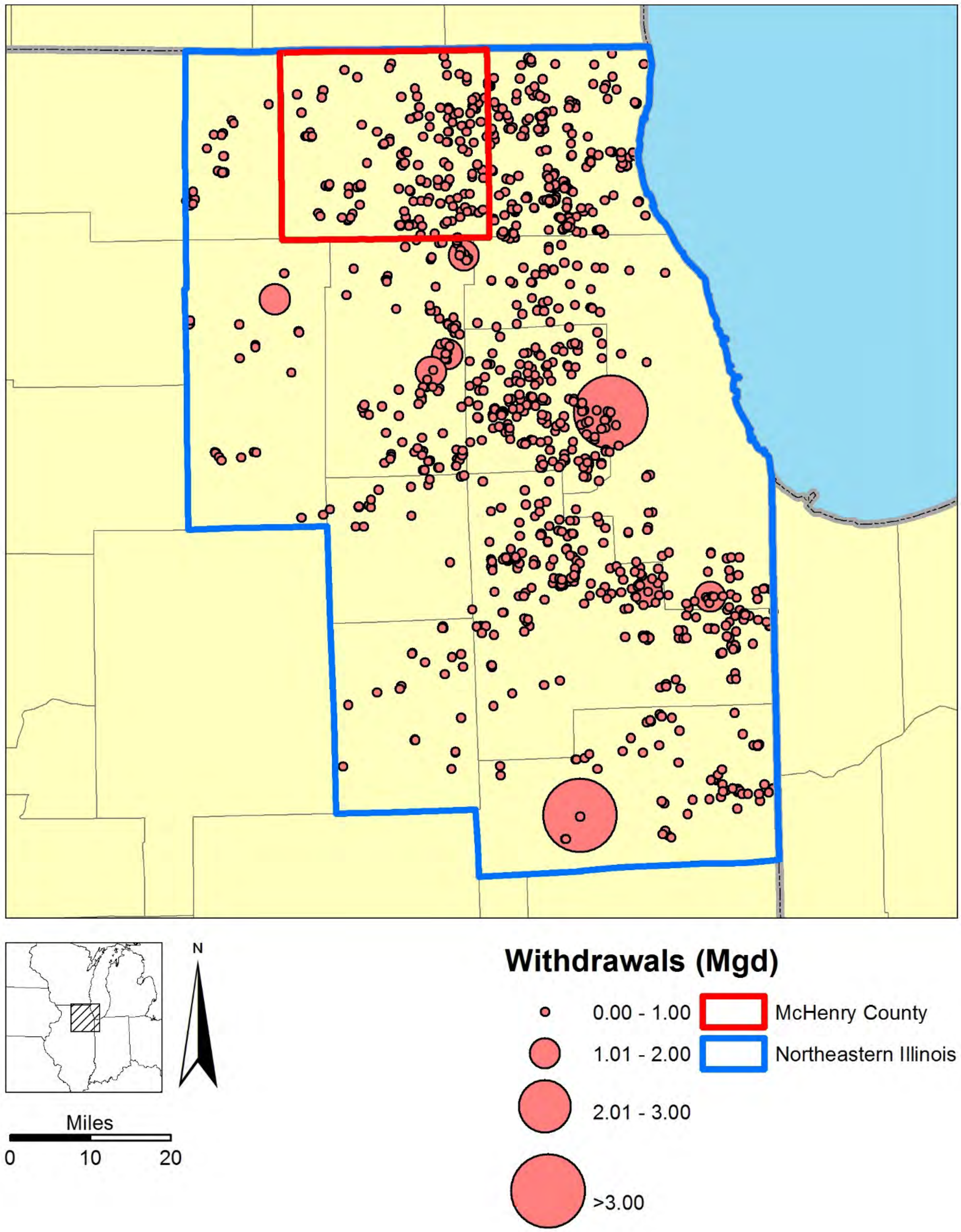

Figure 35 Withdrawals from shallow wells for public supply, self-supplied industrial and commercial facilities, and self-supplied irrigation and agriculture in northeastern Illinois (2009)

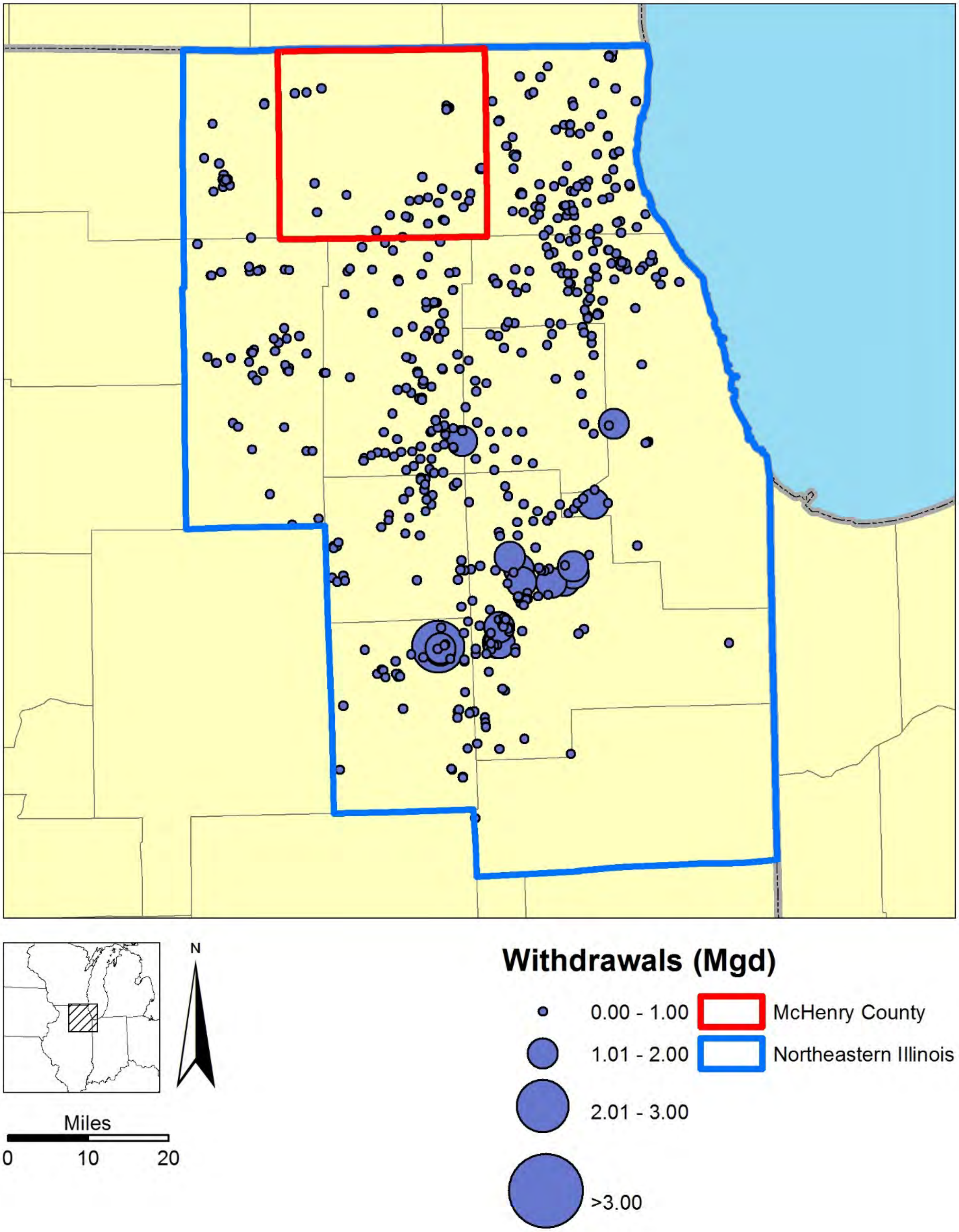

Figure 36 Withdrawals from deep wells for public supply, self-supplied industrial and commercial facilities, and self-supplied irrigation and agriculture in northeastern Illinois (2009)

2.3 Future Withdrawals

In discussing future water use, we use the term *scenarios* for the sets of water withdrawal estimates employed in our analyses (rather than, for example, *predictions* or *projections*) to reflect large uncertainties in estimating future water withdrawals. The scenarios suggest a plausible range of future water withdrawals, but actual future withdrawals may fall outside the range of the scenarios. We examined three scenarios of future withdrawals (Figure 37). The low withdrawal scenario is called the Less Resource Intensive scenario (LRI), and the high withdrawal scenario is called the More Resource Intensive (MRI) scenario. Between these is the Baseline (BL) scenario.

As discussed in Section 4.1.1.3, we developed these estimates from county-level water supply sector estimates computed by Dziegielewski and Chowdhury (2008) for northeastern Illinois and from county-level public supply sector estimates computed by Dziegielewski et al. (2004) for Wisconsin and parts of Illinois within the regional study area, yet not within the 11-county northeastern Illinois region (here termed *downstate Illinois*). Dziegielewski et al. (2004) and Dziegielewski and Chowdhury (2008) did not allocate withdrawals to individual wells, so for purposes of simulation and mapping (Figure 38 and Figure 39), we allocated the adapted county and water supply sector estimates to wells in operation in 2009. Note that the adapted county and water supply sector estimates do not result in increases by a constant proportion from 2010 to 2050. This is because the assumed county and water supply sector withdrawal estimates developed by Dziegielewski et al. (2004) and Dziegielewski and Chowdhury (2008), on which the individual well estimates are based, are themselves based on analysis that does not assume linear rates of change. McHenry County groundwater withdrawals (for the public supply sector, self-supplied commercial and industrial sector, and self-supplied irrigation and agriculture sector) total 67.9, 46.5, and 31.5 Mgd in 2050 under the MRI, BL, and LRI scenarios, respectively (Figure 37).

Distributions of 2030 and 2050 shallow and deep withdrawals within McHenry County, as projected and simulated for this project, are illustrated in Figure 38 and Figure 39. The figures illustrate a key assumption of these projections, this being that the distribution of withdrawal points (both geographic locations and open intervals) remains the same as in 2009, the most recent year for which historical data were available when the projections were developed. Simulation of future withdrawals is discussed further in Section 4.1.1.3.

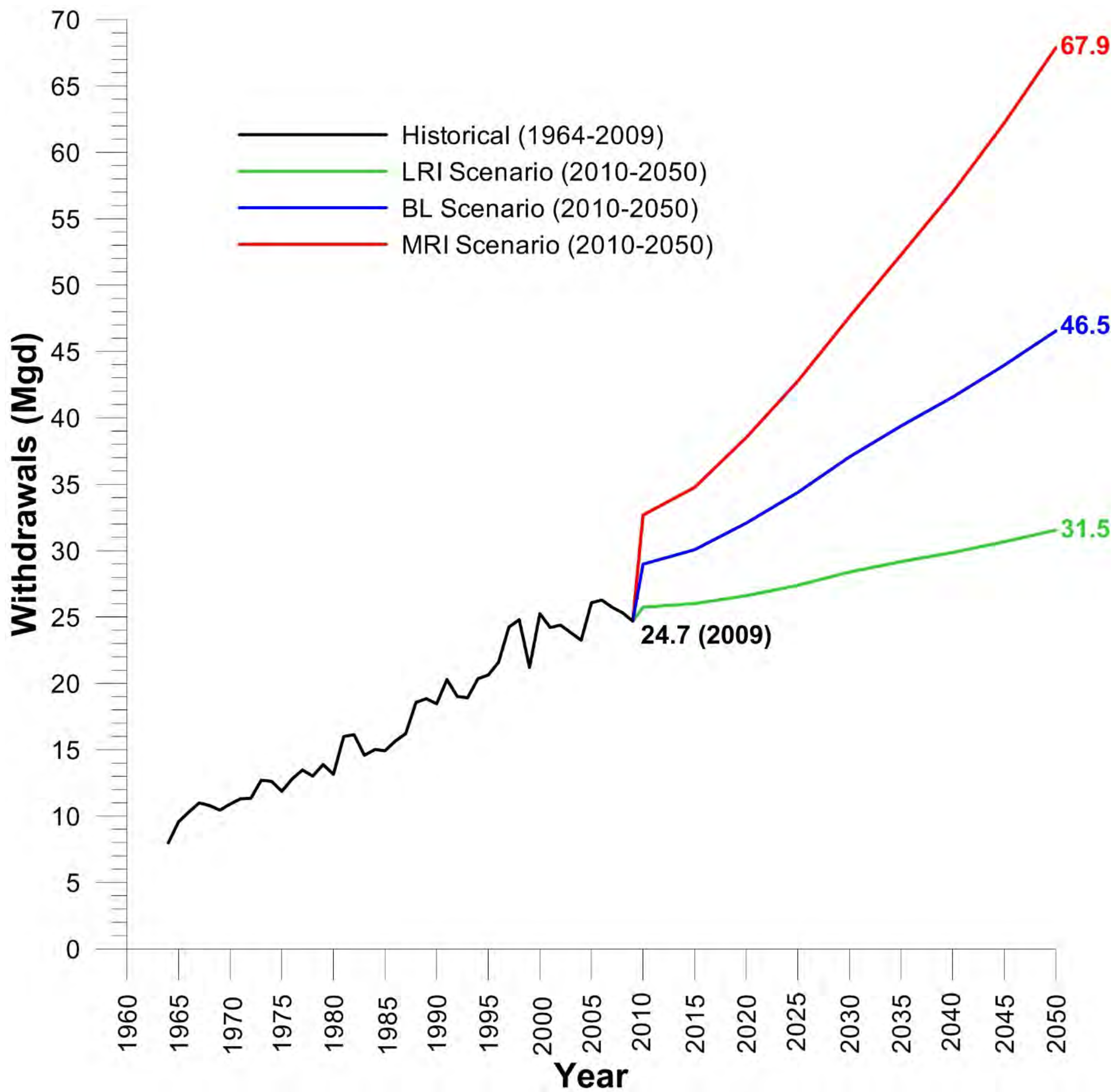

Figure 37 Historical and plausible future withdrawals of groundwater in McHenry County developed from estimates by Dziegielewski and Chowdhury (2008)

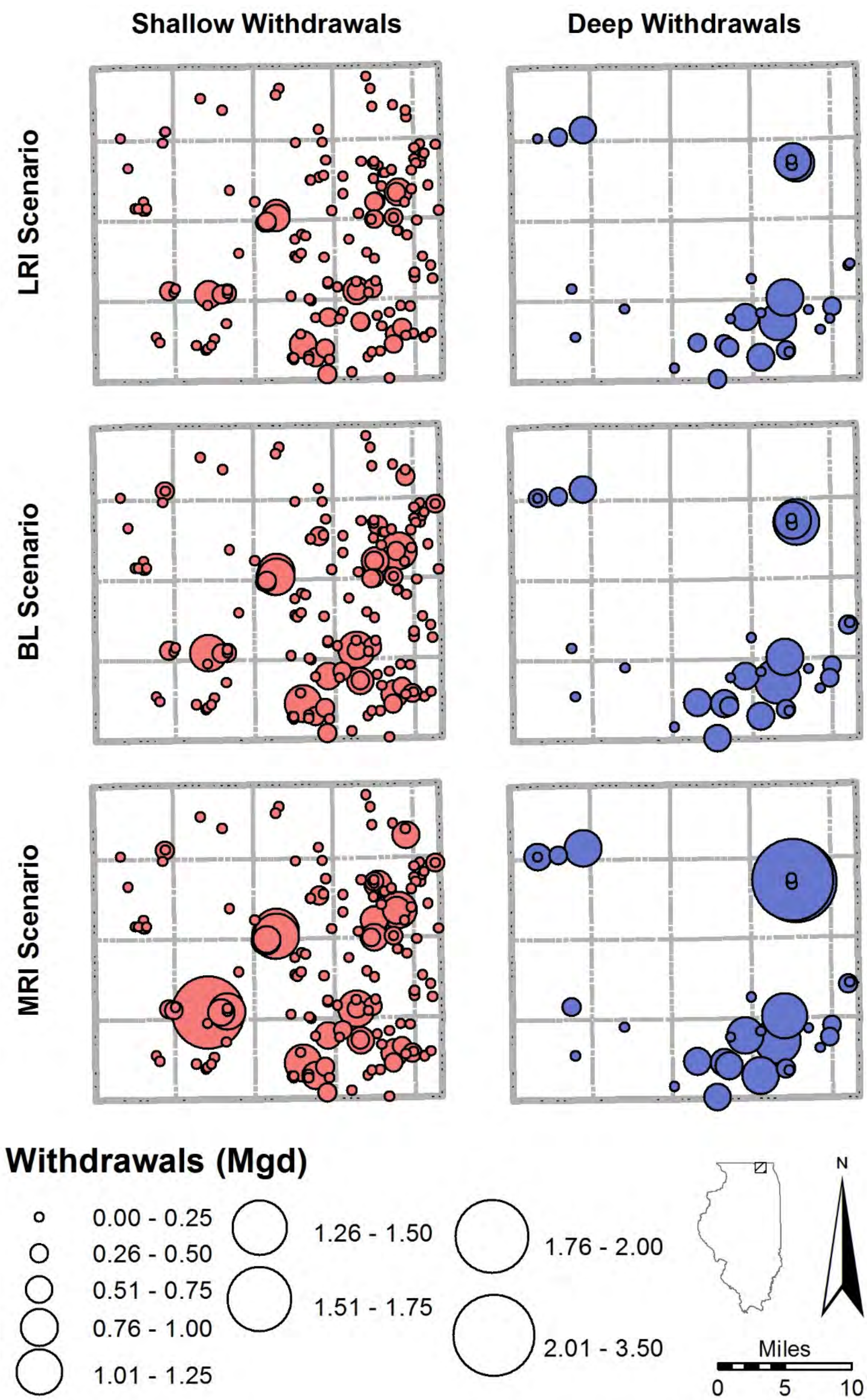

Figure 38 Groundwater withdrawals in McHenry County (2030)

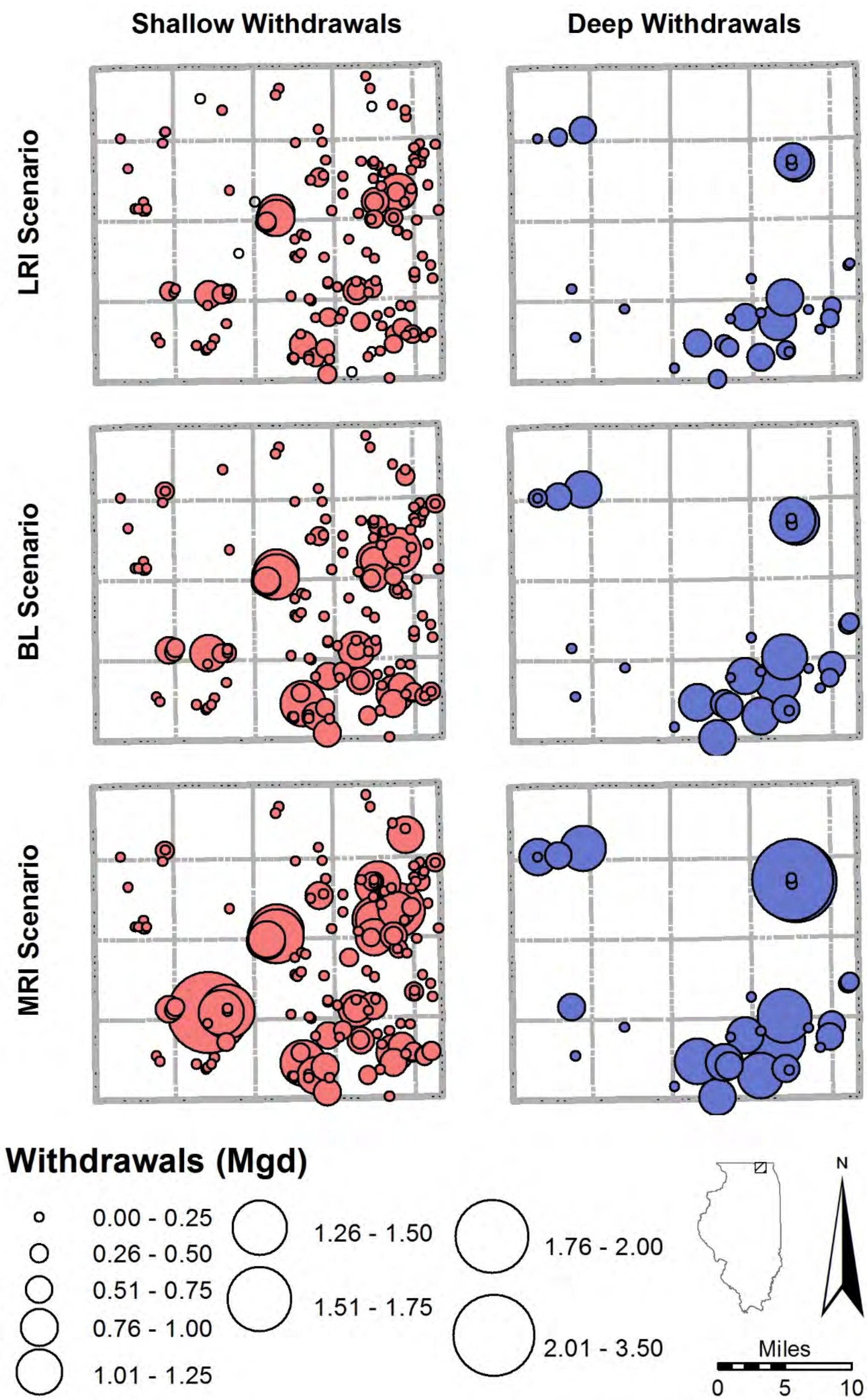

Figure 39 Groundwater withdrawals in McHenry County (2050)

3 Observed Water Levels in Shallow Wells

In 2011, ISWS researchers obtained water levels in 338 shallow wells in McHenry County and adjacent areas. These observed water levels and the potentiometric maps constructed from them have several applications, most notably the following:

- Developing a conceptual understanding of groundwater flow in McHenry County;
- Calibration of future transient groundwater flow models during the 2011 time step; and
- Documentation of water level conditions in 2011 for comparison with past and future water levels in order to measure and evaluate water level changes.

Potentiometric maps were developed for the following units: (1) the Shallow Bedrock Aquifer and overlying, hydrologically connected Lower Glasford Sand Unit; (2) the upper Glasford Sand Unit; (3) the Ashmore Sand Unit; (4) the Yorkville-Batestown Unit; and (5) the Haeger-Beverly Unit.

Potentiometric maps can be constructed for both confined and unconfined aquifers and are sometimes referred to as water level maps or head maps. Head values are represented with equipotentials, contour lines that connect points of equal head (Appendix A). Contour values are expressed as elevations above a datum plane, which, in this report, is mean sea level. This report refers to *hydraulic head* simply as *head*. Assuming at any given point that the resistance to horizontal flow is the same in all directions (referred to as horizontally isotropic), then groundwater flow is perpendicular to the mapped equipotentials.

Potentiometric surfaces of the shallowest aquifers roughly imitate land-surface topography. Nearly all topography, including small hills and valleys, is replicated in the potentiometric surfaces of shallow aquifers, with only minor dampening of the relief. Dampening increases in deeper aquifers, so that only large-scale topographic features are replicated in the potentiometric surfaces of deeply buried aquifers.

Heads rise and fall in response to groundwater withdrawals, recharge, evaporation, and transpiration, and, in the case of confined aquifers, aquifer loading (Freeze and Cherry, 1979). Heads often follow a seasonal cycle that is most noticeable in shallow aquifers and at locations distant from large pumping centers, where pumping effects do not overwhelm natural cycles. Natural declines in heads usually begin in late spring and continue throughout summer and early fall. Heads begin to rise in late fall and peak during the spring, when groundwater recharge from rainfall and snowmelt has its greatest effect (Visocky and Schicht, 1969).

3.1 Methods

3.1.1 Water Level Measurements

Water levels obtained and mapped for this project were measured between May 4 and December 1, 2011. Water levels were measured in 338 wells, but 9 of these measurements were removed from the original dataset because the quality of the data were suspect or because we determined that the source wells were open to minor aquifers, as will be discussed, so a total of 329 measurements were used in mapping potentiometric surfaces (Table 2). The water level measurements originate from three sources: (1) measurements by ISWS staff, (2) measurements by public water system staff that were reported to the ISWS, and (3) measurements from dedicated observation wells in McHenry County and obtained by the ISWS from the USGS

(United States Geological Survey, 2013) (Figure 40, Table 2). A few of these measurements are located immediately outside McHenry County. These are measurements from wells supplying the public water systems of Algonquin and Island Lake, which operate wells in Kane and Lake Counties, respectively.

Water levels were measured in many wells that were used for water level measurement by the ISWS in previously published studies, although the water levels were measured again for the present study. These include water levels measured for (1) groundwater protection studies for McHenry County by Meyer (1998) (water levels measured in 1994), and (2) potentiometric mapping for Kane County by Locke and Meyer (2007) (water levels measured in 2003) (Figure 41). The use of wells employed in previous studies relieved ISWS staff of much of the need to locate additional wells, obtain owner permission for use of these wells, and survey the locations of new wells, since these tasks had already been completed for the wells used in previous studies. Use of previously measured wells also creates a record of water levels at specific locations, useful for assessing changes. In order to develop a set of water level data for the present project, it was necessary to find and obtain permission to use wells that had not been visited in previous ISWS studies.

The goal of the well selection process was to develop a network of regularly spaced wells open to the principal shallow aquifers in McHenry County. Water levels in all public water system wells and in all high capacity self-supplied industrial/commercial and irrigation wells were additionally sought out for this study. These wells were identified using the ISWS Illinois Water Inventory Program (IWIP) database.

3.1.1.1 Water Level Measurements by ISWS Staff

Of the 229 water levels measured by ISWS staff, 189 were obtained from wells used for water level measurements by Meyer (1998) and, in southern McHenry County, by Locke and Meyer (2007), as discussed above and shown in Figure 41. If the well was employed in a previous study, the measurement was typically obtained following a telephone call in which the owner granted permission to use the well in the present study. In other cases, public water system operators were contacted by telephone and asked to report measured water levels to the ISWS or to schedule a visit by ISWS personnel, who then measured the water level. Water levels reported to the ISWS by public systems are discussed further in Section 3.1.1.2.

To fill gaps in the distribution of water level measurements from wells used in previous studies, ISWS staff also obtained water levels from 40 wells that had not been used in previous ISWS studies. These include public water system wells brought into service since the earlier ISWS studies (identified by consultation of the ISWS IWIP database) and wells, mostly used for domestic supply, sought out to fill spatial gaps in the distribution of wells. Copies of well completion reports on file at the ISWS guided the process of locating many wells that had not been previously used in ISWS studies. ISWS staff used the completion reports to identify candidate wells in areas lacking water level data. Where field locations could be matched to locations described in well completion reports, general guidelines were employed for selection of wells for water level measurement. For example, newer wells were favored over older ones, and wells with more comprehensive and detailed completion reports were preferred. Owner permission was obtained before making the water level measurement.

ISWS standard operating procedures were employed for measurement of water levels, and measurements were recorded on a standardized paper water level record. Depth to water in most domestic, commercial, and industrial wells was measured with a disinfected steel measuring tape.

The measuring point (the reference point for depth to water measurements) was, in most cases, the top of the casing after removing the well cap. In other cases, removal of the well cap was not required, and the top of a vent tube, vent hole, or access port was employed as the measuring point. The actual measuring point and its height above land surface were noted on the water level record. All head measurements made with a steel measuring tape were recorded to the nearest 0.01 ft and are likely accurate within ±0.1 ft. Locations of wells not employed in previous studies were surveyed using a Garmin eTrex Legend H GPS having a manufacturer's specified horizontal accuracy of <49 ft.

In public water system wells, ISWS staff attempted to measure the depth to water with a disinfected steel measuring tape inserted through a vent tube or access port, this approach being the most accurate of the available options for measurement. Commonly, however, access for measurement with a steel measuring tape was not available in such wells, so measurement was made with an air line, which is a length of tubing having an open bottom attached to the column pipe in the well. Air lines are typical features of public water system wells. Measurement with an air line is done by displacing water in the tube using compressed air, and reading the air pressure in the tube from a gage open to the tube. The height above the bottom of the air line of an equivalent column of water is then calculated. Measurements of water depth made by air line were recorded to the nearest foot. Accuracy of air line measurements is typically linked to the type of gage used. Typical gages register air pressures up to 100, 200, or 300 pounds per square inch (psi), which equal 230, 460, or 690 ft of water, respectively. Burch (2002) reported gage accuracy within 1 percent in the center of gage range (2.3 and 6.9 ft in 100- and 300-psi gages, respectively) and within 2 percent at full deflection (4.6 and 13.8 ft in 100- and 300-psi gages, respectively). Based on the gage types and water levels encountered, we estimate that most air line measurements obtained for this project are accurate to ±5 ft. Public water system well operators were asked to turn the wells off at least 30 minutes in advance of water level measurement.

3.1.1.2 Water Level Measurement Made by Others and Reported to the ISWS

To conserve costs, ISWS staff contacted public water systems throughout McHenry County to solicit water level data from all shallow wells supplying these systems. Many provided the requested water level data to the ISWS, and a few preferred that ISWS staff visit their systems to collect the requested data (see Section 3.1.1.1). A few systems did not return ISWS calls and e-mails; their wells are not represented in the water level data collected for this project.

The measurement method for these solicited measurements was not universally reported to the ISWS. Of the 51 measurements reported to the ISWS, 41 were reported as having been measured using an air line, the accuracy of which is discussed in Section 3.1.1.1. As discussed in Section 3.1.1.1, we estimate that these measurements are accurate to ±5 ft. One measurement was reported as having been obtained from a pressure transducer, a device that is suspended in the well that measures the pressure of the water column above it. Pressure transducers are manufactured to function under a range of pressures, and accuracy is dependent on the model type. The accuracy of the single measurement reported to us as having been obtained from a pressure transducer is not known. The measurement method employed for the remaining nine measurements was not reported, but, given standard operation methods at public water systems, and the fact that the measurements were reported to us with no decimal places, it is likely that they were obtained using air lines.

Survey data from Meyer (1998) and Locke and Meyer (2007) were used to obtain location coordinates of wells in which the ISWS had previously measured water levels. For wells not previously visited by ISWS staff, coordinates were obtained from the ISWS IWIP database. These coordinates are provided to the ISWS by the Illinois Environmental Protection Agency (IEPA).

3.1.1.3 Water Level Measurements from Dedicated Observation Wells

We obtained 49 water level measurements from dedicated observation wells within McHenry County and documented by the USGS (United States Geological Survey, 2013). Monitoring well data were obtained for a date as near as possible to the median date of ISWS-measured and reported water levels (August 17, 2011), but limited data availability for some wells forced us to employ some measurements from other dates (as early as May 4, 2011). The data documented by the USGS (United States Geological Survey, 2013) include measurements obtained from monitoring wells installed and maintained by the USGS, McHenry County, and the ISGS. Measurements from these wells occur at differing intervals and are obtained by various measurement methods that are not specifically reported. Many of the water levels are high-frequency measurements reported by the USGS (2013) in real time, strongly suggesting that they are obtained by pressure transducer, but others are sporadically collected and are probably obtained using a steel measuring tape or electric dropline.

3.1.2 Aquifer Assignments and Data Validation

Because heads differ vertically within the subsurface, we identified the source aquifer of each well from which we obtained water level measurements Determining the source aquifer is done using screened or open intervals data in well completion records, logs of the wells recorded on well completion records, well depth (either as reported on well completion records or measured in the field), and/or a three-dimensional geological model of the subsurface developed by the ISGS (Thomason and Keefer, 2013). Determining the source aquifer required that we first estimate land surface elevation at each well, thus permitting calculation of elevations of screened and open intervals, elevations of tops and bottoms of geologic units documented in well logs, and well bottom elevation. For wells that were measured by Meyer (1998), we used land surface elevations determined by Meyer (1998) from high-accuracy surveying having an estimated vertical accuracy of ±4 centimeters. For all other wells, we estimated land surface elevation from topographic maps developed by the ISGS from LiDAR data (Illinois State Geological Survey, 2013); these contour maps employ a 2-ft contour interval. LiDAR is a remote-sensing technology that uses a laser to illuminate a target and analyzes the reflected light to determine distance. For topographic mapping, lasers are often mounted on aircraft or satellites.

Table 3 gives counts of water level observations by aquifer. The total number of observations shown in Table 3 exceeds the total number of measurements taken because a single measurement is applicable to more than one aquifer in areas where the thickness of intervening confining units is zero.

3.1.3 Potentiometric Map Development

The 329 measured water level depths used for potentiometric mapping were converted to elevations above mean sea level by subtracting the measured depth from estimated land surface elevation (see Section 3.1.2) corrected for the measuring point offset.

Each of the five potentiometric maps (Figure 42 to Figure 46) was developed by plotting the calculated heads on a base map and then contouring them. The contouring process is one of interpolating heads in areas lying between irregularly spaced head observations. For this project, the potentiometric maps were manually contoured. We manually contoured these maps because experiments with machine contouring of the data showed that machine contouring, while rapid and inexpensive, was unable to readily take into account influences on head distributions such as mapped aquifer connections and hydrologic connections to surface water. Moreover, machine contouring was unable to produce potentiometric surface maps resembling those of Meyer (1998), which were based on many more measurements than were available from 2011. We implicitly assume that the potentiometric surfaces mapped by Meyer (1998) approximate the 2011 potentiometric surfaces, particularly in areas remote from shallow aquifer pumping, even though the water levels measured for each project differ. Manual contouring of the 2011 data thus permitted us to consider the potentiometric surfaces mapped from the 1994 data, as well as the influences of connections with streams and between aquifers. Areas of aquifer desaturation in the Yorkville-Batestown Unit (Figure 45) and Haeger-Beverly Unit (Figure 46) were estimated through comparison of observed water levels with aquifer bottom elevations provided by the ISGS and discussed by Thomason and Keefer (2013).

3.1.4 Discussion of Potentiometric Maps

The potentiometric surface maps (Figure 42 to Figure 46) show heads in five widely distributed shallow aquifers in McHenry County. Because groundwater flows down gradient from high head to low head, these maps indicate directions and patterns of groundwater movement in the aquifers. In map view, groundwater flow is perpendicular to the equipotentials on a potentiometric surface map of the aquifer. Figure 42 to Figure 46 show that topography and hydrostratigraphy, particularly the locations of aquifer connections, are important influences on shallow groundwater flow in McHenry County. The potentiometric surfaces also reflect groundwater withdrawals, hydraulic conductivity, and aquifer thickness.

In general, topography is replicated in the potentiometric surfaces of the aquifers, the degree of replication decreasing with depth. Identifying groundwater flow divides in the shallow aquifers is problematic owing to numerous aquifer pinchouts, aquifer connections, and, in the Haeger-Beverly Unit (Figure 46), desaturated areas. However, the potentiometric surface map of the Shallow Bedrock Aquifer and Lower Glasford Unit (Figure 42), which is continuously distributed across the county, permits approximate mapping of a groundwater flow divide between groundwater discharge to the Kishwaukee and Fox River watersheds, with some areas of groundwater capture by pumping wells. The divide roughly coincides with the surface drainage divide between the Fox and Kishwaukee Rivers but is deflected in some localities, such as in central McHenry County, around cones of depression that have developed around pumping wells. For example, in central McHenry County, the groundwater flow divide is likely deflected from its predevelopment position by pumping from Woodstock public supply wells.

Aquifer connections equalize heads in the area of connection and strongly influence heads in areas where the aquifers are separated by confining layers, so that, in general, head distributions of all the shallow aquifers roughly coincide, with the greatest departures occurring in areas with laterally persistent confining layers and at greater distances from aquifer connections. Connections with surface water likewise strongly influence heads in all of the shallow aquifers. Where aquifers are in hydrologic connection with surface water, such as where a perennial stream flows directly over an aquifer, heads in the aquifer coincide with surface water elevation; this is likely true due to the low resistance to flow of the sandy substrate that defines the surface-groundwater interface.

Aquifer thickness and hydraulic conductivity can influence potentiometric surfaces, but these influences are less obvious than those of topography and aquifer connections. The product of thickness and hydraulic conductivity is termed *transmissivity*, a property that is analogous to the diameter of a pipe—that is, the greater the transmissivity, the greater the capacity of an aquifer to transmit groundwater. High transmissivity favors low hydraulic gradients, which are discernible on a potentiometric surface map as widely spaced equipotentials. Thus, lateral variation in hydraulic gradients within an aquifer may reflect variation in aquifer transmissivity and, by extension, variation in aquifer thickness and/or hydraulic conductivity. Still, variation in hydraulic gradients may reflect other influences, such as topography, lateral variation in aquifer recharge rates, proximity to pumping, and proximity to locations of natural groundwater discharge. Moreover, our understanding of lateral variation in transmissivity of the shallow aquifers of McHenry County is imprecise, and correlation of areas of relatively low or high hydraulic gradient with areas of high or low transmissivity would be highly speculative.

Topography, as well as aquifer thickness, influences the distribution of the desaturated areas of the Haeger-Beverly Unit (Figure 46). Most of the areas where the Haeger-Beverly Unit is desaturated are in locations of dissected topography or in elevated areas adjacent to steep slopes, where any water entering the unit from above can readily drain out.

Recharge and discharge areas cannot be precisely delineated using the maps constructed for this project. Still, the maps, together with the occurrences of perennial surface water, suggest the locations of discharge areas, and recharge areas can reasonably be assumed to include all areas between discharge areas. Locations of recharge and discharge areas are strongly influenced by topography and hydrostratigraphic connections. The Haeger-Beverly Unit is shallow and unconfined throughout most of its distribution in McHenry County, and measured heads in the unit coincide closely with elevations of perennial surface waters. The unit probably discharges groundwater to most perennial surface waters throughout its distribution, except where it is completely desaturated. Much of the groundwater discharged through the Haeger-Beverly Unit is groundwater that moved into the unit from the Yorkville-Batestown Unit, Ashmore Unit, Upper Glasford Sand Unit, Lower Glasford Sand Unit, and Shallow Bedrock Aquifer through connections or by slower movement across aquitards. The same is generally true of the Yorkville-Batestown Unit. Potentiometric surface mapping (Figure 45) suggests that significant discharge from the Yorkville-Batestown Unit occurs through seeps and springs at the base of steep hydraulic gradients in T 44 N, R 8 E.

Given the relatively low density of data points and the 10-ft contour interval employed in constructing the potentiometric surface maps, the shallow cones of depression around domestic and other low-capacity wells are not resolvable. The discrepancy in water levels between some high-capacity wells (i.e., wells pumping greater than 100,000 gallons per day) and the nearest low-capacity wells, and with historical water levels, does, however, suggest the presence of mappable cones of depression surrounding at least a few high-capacity wells. These cones of depression are included in head maps of the Lower Glasford Sand and Shallow Bedrock Aquifer (Figure 42) and Ashmore Unit (Figure 44) as closed equipotentials and nearly closed loops of equipotentials in central McHenry County, north of Woodstock, and in southeastern McHenry County. Their geometries are speculative, however, because no observations exist to support more accurate rendering of these features. Cones of depression are not included in the other potentiometric surface maps largely because too few water level measurements exist to support their mapping.

3.1.4.1 Effect of Temporal Head Variability

Most head mapping studies rely on synoptic measurement of water levels (that is, water level measurements are collected in as brief a time span as possible) [e.g., Meyer (1998); Locke and Meyer (2007)], but this study did not. Synoptic mapping typically requires two phases of effort, each phase requiring a field visit to the wells in the network. Site visits during the first phase, the inventory phase, are conducted for purposes of well network development and documentation. Work tasks include obtaining owner permission for use of the well, inspecting the well to establish its suitability for water level measurement, possibly taking a preliminary water level measurement, and surveying the well location. The inventory phase of the head mapping study conducted in the Kane County area described by Locke and Meyer (2007), which resulted in development of a network of 1010 wells, lasted about 17 months. During the second phase of effort, the synoptic phase, site visits are focused on a single work task: obtaining a water level measurement as efficiently as possible. During the synoptic phase of the Kane County mapping study, water levels were measured in all wells of the 1010-well network in about six weeks. The reasoning behind measuring heads synoptically is to reduce map uncertainty resulting from constantly fluctuating water levels; however, synoptic studies can be expensive owing to the significant man-hours required to make repeat visits to numerous wells and to measure water levels as quickly as possible during the synoptic measurement phase.

To reduce costs, the present study did not rely on synoptic measurement of water levels but instead relied on measurements obtained over a period of 210 days, from May 4, 2011 to November 30, 2011. For this study, the water level measurement used for head mapping was obtained during the same site visit when owner permission was obtained, surveying conducted, etc. That is, wells were only visited a single time.

Thus, the maps developed from these measurements have an associated uncertainty owing to water level fluctuation during the period of measurement, which the authors refer to as temporal variability. The temporal variability of the shallow aquifer heads during this period is inferred from continuously collected head data from McHenry County's dedicated observation well network (United States Geological Survey, 2013). In 27 of these wells for which data are available, the temporal variability during the measurement period ranged from 1.6 to 14.7 ft, with a 25 percent trimmed mean of 3.4. The 25 percent trimmed mean is an outlier-resistant measure of centrality of these ranges that achieves its resistance by eliminating the upper and lower 25 percent of values from the computation of the mean (Helsel and Hirsch, 2002). The 75th percentile (4.6 ft) and 25th percentile (2.4 ft) values suggest that there is a 50 percent probability that the measured value differs from the value that would be measured on any other day by 2.4 to 4.6 ft.

3.1.4.2 Head Change, 1994–2011

Long-term change in head can arise through changes in pumping rates and distribution, climate, land use, land cover, and other factors. A goal of groundwater planning is typically to minimize head reductions, since such reductions can reduce well yield, cause water supply interruptions, and reduce natural groundwater discharge (thereby reducing base flow in streams and water levels in lakes and wetlands). We compared water levels in 1994 and discussed by Meyer (1998) with those measured in the same wells, for this project, in 2011, to quantify the change in water level. To eliminate uncertainty associated with varying measurement methods, we limited the comparison to only those wells in which water levels were measured with a steel measuring tape by ISWS staff.

The median 1994–2011 water level change in these 161 wells was +2.0 ft. This suggests that changes in the factors mentioned above have not resulted in a countywide decline in shallow aquifer heads despite an approximate 4 Mgd increase in countywide shallow aquifer pumping, from 14 to 18 Mgd and, in fact, are coincident with a rise in groundwater levels. It is notable that

2011 was a wetter year than 1994, with precipitation at Marengo totaling 33.56 inches in 1994 and 38.74 inches in 2011 (Illinois State Water Survey, 2013). These results suggest that the 4 Mgd increase in shallow groundwater withdrawals was less important than precipitation variability in influencing shallow groundwater levels in McHenry County between 1994 and 2011.

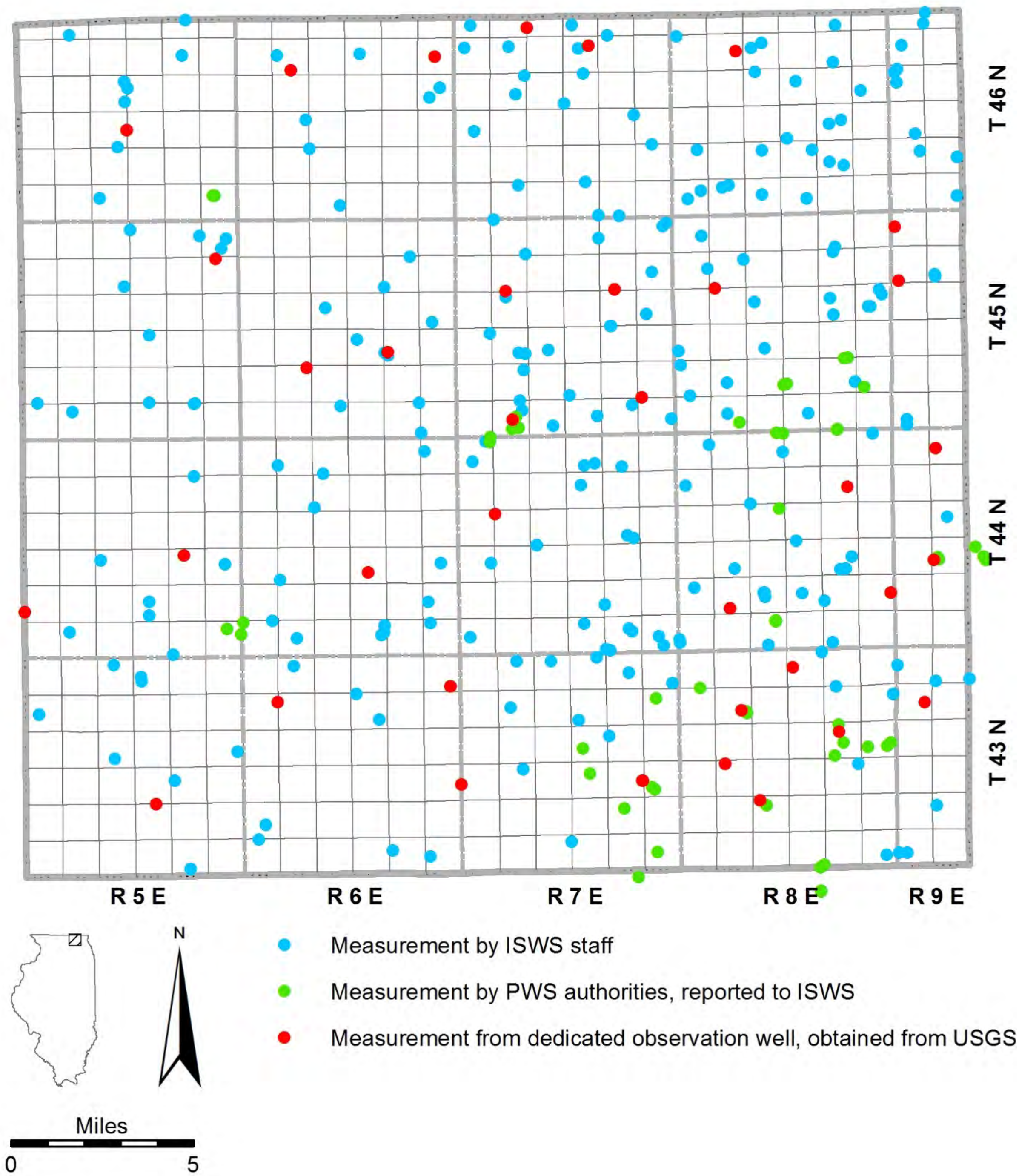

Figure 40 Water level measurements obtained in 2011 and retained for potentiometric surface mapping, colored to show source of measurement

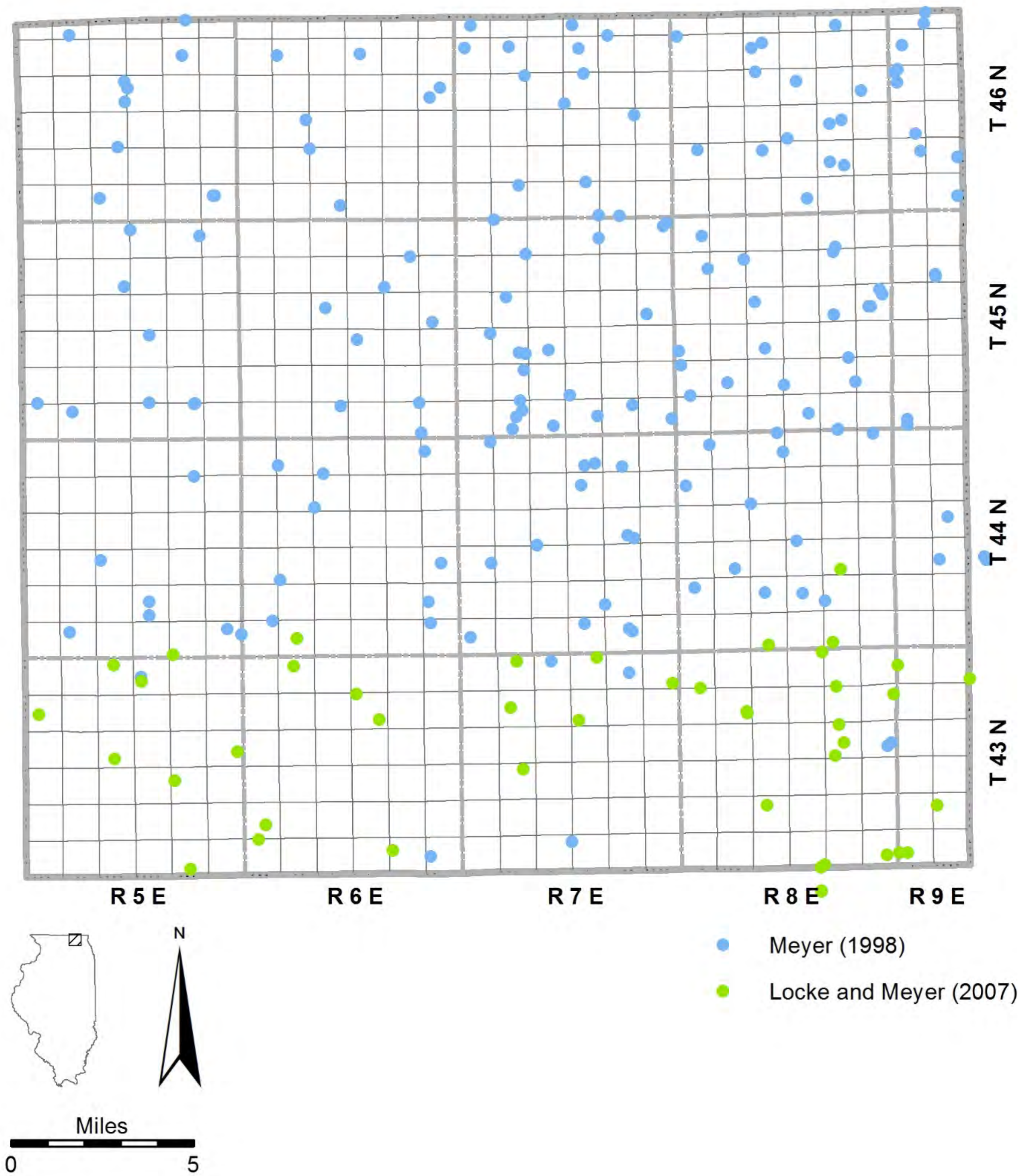

Figure 41 Water level measurements obtained in 2011 that were obtained from wells used in previous ISWS potentiometric mapping

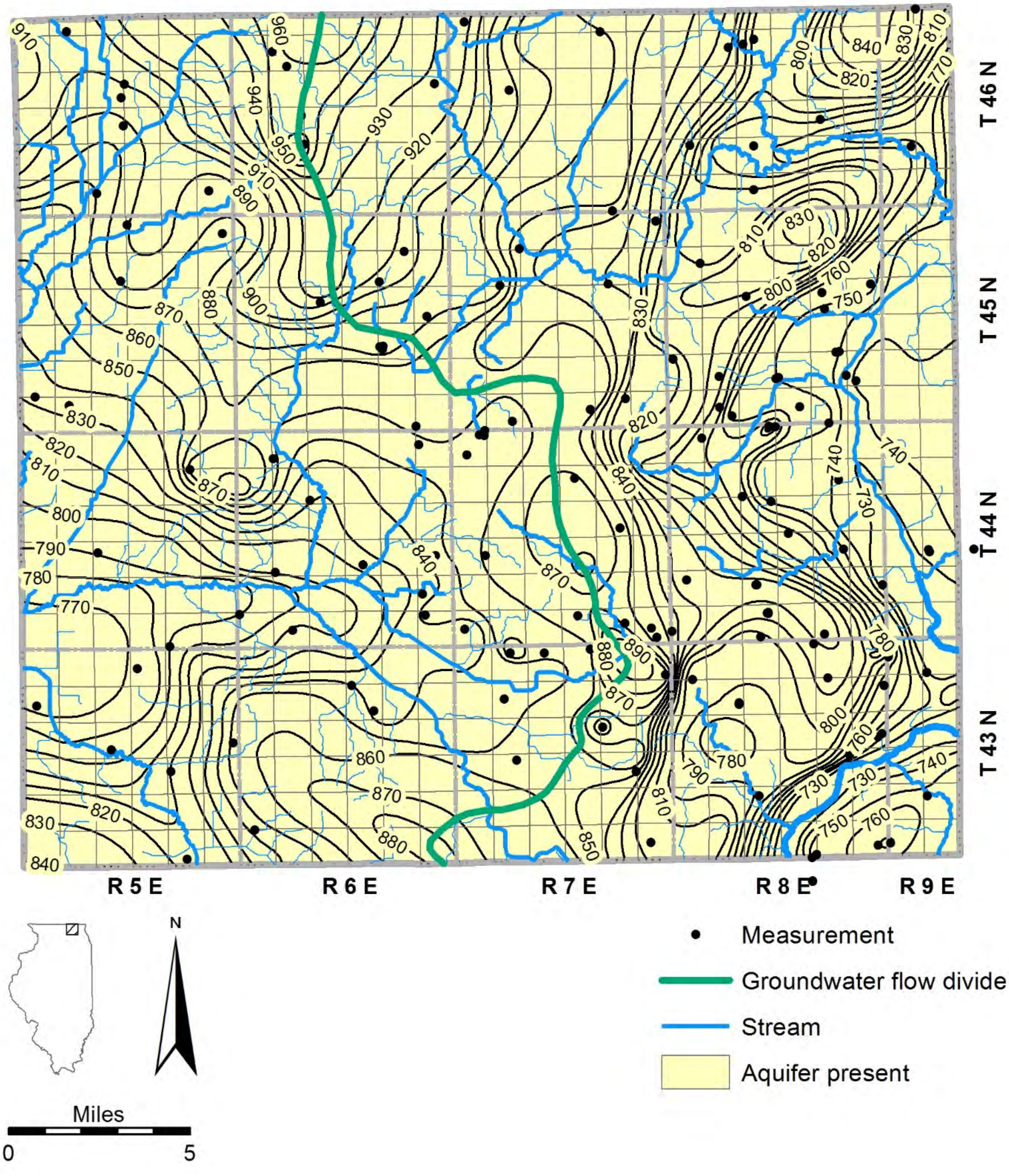

Figure 42 Potentiometric surface of Shallow Bedrock Aquifer and Lower Glasford Sand Unit (2011)

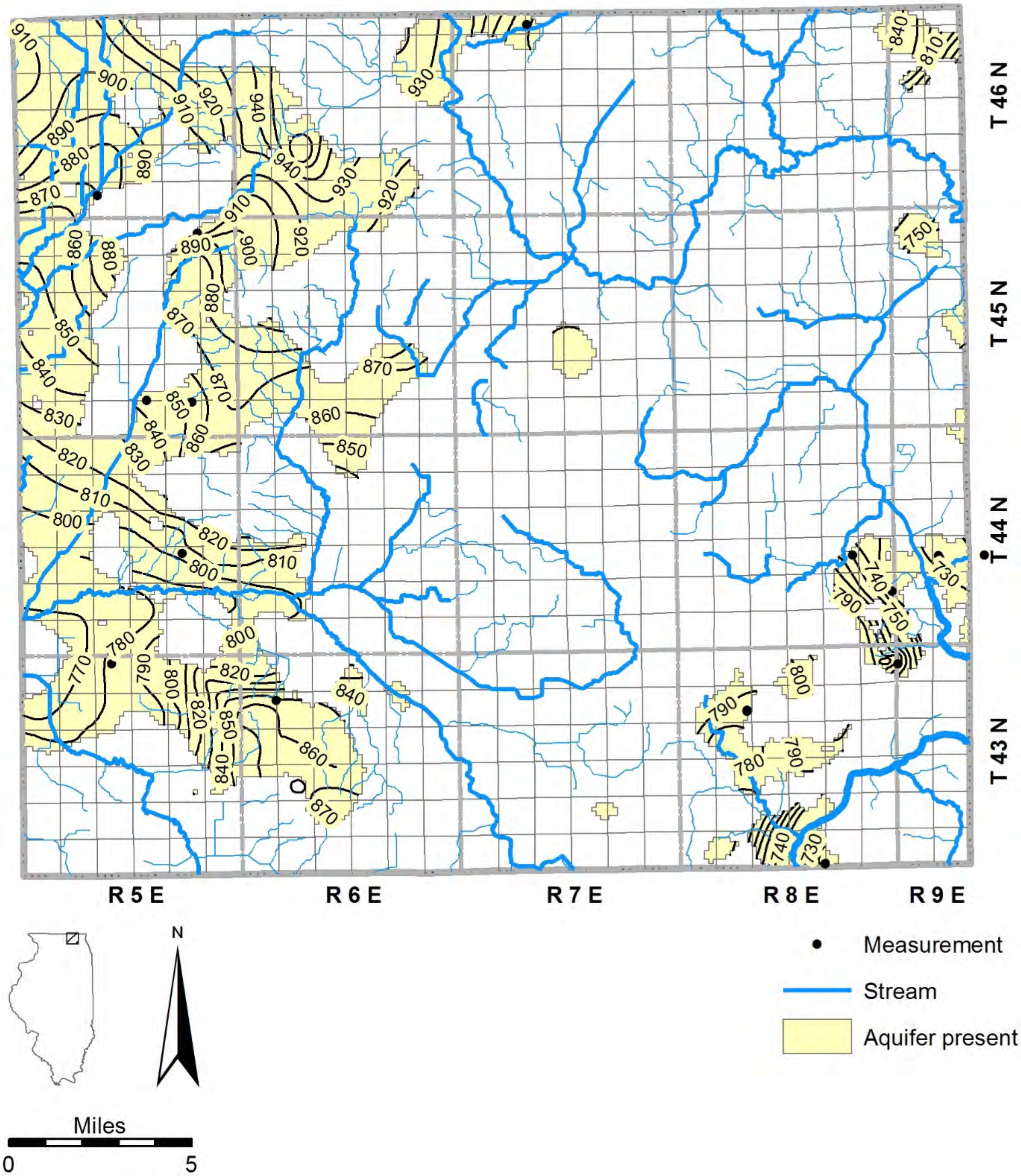

Figure 43 Potentiometric surface of Upper Glasford Sand Unit (2011)

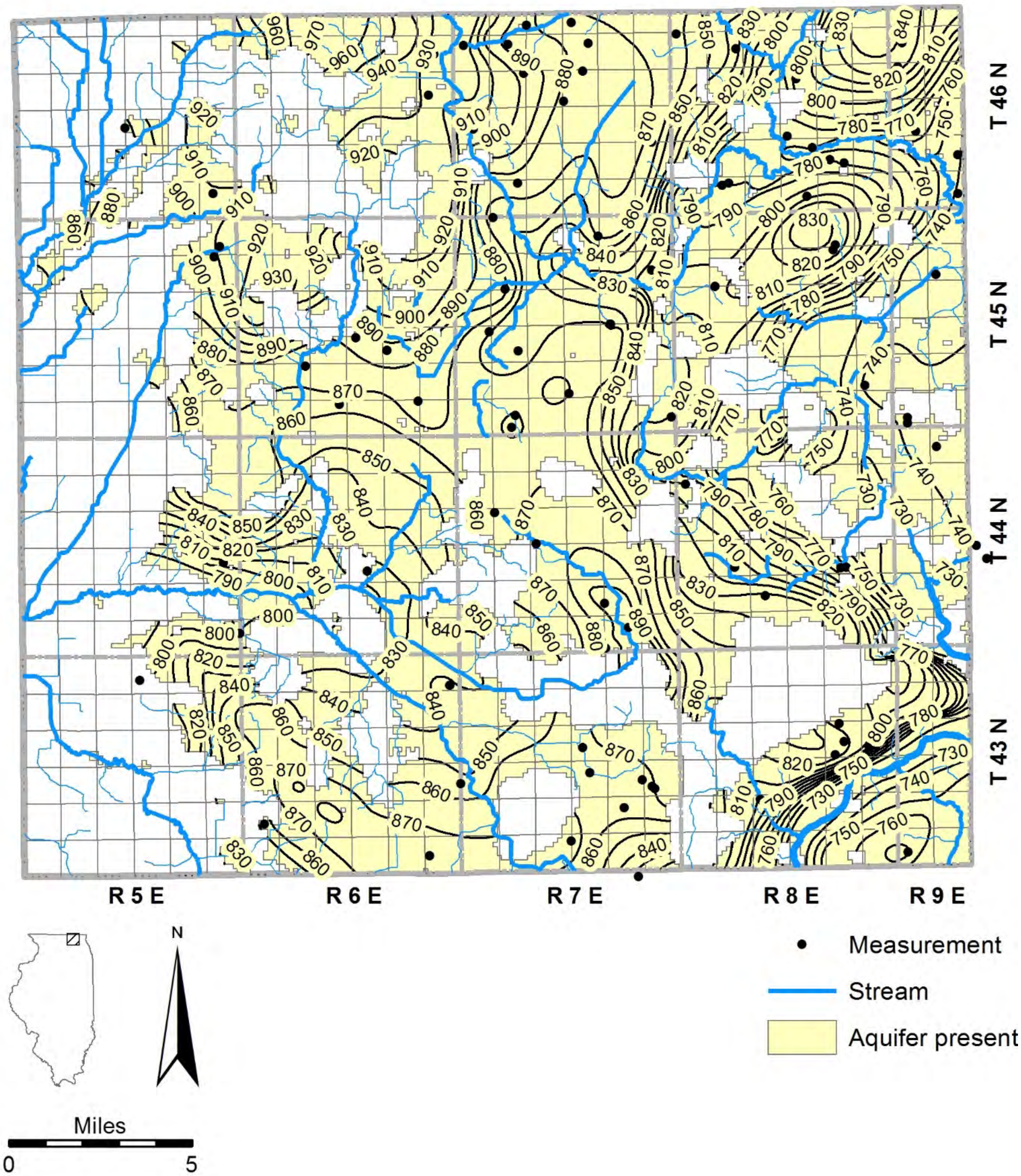

Figure 44 Potentiometric surface of Ashmore Sand Unit (2011)

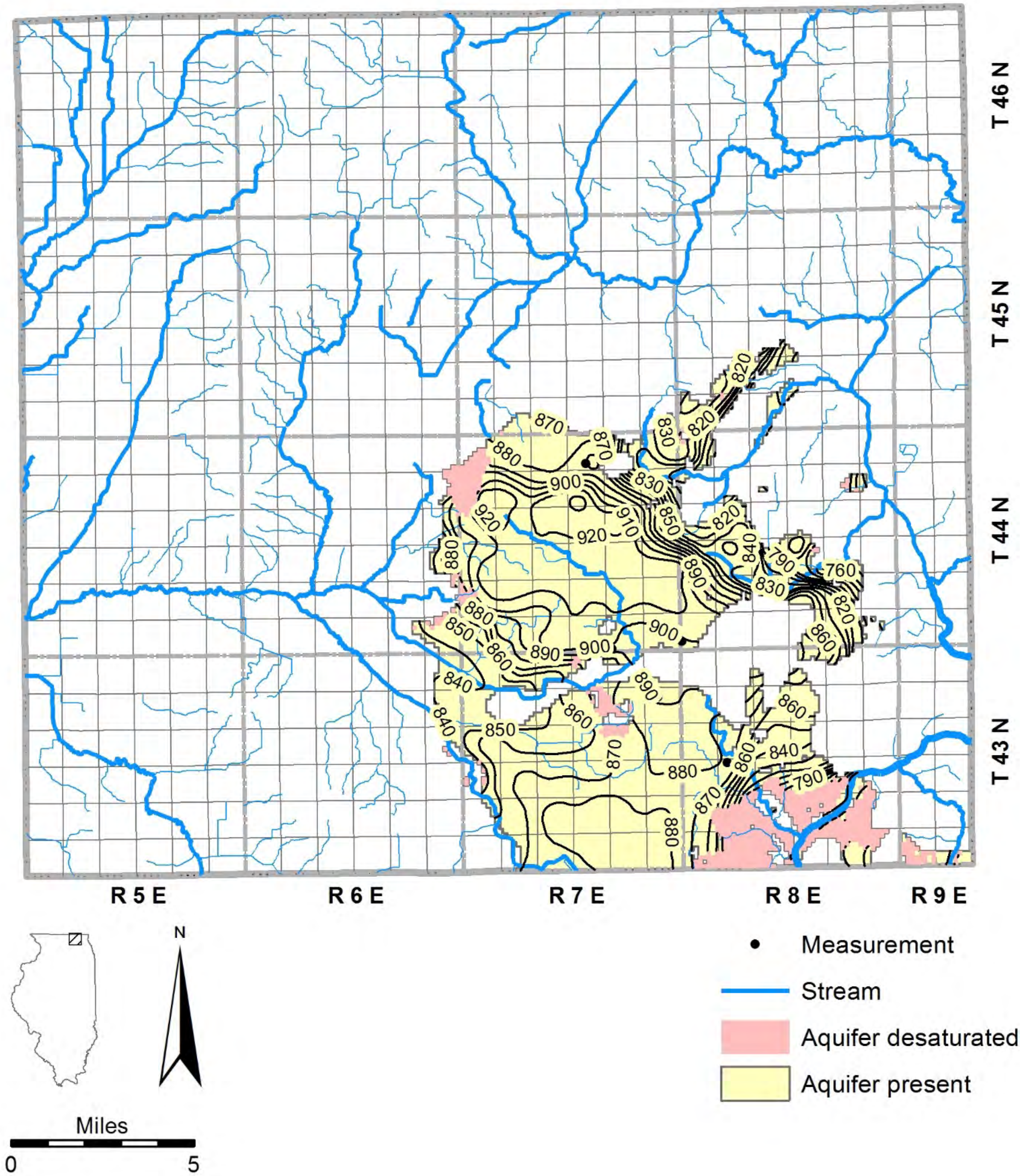

Figure 45 Potentiometric surface of Yorkville-Batestown Unit (2011)

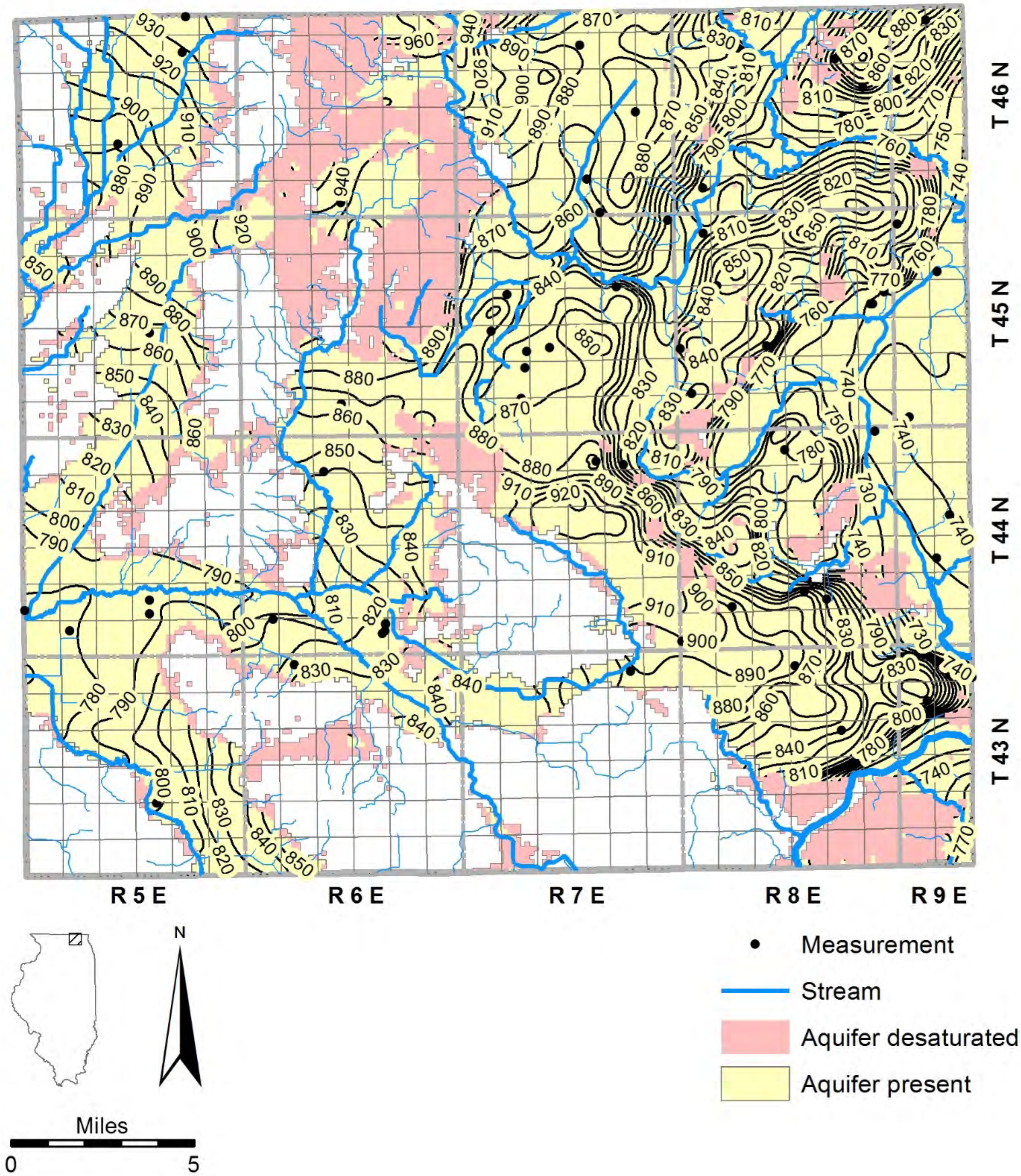

Figure 46 Potentiometric surface of Haeger-Beverly Unit (2011)

Table 2 Water Level Measurements by Data Source

Source	*Total Measurements*	*Measurements Rejected for Data Quality Considerations*	*Measurements Retained for Mapping and Reporting*
Measurement by ISWS staff	234	8	226
Measurement by public water system authorities and reported to ISWS	52	0	52
Measurement from dedicated observation well, obtained from USGS	52	1	51
TOTAL	338	9	329

Table 3 Water Level Measurements Used for Potentiometric Surface Mapping, by Aquifer

Aquifer(s)	***Number of measurements***
Haeger-Beverly Unit	71
Yorkville-Batestown Unit	8
Ashmore Unit	101
Upper Glasford Sand Unit	19
Lower Glasford Sand Unit	107
Shallow Bedrock Aquifer	147

4 Simulation of Groundwater Flow in McHenry County

4.1 Introduction

This section discusses results from computer-based simulations (modeling) of groundwater flow in multiple aquifers in McHenry County as well as in the northeastern Illinois water supply planning region. A three-year program for comprehensive regional water supply planning and management in Illinois was initiated in 2007 under direction of Executive Order 2006-01. Under the framework of the order, the Illinois Department of Natural Resources' Office of Water Resources (IDNR-OWR), in coordination with the ISWS, selected two priority water quantity planning areas for pilot planning: a 15-county area in east-central Illinois and an 11-county area in northeastern Illinois. Meyer et al. (2012) published a report focused on the technical studies in support of water supply planning in the northeastern Illinois region, which includes Boone, Cook, De Kalb, Du Page, Grundy, Kane, Kankakee, Kendall, Lake, McHenry, and Will Counties. This study highlights opportunities and challenges of meeting water demand in the region. The regional groundwater flow model developed for northeastern Illinois by Meyer et al. (2012) formed the principal basis of a model for this planning study for McHenry County, which was developed by revising and recalibrating the northeastern Illinois model. This section discusses the development, application, and results of simulations using this revised computer model to evaluate the impacts from historical and possible future groundwater pumping scenarios. As background for readers unfamiliar with groundwater, Appendix A introduces basic groundwater terminology and concepts. Supplemental information on the groundwater flow modeling developed for this report, including updates to the model and model output, is available at http://www.isws.illinois.edu/docs/pubs/iswscr2013-06/.

Groundwater sources available to McHenry County, discussed in Section 1.5, include the deep aquifers—layers consisting principally of sandstone that are, for purposes of this study, referred to as the Ancell Unit, Ironton-Galesville Unit, and Mt. Simon Unit—and the shallow aquifers, which include the uppermost bedrock and unconsolidated sand and gravel aquifers contained within the overlying Quaternary materials. In McHenry County, the Mt. Simon Unit is used far less than the Ancell and Ironton-Galesville Units because of the expense of drilling to it and because deeper portions of the Mt. Simon contain water that is too salty for most uses. The shallow aquifers include the Shallow Bedrock Aquifer (a layer of weathered dolomite encompassing about the uppermost 25 to 125 ft of bedrock), and five unconsolidated sand and gravel units (Figure 6).

The shallow and deep aquifers are separated by laterally extensive, relatively impermeable aquitards underlying the Shallow Bedrock Aquifer. As mentioned earlier, the terms shallow and deep are extended to other parts of the regional model domain despite the fact that they do not necessarily accurately describe the positions of the materials in these areas. For example, in southern Wisconsin and in Illinois southwest of the Sandwich Fault, rocks above the Ancell formation have been removed by erosion, but the authors still refer to the Ancell and underlying aquifers as "deep aquifers" despite their shallow position.

4.1.1 Groundwater Flow Model

Groundwater withdrawals can change water levels and flow rates in multiple geologic formations, impacting both the availability of groundwater from different aquifers and the relationship between groundwater and surface waters. To develop a quantitative understanding of the impacts of historic and future pumping scenarios, a computer model of groundwater flow, which is a set of interrelated mathematical equations that represent aquifers, wells, and streams, was created for the McHenry County area. Because of the complex hydrogeology of McHenry County, the model developed for this study utilized the finite-difference method, a mathematical technique which divides the aquifer into a grid of blocks to solve the equations representing groundwater flow through porous media.

The finite-difference groundwater flow model used in this study is MODFLOW-2000, a computer code developed by the USGS (Harbaugh et al., 2000). MODFLOW reads data files describing the area of interest, sets up the equations representing groundwater flow, pumping, and the interactions of groundwater and surface water, and solves for the estimated hydraulic head and flow. MODFLOW can simulate steady-state conditions in which hydraulic head and groundwater flow are at equilibrium; such a steady state model assumes that withdrawal rates, river levels, recharge, and other groundwater stresses do not change with time. MODFLOW can also simulate transient conditions, where heads and fluxes change with time as they adjust to changes in withdrawal rates, recharge, river levels, etc. If stresses do not change, steady-state conditions will eventually be reached as a new equilibrium is reestablished.

So that the model accurately reflects existing research on hydrogeological conditions within the model domain, data employed to characterize layer elevations, parameters, and boundary conditions are based to the extent possible on a wide range of published and unpublished observations. Parameters such as hydraulic conductivity and recharge rates are specified on a spatially zoned basis. Detailed information regarding boundary conditions, parameters and other model specifications are available at http://www.isws.illinois.edu/docs/pubs/iswscr2013-06/.

The groundwater flow model simulates all major current and historic groundwater withdrawals in McHenry County and the surrounding areas which could plausibly influence groundwater flow in northeastern Illinois. Flows into and out of major surface-water features are represented using two MODFLOW sink packages (river and drain). The primary difference between the river and drain packages is that the former can freely discharge or recharge water from/to the aquifer, while the latter can only discharge water from the aquifer. Hence, drain cells are used to simulate agricultural and urban drainage systems as well as low order streams that may in reality go dry during portions of the year, while river cells are used to simulate larger streams that may gain or lose water. Drain cells are also used to represent low- permeability till present throughout McHenry County, preventing groundwater from rising above the surface in MODFLOW.

4.1.1.1 Resolution

The groundwater flow model used in this study was developed by revising the 22-layer regional model developed for northeastern Illinois (Meyer et al., 2012) to 26 layers to accept a more detailed 9-layer representation of the Quaternary deposits within a polygonal area surrounding McHenry County (Figure 47, Figure 48). The resulting 26-layer model simulates groundwater flow in all geological materials from land surface down to the crystalline Precambrian basement. This includes both the shallow and deep aquifers in a large portion of Illinois, Indiana, Michigan, Wisconsin, and Lake Michigan. The model employs a variable resolution grid, its highest resolution within a rectangular nearfield covering all of McHenry County, where square cells have horizontal dimensions of 625 ft (Figure 49). This model is most accurate and precise within the detailed nearfield region. The extent of the model permits simulating distant influences on flow in the deep aquifers, including the pumping and recharge in Wisconsin and discharge to the Illinois River near La Salle. The Quaternary deposits (the unconsolidated deposits above bedrock) are most accurately represented within the McHenry County geologic mapping domain (Figure 48).

Model layers represent major hydrostratigraphic units in McHenry County, but representation of the Quaternary materials differs between the McHenry County geologic mapping domain and other areas. Hydrostratigraphic units in northeastern Illinois and in the McHenry County geologic mapping domain are described in Section 1.5, and the model layers representing these units are shown in Figure 47. In some cases, more than one model layer is employed to represent a single hydrostratigraphic unit to more accurately represent hydraulic variability within a unit, if necessary, and to provide for future refinement of the model. With the exception of the Quaternary materials, in instances wherein a hydrostratigraphic unit is represented by more than one model layer, the thickness of each model layer is 1/x of the thickness of the hydrostratigraphic unit, where x is the number of model layers used to represent the hydrostratigraphic unit. Outside the McHenry County geologic mapping domain, the thickness of each of the nine layers devoted to the Quaternary is, likewise, 1/9 of the total thickness of the Quaternary materials. Within the McHenry County geologic mapping domain, nine individual Quaternary hydrostratigraphic units were mapped for this project by the ISGS, and mapped thicknesses were employed for model layers representing each of these units (Jason Thomason, IGSG, personal communication, 2011).

The hydrogeological framework of the groundwater flow model (that is, the hydrogeological model consisting of estimates of top and bottom elevation for each of the 26 model layers for each model cell) was developed from a wide variety of published and unpublished sources. For bedrock units (model layers 10-26) and for the Quaternary materials outside of the McHenry County geologic mapping domain, sources and processing techniques are discussed by Meyer et al. (2012), except that the Quaternary materials for the present study were divided into nine layers as opposed to the five discussed by Meyer et al. (2012). For areas within the McHenry County geologic mapping domain, the elevations and geometries of the bedrock surface and overlying Quaternary deposits were developed from a hydrogeological model by Thomason and Keefer (2013). Their detailed model features complex boundaries between hydrogeological units that result in numerical instabilities in MODFLOW. To achieve a more stable and accurate regional flow solution, a smooth boundary between such units was assigned to the model.

All sink cells in McHenry County were placed into the upper layer of the model with a thickness of no greater than 3 ft. Since some streams intercept deeper hydrostratigraphic layers (i.e. the Haeger Beverly or Ashmore Units), the overlying units that are not present are assigned a conductivity of the first unit that is present and moved directly beneath the sink cell, preserving the proper hydrogeologic representation in the model while allowing for a more realistic representation of the river and drainage network.

		HYDROSTRATIGRAPHIC UNIT	MODEL LAYER
QUATERNARY MATERIALS	SHALLOW UNITS	Wadsworth Unit	1
		Haeger-Beverly Unit	2
		Yorkville-Batestown Unit	3
		Tiskilwa Unit	4
		Ashmore Unit	5
		Winnebago-Upper Glasford Unit	6
		Upper Glasford Sand Unit	7
		Lower Glasford Unit	8
		Lower Glasford Sand Unit	9
BEDROCK		Upper Bedrock Unit	10
		Silurian-Devonian Carbonate Unit	11
			12
			13
		Maquoketa Unit	14
			15
		Galena-Platteville Unit	16
			17
	DEEP UNITS	Ancell Unit	18
		Prairie du Chien-Eminence Unit	19
		Potosi-Franconia Unit	20
		Ironton-Galesville Unit	21
		Eau Claire Unit	22
		Mt. Simon Unit	23
			24
			25
			26

Figure 47 Layer scheme of groundwater flow model

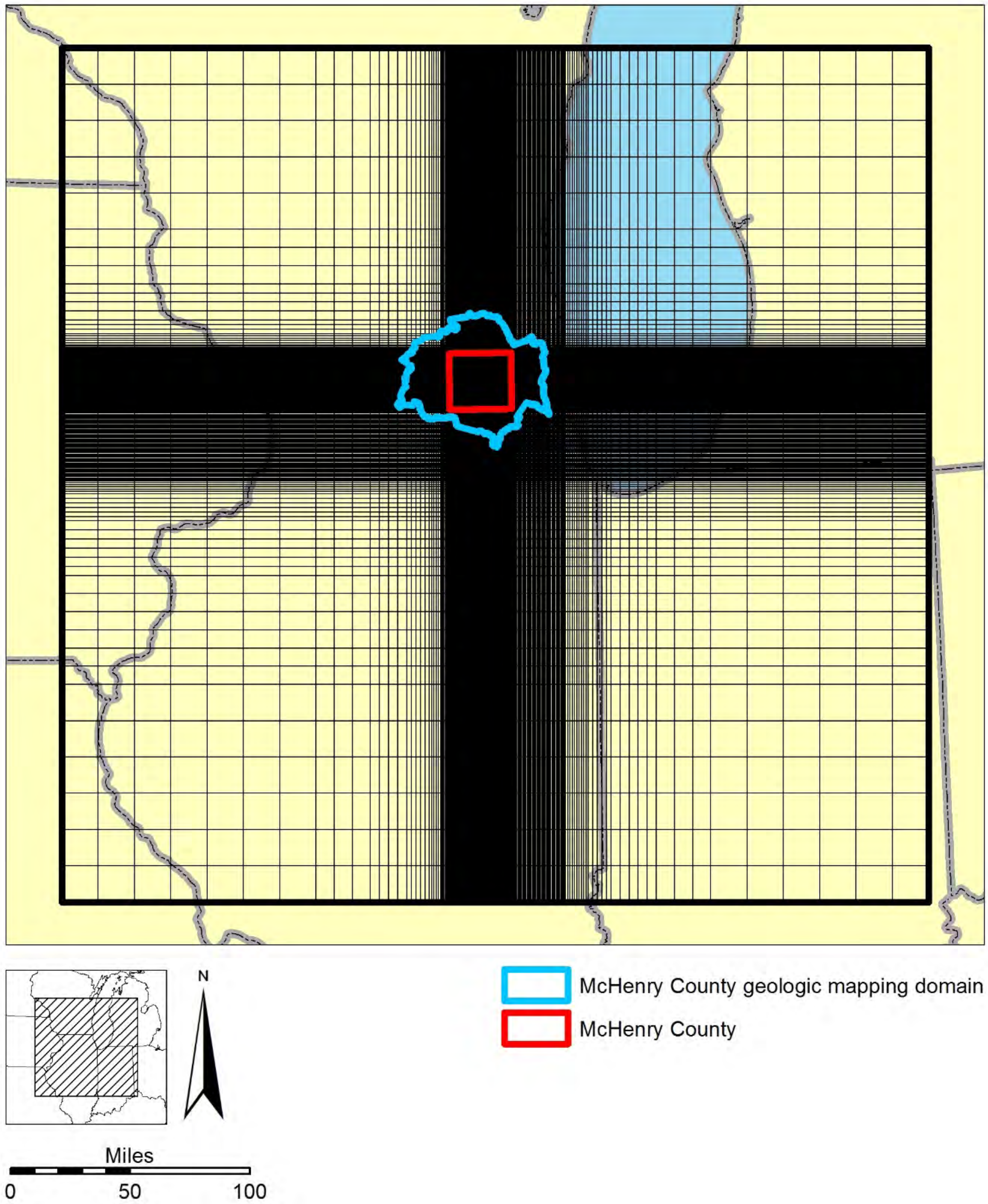

Figure 48 Finite-difference grid of groundwater flow model. Grid cells do not display individually in areas of highest model resolution.

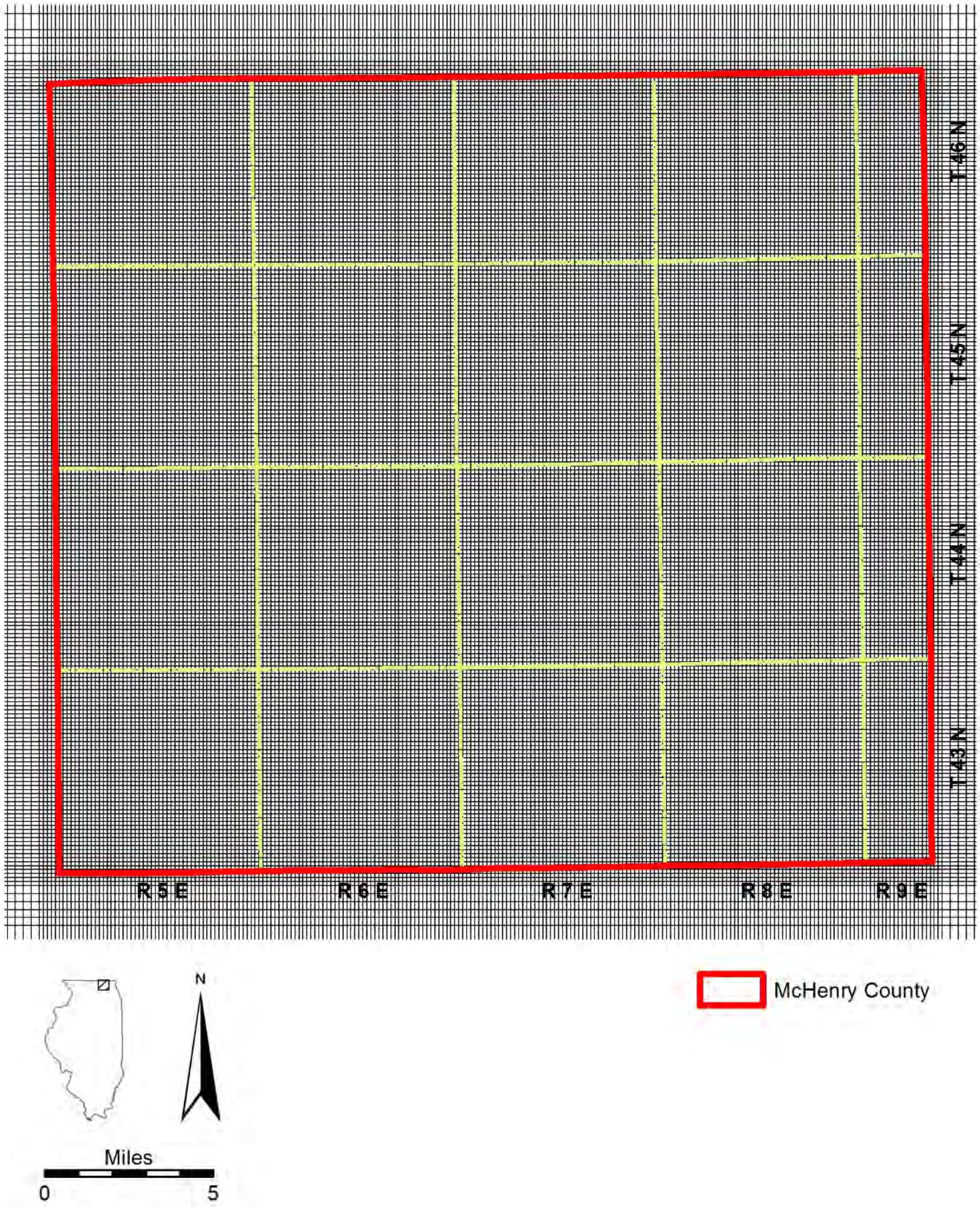

Figure 49 Detail of finite-difference grid in McHenry County and immediate vicinity. Yellow lines show township boundaries.

4.1.1.2 Uncertainty and Model Calibration

Uncertainty in models of natural systems arises from our inability to understand, measure, or completely represent all the features of the true systems (Gorelick, 1997). Uncertainties in groundwater models can be categorized as either parameter uncertainty or conceptual uncertainty (Neuman and Wierenga, 2003). Parameter uncertainties reflect our imperfect knowledge of both the input parameters of the model (hydraulic conductivity, recharge, pumping rates, aquifer geometry, etc.) and the variables the model simulates (hydraulic heads and flow rates). For example, field studies yield estimates of hydraulic conductivity, but spatial variations in hydraulic conductivity prevents a complete characterization. Further, field studies of hydraulic conductivity are plagued by scale effects and simple measurement errors. Calibrating model results to field observations such as groundwater elevations or base flow can reduce the uncertainty of input parameters such as hydraulic conductivity, but the observations themselves may also include errors such that the calibrated values retain uncertainty. Furthermore, there is not one unique calibration that may be applied to a model, particularly if field observations are sparse (as is the case for the deep units in this study).

Conceptual uncertainties arise from our imperfect knowledge of the processes governing the modeled system, which forces us to make assumptions regarding what processes to include in the model. In practice, conceptual models are based on expert judgment and can be evaluated to quantify the possible impact of conceptual uncertainties. For example, this study assumes that the dominant groundwater flow processes for this system are saturated, isothermal flow, driven by hydraulic gradients at relatively low velocities. The effects of salinity, temperature, and flow through unsaturated zones are not included because these processes are generally believed to have minor influences on the aquifers of this system (Mandle and Kontis, 1992; Feinstein et al., 2005a, b). The impact of these conceptual uncertainties on the model can be quantified by ancillary calculations, but evaluating conceptual model uncertainty is an area of ongoing research (Neuman and Wierenga, 2003; LeFrancois and Poeter, 2009; Hill et al., 2010). Both parameter and conceptual uncertainties contribute to the overall uncertainty of this model and cannot be avoided; in short, “With any model, we get uncertainty for free” (Gorelick, 1997).

The groundwater flow model used for this study, which employs a conceptual model developed from expert judgment and calibrated model parameters, represents our best understanding of the system and, as such, might be termed an expected-case model. However, reasonable variations of the expected-case model (employing plausible, but different, conceptual models and parameters that depart from those used in the expected-case model but that are within plausible ranges dictated by parameter uncertainties) will yield a range of plausible predictions rather than a single prediction. Calculating model uncertainty can be computationally intensive, and communication of model uncertainty is frequently challenging. The formal approach to uncertainty analysis would be to develop a number of models that include not just the expected case, but plausible variations reflecting conceptual and parameter uncertainties, and to use the collective model results to determine the probabilities of these predictions and summarize their range using, for example, confidence intervals. Such estimates could then be used by decision-makers to assess the reliability of model predictions and rationally evaluate the risks associated with management alternatives (Pappenberger and Beven, 2006). This approach would allow computation of a range of results (head and groundwater discharge to streams, for example) for each point within a three-dimensional model domain and would permit probabilities to be assigned to the results. Although such results would be ideal for planning purposes in that they would fully acknowledge parameter and conceptual uncertainty, the current technology for assigning probabilities to detailed groundwater models requires repeating the simulation many times (a so-called Monte Carlo analysis), a computationally intensive exercise that, given the complexity of the model developed for this study, is well beyond the project scope. This would involve adjusting values and zonations of hydrologic parameters such as hydraulic conductivity, recharge, saturated thickness, etc. and comparing modeled results to field observations to see which ranges are plausible. Even this sensitivity analysis, which would require multiple simulations, is beyond the scope of this study. However, this study provides valuable insight to our understanding of simulations that should be run in the future, which would allow for a more complete understanding of the sensitivity of the model to uncertain parameters. The future forecast scenarios were created by a limited set of simulations that bound the range of plausible predictions using the most sensitive parameters and assumptions (Walker et al., 2003). This study employs such an approach to examine future projections using three separate simulations of future pumping, a parameter to which groundwater flow models are highly sensitive. Unlike Monte Carlo analysis, the approach used for the projections, although it qualitatively expresses the reliability of model predictions for use in evaluating management alternatives, does not permit computation of the probability of a result.

Groundwater flow models undergo a process of calibration in which system geometry and properties, initial and boundary conditions, and stresses are adjusted so that model simulations are as realistic as possible (Hill and Tiedeman, 2007). The model employed for this study used initial hydraulic conductivity and recharge values based on a prior calibration of the regional groundwater flow model used in the ISWS modeling studies for Kane County and northeastern Illinois (Meyer et al., 2009; Meyer et al., 2012). Manual calibration was conducted on these values to best match the 1994 head contours (Meyer, 1998). More detailed information on parameter estimations are available at http://www.isws.illinois.edu/docs/pubs/iswscr2013-06/.

The estimation of calibration target uncertainty provides a means by which the quality of the calibration and the accuracy of the model can be judged, since the accuracy of the model-simulated heads and flows can be no better than that of the calibration targets. Calibration target uncertainty is the result of measurement errors, unmodeled temporal and spatial variability, and other factors (Anderson and Woessner, 2002). Application of an approach for estimating calibration target errors is described by Meyer et al. (2009) for the calibration targets employed in developing the models used in the ISWS modeling study for Kane County (see their Appendix E). The calibration target uncertainties calculated by Meyer et al. (2009) and discussed in the following paragraphs for the present modeling study are estimates of the accuracy of the targets as predictors of model-simulated values. Conversely, they are estimates of the error of the model-simulated values as predictors of the target values. They are not estimates of the accuracy of the targets as predictors of the actual field values. Thus, a modeler can use these estimates of calibration target uncertainty as an indicator of when to cease the calibration process. That is, calibration can be terminated when the differences between the simulated and target values are less than the calibration target uncertainties. The approach used by Meyer et al.

(2009) and Meyer et al. (2012) was followed to generate calibration target uncertainty estimates for the present study.

The results of our analysis of calibration targets uncertainty are the same as those of the Kane County study. The head calibration targets for deep units are estimated to have a maximum uncertainty of ±200 ft. The greatest source of the uncertainty is the long open interval of the wells that are the sources of deep head targets. These wells are open to many different subsurface units, and heads vary continuously along these long open intervals, so the water level in the well is not representative of the head at specific points along the borehole. The ±200-ft maximum uncertainty means that the calibration target value may be as much as 200 ft higher or lower than the simulated head, principally because the simulated value is calculated at a single point in the deep aquifers at the x, y location of the calibration target. For the three deep aquifer calibration targets in McHenry County, the modeled head was less than 25 ft greater than the observed head, well within the calibration target uncertainty range.

Shallow head calibration targets have an uncertainty of ±29 ft within McHenry County, the same as estimated by Meyer et al. (2009). The analysis suggests that the greatest component of the uncertainty of the shallow head calibration targets is unmodeled heterogeneity. That is, our model cannot reproduce the target values precisely because we are unable to represent the actual heterogeneity of hydraulic conductivity in the shallow units. In McHenry County, the modeled head was within this uncertainty range for 87% of shallow aquifer head targets.

Calibration targets for flux were developed from streamgaging records and the Illinois Streamflow Assessment Model (Knapp et al., 2007) for watersheds within the modeled domain. One of the watersheds of a flux calibration target lies entirely within McHenry County (Boone Creek), and another partially overlaps McHenry County (Coon Creek). The flux targets represent the long-term average of total groundwater discharge, or base flow, to streams and drains within the watershed. The target values are estimated as the arithmetic average of Q_{80} and Q_{50} (Meyer et al., 2009; Meyer et al., 2012). Flux target uncertainty is dependent on the uncertainty of estimates of flow. Due to obscuring effects of the controlled release at Stratton Dam and the addition of effluent discharges, flux targets for the Fox River were not used. Low flow estimates for ungaged tributary streams were determined to have a standard error from 12 to 27 percent depending on whether the watershed upstream of the flux target was underlain by low or high permeability subsoils. Watershed target low flow estimates range from 2 to 76 cfs [see Meyer et al. (2009), Appendix E] with simulation errors averaging 12.8 cfs and ranging from 3.9 to 41.7 cfs.

To restate, assumptions made in the process of simplifying a complex hydrogeological environment and uncertainty in the data being used to calibrate the model give rise to inherent model uncertainty. As an acknowledgment of the limitations in accuracy and comprehensiveness of the observations used for model development, the model results are best used as a screening tool to provide a sense of the locations and magnitudes of groundwater pumping impacts. The outcomes and trends in the results provide insight to the ability of the region's groundwater resources to meet potential future water demands. More detailed information on model calibration is available at http://www.isws.illinois.edu/docs/pubs/iswscr2013-06/.

4.1.1.3 Simulated Groundwater Withdrawals

Historical Pumping (1864–2009). The geographic scope of the withdrawals simulated in the model includes central and northern Illinois and southeastern Wisconsin. Historical groundwater withdrawal data were compiled for 7768 wells in this region (Figure 50, Figure 51) and for an additional seven idealized pumping centers representing pre-1964 withdrawals from deep wells in northeastern Illinois (Figure 52).

Although the geographic, hydrogeological, and temporal scope of the withdrawals represented in the model is not comprehensive, the compiled data represent the major influences on groundwater flow in McHenry County, and the data are progressively more complete and accurate for more recent years. Withdrawals were selectively omitted for several reasons: (1) inclusion of a truly comprehensive representation of groundwater withdrawals would strain computational resources and add significantly to computation time; (2) withdrawals at distant locations, at low rates, in the distant past, and from rapidly recharged shallow aquifers would have little impact on present groundwater flow in the model nearfield; (3) making assumptions regarding locations, rates, timing, and hydrostratigraphic sources of withdrawals in the absence of readily available data from existing databases would strain the project budget and schedule. Thus, existing databases of groundwater withdrawals in the model domain were reviewed, and if omissions in these databases were judged to be significant to modeling groundwater flow in the model nearfield, withdrawal data were assumed in order to address the omissions.

Modeling wells with MODFLOW implicitly introduces two potential errors. First, the well radius is exaggerated in the model, with the effective MODFLOW radius being equal to 0.208 × cell size. Hence, in McHenry County, which is simulated with 625 ft grid spacings, the effective radius is 130 ft, when in reality most wells have a much smaller radius. As a result, drawdown in a cell containing a well is underestimated; drawdown outside of the cell is not impacted. While this issue could potentially be resolved by introducing an additional MODFLOW package, the authors deemed the impacts of this local inaccuracy on regional groundwater flow to be minimal and the potential uncertainties of the additional MODFLOW package to be too great. The second potential error is that MODFLOW aggregates all pumping wells located within a single MODFLOW cell and simulates them with a single pumping center located precisely at the center of the cell. The finite-difference grid of our model is sufficiently refined that this aggregation of pumping does not impact our study results, at least on the scale of this analysis. Furthermore, the aggregation of pumping at cell centers will result in an overestimation of drawdown in the cell, and will have a minimal regional impact. The two errors discussed in this paragraph are thus complementary, one resulting in underestimation and the other in overestimation of drawdown. We expect that the impacts of these local errors are minimal in McHenry County, but they could be more important in areas with greater pumping (such as Joliet or Aurora) or which are represented in a coarser model grid.

A total of 5498 shallow wells are simulated in the groundwater flow model. Because it is unlikely that withdrawals from distant shallow wells would affect heads in McHenry County, shallow wells in Illinois are represented only if located within USGS hydrologic units (watersheds) in the immediate vicinity of McHenry County (Figure 50). This area is referred to as the shallow aquifer withdrawal accounting region (SAWAR). Pre-1964 withdrawals in Illinois from shallow wells within the SAWAR are not represented, and withdrawals from 1964 through 2009 are irregularly represented. Shallow withdrawals in Illinois during the period 1964–1979 are represented only for the portion of the SAWAR within the following counties: Boone, Cook, De Kalb, Du Page, Grundy, Kane, Kankakee, Kendall, Lake, La Salle, Lee, McHenry, Ogle, Will, and Winnebago. Shallow withdrawals within the entire Illinois portion of the SAWAR are represented in the model for the period 1980–2009. Shallow wells in a 10-county area of southeastern Wisconsin are represented for the period 1864–2009 (Figure 50).

A total of 3239 deep wells are simulated in the groundwater flow model (Figure 51). The time period represented by these withdrawals differs by state. Withdrawals from deep wells in Illinois are represented for the period 1864–2009. Deep wells active during the period 1864–1963 were represented by seven idealized pumping centers by Meyer et al. (2009) (Figure 52), with the pumping totals at these seven centers aggregated to represent the significant deep well withdrawals in northeastern Illinois. These aggregated withdrawals represent deep withdrawals in Cook, Du Page, northern Grundy, Kane, Kendall, Lake, McHenry, and Will Counties, Illinois. As discussed above, aggregation of many wells into a single pumping center can overestimate local drawdowns, and in this model, the aggregation resulted in (fictitious) complete desaturation of the deep bedrock at the pumping centers. To overcome this, we utilized the methodology developed in a study of Kendall County (Roadcap et al., in preparation) whereby pumping rates were assigned to a cluster of wells near the pumping centers. As a result, local drawdowns were minimized and the deep bedrock did not go dry, generating more realistic regional drawdowns during that period. Deep withdrawals during the period 1964–2009 are simulated at actual well locations. Deep withdrawals during the period 1964–1979 in Illinois that are simulated in the model are limited to wells located in the following 20 northern Illinois counties for which the ISWS collected withdrawal data: Boone, Carroll, Cook, De Kalb, Du Page, Grundy, Jo Daviess, Kane, Kankakee, Kendall, Lake, La Salle, Lee, McHenry, Ogle, Rock Island, Stephenson, Whiteside, Will, and Winnebago (Figure 53). Most deep withdrawals in the state occur within this area. Deep withdrawals from Illinois wells during the period 1980–2009 are represented in the entire portion of Illinois within the model domain. Deep wells in a 10-county area of southeastern Wisconsin are represented for the period 1864–2009 (Figure 51).

As described by Meyer et al. (2012), because mineralized water from deep wells in Indiana is unacceptable for most uses, the deep units are almost entirely unused there, and Indiana withdrawals from deep wells are not simulated for the present project.

The sources of historical Illinois withdrawal data employed in this study are records on file at the ISWS (covering the period 1964–1979); the Illinois Water Inventory Program (IWIP) database, maintained by the ISWS, a database of post-1979 withdrawal data compiled largely from annual owner-reported withdrawal measurements and estimates; and estimates for years of non-reporting to the ISWS by facility owners (database and estimates cover the period 1980–2009). Pre-1964 withdrawal data were obtained from Stephen L. Burch (retired) of the ISWS (personal communication, 2002). Data derived from this source represent withdrawals from deep wells that were active during the pre-1964 period. As mentioned, pumping activity for the pre-1964 period in Illinois is aggregated to seven idealized pumping centers (Figure 52) intended to represent total deep withdrawals in northeastern Illinois. They were employed in previous modeling studies by Prickett and Lonnquist (1971) and Burch (1991). Aggregation for the Chicago pumping center in southern Cook County is significant; pumping at this center alone totaled as much as 35 Mgd in the 1920s (Suter et al., 1959).

Historical Wisconsin pumping data were obtained from the USGS-Wisconsin Water Science Center (Cheryl Buchwald, personal communication, 2011). These data represent pumping during the period 1864–2009 from both shallow and deep aquifers. They uniformly include both shallow and deep wells in a 10-county region of southeastern Wisconsin for the entire period 1864–2009 (Figure 50, Figure 51).

The completeness of the pumping dataset developed for this project is not known, but it is based on sources that sought, and continue to seek, to document well withdrawals for all community and non-community public water systems, self-supplied commercial and industrial facilities, and self-supplied irrigation. Estimates are included for wells during years when it is probable that the wells were in use, but withdrawal data were not collected. The accuracy of the data is not known, but it is likely that the reported measurements are accurate to within ±10 percent of the actual value (United States Department of the Interior Bureau of Reclamation, 1997).

Future Pumping (2010–2050). Estimates of future withdrawals from individual wells in northeastern Illinois are based closely upon the three withdrawal scenarios developed for the 11-county northeastern Illinois region, for the period 2010–2050, by Dziegielewski and Chowdhury (2008). Dziegielewski and Chowdhury employed three different combinations of assumptions about future socioeconomic conditions to develop these scenarios, but the scenarios each assume 1971–2000 average climate, so they do not anticipate climate change effects on water use. As discussed in Section 2.3, the low withdrawal scenario is called the Less Resource Intensive scenario (LRI), and the high withdrawal scenario is called the More Resource Intensive (MRI) scenario. Between these is the Baseline (BL) scenario, referred to as the Current Trends (CT) scenario in other reports (Dziegielewski and Chowdhury, 2008; Chicago Metropolitan Agency for Planning, 2010). Dziegielewski and Chowdhury (2008) discuss the assumptions on which the three scenarios are based.

Population growth and the percentage of the population employed are assumed to be the same under all three scenarios. Of the factors that differ among the scenarios, the ones accounting for most of the variation in public water supply withdrawals are household income and the price of water. The number of highly water-consumptive commercial and industrial activities and golf courses increases from the LRI scenario, through the BL scenario, to the MRI scenario. Two new power plants are brought into operation in northeastern Illinois under the MRI scenario, and three plants are retired under the LRI and BL scenarios.

Dziegielewski and Chowdhury (2008) reported withdrawals under the three scenarios for each facility and for self-supplied irrigation and agriculture sector for each county. To simulate these withdrawals in the ISWS computer models, Dziegielewski (personal communication, 2008) disaggregated these facility- and county-level estimates to wells and surface intakes active during 2005, using 2005 pumping rates to compute the proportion of the facility- or county-level estimate assigned to each well and intake. Dziegielewski provided the resulting point estimates to the ISWS, which incorporated the estimates into its models. Meyer et al. (2012) simulated LRI, BL, and MRI withdrawals for the period 2006–2050 and used historical withdrawal rates for the period 1864–2005.

For the present study, we simulate historical withdrawals for the period 1864–2009 and LRI, BL, and MRI withdrawals for the period 2010-2050 (Figure 37). The point estimates based on the 2005 pumping distribution and simulated by Meyer et al. (2012) were replaced, however, by estimates based on reconsideration of the county- and sector-level estimates of Dziegielewski and Chowdhury (2008), including reapportionment based on the 2009 pumping distribution. The updated point estimates are based on the facility- and county-level estimates of Dziegielewski and Chowdhury (2008), but they (1) include additional withdrawal points that became active after 2005, (2) eliminate points that were abandoned after 2005, and (3) feature recomputed pumping distributions based on 2009 pumping rates. A small number of new facilities became operational after 2005, and pumping rates at points operated by these facilities are based on the 2009 pumping distribution at the facility together with the trend in aggregate pumping for the county and water supply sector to which the facility belongs. Other facilities were closed, and withdrawals computed by Dziegielewski and Chowdhury (2008) for these facilities, and simulated by Meyer et al. (2012), were not simulated for the present study. As a result of this reconsideration of the future pumping estimates simulated by Meyer et al. (2012), we simulate less groundwater withdrawal both in McHenry County and in the remainder of northeastern Illinois than did Meyer et al. (2012) (Figure 54, Figure 55).

In a procedure similar to that used for northeastern Illinois withdrawal estimation, future pumping rates of wells in Wisconsin and downstate Illinois are estimated on the basis of the county location of each well, the 2009 pumping rate of each well, and on a single scenario of county-level estimates of future public supply water use developed by Dziegielewski et al. (2004) for the period 2005–2025.

Our use of the estimates of Dziegielewski et al. (2004) for Wisconsin and downstate Illinois locations carries with it certain implicit assumptions about future water use in these areas. First, since the estimates of Dziegielewski et al. (2004) extend only to 2025, we use linear extrapolation of the change in modeled county public supply water use between 2020 and 2025 to develop speculative estimates for the years 2030 through 2050. Second, since the estimates of Dziegielewski et al. (2004) apply only to the public supply sector, we assumed that the estimated change in public supply water use applied to wells in the self-supplied industrial and commercial sector and self-supplied irrigation and agriculture sector, as well. Third, since Dziegielewski et al. (2004) provide only a single scenario of future water use, we likewise have developed only a single scenario of future withdrawals per well in Wisconsin and downstate Illinois, not separate estimate sets comparable to those based on the LRI, BL, and MRI scenarios developed for northeastern Illinois by Dziegielewski and Chowdhury (2008). Lastly, the estimates of Dziegielewski et al. (2004) assume historical climate conditions and do not assume that future climate change will impact water use.

In summary, to develop estimates of withdrawals for the period 2010–2050 for wells in Wisconsin and downstate Illinois, the 2009 pumping rate for each well was changed in proportion to the change in county-level public sector demand, based on the estimates of Dziegielewski et al. (2004). We computed only a single set of assumed values for use in concert with the three separate scenarios of northeastern Illinois withdrawals.

Important assumptions were necessary to disaggregate county-level demands to specific wells for use as model input:

- Because we did not wish to speculate or dictate new well locations and source aquifers, no new points of withdrawal were added beyond those wells operating in 2009. Instead, all additional future demands were assigned to existing points.
- Actual future withdrawals will be distributed between existing wells and new wells, the latter at locations and open to source aquifers not known to the authors and not simulated in the model. Model estimates of future pumping impacts will differ from actual future impacts accordingly, since the model cannot predict impacts where it is not designed to simulate pumping. Strategic siting of new wells could distribute withdrawals so as to reduce impacts below model-simulated levels in the most affected areas.
- Assignment of future (post-2009) pumping reflects facility pumping operations in 2009. For example, Crystal Lake withdrew about 4.69 Mgd of groundwater in 2009; about 6.6 percent of this total (0.31 Mgd) was pumped from well 11 at that facility. Under the BL scenario, we estimate that Crystal Lake would pump a total of about 6.59 Mgd in 2050. For purposes of model simulation, the authors assigned 6.6 percent of that total (0.44 Mgd) to well 11, reflecting the proportion pumped from the well in 2009. The authors employed the same convention for the post-2009 period for each of the three scenarios. Although the convention cannot reflect actual evolution of the regional well network–which will be a product of numerous decisions by hundreds of managers in response to a range of factors and perhaps without knowledge of management decisions made by other facilities in the region–it was necessary owing to time and budget constraints of this initial assessment. Nevertheless, the modeling results based on it permit identification of problematic areas for priority follow-up investigation.
- Although assigning additional future demand to existing public and industrial/commercial wells exceeded some actual well pumping capacities (based on 24-hour operation at the well pump's rated capacity), the addition of new wells to accommodate such exceedances would often occur within the grid spacing of the flow model nearfield (625 ft), thus essentially adding that demand to the same model cell anyway.
- Future agriculture/irrigation demands were not assigned to wells if they exceeded the well pumping capacity. Future agriculture/irrigation withdrawals were assigned to existing agriculture/irrigation wells, but additional withdrawals were limited at the pumping capacity of the well (based on 24-hour constant operation at the well pump's rated capacity). In some cases, this meant not all the county agriculture/irrigation demand could be allocated.
- Domestic self-supplied withdrawals were not simulated. This amounted to from 37.3 to 49.3 Mgd in 2050 demand across the 11-county region. Withdrawals were not estimated for domestic wells because 85 to 90 percent of the relatively small quantities of groundwater withdrawn from such wells would be returned via on-site wastewater disposal systems to the shallow interval from which most were obtained (United States Environmental Protection Agency Region V, 1975; Pebbles, 2003), with little net effect on groundwater flow.

Simulated withdrawals in McHenry County increase from 24.7 Mgd in 2009 to between 31.5 Mgd (LRI scenario) and 67.9 Mgd (MRI scenario) in 2050 (Figure 54). The sources of simulated groundwater withdrawals in McHenry County reflect the 2009 proportionality, with 69 to 71 percent derived from the shallow aquifers, and the remainder obtained from the deep aquifers. Projected withdrawals from the deep aquifers in 2050 in the 11-county area total 187 and 237 Mgd under the BL and MRI scenarios, respectively, rates that approximate and exceed the peak historical withdrawal rate from the deep aquifers, in 1980, of about 186 Mgd, a rate known to produce rapidly falling heads in some deep wells. For comparison, the spatial distributions of shallow and deep withdrawals in 2030 and 2050 for the three scenarios are shown in Figure 56 to Figure 67. Groundwater withdrawals in 2009 in northeastern Illinois are shown in Figure 35 and Figure 36.

Note that future withdrawals from all McHenry County wells increase from 2030 to 2050, and they are universally greater under the MRI scenario than under the BL scenario, which in turn specifies greater withdrawals for all wells than the LRI scenario. Nonetheless, the symbol sizes employed in Figure 56 to Figure 67 does not make these increases universally apparent since the temporal and inter-scenario differences in pumping specified for McHenry County wells are not large enough to require that individual wells be represented with different sized symbols. Figure 37 illustrates historical and future McHenry County groundwater withdrawals simulated for this project, and Figure 38 and Figure 39 illustrate in map view the McHenry County withdrawals in 2030 and 2050, respectively, under all three pumping scenarios and with shallow and deep withdrawals segregated.

As stated previously, future withdrawals are assigned to wells that were active in 2009. This approach is reflected by the coincidence in location between wells active in 2009 (shown for McHenry County in Figure 32 and Figure 33, and shown for northeastern Illinois in Figure 35 and Figure 36) with those projected for 2030 (shown for McHenry County in Figure 38, and shown for northeastern Illinois in Figure 56 to Figure 61) and 2050 (shown for McHenry County in Figure 39, and shown for northeastern Illinois in Figure 62 to Figure 67).

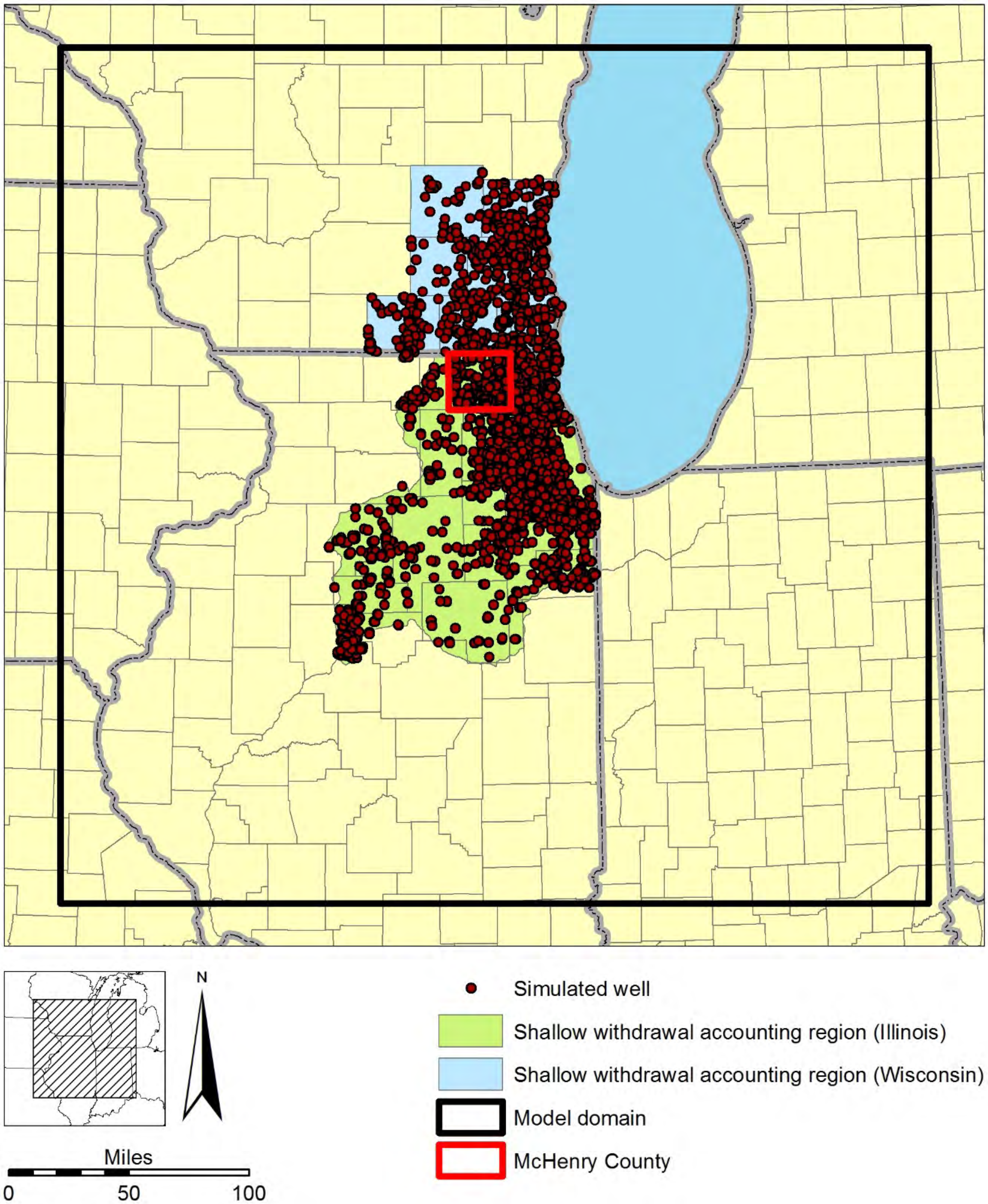

Figure 50 Shallow wells simulated with the groundwater flow model

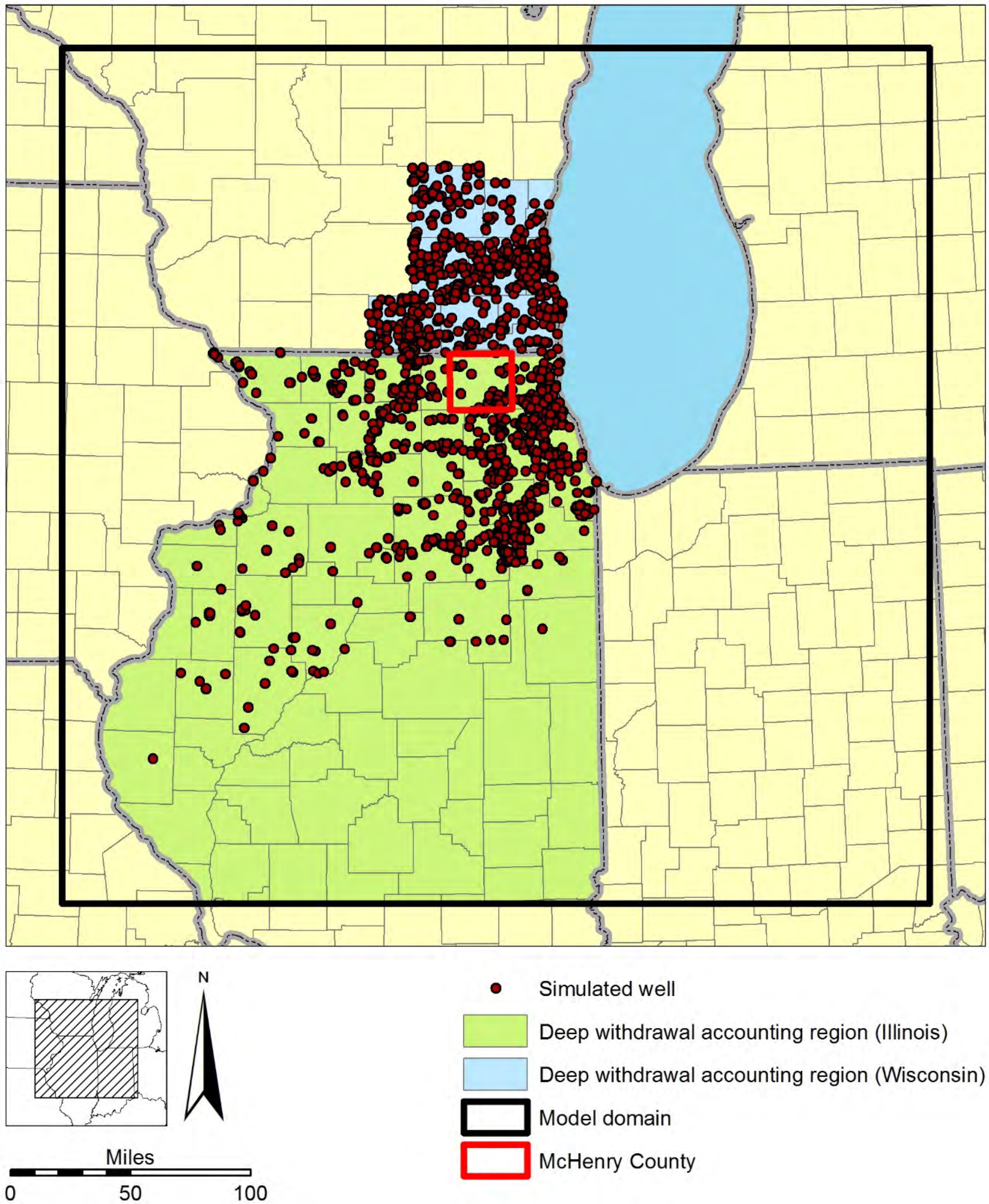

Figure 51 Deep wells simulated with the groundwater flow model

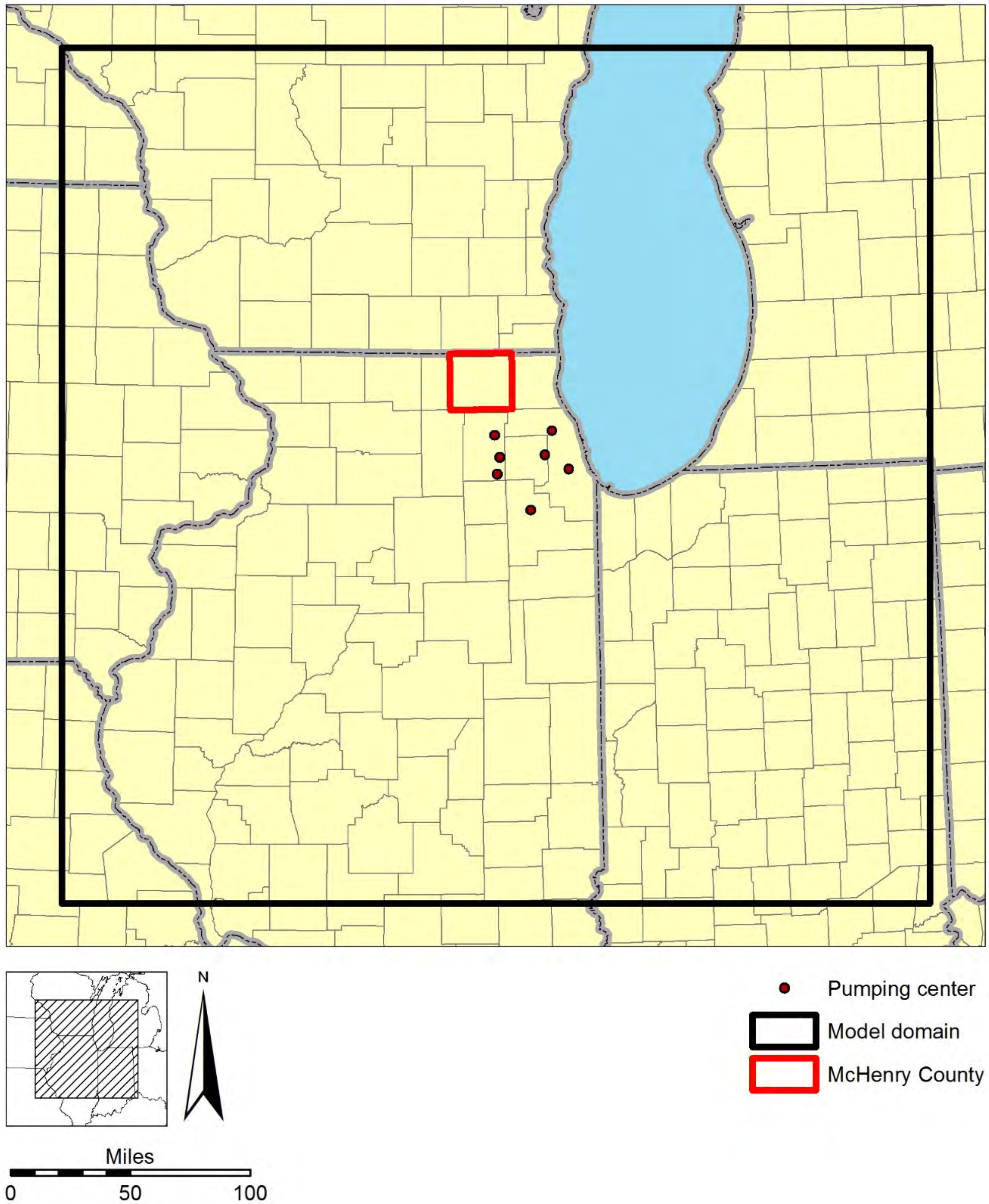

Figure 52 Pumping centers for aggregation and simulation of 1864-1963 deep pumping in northeastern Illinois

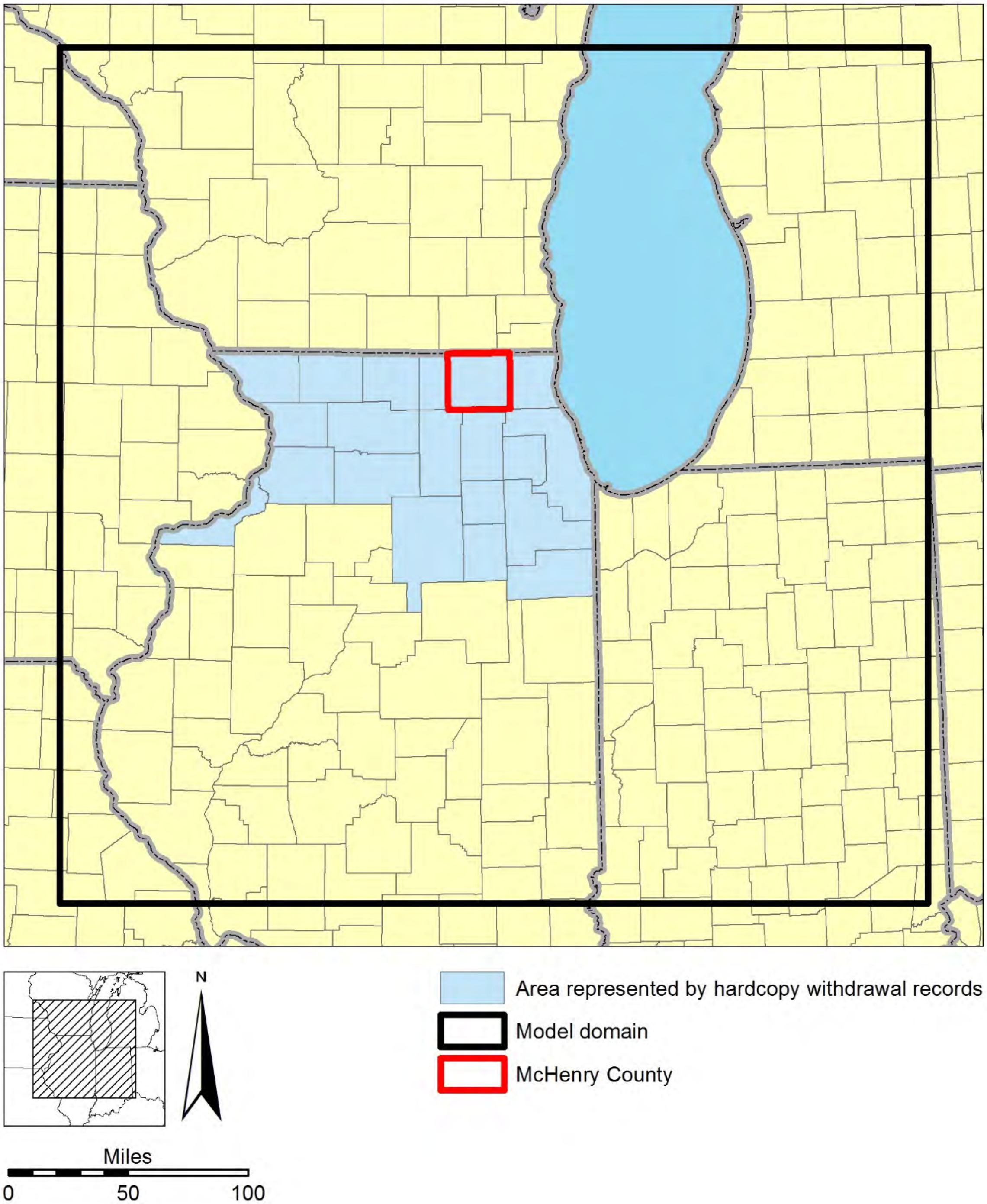

Figure 53 Area covered by withdrawal records documenting groundwater withdrawals in northern Illinois from 1964 through 1979

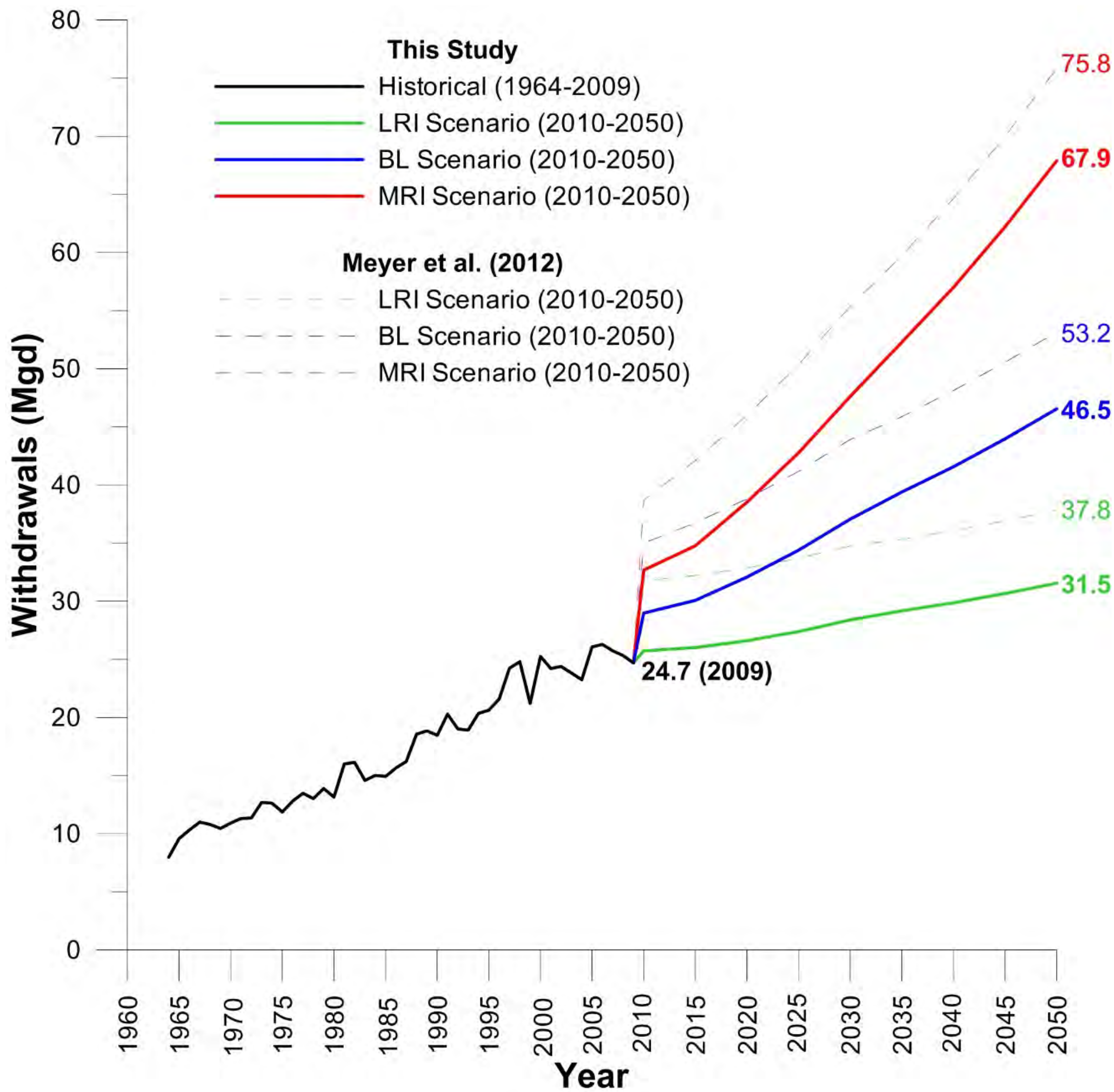

Figure 54 Comparison of McHenry County groundwater withdrawals simulated in the present study and by Meyer et al. (2012)

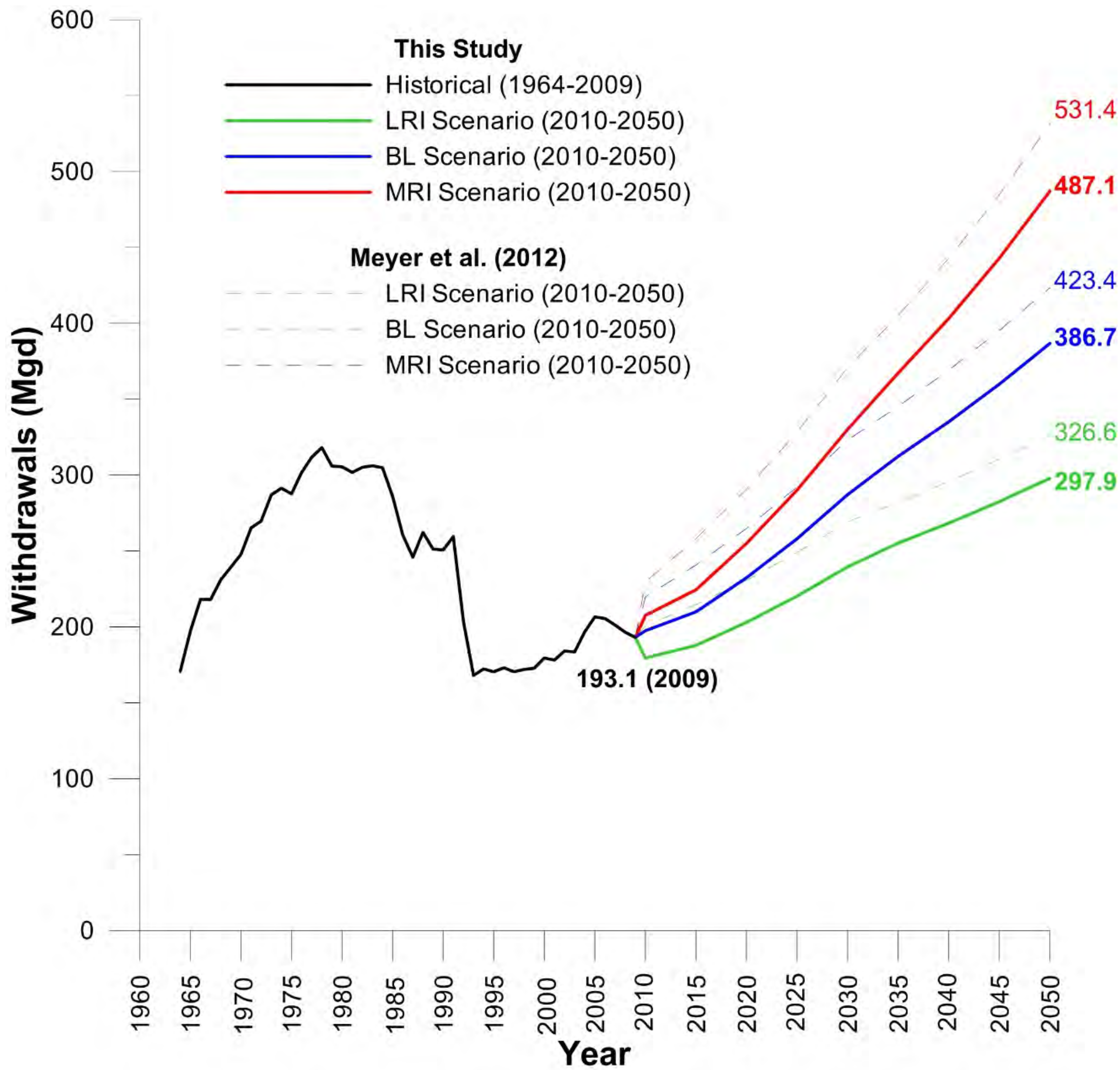

Figure 55 Comparison of northeastern Illinois groundwater withdrawals simulated in the present study and by Meyer et al. (2012)

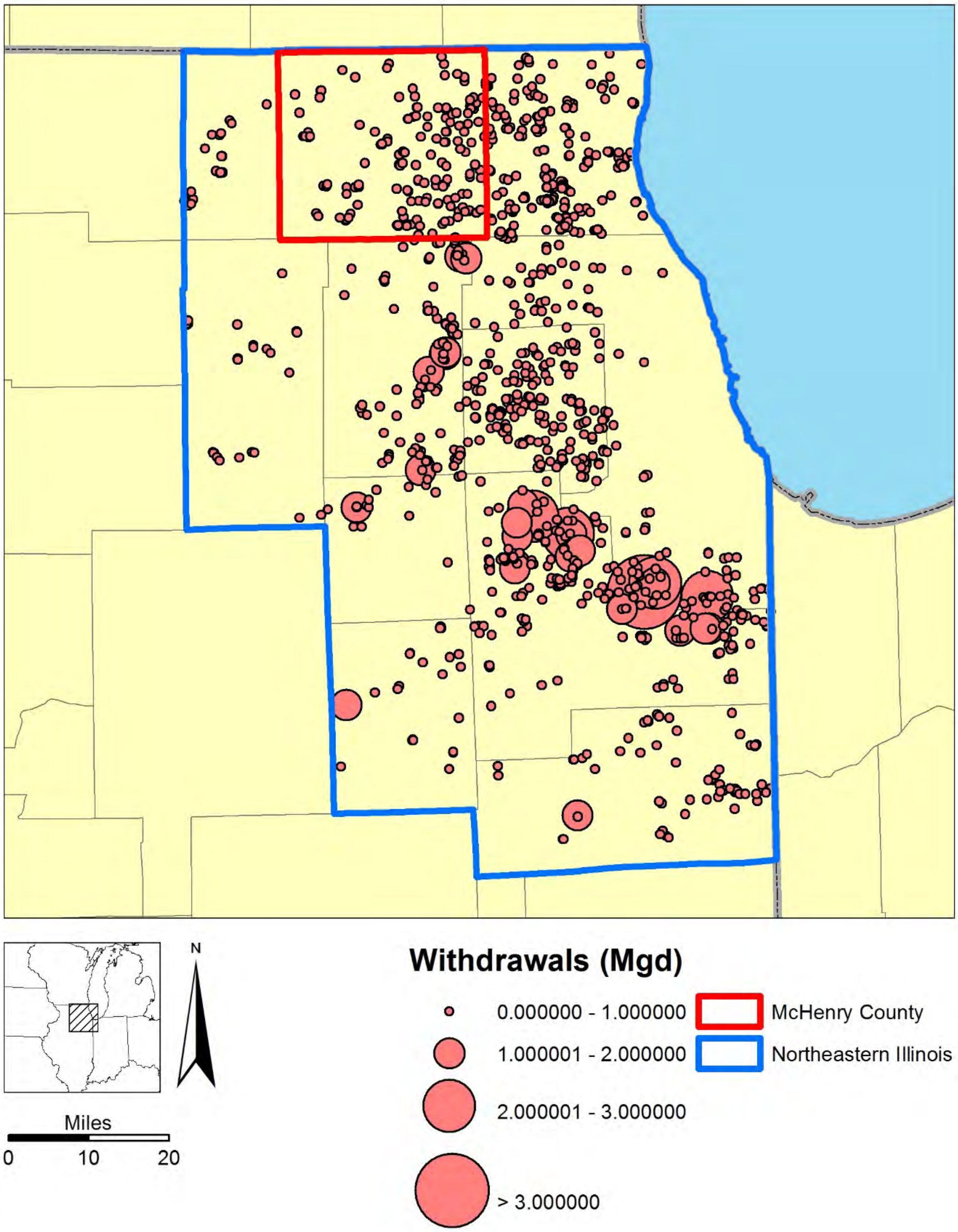

Figure 56 Shallow groundwater withdrawals in northeastern Illinois, 2030 (BL scenario)

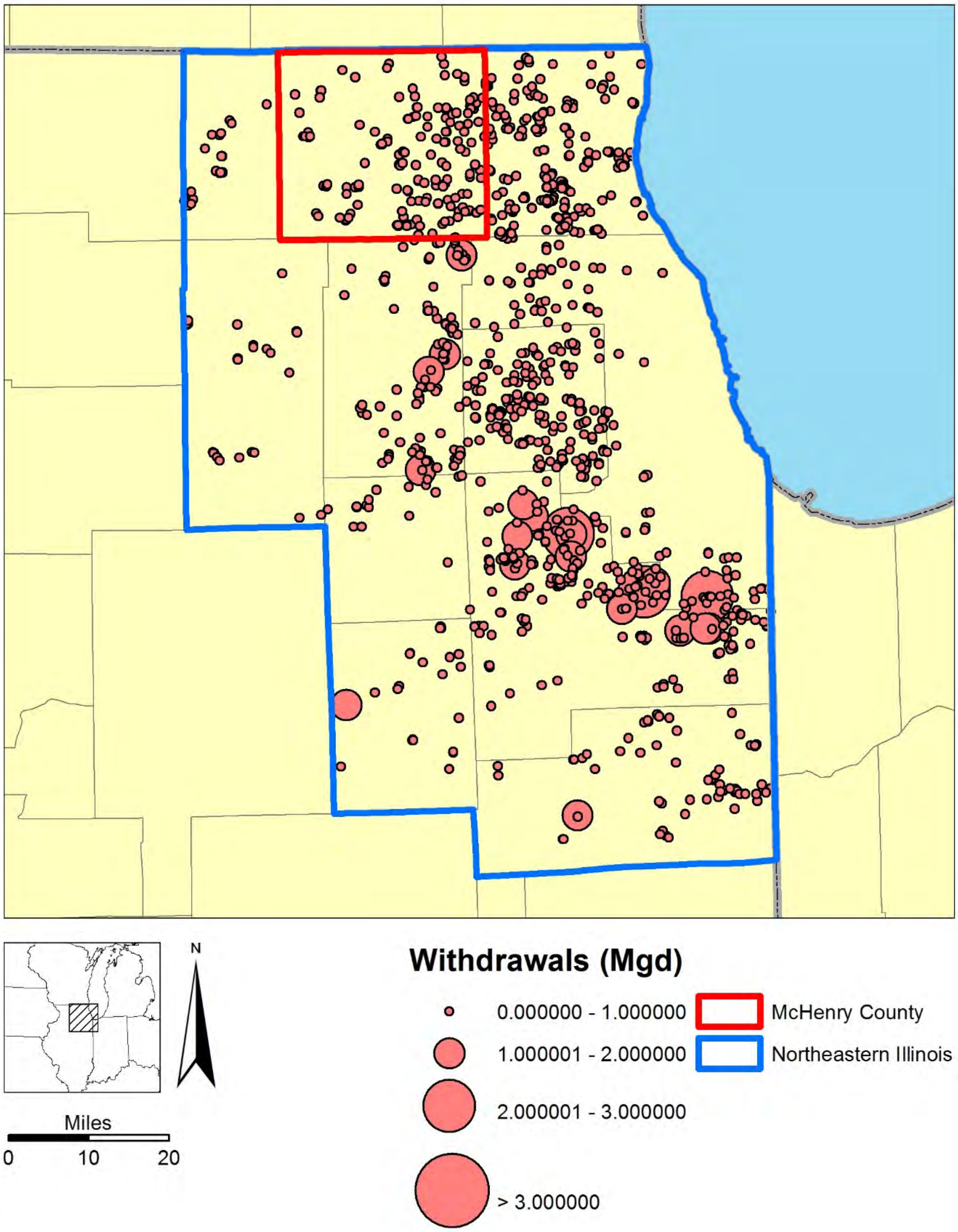

Figure 57 Shallow groundwater withdrawals in northeastern Illinois, 2030 (LRI scenario)

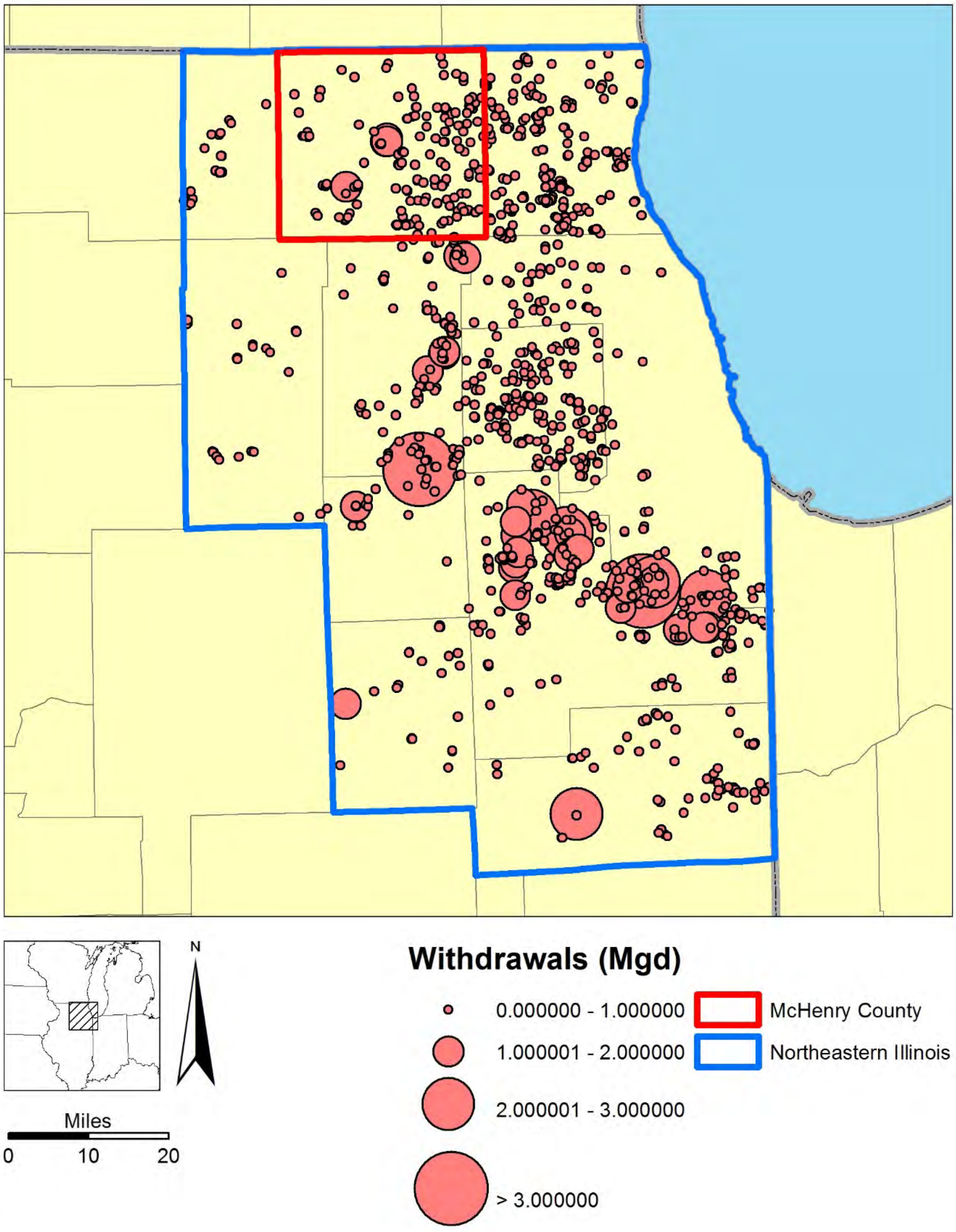

Figure 58 Shallow groundwater withdrawals in northeastern Illinois, 2030 (MRI scenario)

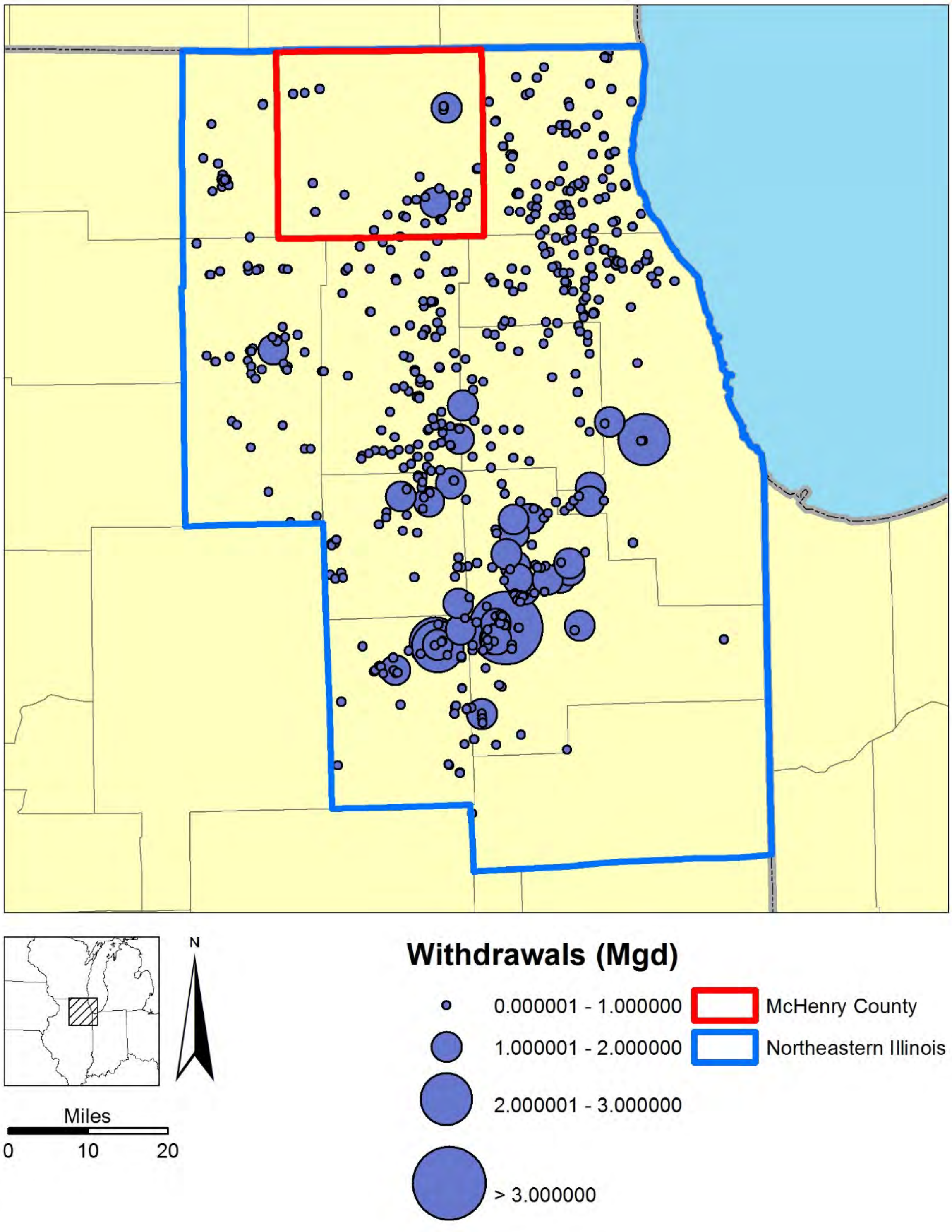

Figure 59 Deep groundwater withdrawals in northeastern Illinois, 2030 (BL scenario)

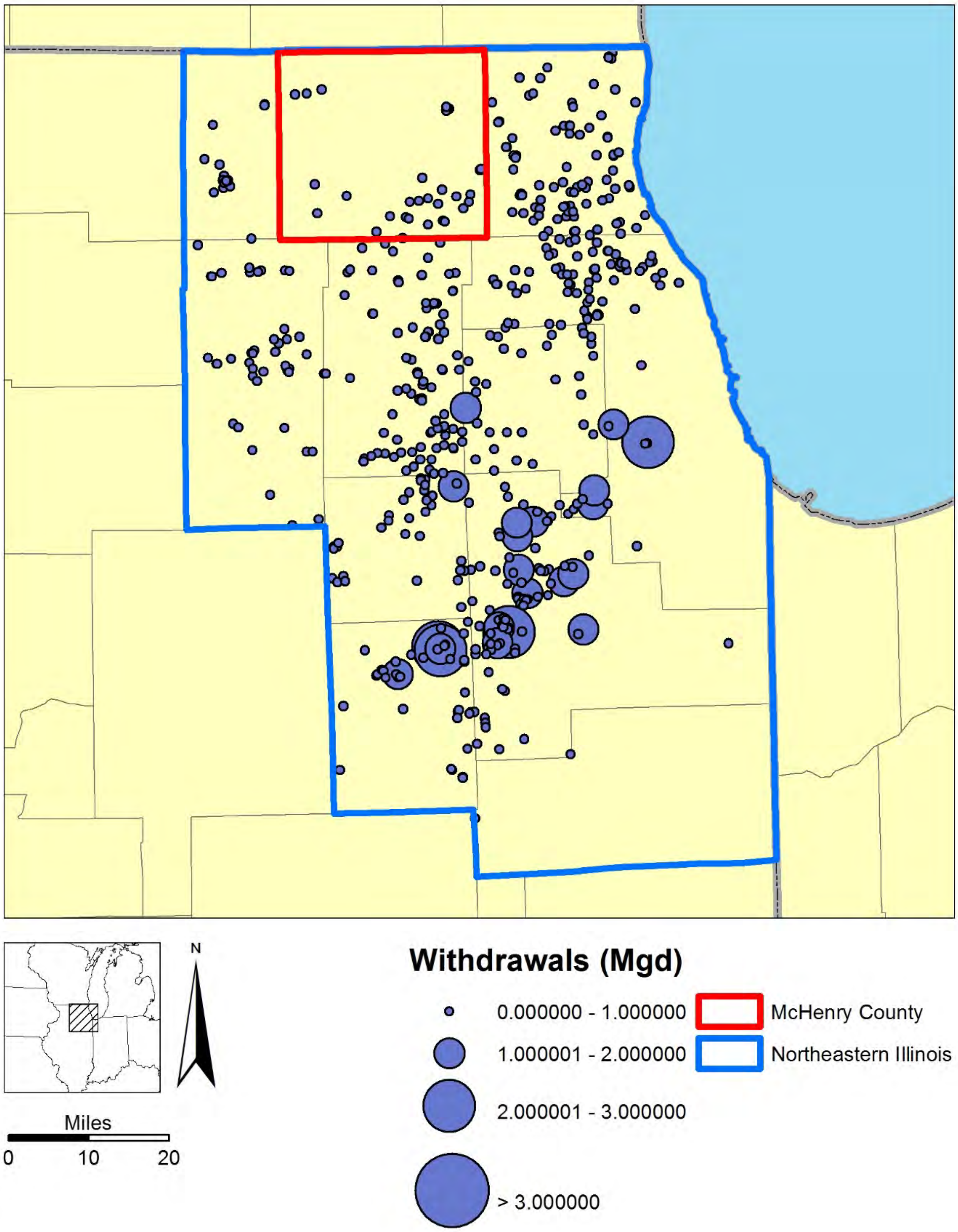

Figure 60 Deep groundwater withdrawals in northeastern Illinois, 2030 (LRI scenario)

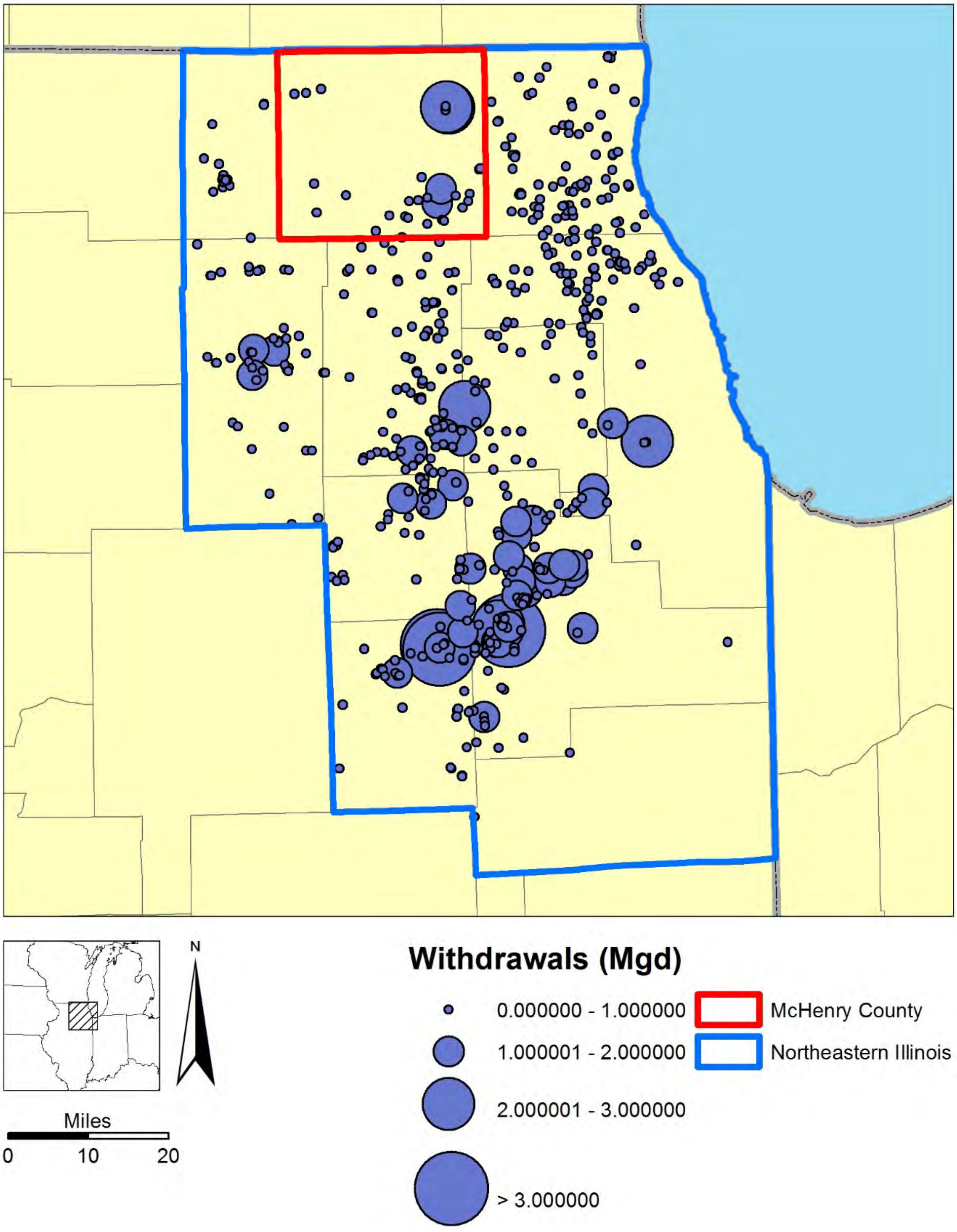

Figure 61 Deep groundwater withdrawals in northeastern Illinois, 2030 (MRI scenario)

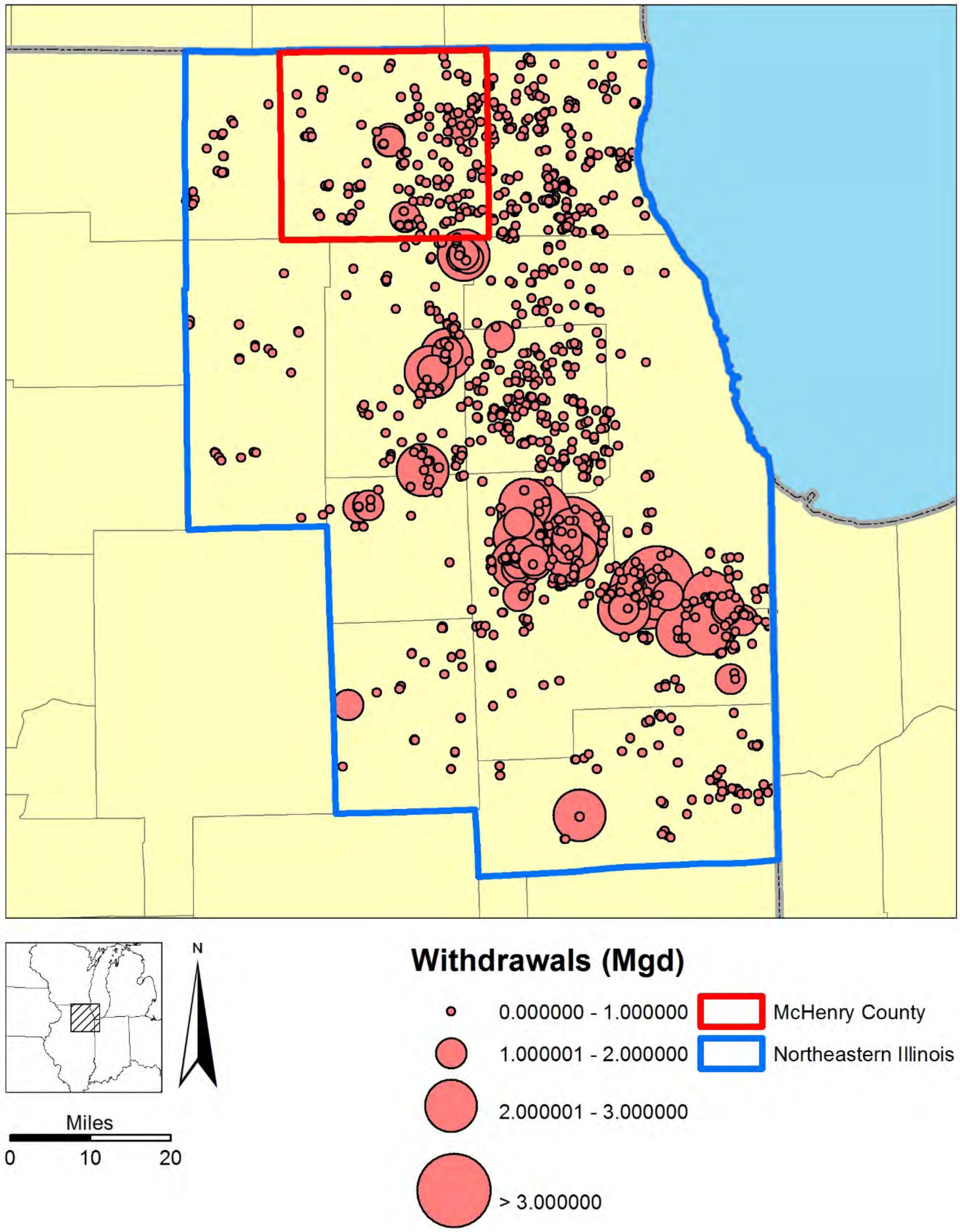

Figure 62 Shallow groundwater withdrawals in northeastern Illinois, 2050 (BL scenario)

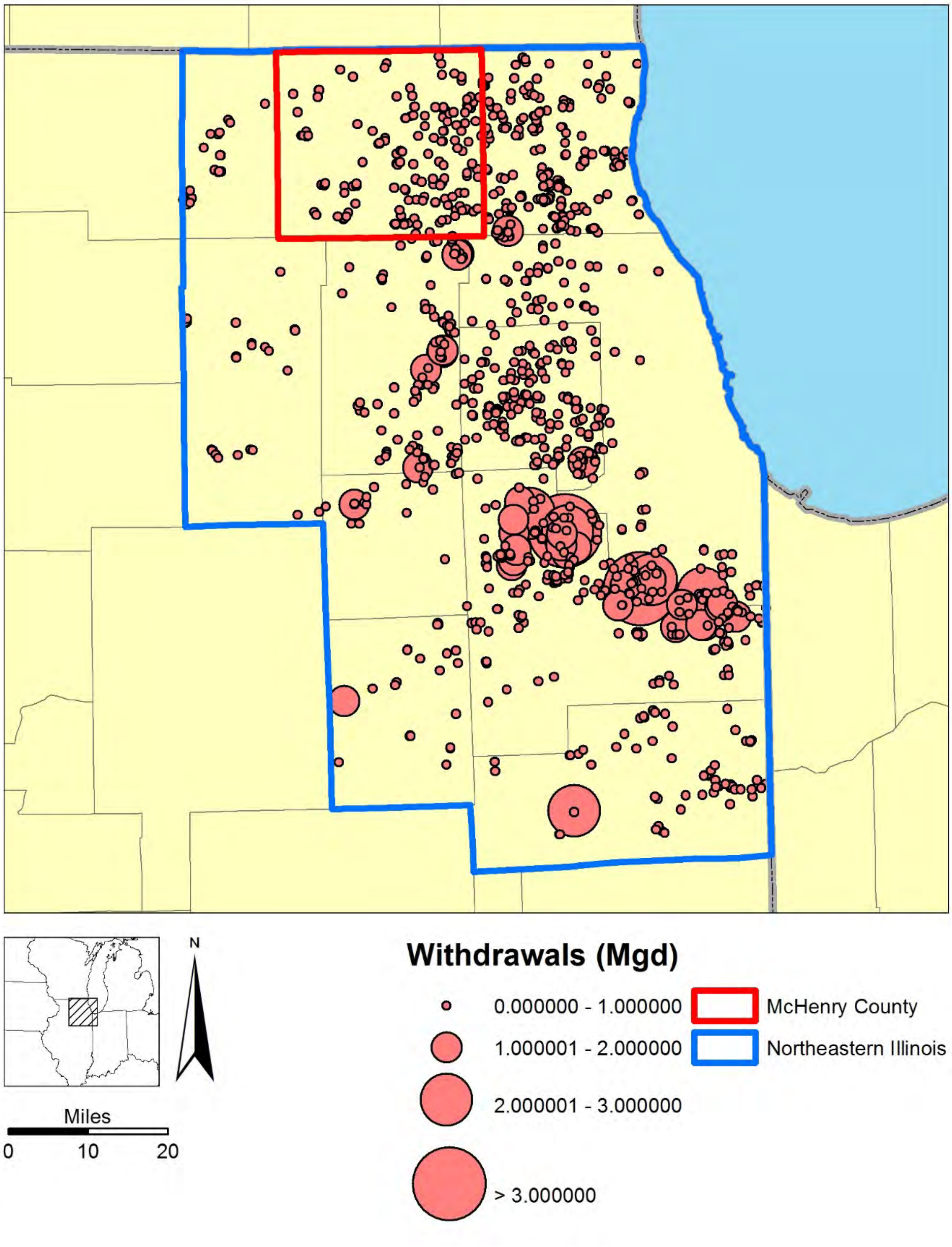

Figure 63 Shallow groundwater withdrawals in northeastern Illinois, 2050 (LRI scenario)

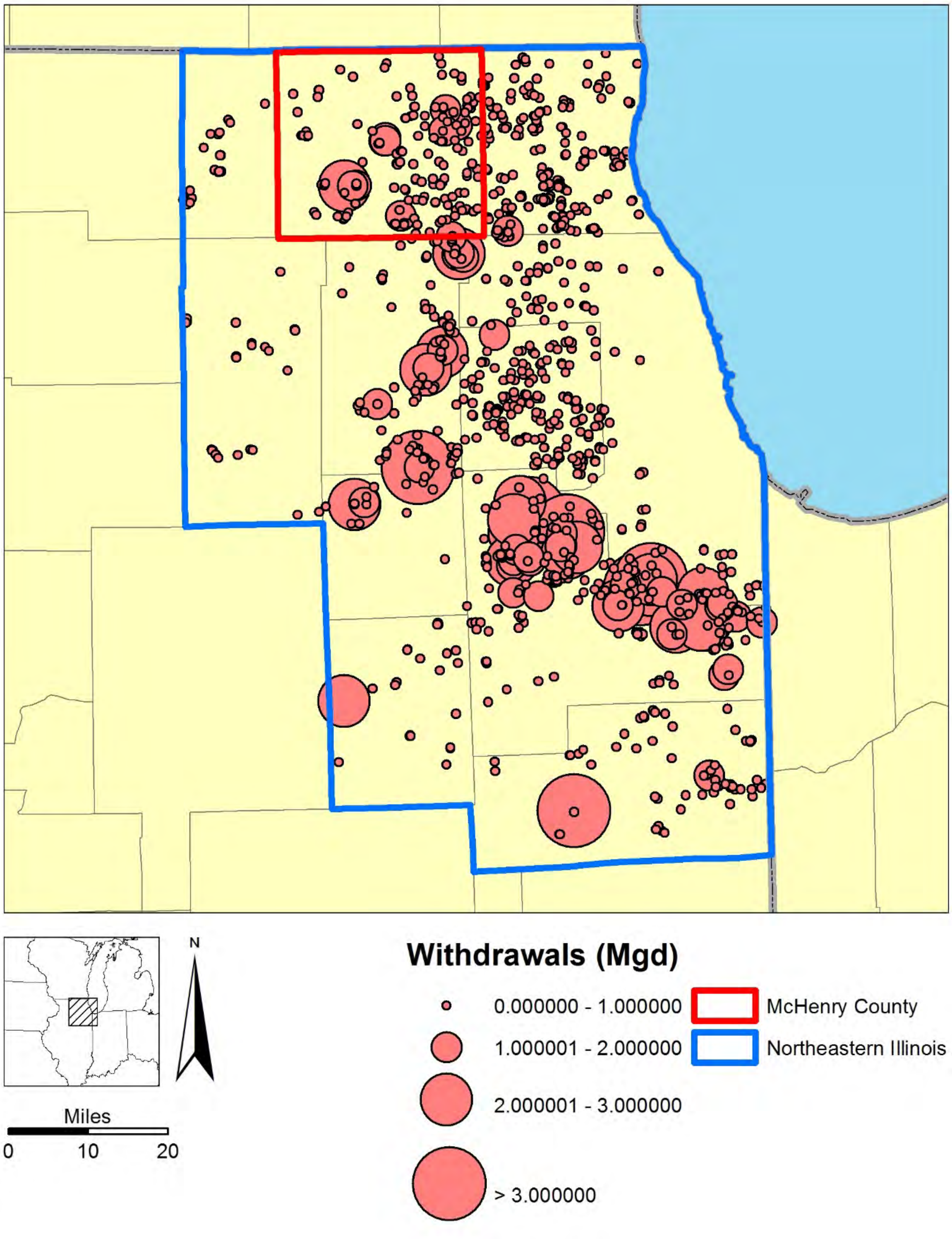

Figure 64 Shallow groundwater withdrawals in northeastern Illinois, 2050 (MRI scenario)

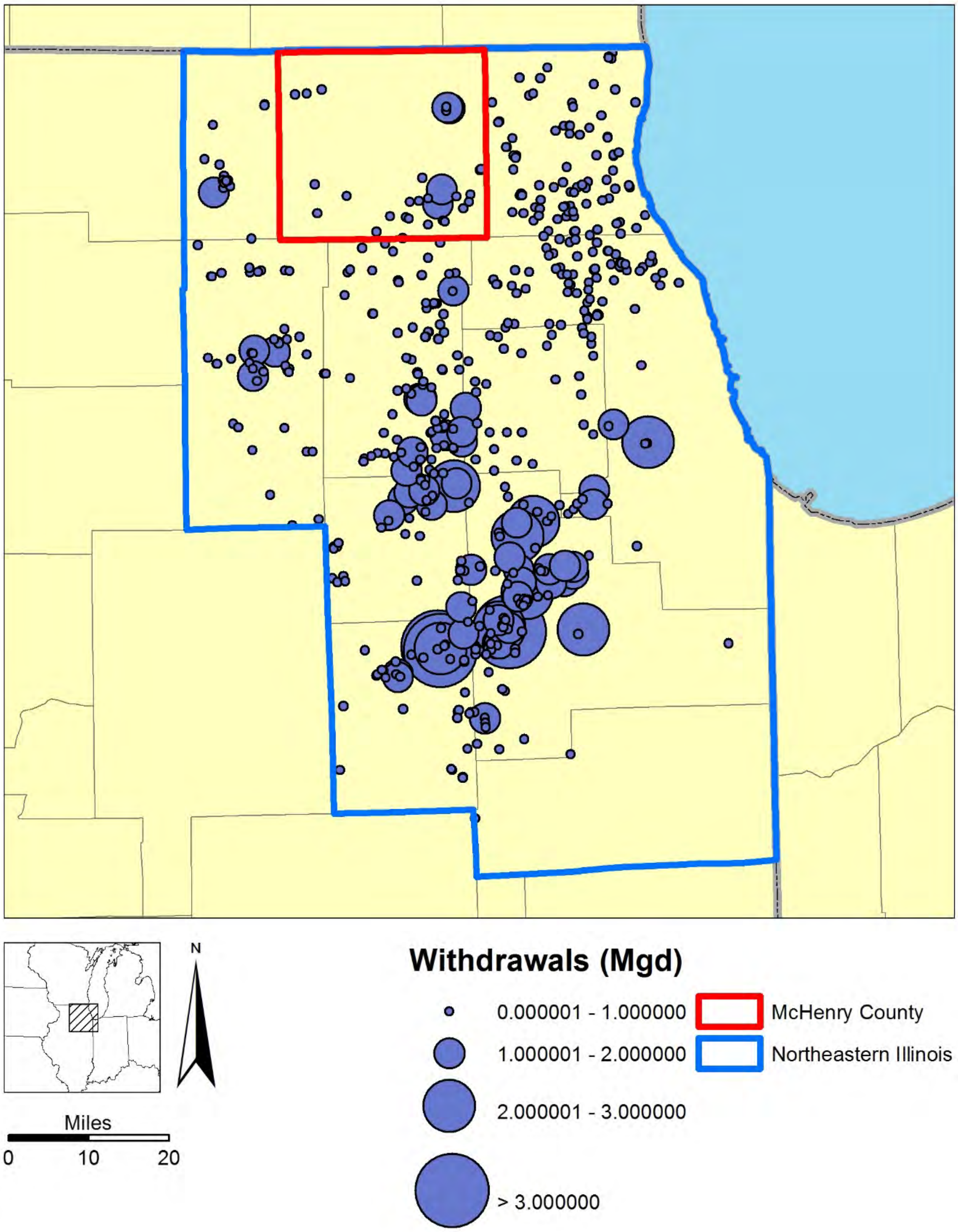

Figure 65 Deep groundwater withdrawals in northeastern Illinois, 2050 (BL scenario)

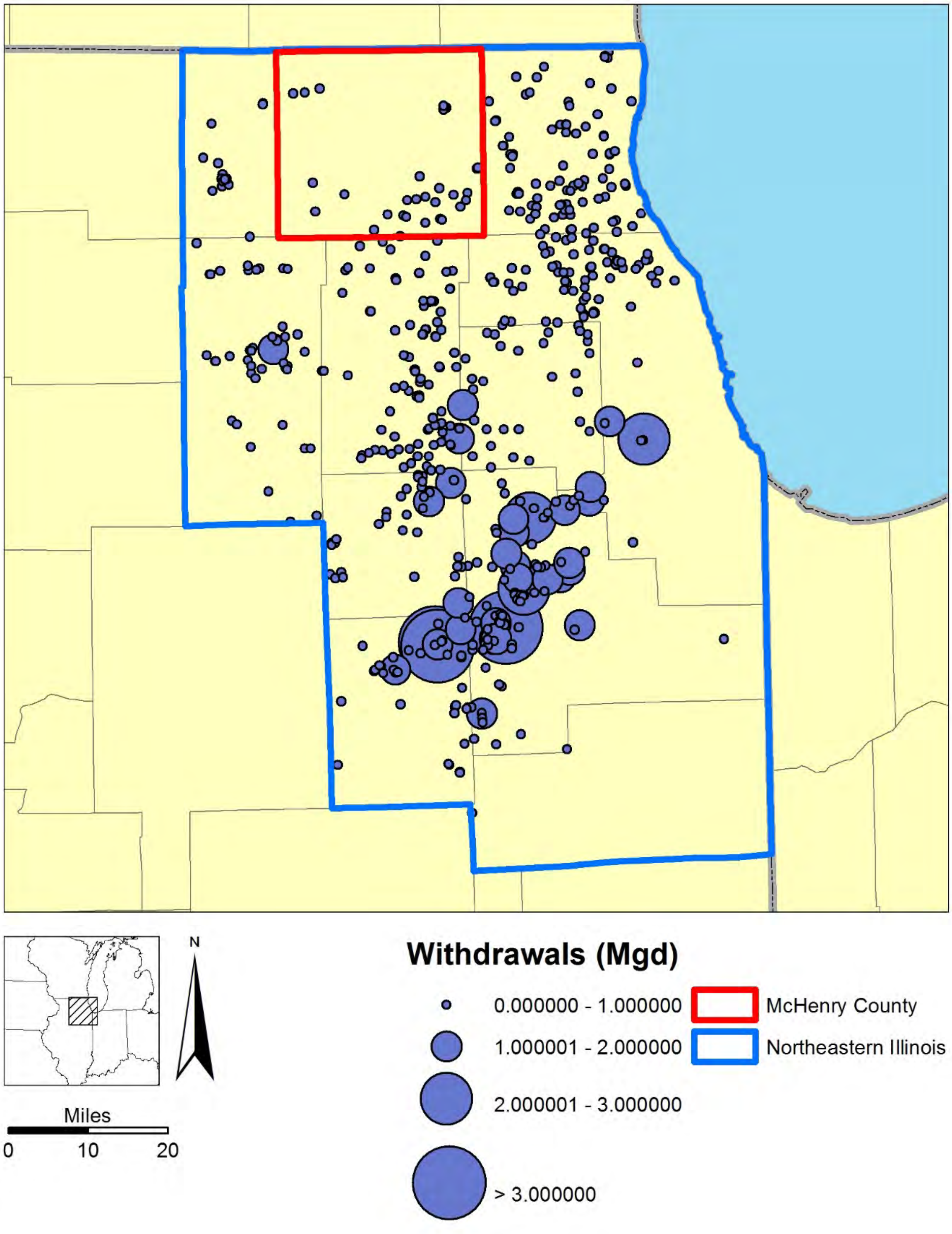

Figure 66 Deep groundwater withdrawals in northeastern Illinois, 2050 (LRI scenario)

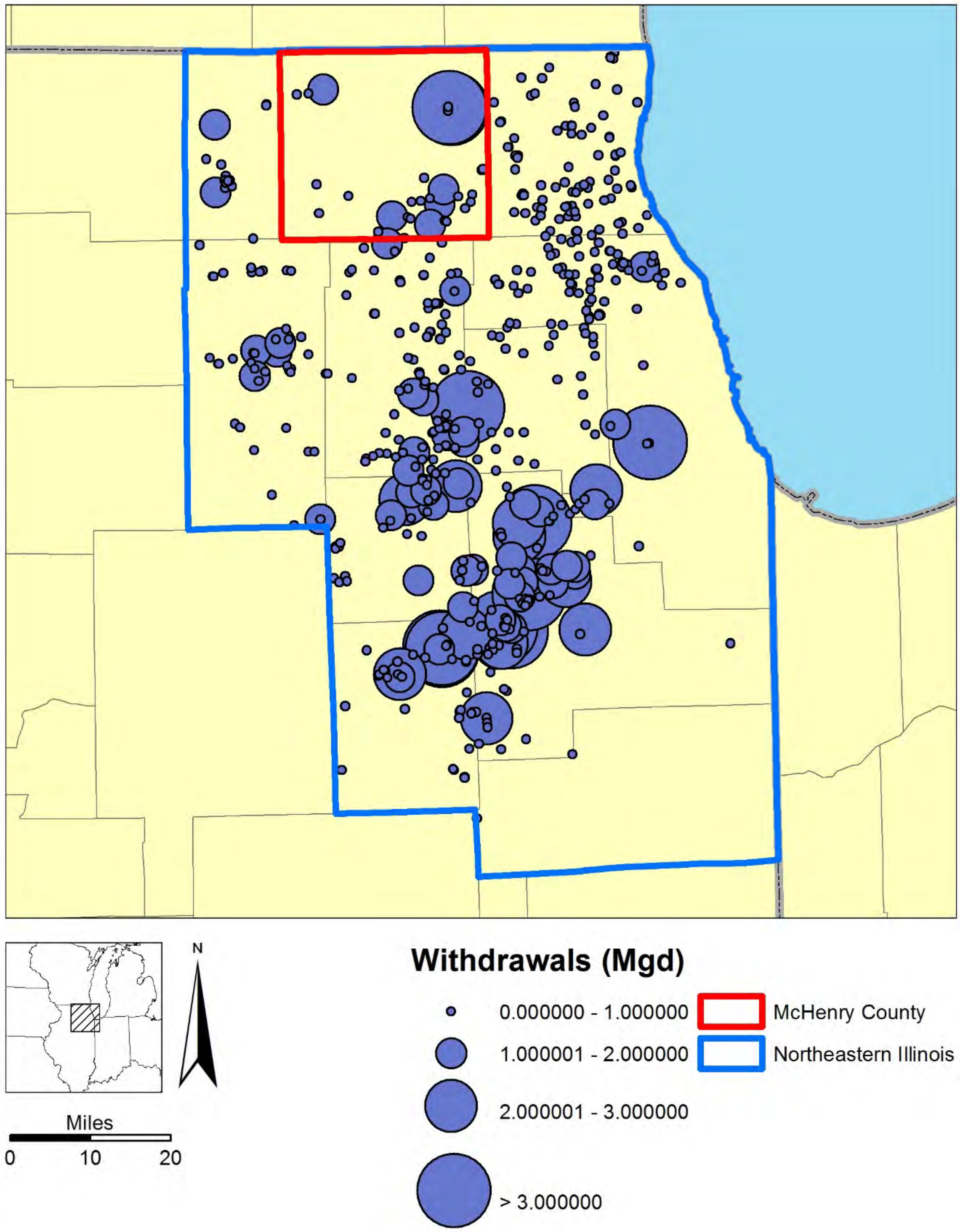

Figure 67 Deep groundwater withdrawals in northeastern Illinois, 2050 (MRI scenario)

4.1.2 Comparison with Meyer et al. (2009)

For a previous modeling study, Meyer et al. (2009) developed a local-scale groundwater flow model covering the shallow subsurface of Kane County and adjacent townships. Since the highly resolved portion of the groundwater flow model of this study and the Kane County local-scale flow model are so similar, a reader familiar with both models may question the difference between model results published here and those published by Meyer et al. (2009). The authors devote this section of the report to comparing inputs to the two flow models. The comparison is summarized in Table 4.

The horizontal domains of the two flow models differ greatly, the model of this study covering much of the upper Midwest and the local-scale model of Meyer et al. (2009) covering only Kane County and adjacent townships of surrounding counties (Figure 68). The area of greatest horizontal resolution of the model of the present study, and its area of greatest accuracy (i.e., the model nearfield), is similar in scale to the local-scale model of Meyer et al. (2009), but it encompasses McHenry County; whereas the local-scale model of Meyer et al. (2009), which is equally highly resolved throughout its domain, encompasses Kane County and vicinity (Figure 68). These areas overlap in the southern tier of townships of McHenry County. The local-scale Kane County flow model employs square cells that measure 660 by 660 ft, whereas the flow model of the present study uses square cells that measure 625 by 625 ft (Figure 49) in its most highly resolved area. The model cells of the present flow model increase gradually to dimensions of 80,000 by 80,000 ft in the *x*-*y* direction in the outer corners of the regional model. The accuracy is greater where cells are smaller.

The vertical domains of the models differ significantly. The domain of the model of the present study includes all geologic materials above the Precambrian basement, which we assume to be impermeable. The domain of the Kane County local-scale flow model includes only the Shallow Bedrock Aquifer and overlying Quaternary materials. The vertical resolution of the Kane County local-scale flow model is greater than the flow model of the present study. The Kane County local-scale flow model represents the Quaternary materials with 14 layers, whereas the flow model of the present study uses only 9 Quaternary layers.

As discussed in Section 4.1.1.1, the representation of the Quaternary materials in the present groundwater flow model is most highly resolved and most accurate within the model nearfield, which approximates McHenry County (Figure 48). Outside the model nearfield, the resolution decreases, although the representation of the Quaternary materials honors mapping in all areas within the McHenry County geologic mapping domain (Figure 48). The local-scale model of Meyer et al. (2009) is equally resolved and is most accurate in its representation of the Quaternary materials throughout its domain, but for reasons discussed in the following paragraph, the model provides its most accurate results within Kane County proper, not within its entire domain.

The local-scale Kane County flow model depends on the approach of telescopic mesh refinement (TMR) to simulate the effects of pumping from outside its domain. Meyer et al. (2009) simulated pumping outside the local-scale model domain using a separate model, which they termed a regional-scale model. The TMR approach, as applied to the Kane County local-scale flow model, used 2002 fluxes computed from the regional-scale model for model cells bordering the local-scale model domain, and applied these fluxes to cells of the local domain. By using TMR, the local model responded to regional pumping stresses outside of the local model domain. Importantly, TMR simulation of regional flow through incorporation of model-boundary fluxes leads to erroneous simulated heads in model cells proximal to the model boundaries. These errors have negligible effects on model accuracy inside Kane County, but they do render the Kane County local-scale model results unusable for meaningful analysis in the southern portion of McHenry County.

Meyer et al. (2009) simulated markedly different scenarios of future pumping than those used in the present study. The scenarios simulated by Meyer et al. (2009) differ from those simulated in the present study because they rely on different statistical models of water use in the region, and the statistical modeling that is the basis of the scenarios modeled in the present study employs updated data. Although they do not claim to represent more probable outcomes, the scenarios employed by Meyer et al. (2009), based on estimates of future water use developed by Dziegielewski et al. (2004) and Dziegielewski et al. (2005), suggest less water use in northeastern Illinois than the scenarios of the present study (Figure 69). The scenarios of Meyer et al. (2009) project total groundwater pumping of 210 to 311 Mgd in the region in 2050, while the LRI, BL, and MRI scenarios of the present investigation project groundwater withdrawals of about 298, 387, and 487 Mgd, respectively, in 2050.

In summary, the Kane County local-scale flow model is vertically more highly resolved than the model of the present study and therefore should provide more accurate results within Kane County. Although its domain partially overlaps McHenry County, the results it provides for the area of overlap, which encompasses southern McHenry County, are likely in error since this area of the model falls along TMR's constant flux boundary. Furthermore, updated mapping of the Quaternary units in McHenry County provides greater certainty to the boundaries of hydrostratigraphic units within the county.

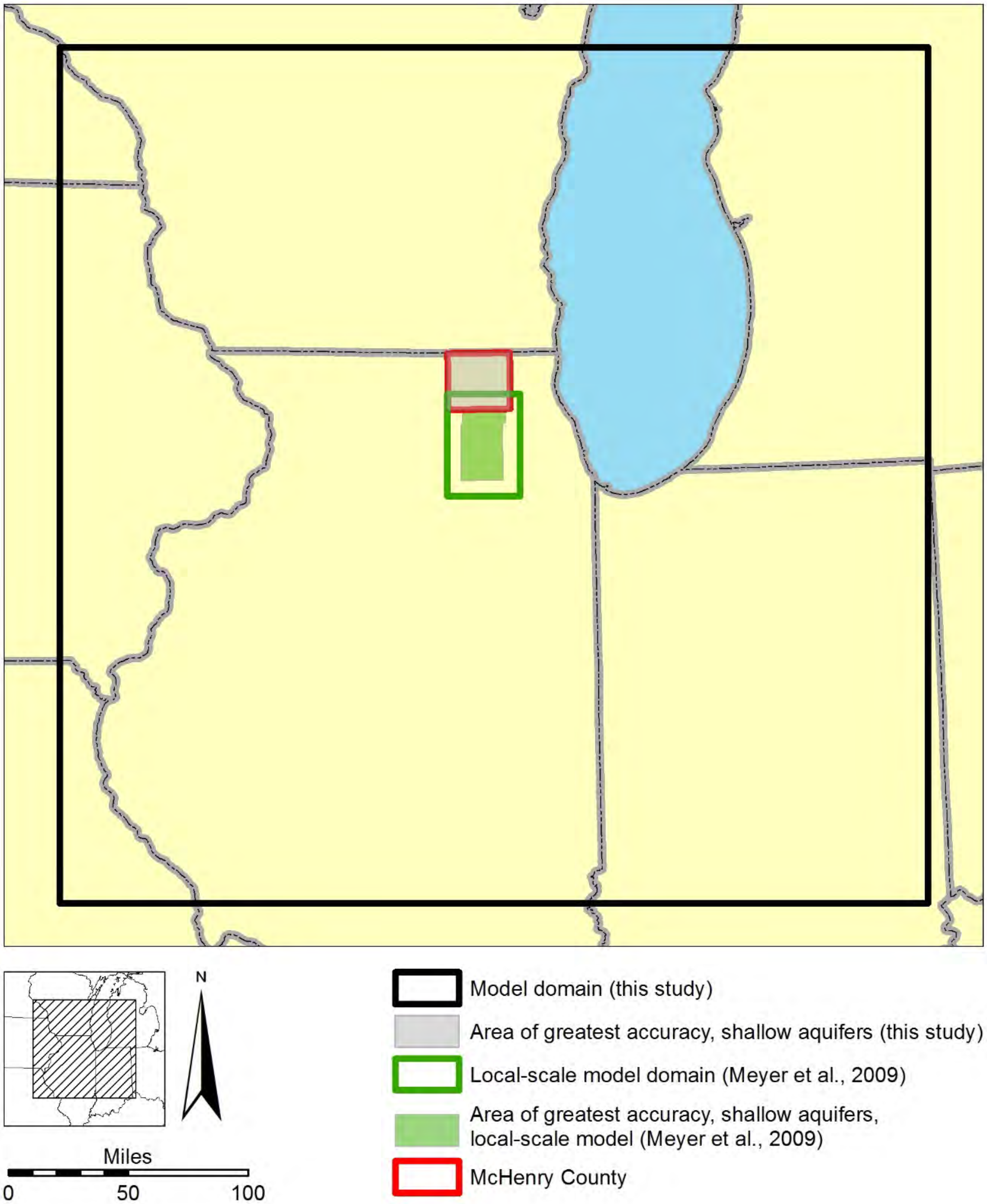

Figure 68 Domains of the groundwater flow model of this study and the local-scale model of Meyer et al. (2009), showing areas of greatest accuracy for the shallow aquifers

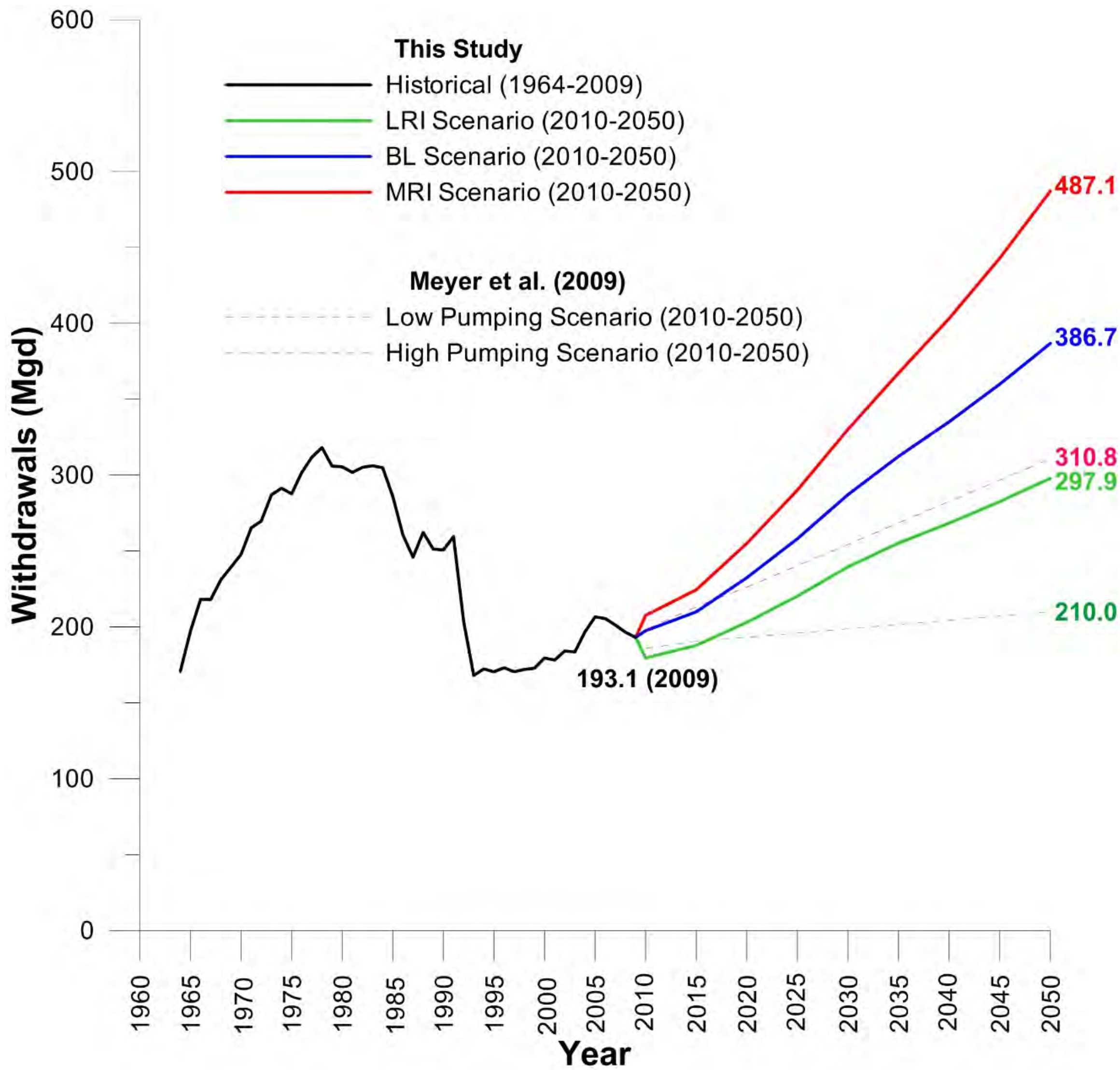

Figure 69 Scenarios of future pumping in northeastern Illinois employed in this study and by Meyer et al. (2009)

Table 4 Comparison of Shallow Groundwater Modeling of McHenry County (This Study) with Local-Scale Model of Kane County Area (Meyer et al., 2009)

Model characteristic	***Present study***	***Kane County local-scale flow model (Meyer et al., 2009)***
Model domain (Figure 68)	Multiple-state area	Kane County and bordering areas within about 6 miles of Kane County
Area of greatest accuracy for simulation of shallow groundwater flow (Figure 68)	McHenry County	Kane County
Horizontal grid resolution	Maximum resolution Δ*x* and Δ*y* =625 ft, Minimum resolution Δ*x* and Δ*y* =80,000 ft, (Figure 48)	Δ*x* and Δ*y* =660 ft
Vertical resolution	Quaternary represented by 9 layers (Figure 47)	Quaternary represented by 14 layers
Geological modeling of area of greatest accuracy for simulation of shallow groundwater flow	Developed by ISGS from borehole data, geophysical data, and previous analysis and mapping (Thomason and Keefer, 2013)	Developed by ISGS from borehole data, geophysical data, and previous analysis and mapping (Dey et al., 2007)
Simulation of boundary flow to/from area of greatest accuracy for simulation of shallow groundwater flow	Flows to/from McHenry County are integral to the regional model covering much of the upper Midwest. As such, flows to/from the area of greatest model accuracy reflect transient changes in pumping within the entire region.	Flows to/from Kane County are linked, using the approach of telescopic mesh refinement, to a separate regional model covering much of the upper Midwest. This approach requires more preparation time for any new configuration.
Simulation of historical withdrawals	1864-2009	1964-2003
Simulation of future withdrawals (Figure 69)	2010-2050; three scenarios (BL, LRI, MRI) developed by modifying estimates for northeastern Illinois by Dziegielewski and Chowdhury (2008) and developed for other areas from estimates by Dziegielewski et al. (2004)	2004-2050; two scenarios (low pumping, high pumping) developed from estimates for the entire Midwest by (Dziegielewski et al., 2004; Dziegielewski et al., 2005)
Numerical model and parameter estimation capability	MODFLOW-2000	MODFLOW with TMR and without parameter estimation

4.1.3 Comparison with Meyer et al. (2012)

Meyer et al. (2012) developed a groundwater flow model similar to that of this study. The authors devote this section of the report to comparing the two flow models. The comparison is summarized in Table 5.

The model of Meyer et al. (2012) simulates groundwater flow in a domain that is identical to that of the present study, but the model developed for the present study provides greater resolution in McHenry County. The model of Meyer et al. (2012) was developed by revising the regional-scale model of Meyer et al. (2009) to provide results accurate enough to guide initial water supply planning efforts (1) pertaining to the deep aquifers throughout northeastern Illinois and (2) pertaining to the shallow aquifers within the Illinois portions of the Fox River watershed. The model of Meyer et al. (2012) employs square cells that measure 2500 by 2500 ft in its most highly resolved area, which encompasses most of northeastern Illinois, including McHenry County. This is significantly less horizontal resolution in McHenry County than is provided by the model of this study which employs square cells measuring 625 ft per side in that area. The model of Meyer et al. (2012) employs 22 layers, including 5 representing Quaternary materials. In contrast, the model developed for the present study uses 26 layers, 9 for Quaternary units. With its greater horizontal and vertical resolution in McHenry County, the model of the present study can provide more realistic simulations of groundwater conditions in McHenry County than those of Meyer et al. (2012).

The representation of the bedrock geology (i.e., the top and bottom elevations of materials below the bedrock surface) in the model of this study and that of Meyer et al. (2012) is essentially identical, as both rely on the same source data. These source data are described by Meyer et al. (2009). With its greater resolution in McHenry County, as discussed in the preceding paragraph, the model of the present study affords more accurate simulation of groundwater flow in the deep aquifers underlying McHenry County. The model of Meyer et al. (2012) does not simulate the effects of interformational transfer of water via boreholes, but the current model simulates such transfer through incorporation of a zone of high vertical hydraulic conductivity in the layers between the Ancell and Ironton-Galesville Units. This zone is delineated to encompass the geographic area in which most deep boreholes are located in northeastern Illinois (Roadcap et al., in preparation).

The models differ in the areas where they represent the Quaternary materials accurately. The model of Meyer et al. (2012) simulates the shallow aquifers most accurately in the Illinois portion of the Fox River watershed, while the model of the present study simulates shallow groundwater flow most accurately in the model nearfield of McHenry County (Figure 70). Since the Illinois portion of the Fox River watershed only covers the eastern part of McHenry County, the model of the present study provides superior simulation of shallow groundwater flow throughout the county. In addition, as discussed above, the model of the present study is more highly resolved, both horizontally and vertically, in McHenry County than is the model of Meyer et al. (2012), permitting greater output accuracy. Finally, to improve simulations of base flow in rivers and drains, all sink cells were moved into the upper model layer in the current model.

As discussed in Section 4.1.1.3 (also see Figure 54 and Figure 55), the present study model simulates less future pumping in northeastern Illinois than does the model of

Meyer et al. (2012). Although the pumping scenarios simulated by both models are speculative, with no stated probability, the scenarios simulated for the present study are more consistent with current conditions in McHenry County and therefore represent more likely future pumping conditions than those simulated by Meyer et al. (2012).

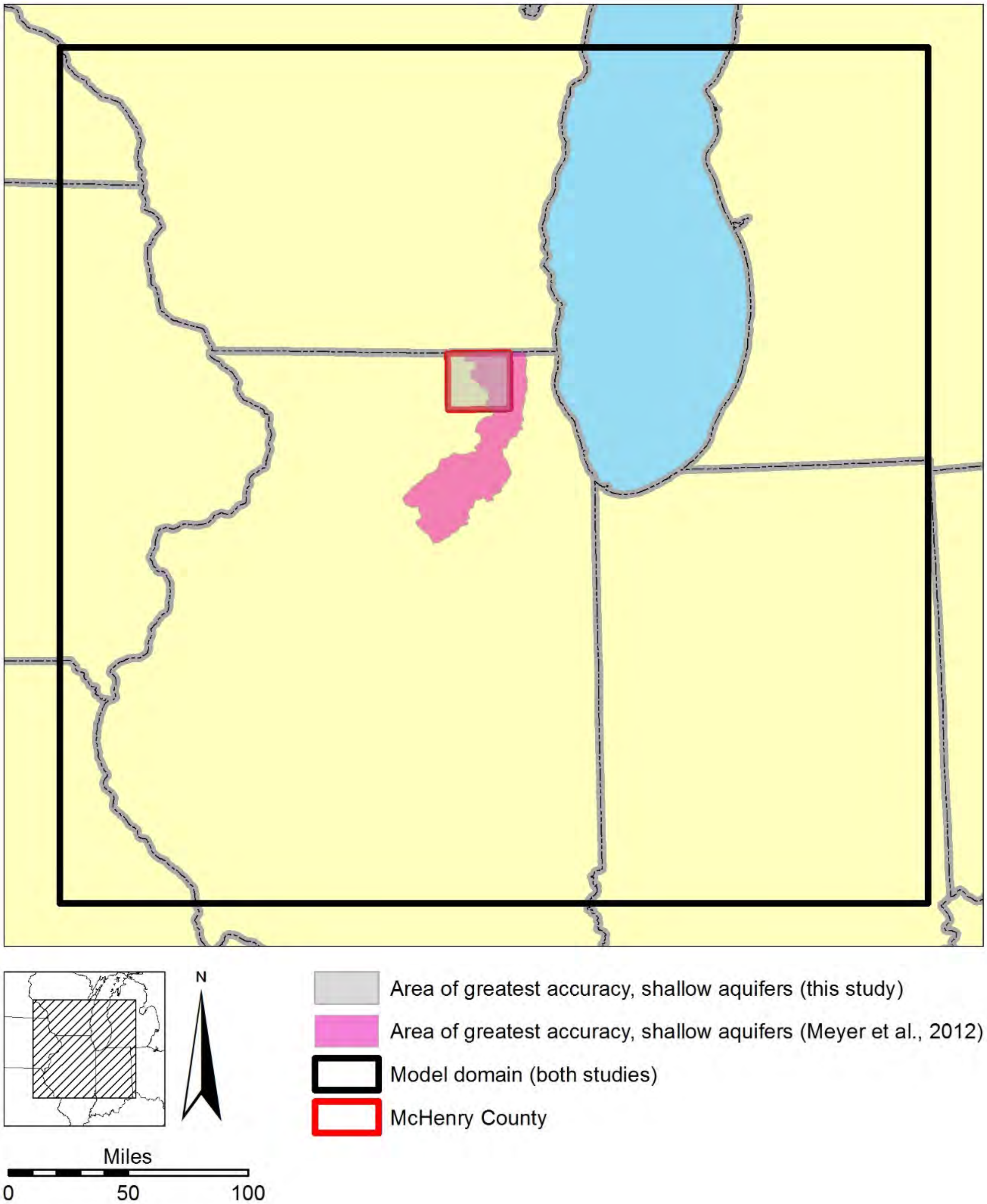

Figure 70 Domains of the groundwater flow model of this study and that of Meyer et al. (2012), showing areas of greatest accuracy for the shallow aquifers

Table 5 Comparison of Groundwater Modeling of McHenry County (This Study) with Groundwater Modeling of Meyer et al. (2012)

Model characteristic	***Present study***	***Meyer et al. (2012)***
Model domain (Figure 70)	Multiple-state area [same as Meyer et al. (2012)]; 2,756,503 active cells	Multiple-state area (same as present study); 823,278 active cells
Area of greatest accuracy for simulation of shallow groundwater flow (Figure 70)	McHenry County	Fox River watershed in Illinois
Horizontal grid resolution	Maximum resolution Δ*x* and Δ*y*=625 ft, Minimum resolution Δ*x* and Δ*y*=80,000 ft (Figure 48)	Maximum resolution Δ*x* and Δ*y*=2,500 ft Minimum resolution Δ*x* and Δ*y*=80,000 ft
Vertical resolution	26 layers Quaternary represented by 9 layers (Figure 47)	22 layers Quaternary represented by 5 layers
Shallow geological modeling of area of greatest accuracy for simulation of shallow groundwater flow	Developed by ISGS from borehole data, geophysical data, and previous analysis and mapping (Thomason and Keefer, 2013)	Developed from a range of previous and ongoing high- moderate-, and low-resolution mapping.
Simulation of boundary flow to/from area of greatest accuracy for simulation of shallow groundwater flow	Flows to/from McHenry County are integral to the regional model covering much of the upper Midwest. As such, flows to/from the area of greatest model accuracy reflect transient changes in pumping within the entire region.	Flows to/from the Illinois portion of the Fox watershed are integral to the regional model covering much of the upper Midwest. As such, flows to/from the area of greatest model accuracy reflect transient changes in pumping within the entire region.
Simulation of historical withdrawals	1864-2009	1864-2005
Simulation of future withdrawals (Figure 54, Figure 55)	2010-2050; three scenarios (BL, LRI, MRI) developed by modifying estimates for northeastern Illinois by Dziegielewski and Chowdhury (2008) and developed for other areas from estimates by Dziegielewski et al. (2004)	2006-2050; three scenarios (BL, LRI, MRI) developed for northeastern Illinois by Dziegielewski and Chowdhury (2008) and developed for other areas from estimates by Dziegielewski et al. (2004)
Numerical model and parameter estimation capability	MODFLOW-2000	MODFLOW-2000 and PEST

4.2 Model Results

This section discusses results of model simulations of historical groundwater conditions and future groundwater pumping scenarios (Section 2.3). The modeling of historical conditions simulates pumping between 1864 (when large-scale pumping is considered to have begun in northeastern Illinois) and 2009. It is a transient simulation in which pumping for each well represented in the model is varied annually. The locations of shallow and deep wells simulated in the model are shown in Figure 50 and Figure 51. Only the pumping rates of these are changed from year to year in the simulations; all other parameters remain constant through time. The simulations provide insight into the principal influences on groundwater flow in the region and permit characterization of past, present, and future pumping impacts.

For both the historical and future simulations, the discussion and illustrations in this section emphasize the following:

- Simulated drawdown in the Haeger-Beverly Unit (model layer 2)
- Simulated drawdown in the Ashmore Unit (model layer 5)
- Simulated drawdown in the Lower Glasford Sand Unit (model layer 9),
- Simulated drawdown in the Ancell Unit (model layer 18),
- Simulated drawdown in the Ironton-Galesville Unit (model layer 21),
- Simulated available head above the top of the Ancell Unit,
- Simulated available head above the top of the Ironton-Galesville Unit, and
- Simulated natural groundwater discharge to streams.

These types of model output indicate the locations and magnitudes of major groundwater pumping impacts. Model output can be used to identify areas for further data collection and analysis, thus reducing modeling uncertainty. It can also provide a basis for formulating management policies directed toward reducing impacts in areas where such impacts are judged unacceptable by local stakeholders, possibly preceding policy implementation with benefit-cost analyses (e.g., alternative water resource development scenarios).

Some model simulations are affected by termination of well withdrawals when model layers became desaturated during model runs. That is, when a layer becomes completely dry, such as around a pumping well, the software automatically terminates the withdrawals assigned to the dewatered cells in that layer. This termination is especially problematic for wells tapping multiple layers, such as many of the deep aquifer wells in this model. In such situations, a specific pumping rate is assigned to each layer in a multi-layer well. If a layer completely desaturates, (typically the upper layers desaturate first as drawdown increases), the pumping assigned to that layer is reset to zero and, unlike the real world, the terminated withdrawal is not assigned to deeper layers tapped by the modeled well.

Automatic termination of withdrawals can, to a limited degree, lead to unexpected and conflicting output. For example, termination of withdrawals due to desaturation under higher-pumping scenarios, with consequent head recovery, may lead to output that shows less drawdown under higher pumping conditions than under lower pumping conditions. However, such conflicting output affects only limited areas and limited periods of simulation. Output affected by automatic termination of withdrawals may reflect a computational cycle in which (1) a model cell/layer desaturates, (2) withdrawals from the desaturated cell/layer are turned off, (3) the model unit resaturates in response to cessation of withdrawals, (4) withdrawals are restarted, and (5) the model unit again desaturates, starting the cycle again. In some cases, this problem may be a result of assigning excessive pumping to an existing well location rather than spreading the added demand to new locations and source aquifers. In other cases, this problem may be a result of dividing a single aquifer unit into multiple layers (e.g., as shown in Figure 47, in this model the Silurian-Devonian Carbonate Unit is split into three layers, and drawdown cannot extend too deeply into a unit before withdrawals are curtailed). An objective during model calibration was to eliminate dry cells due to pumping during historic simulations, as these dry cells represent an unrealistic outcome. Dry cells do influence simulations of future pumping, but these influences are greatest in the deep aquifers of southern Kane and Will Counties, far from McHenry County. Investigation of the specific locations, wells, and timing of the automatic termination of simulated withdrawals is recommended for future analysis.

4.2.1 Transmissivity of the Shallow Aquifers

The process of exploring for new well sites in the shallow aquifers by users seeking to develop new supplies, expand existing supplies, or reduce drawdowns in problem areas can be guided by a transmissivity map (Figure 71). The transmissivity distribution was calculated by multiplying the saturated thickness of each model cell by the assigned permeability. High transmissivities are present in eastern McHenry County along the Fox River where thick glacial sands overlie a permeable Shallow Bedrock Aquifer. High transmissivities also occur near Wonder Lake and Woodstock and in the bedrock valleys near Marengo and Harvard (Figure 5). Transmissivities are generally lower in the southeastern portion of the county where most of the permeable deposits are already being utilized. These low transmissivities and high pumping rates have led to widespread drawdown in southeastern McHenry County, particularly in the Lower Glasford Sand Unit (Figure 71).

High capacity wells are generally constructed in aquifers where the transmissivities exceed 5000 ft^2/d. Fox example, a cluster of wells with a combined pumping rate exceeding 0.3 Mgd is located in the high transmissivity zone at Woodstock. Future groundwater development in this area will require more exploration to find suitable well sites and may ultimately require more wells pumping at lower rates to yield the same supply. The presence of currently untapped highly transmissive shallow deposits throughout McHenry County (particularly in the western part of the county) provides an alternative to development of the deep aquifers, which have a transmissivity of only 3000 ft^2/d. The deep aquifers are also more expensive to use, and groundwater derived from them can have high radium concentrations that require treatment.

4.2.2 Model Analysis of the Shallow Aquifers

Groundwater in the shallow aquifers circulates within local flow cells and discharges to surface waters largely within the Fox and Kishwaukee River watersheds. Under predevelopment (i.e., nonpumping or natural) conditions, discharge of shallow groundwater occurred exclusively by seepage to surface waters and wetlands, but under conditions in which groundwater is pumped from the aquifers, a proportion of discharge occurs through wells. This change has the effect of reducing discharge to wetlands, drains, and surface waters.

Model simulations show that drawdown in the shallow aquifers is generally on the order of a few feet to tens of feet, while drawdown in deep aquifers is on the order of hundreds of feet. This difference is attributable to availability of replacement water to the aquifers (i.e., water entering the aquifers to replace groundwater withdrawn through wells). In northeastern Illinois, the relatively impermeable Maquoketa and Upper Bedrock Units, where present, greatly limit leakage into the deep aquifers from above, so replacement water for these aquifers is derived principally by slow, lateral movement from north-central Illinois where this relatively impermeable cover is absent.

Aquitards are also present within the glacial drift above the bedrock, but they are discontinuous and variable in thickness. These aquitards result in decreased leakage rates with depth in the glacial drift. Lower leakage rates also result in more severe drawdowns with depth. For example, drawdown in 2009 is progressively greater downward within the sequence of shallow hydrostratigraphic units (see Figure 72 to Figure 74). All layers have their greatest drawdown near pumping wells in the Woodstock vicinity of central McHenry County. The drawdown in southeastern McHenry County increases downward, with a ubiquitous drawdown zone in the Lower Glasford Sand Unit. The Lower Glasford Sand is overlain by two aquitards and also experiences more pumping of any of the other shallow units, hence the large drawdowns. The drawdown distribution in the Lower Glasford Sand Unit is similar to that of the underlying Shallow Bedrock Aquifer (not shown), with which it is hydraulically connected. The drawdown in these units reflects relatively unimpeded flow across the interface between the units and is influenced by pumping from both units.

On the north side of Woodstock, a significant cone of depression surrounds Woodstock wells 8, 9, 10, 11, 12, and 101, which are screened in the Ashmore Unit and Lower Glasford Sand Unit. Simulations indicate that pumping had caused as much as 32 and 44 ft of drawdown in the Ashmore and Lower Glasford Sand Units in that area, respectively, as of 2009. Model simulations suggest that pumping from the Ashmore and Lower Glasford Sand Units by the Woodstock wells has additionally caused up to 14 ft of drawdown in the overlying Haeger-Beverly Unit at this location. Coalescing cones of depression, some resulting from pumping in Kane County, affect heads in the shallow aquifers in much of southeastern McHenry County. These features are related to pumping from wells operated by Crystal Lake, Cary, Algonquin, and Carpentersville, which withdraw groundwater from the Ashmore, Upper Glasford, and Lower Glasford Sand Units. Simulated drawdown of up to 58 ft affects head in these aquifers in southeastern McHenry County, the greatest in the Lower Glasford Sand Unit in the vicinity of Crystal Lake wells 12 and 13. The Crystal Lake wells obtain water from the Shallow Bedrock Aquifer and overlying Lower Glasford Sand Unit.

Simulations of future pumping scenarios (Figure 75 to Figure 92) illustrate the expansion and coalescence of the 2009 cones of depression (Figure 72 to Figure 74) and the appearance of others, given the assumptions of this project regarding future pumping—namely, that future pumping will be obtained from the same wells as were active in 2009. Simulation results for 2030 are illustrated in Figure 75 to Figure 83 for the three scenarios, and results for 2050 are shown in Figure 84 Figure 92. In 2050 under the MRI scenario, simulated drawdown exceeds 5 ft in the Ashmore and Lower Glasford Sand Units in much of central and eastern McHenry County, with greatest drawdown surrounding the Woodstock and Crystal Lake wells discussed in the preceding paragraph. Of the 2009 cones of depression discussed in the preceding paragraphs, the most significant expansion occurs in the north Woodstock cone, where maximum drawdown in 2050 ranges from 58 ft (LRI scenario) to 101 ft (MRI scenario). The Lower Glasford Sand Unit incurs the greatest drawdown in the north Woodstock feature, but heads in other shallow aquifers are also affected.

4.2.3 Model Analysis of Natural Groundwater Discharge to Streams

Drawdown is in part reduced through capture of streamflow, so drawdown in the shallow aquifers, while significant in limited areas, is not as widespread as in the deep aquifers (see discussion in Section 4.2.4). Model simulations suggest that pumping from shallow wells with resultant capture of streamflow can significantly reduce natural groundwater discharge to streams (the source of stream base flow) in some areas, although observations do not document such impacts. Streamflow capture occurs by two mechanisms: (1) diversion into shallow wells of groundwater that would otherwise discharge to streams, and (2) inducing streamflow to leak from stream channels. Model analysis suggests that total natural groundwater discharge to 36 sub-basins in a watershed-defined area approximating McHenry County (Figure 93) declined from predevelopment rates by 10.1 and 11.5 percent in 1989 and 2009, respectively, reflecting increased pumping of shallow groundwater in the area (Figure 94, Table 6).

These reductions are not evenly distributed across the Fox River watershed, however, because local hydrogeology is variable and pumping is irregularly distributed. Results of analysis for pumping conditions in 1989 and 2009 for the sub-basins illustrated in Figure 93 are reported and shown in Table 6, Figure 95, and Figure 96. From pre-development (pre-1864) to 1989, decreases in simulated groundwater discharge to individual sub-basins ranged from 3.0 to 30.3 percent (Figure 95). From pre-development to 2009, decreases in simulated groundwater discharge to the sub-basins ranged from 3.3 to 39.3 percent (Figure 96). A decrease of 100 percent represents a stream no longer receiving groundwater, but this does not occur in the model simulations.

In 1989, the greatest simulated reductions occur in the City of Woodstock sub-basin of central McHenry County, reflecting heavy pumping of shallow groundwater in this sub-basin together with the presence of a strong hydraulic connection between the shallow aquifers that facilitates streamflow capture. This heavy pumping is also represented by the large cone of depression shown in Figure 72 to Figure 74. In 2009, the Crystal Lake Outlet sub-basin, which overlays the center of the cone of depression in the Lower Glasford Sand Unit of southeastern McHenry County (Figure 74), exhibits the largest reduction in natural groundwater discharge.

The simulated reductions in natural discharge may not be readily observable, primarily because many streams in McHenry County receive a steady influx of effluent. This is not to suggest that effluent, even treated to high standards, is a substitute for natural groundwater discharge, since effluent and groundwater differ in quality and temperature, and natural groundwater discharge is a diffuse process occurring along the length of stream channels, whereas effluent is added to streams at point locations (outfalls). The tolerance of ecological communities to such subtle differences is a subject that requires further research. Our modeling shows that the reduction in natural groundwater discharge to the Crystal Lake Outlet sub-basin is about 1.9 Mgd in 2009, yet, as of 2001, effluent was discharged to Crystal Lake Outlet at a rate of about 4 Mgd (Illinois State Water Survey, 2003). These data suggest that, even if Crystal Lake Outlet has lost 39% of its natural groundwater discharge, so much effluent is discharged to the stream that its low flows, at least downstream of the effluent outfalls, are probably higher than under predevelopment conditions. Effluent partially offsets the reduction in natural groundwater discharge suggested by our model for the City of Woodstock sub-basin as well. Our modeling suggests the natural groundwater discharge to the City of Woodstock sub-basin has been reduced by about 1.6 Mgd as of 2009, but, as of 2001, effluent was discharged to Silver Creek (the principal stream of the sub-basin) at a rate of about 1.2 Mgd (Illinois State Water Survey, 2003).

Simulated changes in natural groundwater discharge under conditions of future pumping are shown in Figure 94, Figure 97 to Figure 102, and Table 7 to Table 9. The geographic distribution of these reductions (Figure 97 to Figure 102) resembles that of reductions illustrated and discussed for 1989 (Figure 95) and 2009 (Figure 96); this is an expected result since simulated future withdrawal locations are identical to those active in 2009. Total reduction in natural groundwater discharge in the McHenry County area ranges from 10.5 to 14.0 percent in 2030 and 11.5 to 17.7 percent in 2050 (Figure 94, Table 7 to Table 9).

Given the approach employed to model natural groundwater discharge and the scarcity of available observations of historical streamflow, verification of the reductions in streamflow suggested by the model is a critical area for future study. The simulated reductions in groundwater discharge suggested by the modeling of this study are both annualized and aggregated along stream reaches. As such, they may not be observable or easily recognized at specific points along a stream or during all periods of the year. Further, model calibration was based on estimates of average annual groundwater discharge (based on the mean of Q_{50} and Q_{80}), not groundwater discharge under low flow, or drought, conditions (e.g., $Q_{7,10}$). Therefore, the discharge reductions shown in Figure 95 to Figure 102 (and Table 6 to Table 9) may not reflect reductions under low flow conditions.

Reductions will be most noticeable during low flow periods on tributary streams that do not receive effluent and previously very rarely went dry. Such streams will potentially go dry more often than they did historically. In the case of ephemeral streams, dry periods may become more prevalent or more prolonged. Reductions in natural groundwater discharge to streams may already be occurring, but for most streams in the region, historical data are not available to verify the reductions. In addition, analysis of available streamflow data to verify these reductions has not been conducted.

Lastly, reductions in natural groundwater discharge resulting from pumping may be masked by hydrologic factors that are not simulated by the groundwater flow modeling of this study, some of which could offset the simulated reductions, at least in part. These factors include alterations of the hydrologic cycle accompanying land cover changes. For example, urbanization is accompanied both by increasing impermeable surfaces—a factor which potentially reduces discharge by reducing recharge—and by increasing imports of water to the shallow subsurface through leaking pipe networks—a factor which may increase discharge. Increasing discharges of wastewater effluent, such as on the main stem of the Fox River, also mask base flow reductions resulting from groundwater withdrawals. Finally, like most regional groundwater flow models, the current model does not simulate discharge from bank storage as a source of streamflow. In streams where flow has increased, for example as a consequence of effluent or leaking pipe networks, bank storage may have increased, providing greater streamflow than in the historical past.

4.2.4 Model Analysis of the Deep Aquifers

4.2.4.1 Introduction

In most of northeastern Illinois, the exchange of water between the shallow and deep aquifers is greatly limited by relatively impermeable rocks of the Maquoketa and Upper Bedrock Units overlying the deep aquifers. Circulation within the deep aquifers thus occurs on a regional scale, with most recharge into the aquifers occurring in Boone and De Kalb Counties, where the impermeable rocks are absent. Previous modeling studies (e.g., Young, 1992) suggest that, under predevelopment conditions, groundwater in the deep aquifers underlying northeastern Illinois slowly discharged upward into the shallow units, and ultimately to surface waters—primarily the upper Illinois River and lower Fox River, with some diffuse upward leakage to Lake Michigan. Presently, discharge of deep groundwater in the region is dominated by flow to wells. As described in Section 4.2.1, drawdown in the deep aquifers in the area of confinement by the Maquoketa and Upper Bedrock Units is widespread and of much greater magnitude than in the shallow aquifers. The relatively impermeable Maquoketa and Upper Bedrock Units, where present, greatly limit leakage into the deep aquifers from above, so replacement water for these aquifers is derived principally by slow, lateral movement from north-central Illinois where this relatively impermeable cover is absent. The slow lateral movement of water from north-central Illinois cannot keep pace with rates of withdrawal in the area of confinement, so deep well withdrawals are derived from reduction in aquifer storage, and cones of depression deepen and widen. Section 4.2.4 is a discussion of pumping impacts on the Ancell Unit followed by a similar treatment of the Ironton-Galesville Unit.

4.2.4.2 Uncertainty

Observed water levels in deep wells are composites of the heads in all units intercepted by the open borehole of the well. This model simulates individual model layers, however, and thus, the model-simulated heads are not necessarily equal to the composite water levels measured in typical multiple-aquifer deep northeastern Illinois wells. In an earlier version of the model developed for this project, the observed head falls between the simulated aquifer heads in the Ancell, Ironton-Galesville, and Eau Claire Units. The authors attribute a portion of the disagreement between the simulated heads in model layers and the observed water levels to uncertainty in the head measurements used for model calibration estimated in the model nearfield at ±200 ft (Section 4.1.1.2). Much of the remaining difference between observed composite water levels and simulated heads in individual aquifers may be attributable to interformational transfer of groundwater, via open boreholes, between deep aquifers. With the influence of unsimulated downward transfers of groundwater in the thousands of deep wells in northeastern Illinois, then, actual heads are likely to be lower in the Ancell and higher in the Ironton-Galesville than model-simulated heads. As a result, we incorporated a high vertical hydraulic conductivity zone developed in Roadcap et al. (in preparation). This high vertical hydraulic conductivity zone is primarily located southeast of McHenry County and allows for equilibration of heads between the Ancell and Ironton-Galesville consistent with observations from monitoring wells. It extends into the southeastern corner of McHenry County but is not present throughout the rest of the county. The model could be greatly improved if widespread observations of formation-specific heads, rather than composite heads, become available; these would be employed for model calibration and/or verification. Furthermore, research into improved methodologies of modeling interformational boreholes is necessary to elucidate the impact of the transfer of water between the formations.

4.2.4.3 Ancell Unit

Figure 103 shows drawdown in the Ancell Unit at the end of 2009. Over 50 ft of drawdown affects the entire Chicago-Milwaukee area and much of the area underlying Lake Michigan. This large feature is a product of coalescing cones of depression surrounding numerous individual deep wells, the locations of greatest drawdown generally reflecting the greatest historical withdrawals. Drawdown decreases to less than 50 ft to the west of the Chicago-Milwaukee cone of depression, reflecting higher rates of leakage to the deep aquifers in areas where the impermeable Upper Bedrock Unit and Maquoketa Unit are absent. In northeastern Illinois, the greatest drawdown is centered in southeastern Kane County near Aurora and in northern Will County near Joliet; the model simulates drawdown in excess of 700 ft at both locations. Drawdown in southeastern McHenry County exceeds 400 ft, primarily due to pumping in Kane and Will County. Drawdown in the western portion of McHenry County is less than 200 ft, primarily because this area is distant from large pumping centers and is located adjacent to the area of absence of the impermeable Maquoketa and Upper Bedrock Units (Figure 104), where the greater vertical leakage maintains heads nearer predevelopment levels.

By 2030, drawdown under all three demand scenarios increases due to the anticipated increases in pumping in the Aurora and Joliet areas of southeastern Kane and northern Will Counties (Figure 105 to Figure 107). By 2050 (Figure 108 to Figure 110), the Ancell becomes completely desaturated in Aurora and Joliet under the BL and MRI scenario (Figure 108, Figure 110). As a result of this heavy pumping, drawdowns exceed 300 ft in all but the westernmost portions of McHenry County and increase to over 630 ft in the southeastern portion of the county.

In addition to the likely loss of well pumping capacity, a decline of Ancell Unit heads near to and below the top of the Ancell Unit may lead to water quality problems:

- Studies in the Green Bay area of Wisconsin (Schreiber et al., 2000) suggest that exposure to oxygen of a thin interval at the top of the Ancell Unit containing sulfide minerals has caused a dramatic increase in arsenic concentrations in groundwater withdrawn from deep wells to levels exceeding the United States Environmental Protection Agency (USEPA) drinking water standard of 10 micrograms per liter. Available data do not indicate the presence of elevated or increasing arsenic concentrations in groundwater pumped from deep wells in Illinois. However, since the Ancell Unit of northeastern Illinois is similar to that of the Green Bay area, it is possible that the head declines suggested by model simulations could lead to comparable arsenic increases in northeastern Illinois. Further study of the Ancell of the Chicago region is required to establish whether the arsenic-bearing sulfide mineral layer is widely present in the region and whether declining heads would cause the release of arsenic from it.
- Since many deep wells in northeastern Illinois are open to both the Ancell Unit and the Ironton-Galesville Unit, desaturation of the Ancell Unit could increase the proportion of Ironton-Galesville groundwater withdrawn from these wells. This increased proportion of Ironton-Galesville groundwater may reduce water quality, because the Ironton-Galesville groundwater is believed to be poorer in quality than the Ancell Unit groundwater, containing, most notably, high concentrations of dissolved radium and barium (Gilkeson et al., 1983). Concentrations of barium and radium in the Ironton-Galesville often exceed the USEPA drinking water standards of 1 mg/L and 5 picocuries per liter, respectively.
- Although drawdown with retention of saturated conditions creates problems with deep well productivity and increased pumping expenses, greater drawdown, with desaturation of the Ancell Unit, could increase rates of water level decline in deep wells, thus exacerbating these problems.

Figure 111 to Figure 118 illustrate *available head* above the top of the Ancell Unit during predevelopment and in 2009, 2030, and 2050. *Available head*, in these maps, refers to the difference between simulated Ancell Unit head and the top of the Ancell Unit; it is thus a metric of the Ancell Unit's nearness to desaturation, the outcomes of which are cautioned against in the bulleted list above. Areas having less than 200 ft of available head (shaded in Figure 111 to Figure 118) might be considered for monitoring or as priority planning areas. Note, however, that available Ancell Unit head was commonly less than 200 ft under predevelopment conditions in the western part of the region covered by these figures owing to the shallow position of the Ancell in that region (Figure 111). Drawdown in this area will not be on the same order as where the Ancell is truly a deep aquifer because the Ancell will be replenished by recharge. As a result, areas where head above the top of the Ancell is less than 200 ft during pre-development are generally coincident with areas of low drawdown (compare Figure 111 with Figure 103).

Our simulations of groundwater conditions at the end of 2009 show that available head above the top of the Ancell was greater than 200 ft in most of McHenry County. However, in the southeastern-most part of the county, modeled head was only 150-200 ft above the top of the Ancell (Figure 112), which is consistent with the larger drawdowns observed in this portion of the county (Figure 103). In the Aurora area (southeastern Kane County) and the Joliet area (northern Will County), modeled heads in 2009 are below the top of the Ancell (Figure 112), representing partial desaturation of the Ancell. These reduced available heads are a response to heavy pumping from the deep aquifers in those areas. In the LRI scenario, while desaturation in Kane and Will Counties increases in 2030 and 2050 (Figure 114 and Figure 117, respectively), the impact on available heads in McHenry County is small; only in small portions of the county does the head fall below 150 ft above the top of the Ancell. In the BL scenario, the zone of desaturation in Kane and Will Counties increases in 2030 and 2050 (Figure 113 and Figure 116), resulting in complete desaturation of the Ancell at Aurora and Joliet by 2050 (Figure 116). By 2050, modeled heads in most of southern McHenry County are less than 200 ft above the top of the Ancell and, in southeastern McHenry County, the head is less than 100 ft above the top of the Ancell. The results are similar in the 2030 and 2050 MRI simulations, except the area over which the available head is less than 200 ft encompasses the southern half of the county by 2050 (Figure 115 and Figure 118).

4.2.4.4 Ironton-Galesville Unit

Simulated Ironton-Galesville heads reflect uncertainties owing to a lack of formation-specific head observations for use in model calibration and verification (page 125), simulation of interformational transfer of groundwater via open boreholes (page 125), and termination of withdrawals when cells become desaturated (page 120). The ISWS continues to improve its groundwater flow models to reduce error originating from these problems.

Calibration of the model was not constrained by field observations of heads from wells completed solely in the Ironton-Galesville Unit, because a suitable number of such observations does not exist. Ideally the model calibration procedure selects plausible hydraulic properties and other model parameters so that differences between simulated heads and observed heads (*head calibration targets*) are minimized. Without formation-specific head observations for the Ironton-Galesville Unit, however, constraints on simulated Ironton-Galesville heads do not exist, and the simulated heads themselves must be regarded judiciously.

Further study is needed to clarify how interformational transfer of groundwater via boreholes open to the Ancell and the Ironton Galesville Units affects heads. The simulations discussed in this report assume interformational transfer at deep well fields in northeastern Illinois (Roadcap et al., in preparation). The Ironton-Galesville heads in this zone of interformational transfer are generally within 20 ft of the Ancell heads. This similarity is consistent with measurements by Burch (2002) at Joliet and Nicholas et al. (1987) at Zion that suggest that head differences between the two aquifers are less than 60 ft. Where this zone is located in southeastern McHenry County, heads in the Ancell and Ironton-Galesville are virtually identical in all simulations. In northwestern McHenry County, where the zone is not present, the heads differ by greater than 100 ft in 2009 simulations.

Meyer et al. (2012) discussed software issues contributing to uncertainty of Ironton-Galesville simulations, namely (1) automatic termination of withdrawals from wells open to the Ironton-Galesville caused by complete desaturation of the unit; and (2) persistent desaturated conditions indicative of the limitations of controlling cell resaturation in MODFLOW. The second problem contributed to the first, in that simulated withdrawals from the model were unrealistically reduced by termination of Ironton-Galesville withdrawals in areas of complete desaturation of the unit. The assignment of a high vertical hydraulic conductivity between the Ancell and Ironton-Galesville resulted in head increases in the Ironton-Galesville on the order of hundreds of feet as compared with Meyer et al. (2012) and eliminated all desaturation in the Ironton-Galesville.

Simulated Ironton-Galesville drawdown at the close of 2009 exceeds 700 ft in the Joliet area (northern Will County), with significant drawdown extending into the Aurora area (southeastern Kane County) (Figure 119). By 2030, the cone of depression centered in Will County expands (Figure 120 to Figure 122), and by 2050, a pattern of greater drawdown along the Fox River Valley becomes established (Figure 123 to Figure 125). Slightly greater drawdown in some of the simulation results (e.g., Figure 125) in the Ringwood area of northeastern McHenry County marks the location of industrial pumping in that community.

Despite the relatively large drawdowns, the simulated available Ironton-Galesville head remains greater than 200 ft throughout northeastern Illinois, even in the 2050 MRI simulation. This result is quite different from the previous model simulations in Meyer et al. (2009) and Meyer et al. (2012), in which the available head was below 200 ft around Joliet and Aurora in multiple future pumping scenarios. However, those models did not simulate the impacts of interformational transfer through boreholes; hence the Ironton-Galesville received much less water from the overlying Ancell Unit.

4.2.4.5 Comparison of Observed and Simulated Deep Available Heads

Mapping of observed available deep composite head above the top of the Ancell Unit (Figure 126), based on 2007 potentiometric surface mapping by Burch (2008), is similar to the 2009 simulated available Ancell head shown in Figure 112. A map of available observed deep composite head above the top of the Ironton-Galesville is not included in this report, because nowhere in northeastern Illinois is the 2007 available observed deep composite head above the top of the Ironton-Galesville Unit less than 200 ft, the threshold value for shading of available head used in this report.

The exact relationship of heads in the Ironton-Galesville and Ancell Units in unclear. The USGS constructed a deep test well at Zion, Lake County, Illinois using discrete, packed-off intervals to separate the two aquifers (Nicholas et al., 1987). The USGS drilled this test well in 1980 to a depth of 3475 ft, penetrating 40 ft of Precambrian granite. Portions of the Zion well were isolated from the rest of the open interval of the well using packers so that heads could be measured in the isolated intervals. This is the only well in the model nearfield from which such data are available. The median heads in the two deep aquifers only differed by 4 ft, which is qualitatively consistent with interformational transfer of groundwater between deep aquifers via boreholes open to more than one of these aquifers; this is a flow of groundwater that our model does not simulate (see page 125). It is likely that interformational transfers between deep aquifers have occurred. Wells open to the deep aquifers have been present in northeastern Illinois since the mid-nineteenth century, and these wells were commonly left open to more than deep bedrock aquifer (Meyer et al., 2012).

Heads in the deep aquifers are probably also influenced by downward transfers of groundwater from shallow aquifers along boreholes open to both shallow and deep aquifers, but such wells are less numerous than are deep wells open to more than one deep aquifer. Pumping records at the ISWS indicate that 183 of the 1200 deep wells simulated by Meyer et al. (2012) from 1964 to 2005 (15 percent) were open to the shallow aquifers as well as the deep ones (Table 10). These transfers of water would have the effect of reducing heads in the shallow aquifers and increasing heads in the deep aquifers to which they are open. Of the 183 wells, most (110 wells) are not open to the Ironton-Galesville and Mt. Simon Unit, but are instead open to the shallow aquifers together with the Ancell Unit. Thus, of the deep aquifers, it is likely that the Ancell Unit is the most affected by these transfers of groundwater from the shallow aquifers.

4.3 Conceptual Model Uncertainties

MODFLOW is limited in the flexibility it provides for simulation of completely desaturated (dry) layers. These limitations are problematic for our model accuracy because dry cells are present under predevelopment condition and propagate further throughout the model during transient simulations. Particular difficulties are posed where dry cells represent surficial sand, and the dry sand overlies diamicton; this is a common hydrogeological sequence in McHenry County. The specific problem associated with this situation pertains to simulating the fate of recharge applied to the dry surficial sand. Options permitted by MODFLOW include (1) assigning the recharge rate to the first saturated layer, which results in unrealistically high recharge rates for the low-permeability diamicton underlying the dry sand; and (2) completely removing the recharge to cells that have gone dry. Neither option is consistent with reality, in which recharge would mostly run off the upper surface of the diamicton and recharge the sands at the periphery of the diamicton. However, only option (1) preserves water balance in the model, which is essential for simulation of both drawdown and natural groundwater discharge. However, applying recharge to diamicton at rates that are unrealistically high results in unrealistic, though localized, peaks in simulated head. These peaks do not appear to impact the accuracy of simulated drawdown and reductions in natural groundwater discharge, but future research is required to explore other options for simulation of groundwater flow in this setting.

A second conceptual model uncertainty is the simulation of interformational transfer of groundwater via boreholes between the Ancell and Ironton-Galesville units. We have adopted a high vertical hydraulic conductivity (K_v) zone developed in Roadcap et al. (in preparation) as a proxy for boreholes; this approach results in equilibration of heads in the Ancell and Ironton-Galesville Unit throughout the lateral extent of the high K_v zone. In contrast, the studies of Meyer et al. (2009) and Meyer et al. (2012) do not incorporate a high K_v zone between the Ancell and Ironton-Galesville and thereby assume implicitly that borehole transfer of groundwater does not occur; as a result, the heads are separated by hundreds of feet. The actual impact of boreholes is likely to result in an equilibration of head between the two units closer to the borehole [such as simulated in this study and Roadcap et al. (in preparation)], but have a lesser influence farther away [such as simulated as Meyer et al. (2009) and Meyer et al. (2012). Further uncertainty is contributed by the delineation of the high K_v zone that is intended to simulate the area where interformational transfers affect groundwater flow. The delineation we employ was developed by Roadcap et al. (in preparation) on the basis of professional judgment and is intended to encompass the region of greatest density of boreholes open to both the Ancell and Ironton-Galesville Units. In actuality, records of interformational boreholes are not comprehensive, and the effectiveness of abandonment of older boreholes at sealing off interconnections between units is not known. MODFLOW discretization prevents a proper geometric representation of such a zone regardless. Future research should employ MODFLOW packages (such as the Multi-Node Well package) that were developed to better model the geometry of wells and interformational transfers.

These conceptual model uncertainties are unavoidable consequences of constructing a regional finite difference groundwater flow model. The development of new modeling technologies will continue to allow us to improve the models of northeastern Illinois, and such updates will be made available via http://www.isws.illinois.edu/docs/pubs/iswscr2013-06/.

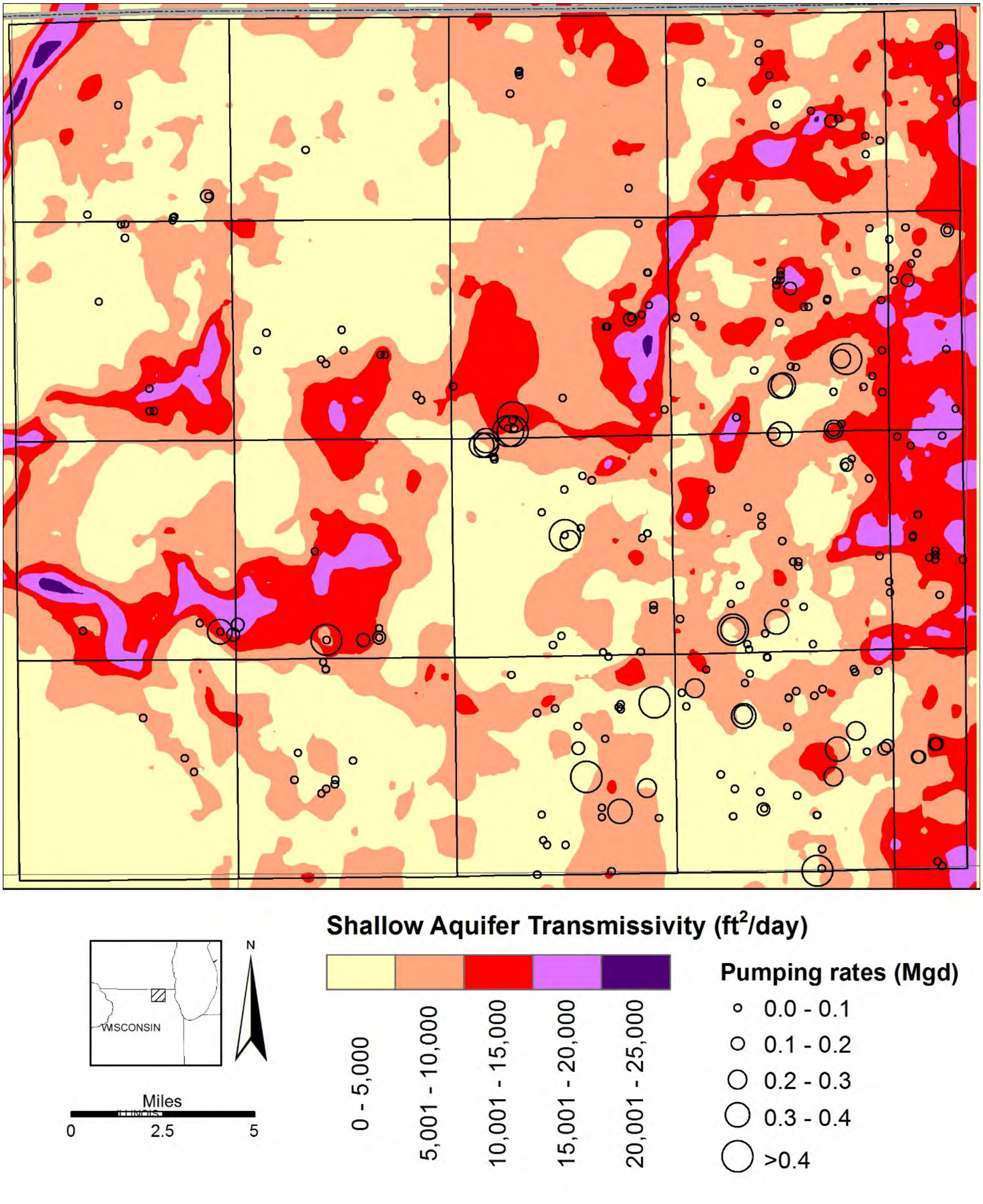

Figure 71 Transmissivity of Quaternary and shallow bedrock materials in McHenry County with 2009 shallow aquifer withdrawals superimposed

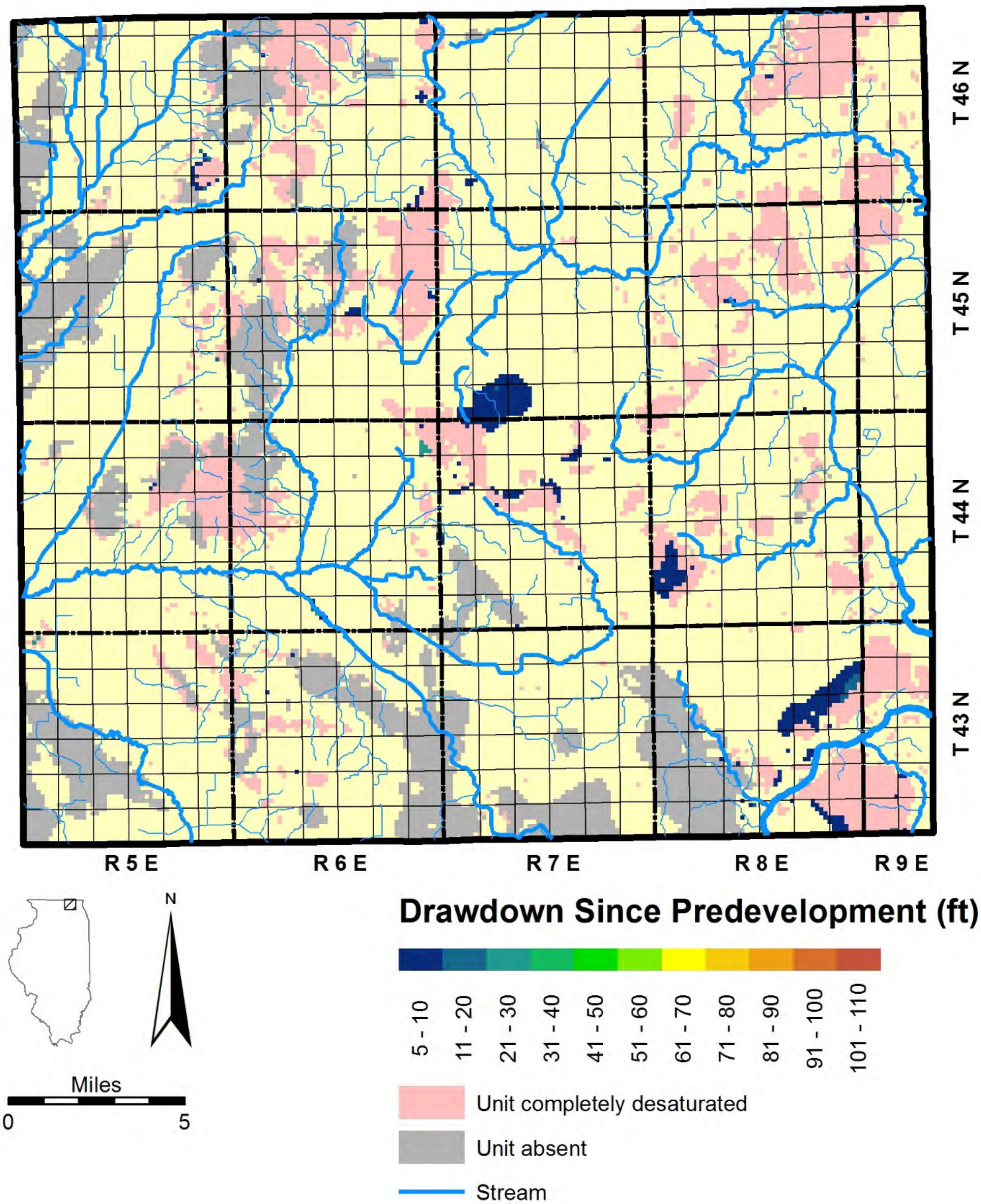

Figure 72 Simulated drawdown since predevelopment, Haeger-Beverly Unit (model layer 2), 2009

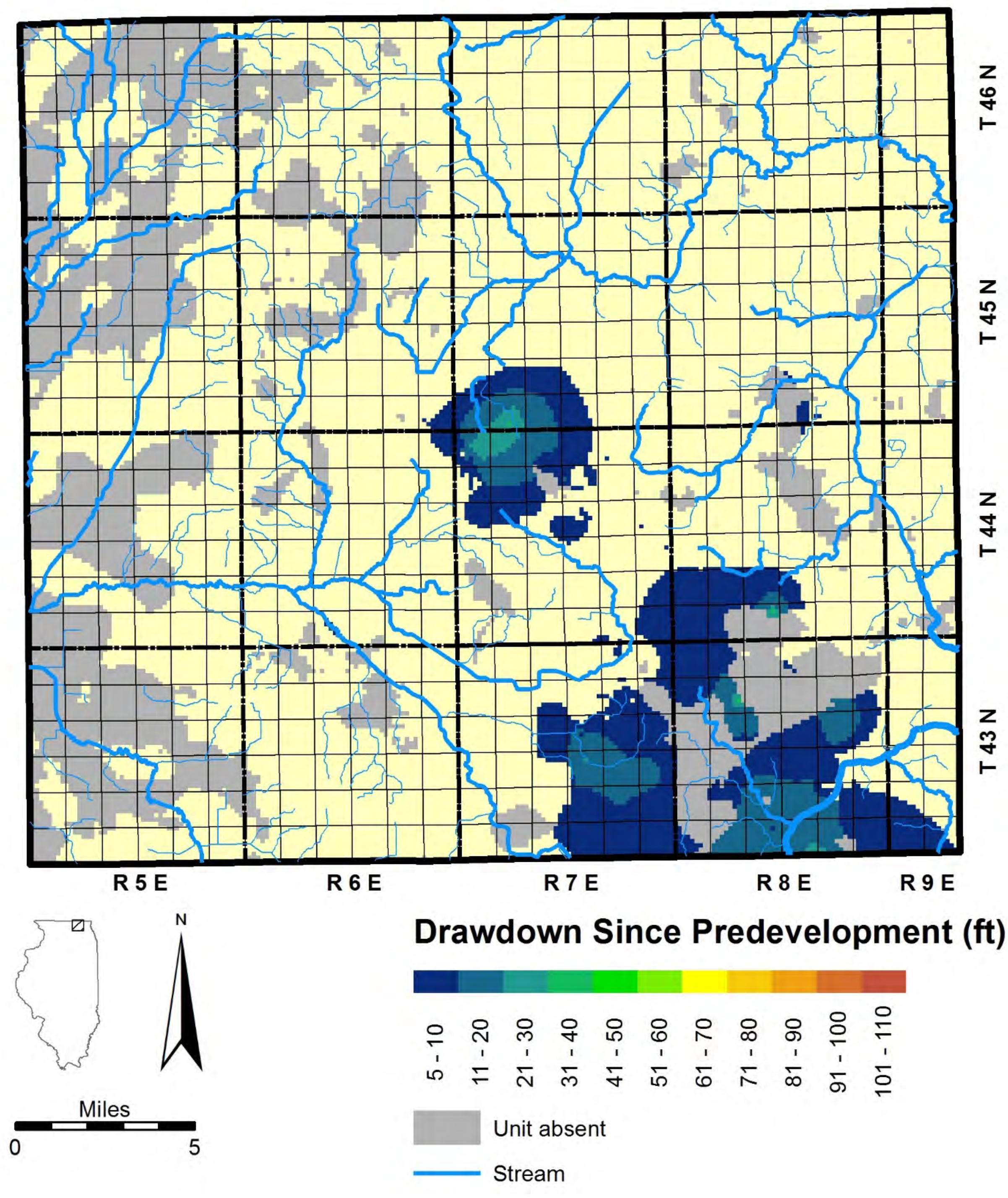

Figure 73 Simulated drawdown since predevelopment, Ashmore Unit (model layer 5), 2009

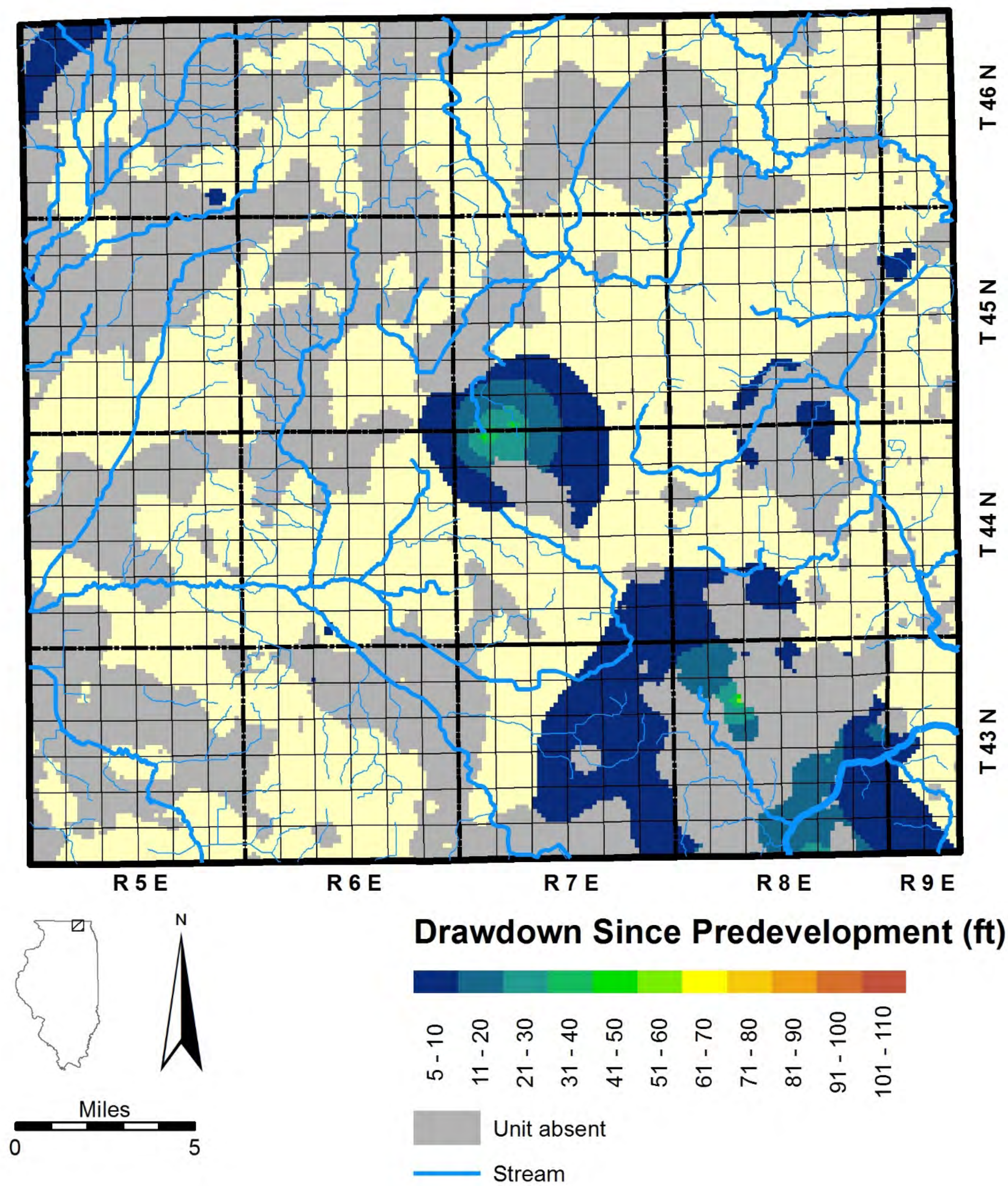

Figure 74 Simulated drawdown since predevelopment, Lower Glasford Sand Unit (model layer 9), 2009

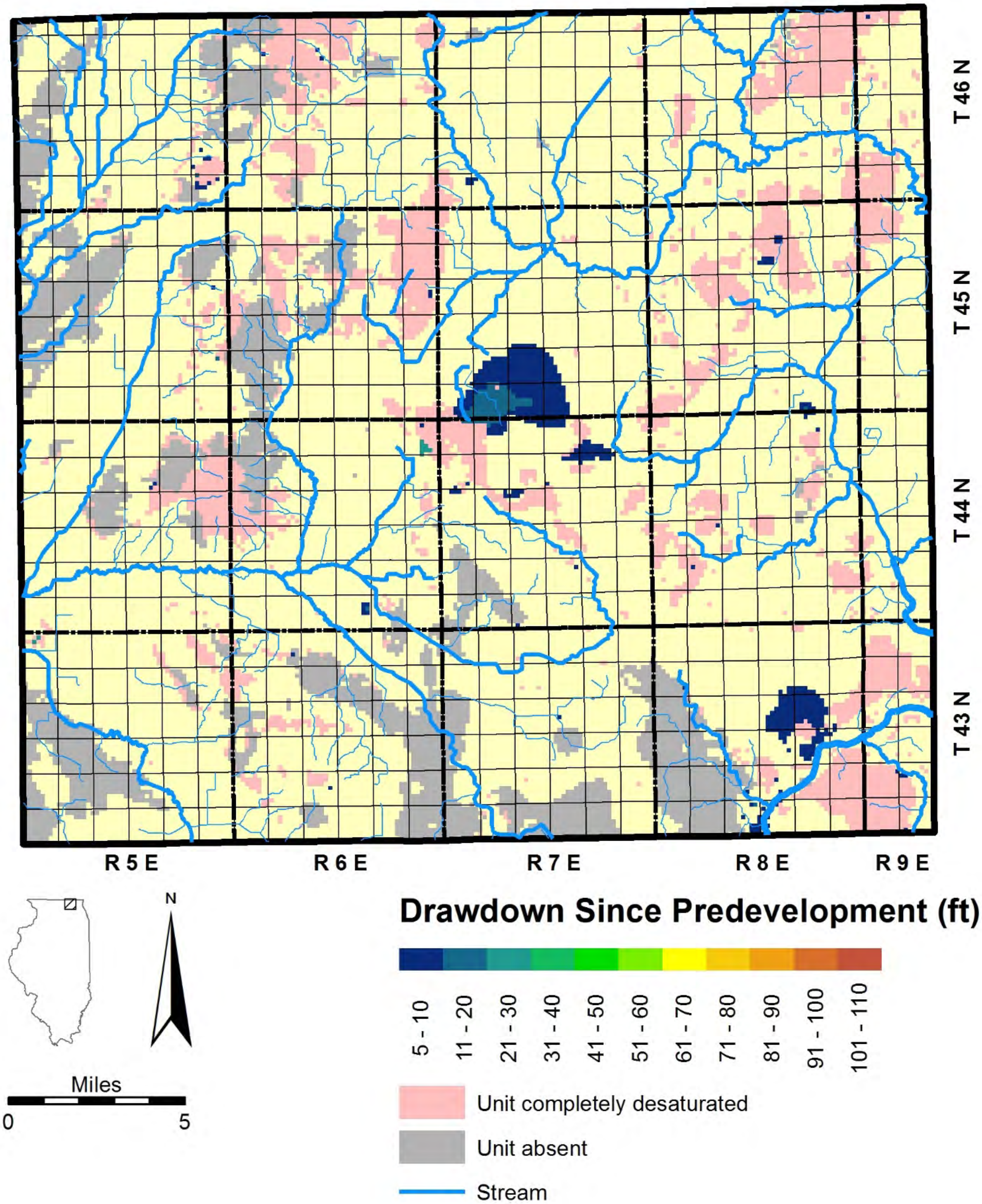

Figure 75 Simulated drawdown since predevelopment, Haeger-Beverly Unit (model layer 2), 2030 (BL scenario)

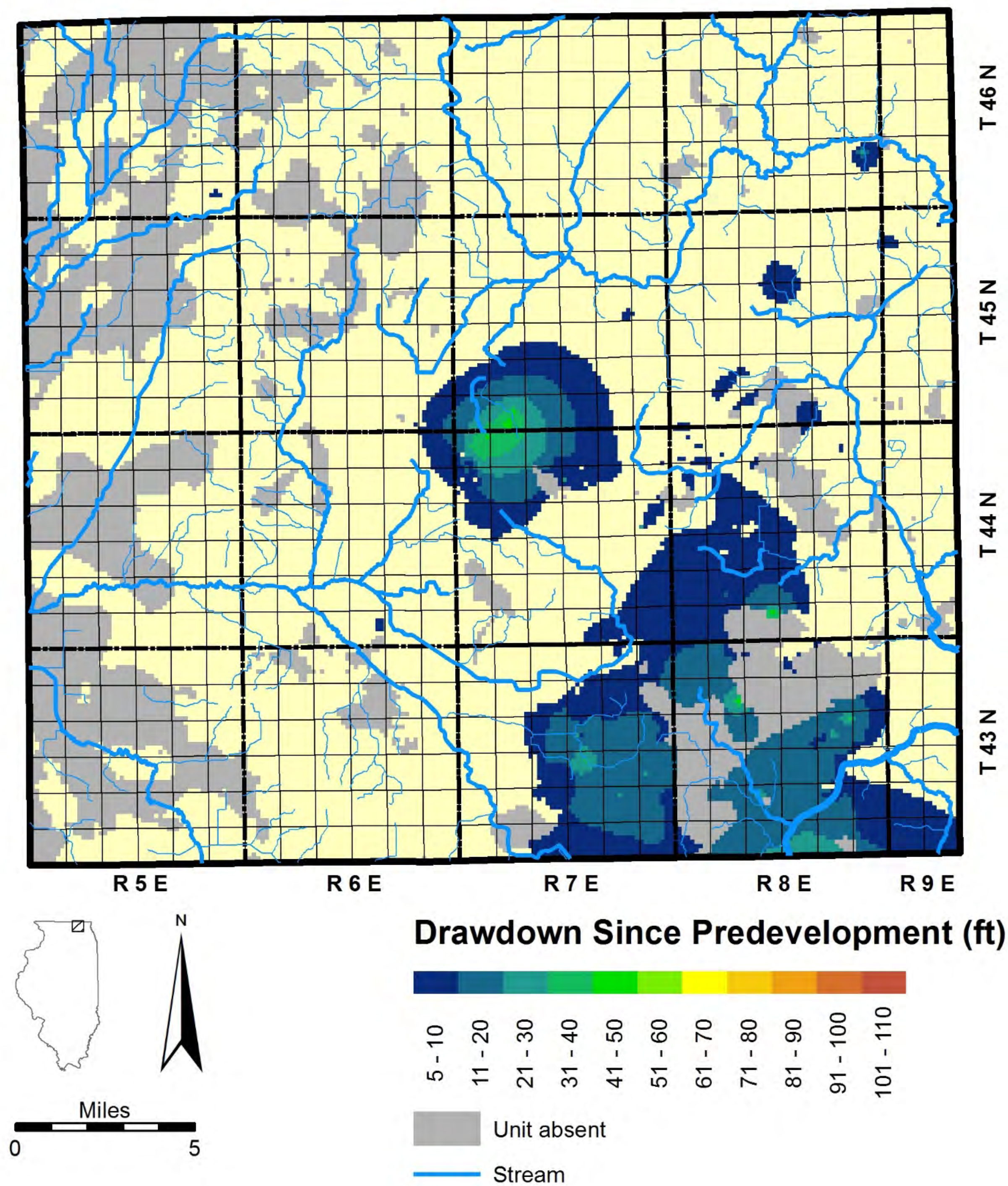

Figure 76 Simulated drawdown since predevelopment, Ashmore Unit (model layer 5), 2030 (BL scenario)

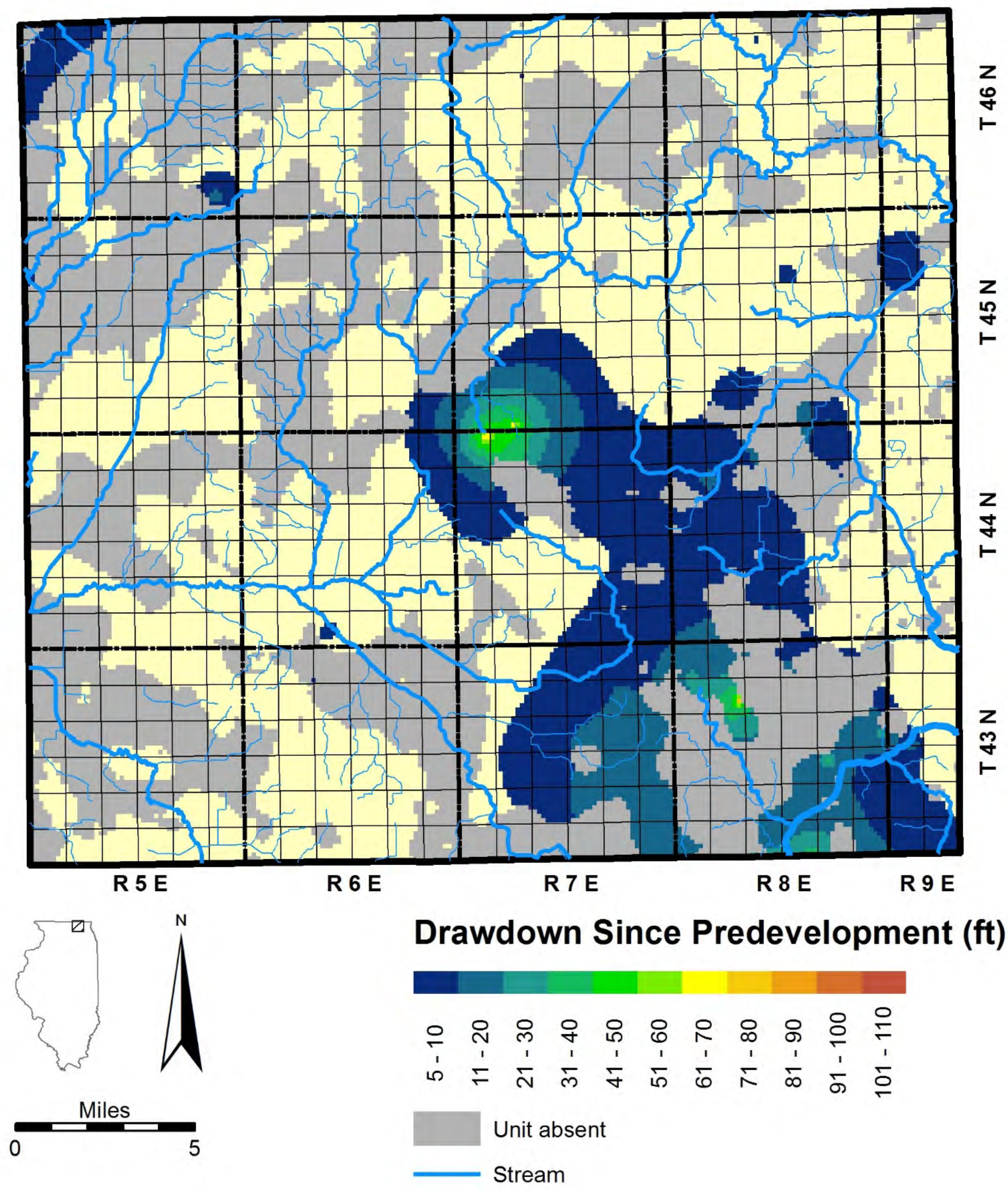

Figure 77 Simulated drawdown since predevelopment, Lower Glasford Sand Unit (model layer 9), 2030 (BL scenario)

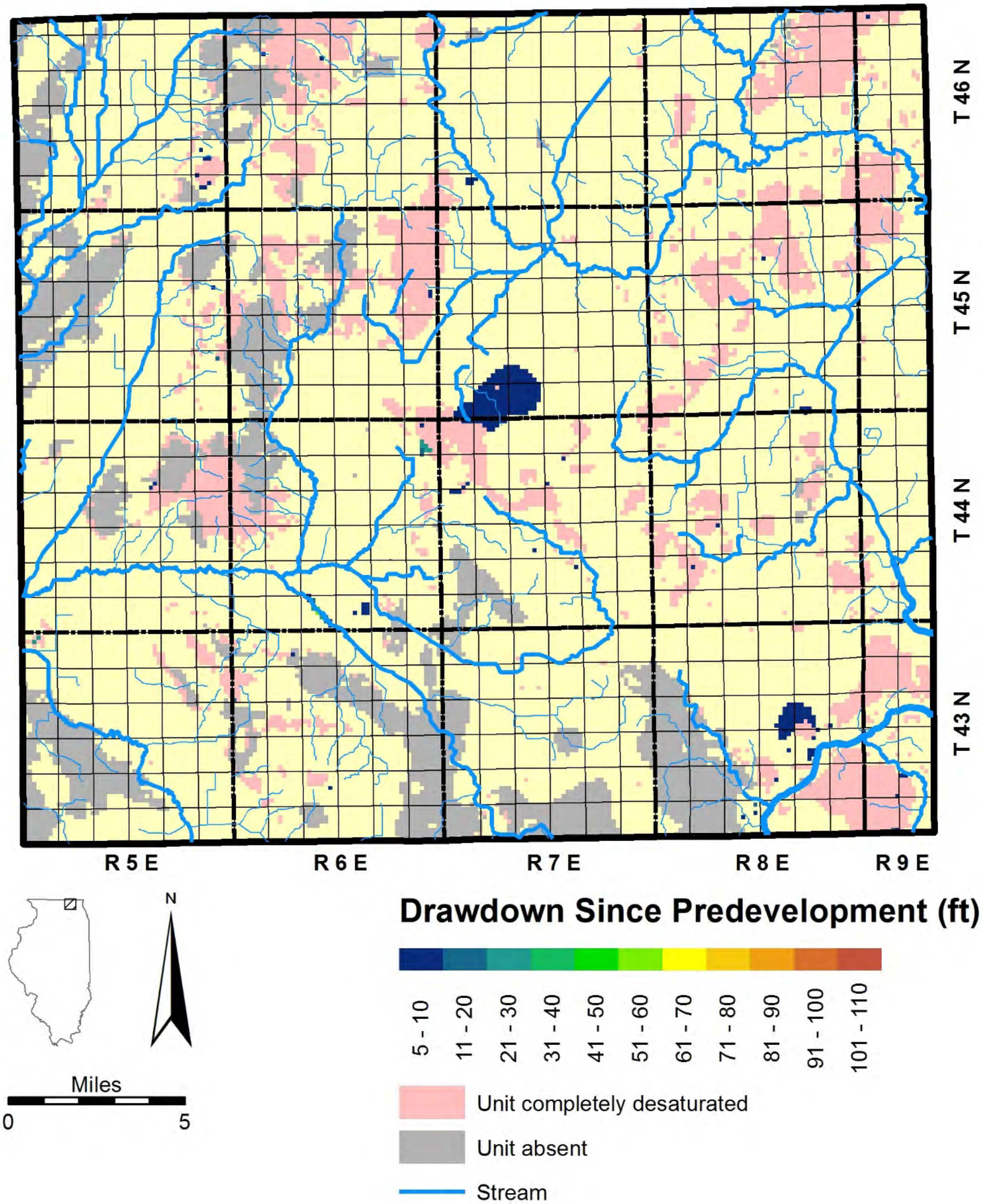

Figure 78 Simulated drawdown since predevelopment, Haeger-Beverly Unit (model layer 2), 2030 (LRI scenario)

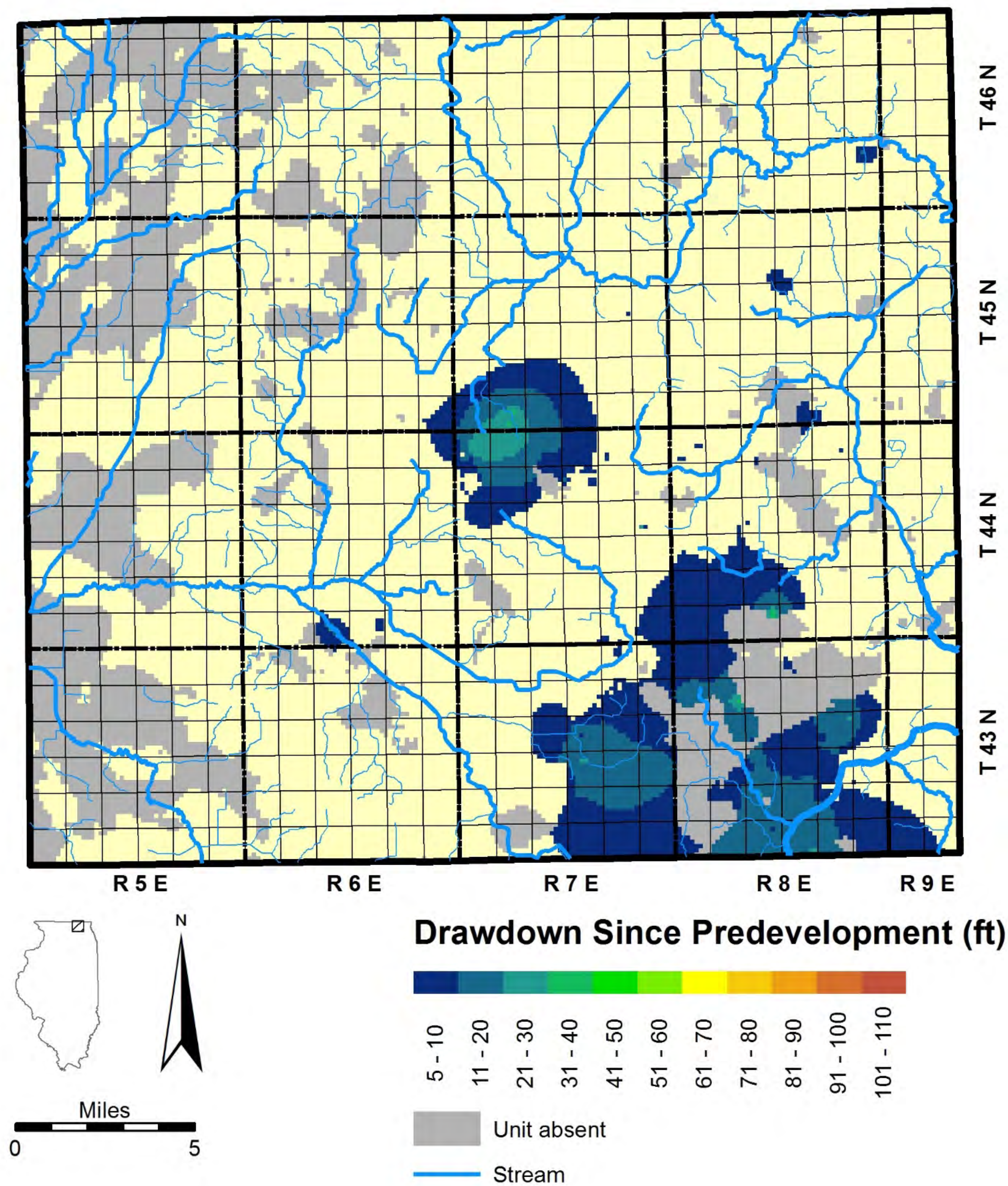

Figure 79 Simulated drawdown since predevelopment, Ashmore Unit (model layer 5), 2030 (LRI scenario)

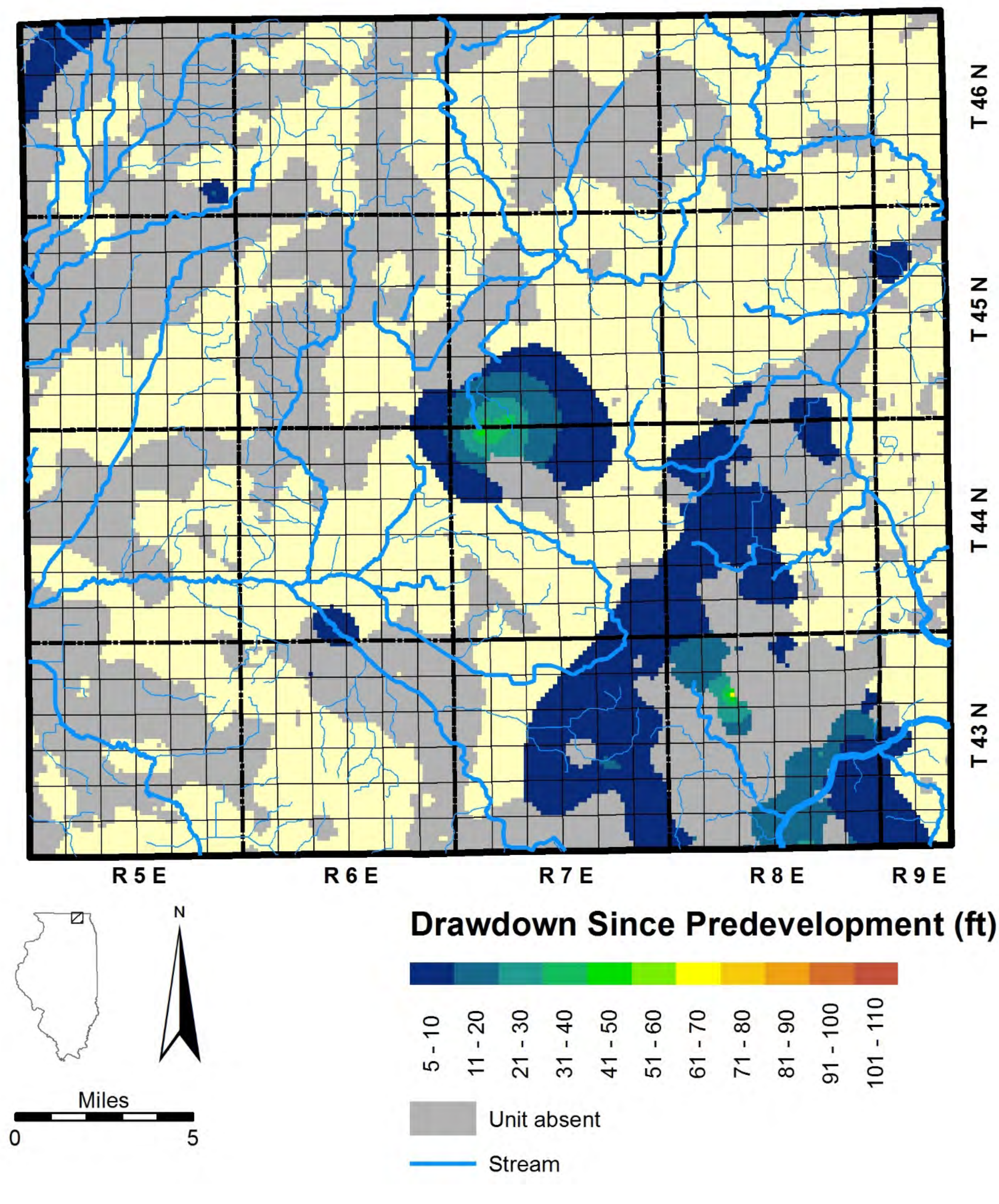

Figure 80 Simulated drawdown since predevelopment, Lower Glasford Sand Unit (model layer 9), 2030 (LRI scenario)

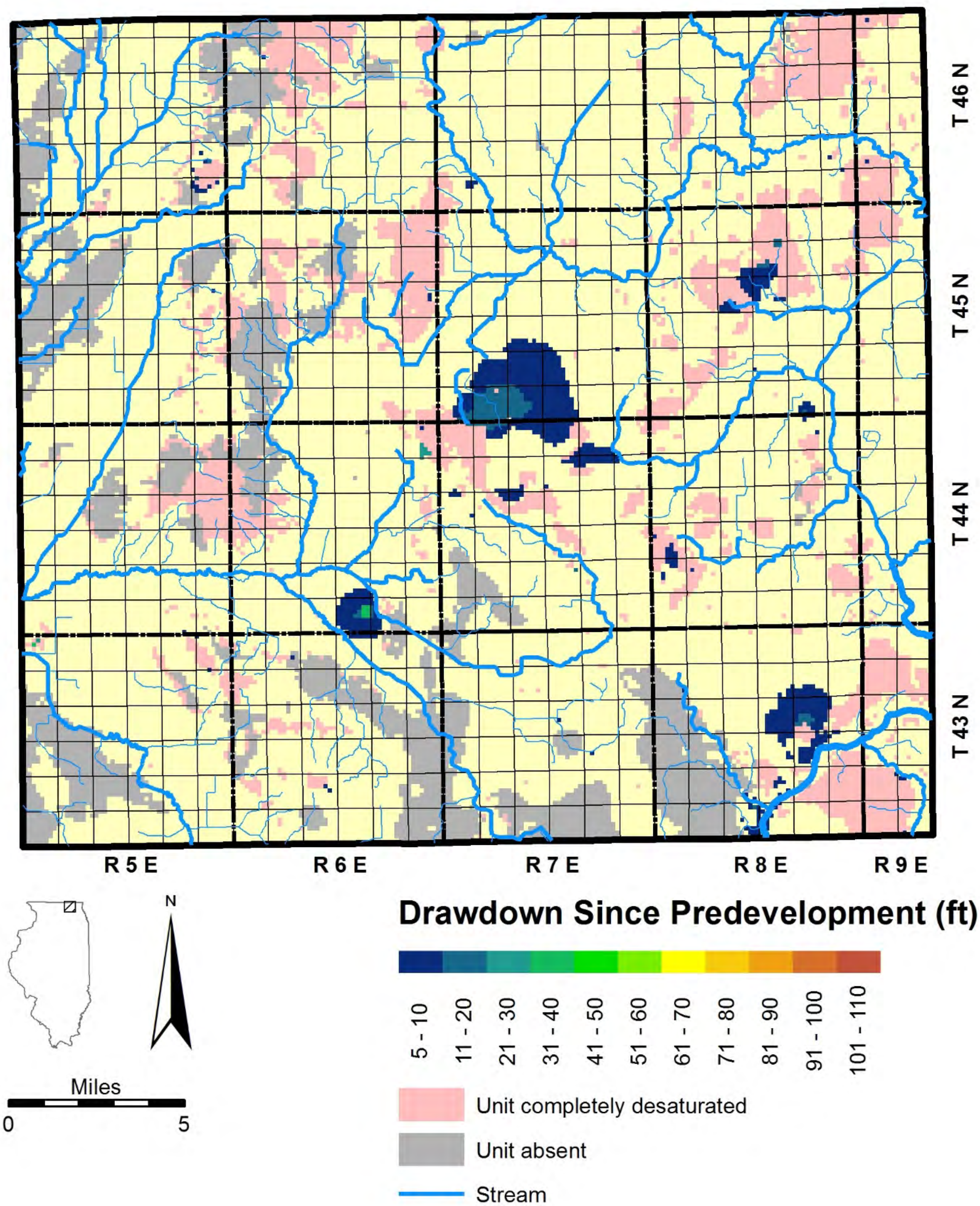

Figure 81 Simulated drawdown since predevelopment, Haeger-Beverly Unit (model layer 2), 2030 (MRI scenario)

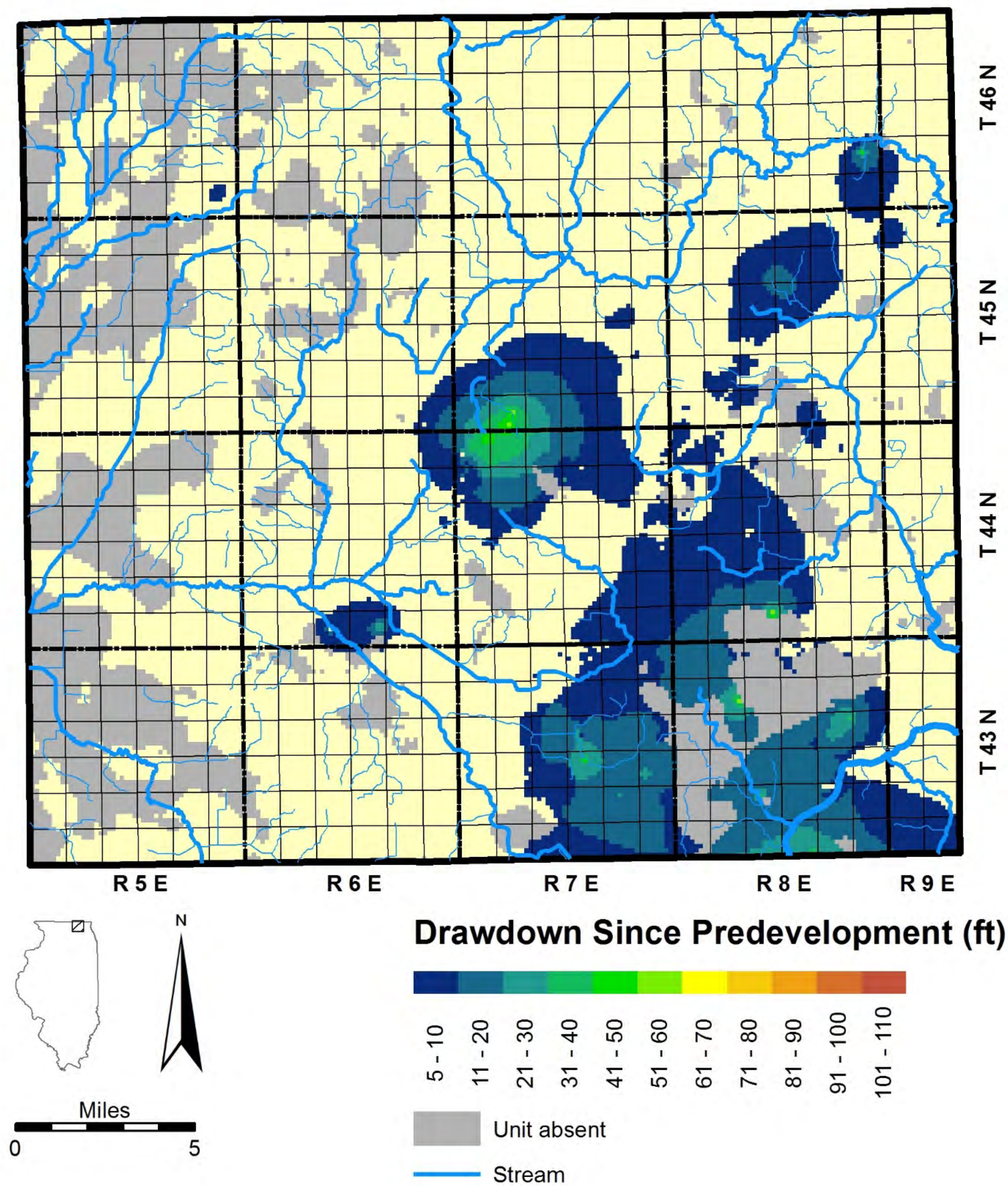

Figure 82 Simulated drawdown since predevelopment, Ashmore Unit (model layer 5), 2030 (MRI scenario)

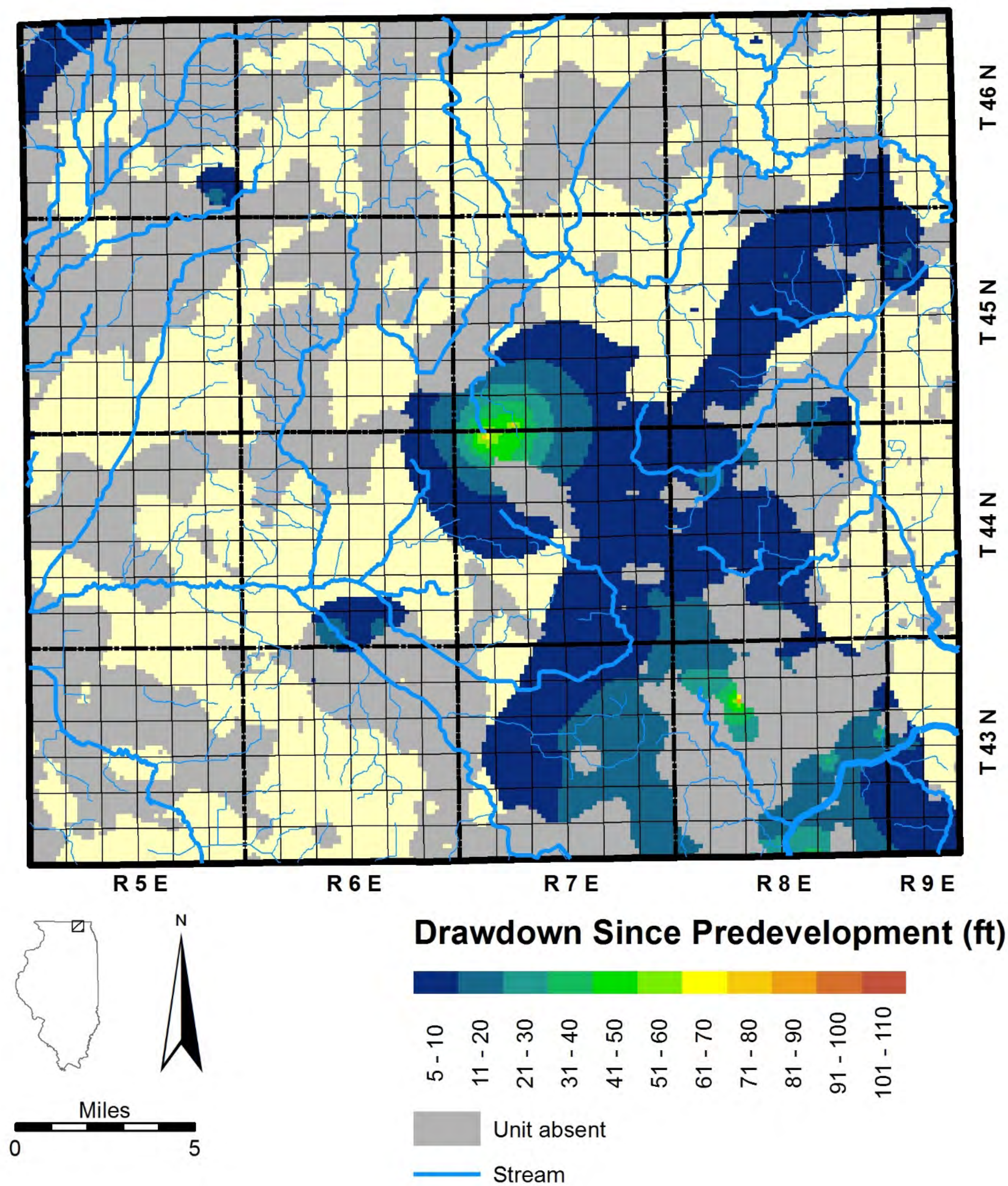

Figure 83 Simulated drawdown since predevelopment, Lower Glasford Sand Unit (model layer 9), 2030 (MRI scenario)

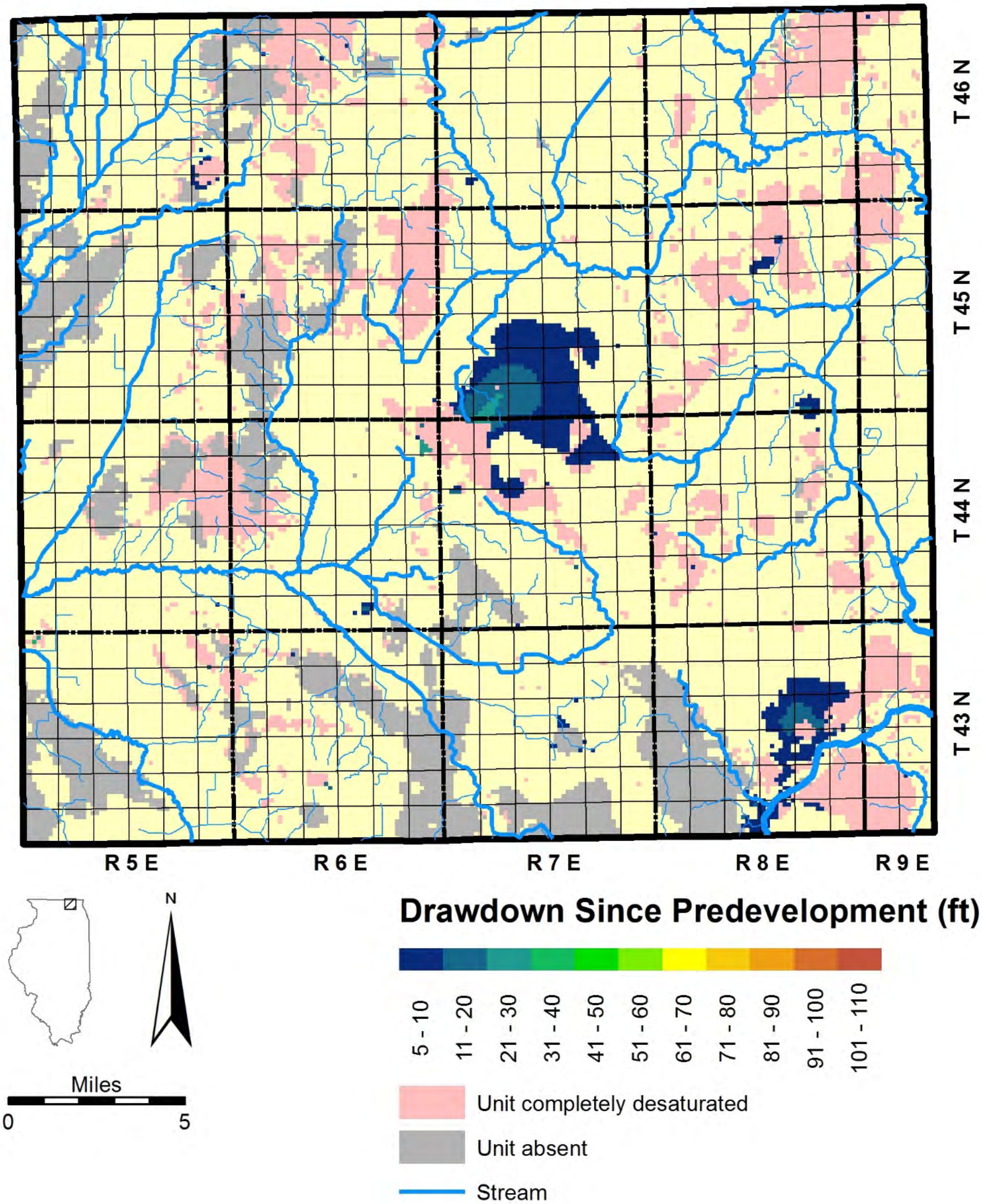

Figure 84 Simulated drawdown since predevelopment, Haeger-Beverly Unit (model layer 2), 2050 (BL scenario)

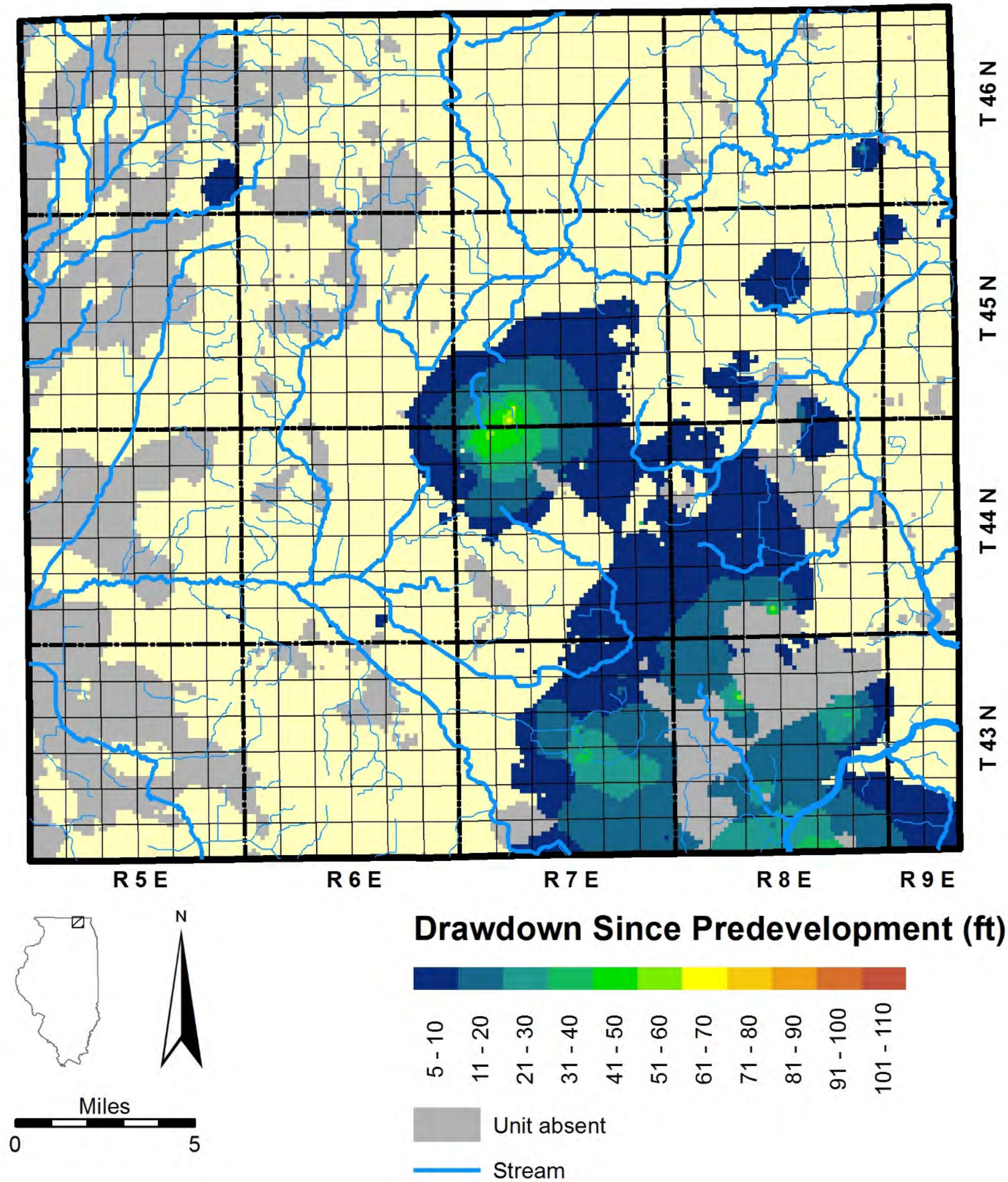

Figure 85 Simulated drawdown since predevelopment, Ashmore Unit (model layer 5), 2050 (BL scenario)

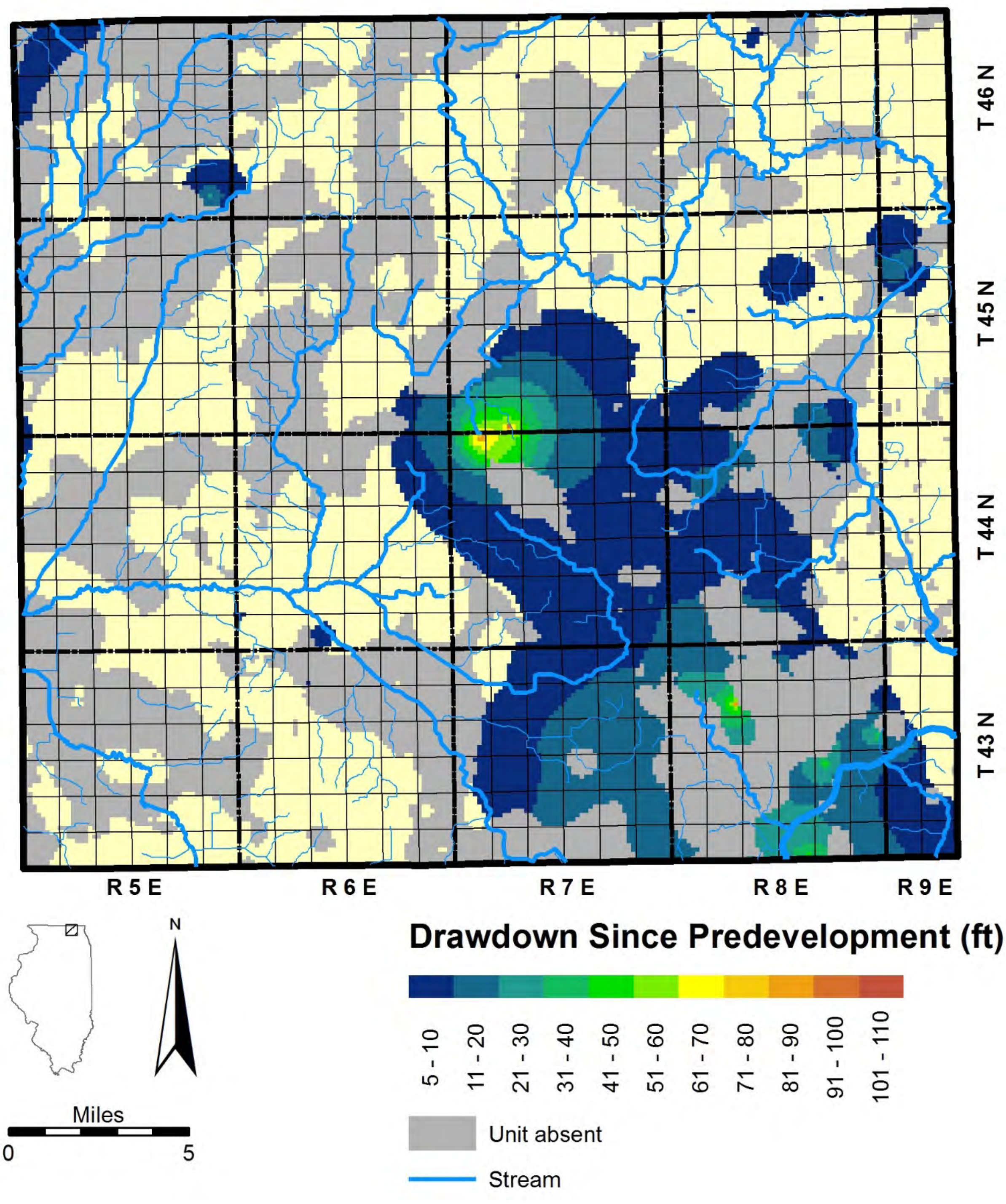

Figure 86 Simulated drawdown since predevelopment, Lower Glasford Sand Unit (model layer 9), 2050 (BL scenario)

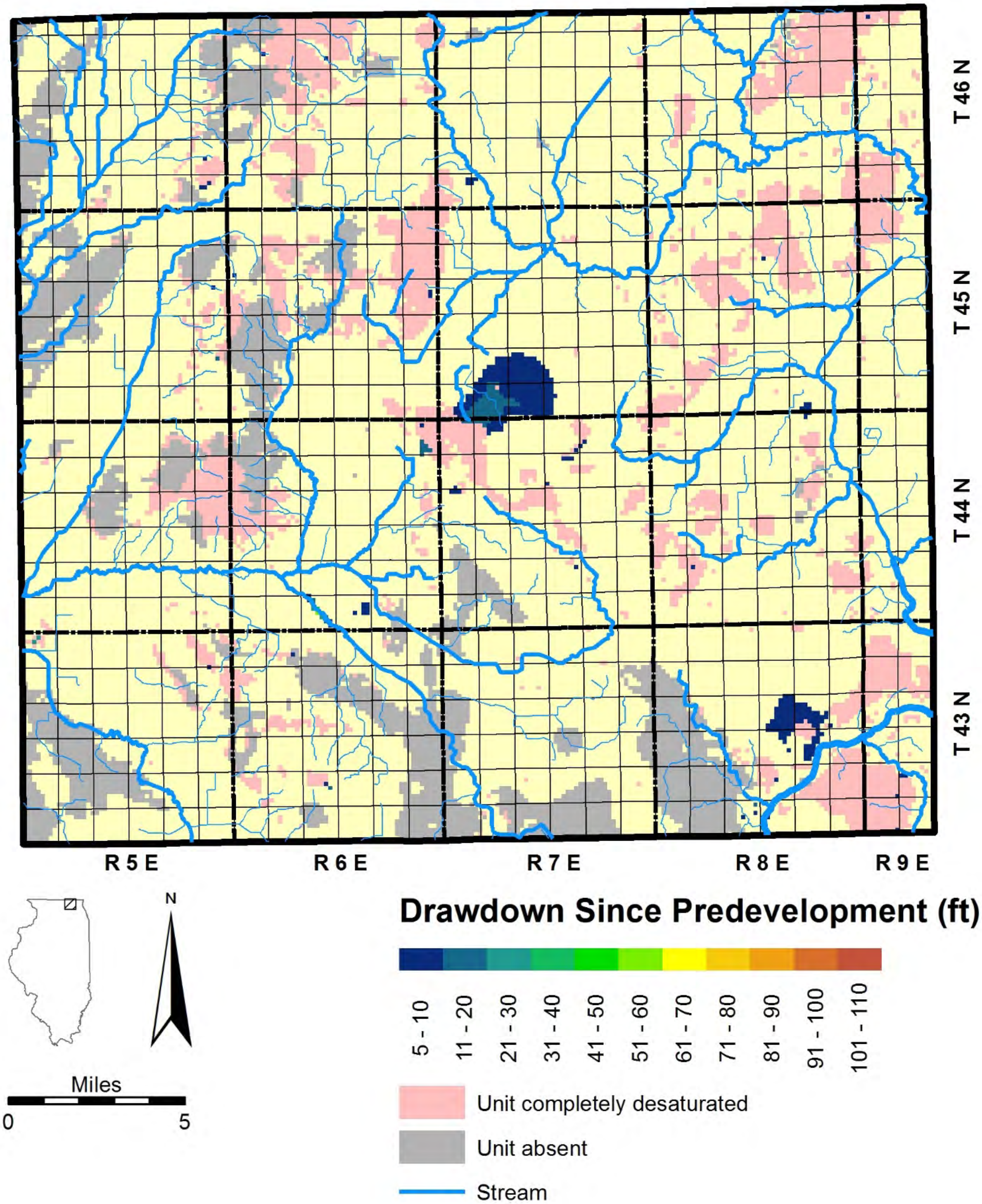

Figure 87 Simulated drawdown since predevelopment, Haeger-Beverly Unit (model layer 2), 2050 (LRI scenario)

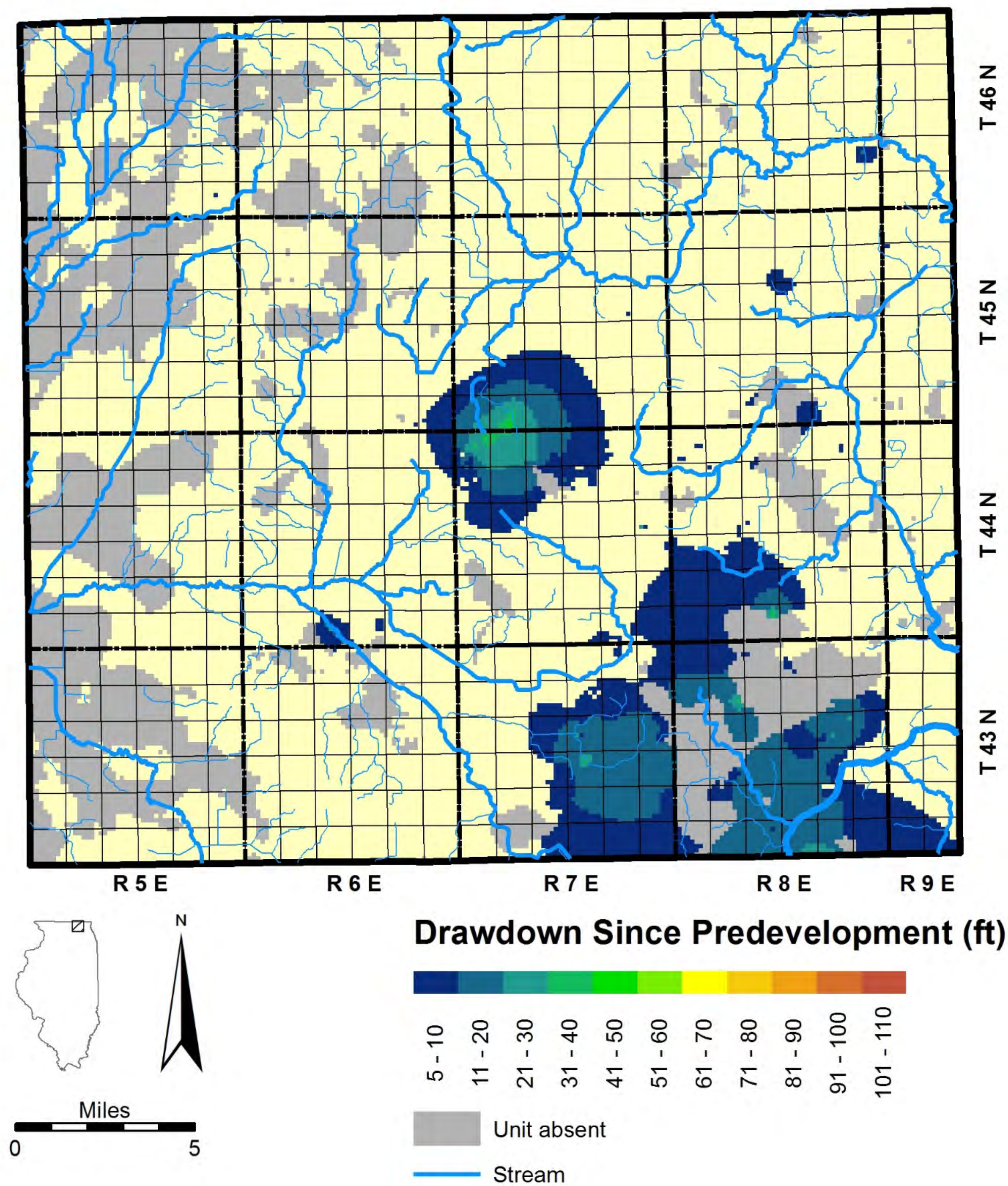

Figure 88 Simulated drawdown since predevelopment, Ashmore Unit (model layer 5), 2050 (LRI scenario)

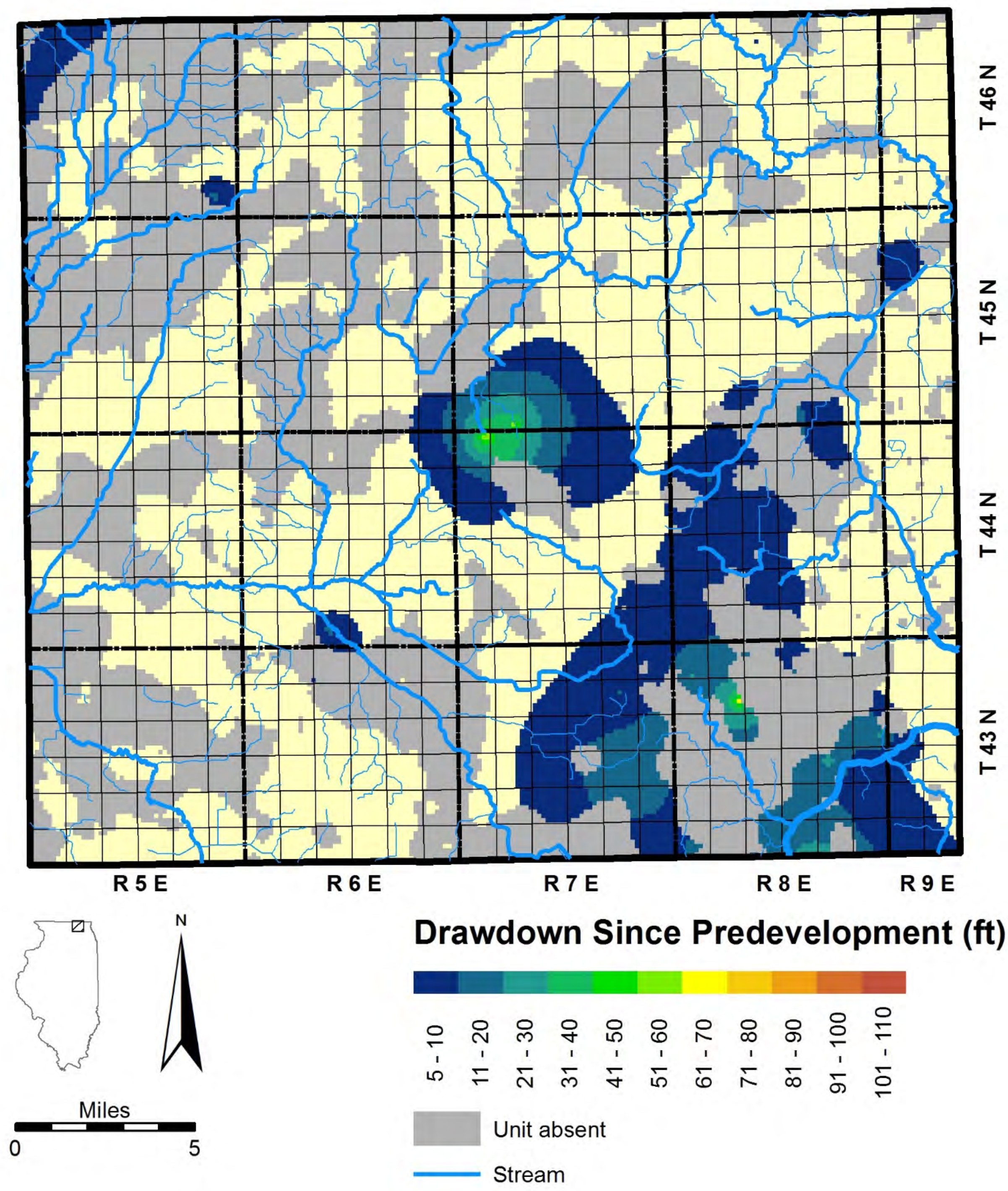

Figure 89 Simulated drawdown since predevelopment, Lower Glasford Sand Unit (model layer 9), 2050 (LRI scenario)

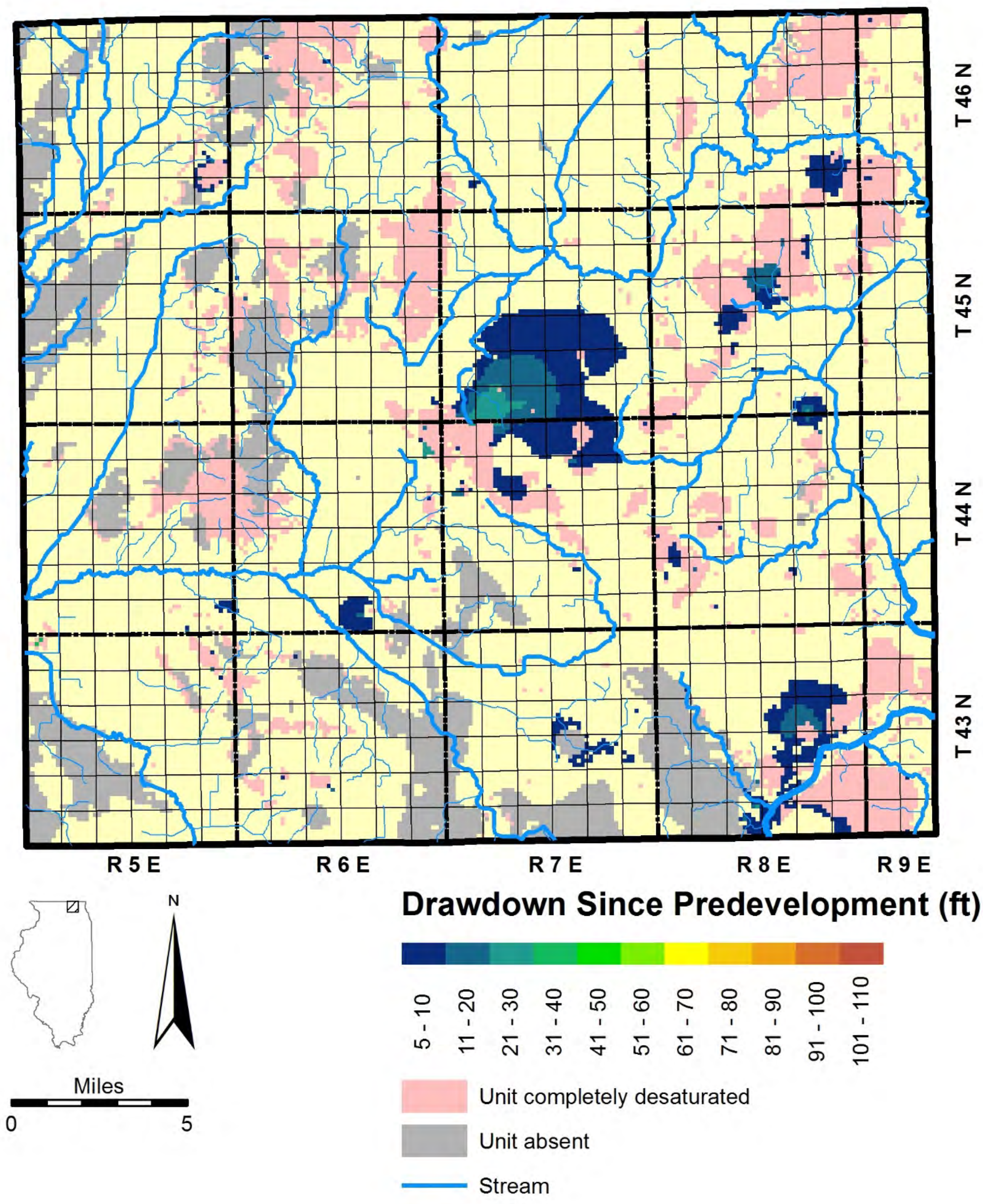

Figure 90 Simulated drawdown since predevelopment, Haeger-Beverly Unit (model layer 2), 2050 (MRI scenario)

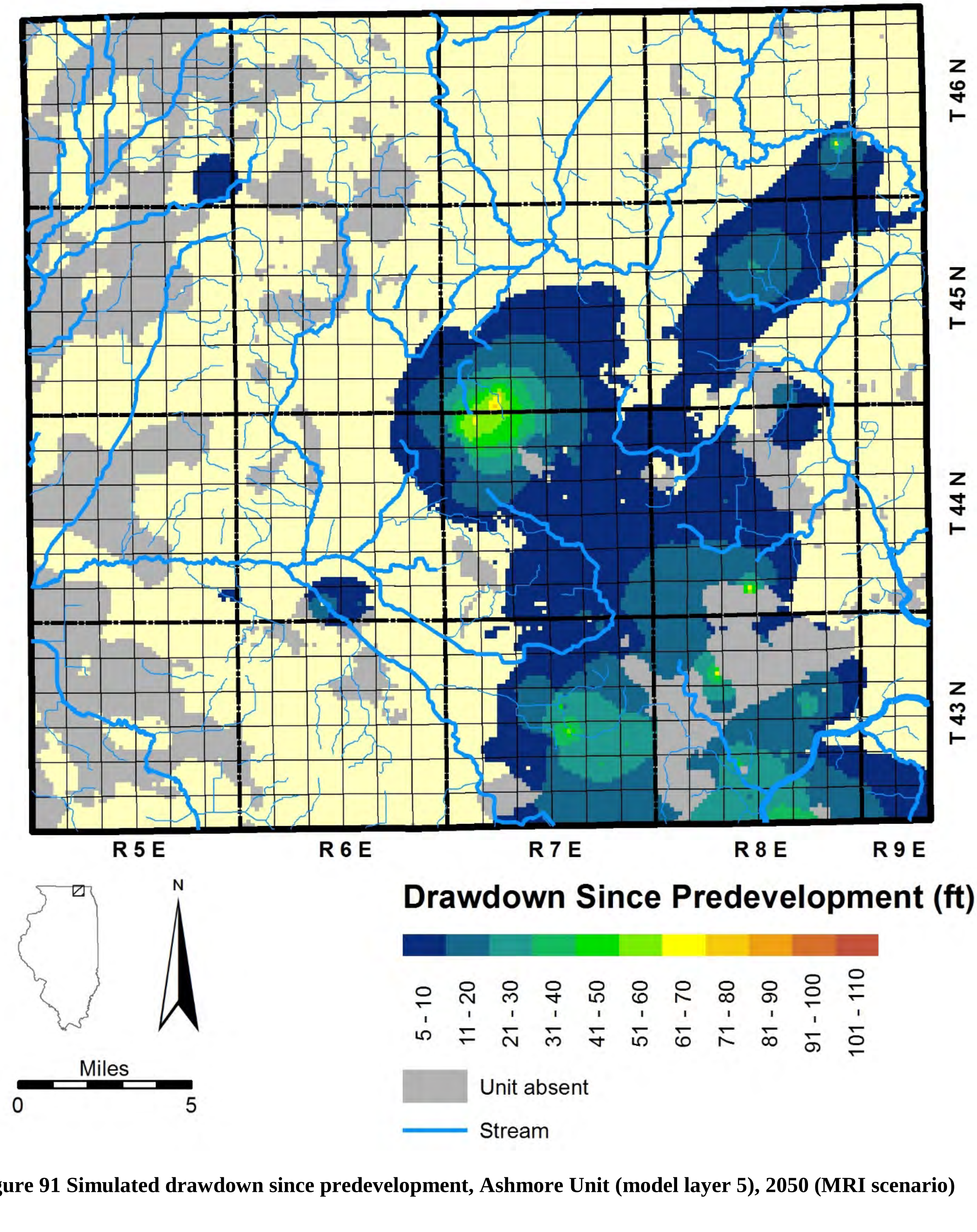

Figure 91 Simulated drawdown since predevelopment, Ashmore Unit (model layer 5), 2050 (MRI scenario)

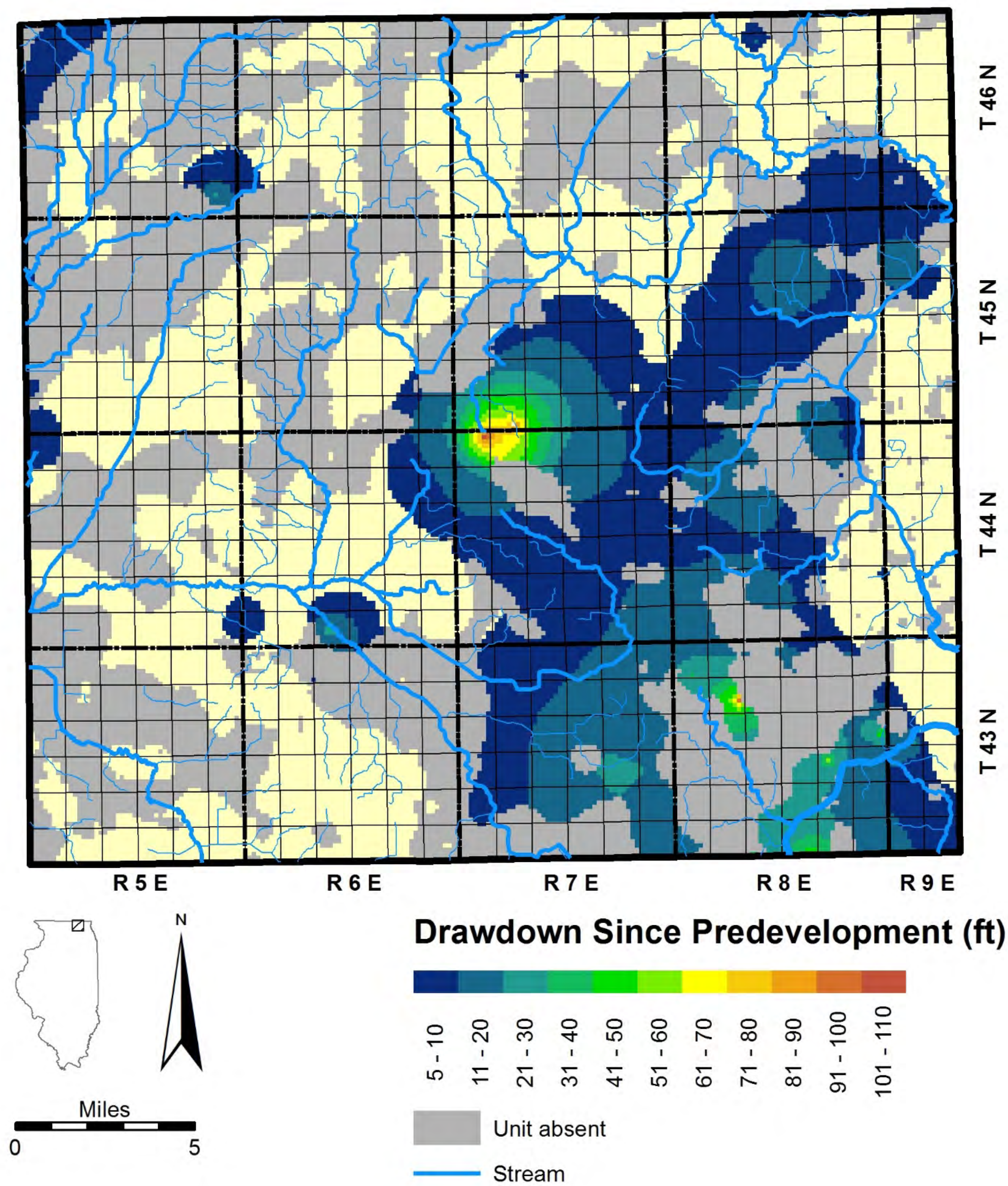

Figure 92 Simulated drawdown since predevelopment, Lower Glasford Sand Unit (model layer 9), 2050 (MRI scenario)

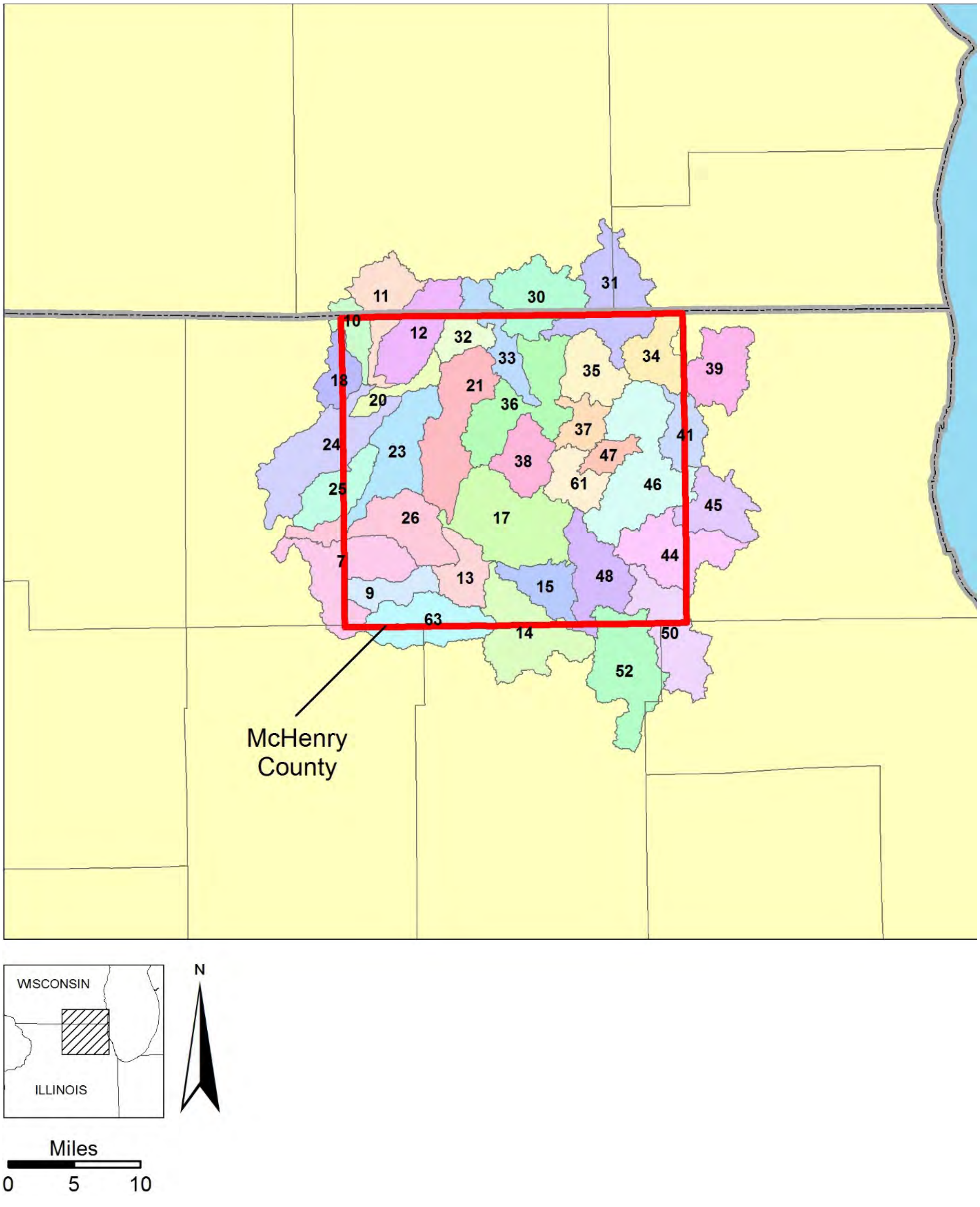

Figure 93 Sub-basins used for accounting of simulated natural groundwater discharge

Figure 93 Sub-basins used for accounting of simulated natural groundwater discharge (Concluded)

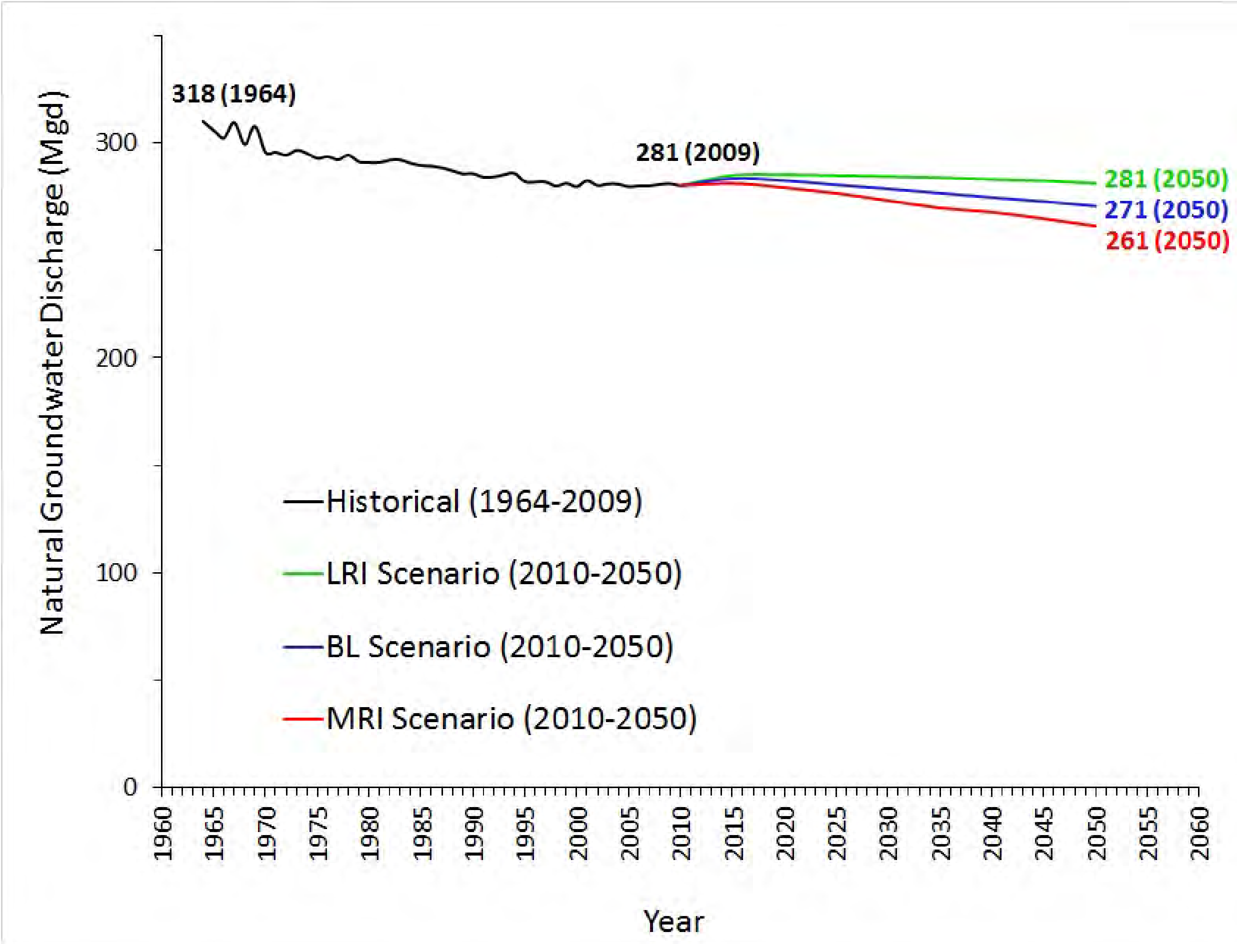

Figure 94 Simulated natural groundwater discharge in the McHenry County area (Figure 93), 1964-2050

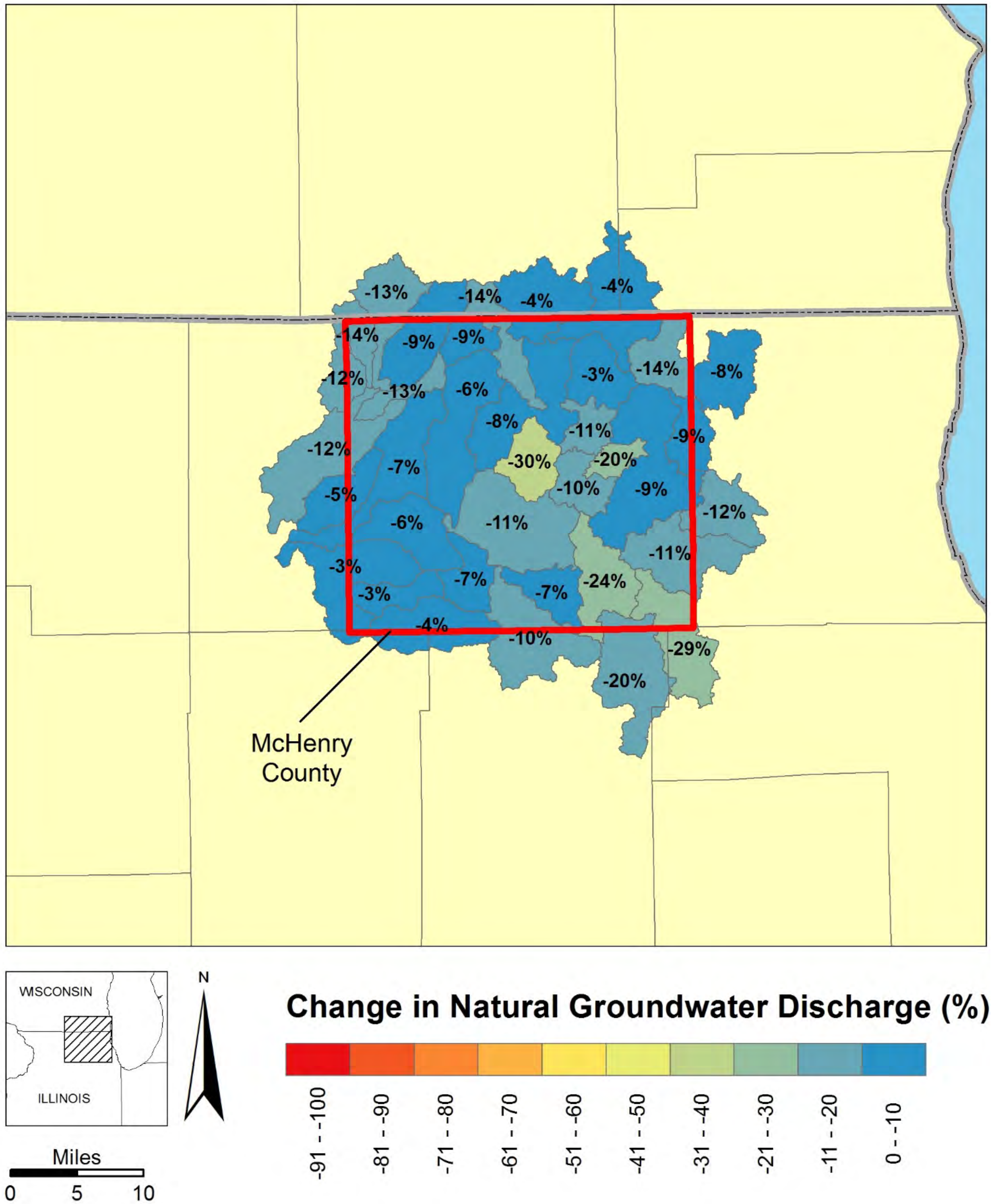

Figure 95 Change in simulated natural groundwater discharge (predevelopment to 1989) in watersheds of the McHenry County area

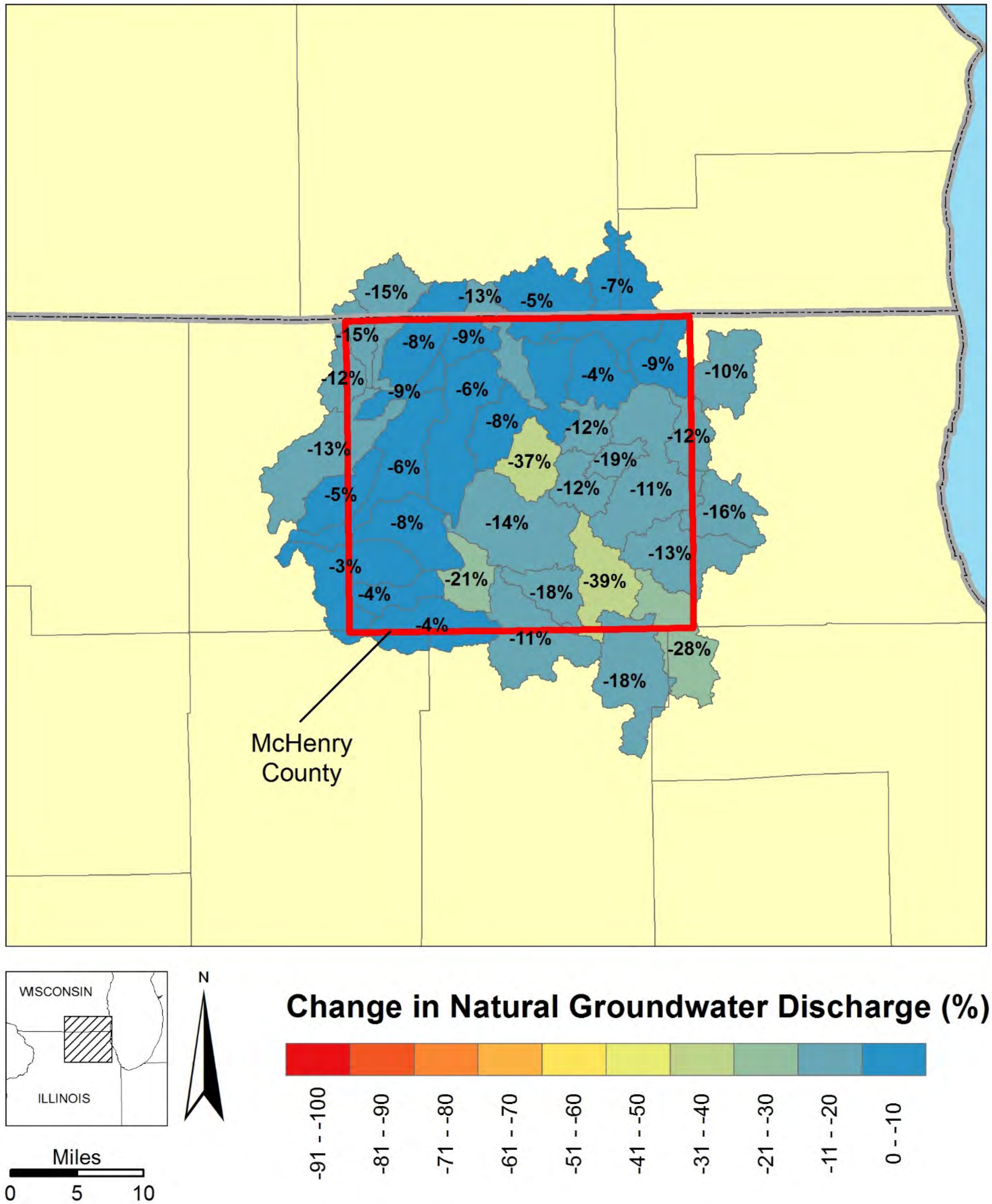

Figure 96 Change in simulated natural groundwater discharge (predevelopment to 2009) in watersheds of the McHenry County area

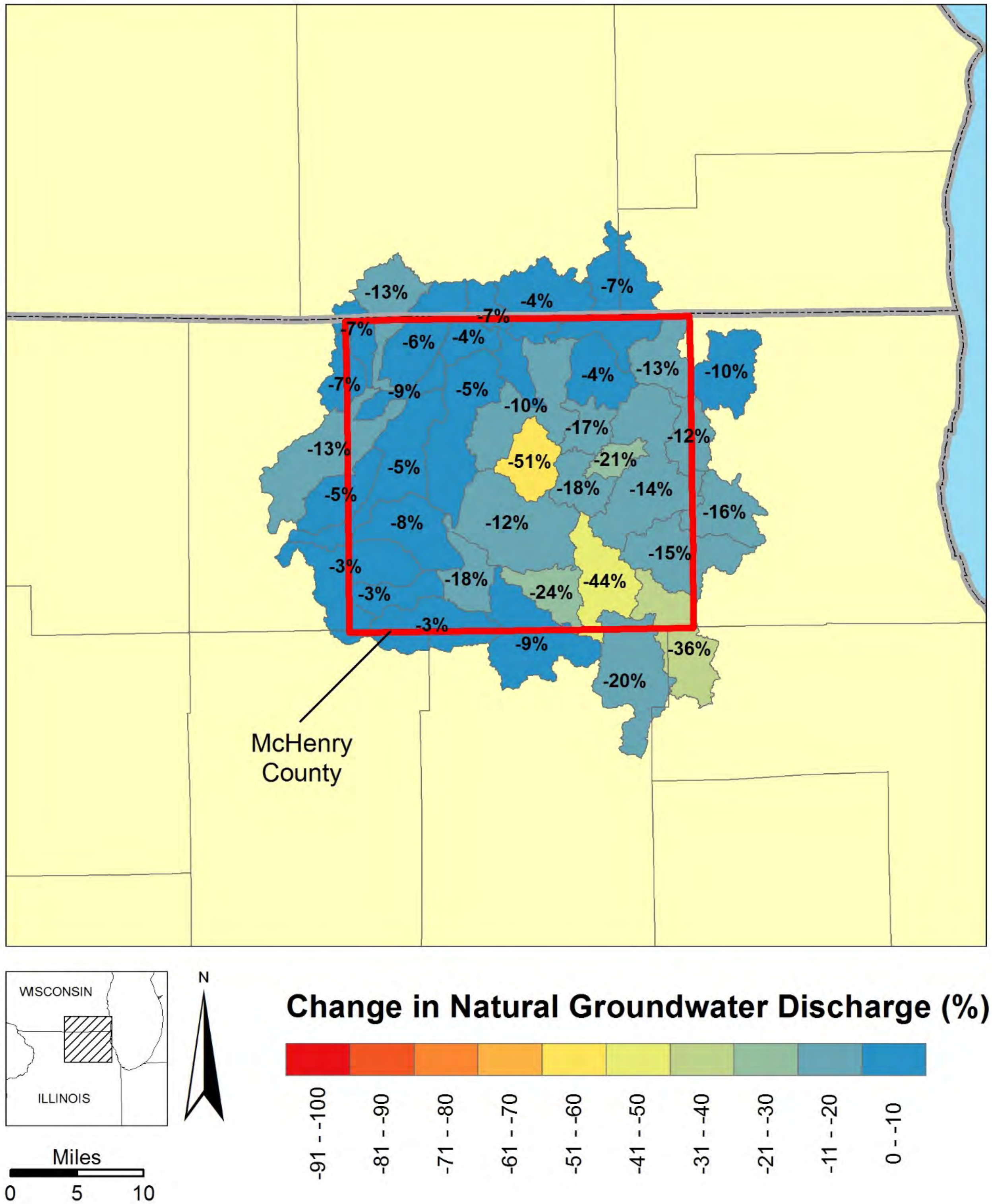

Figure 97 Change in simulated natural groundwater discharge (predevelopment to 2030, BL scenario) in watersheds of the McHenry County area

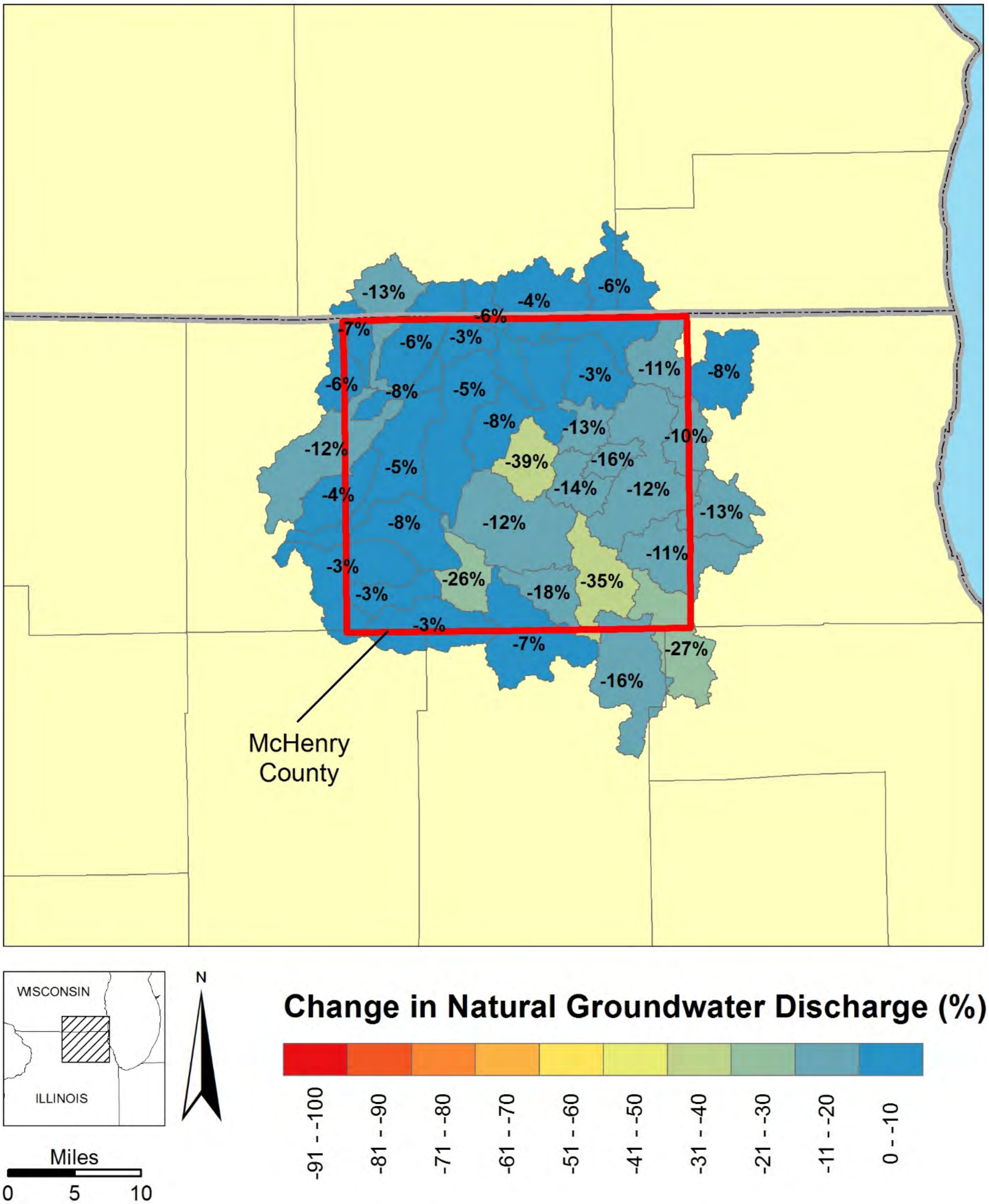

Figure 98 Change in simulated natural groundwater discharge (predevelopment to 2030, LRI scenario) in watersheds of the McHenry County area

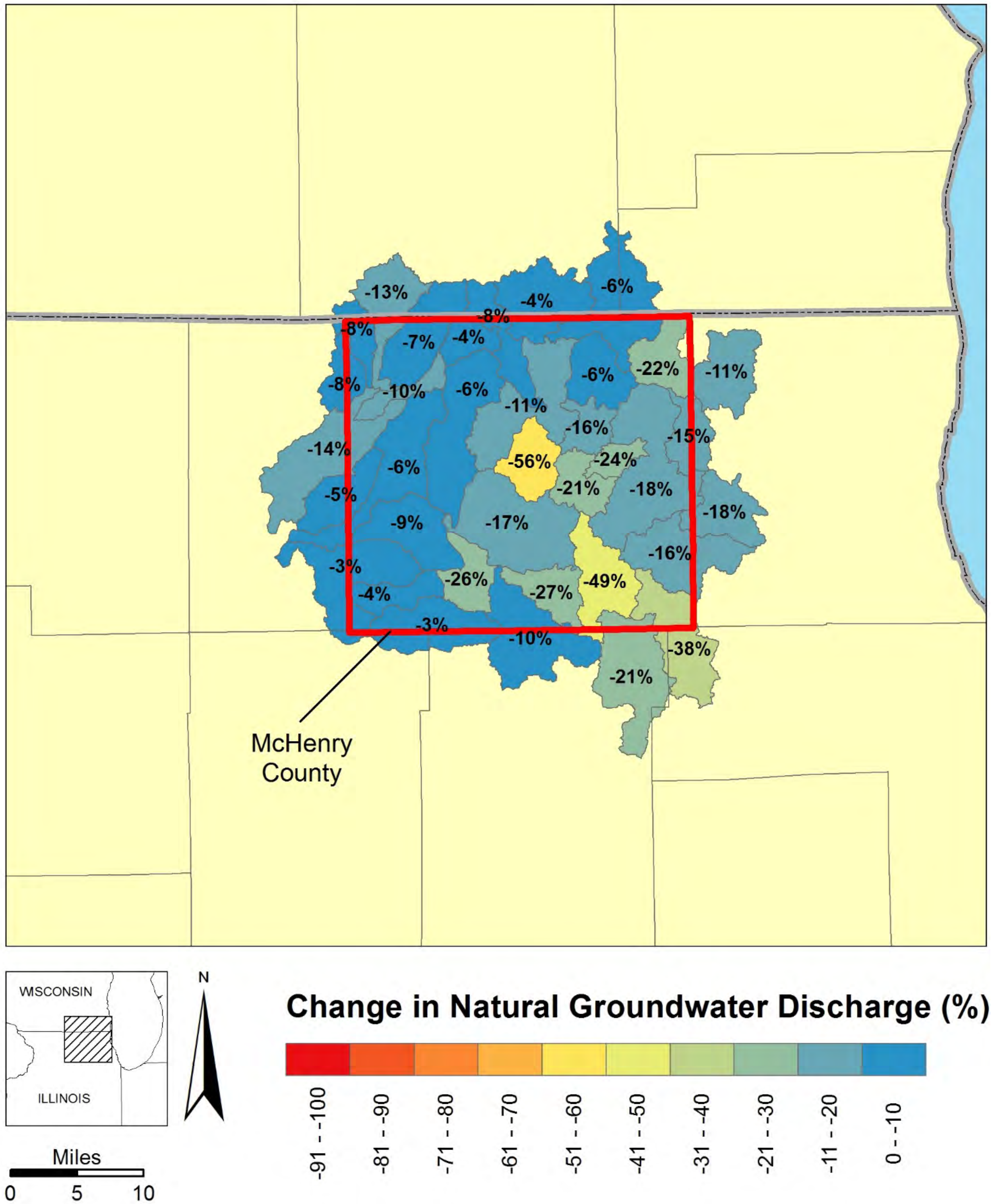

Figure 99 Change in simulated natural groundwater discharge (predevelopment to 2030, MRI scenario) in watersheds of the McHenry County area

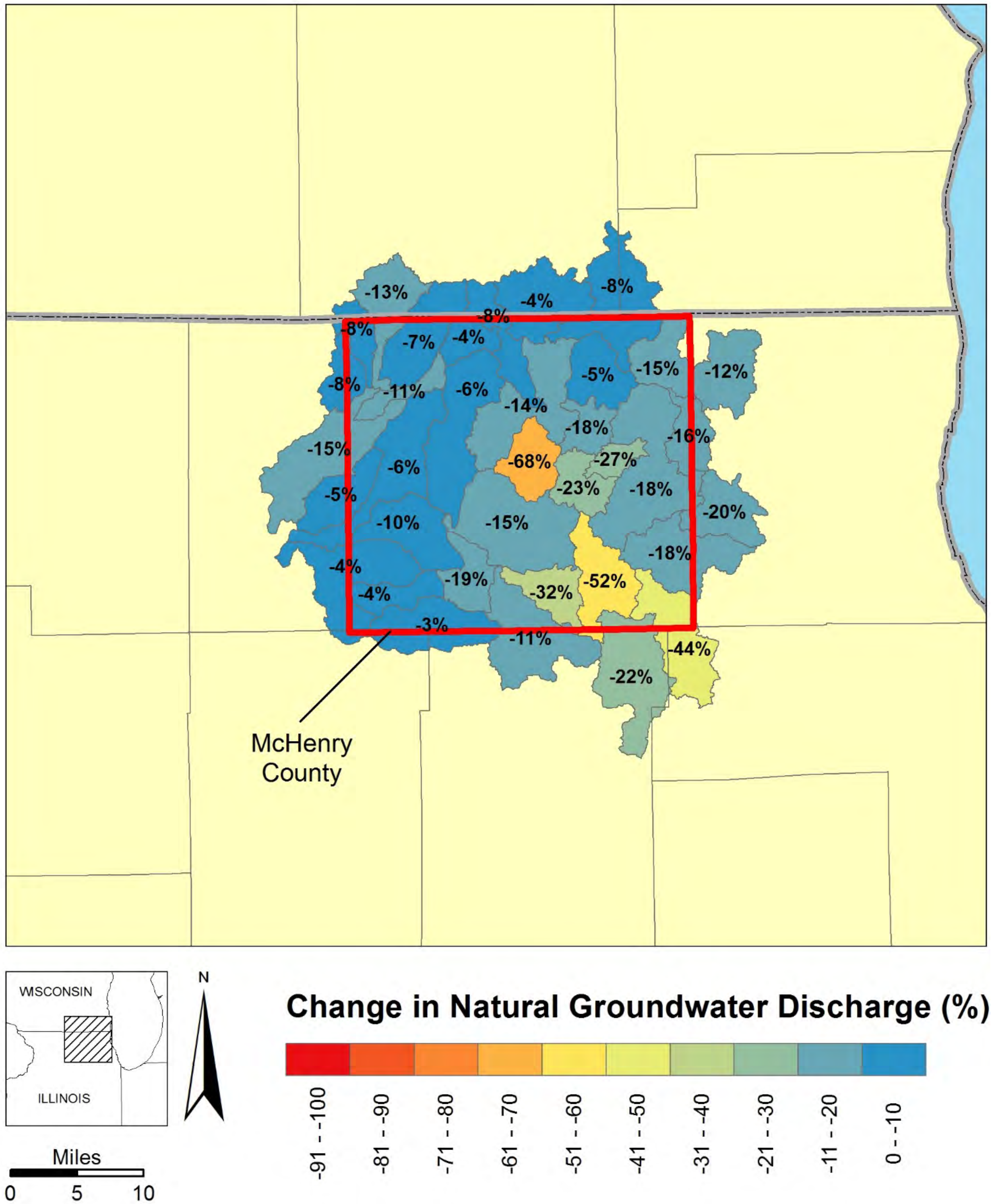

Figure 100 Change in simulated natural groundwater discharge (predevelopment to 2050, BL scenario) in watersheds of the McHenry County area

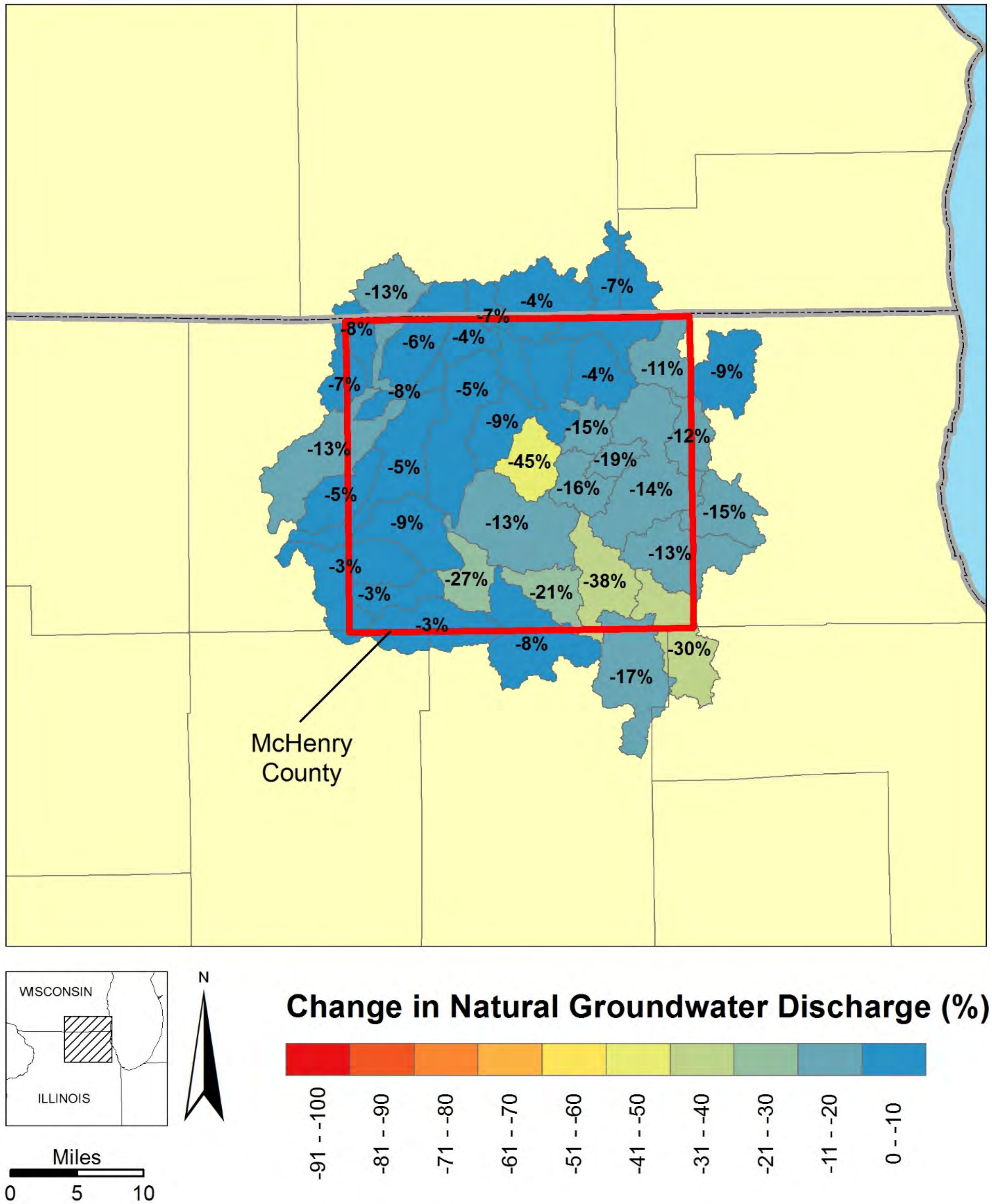

Figure 101 Change in simulated natural groundwater discharge (predevelopment to 2050, LRI scenario) in watersheds of the McHenry County area

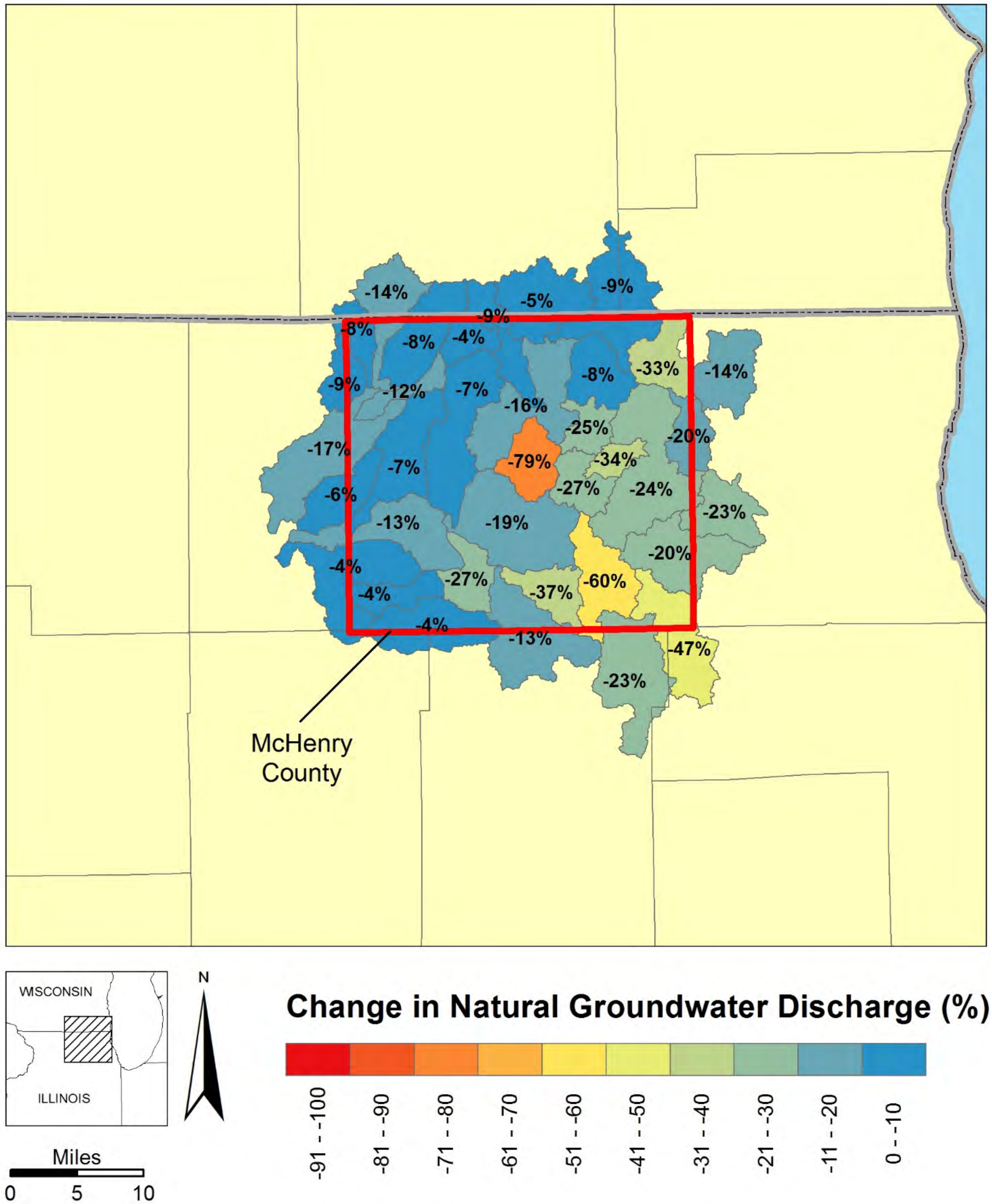

Figure 102 Change in simulated natural groundwater discharge (predevelopment to 2050, MRI scenario) in watersheds of the McHenry County area

aquifers in the northeastern Illinois region

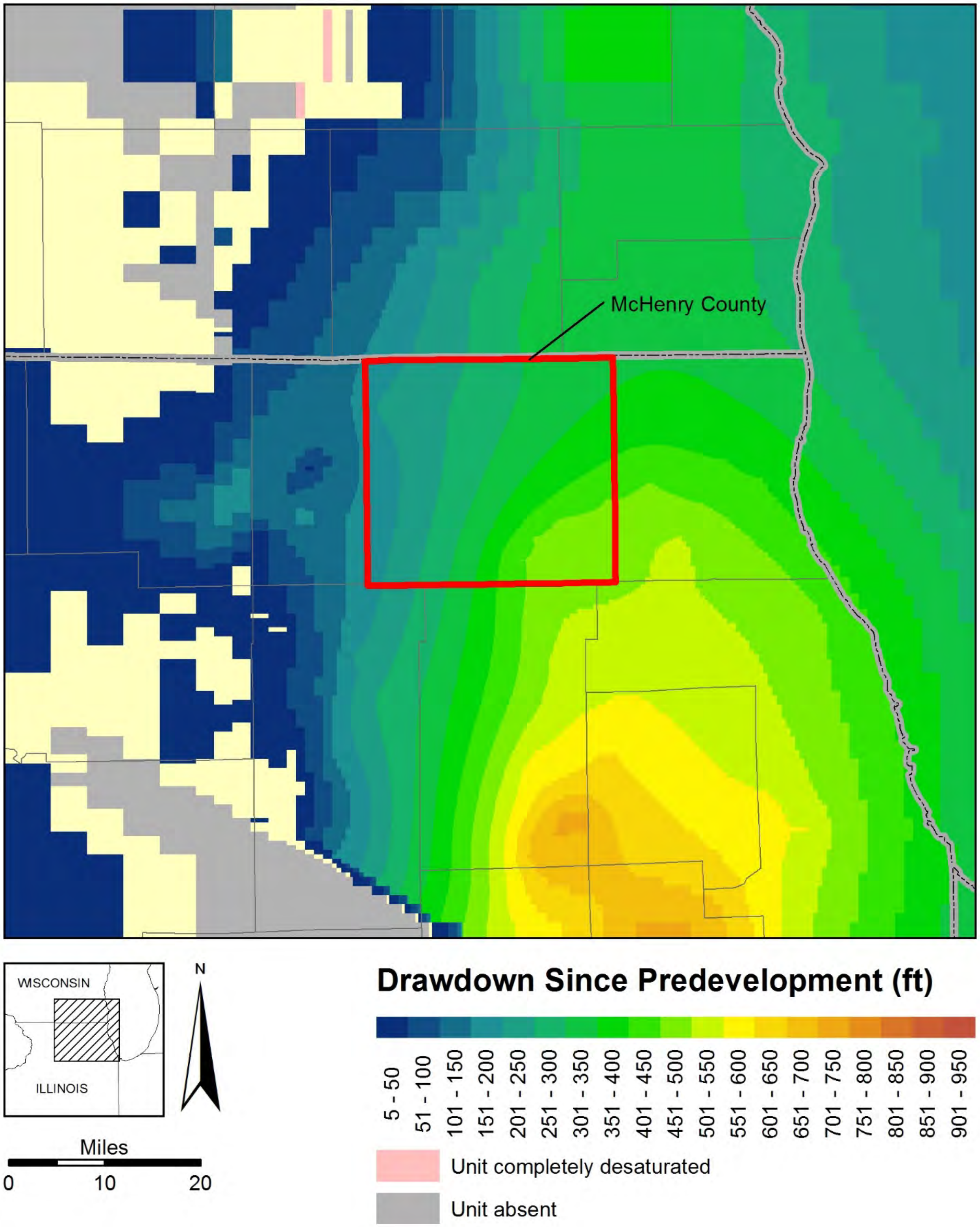

Figure 103 Simulated drawdown since predevelopment, Ancell Unit (model layer 18), 2009

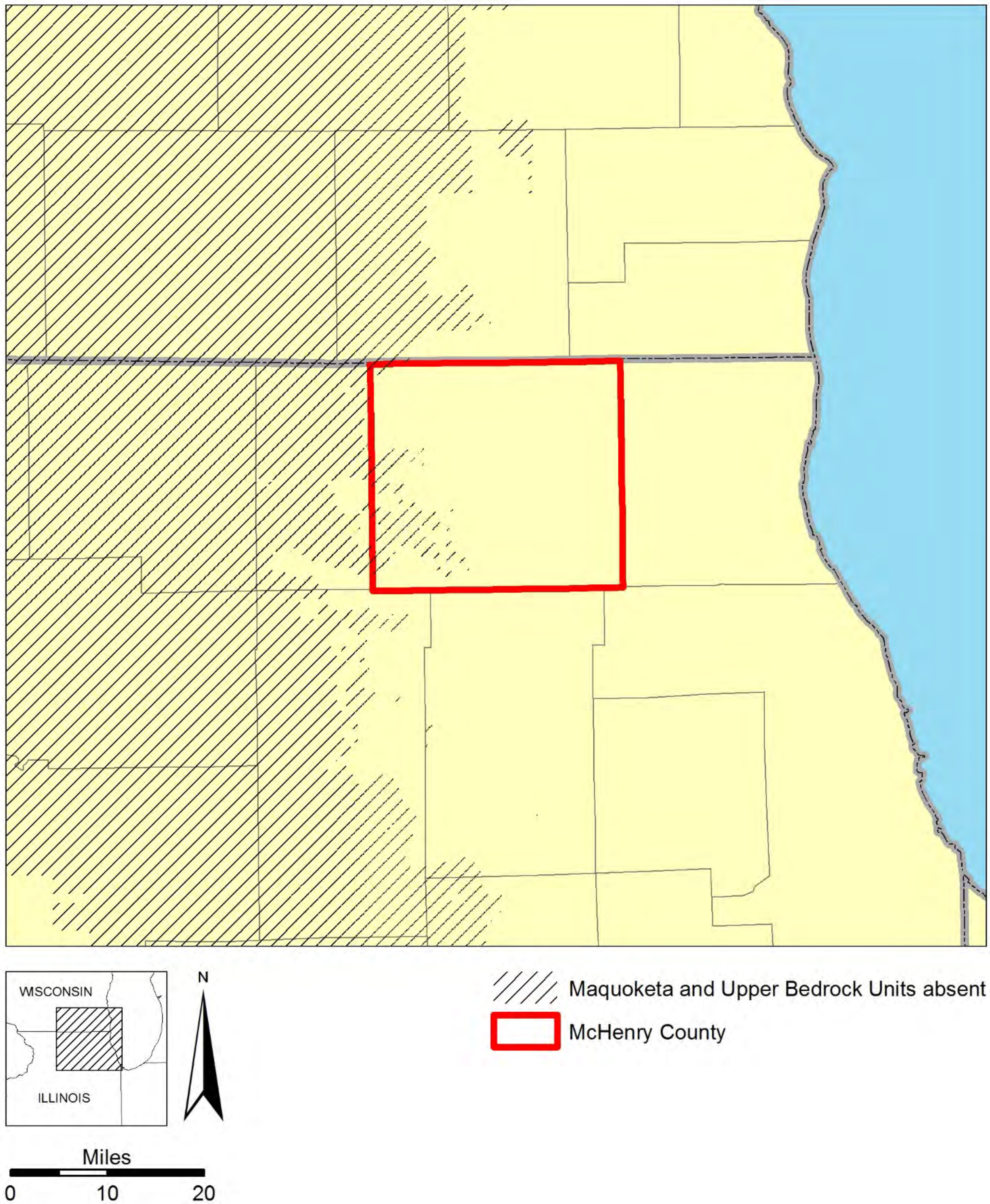

Figure 104 Area of absence of Maquoketa and Upper Bedrock Units, which together form the principal confining unit overlying the deep aquifers

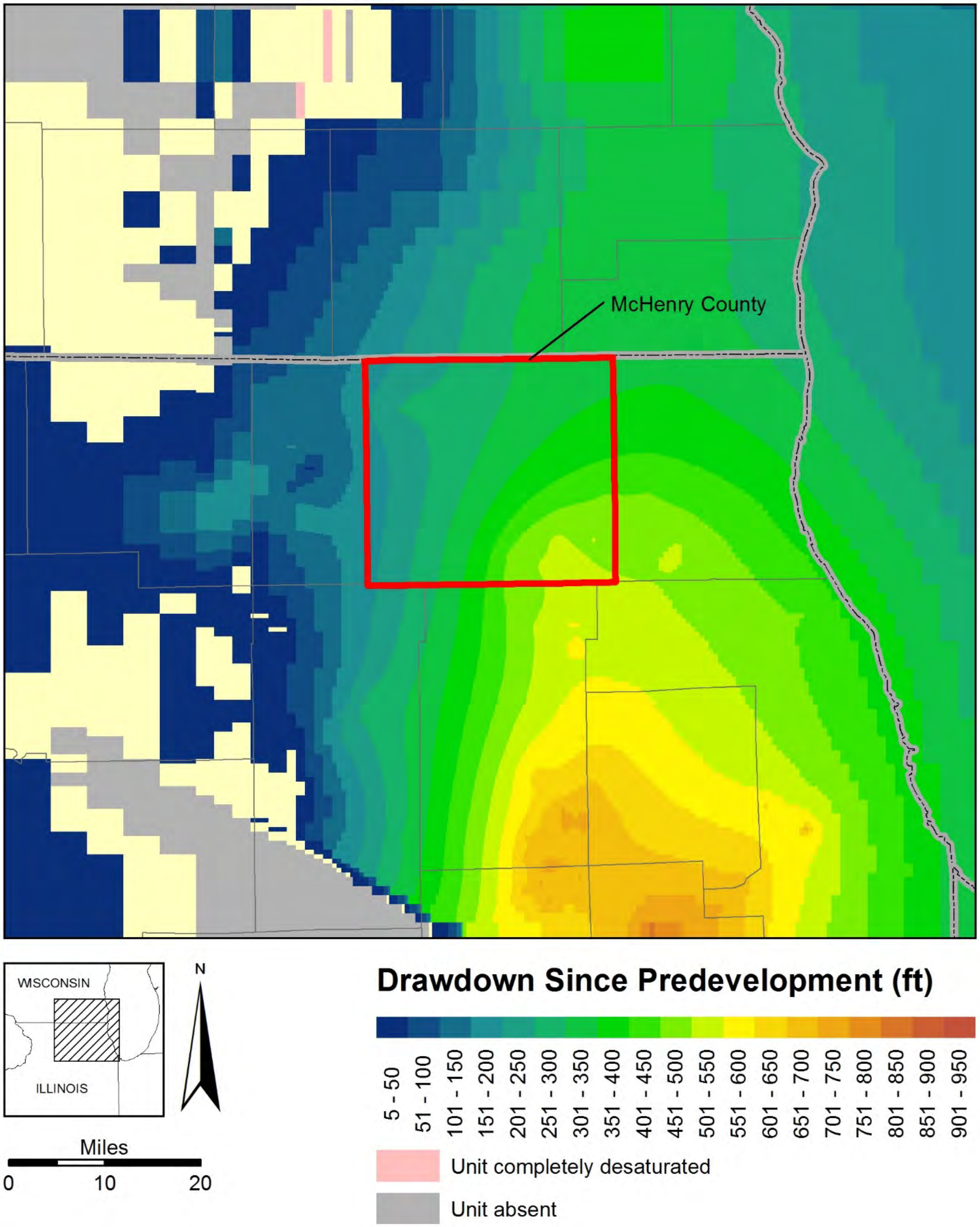

Figure 105 Simulated drawdown since predevelopment, Ancell Unit (model layer 18), 2030 (BL scenario)

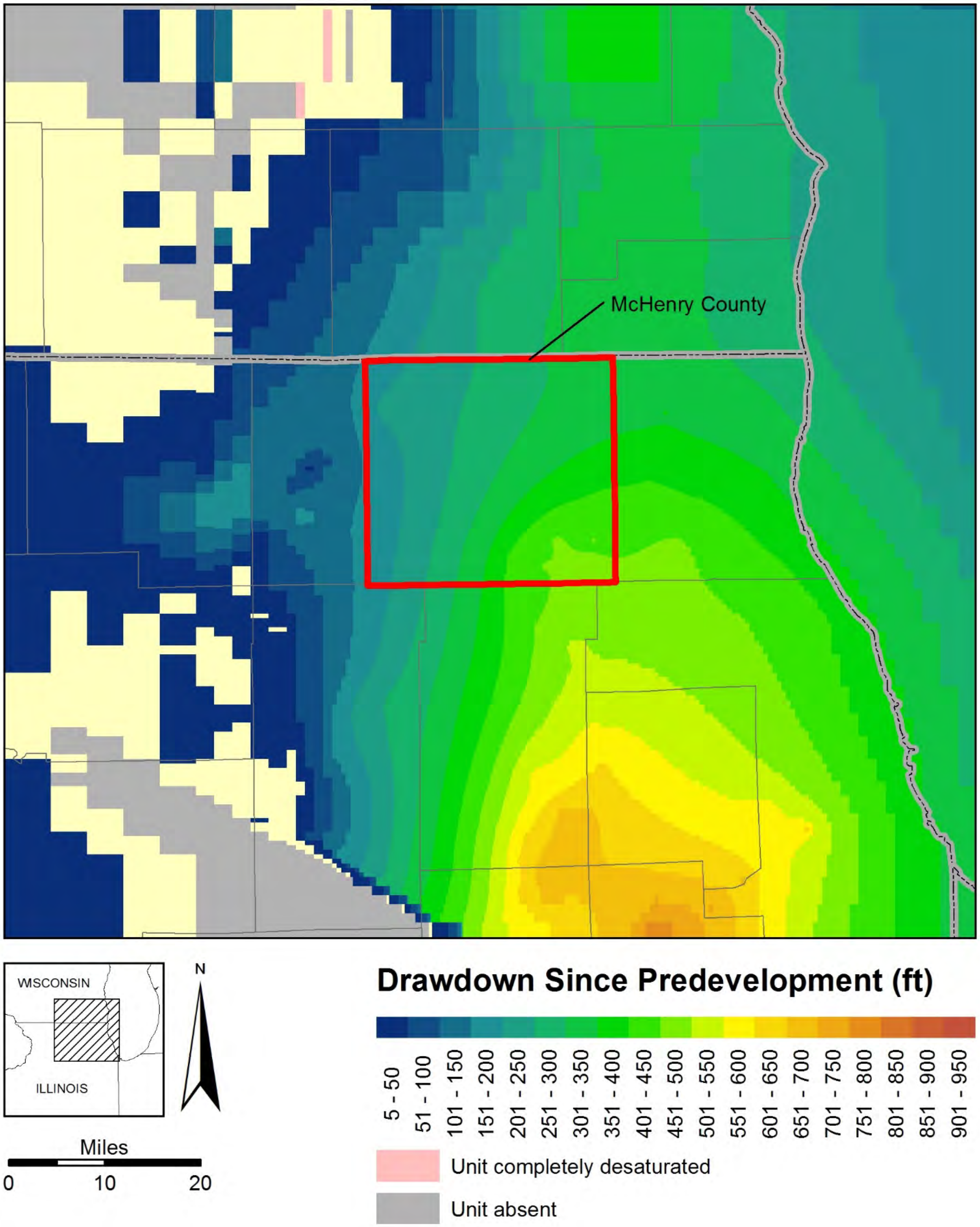

Figure 106 Simulated drawdown since predevelopment, Ancell Unit (model layer 18), 2030 (LRI scenario)

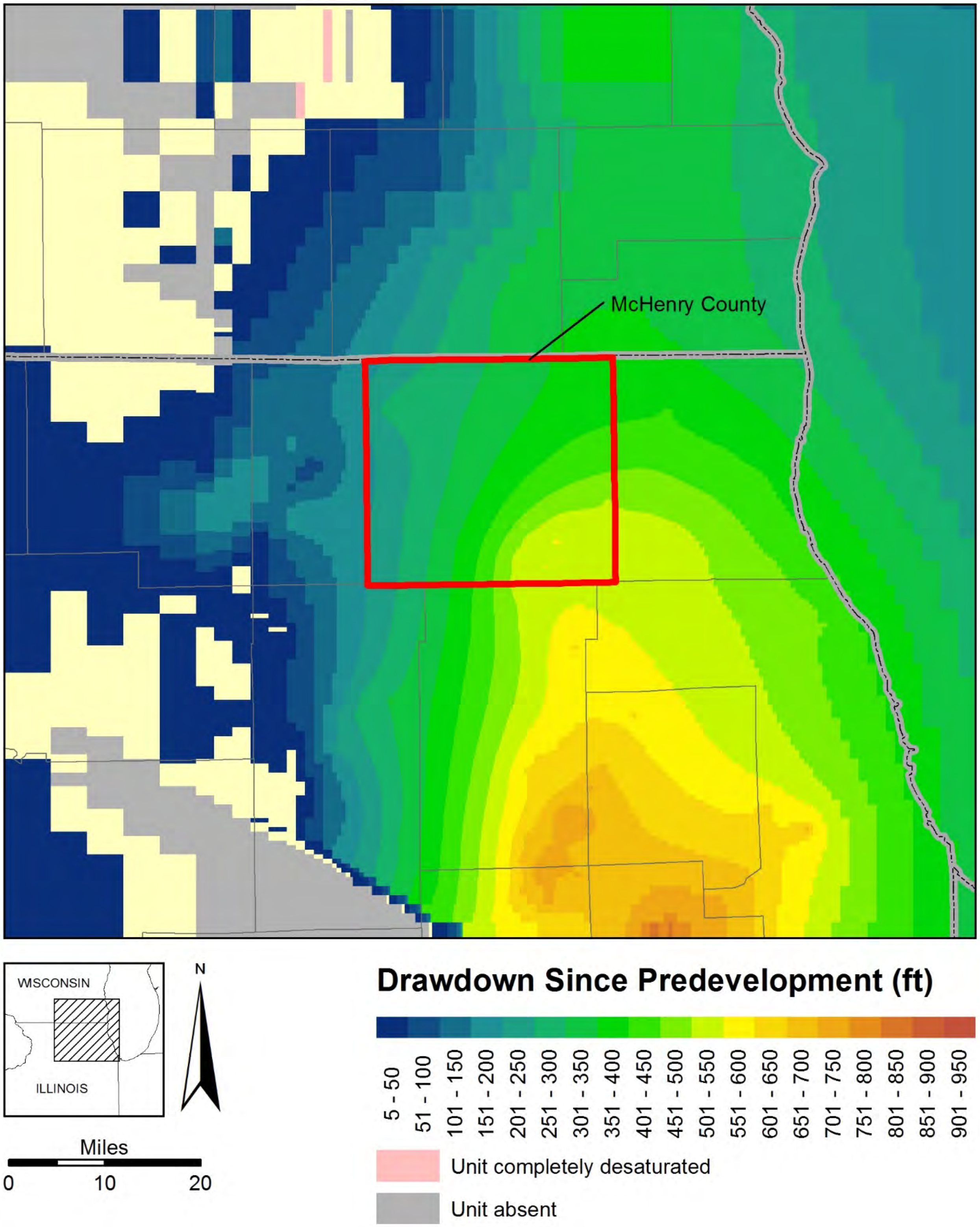

Figure 107 Simulated drawdown since predevelopment, Ancell Unit (model layer 18), 2030 (MRI scenario)

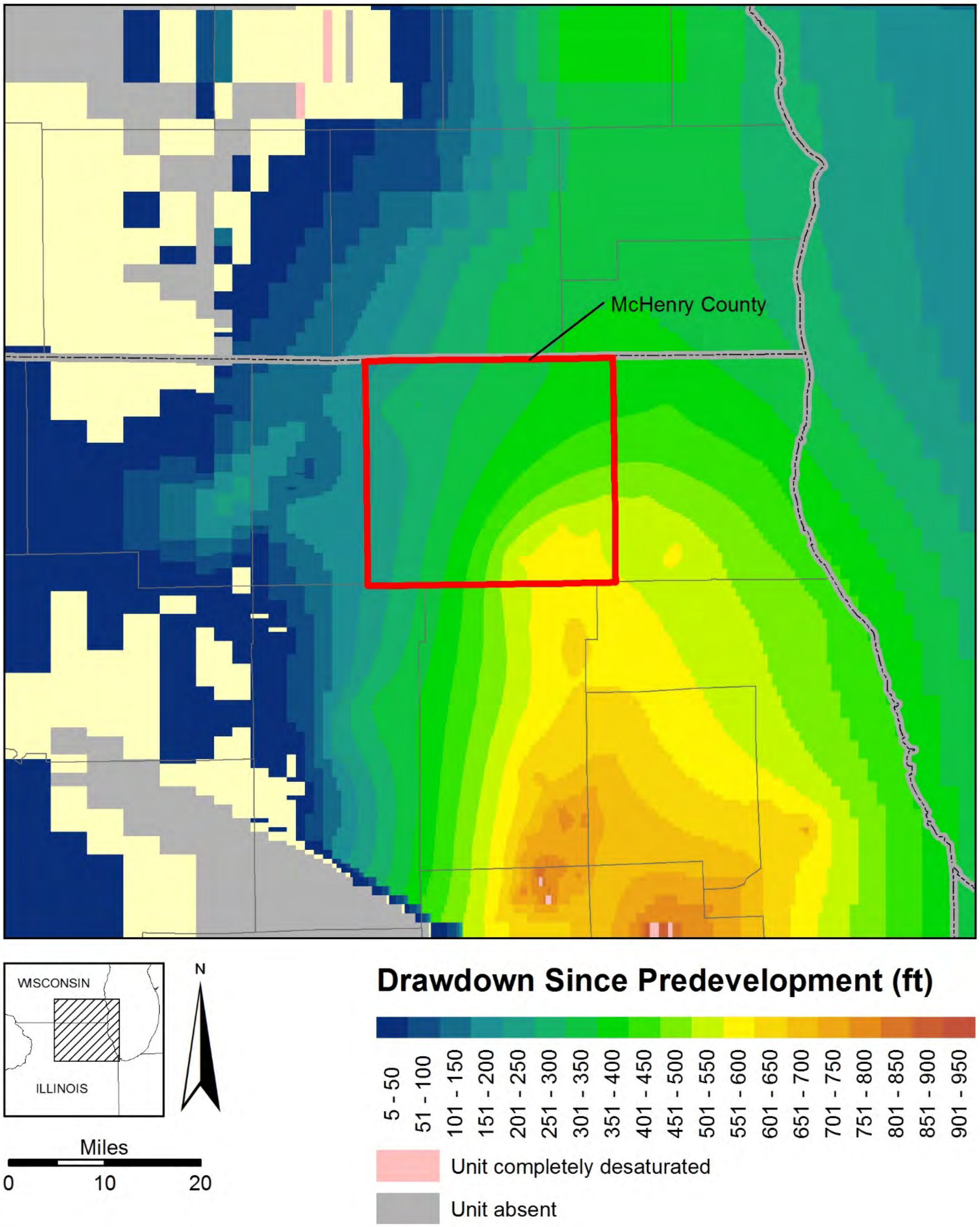

Figure 108 Simulated drawdown since predevelopment, Ancell Unit (model layer 18), 2050 (BL scenario)

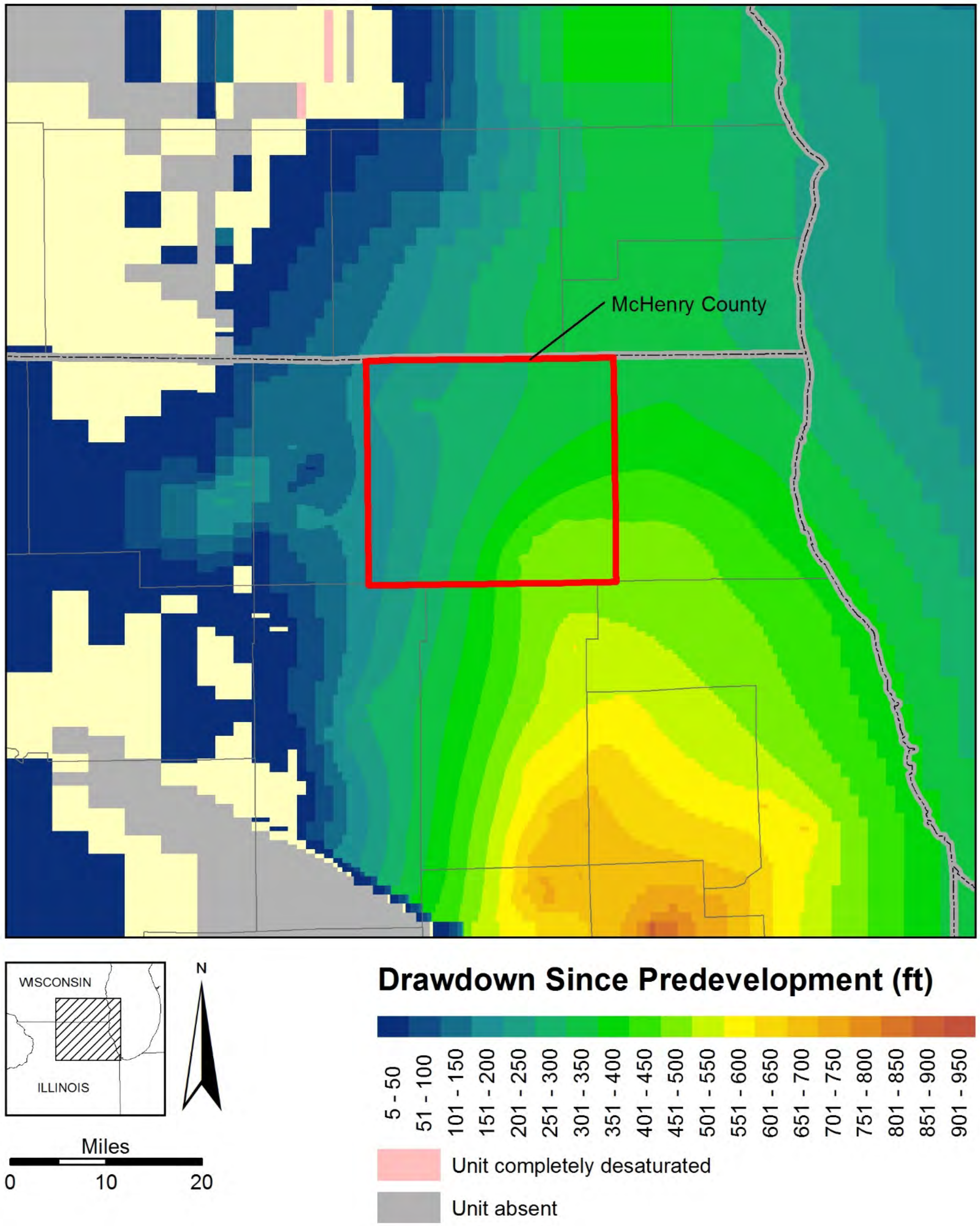

Figure 109 Simulated drawdown since predevelopment, Ancell Unit (model layer 18), 2050 (LRI scenario)

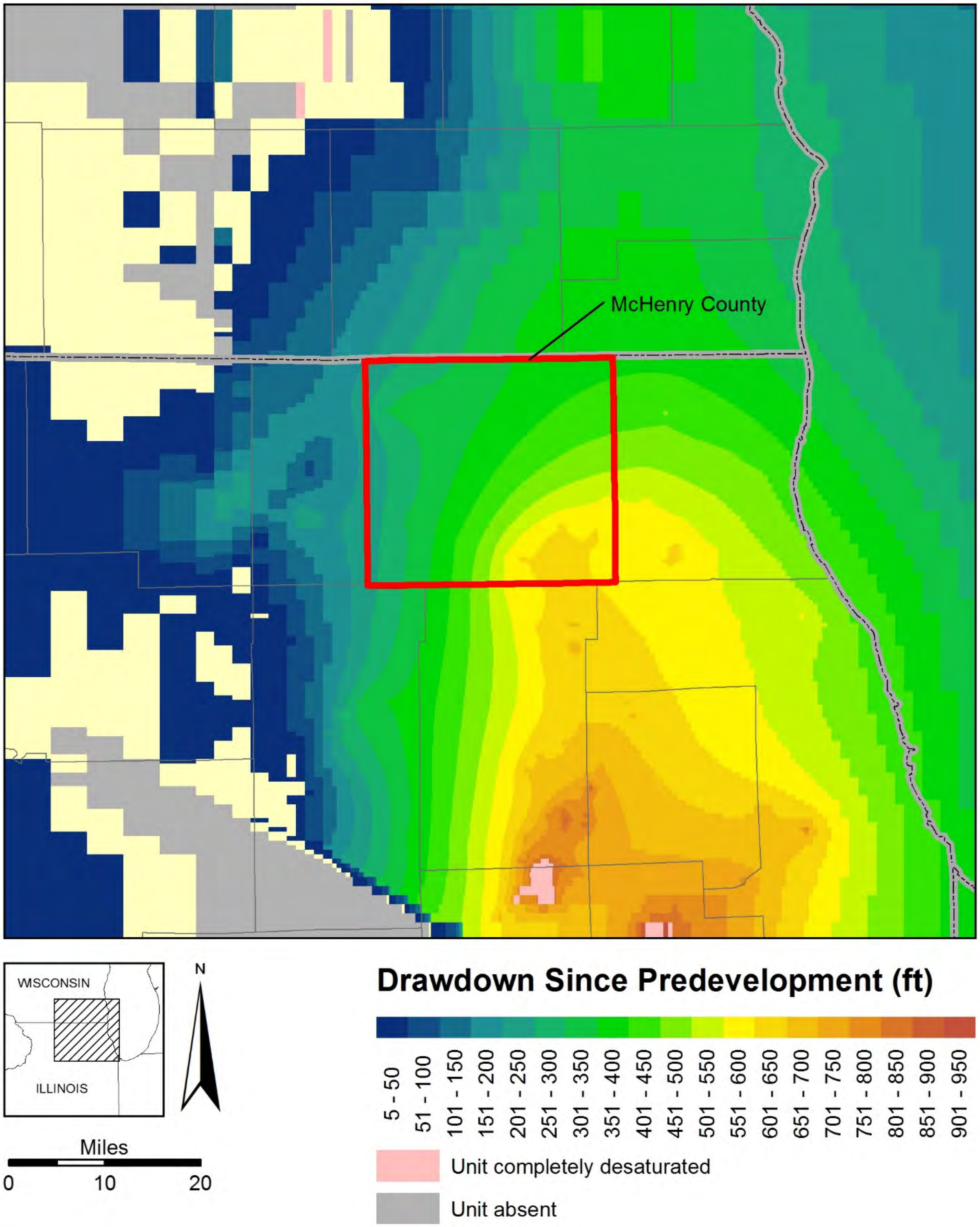

Figure 110 Simulated drawdown since predevelopment, Ancell Unit (model layer 18), 2050 (MRI scenario)

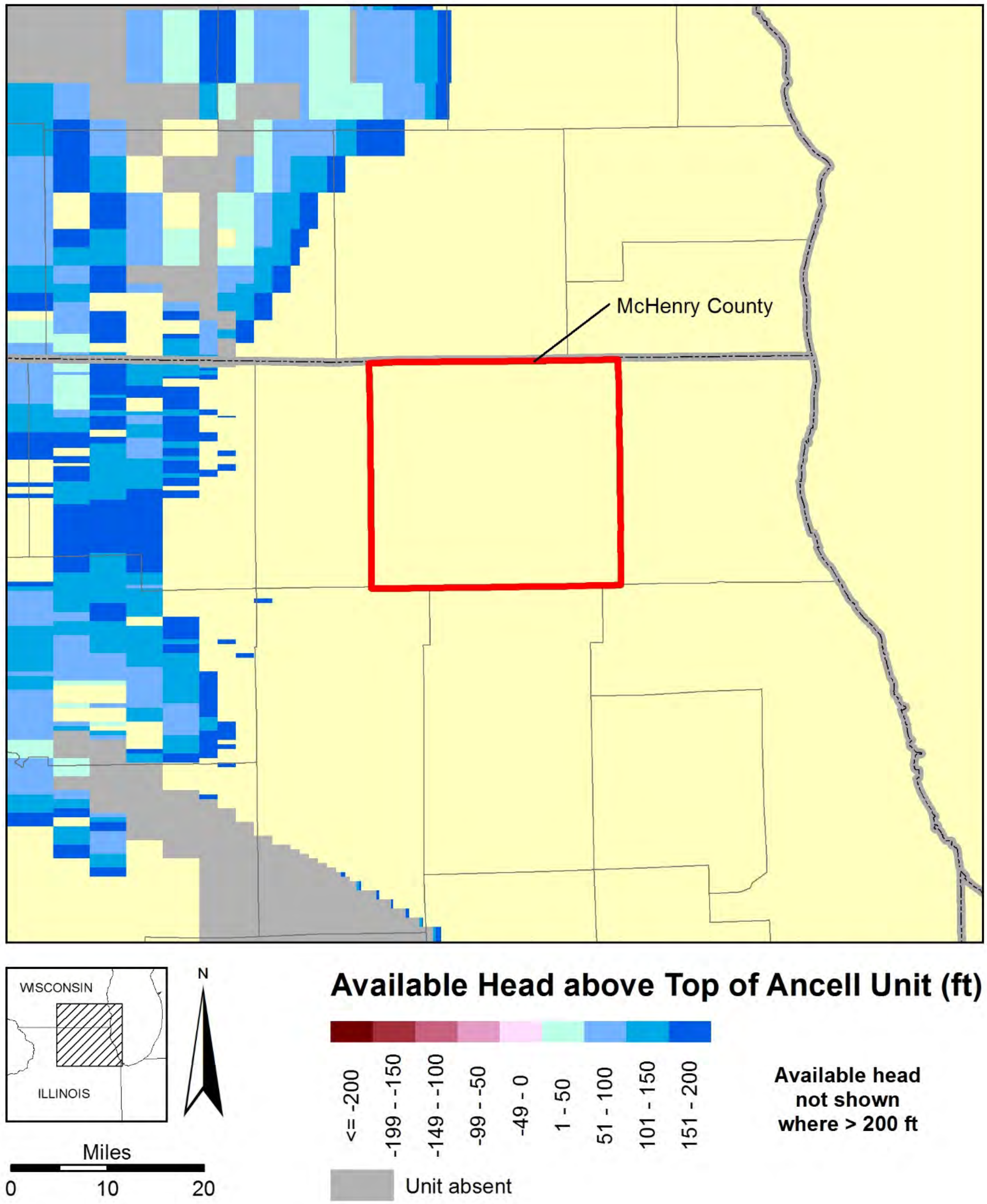

Figure 111 Available simulated head above the top of the Ancell Unit (model layer 18) under predevelopment conditions. Available head is not shaded where greater than 200 ft.

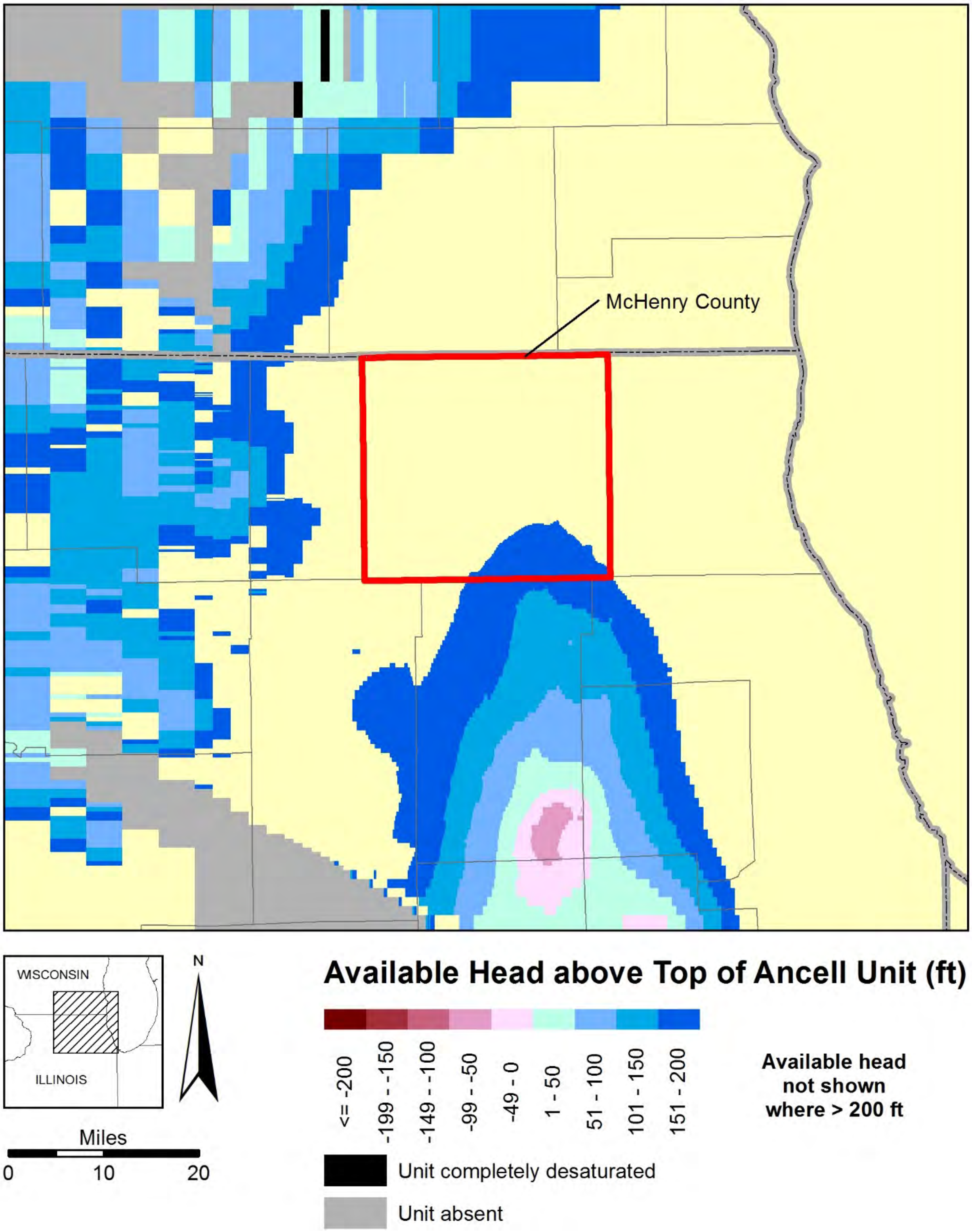

Figure 112 Available simulated head above the top of the Ancell Unit (model layer 18), 2009. Available head is not shaded where greater than 200 ft.

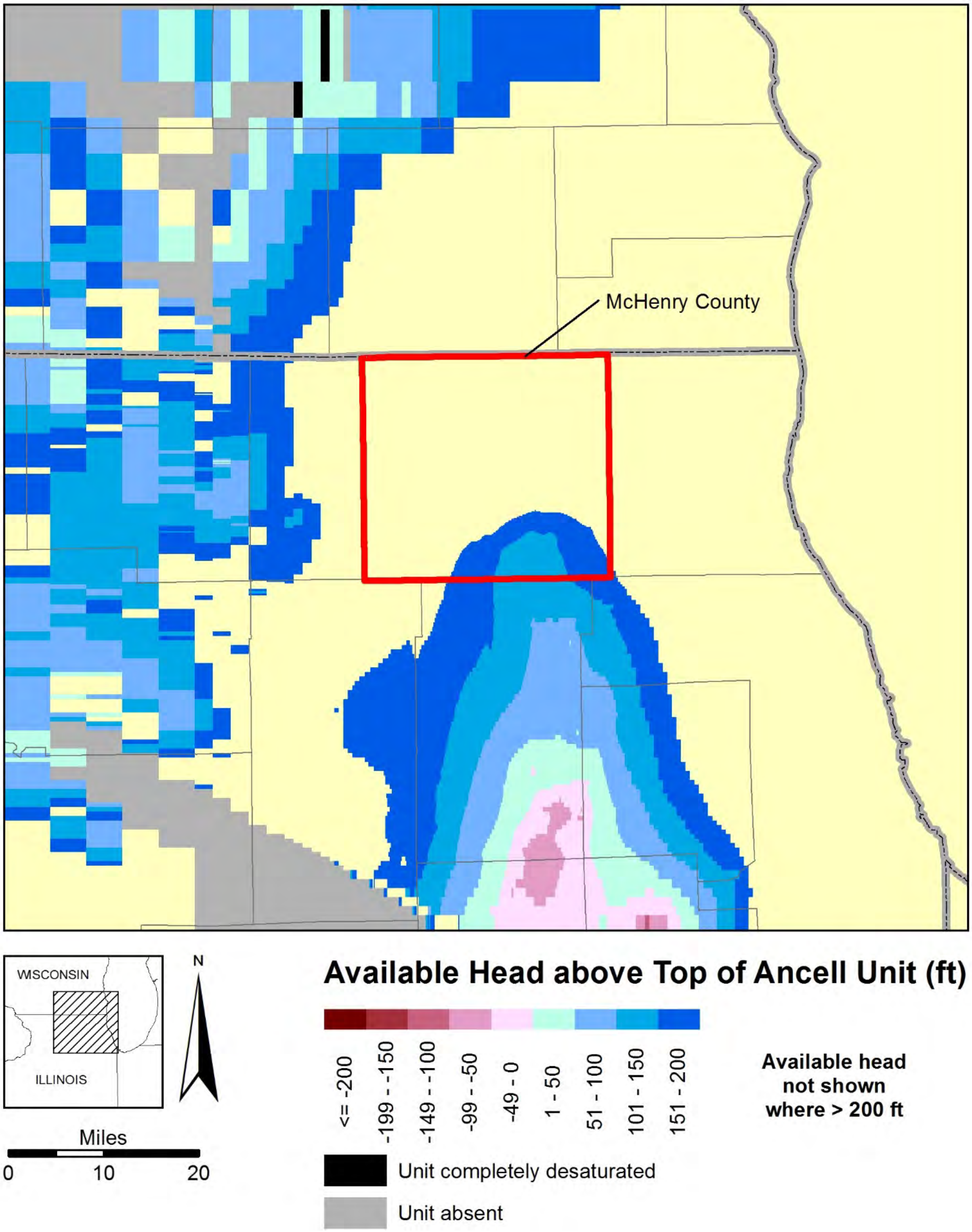

Figure 113 Available simulated head above the top of the Ancell Unit (model layer 18), 2030 (BL scenario). Available head is not shaded where greater than 200 ft.

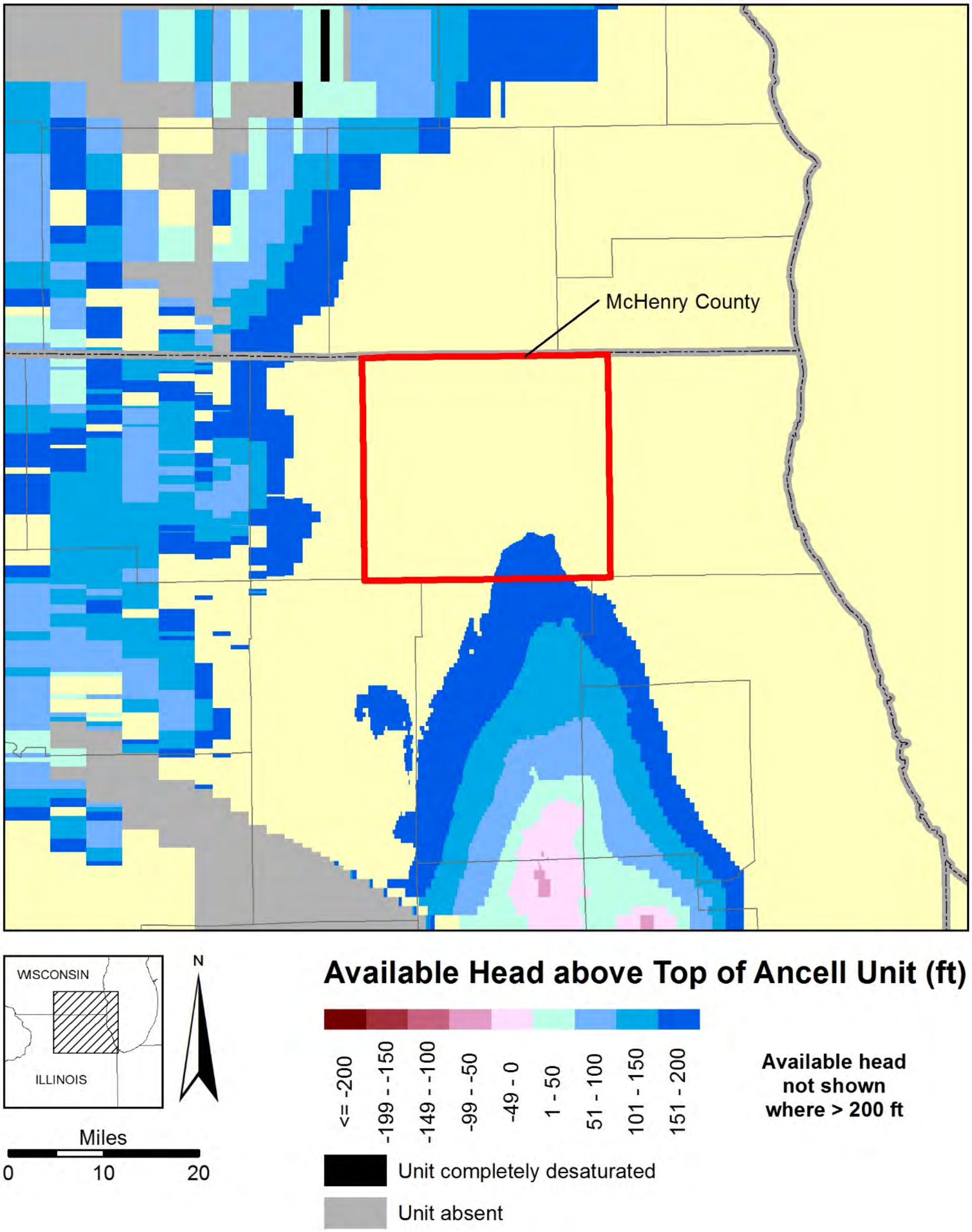

Figure 114 Available simulated head above the top of the Ancell Unit (model layer 18), 2030 (LRI scenario). Available head is not shaded where greater than 200 ft.

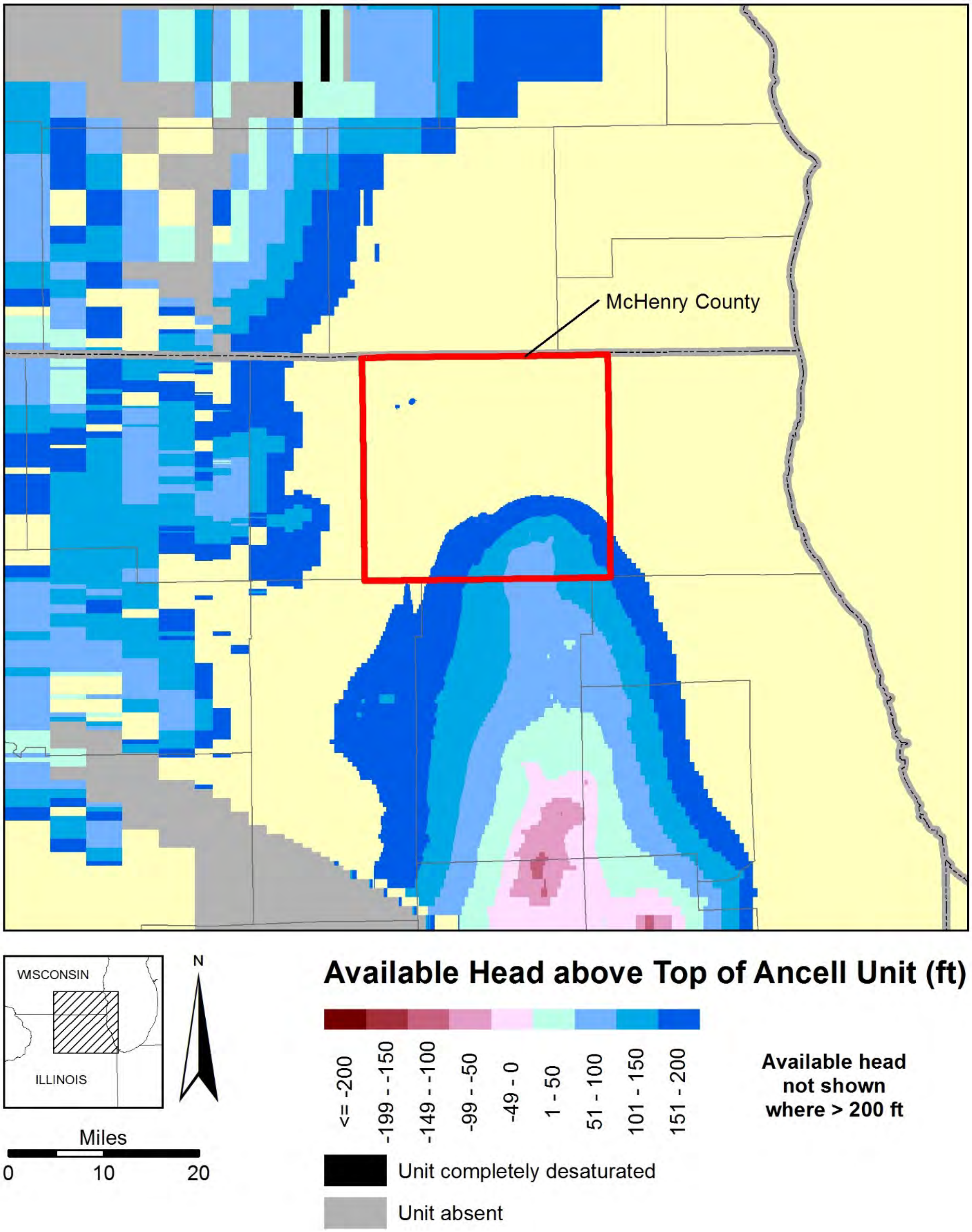

Figure 115 Available simulated head above the top of the Ancell Unit, end of 2030 (MRI scenario). Available head is not shaded where greater than 200 ft.

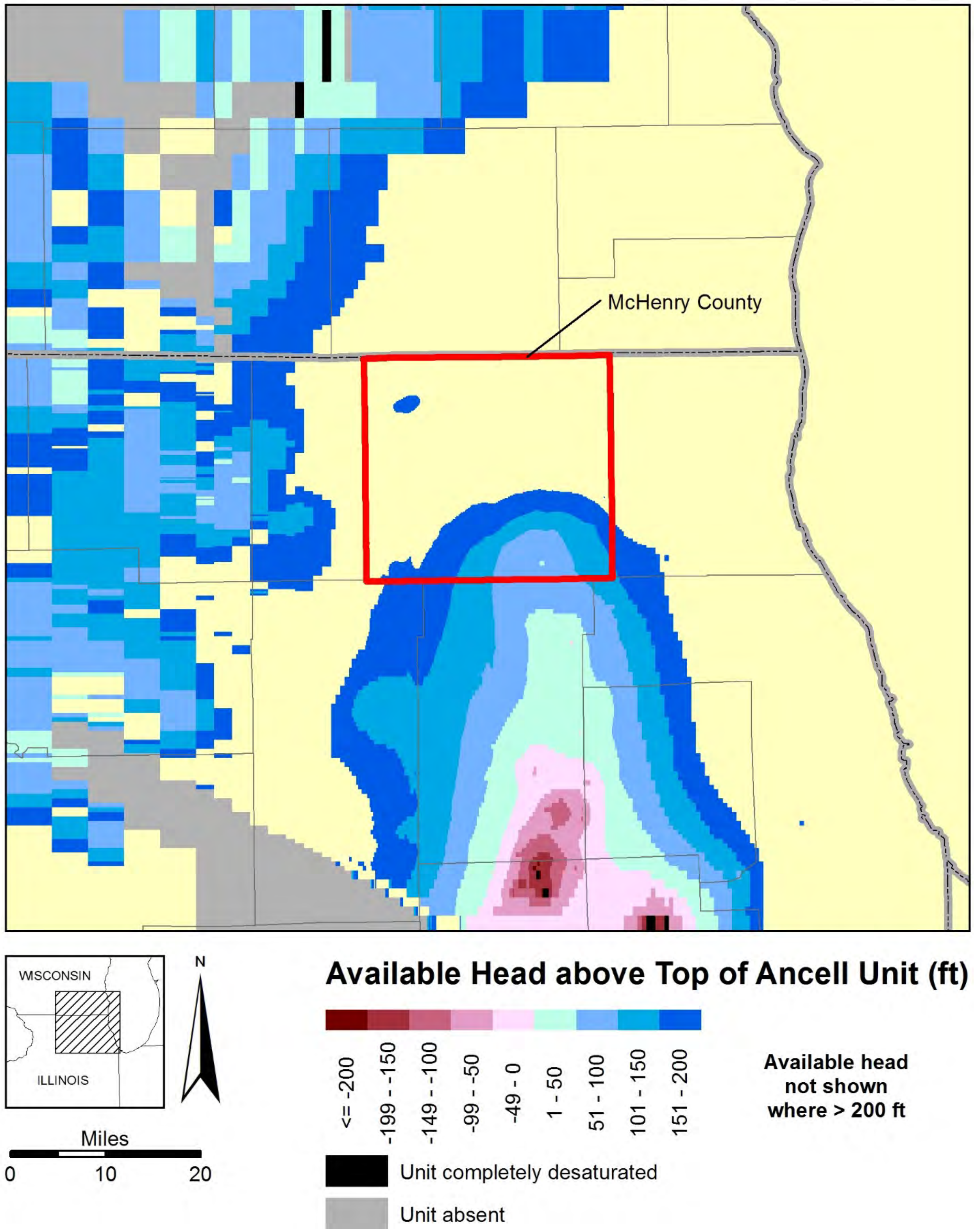

Figure 116 Available simulated head above the top of the Ancell Unit (model layer 18), 2050 (BL scenario). Available head is not shaded where greater than 200 ft.

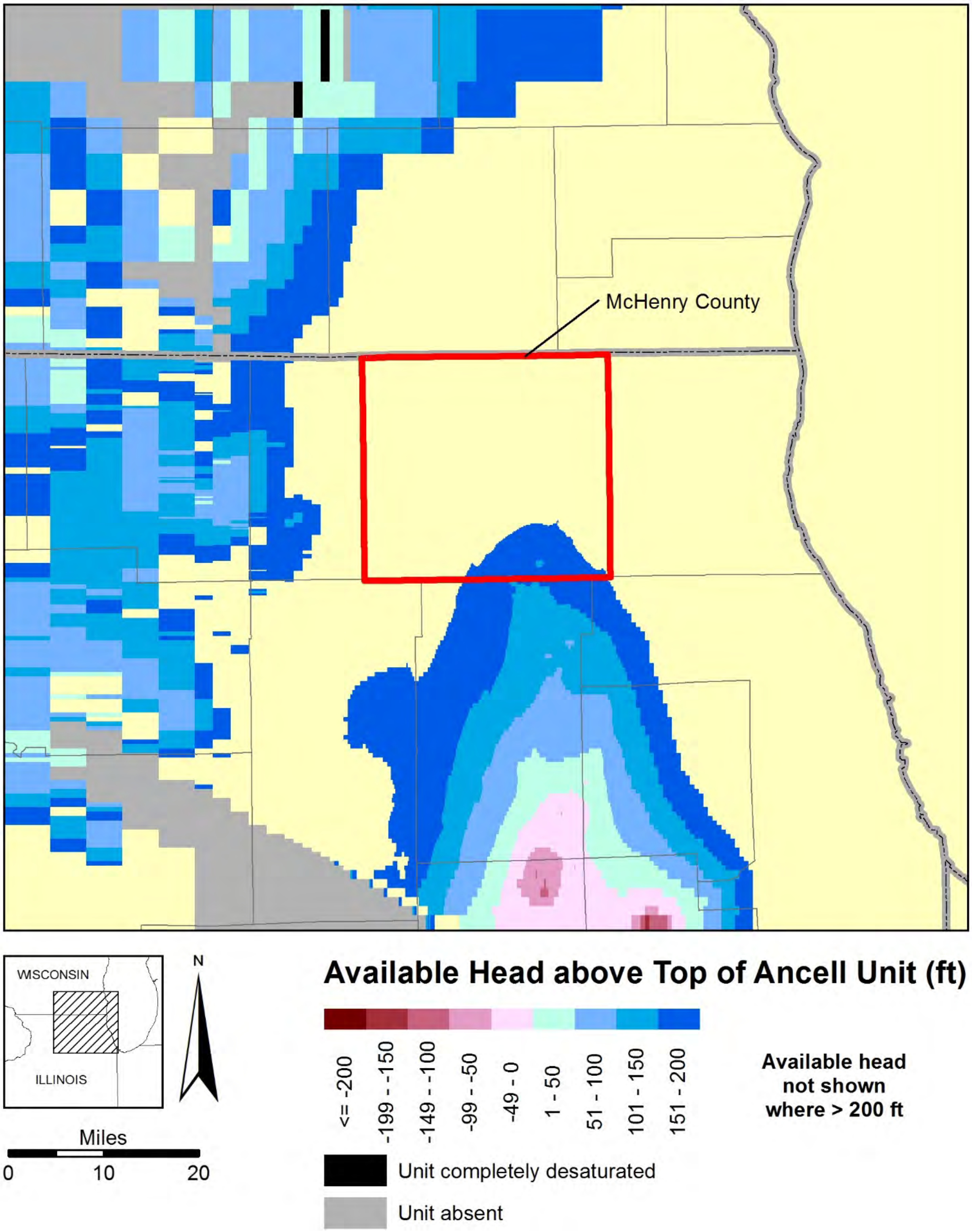

Figure 117 Available simulated head above the top of the Ancell Unit (model layer 18), 2050 (LRI scenario). Available head is not shaded where greater than 200 ft.

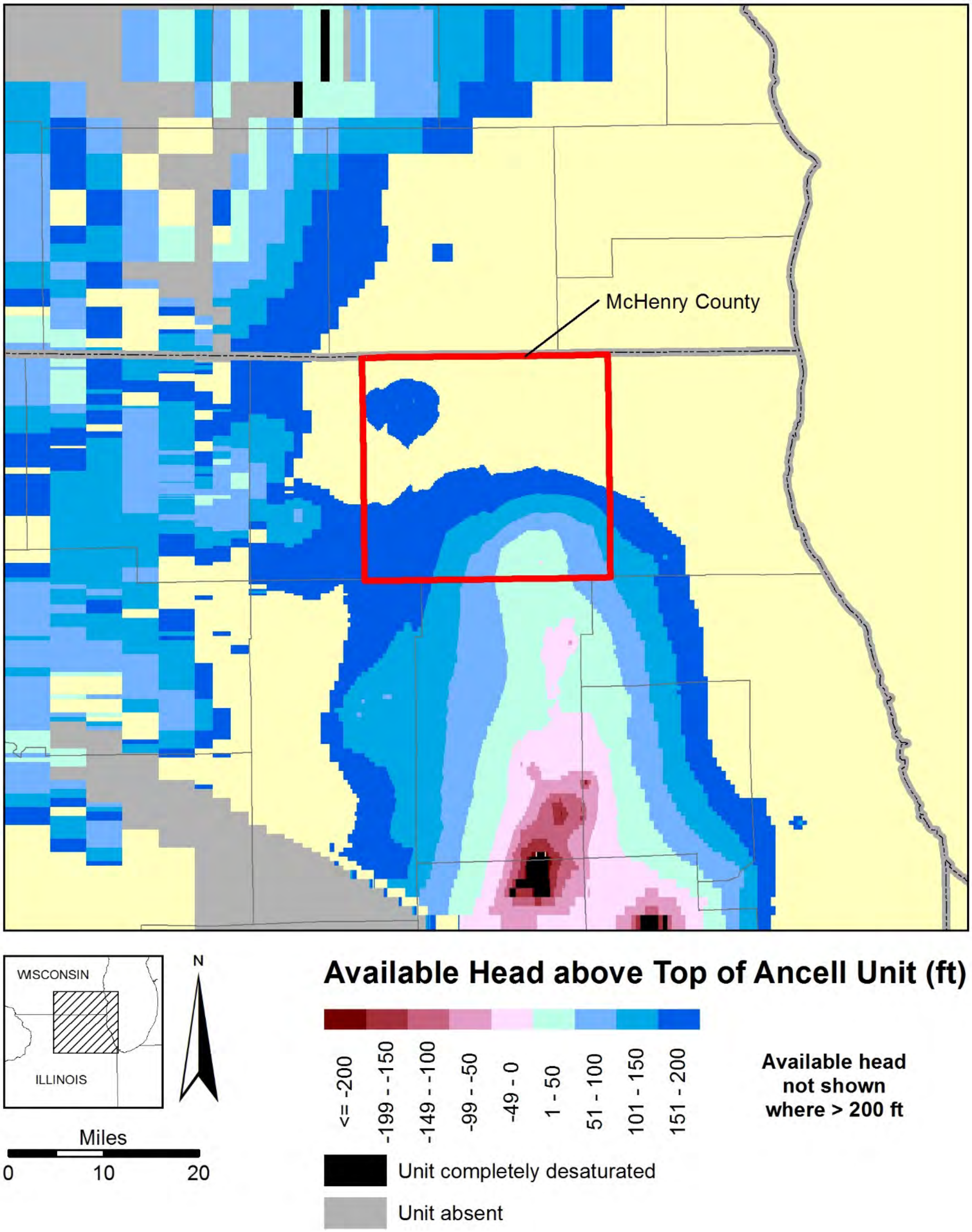

Figure 118 Available simulated head above the top of the Ancell Unit (model layer 18), 2050 (MRI scenario). Available head is not shaded where greater than 200 ft.

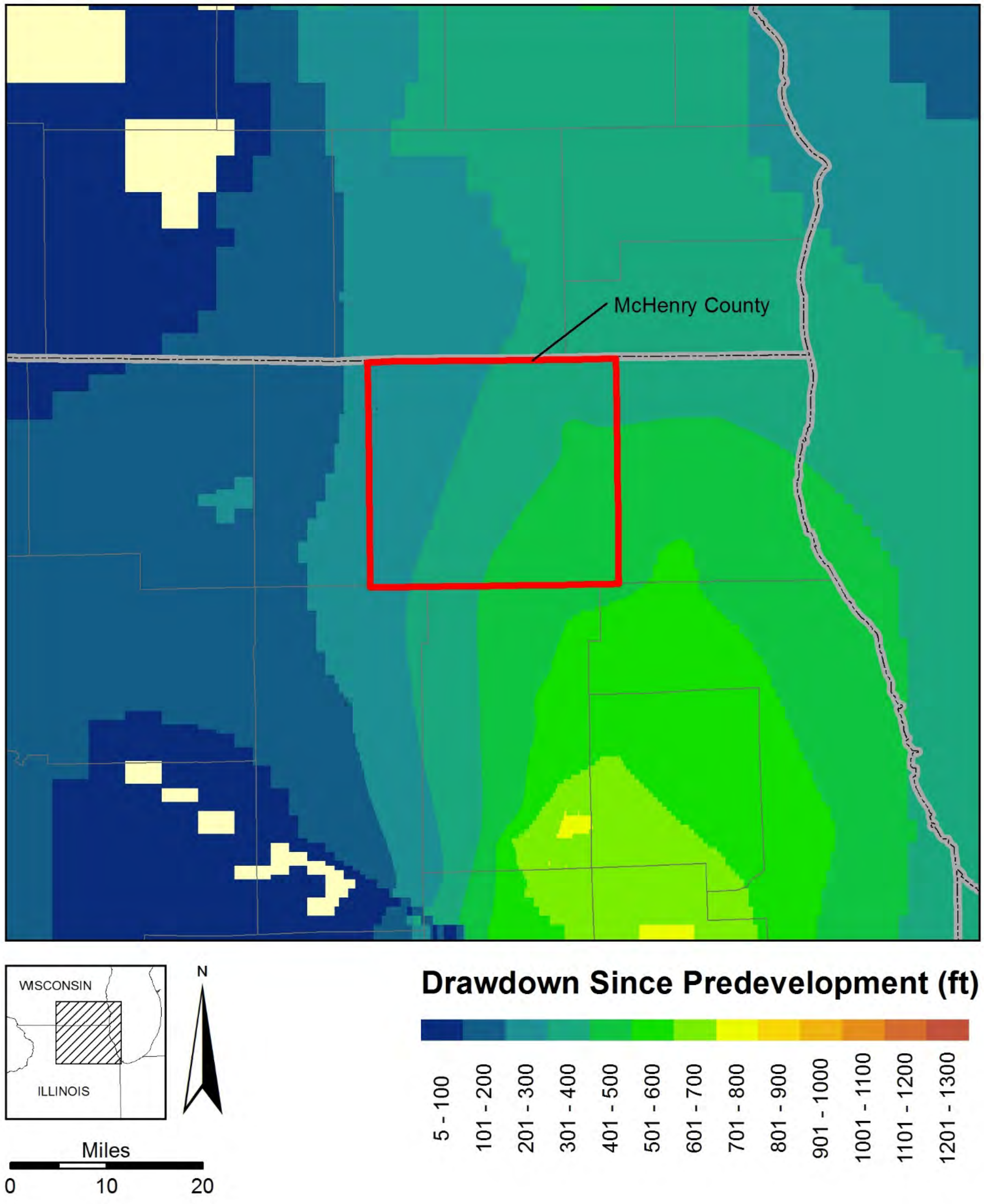

Figure 119 Simulated drawdown since predevelopment, Ironton-Galesville Unit (model layer 21), 2009

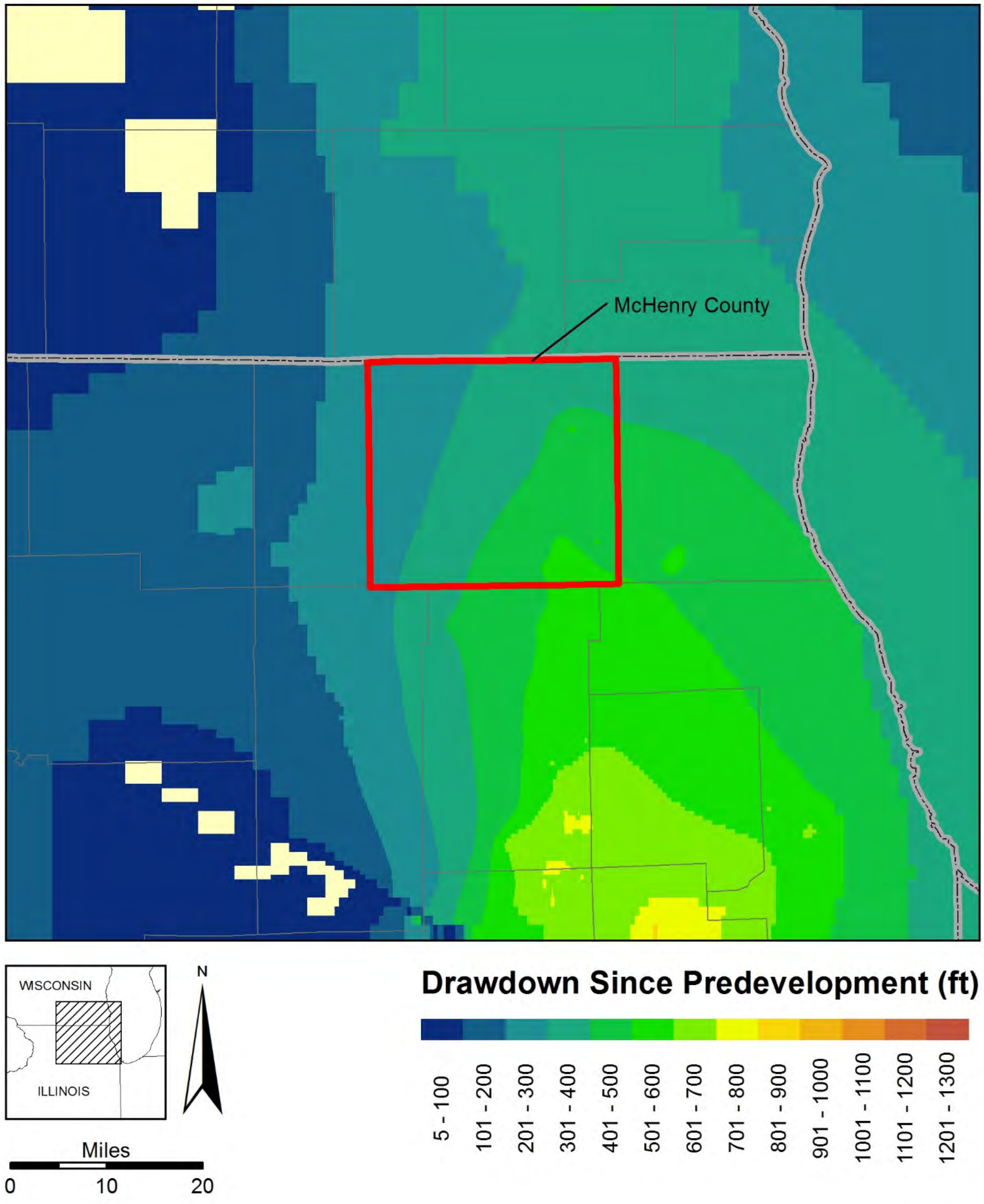

Figure 120 Simulated drawdown since predevelopment, Ironton-Galesville Unit (model layer 21), 2030 (BL scenario)

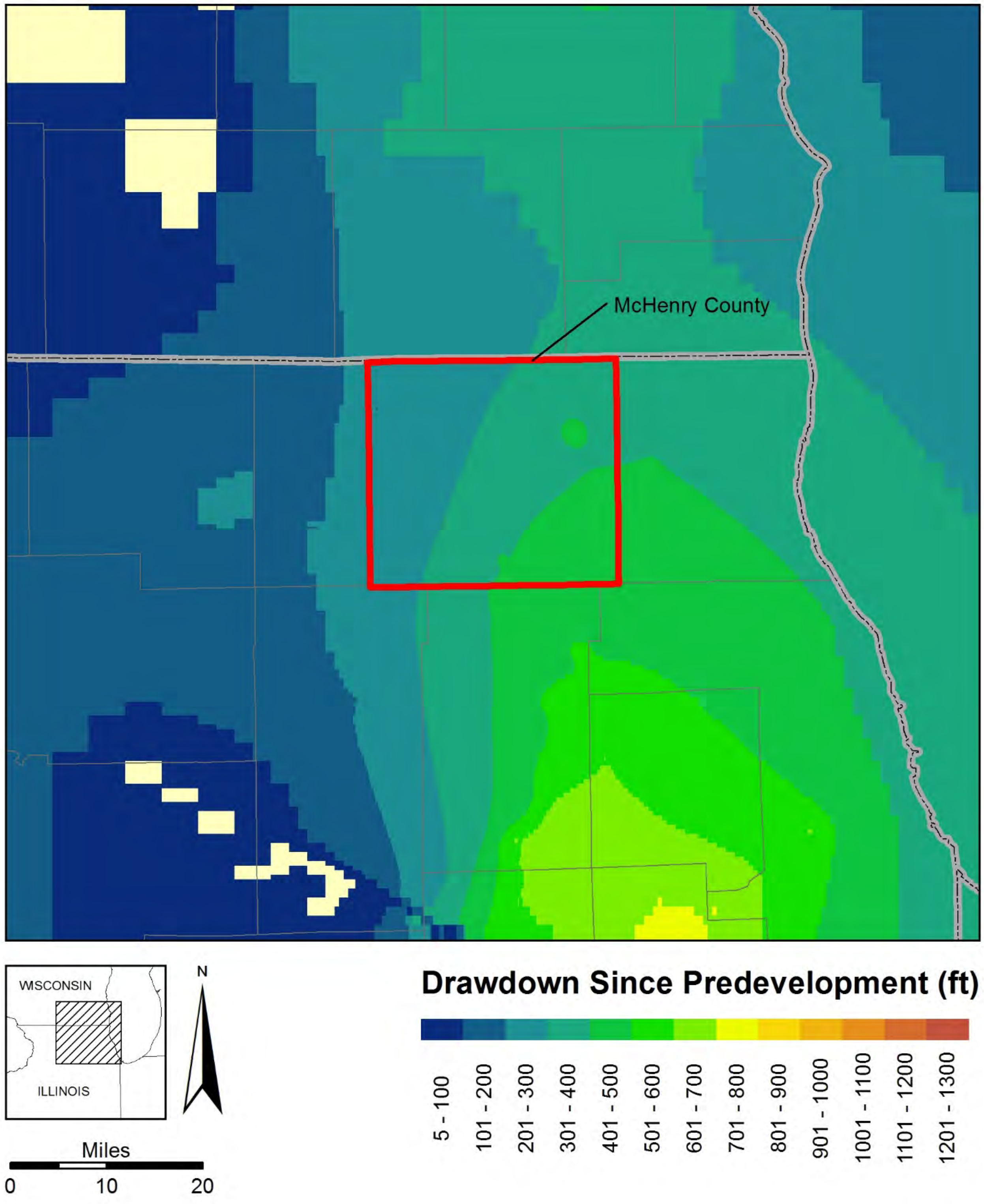

Figure 121 Simulated drawdown since predevelopment, Ironton-Galesville Unit (model layer 21), 2030 (LRI scenario)

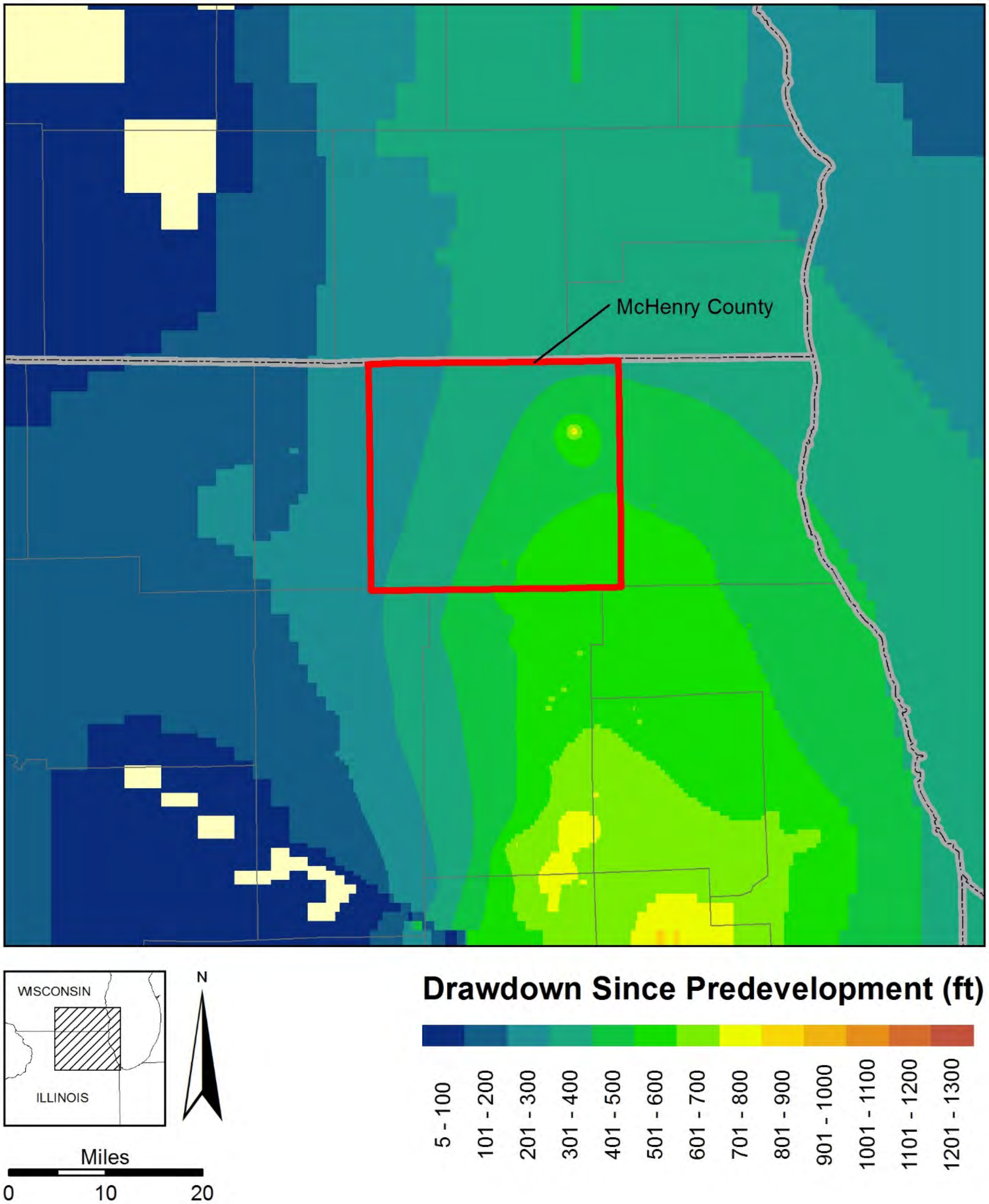

Figure 122 Simulated drawdown since predevelopment, Ironton-Galesville Unit (model layer 21), 2030 (MRI scenario)

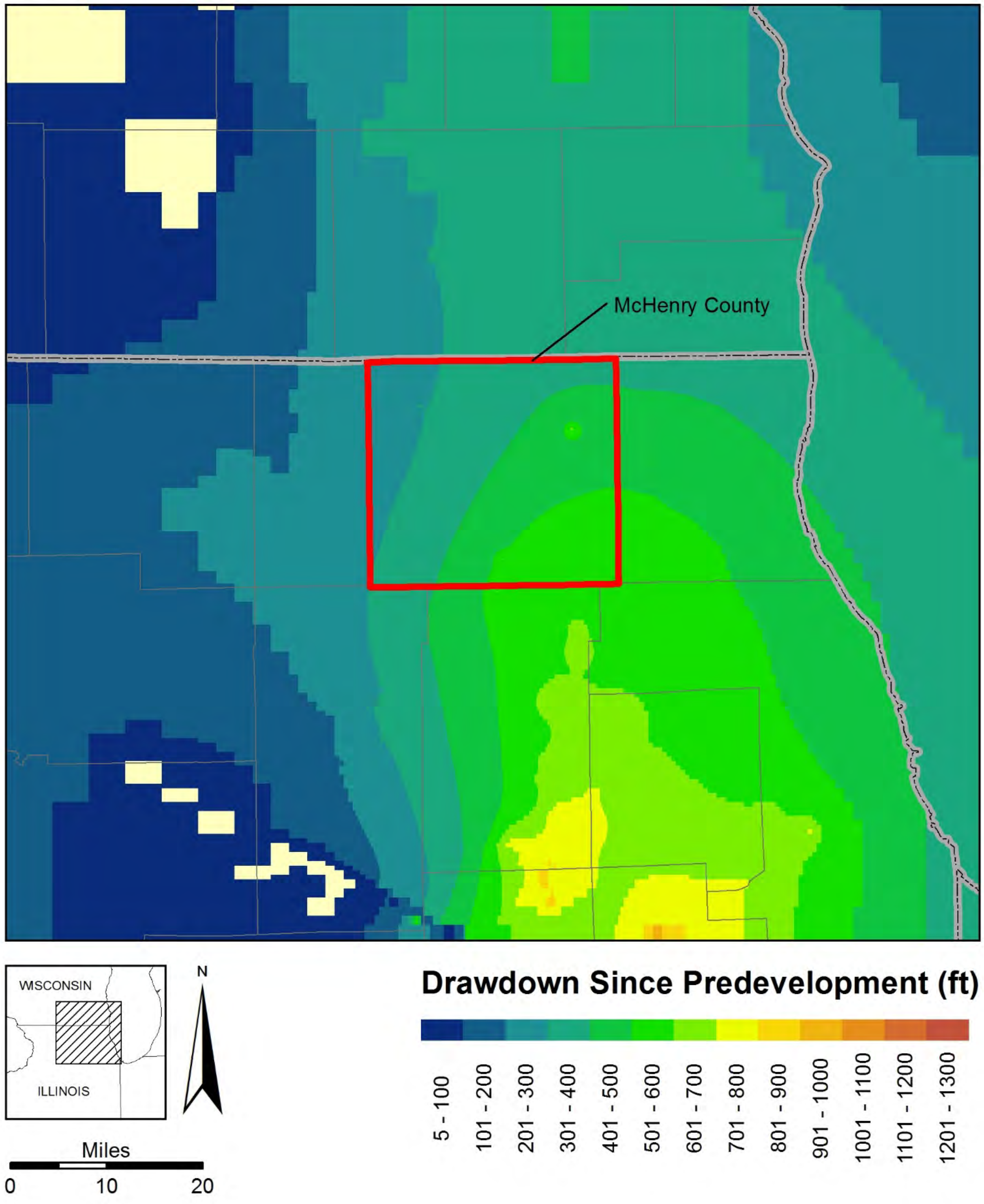

Figure 123 Simulated drawdown since predevelopment, Ironton-Galesville Unit (model layer 21), 2050 (BL scenario)

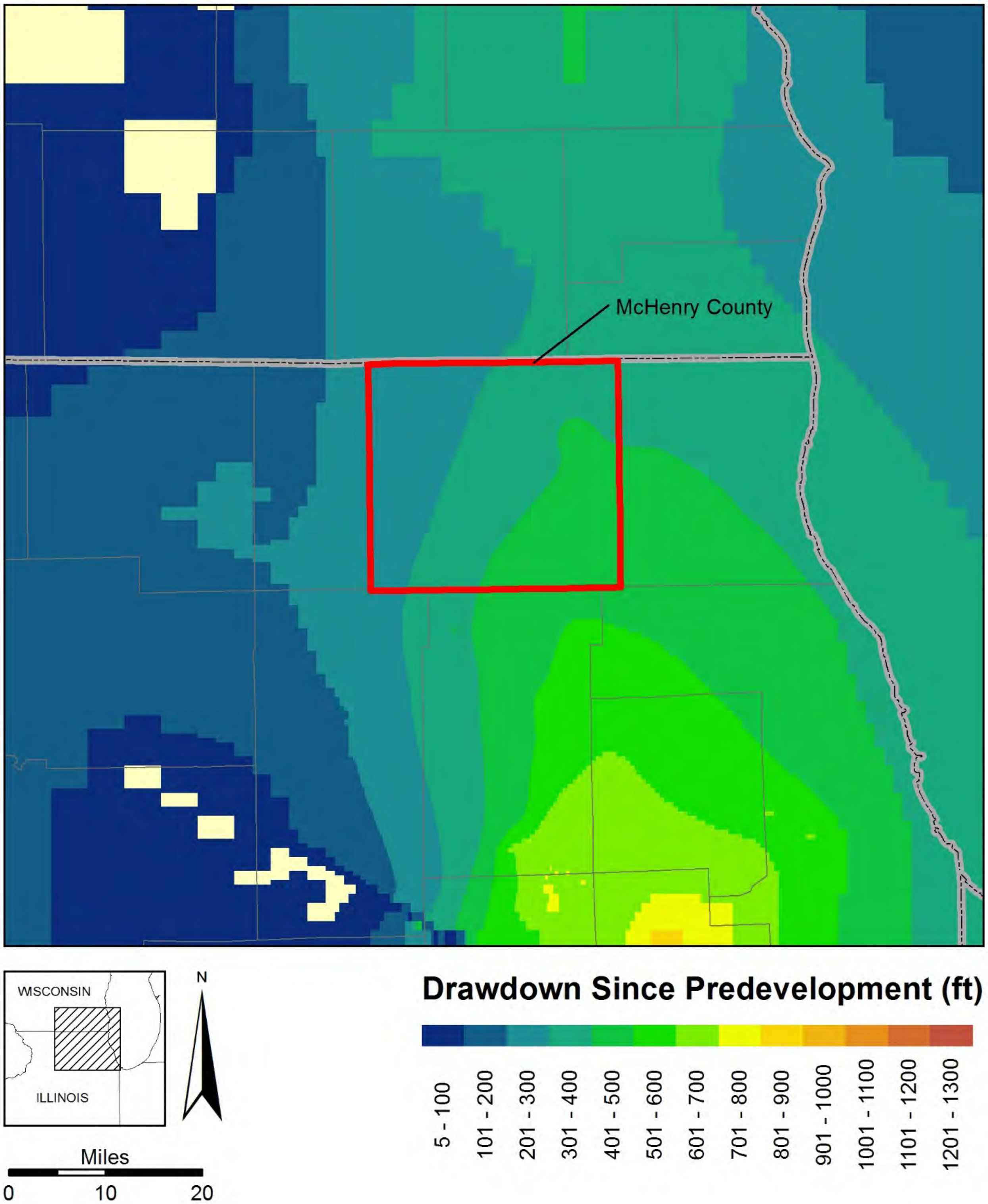

Figure 124 Simulated drawdown since predevelopment, Ironton-Galesville Unit (model layer 21), 2050 (LRI scenario)

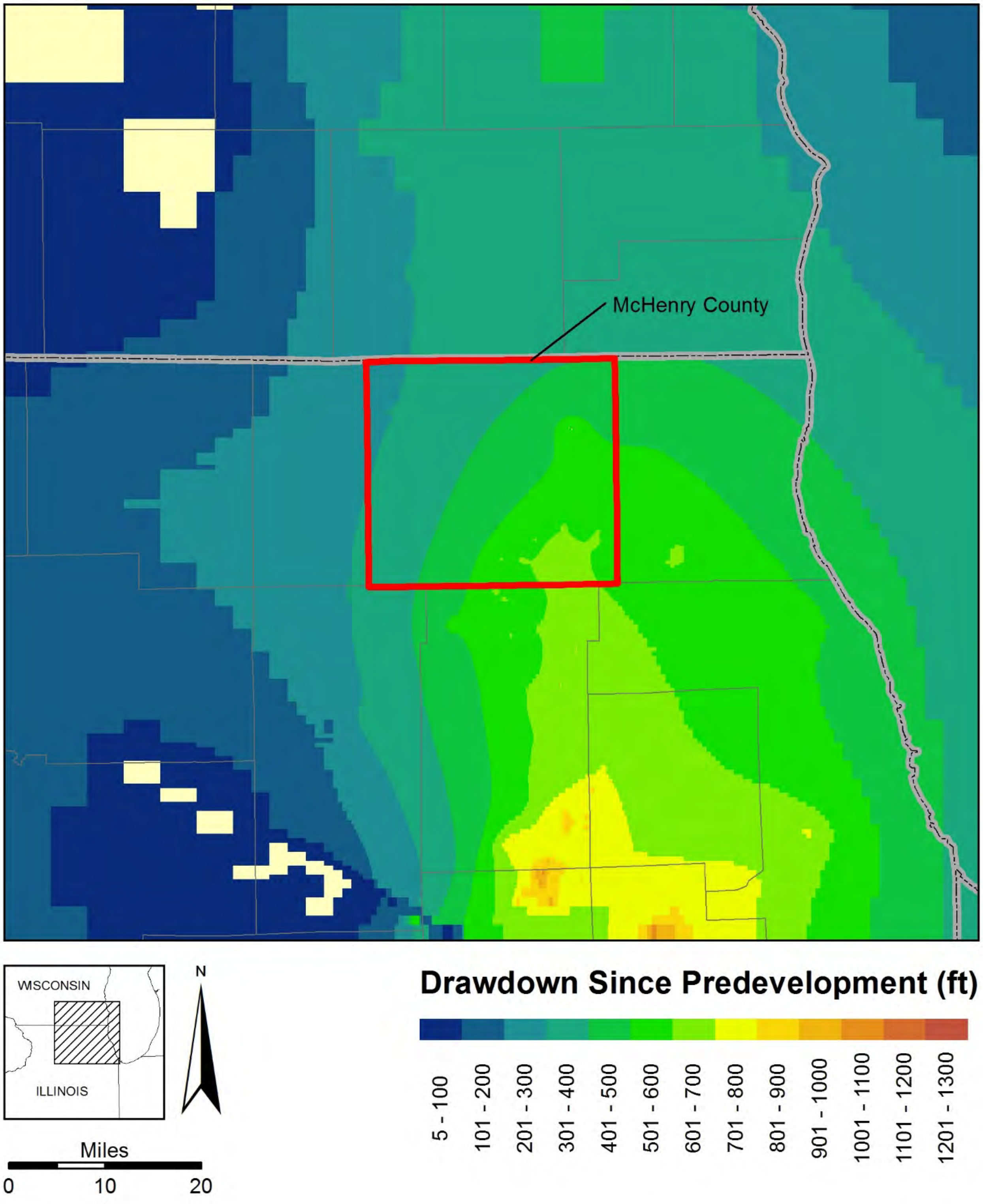

Figure 125 Simulated drawdown since predevelopment, Ironton-Galesville Unit (model layer 21), 2050 (MRI scenario)

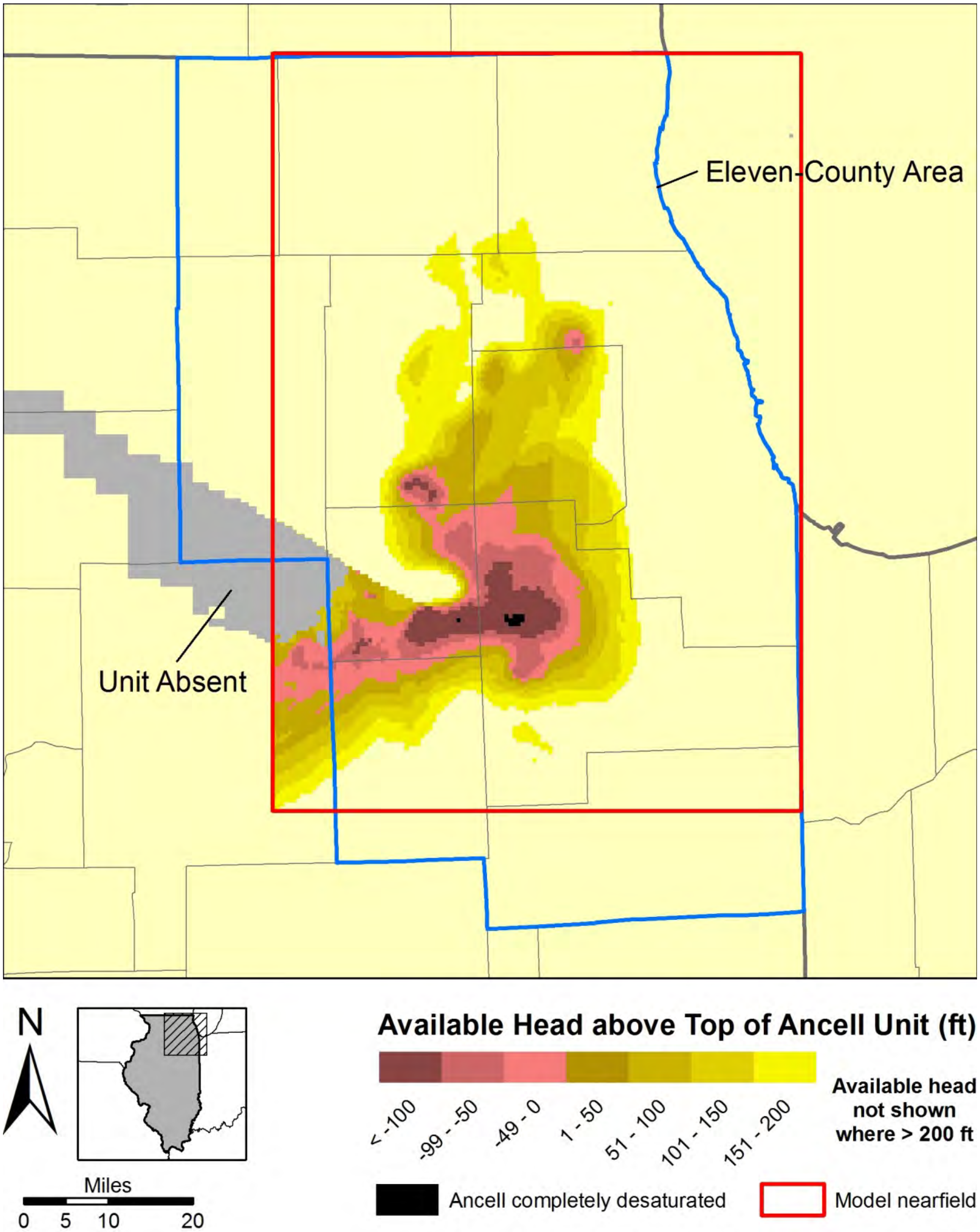

Figure 126 Available observed composite deep well head in 2007, not shown in area outside groundwater flow model nearfield of Meyer et al. (2012), based on mapping by Burch (2008). Available head is not shaded where greater than 200 ft.

Table 6 Simulated Natural Groundwater Discharge in Watersheds in the McHenry County Area, Historical Pumping Conditions

ID (Figure 93)	*Sub-Basin*	*Predevelopment (Mgd)*	*1989 (Figure 95)*			*2009 (Figure 96)*		
				Change Since Predevelopment			*Change Since Predevelopment*	
			Mgd	*Mgd*	*%*	*Mgd*	*Mgd*	*%*
7	Lower Coon Creek	12.8	12.4	-0.4	-3.0	12.3	-0.4	-3.3
9	Middle Coon Creek	4.5	4.4	-0.2	-3.3	4.3	-0.2	-3.6
10	West Branch Piscasaw Creek	3.1	2.7	-0.4	-13.5	2.6	-0.5	-14.9
11	Headwaters Piscasaw Creek	5.9	5.2	-0.8	-13.1	5.1	-0.9	-14.5
12	Lawrence Creek	7.4	6.8	-0.6	-8.5	6.9	-0.6	-7.6
13	Town of Union-South Branch Kishwaukee River	4.8	4.4	-0.3	-7.3	3.8	-1.0	-21.3
14	City of Huntley-South Branch Kishwaukee River	11.4	10.2	-1.2	-10.3	10.2	-1.2	-10.9
15	Town of Lakewood	5.5	5.1	-0.4	-6.6	4.5	-1.0	-18.1
17	Lily Lake-Kishwaukee River	14.0	12.5	-1.5	-11.0	12.0	-2.0	-14.0
18	Burr Oak Cemetery	3.9	3.5	-0.5	-11.8	3.4	-0.5	-12.3
20	Mokeler Creek	2.4	2.1	-0.3	-13.2	2.2	-0.2	-9.3
21	North Branch Kishwaukee River	11.9	11.3	-0.7	-5.5	11.2	-0.7	-5.7
23	Rush Creek	10.4	9.6	-0.7	-7.1	9.8	-0.6	-6.0
24	Piscasaw Creek	17.3	15.2	-2.1	-12.4	15.1	-2.2	-12.9
25	Mud Creek	6.5	6.2	-0.3	-4.7	6.2	-0.3	-4.8
26	City of Marengo-Kishwaukee River	15.0	14.1	-0.9	-6.0	13.8	-1.2	-8.1
30	West Branch North Branch Nippersink Creek-North Branch Nippersink Creek	11.0	10.6	-0.4	-3.6	10.4	-0.5	-4.6
31	North Branch Nippersink Creek	12.4	11.9	-0.5	-4.4	11.6	-0.8	-6.7
32	Town of Alden	2.1	1.9	-0.2	-9.5	1.9	-0.2	-8.7
33	Headwaters Nippersink Creek	2.2	1.9	-0.3	-13.5	1.9	-0.3	-12.6
34	Nippersink Creek	6.4	5.5	-0.9	-14.1	5.8	-0.6	-8.9
35	Carr Harrison Cemetery-Nippersink Creek	8.3	8.1	-0.3	-3.2	8.0	-0.3	-3.6
36	Greenwood-Nippersink Creek	8.3	7.7	-0.6	-7.6	7.7	-0.7	-8.3
37	Wonder Lake-Nippersink Creek	5.4	4.8	-0.6	-10.8	4.8	-0.6	-11.9
38	City of Woodstock	4.3	3.0	-1.3	-30.3	2.7	-1.6	-36.7
39	Nippersink Lake-Fox River	14.0	12.8	-1.2	-8.4	12.5	-1.5	-10.4
41	Pistakee Lake-Fox River	6.1	5.6	-0.6	-9.0	5.4	-0.7	-11.6
44	Cary Creek-Fox River	21.2	18.9	-2.3	-10.7	18.5	-2.6	-12.5
45	Cotton Creek	4.6	4.1	-0.6	-12.4	3.9	-0.7	-16.2
46	Griswold Lake-Fox River	20.1	18.3	-1.8	-8.8	17.8	-2.3	-11.4

Table 6 Simulated Natural Groundwater Discharge in Watersheds in the McHenry County Area, Historical Pumping Conditions

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ID (Figure 93)	***Sub-Basin***	***Predevelopment (Mgd)***	***1989 (Figure 95)***			***2009 (Figure 96)***		
			Mgd	***Change Since Predevelopment***		***Mgd***	***Change Since Predevelopment***	
				Mgd	***%***		***Mgd***	***%***
47	Boone Creek	4.0	3.2	-0.8	-20.4	3.3	-0.8	-18.8
48	Crystal Lake Outlet	4.9	3.7	-1.2	-24.1	3.0	-1.9	-39.3
50	Spring Creek-Fox River	6.9	5.0	-2.0	-28.6	5.0	-2.0	-28.5
52	Jelkes Creek-Fox River	20.4	16.3	-4.0	-19.7	16.6	-3.7	-18.2
61	Boone Creek	8.4	7.5	-0.9	-10.4	7.3	-1.0	-12.5
63	Middle Coon Creek	9.8	9.4	-0.3	-3.5	9.4	-0.4	-3.9
	Total	**317.6**	**285.6**	**-32.0**	**-10.1**	**280.9**	**-36.6**	**-11.5**

Table 7 Simulated Natural Groundwater Discharge in Watersheds in the McHenry County Area, BL Scenario

ID (Figure 93)	*Sub-Basin*	*Predevelopment (Mgd)*	*2030 (Figure 97)*			*2050 (Figure 100)*		
				Change Since Predevelopment			*Change Since Predevelopment*	
			Mgd	*Mgd*	*%*	*Mgd*	*Mgd*	*%*
7	Lower Coon Creek	12.8	12.4	-0.4	-3.1	12.3	-0.5	-3.6
9	Middle Coon Creek	4.5	4.4	-0.1	-3.3	4.3	-0.2	-3.5
10	West Branch Piscasaw Creek	3.1	2.8	-0.2	-7.3	2.8	-0.2	-7.7
11	Headwaters Piscasaw Creek	5.9	5.2	-0.8	-12.6	5.1	-0.8	-13.4
12	Lawrence Creek	7.4	6.9	-0.5	-6.5	6.9	-0.6	-7.4
13	Town of Union-South Branch Kishwaukee River	4.8	3.9	-0.9	-18.1	3.9	-0.9	-19.2
14	City of Huntley-South Branch Kishwaukee River	11.4	10.4	-1.0	-8.6	10.2	-1.2	-10.8
15	Town of Lakewood	5.5	4.1	-1.3	-24.0	3.7	-1.8	-32.1
17	Lily Lake-Kishwaukee River	14.0	12.3	-1.7	-12.1	11.9	-2.1	-14.7
18	Burr Oak Cemetery	3.9	3.6	-0.3	-7.2	3.6	-0.3	-7.8
20	Mokeler Creek	2.4	2.2	-0.2	-8.9	2.2	-0.3	-10.6
21	North Branch Kishwaukee River	11.9	11.3	-0.6	-5.0	11.2	-0.7	-6.0
23	Rush Creek	10.4	9.8	-0.6	-5.5	9.7	-0.7	-6.3
24	Piscasaw Creek	17.3	15.0	-2.3	-13.3	14.7	-2.6	-15.1
25	Mud Creek	6.5	6.2	-0.3	-4.7	6.2	-0.3	-5.3
26	City of Marengo-Kishwaukee River	15.0	13.9	-1.2	-7.7	13.5	-1.5	-9.8
30	West Branch North Branch Nippersink Creek-North Branch Nippersink Creek	11.0	10.5	-0.5	-4.2	10.5	-0.5	-4.5
31	North Branch Nippersink Creek	12.4	11.6	-0.9	-6.9	11.5	-1.0	-7.8
32	Town of Alden	2.1	2.0	-0.1	-3.6	2.0	-0.1	-4.0
33	Headwaters Nippersink Creek	2.2	2.0	-0.2	-7.1	2.0	-0.2	-8.2
34	Nippersink Creek	6.4	5.5	-0.9	-13.4	5.4	-1.0	-15.4
35	Carr Harrison Cemetery-Nippersink Creek	8.3	8.0	-0.3	-4.0	8.0	-0.4	-4.6
36	Greenwood-Nippersink Creek	8.3	7.5	-0.8	-10.0	7.2	-1.2	-13.8
37	Wonder Lake-Nippersink Creek	5.4	4.5	-0.9	-16.5	4.5	-1.0	-17.5
38	City of Woodstock	4.3	2.1	-2.2	-51.1	1.4	-2.9	-67.8
39	Nippersink Lake-Fox River	14.0	12.7	-1.3	-9.6	12.4	-1.6	-11.7
41	Pistakee Lake-Fox River	6.1	5.4	-0.8	-12.4	5.1	-1.0	-15.8
44	Cary Creek-Fox River	21.2	18.1	-3.1	-14.5	17.3	-3.9	-18.2
45	Cotton Creek	4.6	3.9	-0.7	-15.9	3.7	-0.9	-19.6
46	Griswold Lake-Fox River	20.1	17.2	-2.8	-14.2	16.6	-3.5	-17.5

Table 7 Simulated Natural Groundwater Discharge in Watersheds in the McHenry County Area, BL ScenarioTable 7 Simulated Natural Groundwater Discharge in Watersheds in the McHenry County Area, BL Scenario (Concluded)

ID (Figure 93)	***Sub-Basin***	***Predevelopment (Mgd)***	***2030 (Figure 97)***			***2050 (Figure 100)***		
				Change Since Predevelopment			***Change Since Predevelopment***	
			Mgd	***Mgd***	***%***	***Mgd***	***Mgd***	***%***
47	Boone Creek	4.0	3.2	-0.8	-20.7	2.9	-1.1	-27.2
48	Crystal Lake Outlet	4.9	2.7	-2.2	-44.5	2.4	-2.6	-52.3
50	Spring Creek-Fox River	6.9	4.5	-2.5	-35.5	3.9	-3.1	-44.5
52	Jelkes Creek-Fox River	20.4	16.3	-4.0	-19.8	15.8	-4.5	-22.3
61	Boone Creek	8.4	6.9	-1.5	-17.7	6.5	-1.9	-23.1
63	Middle Coon Creek	9.8	9.5	-0.3	-2.8	9.5	-0.3	-3.2
	Total	**317.6**	**278.6**	**-39.0**	**-12.3**	**270.6**	**-47.0**	**-14.8**

Table 8 Simulated Natural Groundwater Discharge in Watersheds in the McHenry County Area, LRI Scenario

ID (Figure 93)	*Sub-Basin*	*Predevelopment (Mgd)*	*2030 (Figure 98)*			*2050 (Figure 101)*		
				Change Since Predevelopment			*Change Since Predevelopment*	
			Mgd	*Mgd*	*%*	*Mgd*	*Mgd*	*%*
7	Lower Coon Creek	12.8	12.4	-0.4	-2.8	12.4	-0.4	-3.1
9	Middle Coon Creek	4.5	4.4	-0.1	-2.9	4.4	-0.1	-3.2
10	West Branch Piscasaw Creek	3.1	2.9	-0.2	-6.7	2.8	-0.2	-7.6
11	Headwaters Piscasaw Creek	5.9	5.2	-0.7	-12.5	5.2	-0.8	-13.1
12	Lawrence Creek	7.4	7.0	-0.4	-5.8	7.0	-0.5	-6.2
13	Town of Union-South Branch Kishwaukee River	4.8	3.5	-1.3	-26.3	3.5	-1.3	-26.6
14	City of Huntley-South Branch Kishwaukee River	11.4	10.6	-0.8	-7.2	10.5	-0.9	-8.0
15	Town of Lakewood	5.5	4.5	-1.0	-17.9	4.3	-1.1	-20.7
17	Lily Lake-Kishwaukee River	14.0	12.3	-1.7	-11.9	12.2	-1.8	-12.8
18	Burr Oak Cemetery	3.9	3.7	-0.3	-6.5	3.6	-0.3	-7.2
20	Mokeler Creek	2.4	2.3	-0.2	-7.6	2.2	-0.2	-8.5
21	North Branch Kishwaukee River	11.9	11.4	-0.5	-4.5	11.3	-0.6	-4.9
23	Rush Creek	10.4	9.9	-0.5	-4.9	9.8	-0.5	-5.3
24	Piscasaw Creek	17.3	15.2	-2.1	-12.2	15.0	-2.3	-13.2
25	Mud Creek	6.5	6.2	-0.3	-4.3	6.2	-0.3	-4.6
26	City of Marengo-Kishwaukee River	15.0	13.8	-1.2	-8.2	13.7	-1.4	-9.1
30	West Branch North Branch Nippersink Creek-North Branch Nippersink Creek	11.0	10.5	-0.4	-4.0	10.5	-0.5	-4.1
31	North Branch Nippersink Creek	12.4	11.7	-0.7	-5.9	11.6	-0.8	-6.7
32	Town of Alden	2.1	2.0	-0.1	-3.5	2.0	-0.1	-3.5
33	Headwaters Nippersink Creek	2.2	2.0	-0.1	-6.4	2.0	-0.1	-6.5
34	Nippersink Creek	6.4	5.7	-0.7	-10.9	5.6	-0.7	-11.5
35	Carr Harrison Cemetery-Nippersink Creek	8.3	8.0	-0.3	-3.5	8.0	-0.3	-3.6
36	Greenwood-Nippersink Creek	8.3	7.7	-0.6	-7.7	7.6	-0.7	-8.9
37	Wonder Lake-Nippersink Creek	5.4	4.7	-0.7	-13.0	4.6	-0.8	-14.6
38	City of Woodstock	4.3	2.6	-1.7	-39.1	2.3	-1.9	-45.1
39	Nippersink Lake-Fox River	14.0	12.9	-1.1	-8.1	12.7	-1.3	-9.2
41	Pistakee Lake-Fox River	6.1	5.5	-0.6	-10.2	5.4	-0.7	-11.7
44	Cary Creek-Fox River	21.2	18.7	-2.4	-11.5	18.4	-2.7	-12.8
45	Cotton Creek	4.6	4.0	-0.6	-13.1	3.9	-0.7	-14.6
46	Griswold Lake-Fox River	20.1	17.6	-2.5	-12.3	17.3	-2.7	-13.7

Table 8 Simulated Natural Groundwater Discharge in Watersheds in the McHenry County Area, LRI Scenario (Concluded)

ID (Figure 93)	*Sub-Basin*	*Predevelopment (Mgd)*	*2030 (Figure 98)*			*2050 (Figure 101)*		
				Change Since Predevelopment			*Change Since Predevelopment*	
			Mgd	*Mgd*	*%*	*Mgd*	*Mgd*	*%*
47	Boone Creek	4.0	3.4	-0.7	-16.3	3.3	-0.8	-18.7
48	Crystal Lake Outlet	4.9	3.2	-1.7	-35.0	3.1	-1.9	-38.0
50	Spring Creek-Fox River	6.9	5.1	-1.9	-27.0	4.8	-2.1	-30.3
52	Jelkes Creek-Fox River	20.4	17.2	-3.2	-15.6	16.9	-3.5	-17.0
61	Boone Creek	8.4	7.2	-1.2	-14.3	7.1	-1.3	-15.6
63	Middle Coon Creek	9.8	9.5	-0.3	-2.6	9.5	-0.3	-2.8
	Total	**317.6**	**284.3**	**-33.2**	**-10.5**	**281.0**	**-36.5**	**-11.5**

Table 9 Simulated Natural Groundwater Discharge in Watersheds in the McHenry County Area, MRI Scenario

ID (Figure 93)	Sub-Basin	Predevelopment (Mgd)	2030 (Figure 99)			2050 (Figure 102)		
				Change Since Predevelopment			Change Since Predevelopment	
			Mgd	Mgd	%	Mgd	Mgd	%
7	Lower Coon Creek	12.8	12.3	-0.4	-3.4	12.2	-0.5	-4.1
9	Middle Coon Creek	4.5	4.3	-0.2	-3.6	4.3	-0.2	-4.3
10	West Branch Piscasaw Creek	3.1	2.8	-0.2	-7.7	2.8	-0.2	-8.0
11	Headwaters Piscasaw Creek	5.9	5.1	-0.8	-13.5	5.1	-0.9	-14.3
12	Lawrence Creek	7.4	6.9	-0.5	-6.9	6.8	-0.6	-8.2
13	Town of Union-South Branch Kishwaukee River	4.8	3.5	-1.2	-25.9	3.5	-1.3	-26.7
14	City of Huntley-South Branch Kishwaukee River	11.4	10.3	-1.1	-9.6	10.0	-1.4	-12.6
15	Town of Lakewood	5.5	4.0	-1.5	-26.7	3.4	-2.0	-37.4
17	Lily Lake-Kishwaukee River	14.0	11.6	-2.4	-17.2	11.3	-2.6	-18.9
18	Burr Oak Cemetery	3.9	3.6	-0.3	-7.7	3.6	-0.3	-8.6
20	Mokeler Creek	2.4	2.2	-0.2	-10.1	2.1	-0.3	-12.4
21	North Branch Kishwaukee River	11.9	11.2	-0.7	-5.9	11.0	-0.9	-7.4
23	Rush Creek	10.4	9.8	-0.6	-5.9	9.7	-0.7	-6.8
24	Piscasaw Creek	17.3	14.8	-2.5	-14.3	14.4	-2.9	-16.8
25	Mud Creek	6.5	6.2	-0.3	-5.1	6.1	-0.4	-5.9
26	City of Marengo-Kishwaukee River	15.0	13.6	-1.4	-9.5	13.1	-1.9	-12.7
30	West Branch North Branch Nippersink Creek-North Branch Nippersink Creek	11.0	10.5	-0.5	-4.3	10.4	-0.5	-4.7
31	North Branch Nippersink Creek	12.4	11.7	-0.8	-6.2	11.4	-1.1	-8.5
32	Town of Alden	2.1	2.0	-0.1	-4.4	2.0	-0.1	-4.3
33	Headwaters Nippersink Creek	2.2	2.0	-0.2	-7.8	2.0	-0.2	-9.2
34	Nippersink Creek	6.4	5.0	-1.4	-22.2	4.3	-2.1	-32.9
35	Carr Harrison Cemetery-Nippersink Creek	8.3	7.9	-0.5	-5.8	7.7	-0.7	-8.1
36	Greenwood-Nippersink Creek	8.3	7.4	-1.0	-11.5	7.0	-1.4	-16.3
37	Wonder Lake-Nippersink Creek	5.4	4.6	-0.9	-15.8	4.1	-1.3	-24.6
38	City of Woodstock	4.3	1.9	-2.4	-56.5	0.9	-3.4	-78.7
39	Nippersink Lake-Fox River	14.0	12.5	-1.5	-10.8	12.1	-1.9	-13.8
41	Pistakee Lake-Fox River	6.1	5.2	-0.9	-14.5	4.9	-1.2	-19.7
44	Cary Creek-Fox River	21.2	17.8	-3.4	-16.0	16.8	-4.3	-20.5
45	Cotton Creek	4.6	3.8	-0.8	-17.5	3.6	-1.1	-23.1
46	Griswold Lake-Fox River	20.1	16.5	-3.5	-17.6	15.2	-4.8	-24.1

Table 9 Simulated Natural Groundwater Discharge in Watersheds in the McHenry County Area, MRI Scenario (Concluded)

ID (Figure 93)	*Sub-Basin*	*Predevelopment (Mgd)*	*2030 (Figure 99)*			*2050 (Figure 102)*		
				Change Since Predevelopment			*Change Since Predevelopment*	
			Mgd	*Mgd*	*%*	*Mgd*	*Mgd*	*%*
47	Boone Creek	4.0	3.1	-1.0	-23.8	2.7	-1.4	-33.8
48	Crystal Lake Outlet	4.9	2.5	-2.4	-48.9	2.0	-2.9	-59.9
50	Spring Creek-Fox River	6.9	4.3	-2.7	-38.2	3.7	-3.2	-46.8
52	Jelkes Creek-Fox River	20.4	16.2	-4.2	-20.6	15.6	-4.7	-23.2
61	Boone Creek	8.4	6.7	-1.7	-20.5	6.1	-2.3	-27.1
63	Middle Coon Creek	9.8	9.5	-0.3	-3.2	9.4	-0.4	-3.7
	Total	**317.6**	**273.2**	**-44.4**	**-14.0**	**261.4**	**-56.2**	**-17.7**

Table 10 Source Aquifers of Deep Wells in 11-County Region, 1964–2005 (Meyer et al., 2012)

Principal Source Aquifers					*Number of Wells*
Quaternary	*Shallow Bedrock*	*Ancell*	*Ironton-Galesville*	*Mt. Simon*	
×	×	×			1
	×	×			110
	×	×	×		50
	×	×	×	×	22
		×			273
		×	×		508
		×	×	×	74
			×		137
			×	×	21
				×	4
				Total	**1,200**

5 Summary and Conclusions

We conducted studies to document present-day heads in the shallow aquifers of McHenry County and to simulate the impacts in McHenry County of plausible scenarios of groundwater withdrawals in the McHenry County region to the year 2050.

5.1 Groundwater Withdrawals

McHenry County is entirely dependent on groundwater for water supplies, and in 2009 the county obtained 24.7 Mgd for use by public water systems, self-supplied commercial and industrial facilities, and self-supplied irrigation and agriculture (Figure 31, Table 1). About 28 percent of this total was obtained from the deep aquifers (Figure 32), and about 72 percent was obtained from the shallow aquifers (Figure 33). Under the three scenarios of future groundwater withdrawals developed and simulated for this project, McHenry County groundwater withdrawals increase to between 31.5 and 67.9 Mgd in 2050 Figure 37), an increase of 6.8 to 43.2 Mgd (38 to 175 percent) from the 2009 total of 24.7 Mgd.

5.2 Water Level Mapping

We mapped 329 water levels measured in 2011 in wells finished in shallow aquifers in and near McHenry County (Figure 40). These water levels indicate heads in 5 shallow aquifers: (1) the Lower Glasford Sand Unit (Figure 11) and Shallow Bedrock Aquifer, which are hydrologically connected; (2) the Upper Glasford Sand Unit (Figure 13); (3) the Ashmore Unit (Figure 15); (4) the Yorkville-Batestown Unit (Figure 17); and (5) the Haeger-Beverly Unit (Figure 18). Potentiometric surface maps were developed for each (Figure 42 to Figure 46). The water levels are strongly influenced by connections between the aquifers, which equalize heads between aquifers, and between the aquifers and surface waters, which equalize surface water elevations and heads in the connected aquifer. The data do not permit detailed mapping of cones of depression, but they suggest cones of depression in the Ashmore Unit and Lower Glasford Sand Unit/Shallow Bedrock Aquifer surrounding high-capacity wells in southeastern McHenry County and in the Woodstock area. The Haeger-Beverly Unit, the shallowest of the shallow aquifers, is desaturated in areas of dissected topography and in elevated areas adjacent to steep slopes, where any water entering the unit from above can readily drain out. The median water level change in 161 wells measured both in 1994 by Meyer (1998) and in 2011 for this study, selected for comparison because they were measured using closely comparable methods, was +2.0 ft. This value suggests that changes in pumping rates and distribution, climate, land use, land cover, and other factors, have not resulted in a countywide decline in shallow aquifer heads.

5.3 Groundwater Flow Models

Modeling of historical groundwater conditions simulates pumping between 1864 (when large-scale pumping is considered to have begun in northeastern Illinois) and 2009, and modeling of future conditions extends from 2010 through 2050. The modeling consists of transient simulations in which pumping for each represented well is varied annually. Only the pumping rates of the wells are changed from year to year in the historical and future pumping simulations; all other parameters (e.g., recharge, hydraulic conductivity, stream characteristics, and drainage parameters) remain constant through time.

5.3.1 *Uncertainty and Calibration*

As an acknowledgment of the limitations in accuracy and comprehensiveness of the observations used for model development, the model results are most appropriately employed as a screening tool providing a sense of the locations and relative magnitudes of groundwater pumping impacts. That is, the results suggest locations and aquifers affected by drawdown and reductions in natural groundwater discharge, and the magnitudes of the simulated effects suggest the severity of the impacts. The results are useful for identifying areas for further data collection and analysis and to provide a basis for formulating management policy directed toward reducing impacts. For example, monitoring of head might be emphasized in areas of greater simulated drawdown, and monitoring of streamflow might be emphasized in streams incurring greater simulated reduction of natural groundwater discharge. Policies might be formulated to require analysis of impacts prior to installation of additional wells in areas of greater simulated impacts.

As values for model calibration, the head targets for this regional model have an accuracy of about ±200 ft, and the calibration results shows the error between 111 to -98 ft in McHenry County. Since modeled heads can be no more accurate than the calibration targets, these are reasonable estimates of the accuracy of simulated head and drawdown. We also caution readers that reductions in groundwater discharge to streams suggested by the modeling may not be observable or easily recognized. Few data are available to verify the reductions, and analysis of existing data is lacking. Moreover, reductions in natural groundwater discharge suggested by this study, all of which result from simulated increases in groundwater withdrawal, may be masked by hydrologic factors that are not simulated by the groundwater flow modeling of this study. Some of these unsimulated processes, such as discharge of effluent, could, in fact, offset the simulated reductions.

5.3.2 *Deep Aquifer Model Results*

Simulated heads in the deep aquifers reflect coalescing cones of depression resulting from significant pumping in the Chicago and Milwaukee areas since the mid-nineteenth century. The simulated head distributions approximate maps of measured deep well heads (e.g., Burch, 2008). Differences between observed deep well heads and simulated heads in individual deep aquifers reflect scale effects, estimated parameters and boundary conditions, calibration target uncertainty, termination of pumping by the model upon complete cell desaturation, and unmodeled interformational transfer of groundwater through boreholes open to multiple aquifers.

Drawdown in 2009 in the deep aquifers of McHenry County increases from west to east across the county (Figure 103, Figure 119). This eastward increase in drawdown reflects (1) the westward thinning to a zero edge of the impermeable Maquoketa Unit across the county and consequent increased vertical leakage to the deep aquifers as the Maquoketa thins and disappears (Figure 104), and (2) greater pumping from the deep aquifers in Will and Kane Counties to the southeast of McHenry County and the expansion into McHenry County of coalescing cones of depression surrounding pumping wells in that area. Simulated drawdown in the Ancell Unit increases from 150 ft in the extreme northwestern corner of McHenry County, where erosion in the axis of the Troy Bedrock Valley permits greater vertical leakage to the Ancell, to nearly 500 ft in the southeastern part of the county (Figure 103). Drawdown in 2009 in the deeper Ironton-Galesville Unit, which receives less vertical leakage owing to its deeper position underlying the relatively impermeable Prairie du Chien-Eminence and Potosi-Franconia Units, is greater than in the Ancell, increasing from 200 to just over 500 ft in southeastern McHenry County (Figure 119). Greater present and future drawdown in northeastern Illinois is simulated farther south, in the

Aurora and Joliet areas (Figure 103 to Figure 110, Figure 119 to Figure 125). This is a consequence of large withdrawals from the deep aquifers in that area by both public water systems and self-supplied commercial and industrial facilities (Figure 36, Figure 59 to Figure 61, Figure 65 to Figure 67), together with the presence of Maquoketa cover in that area (Figure 104), which greatly inhibits vertical leakage to the deep aquifers.

Drawdown in the deep aquifers could lead to increases in salinity of deep well water as well as increases in concentrations of radium, barium, and arsenic. In some parts of northeastern Illinois, but not McHenry County, the modeling suggests desaturation (draining of pore spaces) of the Ancell Unit aquifer (Figure 107 to Figure 110). Historical experience in Wisconsin has shown such desaturation can lead to elevated arsenic concentrations in water from deep wells (Schreiber et al., 2000). Although deterioration of groundwater quality is a possible consequence of large groundwater withdrawals from the deep aquifers, Kelly and Meyer (2005) identified no trends in sampling results from McHenry County and adjacent parts of northeastern Illinois but found that data from the two largest deep bedrock pumping centers in northeastern Illinois—Joliet and Aurora—suggested slightly increasing mineralization.

Simulation of plausible scenarios of future pumping suggests that partial desaturation may affect the Ancell Unit in the Joliet and Aurora areas, but not McHenry County, by 2050 (Figure 115 to Figure 118). McHenry County, in the most extreme pumping scenario, would incur a reduction in available head to less than 50 ft above the top of the Ancell by 2050. Desaturation of a deep aquifer unit would lead to a decline in well yield and increasing pumping expenses. Deep wells in the areas of partial to full desaturation of the Ancell Unit also may be vulnerable to increases in arsenic, barium, and radium concentrations that, left untreated, may be harmful to human health. Both the model and observed 2007 water levels in deep wells suggests that desaturation of the Ancell Unit may already be occurring in the area surrounding Aurora and Joliet (Figure 126). Modeled available head above the top of the Ironton-Galesville Unit, conversely, remains above 200 ft for all of Northeastern Illinois throughout 2050, even in the MRI scenario.

5.3.3 Shallow Aquifer Model Results

Modeling shows that shallow aquifer drawdown exceeding 5 ft affected many locations in McHenry County in 2009 (Figure 72 to Figure 74), but drawdown in the shallow aquifers is not as widespread as in the deep aquifers, and drawdown magnitude is much less (compare Figure 72 to Figure 74 with Figure 103 and Figure 119). The lesser drawdown in the shallow aquifers reflects increased availability of replacement water for water withdrawn from shallow wells relative to deep wells. The cones of depression in the shallow aquifers increase in size with depth because of the presence of aquitards that limit replacement water for deeper pumping. The largest cones of depression surround public water system wells and commercial/industrial wells in and near Woodstock, Algonquin, Carpentersville, Cary, McHenry, and Crystal Lake.

Model simulations suggest that pumping from the shallow aquifers has decreased natural groundwater discharge in a watershed-defined area approximating McHenry County from about 318 Mgd under predevelopment conditions to about 286 Mgd in 2009, a 32 Mgd (10 percent) reduction (Figure 96, Table 6). This reduction would manifest as a reduction in stream base flow (the portion of streamflow maintained by groundwater discharge), not as a reduction in total streamflow, which contains water derived from other sources, such as runoff and effluent discharge. Of the watersheds intersecting McHenry County, the Crystal Lake Outlet incurs the greatest simulated reduction in 2009 of natural groundwater discharge from predevelopment conditions (39 percent). This large reduction reflects comparatively large shallow aquifer withdrawals in that watershed together with the presence of hydrologic connections facilitating capture by wells of shallow groundwater that would otherwise discharge by seepage to the stream. It is noteworthy that reductions in base flow may not be readily observable in streamflow data since many streams in McHenry County receive effluent at rates that equal or exceed simulated base flow reductions. For example, Singh and Ramamurthy (1993) show that the watershed of the Crystal Lake Outlet receives about 4.0 Mgd of effluent, approximately twice the simulated base flow reduction of 1.9 Mgd.

The model suggests that 2009 natural groundwater discharge to the City of Woodstock (Silver Creek) watershed has also been significantly affected by pumping, having been reduced by about 1.6 Mgd since predevelopment. This reduction is approximately offset by effluent discharge of 1.9 Mgd to Silver Creek (Singh and Ramamurthy, 1993). We note that effluent discharge cannot be regarded as a substitute for natural groundwater discharge since it differs in quality from groundwater and since effluent discharges occur at point locations as contrasted from diffuse seepage of groundwater along stream channels. All three future model simulations (LRI, BL, and MRI) indicate that the City of Woodstock (Silver Creek) watershed will be have the greatest reduction of natural groundwater discharge in 2030 and 2050 (Figure 97 to Figure 102), potentially with a reduction of up to 79%. None of these future simulations account for compensating increases in effluent discharge.

Few streamflow data are available to verify simulated reductions in natural groundwater discharge, and analysis of existing data is lacking. Moreover, reductions in natural groundwater discharge suggested by this study, which result from increases in groundwater withdrawals, may be masked by hydrologic factors that are not simulated by the groundwater flow modeling of this study. Unmodeled processes that could affect natural groundwater discharge include leakage from buried pipe networks and climate variability.

Model simulations suggest that the summed natural groundwater discharge of all watersheds intersecting McHenry County will likely decline to rates in 2050 that are 11.5 to 17.7 percent below predevelopment rates (Figure 100 to Figure 102, Table 7 to Table 9). The greatest reductions occur in the watershed of the City of Woodstock and the Crystal Lake Outlet.

5.3.4 Conclusions from Model Simulations

In general, simulations using the groundwater flow model developed for this study show that drawdown in the deep aquifers (Figure 103 to Figure 110, Figure 119 to Figure 125) is much greater than in the shallow aquifers (Figure 72 to Figure 92), this difference attributable to the availability of replacement water to the aquifers—i.e., water entering the aquifers to replace groundwater withdrawn through wells. In the McHenry County region, relatively impermeable confining units overlie the deep aquifers (Figure 104) and greatly limit leakage into the aquifers from above, so replacement water to these aquifers is derived principally by slow lateral movement from north-central Illinois and south-central Wisconsin, where the relatively impermeable cover is absent. In contrast, low-permeability materials do not as greatly limit entry of replacement water into the very shallow aquifers (i.e. the Haeger-Beverly Unit), and drawdown in these aquifers is thus offset by higher rates of leakage into the aquifers and by captured streamflow. Drawdown is greater in the deeper glacial units (i.e. the Lower Glasford Sand Unit) because of overlying aquitards, though not to the same extent as observed in the deep.

Drawdown in the shallow aquifers reflects the distribution of shallow withdrawals shown in Figure 71. The high number of shallow pumping wells at Woodstock has resulted in both the greater drawdown and greater reduction of natural groundwater discharge than in the rest of the

McHenry County. While the network of shallow wells is not as dense in southeastern McHenry County as in the Woodstock area, considerable pumping still takes place in this part of the county, and since the transmissivities there are relatively low, drawdown in greater than in many other parts of the county. The high transmissivity zones in the western McHenry County do not supply as great a density of pumping wells, and as simulated drawdown and reduction in natural groundwater discharge there are, as a result, lower. High transmissivity zones with low pumping (e.g, in western McHenry County) could be considered for future development of groundwater resources.

For supplemental information on the model, including updated model results, see http://www.isws.illinois.edu/docs/pubs/iswscr2013-06/.

6 Ongoing and Future Work

6.1 Introduction

Research tasks that would extend the support for water resources planning in McHenry County begun by the efforts described in this report fall into several categories: (1) revision of the existing hydrologic models (Section 6.2), (2) studies that employ the existing and future iterations of the groundwater flow model (Section 6.3), (3) database expansion and improvement (Section 6.4), and (4) monitoring (Section 6.5). Considerable overlap between these categories exists, and efforts in one category may contribute to others. For example, data acquired through monitoring constitute an expansion and improvement of the existing database and may be employed in models for characterization of boundary conditions and calibration. Some of these tasks, particularly those relating to model improvement, are already underway at the ISWS, ISGS, USGS, and within McHenry County.

6.2 Revision of Existing Model

- Integrated surface-groundwater hydrologic models would more accurately simulate flow interactions between streams and aquifers than the groundwater flow model employed for the present project. An effort to integrate surface water and groundwater models would require supporting field studies of surface water/groundwater interactions, as listed in Section 6.4.1.
- Revising the groundwater flow model so that surface water and drained conditions are represented as boundary conditions in the lower Rock River watershed, west of the area where surface water and drained conditions are represented in the current model, would provide more accurate simulations in western parts of northeastern Illinois, including western McHenry County. The lower Rock River watershed influences groundwater availability at pumping centers in the more urbanized areas to the east because the lack of Maquoketa and Upper Bedrock Unit cover in much of the watershed permits comparatively high rates of leakage to the deep aquifers (Figure 104).
- The existing groundwater flow model could be revised to better simulate interformational transfer of groundwater via open boreholes. Numerous such boreholes exist in northeastern Illinois, and transfers of groundwater, most notably between the Ancell and Ironton-Galesville Units, have likely affected heads in the region (page 125). Such effects are approximated in the current model with a high vertical hydraulic conductivity in the vicinity of major groundwater withdrawals from deep aquifers where such boreholes are expected. The recently published MODFLOW-USG (Panday et al., 2013) might permit their simulation by refining only those cells within a dense well field. A second alternative might be application of MODFLOW's multi-node well (MNW) package (Konikow et al., 2009), which allows a user specification of the radii of interformational wells. However, a limitation will remain that the exact location of boreholes is not known; hence MODFLOW-USG and MNW will only offer the development of "what-if" scenarios using hypothetical borehole networks.
- Transient simulations conducted using the groundwater flow model are affected by cessation of withdrawals from units as they become desaturated during model runs (page 120). That is, when a unit becomes completely desaturated, the modeling software automatically terminates withdrawals from the desaturated cells rather than reassigning the withdrawals to another unit. While the model has been developed to limit a majority of these effects in historic

simulations (i.e., by spreading out the pumping from the major pumping centers in pre-1964 simulations), further model development will continue to improve on limiting desaturated cells, such as by revising model layering and hydrologic properties (hydraulic conductivity, recharge) to reduce the effect.

6.3 Modeling Studies

6.3.1 Applications

- Water supply planners could benefit from an accounting process to identify where and when the modeling software has automatically reduced simulated withdrawals to zero as described on page 120. Such accounting could provide insight on the water demand that cannot be accommodated by existing wells.
- The groundwater flow model developed for this project could be employed to simulate additional pumping scenarios to support formulation of policy and management strategies for water resources in McHenry County. A toolkit for decision makers and the general public to access, apply, and manipulate the complex model simulations for future planning is available to extend the benefits and impacts of the present scientific study as well as future simulations (Illinois State Water Survey, 2010; Yang and Lin, 2011b; a).
- Scenarios simulated for this project cover a range of plausible future developments, but other scenarios are possible, and additional scenarios might be developed with input from individual communities and local planners (Wan et al., 2013a; Wan et al., 2013b). In McHenry County, scenarios might be tested which distribute shallow groundwater pumping in such a way as to reduce impacts to natural groundwater discharge in the most heavily affected sub-basins identified in this project. As discussed (page 89), the present study assumes a pumping network that reflects the 2009 network both in terms of geographic distribution and distribution of pumping rates among facility points of withdrawal.
- Groundwater simulations could be conducted for extended periods to evaluate transient effects beyond the mid-twenty-first century (the time horizon employed for transient simulations conducted for this project). This is particularly important for McHenry County, where the available head above the Ancell is decreasing in the year 2050.
- The groundwater flow model can be adapted to simulate climate change effects and optimization for water resource management (Wan et al., 2013a; Wan et al., 2013b). Climate change is likely to affect groundwater recharge rates, groundwater demand, and surface water boundary conditions utilized in the model.
- If required for more detailed local studies, the groundwater flow model can be used to provide boundary fluxes for high-resolution inset models. Such model integration, accomplished using the approach of telescopic mesh refinement, permits distant influences on groundwater flow to be represented in a rational and non-arbitrary manner in the inset models. Alternatively, MODFLOW-USG may be utilized to assign a grid refinement in a nested area within the currently existing model.

6.3.2 Research

- There is a need for research to determine the sensitivity of stream ecology to reduction in natural groundwater discharge. This study estimates reductions in natural groundwater discharge resulting from pumping, but we cannot advise readers regarding the effects of such reductions. This uncertainty in the ecological impacts is exacerbated by the effluent discharges that stabilize low flow rates but alter water quality and temperature.

- The current model assumes that all groundwater has an equal density. However, salinity can potentially impact the density, and hence the flow, of water in the subsurface. By employing modeling codes not used in the present project that explicitly simulate saline water density, the accuracy of the groundwater flow model developed for the present study can be improved to reflect the hydraulic effects of density barriers to flow and to indicate the potential for saline water to enter deep wells in McHenry County. Saline water is present in lower portions of the Mt. Simon Unit and in downdip areas of the important deep aquifers, including the Ancell Unit, Ironton-Galesville Unit, and Mt. Simon Unit. Because it is denser than fresh water, this saline water influences groundwater circulation. Pumping in northeastern Illinois could eventually induce saline water into deep wells, reducing groundwater quality and limiting use of deep groundwater. Movement of saline groundwater into deep wells is facilitated where the Eau Claire is more permeable, an area that includes McHenry County. However, density-dependent modeling is computationally demanding. Preliminary simulations could be developed using available head data and groundwater quality data from the Mt. Simon Unit and downdip portions of other bedrock units, which are scarce, but these simulations will be limited in accuracy until additional head and groundwater quality data became available. Acquisition of these additional data is recommended in Section 6.4.
- Investigation of the effects of urbanization on groundwater circulation and on surface water/groundwater interactions, and incorporation of these effects into computer models, could be a valuable contribution to water resources management in McHenry County. Groundwater simulations suggest that withdrawals can be expected to appreciably reduce natural groundwater discharge to many streams in McHenry County. The extent to which these reductions are offset by other changes within the watershed is not well understood, however. It is possible that while shallow aquifer pumping has reduced groundwater contribution to streams from predevelopment rates, other effects of urbanization (e.g., leaking infrastructure, lawn watering, land application of effluent) may have added to stream base flows (Meyer, 2005). Furthermore, the model could be utilized to assess water quality issues. For example, high concentrations of chloride, which originate from road salt application, have been observed in surface waters and wells in groundwater and base flow samples throughout northeastern Illinois. MODPATH (Pollock 1994) and MT3D-MS (Zheng and Wang 1999) are two post-processing packages that could be used to track contaminates through the subsurface. Such research is valuable because contaminants entering groundwater may take many years or decades to discharge to a sink, so groundwater models are necessary to assess the future impact of current best management practices.

6.4 Database Expansion and Improvement

One of the outcomes of modeling studies and the related data collection and analysis is the evaluation of the worth of additional data, including the value of additional monitoring and measurement. Scientists and engineers are always tempted to ask for additional data, but it is important to identify those data that will do the most to improve model accuracy by investigating alternative conceptual models, providing additional calibration targets, or quantifying heterogeneity. In general, the available database for justification of the hydraulic parameters, boundary conditions, and conceptual models suffers from imprecision, geological and geographical bias, sporadic and irregular data collection and compilation efforts, and poor documentation. These shortcomings reflect the fact that data collection, analysis, and mapping have largely been conducted for local studies over a long period of time, using a range of technologies and approaches, and for purposes other than groundwater flow modeling. Moreover, the groundwater flow model domain covers parts of four states, each with different governmental and institutional authorities responsible for hydrogeological research and data collection, and has at its center a notable absence of data and understanding of groundwater interactions with Lake Michigan.

This category of future work covers an array of efforts, including field studies; identification, compilation, and possible reanalysis of archived data and information; revision of existing governmental and institutional database-compilation practices; and compilation of comprehensive datasets. In this section, the term database is used with its most expansive meaning, and includes the complete array of published, unpublished, digital, and hardcopy data, information, mapping, and analysis employed to justify the hydraulic parameters, boundary conditions, and conceptual models that are synthesized as hydrologic models.

6.4.1 Hydraulic Properties and Boundary Conditions

- The most significant need for database expansion and improvement is for compilation of comprehensive, accurate withdrawal data. Analysis of alternative scenarios of future pumping (Section 4) clearly shows that pumping rate uncertainty is responsible for much of the variation in mode output. This also applies to simulations of historical pumping in which temporal changes in drawdown distribution and magnitude are solely a function of the assumed distribution of pumping. Historical pumping simulated by the models is limited in accuracy. For example, pre-1964 shallow pumping in Illinois is not simulated, and pre-1964 pumping from deep wells in Illinois is equally distributed to wells in the vicinity of seven fictitious pumping centers. This equal distribution prevents the model from exaggerating local drawdown at the seven pumping centers, but still is not an accurate representation of reality.
- The limited accuracy of the simulated historic pumping is largely due to the lack of readily available data, but it might be possible to fill gaps in the record with assumptions or with withdrawal data from historic pumping records discovered through organized research. Both efforts would require research using hardcopy records, possibly at several local and state facilities. Improvement of the database of historic pumping would be of greatest value in simulating groundwater flow in the deep units, because, in comparison with shallow groundwater flow, deep groundwater flow requires significant time to reach a steady state following changes in pumping rates and locations.
- Simulation accuracy could be enhanced by improving existing withdrawal databases, which might also involve changes in institutional/governmental requirements for reporting of groundwater withdrawals. In general, regional groundwater flow modeling in the urban corridor surrounding southern Lake Michigan, which covers an area extending from Michigan through Indiana and Illinois to Wisconsin, would benefit from a consistent approach to withdrawal measurement, reporting, and data compilation by all states surrounding the lake.
- Continued funding for the ISWS Illinois Water Inventory Program (IWIP), which collects water withdrawal data statewide, is critical to any future water supply planning efforts in this McHenry County and elsewhere in Illinois.

- More accurate modeling of streamflow capture by groundwater pumping, whether in the context of a groundwater flow model or integrated groundwater and surface water models, will require field studies of surface water/groundwater interactions to provide supporting data.
- As a parameter in most groundwater flow models to which shallow heads and streamflow are highly sensitive, groundwater recharge is a significant subject for additional study, yet accurate measurement of recharge is problematic and a subject of active research (National Research Council, 2004). Recharge rates employed in the groundwater flow model are based on watershed-scale estimates that do not portray the local variability arising from such factors as vegetation, land cover, slope, and geology. Studies directed toward detailed characterization of recharge rates in the region would be of considerable value in future modeling studies, including improvement of the model employed in this study. Further, current research into climate variability suggests that the climatic factors affecting recharge might be dramatically different in the future, yet the relationship between climate and recharge is not clear. Reducing uncertainties in recharge and discharge—or at least understanding their impact on model predictions—will require continued monitoring and analysis of streamflow, groundwater levels, and soil moisture to assess the temporal variability of the water table.
- Future groundwater flow modeling in the region would benefit from systematic research on the hydraulic properties of all the modeled units, aquifers and aquitards alike. This research would logically include an effort devoted to reanalysis, using a consistent approach, of available pumping and slug tests from the multi-state region surrounding northeastern Illinois.
- Groundwater flow modeling would be improved by field studies of hydraulic properties of units that are, at best, poorly understood hydraulically. For example, the aquitard consisting of unweathered Silurian-Devonian Carbonate Unit, Maquoketa Unit, and Galena-Platteville Unit underlying the Shallow Bedrock Aquifer exerts significant control on groundwater circulation within the deep aquifers of northeastern Illinois, yet the hydraulic character of this interval is poorly known. Little is known about the hydraulic properties of the Ironton-Galesville, because most tested wells open to the aquifer are also open to the Ancell Unit. Testing of such wells does not permit computation of hydraulic properties specific to the Ironton-Galesville. The Eau Claire Unit grades northward from aquitard to aquifer in northeastern Illinois, and our model places McHenry County in the region where previous studies of lithology, and model calibration, suggest that it functions more as an aquifer, but the hydraulic properties of the Eau Claire are poorly known.
- Additional field studies would provide observations to support groundwater flow modeling of the shallow materials. Comparatively few high-quality pumping tests of the shallow materials in northeastern Illinois exist, and many units have not been tested. Diamicton units, for example, exert major influence on shallow groundwater movement, yet their hydraulic characteristics are not well understood. In general, the spatial variability of the hydraulic conductivity of the vitally important sand and gravel aquifers is not well known and is only suggested by differences in well productivity. The horizontal and vertical distributions of hydraulic conductivity of the widely used Shallow Bedrock Aquifer are poorly documented by available high-quality pumping tests, which are sparsely distributed, influenced by overlying sand and gravel aquifers, and are from wells open to bedrock intervals that frequently extend downward into the underlying aquitard.

- With the exception of pumping rates, the hydraulic parameters and boundary conditions in the groundwater flow model do not change with time, and they reflect modern conditions (roughly those of the late twentieth century). Yet land cover changes associated with settlement, agricultural development, and urbanization have exerted significant hydrologic impacts, and more accurate model simulations might be possible if the models portrayed historically accurate changes in such characteristics as recharge rates and drained areas, both of which have probably changed as the region has developed. Such an effort would require research into land cover/land use changes and estimation of hydraulic characteristics of historic land cover/land use regimes.
- The locations and characteristics of drained areas in the groundwater flow model are poorly known and, for this project, are based on soils and urban-area mapping and on general assumptions regarding agricultural and urban drainage systems in the region. The actual locations of the many drainage systems are not documented, and the locations and characteristics of agricultural drains are, in particular, debatable. Future modeling would benefit from mapping of both agricultural and urban drainage systems and field studies to support accurate characterization of these systems.
- As discussed in Section 6.3.2, the effect of saline water in downdip areas and in the Mt. Simon Unit is not simulated directly in the groundwater flow model. The accuracy of additional modeling to simulate these effects would be severely limited without acquisition of groundwater quality data from the downdip areas and from the Mt. Simon Unit.

6.4.2 Geological Models

The groundwater flow model is based on a single geological model, or geological framework. In reality, subsurface geology is a subject of continuing scientific inquiry. Interpretations of the geometry and relationships of stratigraphic units are numerous and continually evolving. Each different interpretation of the geology is equivalent to a different conceptual model, and each interpretation employed in a groundwater flow model would result in different simulations of groundwater flow, although the differences might be subtle. The only way to evaluate the uncertainty generated by the conceptual model is by developing separate groundwater flow models based on each separate conceptual model, then comparing the results. Such an undertaking would be helpful in understanding the uncertainty of model simulations, but it would require considerable effort.

6.4.3 Calibration Data

- The groundwater flow model is calibrated to observations of streamflow and head, but these observations are limited in their applicability for model calibration, many having been collected for other purposes. Future modeling could benefit from focused monitoring efforts, begun in the present, to acquire and compile higher quality data for model calibration. Sites having suitable long-term streamflow data, useful for estimating the component of groundwater discharge known as base flow, are sparsely distributed in the northeastern Illinois region, the historical gage network having been monitored sporadically. Calibration of future models and model characterization of streambed properties would benefit from expansion of the existing gage network and a commitment to long-term data collection by monitoring authorities. Further, studies to quantify actual groundwater discharge to streams in the region would be helpful for calibration of future models to fluxes. Lacking accurate estimates of base flow, the groundwater flow model of the present study was calibrated, somewhat speculatively, to the range of streamflows between Q_{80} and Q_{50}.

- There is no alternative to employing speculative predevelopment heads for steady-state calibration of the groundwater flow model under nonpumping conditions, but deep aquifer head data for verification of model simulations under pumping conditions could be improved and could reduce model uncertainty discussed on page 85. These data have been collected from a sparse network of active or retired supply wells frequently open to numerous hydrostratigraphic units, giving them a very low level of reliability. In addition, collection of water level data from the wells occurred sporadically, and some of the wells served as water supply wells during the time the water level data were collected, limiting their usefulness for model calibration. Future model development would greatly benefit from systematic, long-term collection of single-unit head data from a network of dedicated deep observation wells that are not subject to pumping. Installation, maintenance, and measurement of monitoring wells are relatively inexpensive for the shallow, unconsolidated aquifers, but can be very expensive for the deep aquifers. Collaborating with owners of existing deep wells may permit converting old wells into monitoring wells at a minimal cost. Long-term, rather than sporadic, monitoring of water levels in these observation wells would be critical for the data to be most useful for model calibration and/or verification, requiring a commitment to the effort from monitoring authorities. Some deep observation wells would need to be constructed, at considerable expense, as it is unlikely that a suitable number of retired deep water supply wells, adaptable for observation of single-unit heads, will ever become available for use as observation wells in the region. It is practical for water supply purposes to leave deep wells open to all rocks underlying the Maquoketa Unit.
- Synoptic studies involving low flow measurements at multiple locations along suspect stream reaches are needed to identify specific locations where the stream may be losing flow to groundwater. Such measurements might be targeted to streams where simulated natural groundwater discharge decreases markedly through time, such as the Crystal Lake Outlet and Silver Creek. This type of synoptic study is most effective when streams are experiencing their very lowest flow conditions.

6.5 Monitoring

Monitoring is essential for early identification of problematic trends and establishes a database of historic heads that is irreplaceable for model calibration. McHenry County has wisely constructed a network of shallow observation wells (United States Geological Survey, 2013), but the county could benefit from deep observation wells.

Construction of a network of deep observation wells is likely to be cost-prohibitive. Lacking such a network, existing monitoring of the deep aquifers should be continued on the five-year basis employed historically by the ISWS and enhanced with more frequent and additional monitoring of selected wells. Owners of deep wells slated for sealing or abandonment might maintain the wells for observation purposes. Coordinated measurement of water levels in deep wells in both Illinois and Wisconsin would provide for interstate mapping of heads in the region. Additionally, observation wells could be sampled periodically to permit tracking of water quality trends.

Enhanced gaging of streamflow is recommended to improve (1) understanding of base flow, (2) the role of effluent in offsetting reduction in natural groundwater discharge, (3) stream-aquifer interactions, and (4) aquatic ecosystem function. Because long-term records are needed to identify flow trends, the authors advise that new stream gages be installed on tributary streams that are both known to have strong surface water/groundwater interactions and in locations expected to have future growth in water use from shallow groundwater sources. Monitoring of streams projected to incur significant simulated base flow reduction, such as the Crystal Lake Outlet and Silver Creek, is particularly advisable.

Understanding surface water/groundwater (SW/GW) interaction is critical to defining the relationships between groundwater, surface water, climate, land use, and human activity that constrain management options for water supply. The National Research Council (NRC) (2004) identifies SW/GW interaction as one of the most important research priorities in hydrology. Rates and patterns of SW/GW interaction result from processes that are complex and dynamic in both the spatial and temporal scales and are difficult to quantify. SW/GW interaction is also a key process affecting stream temperature due to the difference in temperature signatures between surface water and groundwater.

Recent acquisition of state-of-the-art technology by the ISGS, a distributed temperature sensor with a laser connected to a fiber optic cable (FO-DTS, http://water.usgs.gov/ogw/bgas/fiber-optics/), will be able to measure synoptic high resolution temperature distributions at both fine spatial and temporal scales. This approach will examine how streambed temperature patterns reflect spatiotemporal changes in SW/GW interaction. The measurement will provide detailed information on the processes and dynamics of SW/GW water interaction in the measured watershed, which will significantly improve estimation of flow quantity and the understanding of impact on water quality in both hydrology and ecology of the county.

7 Glossary

Definition sources: American Geological Institute, American Meteorological Society, Fetter (1988), Heath (1983), Illinois State Water Survey (2008), and Langbein and Iseri (1972)

aquifer: A saturated geologic formation that can yield economically useful amounts of *groundwater* to wells, springs, wetlands, or streams.

aquitard: A geologic formation of low permeability that does not yield useful quantities of *groundwater* when tapped by a well and hampers the movement of water into and out of an *aquifer*.

bank storage: Water absorbed into the banks of a stream channel when the stage rises above the *water table* in the bank that then returns to the channel as seepage when the stage falls below the *water table*.

base flow: That part of the *streamflow* that is not attributable to direct runoff from precipitation or melting snow; it is usually sustained by *groundwater discharge*.

bedrock: A general term for the consolidated rock that underlies soils or other unconsolidated surficial material (such as *glacial drift*).

capture zone: The portion of the subsurface contributing the *groundwater* withdrawn by a well during a selected time period (for example, five-year capture zone shows the portion of the subsurface contributing the *groundwater* withdrawn by a well over the course of five years of operation).

climate: The slowly varying aspects of the atmosphere–hydrosphere–land surface system.

climate change: Any systematic change in the long-term statistics of *climate* elements (e.g., temperature, pressure, winds) sustained over several decades or longer.

climate variability: The temporal variations of the atmosphere–ocean system around a mean state.

cone of depression: A three-dimensional representation of the *drawdown* created around a pumping well. Taking the shape of an inverted cone, the *drawdown* is greatest at the pumping well and decreases logarithmically with distance from the pumping well to zero at the *radius of influence*.

confined aquifer: An *aquifer* that is both overlain and underlain by *aquitards*, is fully saturated (i.e., all pore spaces are filled with water), and within which head is higher than the elevation of the upper boundary of the aquifer.

confining bed: See *aquitard*

confining unit: See *aquitard*

contour line: A line on a cross section or map connecting points of equal value.

desaturation: The act, or the result of the act, of draining pores in a *confined aquifer*, leading to unsaturated conditions within the *aquifer*, thereby causing its conversion to an *unconfined aquifer*.

diamicton: A nonsorted or poorly sorted sediment typically containing sand or larger particles suspended in a matrix of clay and/or silt; *diamicton* is a nongenetic term, but it is commonly and accurately applied to glacial deposits known by the genetic term *till*.

discharge: (1) Groundwater that exits the *saturated zone* by processes of seepage, evapotranspiration, or artificial withdrawal; (2) the process of removal of groundwater from the *saturated zone.*

discharge area: An area where groundwater exits the *saturated zone* through *evapotranspiration* and/or seepage to springs or stream channels in response to an upward vertical *head gradient*.

drawdown: The reduction of the *water table* of an *unconfined aquifer* or the potentiometric surface of a *confined aquifer* caused by *groundwater* withdrawals from wells.

drought: (1) A deficiency of moisture that results in adverse impacts on people, animals, or vegetation over a sizeable area; (2) a regional water shortage caused by a prolonged period of below-average precipitation, above-average temperatures, or a combination of the two.

effluent: Wastewater, treated or untreated, that flows out of a treatment plant, or industrial outfall. Generally refers to wastes discharged into *surface waters*.

equipotential: A type of *contour line* on a cross section or *potentiometric surface map* along which *head* is equal.

evapotranspiration: The process by which water is returned to the atmosphere by evaporation and transpiration caused by molecular activity at the liquid (water) surface where the liquid turns to vapor. Evaporation occurs at a free-water surface interface; transpiration is essentially the same as evaporation except that the surface from which the water molecules escape is leaves.

glacial drift: Sediment, including boulders, *till*, gravel, sand, silt, or clay, transported by a glacier and deposited by or from the ice or by or in water derived from the melting of the ice.

glacial till: See *till*

groundwater: Generally all subsurface water as distinct from surface water; specifically, that part of the subsurface water in the *saturated zone*. Groundwater can be hydraulically connected to *surface waters*.

groundwater flow model: An idealized mathematical description of the movement of water through earth materials under a given set of geologic and hydraulic conditions. In common usage, the term is understood to refer to both the computer program that solves the set of equations and to the application of the program to a particular *groundwater* system.

head: The height above a datum plane (commonly mean sea level) of a column of water. Water levels in tightly cased wells indicate head in the *aquifer* to which the well is open.

head gradient: The change in *head* per unit of distance measured in the direction of steepest change. All other factors being equal, *groundwater* flow is directly proportional to the head gradient; that is, the steeper the head gradient, the greater the flow. Head gradients are most commonly discussed for lateral distances within units (i.e., a *horizontal head gradient*) and for vertical distances within or across units (i.e., a *vertical head gradient*).

horizontal hydraulic conductivity (K_h): The *hydraulic conductivity* parallel to bedding in horizontally stratified earth materials, frequently orders of magnitude greater than *vertical hydraulic conductivity*.

hydraulic conductivity (K): A *hydraulic property* expressing the capacity of an earth material to transmit *groundwater*, or permeability. It is expressed as the volume of water that will move in a unit time under a unit *head gradient* through a unit area measured at right angles to the direction of flow. In this report, hydraulic conductivities are expressed in units of ft per day (ft/d). Because earth materials are frequently stratified or have a preferred grain orientation, hydraulic conductivity frequently is directional in nature, the most common distinction being between *horizontal* and *vertical hydraulic conductivity* in stratified rocks.

hydraulic gradient: See *head gradient*

hydraulic properties: Numbers describing the capacity of a material to store and transmit water, most notably the *vertical* and *horizontal hydraulic conductivity*, *transmissivity*, *storage coefficient*, and *porosity*.

hydrostratigraphic unit: A body of earth materials distinguishable on the basis of its hydraulic characteristics

hydrostratigraphy: *Stratigraphy* based on the hydraulic characteristics of earth materials.

interference: See *well interference*

leakage: (1) The process by which water enters or exits an *aquifer*, generally by vertical movement under the influence of *vertical head gradients* within the *saturated zone*; (2) the quantity of water contributed to or removed from an *aquifer* by movement under the influence of *vertical head gradients* within the *saturated zone*.

leakance: The *vertical hydraulic conductivity* of the streambed or lakebed divided by its thickness. Leakance controls the flow of water between the *saturated zone* and the *surface water*.

leakage: The flow of *groundwater* from one *hydrostratigraphic* unit to another.

lithology: The physical character of a rock or earth material, generally as determined megascopically or with the aid of a low-power magnifier.

lithostratigraphy: *Stratigraphy* based on *lithology*.

low flow: Seasonal and climatic periods during which *streamflows* are notably below average or the flow rates that occur during such periods.

minimum flow: *Streamflow* reserved to support aquatic life, minimize pollution, or provide for recreation. Values are set by a regulatory agency.

outwash: Sand and/or gravel deposited by running water derived from a melting glacier

porosity: A hydraulic property describing the volume of open space (pore space) within a material. It is calculated as the volume of open space divided by the total volume of the material and is sometimes expressed as a percentage.

potentiometric surface: A surface representing the level to which water will rise in tightly cased wells. The *water table* is a potentiometric surface for an *unconfined aquifer*.

potentiometric surface map: A map showing a *potentiometric surface* by means of *contour lines* (*equipotentials*).

$Q_{7,10}$ *(7-day 10-year low flow)*: A 7-day low flow for a stream is the average flow measured during the 7 consecutive days of lowest flow during any given year. The 7-day 10-year low flow ($Q_{7,10}$) is a statistical estimate of the lowest average flow that would be experienced during a consecutive 7-day period with an average recurrence interval of ten years. Because it is estimated to recur on average only once in 10 years, it is usually an indicator of *low flow* conditions during *drought*.

radius of influence: The horizontal distance (R) from the center of a pumping well to the point where there is no *drawdown* caused by that well, or the limit of its *cone of depression*.

recharge: (1) Water that infiltrates and percolates downward to the *saturated zone*; (2) the process by which water infiltrates and percolates downward to the *saturated zone.*

recharge area: An area where *groundwater* moves downward from the *water table* in response to a downward *vertical head gradient*.

saturated zone: The subsurface zone, below the water table, in which all *porosity* is filled with water and within which the water is under pressure greater than that of the atmosphere.

specific storage (S_s): A *hydraulic property* related to the *storage coefficient*, equivalent to the volume of water released from or taken into storage per unit volume of a porous material per unit change in *head*. The specific storage is unitless. *Specific yield* is a term reserved for the specific storage of an *unconfined aquifer*.

specific yield (S_y): A *hydraulic property* describing the capacity of an *unconfined aquifer* material to store water and the source of water pumped from wells finished in the *aquifer*. It is the ratio of the volume of water the material will yield by gravity drainage to the volume of porous material. The specific yield is unitless. Specific yield is a term reserved for the *specific storage* of an *unconfined aquifer*.

steady-state conditions: As contrasted from *transient conditions*, steady-state conditions are those in which heads and exchange with surface waters in an area do not change over time, having adjusted to the spatial distribution and rates of water inflow and outflow in the area. They describe an equilibrium condition. When stresses change, transient conditions prevail for a time, but given no additional changes, a new equilibrium will become established, and *steady-state conditions* will be re-established.

storage coefficient (S): A *hydraulic property* describing the capacity of an *aquifer* to store water as well as the source of water pumped from wells finished in the *aquifer*. It is the volume of water that an *aquifer* releases from or takes into storage per unit surface area per unit change in *head*. The storage coefficient is unitless.

stratigraphy: (1) The arrangement of strata, especially as to the position and order of sequence; (2) the branch of geology that deals with the origin, composition, distribution, and succession of strata.

streamflow: The total discharge of water within a watercourse, including runoff, diversions, *effluent*, and other sources.

streamflow capture: The process of reduction of *streamflow* resulting from *groundwater* withdrawals by wells. Streamflow capture occurs both by diversion into wells of *groundwater* that would, under nonpumping conditions, *discharge* to *surface water*, and by inducement of water directly from stream channels.

surface water: An open body of water, such as a stream, lake, reservoir, or wetland.

till: Nonsorted glacial sediment deposited directly by the glacier, as contrasted from sediments, such as *outwash*, deposited by glacial meltwater

transient conditions: As contrasted from *steady-state conditions*, transient conditions are hydraulic conditions in which heads and exchange with surface waters change with time as they adjust to a new or changed stress, such as the establishment of a new pumping well or a change in withdrawal rate at a new well. If stresses do not change, transient conditions will eventually pass, and a new equilibrium and *steady-state conditions* will be established.

transmissivity (T): A *hydraulic property* that is a measure of the capacity of the entire thickness of an *aquifer* to transmit *groundwater*. It is defined as the rate at which water is transmitted through a unit width of an *aquifer* under a unit *head gradient*, and it is equivalent to the product of *the hydraulic conductivity* and the *aquifer* thickness. In this report, transmissivity is expressed in units of ft squared per day (ft^2/d).

unconfined aquifer: An *aquifer* having no overlying *aquitard*.

unsaturated zone: A subsurface zone containing water under pressure less than that of the atmosphere, including water held by capillarity, and containing air or gases generally under atmospheric pressure. This zone is limited above by land surface and below by the surface of the *saturated zone* (i.e., the *water table*).

vertical hydraulic conductivity (K_v): *Hydraulic conductivity* perpendicular to bedding in horizontally stratified earth materials, frequently orders of magnitude less than *horizontal hydraulic conductivity*.

water availability: The amount of water that occurs in rivers, streams, lakes, reservoirs, and *aquifers* at any given time or over a period of time.

water quality: The suitability of water for an intended use. Water that is suitable for irrigation may require treatment to be suitable for drinking. Also refers to a comprehensive description of water composition (e.g., water quality studies).

water table: The surface of the *saturated zone*, at which the pressure is equal to that of the atmosphere.

water withdrawal: An amount of water that is withdrawn from *groundwater* or *surface water* sources to meet water demand.

well interference: *Drawdown* caused by a nearby pumping well. Interference between pumping wells can affect well yield and is a factor in well spacing for well field design.

withdrawal: Water removed from the ground or diverted from a surface water source for use.

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Appendix A. Groundwater Concepts

A.1. Aquifers and Confining Beds

Although nearly all geologic materials will transmit water, the transmission rate varies widely and is dependent on the permeability of the material and the hydraulic pressure gradient. Groundwater moves relatively rapidly through highly permeable materials and relatively slowly through those of lower permeability. An *aquifer* is a layer of saturated geologic materials that, by virtue of its comparatively high permeability, will yield useful quantities of water to a well or spring. Materials that can function as aquifers include sand and gravel, fractured and jointed carbonate rocks (limestone and dolomite), and sandstone. A *confining bed*, *confining unit*, or *aquitard* is a layer of low-permeability geologic materials having low permeability that impedes water movement to and from adjacent aquifers. Materials that can function as confining beds include shale, unweathered and unfractured carbonate rocks (limestone and dolomite), silt, clay, and diamicton (a nonsorted sediment, typically of glacial origin, composed of sand-sized or larger particles dispersed through a fine-grained matrix of clay- and silt-sized particles). In general, the term *hydrostratigraphy* refers to the study of spatial relationships, both vertical and lateral, of geologic layers grouped by hydraulic characteristics (e.g., aquifers and confining beds).

Aquifers can be unconfined or confined. An *unconfined aquifer* has no overlying confining bed. The water level in a well open to an unconfined aquifer approximates the water table. The water table represents the top of an unconfined aquifer, and as it rises and falls, aquifer thickness increases and decreases, respectively. Unconfined aquifers frequently have a direct hydraulic connection to rivers, lakes, streams, or other surface-water bodies. In such situations, the water level of the surface-water body may closely approximate the water level in the adjacent unconfined aquifer. A *confined aquifer* has confining beds both above and below it. The materials composing a confined aquifer are completely saturated and are under pressure, so that the water level in a well open to it stands above the top of the aquifer.

A.2. Potentiometric Surface Maps

A *potentiometric surface map* is a contour map of the potentiometric, or pressure, surface of a particular hydrogeologic unit (Fetter, 1988) that illustrates hydraulic head, or the level to which water will rise, in tightly cased wells in that hydrogeologic unit. A potentiometric surface map is analogous to a topographic map of the land surface, but rather than the land surface, it depicts the surface defined by water levels in wells. These maps can be constructed for both confined and unconfined aquifers and are sometimes referred to as water level maps or head maps. A potentiometric surface map of an unconfined aquifer is essentially a map of the water table; a potentiometric surface map of a confined aquifer is a map of an imaginary pressure surface. Both are based on the elevation to which water levels rise in wells completed in the aquifer of interest. *Contour lines* or *equipotentials* connect points of equal head and represent head values. Groundwater flows from high head to low head, and directions of groundwater flow are perpendicular to equipotentials. A head map can be used to determine groundwater flow directions as well as variations in head distribution.

The potentiometric surfaces of the shallowest aquifers closely approximate land-surface topography. Nearly all topography, including small hills and valleys, is replicated in the potentiometric surface with only a minor dampening of the relief. Dampening of the relief increases as aquifers become deeper, so that only large-scale topographic features are replicated in the potentiometric surfaces of deeply buried aquifers.

Heads rise and fall in response to groundwater withdrawals, recharge, evaporation, and transpiration, and, specifically in the case of confined aquifers, aquifer loading (Freeze and Cherry, 1979). Heads typically follow a seasonal cycle that is most noticeable in shallow aquifers and at locations remote from large pumping centers, where pumping effects do not overwhelm natural cycles. Natural declines in heads usually begin in late spring and continue throughout the summer and early fall. Heads begin to rise again in late fall and peak during the spring, when groundwater recharge from rainfall and snowmelt has its greatest effect (Visocky and Schicht, 1969).

A.3. Hydraulic Properties

The ability of an earth material to store and transmit water is generally a function of its hydraulic conductivity, transmissivity, and storage coefficient.

Hydraulic conductivity is the capacity of an earth material to transmit groundwater, or its permeability. It is expressed as the volume of water that will move in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the directions of flow (Heath, 1983). The terms *head gradient* or *hydraulic gradient* refer to the change in head per unit of distance measured in the direction of steepest change. All other factors being equal, groundwater flow is directly proportional to the hydraulic gradient; that is, the steeper the hydraulic gradient, the greater the flow. In this report, hydraulic conductivities are expressed in units of feet per day (ft/d). Thus, a 1-square-foot (ft^2) area of a material having a hydraulic conductivity of 100 ft/d could transmit 100 cubic feet (ft^3) of water during a one-day period under a hydraulic gradient of 1 foot of head change per foot of horizontal distance (if the 1 ft^2 area is perpendicular to the hydraulic gradient).

The hydraulic conductivity of a material varies with the density and viscosity of the water flowing through the material (which in turn are functions of temperature) as well as with the permeability of the material. For a given temperature, however, hydraulic conductivity is largely a function of permeability. Permeability is, in turn, a function of the size and degree of interconnection of pore spaces. In unconsolidated sand and gravel aquifers of northeastern Illinois, the porosity consists primarily of the voids lying between the sand and gravel grains composing the aquifer framework. In underlying consolidated rocks such as limestone and dolomite, the typically low primary porosity is enhanced by fractures and dissolution of the fracture openings (called secondary porosity). Hydraulic conductivity varies across several orders of magnitude, ranging from 10^{-8} ft/d (in the case of shale and dense, unfractured rocks) to 10^4 ft/d (coarse gravels) (Table A-1). The hydraulic conductivity of diamicton alone can vary over 6 orders of magnitude (from 10^{-7} to 10^{-1} ft/d). This variability often reflects the predominance of sand versus clay in the material's composition. In northeastern Illinois, this extreme variability in hydraulic conductivity has implications for whether diamicton units function as aquitards or poor aquifers.

Table A-1. Representative Values of Hydraulic Conductivity for Various Rock Types (after Domenico and Schwartz, 1990)

Material	Hydraulic Conductivity (ft/d)
Unconsolidated Rocks	
Gravel	$1\times10^{2} – 1\times10^{4}$
Coarse sand	$2\times10^{-1} – 2\times10^{3}$
Medium sand	$2\times10^{-1} – 1\times10^{2}$
Fine sand	$6\times10^{-2} – 6\times10^{1}$
Silt, loess	$3\times10^{-4} – 6\times10^{0}$
Diamicton (till)	$3\times10^{-7} – 6\times10^{-1}$
Clay	$3\times10^{-6} – 1\times10^{-3}$
Sedimentary Rocks	
Limestone, dolomite	$3\times10^{-6} – 2\times10^{0}$
Sandstone	$1\times10^{-4} – 2\times10^{0}$
Shale	$3\times10^{-8} – 6\times10^{-4}$

Because earth materials are frequently stratified or have a preferred grain orientation, hydraulic conductivity frequently is directional in nature. The most common distinction is between *horizontal* and *vertical hydraulic conductivity* in stratified rocks, with vertical hydraulic conductivity (hydraulic conductivity perpendicular to bedding) being less than horizontal hydraulic conductivity (hydraulic conductivity parallel to bedding). Horizontal hydraulic conductivity is sometimes orders of magnitude greater than vertical hydraulic conductivity in shaly aquitards because the long dimensions of the tabular clay mineral crystals composing these rocks are oriented parallel to bedding.

Transmissivity is a measure of the capacity of the entire thickness of an aquifer to transmit groundwater. It is defined as the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient (Heath, 1983), and it is equivalent to the product of the hydraulic conductivity and the aquifer thickness. In this report, transmissivity is expressed in units of feet squared per day (ft^2/d). Whereas hydraulic conductivity may be thought of as an expression of the capacity of a block of aquifer material (1 ft^2 in cross-sectional area) to transmit water under a unit hydraulic gradient, transmissivity may be thought of as an expression of the capacity of a slice of the aquifer, (1 foot wide with a height equal to the aquifer thickness) to transmit water under a unit hydraulic gradient.

The amount of water stored in and released from an aquifer varies with the type of aquifer and the amount of change in the hydraulic head in the aquifer. For confined aquifers, groundwater is stored and released through the elastic expansion and compression of the formation and of water in the pores. The *storage coefficient* is a unitless parameter describing the volume of water released per square foot of aquifer, per foot decrease in hydraulic head. The storage coefficient generally ranges between 10^{-5} to 10^{-3} (Heath, 1983) with a typical value in northeastern Illinois of 10^{-4} (Suter et al., 1959; Walton, 1964). This means that as pumping in northeastern Illinois reduces the hydraulic head by 1 foot in a square foot of a confined aquifer, 10^{-4} ft^3 of groundwater will be released as the water expands and pore spaces in the aquifer compress. For unconfined aquifers, water is derived primarily by gravity draining the pore space in the aquifer, and the storage is described by the *specific yield*, ranging from 0.1 to 0.3 (Fetter, 1988).

Thus if the head in a 1 ft^2 area of an unconfined aquifer having a storage coefficient of 0.2 declines 1 foot, then 0.2 ft^3 of groundwater has been removed from storage. A hydraulic property related to the storage coefficient is the *specific storage*, which is the amount of water released from or taken into storage per unit volume of a porous medium per unit change in head (Fetter, 1988).

The combination of hydraulic conductivity and the thickness of a streambed or lakebed controls the flow of water between the saturated zone of the subsurface and surface-water features. The vertical hydraulic conductivity of the streambed or lakebed divided by thickness is referred to as the *leakance*. Field estimates of leakance are generally not available, and this is the case for northeastern Illinois, but typical values for riverbeds assumed to be several feet thick are between 0.1 and 10 foot/day-foot (Calver, 2001).

A.4. Groundwater Recharge and Discharge

Groundwater recharge is a process by which water is added to the *saturated zone* in which all pore spaces are filled with water. Although most precipitation runs off to streams or evaporates, some of it percolates downward through the soil and unsaturated zone. A portion of the recharging water is taken up by plants and returned to the atmosphere by transpiration. Water that passes through the unsaturated zone reaches the *water table* and is added to the saturated zone. Groundwater recharge occurs most readily where the materials composing the unsaturated zone are relatively permeable and where such factors as slope and land-use practices discourage runoff and uptake of water by plants.

Groundwater eventually discharges to surface-water bodies, including springs, wetlands, streams, rivers, and lakes. Discharge processes sustain flow from springs, maintain saturated conditions in wetlands, and provide base flow of streams and rivers. The groundwater contribution to all streamflow in the United States may be as large as 40 percent (Alley et al., 1999). Groundwater discharge also occurs directly to the atmosphere through evapotranspiration. Pumping of groundwater from wells is also a discharge process.

In northeastern Illinois, as in roughly the eastern half of the contiguous United States that is humid, recharge to the saturated zone occurs in all areas between streams or in areas where surface water infiltrates the subsurface. Under predevelopment conditions, discharge from the saturated zone occurs only in streams, lakes, and wetlands together with floodplains and other areas where the saturated zone intersects the land surface or the root zone of plants.

Recharge and discharge also can be considered in terms of movement of water between aquifers. Where downward vertical hydraulic gradients exist (i.e., where heads decrease with depth within the saturated zone), groundwater moves downward from the water table or from a surficial unconfined aquifer to recharge underlying confined aquifers through the process of *leakage*. Where an upward vertical hydraulic gradient exists between a confined aquifer and the land surface, groundwater moves upward from the confined aquifer towards the land surface.

In general, recharge areas of aquifers become separated from their discharge areas by progressively greater distances as aquifer depths increase. The shallowest groundwater, which directly underlies the water table, is part of a local flow system and discharges to very small ditches and depressions. Recharge to the water table occurs only in the relatively small areas between these local discharge features. Groundwater in more deeply buried confined aquifers is part of a regional flow system and discharges to comparatively large-scale rivers, such as the Fox River, and lakes occupying major valleys and depressions. The recharge areas for these aquifers include the broad areas between the regional discharge features.

Much of northeastern Illinois has relatively impermeable clay-rich diamicton at or near the land surface that can inhibit the infiltration of precipitation into underlying aquifers. Appendix C discusses the occurrence of these deposits in northeastern Illinois and illustrates their distribution with geologic cross sections. Prior to European settlement, the region contained vast areas where the water table was at or near the land surface much of the year. This shallow water table developed as a consequence of flat topography in combination with widespread, near-surface occurrence of relatively impermeable clayey diamicton and water-retentive organic soils. To develop areas for agricultural use, extensive networks of tile drains and drainage ditches were constructed.

Because the permeability of sand is much greater than that of diamicton, recharge to aquifers tends to be concentrated in areas with sand at or near the land surface. Pathways followed in the shallow subsurface by recharge water may be complex because the Quaternary materials occupying this subsurface interval are heterogeneous, and groundwater circulation is concentrated within aquifers and through sporadically-occurring connections between aquifers where the thickness of intervening aquitards is zero. Leakage across aquitards is sluggish by comparison. Cross sections and maps in Appendix C illustrate the extreme thickness variability typical of the Quaternary materials in northeastern Illinois.

Groundwater recharge occurs mainly during the spring when rainfall levels are high and water losses to evaporation and transpiration are low. Recharge decreases during the summer and early fall when evaporation and transpiration divert most precipitation and infiltrating water back into the atmosphere. Likewise, during winter months surface infiltration is often negligible when soil moisture is frozen, which diverts precipitation into surface-water bodies as runoff. Recharge can occur, however, during mild winters when soil moisture is not frozen (Larson et al., 1997).

Several factors affect the rate of groundwater recharge. Among these are the hydraulic characteristics of the materials both above and below the water table; topography; land cover; vegetation; soil moisture content; depth to the water table; intensity, duration, areal extent, and seasonal distribution of precipitation; type of precipitation (rain or snow); and air temperature (Walton, 1965). Hensel (1992) presented a detailed discussion of groundwater recharge processes in Illinois.

Water managers commonly express concern that groundwater recharge rates and the availability of groundwater are reduced by urban land cover. This belief is understandable since pavements and rooftops are highly observable features of the urban landscape that are presumed to be impermeable. However, research from urban areas throughout the world (Brassington and Rushton, 1987; Foster, 1990; Foster et al., 1999; Lerner, 1986; Lerner, 2002; Pierce et al., 2004; Price and Reed, 1989; Rushton et al., 1988) suggests that leakage from buried pipe networks—primarily water distribution systems and storm drains—may generate large amounts of recharge in urban areas that can offset the effects of reduced infiltration. Research on fractures in urban land cover has shown that pavements may be more permeable than suggested by casual observation (Wiles and Sharp, 2008). So, while decreasing the area of impermeable surfaces and capturing runoff have benefits in terms of reducing storm runoff and improving water quality, the benefits of enhancing recharge are less certain, particularly if there is no aquifer to recharge immediately underlying the area. That said, capturing runoff to provide opportunities for infiltration and other uses (e.g., gardening) has particular advantages, especially in the Lake Michigan service area, where storm runoff flowing past the stream gage at Lockport is counted against Illinois' Lake Michigan diversion (see discussion of Lake Michigan diversion in Chapter 3).

A.5. Effects of Pumping

Under predevelopment conditions, long-term recharge and discharge rates are approximately equal, and changes in the quantity of groundwater stored in the saturated zone are negligible. Recharge is provided by infiltration of precipitation and—particularly in arid areas—by loss of water from streams, lakes, and wetlands. Discharge occurs to surface waters through springs and seeps and directly to the atmosphere by evapotranspiration, processes that the authors call "natural" discharge to distinguish them from well withdrawals, also a discharge process. This equilibrium condition is described by the following equation:

$$\text{Recharge} = \text{"Natural" Discharge}$$

In other words, inflows to the saturated zone (recharge) are equal to outflows from it (discharge by evapotranspiration and through springs and seeps).

The withdrawal of groundwater from a well causes lowering of heads in the area around the well. This decline in head is called drawdown. In three dimensions, the head distribution surrounding a single pumping well resembles a cone with its apex pointed downward. The lowest head (and greatest drawdown) occurs at the pumping well, and drawdown decreases with distance from the well. The area of lowered heads surrounding a pumping well or well field is therefore called a cone of depression. In the simplest case—a single well pumping at a uniform pumping rate—the cone of depression typically deepens and widens until gradients are sufficient to divert groundwater into the cone at a rate equivalent to the withdrawal rate, a condition called *equilibrium* or *steady-state*. The size and shape of the cone of depression vary with the hydraulic properties of the subsurface environment, the location of the well in relation to source aquifer boundaries and surface waters in hydraulic connection with the source aquifer, pumping rate and schedule, and other factors. In the common case of numerous, closely spaced wells, which, over time, are brought into and out of service and are pumped at changing rates, actual equilibrium conditions are rare. Even in some very simple cases—that of a high-capacity well removing water from an aquifer receiving little or no recharge, for example—equilibrium cannot be established, and heads decline until withdrawals from the well cease.

Drawdown is a natural consequence of well withdrawals and cannot be avoided, but excessive drawdown can create problems. The drawdown generated by one well causes water levels to decline in nearby wells. This *interference drawdown* can result in increased pumping expenses and, in more extreme cases, can cause a well to fail to deliver its expected supply. The amount of drawdown that is tolerable, however, depends on local hydrogeologic conditions and individual well construction characteristics such as total depth and pump setting depth. As discussed in the following paragraphs, drawdown leads to a decrease in natural groundwater discharge. Lastly, the changes in groundwater flow resulting from drawdown can sometimes result in deterioration of groundwater quality.

Withdrawals of groundwater from a well are initially supplied by a reduction in storage as heads decline in the source aquifer and a cone of depression forms around the well. This reconfiguration of the predevelopment potentiometric surface induces flow of groundwater to the well. In most settings, the removal of groundwater from storage creates a transient state, and an increasing proportion of the water withdrawn from the well is supplied by increased groundwater recharge and/or reduction of “natural” groundwater discharge via the predevelopment pathways of springs, seeps, and evapotranspiration. All three components must be considered in any accounting of the water supplied to the well; however,

$$\text{Withdrawal} = \text{Recharge Increase above Predevelopment Rate} + \\ \text{Removal from Storage} + \text{"Natural" Discharge Decrease below Predevelopment Rate}$$

The time required for transient removal of water from storage by a new pumping well to cease and for new equilibrium conditions to become established may range from days to decades. During this time, the cone of depression around the well continues to deepen and widen. In some cases, a new equilibrium cannot be established because predevelopment recharge and discharge rates cannot be altered enough to balance withdrawals.

If a new equilibrium can be established, inflows and outflows will again balance:

$$\text{Withdrawal} = \text{Recharge Increase above Predevelopment Rate} + \\ \text{"Natural" Discharge Decrease below Predevelopment Rate}$$

Thus, long-term pumping of any well or group of wells requires that recharge and/or “natural” discharge rates change, and that water be removed from storage. How much water is available long-term—that is, the sustainable pumping rate—depends on how these changes affect the surrounding environment and what the public considers to be acceptable environmental impacts (Alley et al., 1999; Bredehoeft, 2002; Bredehoeft et al., 1982; Devlin and Sophocleus, 2005).

In most settings, withdrawals are accommodated by removal of water from storage and decreased “natural” discharge (Alley et al., 1999). Removal of water from storage causes reduced heads, which may result in increased pumping expenses and in water supply interruptions where heads decline to the levels of pump intakes. In addition, this head reduction may, in some settings, induce movement of poor quality water into source aquifers, rendering groundwater pumped from wells unusable or requiring expensive treatment. Decreased “natural” discharge is reflected in reduced streamflow, reduced water levels in lakes and wetlands, reduced saturated conditions in wetlands, and changes in the vegetation. Such alterations may interfere with instream-flow requirements for fish habitat or other instream environmental needs, ecology of groundwater-dependent habitats such as fens, and availability of surface water for water supply.

This range of pumping effects and their spatial variability illustrate the importance of human judgment in developing sound groundwater management schemes, and they underscore the importance of groundwater flow models as tools for synthesizing a wide range of data, organizing thinking, and mapping and quantifying the diversity of impacts. The simple prescription that groundwater withdrawals are sustainable if they are maintained at or below the recharge rate—the Water-Budget Myth (Bredehoeft, 2002; Bredehoeft et al., 1982)—could have unexpected and disastrous impacts if used for long-term groundwater planning and management. In the typical case in which withdrawals are accommodated by removing water from storage and decreased "natural" discharge, withdrawals at the rate of predevelopment recharge would likely result in significant drawdown and profound effects on surface waters.

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