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Changing Groundwater Levels in the Sandstone Aquifers of Northern Illinois and Southern Wisconsin: Impacts on Available Water Supply

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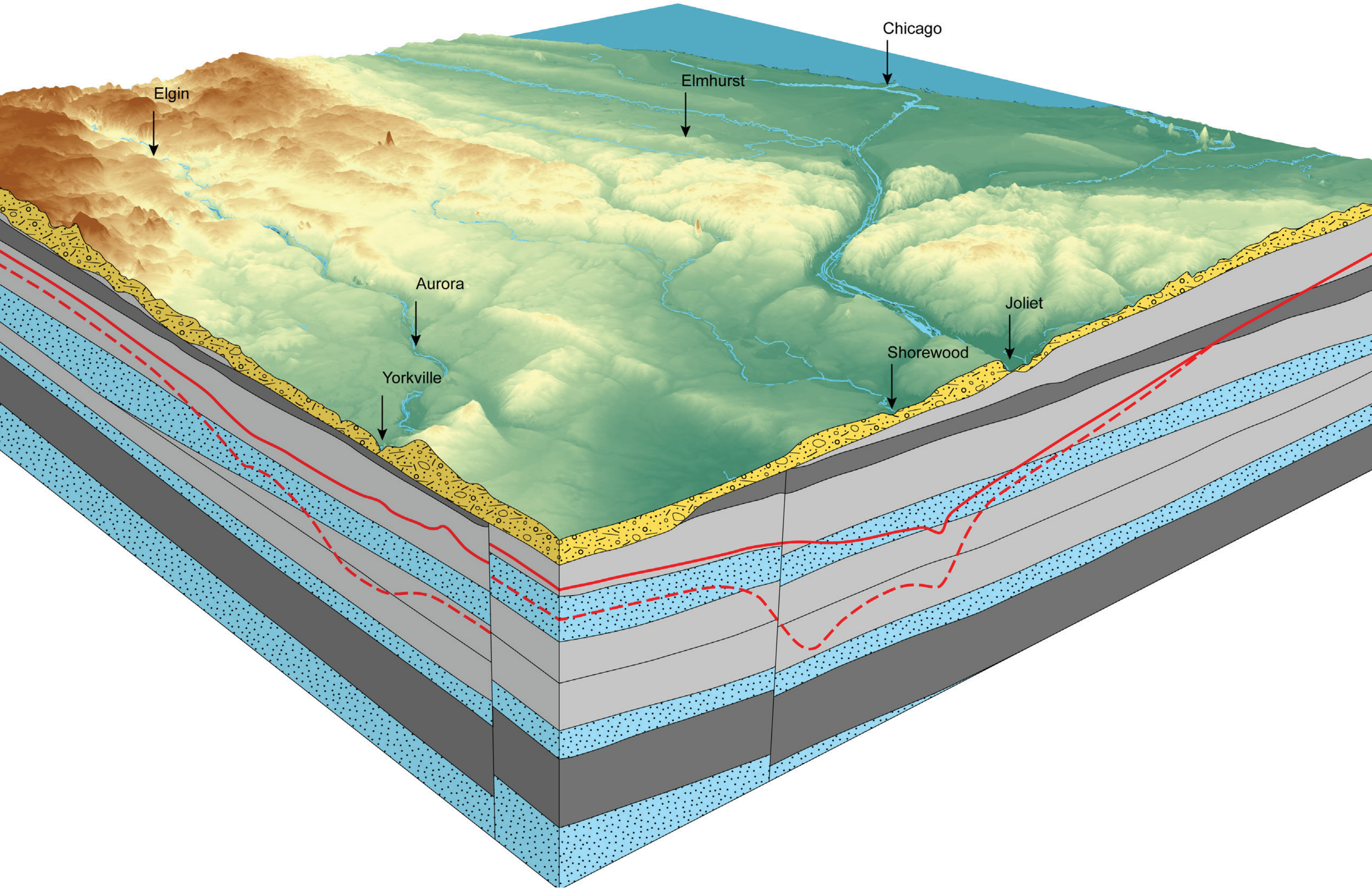

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Abstract

In 2014-15, the Illinois State Water Survey conducted their largest synoptic measurement of water levels (i.e., heads) in Cambrian-Ordovician sandstone wells since 1980. The study covered 33 counties in the northern half of Illinois where demands for water are satisfied, in part, by sandstone aquifers. The Wisconsin Geological and Natural History Survey also measured sandstone wells in 10 counties in southern Wisconsin. These observations were used to generate head contours of the sandstone aquifers. These contours provide insight into the direction and magnitude of groundwater flow. They also can be compared with historic measurements, providing insight into the impact of changing groundwater withdrawals through time.

In predevelopment conditions, heads in the Cambrian-Ordovician sandstone aquifers were near or above land surface. Due to pumping from the sandstone aquifers, heads have decreased over time; this decrease is referred to as drawdown. In 2014, drawdown in northeastern Illinois was typically over 300 ft and exceeded 800 ft in the Joliet region. Three factors drove this large drawdown. First, demands for water from sandstone aquifers are much greater in northeastern Illinois than in the rest of the study region. Second, the sandstone aquifers are overlain by aquitards, which are low permeable materials that limit vertical infiltration of water. Third, the Sandwich Fault Zone limits water flowing into the sandstone aquifers of northeastern Illinois from the south. Heads near the center of the cone of depression continue to have a decreasing trend.

The more severe drawdown in northeastern Illinois has resulted in local areas where heads have fallen below the top of the sandstone, known as desaturation. Desaturation of a sandstone aquifer can create a number of water quality and quantity concerns. The uppermost sandstone, the St. Peter, was observed to be partially desaturated in portions of Will, Kane, and Kendall Counties under non-pumping conditions. Other areas in these counties are at risk of desaturation under pumping conditions or with the installation of additional wells connecting the St. Peter to deeper, more heavily stressed sandstones. Simulations from a groundwater flow model indicate that the risk of desaturation will increase with increased future withdrawals.

Despite the relatively small demand for water throughout much of central Illinois, heads have been declining since predevelopment, likely due to the shale overlying the sandstone. This shale serves as an aquitard, minimizing vertical infiltration of groundwater to the sandstone. Sustained drawdown in this region could potentially induce flow from the southern half of the state, where water in the sandstone is highly saline and not suitable as a drinking water supply.

Drawdown in northwestern Illinois was also typically small (<100 ft), primarily due to two factors: 1) low demands from the sandstone aquifers and 2) the absence of shale aquitards. The notable exception is in Winnebago County, near Rockford, where demands are historically high and drawdown was on the order of 100-200 ft. While the quantity of water in the aquifer is not a concern in this region, large withdrawals could result in reductions of natural groundwater discharge to surface waters, impacting stream ecosystems under low flow conditions.

Drawdown since predevelopment was over 300 ft in southeastern Wisconsin, with the greatest drawdown in Waukesha County of over 400 ft. Recent trends indicate heads in the Waukesha area are recovering, although they are still well below predevelopment levels.

1 Introduction

1.1 Large-scale synoptic measurement of sandstone wells

The Illinois State Water Survey (ISWS) has long studied the impact of groundwater withdrawals on water levels (i.e., heads) in sandstone aquifers throughout the northern part of the state. In 1959, the ISWS, in coordination with the Illinois State Geologic Survey (ISGS), published a comprehensive analysis of groundwater demand and availability in northeastern Illinois (Suter et al., 1959). The northeastern Illinois area was of particular interest because of the rapidly increasing withdrawal rates from the sandstone. Furthermore, the sandstone aquifers in this area are generally hundreds of feet deep with limited opportunity for replenishment via precipitation. The report concluded that the withdrawal rates from the sandstone aquifers in northeastern Illinois were nearing their sustainable yield, which is defined in this report as the maximum withdrawal rate that could be sustained indefinitely without partially desaturating the sandstone aquifers. Partial desaturation occurs when the head in a well falls below the top of the sandstone aquifer, and can result in a number of water quality and quantity issues as outlined in Section 6.1. Suter et al. (1959) concluded that future changes in the locations and rates of groundwater withdrawals, if left unmanaged, could jeopardize the long-term viability of the sandstone aquifers. Partly due to these findings, the ISWS began intensively to collect data related to groundwater withdrawals and their impacts on heads. To proactively monitor risks to the sandstone aquifers due to changing withdrawals, the ISWS has conducted a synoptic measurement of sandstone heads in Northeastern Illinois over regular intervals (annually from 1963 to 1980 and every four to seven years from 1980 to 2014).

Groundwater withdrawals from the Cambrian-Ordovician sandstone aquifers have also taken place in states neighboring Illinois, with the largest withdrawals occurring in southeastern Wisconsin. Like northeastern Illinois, the sandstone in this area is deep and has limited opportunity for replenishment via precipitation. In 1973, a study indicated that heads were decreasing at a rapid rate in both southeastern Wisconsin and northeastern Illinois, creating two competing cones of depression (Fetter, 1981). Since that study, large-scale changes in withdrawals from sandstone aquifers have occurred in both states, with some areas experiencing large decreases in demand while other areas have switched completely to alternative water sources (Lake Michigan, shallow groundwater, river water). The 2014 synoptic measurement detailed in this report represents the first update of these competing cones of depression since 1973.

To help assess the sustainability of current and future demands, the Illinois Department of Natural Resources (IDNR) has funded the development of water supply planning regions (WSPRs) throughout the state. The initial phase of water supply planning has been completed for two WSPRs that utilize the sandstone aquifers in Illinois: Northeastern Illinois (Meyer et al., 2012), which heavily uses the sandstone aquifers, and East-Central Illinois (Roadcap et al., 2011), which currently uses the sandstone aquifers sparingly. IDNR is currently funding the development of three new WSPRs: Middle Illinois Basin, Northwestern Illinois, and the Kankakee River watershed (Figure 1). The Spoon and La Moine Basins WSPR, shown in Figure 1, will be a focus of future work.

A major outcome of the water supply planning study for the Northeastern and East-Central Illinois WSPRs was the development of numerical groundwater flow models for each region. The models are used to simulate the impacts of future pumping scenarios (Meyer et al., 2009; Meyer et al., 2013; Roadcap et al., 2013). In 2014, the ISWS started combining the Northeastern and East-Central Illinois models into a single groundwater flow model that will extend over much of the northern half of the state (Figure 1). This new model will be updated with available geologic and groundwater withdrawal data for the WSPRs shown in Figure 1. The large domain of this groundwater flow model allows for simulation of interregional impacts of groundwater withdrawals, particularly from the sandstone aquifers. The model domain also extends into Wisconsin and Iowa, where the sandstone aquifer is heavily utilized, as well as Indiana, where the sandstone aquifer is present but not used for water supply.

The groundwater flow models developed by the ISWS are periodically updated with pumping data obtained from the Illinois Water Inventory Program (IWIP). Upon completion of each synoptic measurement, the model parameters are adjusted to improve the fit between simulated and observed heads, a process known as calibration. New parameters or even a new conceptualization of the groundwater flow regime may be required to achieve calibration; this is particularly true when a stress is placed on the aquifers that was not present in previous synoptic measurements. Hence, synoptic measurements at regular intervals are essential to understanding the response of an aquifer to pumping, in particular in heavily stressed regions.

The last statewide study of heads from the productive sandstone aquifers of Illinois was conducted by the ISWS in 1980. The area outside of northeastern Illinois has not historically been studied as heavily due to relatively low demands from the sandstone. However, in north-central Illinois, the sandstone is at or near land surface; consequently, precipitation can more easily replenish the sandstone than in other areas of the state. Monitoring heads in this region is vital to understanding modern sources of water to the Cambrian-Ordovician sandstone aquifers. Furthermore, in northwestern and central Illinois, the sandstone is deep, overlain by a variety of materials that can potentially limit vertical infiltration of water to the sandstone. Monitoring how the small demands in these regions have impacted heads since 1980 is critical to understanding the hydrologic behavior of both the sandstone and the material overlying it.

An update of the 1980 statewide study was needed, so from July 2014 to February 2015, the ISWS conducted a large-scale measurement of public, commercial, industrial, and irrigation wells that are open to at least one sandstone aquifer. The ISWS also coordinated with the Wisconsin Geological and Natural History Survey (WGNHS) to obtain non-pumping heads from sandstone wells in southeastern Wisconsin over the same time interval (July 2014 to February 2015). Dedicated United States Geological Survey (USGS) wells were utilized to obtain non-pumping head measurements in the western portions of Wisconsin. The resulting study area consists of 33 counties in Illinois and 10 counties in Wisconsin (Figure 2). Note that the study covers only the northern half of Illinois; the Cambrian-Ordovician sandstones are not viable aquifers in the southern portion of the state due to high salinity.

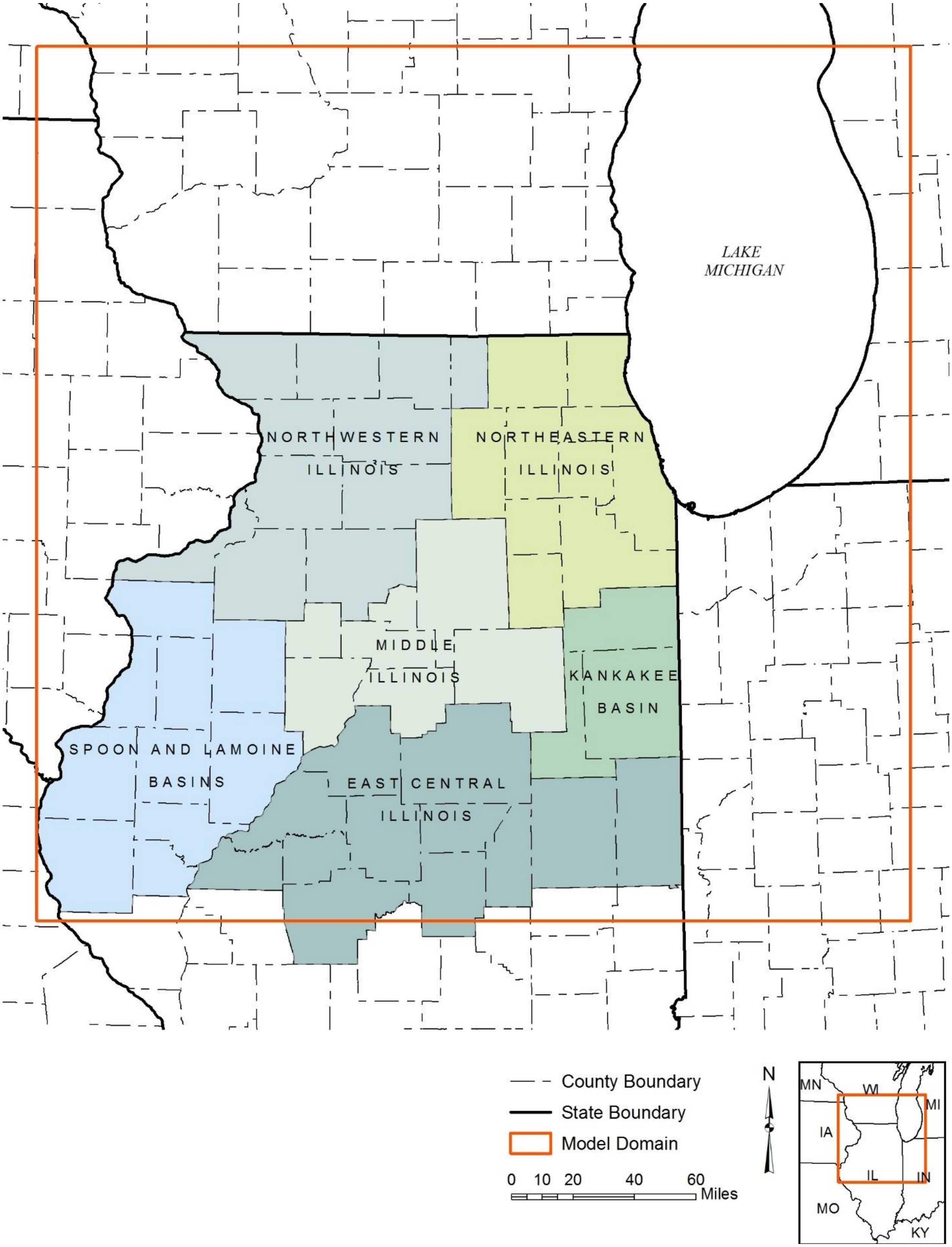

Figure 1: Water supply planning regions (WSPRs) where the Cambrian-Ordovician sandstone aquifers are utilized. The orange line represents the boundary of a groundwater flow model that is under development.

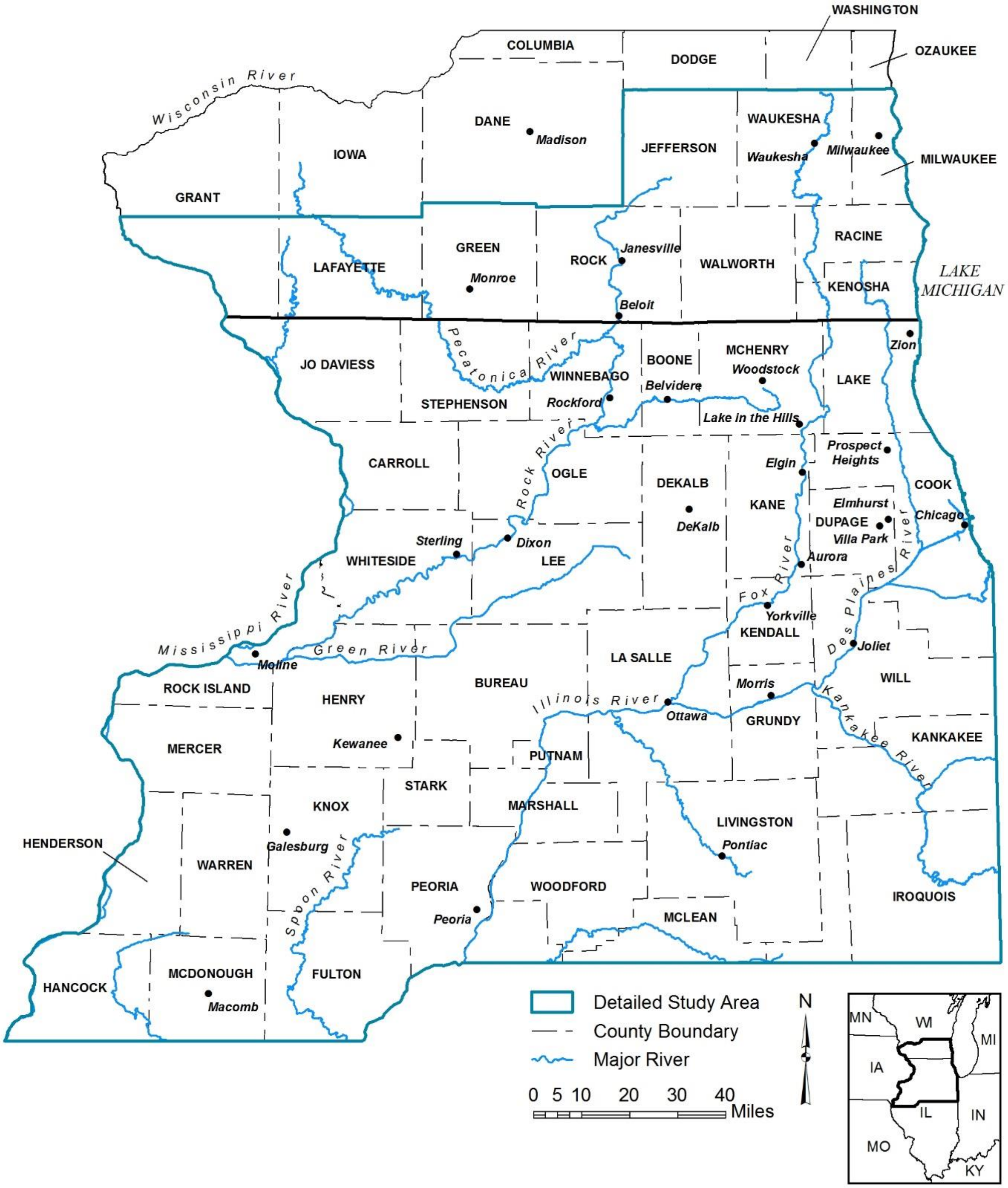

Figure 2: Study area for the 2014 synoptic measurement of wells in the Cambrian-Ordovician sandstone aquifers.

1.2 Updated contours from previous reports

Since Suter et al. (1959), the ISWS has released a number of publications discussing heads in the Cambrian-Ordovician sandstone aquifers. Annual measurements from 1959 to 1980 are discussed in Walton et al. (1960), Sasman et al. (1961), Sasman et al. (1962), Sasman et al. (1967), Sasman et al. (1973), Sasman et al. (1977), and Sasman et al. (1982). Since 1980, synoptic measurements have been conducted every four to seven years, specifically 1985 (Sasman et al., 1986), 1991 (Visocky, 1993), 1995 (Visocky, 1997), 2000 (Burch, 2002), and 2007 (Burch, 2008). This work represents a long history of data collection that is essential to understand the impact of changing water demand on heads in the sandstone aquifers.

Every previous synoptic measurement report since 1959 has generated head contours, more commonly referred to as a potentiometric surface, over at least northeastern Illinois. These contours have traditionally been created by hand. However, interpreting changing heads through time via contours drawn by multiple individuals over a span of decades can be difficult. For this report, a groundwater flow model was utilized to create these potentiometric surfaces. The primary advantage of this model is that, in addition to contours, the model generates a grid of heads that can easily be compared between years. Using data from the original synoptic measurements, potentiometric surfaces were generated for the entire study area in 1980 and 2014 and for northeastern Illinois in 1959, 1966, 1971, 1975, 1985, 1991, 1995, 2000, and 2007.

1.3 Acknowledgments

The sponsor of this report is the Illinois Department of Natural Resources Division of Water Resources Management. This funding facilitated the completion of the 2014 synoptic measurements, a comparison to previous synoptic measurements, and a revision of an existing groundwater flow model. Additional support was provided by ISWS General Revenue Funds.

The authors wish to acknowledge numerous individuals who generously granted access to their wells so heads could be measured. To obtain the non-pumping heads necessary for this study, wells had to be off for at least half an hour, and often up to a day in the deepest parts of the cone of depression. Many industries had to alter their production schedules to accommodate this study. The cooperation of these many individuals was invaluable and is greatly appreciated.

The authors also wish to acknowledge the many drilling companies throughout the state that provided us well data and airline lengths necessary to calculate heads. In particular, thank you to Kathy Vance at Layne-Christensen, Ernie Lija with Olson Well and Pump, Terry Nauman and Jim Sass at Peerless Service Company, Larry Lyons at Lyons Well Drilling, and Robert and Harold Albrecht at Albrecht Well Drilling, Inc.

This report was greatly improved by the input from many individuals. Steve Wilson and Adrian Visocky provided technical review of this report. Lisa Sheppard provided editorial review of the content of this report. Sara Olson provided assistance in developing and revising the figures. Conor Healy, ISWS IWIP coordinator, provided pumping data for Illinois and Cheryl Buchwald of the Wisconsin Water Science Center provided pumping data for Wisconsin. Greg Rogers helped design the database used to store data from this study. Wendy Kunde provided assistance in contacting water operators and engineers. Walt Kelly provided advice regarding the content of this report. Phil Graff assisted in archiving the data collected for this report.

2 Geology and hydrology

2.1 Lithology and hydrology of Illinois bedrock

The bedrock of Illinois consists of a sequence of layers that can be distinguished by lithology (rock type) and other characteristics. Arguably the most important hydrologic characteristic is permeability, which refers to the ability of a medium to transmit a liquid through its open spaces (interconnected pores, fractures, or bedding planes). Layers and lenses of material with high permeability are referred to as aquifers if economically useful withdrawals of groundwater can be obtained from them. The study area encompasses most of northern Illinois (Figure 2), where two general classes of bedrock aquifers are present: 1) sandstone and 2) weathered carbonate.

Sandstone is a sedimentary rock composed of sand-sized grains with significant primary intergranular porosity, at least in Illinois. In other words, the pore spaces between grains in the sandstone are comparatively large. Furthermore, the pore spaces are generally interconnected, resulting in high permeability. It is noted that sandstone can also develop secondary fractures which can further increase permeability, in particular where the sandstone is shallow. Since the major sandstone aquifers in northern Illinois are mostly Cambrian or Ordovician in age, they are collectively referred to as the ***Cambrian-Ordovician sandstone aquifers***.

Carbonate rocks (limestone and dolomite) can also be aquifers in Illinois, in particular where they are within 25 to 125 ft of the bedrock surface. In Illinois, carbonates are more susceptible to weathering than other lithologies (e.g., sandstone and shale); this weathering causes dissolution and removal of carbonates and consequent development of secondary porosity in the form of solution-enlarged fractures, cracks, and crevices. These aquifers are referred to as ***shallow carbonate bedrock aquifers***.

The sandstone and weathered carbonate aquifers contained within the sequence of bedrock layers in Illinois are often separated by low-permeability bedrock layers. These layers, referred to as aquitards, impede the horizontal and vertical flow of groundwater. In the presence of aquitards, the exchange of groundwater between aquifers, at least under natural conditions, is minimal. In Illinois, bedrock layers that function as aquitards are generally composed of: 1) fine-grained clastic sedimentary lithologies (shale and siltstone), 2) unweathered carbonates, and 3) crystalline, deeply-buried, igneous and metamorphic rocks.

In local areas, there are also unconsolidated glacial materials that overlie the bedrock. Fine-grained unconsolidated materials such as clay often have low permeability and serve as an aquitard. Coarse-grained unconsolidated materials such as sand and gravel are generally productive aquifers, with higher permeability than most bedrock aquifers. However, these aquifers are often more susceptible to contamination, in particular if the sand and gravel is at or near land surface.

2.2 Hydrostratigraphic units

Groundwater researchers commonly combine adjacent geologic strata with similar hydrologic characteristics into individual hydrostratigraphic units. Eleven hydrostratigraphic units are employed for this study (Table 1). Each unit is assigned a generalized lithology (carbonate, sandstone, shale, or crystalline) based on available geologic information and insight from calibrated groundwater flow models (Meyer et al., 2009; Meyer et al., 2012; Meyer et al., 2013; Roadcap et al., 2013). The generalized lithology of each hydrostratigraphic unit reflects its regional effect on groundwater flow, as discussed in Section 2.1. However, other lithologies are frequently present and may affect groundwater flow on a local scale.

The hydrostratigraphic unit present at the bedrock surface differs with location in the study area and is a function of unit thicknesses, structural geology (the deformational history of the region and the resulting three-dimensional orientation of bedrock units), and erosion of the bedrock surface. In Illinois, the hydrostratigraphic units present at the bedrock surface include the Pennsylvanian-Mississippian, Silurian-Devonian, Maquoketa, Galena-Platteville, St. Peter, Prairie du Chien-Eminence, and Potosi-Franconia Units (Figure 3). In Wisconsin, older hydrostratigraphic units–including the Ironton-Galesville, Eau Claire, and Mt. Simon Units–can be present at the bedrock surface, although these rocks are not differentiated in available geologic mapping and are grouped with the Potosi-Franconia Unit as undifferentiated Cambrian in Figure 3.

The hydrostratigraphic units in northern Illinois dip gently northeastward and southwestward from the axis of a broad, northwest-to-southeast-trending structural arch known as the Kankakee Arch, which separates the Illinois Basin, to the south, from the Michigan Basin, to the northeast. The west-to-east cross-section shown in Figure 4 shows the axis of this feature to be located between DeKalb and the Rock River. Because of the location of the north-to-south cross-section (Figure 5) relative to the trend of the Kankakee Arch and the deepest points in the Illinois and Michigan Basins, that cross section predominantly shows only the southward dip of the hydrostratigraphic units into the Illinois Basin. Both Figure 4 and Figure 5 show that the structural geology of the region is complicated by displacement along the Sandwich Fault Zone.

The hydrostratigraphic units have been modified from previous ISWS reports (Meyer et al., 2009; Meyer et al., 2013; Roadcap et al., 2013). Previously, the Ancell Unit has included the entirety of the Ancell Group, which consists of sandstones (the St. Peter Sandstone and the Glenwood Formation) and carbonates (the Joachim Dolomite and Dutchtown Limestone). These carbonates form the upper portion of the Ancell Group in the southern half of the state (Willman et al., 1975). In our study area, the Dutchtown Limestone is not present, and the Joachim Dolomite is only present in southeastern Iroquois County. For purposes of this and future studies, the Joachim Dolomite and Dutchtown Limestone have been moved into the overlying Galena-Platteville Unit due to its generalized carbonate lithology (Table 1). Consequently, the Glenwood Formation and St. Peter Sandstone have been combined into the St. Peter Unit, which replaces the Ancell Unit.

Table 1: Geologic composition of the hydrostratigraphic units present in the study area, along with an associated generalized lithology. The St. Peter Unit replaces the Ancell Unit used in previous ISWS reports (Meyer et al., 2009; Roadcap et al., 2013).

AGE (SYSTEM OR SERIES)	**LITHOSTRATIGRAPHY**		**HYDROSTRATIGRAPHIC BEDROCK UNIT**	**GENERALIZED LITHOLOGY**
CRETACEOUS	*Lithostratigraphic units not detailed*		Pennsylvanian-Mississippian	Shale
PENNSYLVANIAN				
MISSISSIPPIAN				
UPPER DEVONIAN				
MIDDLE DEVONIAN	*Lithostratigraphic units not detailed*		Silurian-Devonian	Carbonate
LOWER DEVONIAN				
SILURIAN				
ORDOVICIAN	Maquoketa Group		Maquoketa	Shale
	Galena Group		Galena-Platteville	Carbonate
	Platteville Group			
	Ancell Group	Glenwood Formation	St. Peter	Sandstone
		St. Peter Sandstone		
	Prairie du Chien Group		Prairie du Chien-Eminence	Carbonate
CAMBRIAN	Jordan Formation (only northwestern Illinois), Eminence Formation			
	Potosi Dolomite		Potosi-Franconia	Carbonate
	Franconia Formation			
	Ironton Formation		Ironton-Galesville	Sandstone
	Galesville Formation			
	Eau Claire Formation	Proviso Member	Eau Claire	Shale and Carbonate
		Lombard Member		
		Elmhurst Member	Mt. Simon	Sandstone
	Mt. Simon Formation			
PRECAMBRIAN	*Lithostratigraphic units not detailed*		Precambrian	Crystalline

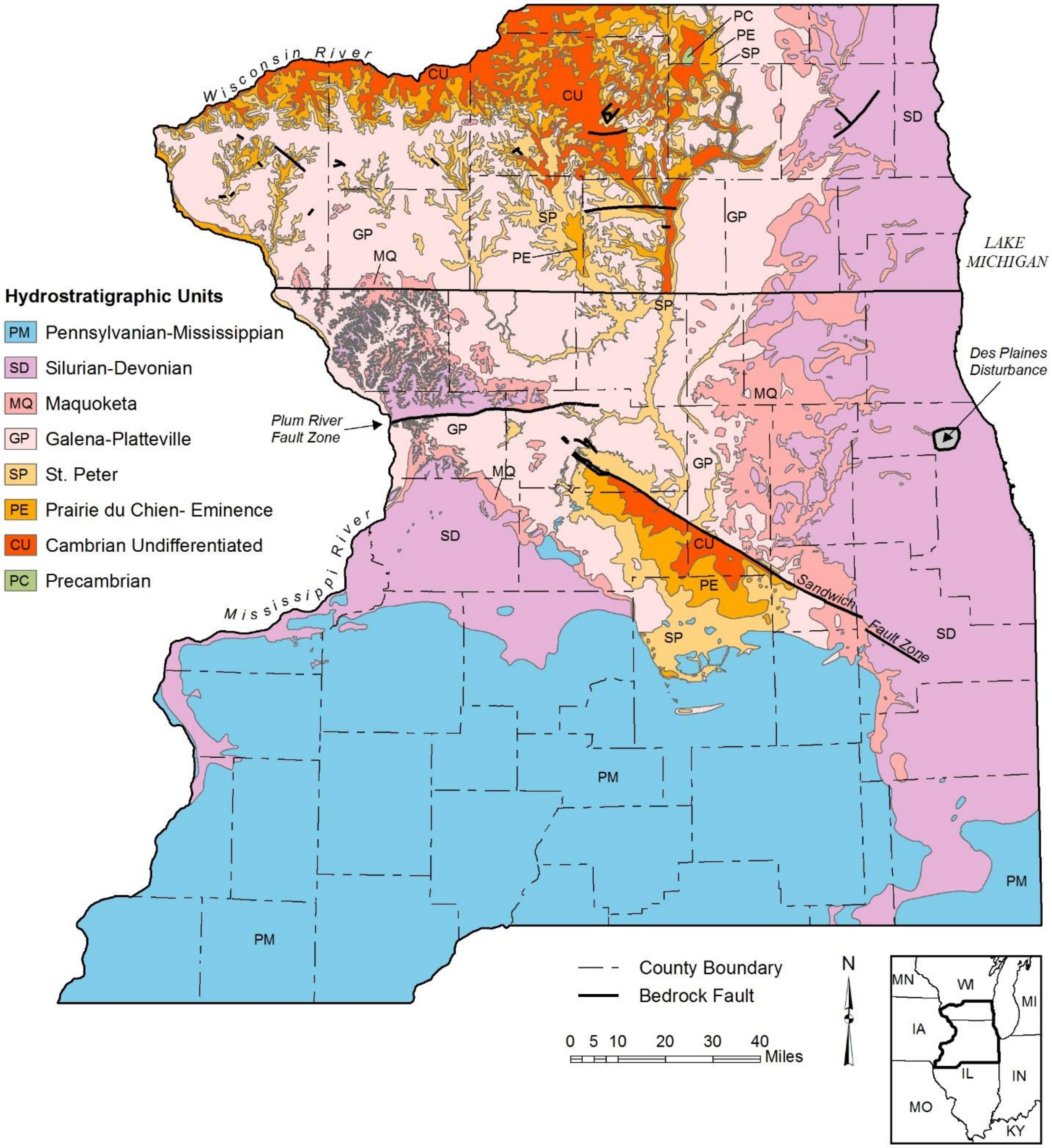

Figure 3: Hydrostratigraphic units present at the bedrock surface (Mudrey et al., 1982; Kolata et al., 2005). Note that all units below the Prairie du Chien-Eminence Unit are grouped into a Cambrian Undifferentiated category.

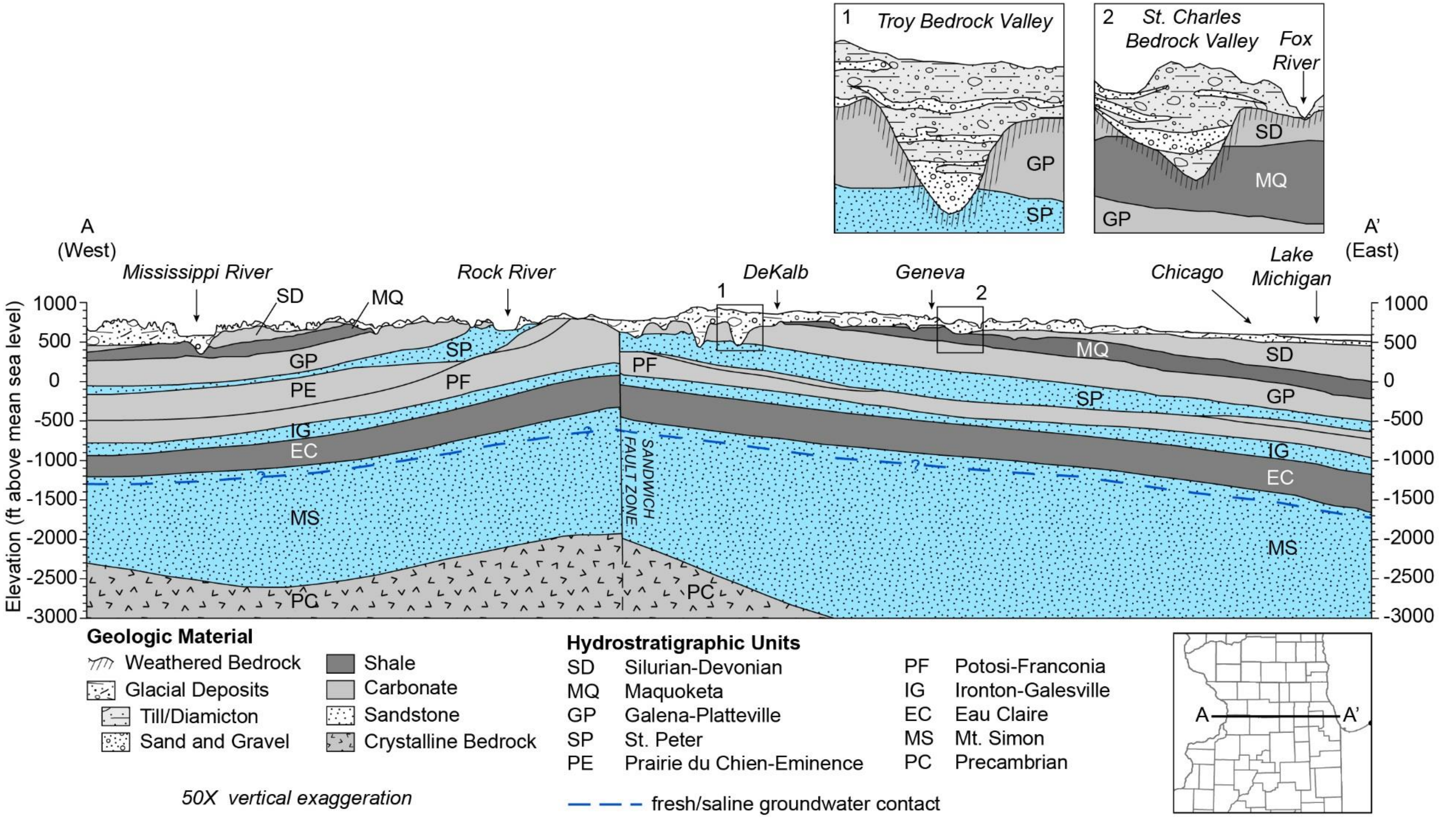

Figure 4: West-to-east cross section across northern Illinois from the Mississippi River to Lake Michigan showing the hydrostratigraphic units of the study area. Note the presence of the Sandwich Fault Zone, which offsets the hydrostratigraphic units. The Troy Bedrock Valley and the St. Charles Bedrock Valley are shown, illustrating the hydrologic connection between glacial sand and gravel aquifers and deeper bedrock aquifers. Troy Bedrock Valley inset modified from Vaiden et al. (2004); St. Charles Bedrock Valley inset modified from Dey et al. (2007).

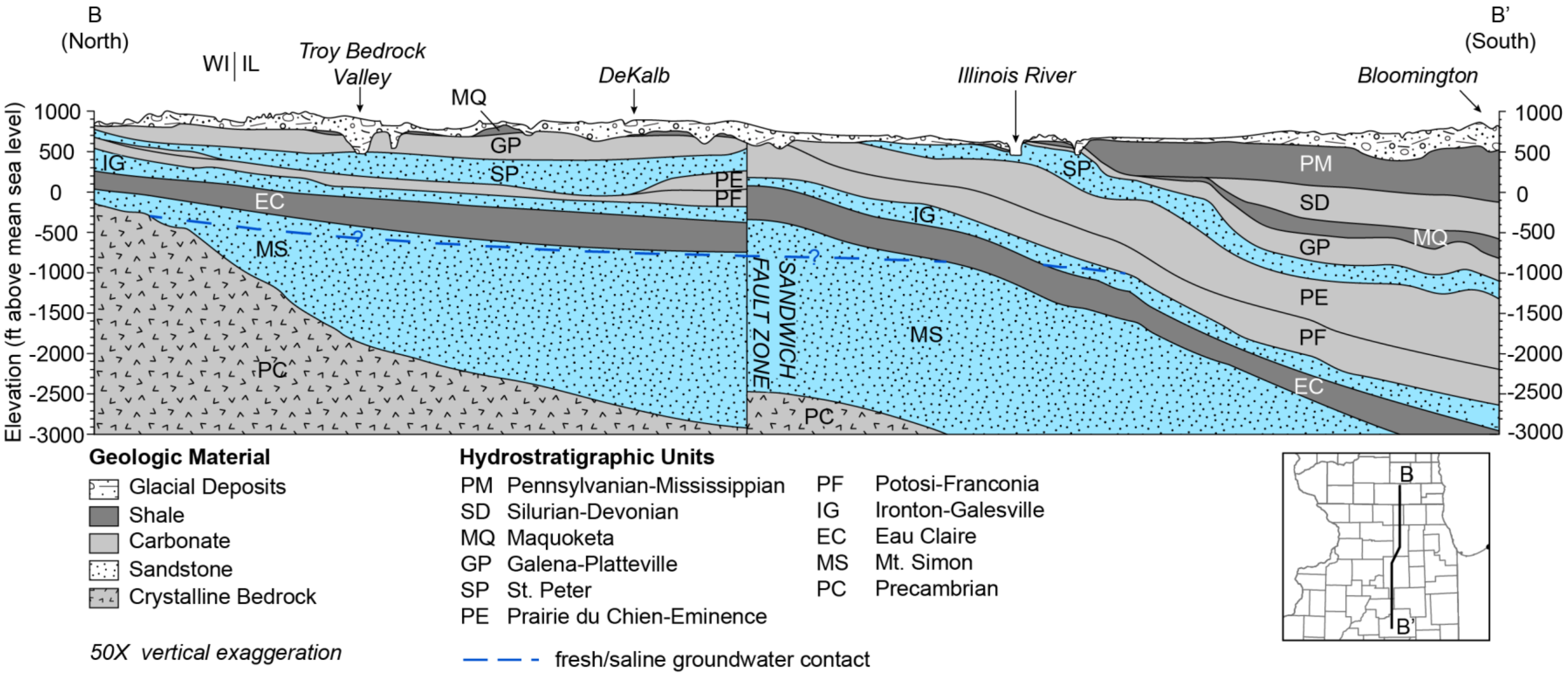

Figure 5: North-to-south cross section from southern Wisconsin to central Illinois showing the hydrostratigraphic units of the study area. Note the presence of the Sandwich Fault Zone, which offsets the hydrostratigraphic units.

2.3 Cambrian-Ordovician sandstone aquifers in Illinois

For purposes of this report, the hydrostratigraphic nomenclature is sufficient in describing aquitards, shallow carbonate bedrock aquifers, and major sandstone aquifers. For minor sandstone aquifers, it is often necessary to refer to the name of individual sandstone layers within a hydrostratigraphic unit. For example, the Prairie du Chien-Eminence Unit has a generalized lithology of carbonate, but sandstone strata within this unit are often used as (local) aquifers. The sandstone aquifers found within each Cambrian-Ordovician hydrostratigraphic unit are detailed in Table 2.

2.3.1 Sandstone aquifers in Illinois

2.3.1.1 St. Peter Sandstone

In our study area, the St. Peter Sandstone generally comprises at least 75 percent of the total thickness of the St. Peter Unit (Figure 4 and Figure 5). This sandstone, which consists mostly of well-sorted and well-rounded quartz sand, is the most permeable portion of the St. Peter Unit (Willman et al., 1975). The St. Peter Sandstone is at the bedrock surface in portions of north-central Illinois (Figure 3). In deeply incised bedrock valleys, such as the Troy Bedrock Valley, the St. Peter Sandstone often underlies coarse grained glacial aquifers (Figure 4, Inset 1).

The Glenwood Formation, which overlies the St. Peter Sandstone in the northern portion of Illinois, consists of poorly sorted sandstone, dolomite, and shale, generally not exceeding 25 to50 ft thick. The Glenwood Formation is not a major source of water for municipalities or industries. For purposes of this report, the Glenwood Formation is considered insignificant, and the terms St. Peter Sandstone and St. Peter Unit will be used interchangeably.

2.3.1.2 Ironton-Galesville Sandstone

The Ironton and Galesville Sandstones are collectively referred to as the Ironton-Galesville Sandstone. This sandstone comprises the entirety of the Ironton-Galesville Unit (Table 1) and consists of well-rounded quartz sand grains similar to the St. Peter Sandstone. In our study area, the Ironton-Galesville Sandstone is overlain and separated from the St. Peter Sandstone by two predominantly (unweathered) carbonate hydrostratigraphic units, the Prairie du Chien-Eminence and the Potosi-Franconia, which together function as an aquitard.

2.3.1.3 Mt. Simon, Elmhurst, Jordan, and New Richmond Sandstones

Other sandstone aquifers are present in northern Illinois (Table 2), but they are used sparingly for purposes of water supply. The Elmhurst and Mt. Simon Sandstones, which together comprise the Mt. Simon Unit, provide groundwater of poor quality, primarily due to high salinity, in all but the far northern portion of Illinois. The Jordan and New Richmond Sandstones, which are included in the Prairie du Chien-Eminence Unit, are not widely distributed and function as aquifers in limited areas of the state (Jo Daviess and LaSalle Counties, respectively). The Mt. Simon, Elmhurst, and Jordan Sandstones are widely used as aquifers in Wisconsin, where they are closer to (or at) land surface and have low salinity.

2.3.2 Geologic controls on leakage to sandstone

Drawdown due to groundwater withdrawals from the Cambrian-Ordovician sandstone aquifers is contingent on the rate of water vertically infiltrating to the sandstone aquifers, henceforth referred to as leakage. Where carbonate rocks overlie the sandstone aquifers (Figure 6), leakage will be somewhat impeded, particularly if the carbonates have not developed secondary porosity with vertical orientation. Where the sandstones are overlain by shale or a combination of shale and unweathered carbonates (Figure 6), resistance to vertical flow will be high and very little leakage to the sandstones is expected. As a result, if all other factors influencing leakage are equal, drawdown is least where the sandstone is at the bedrock surface and greatest when it is overlain by an impermeable shale (Figure 6).

The magnitude of leakage to sandstone will also be impacted by glacial drift overlying the bedrock. Comparatively thin glacial drift, or glacial drift composed of coarse-grained materials (e.g., sand and gravel), permit greater leakage. In Wisconsin and areas along the Illinois and Rock Rivers, the sandstone is often at the bedrock surface where no glacial drift is present. In this case, water that infiltrates to the saturated subsurface is correctly referred to as *recharge*.

2.3.2.1 Leakage to the St. Peter and Ironton-Galesville Sandstones

In much of the study area, shale overlies the St. Peter (compare Figure 3 with Figure 6), reducing leakage to the sandstone. In the northeastern and northwestern portion of the study area, this shale is generally included in the Maquoketa Unit (Figure 4). In the southern portion of the study area, two shale units overlie the St. Peter Sandstone: the Maquoketa and Pennsylvanian-Mississippian Units (Figure 5). This shale is present even along the axes of some deeply incised bedrock valleys, such as the St. Charles Bedrock Valley (Figure 4, Inset 2).

In contrast to the St. Peter, the Ironton-Galesville Sandstone is not exposed at the bedrock surface in Illinois. It is exposed at the bedrock surface within the undifferentiated Cambrian in Wisconsin (Figure 3), where leakage rates (or recharge if glacial deposits are not present) are comparatively high.

Table 2: Sandstone aquifers found within each Cambrian-Ordovician hydrostratigraphic unit. The major sandstone aquifers that are the focus of this study are highlighted in bold text.

HYDROSTRATIGRAPHIC UNIT	**SANDSTONE AQUIFER WITHIN EACH HYDROSTRATIGRAPHIC UNIT**	**SANDSTONE USED FOR MAJOR WATER SUPPLY IN NORTHERN ILLINOIS?**
Galena-Platteville	Base of the Platteville Group	No, sandstone contains unweathered dolomite
St. Peter	Glenwood Formation	No, sandstone contains unweathered dolomite and shale
	St. Peter Sandstone	**Yes**
Prairie du Chien-Eminence	New Richmond Sandstone	Yes, but only in LaSalle County
	Gunter Sandstone	No
	Jordan Sandstone	Yes, but only where present in northwestern Illinois
Potosi-Franconia	Local, thin sandstones	No
Ironton-Galesville	**Ironton Sandstone**	**Yes**
	Galesville Sandstone	**Yes**
Eau Claire	Grades into sandstone in Wisconsin	No, but used for gas storage
Mt. Simon	Elmhurst Sandstone Member	Yes, but only near Wisconsin border
	Mt. Simon Sandstone	Yes, but only near Wisconsin border
Precambrian	No sandstone in study area	

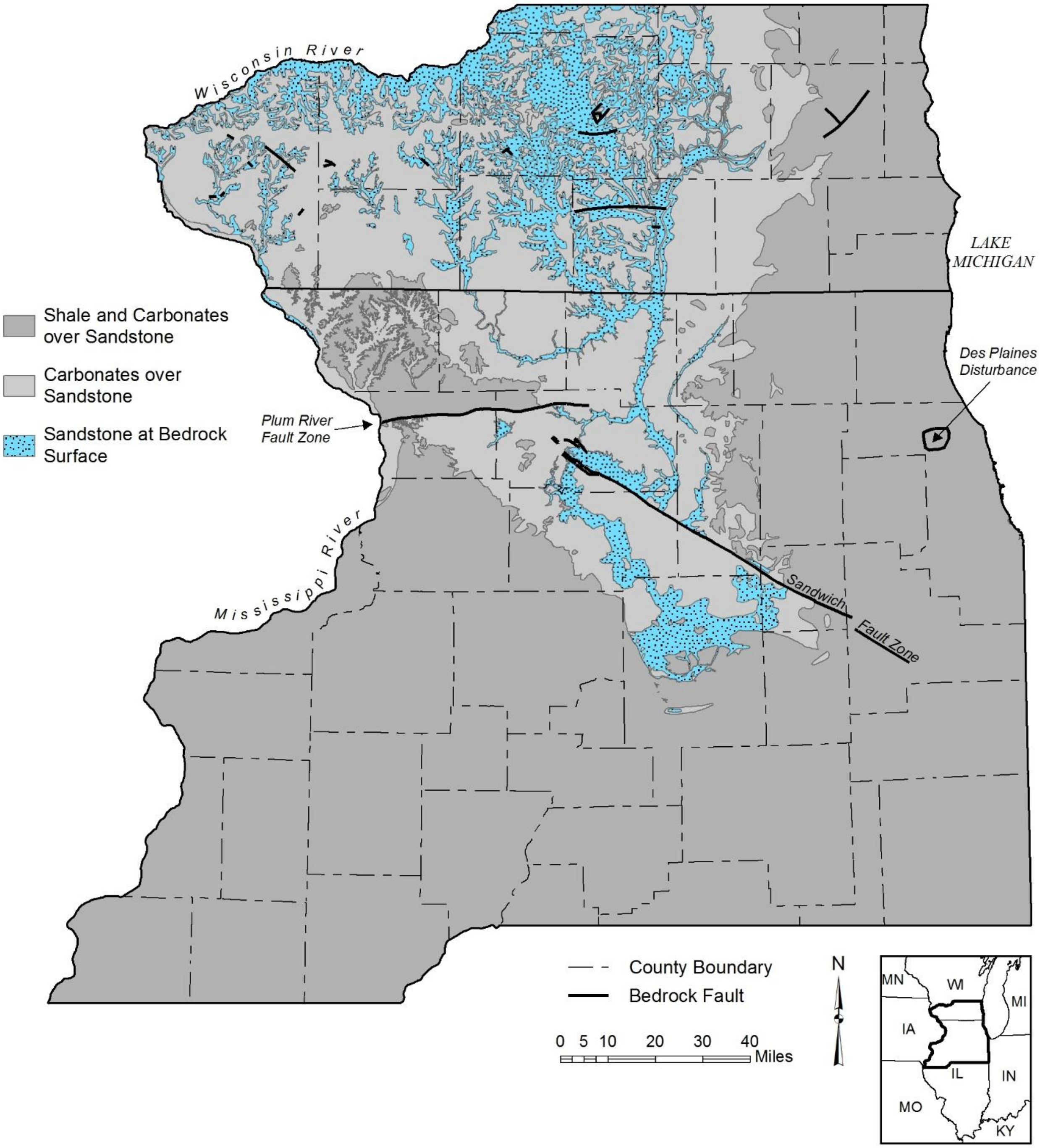

Figure 6: Lithology of bedrock materials overlying the Cambrian-Ordovician sandstone aquifers.

2.4 Fault zones

The Sandwich Fault Zone is an important geologic feature that dictates flow in northeastern and northcentral Illinois. The individual hydrostratigraphic units in the vicinity of this fault zone are vertically displaced (Figure 4 and Figure 5), interfering with lateral flow. The net effect of the Sandwich Fault Zone is hypothesized to be a decrease in horizontal permeability due to the potential development of deformation bands, increased cementation, and offset of high permeability zones (Kolata et al., 1978; Antonellini and Aydin, 1994; Gutmanis et al., 1998; Jourde et al., 2002). Heads in the Cambrian-Ordovician sandstone aquifers have been observed and simulated to differ on opposing sides of the Sandwich Fault Zone, often by more than 100 ft (Roadcap et al., 2013). Two other areas in northern Illinois contain fault structures that may impact regional groundwater flow in a similar manner, the Plum River Fault Zone and the Des Plaines Disturbance (Figure 3 and Figure 6).

2.5 Anthropogenic impacts on hydrogeology

2.5.1 Impacts of withdrawals from confined aquifers

The Cambrian-Ordovician sandstone aquifers in most of Illinois are overlain by carbonate or shale aquitards (Figure 6). Where such aquifers are completely saturated, they are referred to as *confined*. Under predevelopment conditions–i.e., before 1863–all sandstone aquifers overlain by an aquitard in Illinois were confined (Anderson, 1919). Groundwater within confined aquifers is under pressure, and this pressure is relieved when a well is drilled into and left open to the aquifer. Water in the well rises above the top of the aquifer to a level that represents the pressure; this water level is referred to as *head*. Many of the first wells drilled into the Cambrian-Ordovician aquifers in Illinois had heads above land surface, resulting in flowing artesian wells (Anderson, 1919).

As water is withdrawn from a confined aquifer, pressure (and consequently heads) in the aquifer is reduced. Eventually, if withdrawals from a confined sandstone aquifer are great enough, then the head may fall below the top of the aquifer, causing the aquifer to become unconfined. An unconfined aquifer has an upper boundary that is defined by the head in the aquifer and not an aquitard (Freeze and Cherry, 1979). In an unconfined aquifer, additional groundwater withdrawals beyond ambient groundwater flow are satisfied by drainage of water from the pore spaces in the aquifer. Thus, the transition of an aquifer from confined to unconfined conditions is referred to as *desaturation*. It should be noted that unconfined sandstone aquifers can also occur naturally where overlying aquitards are not present. Further discussion on the impacts of desaturation can be found in Section 6.1.

2.5.2 Cross-connected wells

Prior to the drilling of wells into the Cambrian-Ordovician sandstone aquifers, the aquitards separating the aquifers formed continuous, widespread barriers to flow. But since the mid-nineteenth century, numerous wells have been constructed that are open to multiple aquifers, providing discrete pathways for exchange of water between aquifers. These wells are referred to as *cross-connected wells*. The groundwater circulation between aquifers that can result from cross-connected wells often plays a major influence on available water supply. Specific impacts of cross-connected wells will be discussed further in Section 5.5.2.

3 Demands on the Cambrian-Ordovician sandstone aquifers

3.1 Historical demands from Cambrian-Ordovician sandstone aquifers

Multiple groundwater and surface water sources exist in Illinois that are preferred to or can provide an alternative to the Cambrian-Ordovician sandstone aquifers. Many communities and industries have a history going on or off the sandstones as their water quantity and quality requirements have changed. Thick sand and gravel deposits, where present, are generally the most preferred aquifer for a large-capacity well because they can be highly productive and less expensive to drill and operate. In northeastern Illinois, the shallow Silurian-Devonian carbonates are generally the second choice if a well can be located in an area with high secondary permeability. The deep sandstones are generally the third choice and are mostly found in areas where the two shallower units do not exist or are relatively impermeable. Total groundwater use for northeastern Illinois was 250 Mgd in 2005 with approximately 50 percent from the sandstone, 30 percent from the carbonates, and 20 percent from the sand and gravels (Meyer et al., 2012). Surface water is the primary source of water for very high-demand users, such as large cities or thermoelectric plants, or where groundwater sources are insufficient or of poor water quality. Many communities use water from multiple sources to meet demands (Figure 7) or to dilute unwanted chemical constituents in their primary source, such as high sulfate in the carbonate, radium in the sandstone, or nitrate in the surface water. While Illinois can be considered a water-rich state as a whole, local areas within the study area may not have the available water resources for large demands or may be at risk to droughts, overuse, or contamination.

The Cambrian-Ordovician sandstone aquifers are utilized throughout most of the upper third of Illinois. Demands for public water supplies, self-supplied industrial and commercial facilities, and some irrigation across the entire state have been collected and documented by the IWIP since 1980. The total demands from the Cambrian-Ordovician sandstone aquifers in Illinois are shown in Figure 8. Total demands decreased from 1980 to 1993, fluctuated between 1993 and 1998, increased from 1998 to 2007, slightly decreased from 2007 to 2011, and increased slightly in 2012.

3.1.1 Northeastern Illinois WSPR demands

Due in large part to the findings of Suter et al. (1959), groundwater withdrawals from the sandstone aquifers of northeastern Illinois have been extensively collected since 1963, predating the IWIP program. From 1963 to 1979, demands increased in the Northeastern Illinois WSPR (Figure 8). The expanding communities in the western portion of the greater Chicago metropolitan area heavily utilized the sandstone aquifers throughout this period, with only a few switching to alternative sources of water (Figure 9). While Figure 9 shows the change in the source of water for communities, most industries have followed a similar pattern.

Total demands from the Cambrian-Ordovician sandstone aquifers in Illinois mimic the demand curve for the Northeastern Illinois WSPR. In the 1980s, most communities in Cook County that had previously been using groundwater (either shallow or deep) switched to Lake Michigan water (Figure 9), which greatly reduced demand on the Cambrian-Ordovician sandstone aquifers. Elgin, located in Kane County, also greatly reduced usage of the sandstone aquifers, switching almost exclusively to Fox River water in the 1980s.

At the start of the 1990s, almost all communities in DuPage County relied on groundwater (either shallow or deep); by 1993, all but a few communities in western DuPage County had switched to Lake Michigan water (Figure 9). Also, in the early 1990s, Aurora, located in Kane County, reduced their usage of the Cambrian-Ordovician sandstone aquifers by partially meeting their demand with Fox River water.

From 1993 to 2007, groundwater demands began to increase in the Northeastern Illinois WSPR (Figure 8). This was primarily driven by the growth of the westernmost communities of the greater Chicago metropolitan area. While a few communities switched to Lake Michigan water in Will County during the 2000s, many of these communities had previously used shallow carbonate bedrock aquifers; hence this switch did not greatly impact demand from the Cambrian-Ordovician sandstone aquifers. Since 2007, demands have steadily (albeit slightly) decreased, likely due to the economic recession.

3.1.2 Demands for other WSPRs

The Northeastern Illinois WSPR has historically had both the highest demand and the most fluctuation in demand for water from the Cambrian-Ordovician sandstone aquifers of Illinois. The second greatest demands come from the Northwestern Illinois WSPR, as high as 67 Mgd in 1992 (Figure 8). Demands in this region have slowly, but steadily, been decreasing. The 48 Mgd withdrawn from the sandstone aquifers in 2012 was the lowest since the advent of IWIP in 1980, although demands increased to 53 MGD in 2012 (the most recent record).

The Middle Illinois Basin WSPR has the third highest demands, largely driven by communities and industries that have grown along the Illinois River. These demands have ranged from 11 to 16 Mgd (Figure 8) since 1980, with no clear increasing or decreasing trend. Demands in the Spoon and La Moine Basins WSPR have steadily decreased from 5 Mgd in 1980 to 3 Mgd in 2012. Demands from the other two regions with wells in the Cambrian-Ordovician sandstone aquifers, East-Central Illinois and Kankakee, have never exceeded 0.3 Mgd.

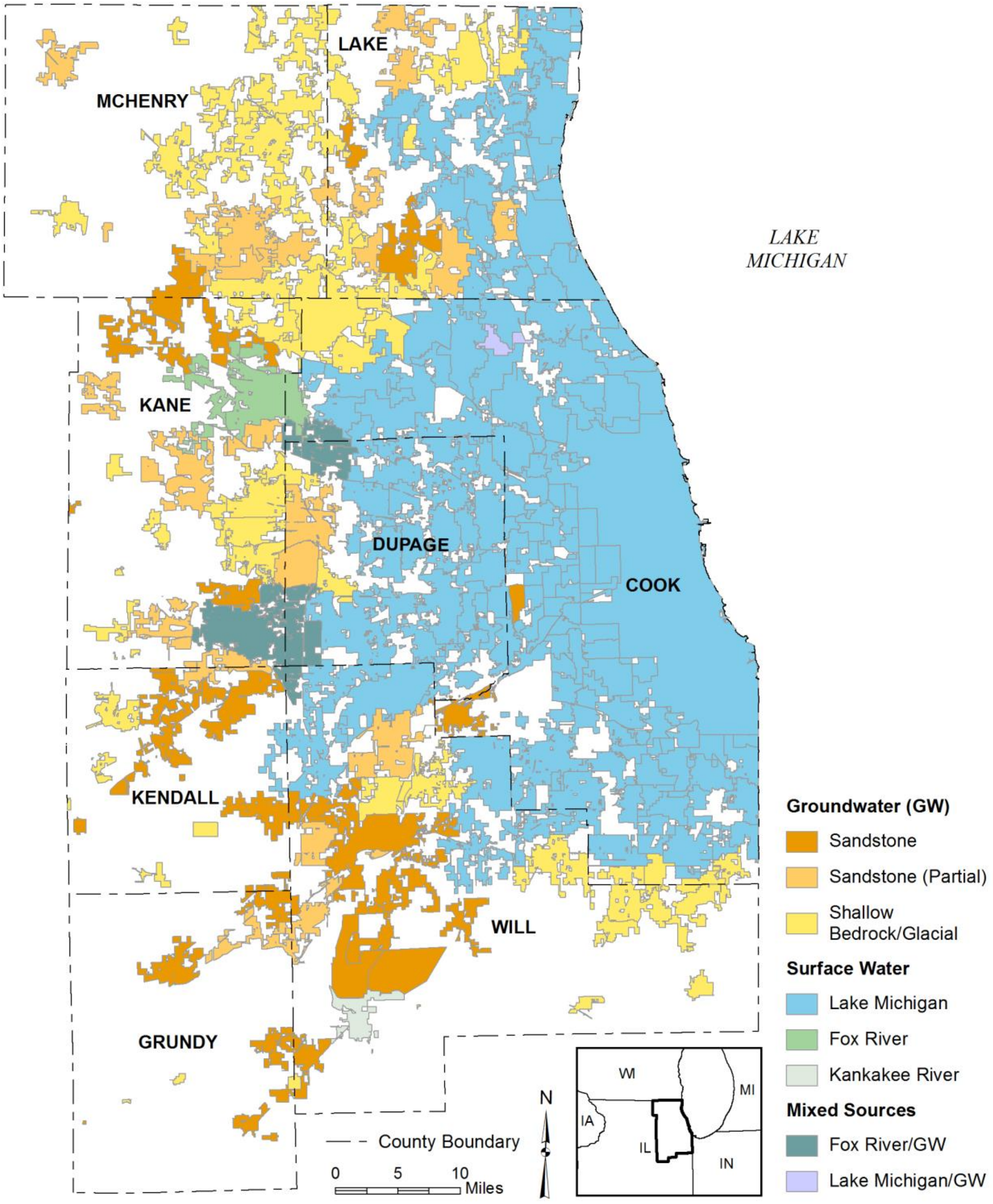

Figure 7: Source of municipal water used by each community in northeastern Illinois as of 2014.

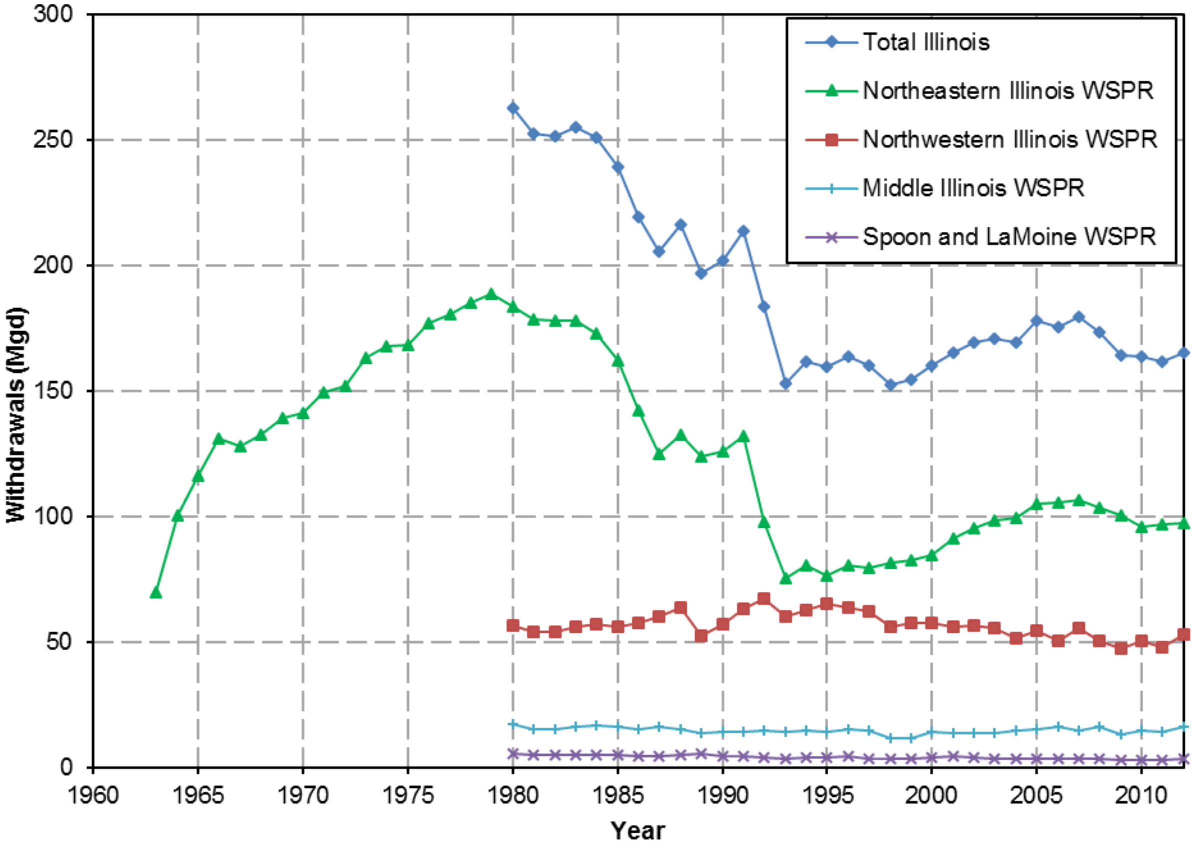

Figure 8: Demand for groundwater from the Cambrian-Ordovician sandstone aquifers in four water supply planning regions (WSPRs).

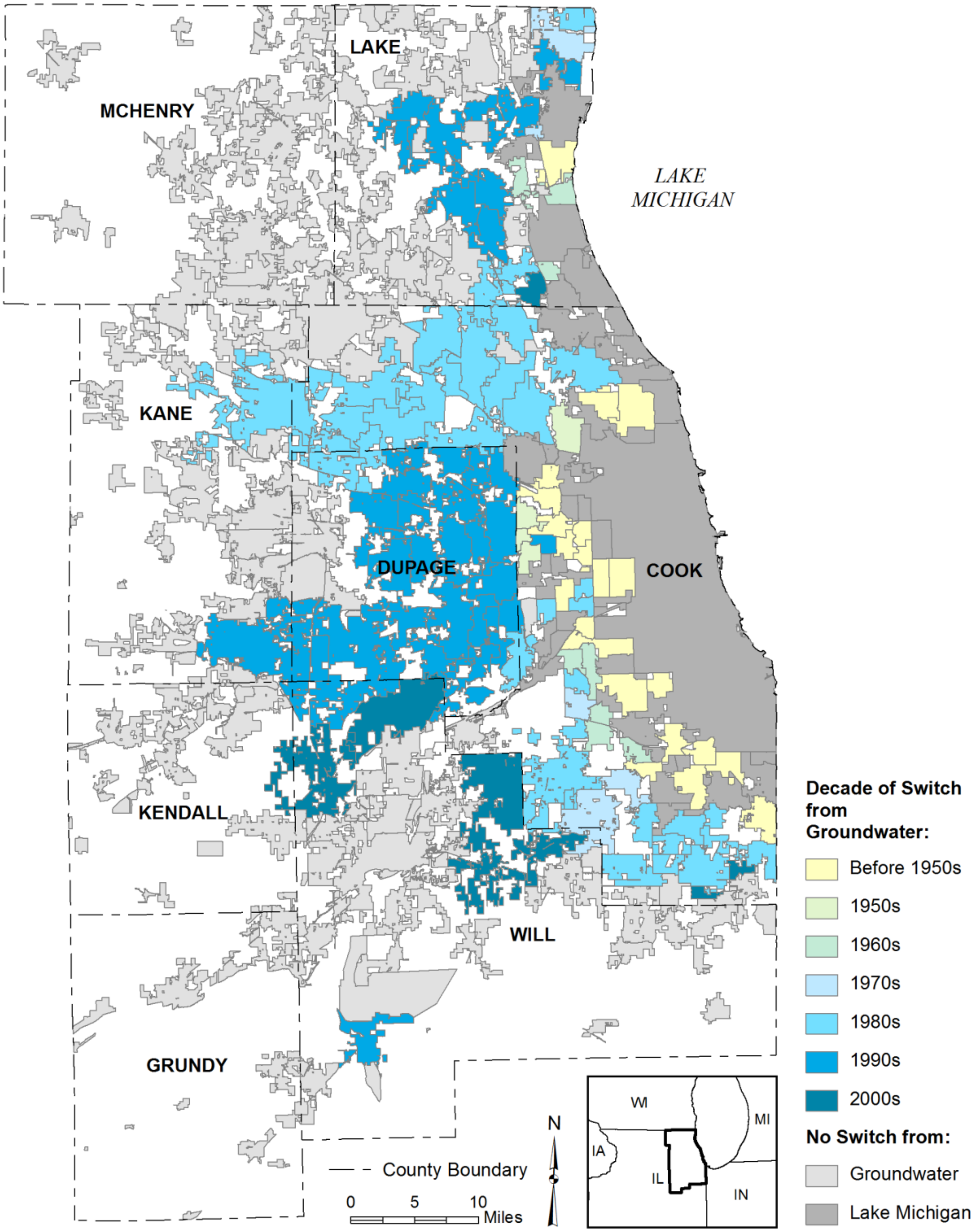

Figure 9: Decade of switch for northeastern Illinois communities that ceased using groundwater for an alternative water supply.

3.2 2012 withdrawals from the Cambrian-Ordovician sandstone aquifers

In 2012, Illinois withdrew 165 Mgd from the Cambrian-Ordovician sandstone aquifers. The majority of these demands are satisfied by communities and industries along the Des Plaines, Fox, Rock, and Illinois Rivers (Figure 10). The highest demands occurred along the Des Plaines River, particularly in Will, Kendall, and Grundy Counties. Alternative water sources along the Des Plaines River have historically been limited. Shallow groundwater (i.e., groundwater from weathered carbonate or sand and gravel aquifers) is often not available or has poor quality. Furthermore, the Des Plaines River is largely composed of effluent; hence the water quality is poor. Finally, the Lake Michigan distribution network has only recently extended into Will County and, as a result, was not a viable option before the year 2000.

Demands along the Fox River are considerably less than along the Des Plaines (Figure 10). This is partially because communities and industries along the Fox River have more access to shallow groundwater in the form of sand and gravel or shallow carbonate bedrock aquifers. Furthermore, water quality in the Fox River is relatively good, so several communities utilize it as a source of water (Figure 7).

A large portion of withdrawals in the Northwestern Illinois WSPR occur in the vicinity of Rockford, which falls along the Rock River. The sandstone aquifers are prevalently used in this area due to contamination of the shallow sand and gravel aquifers with volatile organic compounds (Wehrmann et al., 1988).

Finally, withdrawals from sandstone aquifers are prevalent along the Illinois River, in particular LaSalle County (Figure 10). The hydrostratigraphic units containing sandstone in this region are at or near the bedrock surface (Figure 5). Unlike the rest of the state, these demands are partially met by groundwater from the New Richmond Sandstone, as well as the St. Peter and Ironton-Galesville Sandstones.

In addition to the heavy withdrawals along the four aforementioned river corridors, there are also smaller withdrawals distributed throughout the northern third of Illinois (Figure 10). Also, there are withdrawals from the sandstone throughout southern Wisconsin, with the heaviest occurring in Dane County at 53 Mgd (Figure 10). Model simulations indicate that drawdown due to these withdrawals is less than 5 ft outside of Dane County (Bradbury et al., 2013), primarily due to the widespread areas where sandstone is at or near the bedrock surface throughout the county (Figure 6). It is noted that heads in Dane County were not measured in the 2014 synoptic measurement detailed in this report (Figure 2). Although not pictured, withdrawals from the Cambrian-Ordovician sandstone aquifers also occur in Iowa, in particular near Des Moines (Gannon et al., 2009). Withdrawals in Indiana from the sandstone are very small.

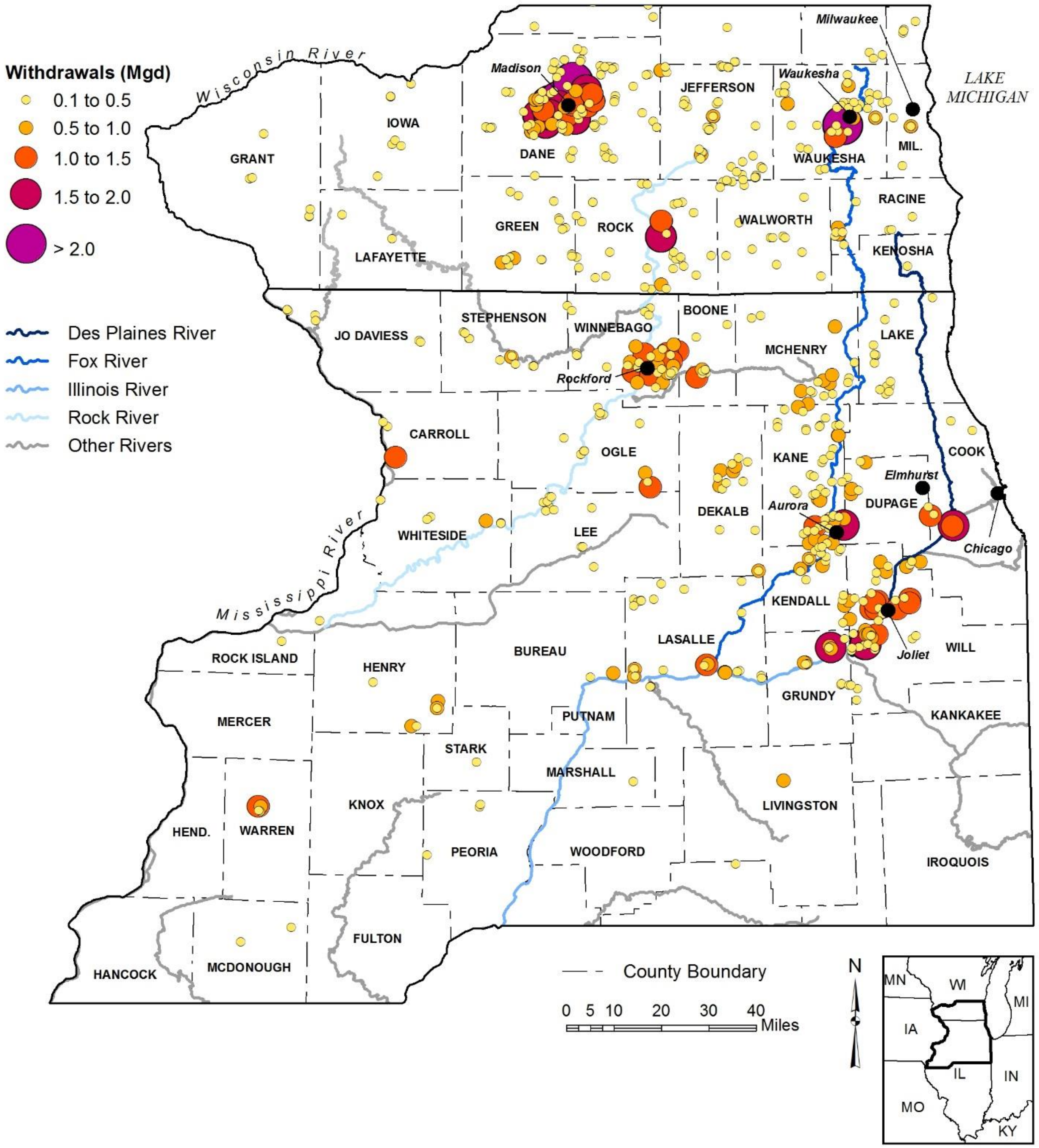

Figure 10: Groundwater withdrawals from the Cambrian-Ordovician sandstone aquifers in 2012 in northern Illinois and southern Wisconsin. Illinois withdrawals are from IWIP and Wisconsin withdrawals were provided by the Wisconsin Water Science Center.

4 Measurement and contouring methodology

The synoptic measurement of Cambrian-Ordovician sandstone wells required eight scientists at the ISWS, three scientists at the WGNHS, and hundreds of water operators for public water systems, self-supplied commercial and industrial facilities, and golf courses. A total of 675 head measurements were obtained by ISWS and WGNHS staff between July 2014 and February 2015 (Figure 11). Of these, 643 were used for contouring and potentiometric surface maps. The methodology of the study can be divided into three phases: 1) identifying Cambrian-Ordovician sandstone wells to visit, 2) obtaining non-pumping heads from the wells, and 3) generating a potentiometric surface. This report details the methodology that was incorporated by the ISWS; the WGNHS employed a similar methodology.

4.1 Identifying wells to visit

The ISWS had nine dedicated monitoring wells in the Cambrian-Ordovician sandstone aquifers in 2014. As a result, the majority of the measurements from this study had to be obtained from other sources. Databases developed and maintained by ISWS staff were used to identify over 1,000 prospective wells to visit and measure, which exceeded the capability (and need) of this study. These were wells identified as being open to at least one of the Cambrian-Ordovician sandstone aquifers based on well logs and casing information. To reduce the scope, ISWS staff tried to revisit as many wells as possible from the most recent synoptic measurement (2007 for the Northeastern Illinois WSP and 1980 for the remainder of the state). This study also placed particular emphasis on wells that had been constructed after 2007, with the goal of capturing any new stresses on the sandstone aquifers that had not previously been observed. To fill in data gaps, databases maintained and updated by IWIP were also used to identify additional wells that are actively pumping, are for emergency use, or were recently abandoned. Where available in Wisconsin, dedicated monitoring wells jointly maintained by the USGS and WGNHS were also used in this study (Figure 11). In Illinois, the majority of the Cambrian-Ordovician sandstone wells visited in this study were open to at least the St. Peter or Ironton-Galesville Sandstones, while a few were also open to the New Richmond, Jordan, Elmhurst, or Mt. Simon Sandstones.

4.2 Obtaining non-pumping heads

After identifying the Cambrian-Ordovician wells to be used in this study, the ISWS contacted facilities with a request to obtain non-pumping head measurements. A non-pumping head is obtained after a well has been off for a long enough time such that the head is no longer (appreciably) increasing. The length of time that a well must be off to obtain a non-pumping head is contingent on whether the aquifer(s) that the well is open to is confined or unconfined. For most facilities, the sandstone aquifers from which water was withdrawn were confined and the head at the well recovered very quickly (Figure 12a). Facilities withdrawing from confined aquifers were asked to keep their wells off for a minimum of 15 minutes, and preferably 30 minutes, before obtaining the non-pumping head. The head recovery once a well has shut off is much slower in an unconfined aquifer (Figure 12b). Facilities potentially withdrawing from unconfined aquifers were asked to keep the wells off for at least 4 hours, and preferably 24 hours, to achieve a reasonably accurate non-pumping head.

Non-pumping head measurements were obtained for 675 wells, 576 by the ISWS and 99 by the WGNHS. Due to the large geographic size of the study area, it was not feasible to obtain all measurements over a time frame of one or two months, as would generally be preferred in a true synoptic measurement. To minimize seasonal variability within a region, all of the measurements in northeastern Illinois took place from July to November 2014, while all of the measurements in the rest of the state took place from October 2014 to February 2015. Eighty-nine of the measurements obtained by the WGNHS were taken between October 2014 and December 2014.

A variety of approaches were used in this study to obtain non-pumping heads measurements, summarized in Table 3. The most commonly used approach was the airline methodology, which is a very practical approach for deep wells which are outfitted with a pump (Driscoll, 1986). The airline is a small-diameter (usually 1/4" or 3/8") tube inside the well casing that extends from the top of the well down to the pump. To obtain a non-pumping head, the airline must be purged of all standing water within it by injecting compressed air (typically 200 to 300 psi) down the airline. After the airline is purged of water, the compressed air is removed. The airline fills with groundwater, compressing the air space above the water. This increased pressure is read on a gauge that is attached to the airline until it stabilizes, which indicates that water has completed rising. This process must be repeated multiple times for very long airlines (>800 ft) to ensure that all water has been purged; the non-pumping head is obtained once the pressure gauge gives the same reading after multiple applications of compressed air. The pressure, measured in pound per square inch (psi), can then be converted to a height of water in feet above the top of the pump (1 psi = 2.31 ft). A depth to water in the well is then obtained by subtracting the gauge reading from the length of airline. Head above mean sea level (AMSL) was calculated by subtracting the depth to water from the land surface elevation.

As an alternative to airline measurements, electric droplines and steel tapes can be dropped directly down a well to measure depth to water. While both droplines and steel tape are more accurate than the airline method, they are not always practical, in particular for deep sandstone production wells. There are numerous reasons that these methods were used sparingly: 1) casing tops of wells may not have an access plug, 2) the dropline or steel tape may catch on the pump or scale buildup within the casing of a deep well, or 3) the dropline or steel tape may be shorter than the depth to water in a deep well.

A variety of other approaches were also used in this study (Table 3). Pressure transducers provide real-time data of the head at a well under pumping and nonpumping conditions. Acoustic water level sensors transmit an acoustic signal that reflects off the water surface and back to the device; the travel time of the signal is used to calculate the depth to water. Geophysical logging was used to obtain depth to water if a geologic study of a well had taken place during the period of measurement.

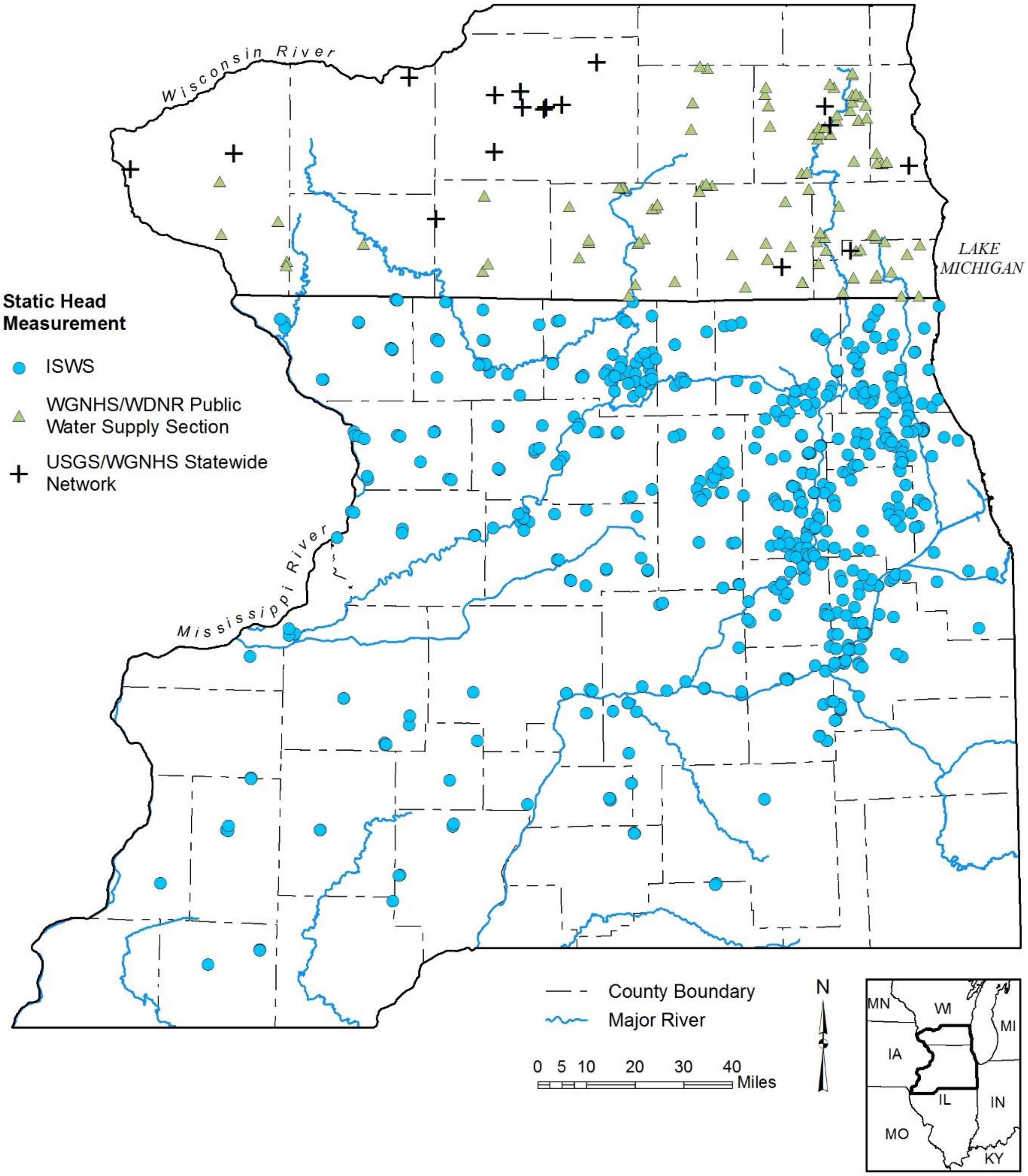

Figure 11: Map of all well locations from which non-pumping head measurements were obtained by the ISWS, WGNHS, or from USGS data records.

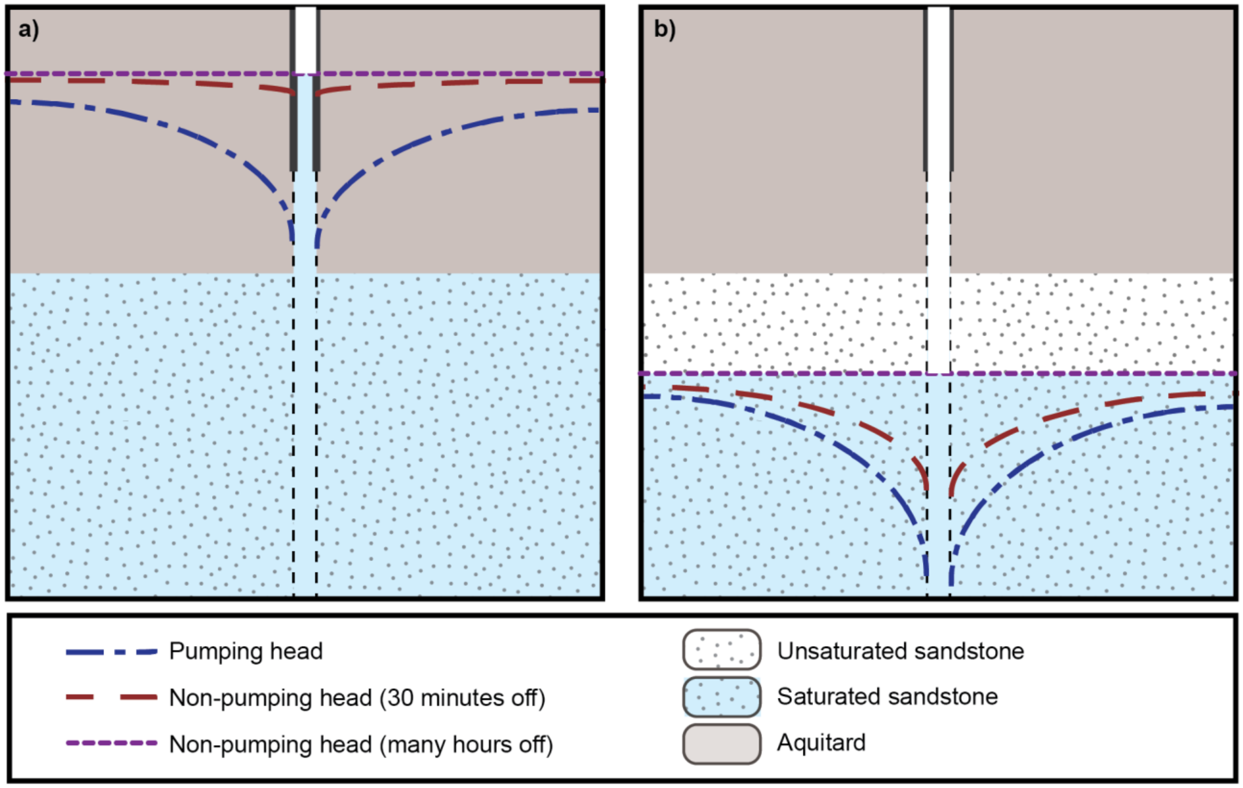

Figure 12: Conceptual diagram of head recovery in a well after 30 minutes for a) a confined aquifer and b) an unconfined aquifer.

Table 3: Number of wells measured using different approaches in Illinois and Wisconsin.

Measurement Approach	Illinois	Wisconsin
Airline	533	79
Dropline	12	-
Steel Tape	10	-
Pressure Transducer	18	10
Acoustic	-	7
Geophysical/Other	3	3
Total	576	99

4.3 Generating a potentiometric surface

A primary outcome of the 2014 synoptic measurement was the development of a Cambrian-Ordovician sandstone head contour map, also referred to as a potentiometric surface. This map can be used to make assessments of the directions of groundwater flow, identify zones where leakage rates to the sandstone are high, and, when compared to previous potentiometric surfaces, determine the change in heads over time.

In previous synoptic measurement reports developed by the ISWS, the potentiometric surface was developed by contouring heads by hand. However, it can be difficult to compare the changes in potentiometric surfaces through time, particularly when developed by different individuals. The methodology for generating a potentiometric surface that is employed in this report follows Roadcap et al. (2011). This method generates contours with the groundwater flow model MODFLOW (McDonald and Harbaugh, 1988; Harbaugh et al., 2000), which is a three-dimensional finite difference model that simulates both groundwater flow and potentiometric surfaces. In practical terms, the model divides the groundwater flow system into a number of three-dimensional cells which can be assigned hydrologic properties or treated as boundary conditions that the model must account for when generating a solution.

MODFLOW offers a number of distinct advantages over hand contouring or digitized interpolation techniques. First, in addition to contours, MODFLOW generates a grid of heads. This grid allows for direct comparison of head contours between different years. Second, the model solution explicitly obeys the two fundamental laws of groundwater flow, water balance and Darcy’s Law. These can only be approximately accounted for when contouring by hand and are ignored using packaged interpolation techniques. Third, the model solution can explicitly account for boundary conditions, such as surface waters and no-flow barriers.

Use of the MODFLOW solver in this way requires several assumptions. First, it assumes that the groundwater system is at steady state, so that a steady-state simulation is appropriate. Second, it assumes that water added to or discharged from the aquifer is exactly equal to a combination of sources and sinks of water (recharge, discharge to streams, vertical leakage, discharge by wells, etc.) that is not explicitly simulated. Third, it assumes that the distribution of transmissivity in the model is correct if flow budgets are interpreted.

The heads from all measurement points are honored in the MODFLOW solution. This can be considered a disadvantage over traditional hand contouring when local heads are higher or lower than the regional heads; the model will simulate a number of local-scale contours in addition to contours representative of the regional patterns. These local contours may be real, driven by small cones of depression or recharge zones, or an artifact of incorrect measurements. Regardless, these local contours can distract from the regional trends.

To eliminate some of the noise from the regional contours, it is necessary to remove heads that conflict greatly with the regional trend. This is similar to the interpretation that must be conducted during hand-contouring of regional contours, where decisions must be made regarding which heads to give priority to when there is some variability. An extensive QA-QC process is necessary to remove these data points that are too high or too low (see Section 4.3.1). Although most of the local-scale contours that did not fit the regional trend were removed during the QA-QC process, a few smaller contours often remain. These are generally minor and only distract from the regional contours when a smaller contour interval (< 50 ft) is utilized. In this report, when necessary, the authors remove these local scale contours in post-processing to generate a "smoothed" set of contours. However, since some of the local contours may in fact be representative of actual variability in the Cambrian-Ordovician surface, the authors also include a "raw" version with no post-processing.

The contouring model is composed of a single layer of constant thickness, with a top elevation consistent with the top of the St. Peter Sandstone shown in Figure 5; where the St. Peter Sandstone was not present, the bedrock surface was utilized as the top elevation. The head contours were insensitive to the other properties assigned, including hydraulic conductivity and aquifer thickness. The cell size was 1000 ft and the model grid covered the area shown in Figure 13.

Two types of boundary condition cells were used in the contouring model: 1) constant head and 2) no flow. Constant-head cells force the simulated MODFLOW head to match the head assigned in the contouring model. These cells were used to simulate non-pumping heads from the synoptic measurement and a few other boundary heads that are discussed in Section 4.3.2. In contrast, no-flow boundaries prevent any flow from entering a cell.

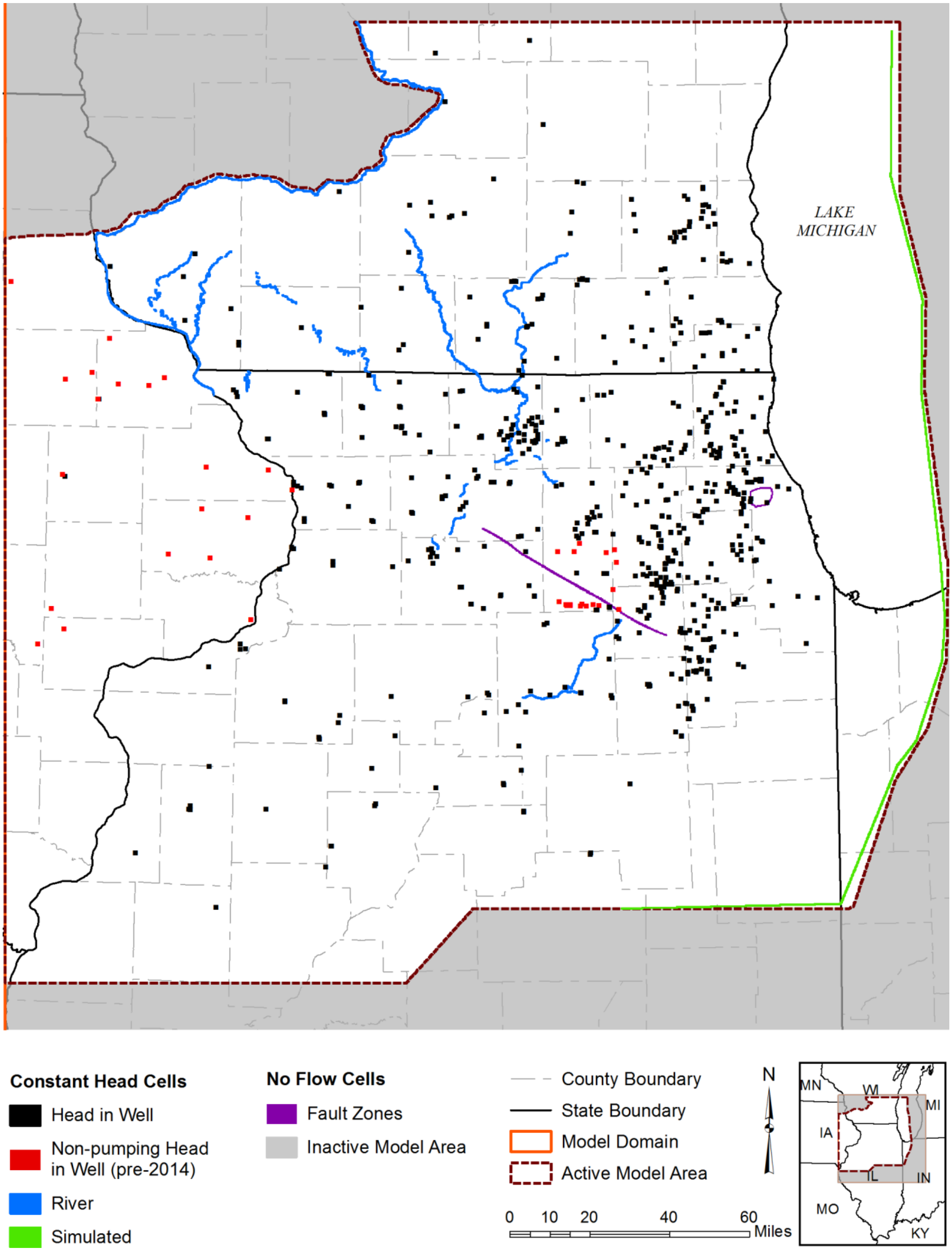

Figure 13: Model input values for purposes of contouring. Note that constant-head cell sizes have been exaggerated for display purposes for "Head in well" and "Non-pumping head in well (pre-2014)". All other cells have been maintained at their original cell size of 1000 ft.

4.3.1 QA/QC of non-pumping heads

Constant-head cells either provide water to or remove water from a groundwater flow model developed with MODFLOW. Constant-head cells with a higher head than surrounding cells are simulated as a source of water, representative of physical processes such as leakage to the sandstone or resaturation of empty pore spaces. Conversely, constant-head cells with a very low head remove water from the aquifer, representing physical processes such as groundwater withdrawals or groundwater discharge to surface water features.

In this study, inaccurate measurements could have resulted in a head that is much higher or much lower than the surrounding heads. If these points were not filtered, too much water would have been added or removed from the model, resulting in incorrect contours. To avoid this, all non-pumping heads underwent a quality assurance/quality control procedure before being added to the model. Of the 675 measurements obtained, 32 were filtered. Data had to be filtered for a number of reasons. First, airline lengths used for calculation of a head may be in error; this can occur if a pump has been lowered or raised but the airline length was not updated accordingly. Second, an airline may not have been completely purged of water; incomplete purging generally results in heads being too low. Finally, some data points may have been accurately measured, but were not representative of the regional contours. This could be a result of head differences that have developed between Cambrian-Ordovician sandstone aquifers or local heterogeneities.

4.3.2 Additional constant-head cells

A sufficiently dense network of observations is required to create an accurate potentiometric surface using MODFLOW (or any other interpolation technique). In areas where data were too sparse, non-pumping heads were obtained from drilling records of residential wells. A total of 18 constant-head cells were added in this manner in central Illinois (Figure 13). These measurements often fell outside of the time frame for the 2014 synoptic study, but never predated 2010.

Cambrian-Ordovician sandstone heads have been changing in Iowa over the past few decades. While the Mississippi River appears to serve as a flow boundary between Iowa and northwestern Illinois, this does not appear to be true south of Carroll County (Young and Siegel, 1992; Gannon et al., 2009). To better capture the contours along the state boundary, 20 sandstone heads in Iowa were inferred from a 2005 potentiometric surface developed in Gannon et al. (2009), see Figure 13.

Non-pumping heads could not be obtained underneath Lake Michigan or in Indiana. However, some assumptions about these heads is necessary to delineate contours within northeastern Illinois, in particular in eastern Lake, Cook, and Will Counties. To this end, a Great Lakes Basin model developed by the USGS (Feinstein et al., 2010) was used to simulate the St. Peter Sandstone heads underneath Lake Michigan and in northwestern Indiana. The last year simulated in that model was 2005, which was used to define the simulated boundary for 2014 (Figure 13).

Finally, the St. Peter Sandstone is present at the bedrock surface in portions of Illinois and Wisconsin (Figure 3). Similarly, the undifferentiated Cambrian Units in Wisconsin, which include the Ironton-Galesville Sandstone, are at the bedrock surface in large areas of central Wisconsin (Figure 3). Where sandstone is at the bedrock surface, surface water will dictate some control on heads. After comparing surface water elevations with nearby non-pumping heads, it appears appropriate for purposes of this regional contouring model to assign a constant-head cell that is equivalent to the surface water elevation where the sandstone is at the bedrock surface (Figure 13).

4.3.3 No-flow boundaries

The original model boundary, shown in Figure 1, was larger than the study area. However, the contouring model cannot accurately simulate heads in areas where observations were not available, such as in southern Illinois or east of Lake Michigan. As a result, areas with no information are treated as no-flow cells (Figure 13); that is, they neither contribute nor remove water from the simulation. While arbitrarily assigned, these boundaries are far enough away from the study area that they do not considerably influence the solution.

Another set of no-flow boundaries was assigned to represent the Sandwich Fault Zone (Figure 13). This fault is believed to restrict horizontal flow, in particular where sandstone aquifers are completely offset across a fault block (Figure 4 and Figure 5). To simulate the corresponding jump in heads across this boundary, the Sandwich Fault Zone had to be conceptualized differently than the rest of the sandstone aquifers. For contouring purposes, it appears that assigning no-flow cells to simulate the Sandwich Fault Zone in areas where it experienced the greatest offset was appropriate.

4.3.4 Model run

After assigning all of the preceding parameters, the model was run to steady state. The head contours that were generated were analyzed to ensure that additional data filtering was not required. This process was repeated numerous times until the 2014 potentiometric surface was satisfactory.

The same process was repeated to develop a potentiometric surface for 1980, which was the last previous synoptic measurement conducted over the entire study area. The no-flow boundaries and constant-head boundaries representing surface waters were left unchanged from the 2014 simulation. All other constant heads were removed from the contouring model and replaced with: 1) 640 heads from the 1980 synoptic measurement conducted by the ISWS, 2) USGS data for 76 Wisconsin wells over a span of 1977-1983, 3) simulated 1980 heads from underneath Lake Michigan (Feinstein et al., 2010), and 4) 20 head values estimated from a 1980 potentiometric surface in Iowa (Gannon et al., 2009). Nineteen heads were obtained from residential well drilling records in areas where data gaps were present in 1980.

This process also was repeated in northeastern Illinois for the following years: 1959, 1966, 1971, 1975, 1985, 1991, 1995, 2000, and 2007. There were only two changes to this process. First, because the focus area is northeastern Illinois, it was not necessary to update data in the western half of the state or Iowa. Second, data from Joliet in the year 2000 are not available. As a result, heads were interpolated between the 1995 and 2007 observations in that region; no other data interpolation took place for these runs. These results are shown in Section 5.4.3 for northeastern Illinois only.

5 2014 Potentiometric surface of Cambrian-Ordovician heads

This chapter presents the results of the 2014 synoptic measurement. Sections 5.1, 5.2, and 5.3 are a holistic discussion of the regional study area. Section 5.4 expands this discussion for the individual water supply planning regions shown in Figure 1, and as a result, will have overlapping content with the previous sections. Section 5.5 includes discussions pertinent to further analysis of the contours.

5.1 2014 Head contours

The 2014 potentiometric surface of the Cambrian-Ordovician sandstone aquifers for northern Illinois and southern Wisconsin is shown in Figure 14. The highest heads were located in north-central Illinois and south-central Wisconsin. Heads that exceeded 600 ft in Illinois are generally located in the area where leakage to sandstone is relatively high due to the absence of shale (see Section 2.3 and Figure 6). The exception to this is in LaSalle County, where even though shale is absent, heads fell below 600 ft. This is largely because the sandstone in LaSalle County is close to the surface, so heads are controlled by elevations in the Illinois River, which range from 450 to 540 ft AMSL.

Multiple cones of depression have formed in the study area (Figure 14). A cone of depression occurs when the head is lowest at a well (or cluster of wells) and increases exponentially with distance from the pumping center. The northeastern Illinois cone of depression is the largest of the three regional cones, both in spatial extent and depth. In 2014, the heads at the center of this cone are deepest in the Joliet region at -300 ft AMSL (Figure 14) and were below 0 ft AMSL throughout most of northwestern Will County (Figure 14). Two primary factors contribute to the size and depth of this cone. First, sandstone withdrawals are relatively large throughout northeastern Illinois, in particular in northwestern Will County, Kendall County, eastern Kane County, and southeastern McHenry County (Figure 10). Second, the sandstone is overlain by shale in these heavy pumping areas (Figure 6), hence vertical leakage is small and replenishment of water removed by pumping is minimal. Groundwater flows into the northeastern Illinois cone of depression from all directions in response to these withdrawals. However, the contours in the western portion of the cone are much closer together than those to the north, south, and east. Tightly spaced contours generally indicate greater flow rates. As a result, it appears that most of the groundwater that flows into the northeastern Illinois cone of depression is from north-central Illinois.

A second, much smaller cone of depression is centered on Rockford, IL (Figure 14). Despite the large withdrawals from the area surrounding Rockford (Figure 10), the cone of depression has a drastically smaller spatial extent and drawdown than the northeastern Illinois cone, with water levels generally around 500-550 ft AMSL. The Rockford cone of depression is smaller because the St. Peter Sandstone is at or near the bedrock surface in this region (Figure 3); hence vertical leakage to the sandstone is higher than in northeastern Illinois and water removed via withdrawals is more easily replenished by precipitation.

A third distinct cone of depression is centered on Waukesha, WI, which is much smaller than the northeastern Illinois cone of depression, with heads in the Waukesha area around 450 ft AMSL (Figure 14). Like northeastern Illinois, the sandstone aquifers in this area are covered by shale, hence replenishment of water removed by pumping is minimal. Most of the water that flows into this cone is from the west and north where the sandstone is at or near the bedrock surface and the shale is absent.

The southwestern portion of the study region is unique from the rest of the study region for two reasons. First, the sandstone aquifers have very few withdrawals (Figure 10), hence no regional cones of depression have formed. Furthermore, the area is overlain by shale (Figure 6), limiting downward vertical leakage. Subsequently, heads in this area are fairly level, ranging from 400 to 500 ft AMSL (Figure 14).

The Sandwich Fault Zone influences heads in the Cambrian-Ordovician sandstone aquifers. The head jumps discretely across the fault zone by as much as 100-150 ft in DeKalb County, with the higher heads generally occurring on the south side of the fault (Figure 14). This is likely due to the regional drawdowns in northeastern Illinois disproportionately impacting heads north of the fault zone, but could also be because sandstone is closer to the surface to the south (Figure 4), which would lead to relatively high rates of leakage. The Des Plaines Disturbance also influences regional flow patterns, with higher heads occurring within the disturbance (Figure 14). The Plum River Fault Zone appears to have minimal impact on heads in this area.

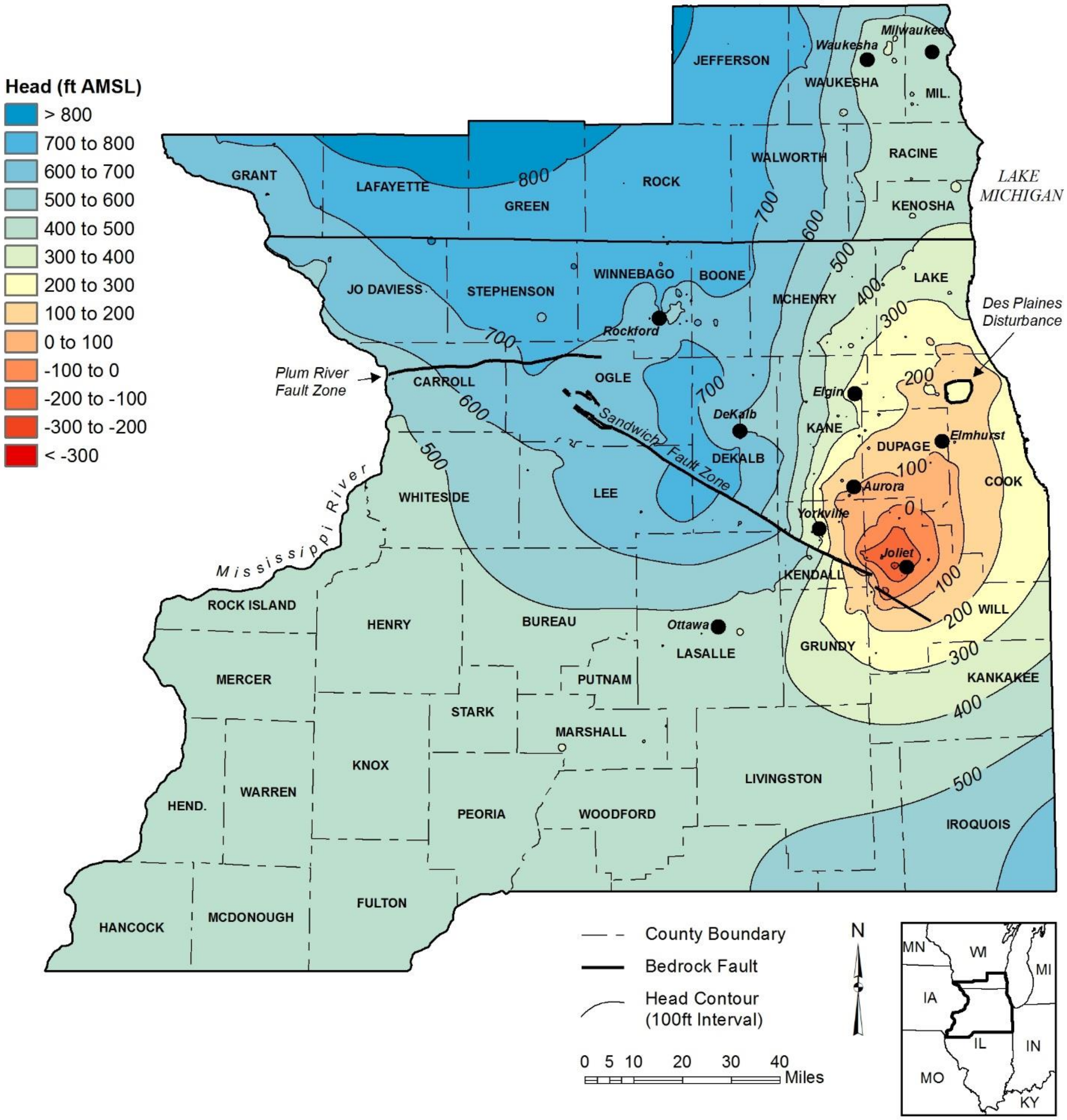

Figure 14: Potentiometric surface of the Cambrian-Ordovician sandstone aquifers in 2014 (100 ft contour).

5.2 Comparison with predevelopment

Drawdown, which is the decrease in heads over a given time, provides an historical perspective on present-day heads. The ISWS developed a composite potentiometric surface for predevelopment (Figure 15) using previously developed surfaces from Anderson (1919), Weidman and Schultz (1915), Young and Siegel (1992), and Burch (2002). While the potentiometric surface has been previously contoured in the driftless area of Wisconsin and Illinois, it did not account for detailed connections between surface water and sandstone aquifers that are critical to accurately contour heads in this region; this area is omitted in Figure 15.

The heads in the study area during predevelopment generally ranged from 600 to 850 ft AMSL, with the highest heads occurring in McHenry, Stevenson, and Jo Daviess Counties for Illinois and Walworth, Waukesha, Green, and Rock Counties for Wisconsin. The lowest predevelopment heads occur in the southern portion of the study region (Figure 15). Heads in DuPage County range from 700 to 750 ft AMSL, while land surface is closer to 600 ft AMSL. Indeed, since the head was above land surface, many of the first wells that were drilled in northeastern Illinois were actually flowing artesian wells (Suter et al., 1959).

In 2014, drawdown from predevelopment conditions is prevalent throughout the study region (Figure 16). Areas with drawdown of less than 100 ft coincide with areas where shale is not present above the sandstone, including the area in LaSalle County where the sandstone aquifers are at the bedrock surface beneath the Illinois River (compare Figure 6 with Figure 16). Conversely, most areas covered by shale have at least 100 ft of drawdown. This is even true if demand is low, such as in the southwestern portion of the study region. The greatest drawdown is located in the northeastern Illinois cone of depression, reaching 700 to 900 ft in northwestern Will County (Figure 16). The drawdown at the Rockford and Waukesha cones of depression (100-200 ft and 300-400 ft, respectively) are much smaller.

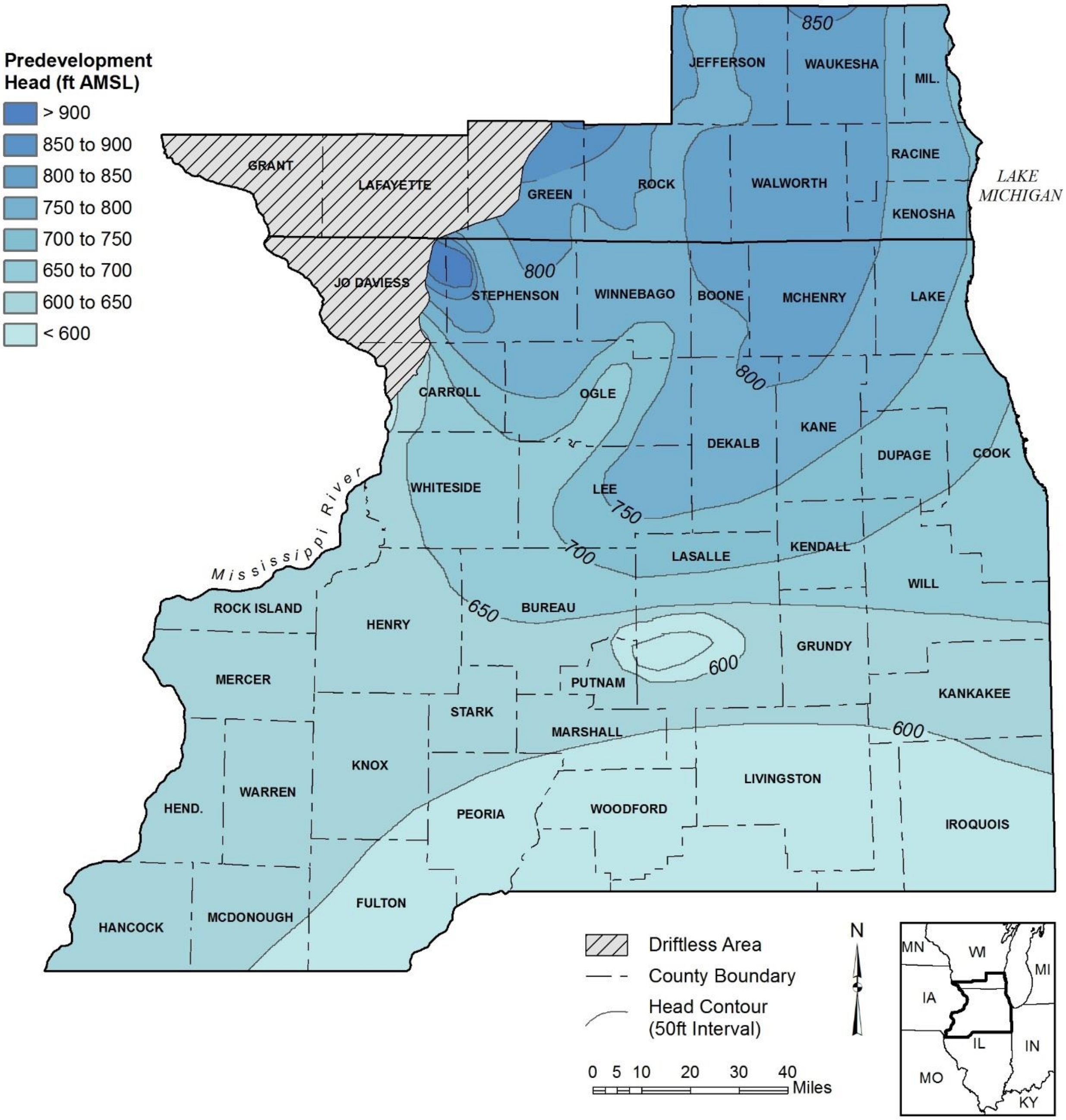

Figure 15: Potentiometric surface of the Cambrian-Ordovician sandstone aquifers for 1863 (predevelopment conditions).

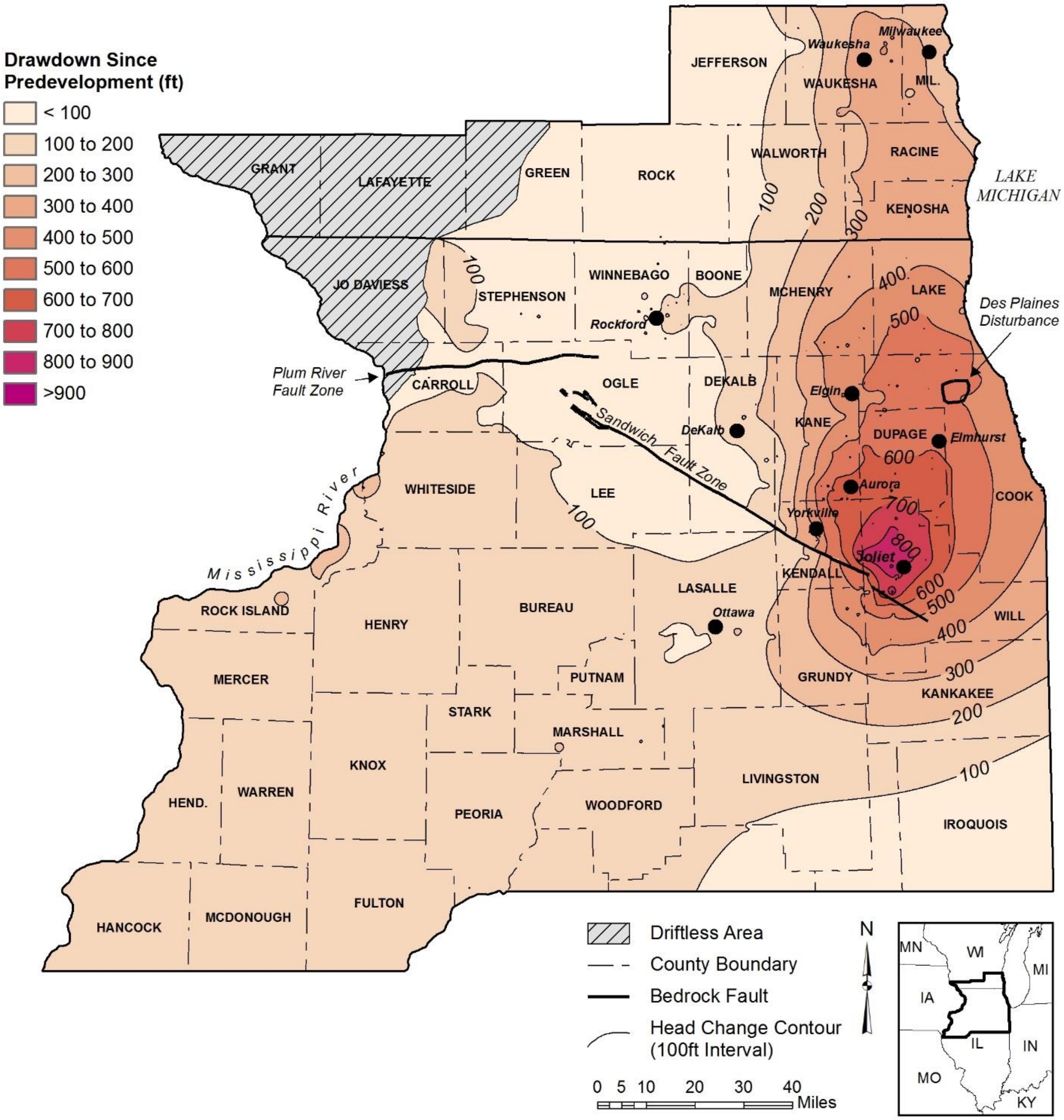

Figure 16: Drawdown of heads in the Cambrian-Ordovician sandstone aquifers from predevelopment to 2014.

5.3 Comparison with 1980

The last synoptic study of Cambrian-Ordovician sandstone aquifers over all of northern Illinois was conducted by the ISWS in 1980, when withdrawals in Illinois (particularly the northeastern portion of the state) were near their peak (Figure 8 and Figure 17). A potentiometric surface was developed for this year over the entire study area (Figure 18). A head change map was also generated. The raw model output generates local head differences, which may be artificial and undesirable (see Section 4.3). Figure 19 is a smoothed version of the head change map that is most suitable for assessing regional flow patterns at the scale of the study area.

Withdrawals from the Cambrian-Ordovician sandstone aquifers have changed extensively since the ISWS started collecting more complete withdrawal data in the early 1960s. In the last statewide study of Cambrian-Ordovician sandstone wells in Illinois, total withdrawals were 263 Mgd, as opposed to 165 Mgd in 2012 (Figure 8). By far the primary driver for this change was a decrease in withdrawals from northeastern Illinois as communities moved to Lake Michigan for water supply (Section 3.1.1). By comparing the locations and magnitudes of withdrawals in 1980 (Figure 17) with 2012 (Figure 10), three trends can be observed which have implications for the potentiometric surfaces of each year, as discussed below.

First, in 1980, groundwater withdrawals in Cook, DuPage, and Lake Counties were 67.1, 28.6, and 11.0 Mgd, respectively (Table 4); heads in these counties were often less than 0 ft AMSL (Figure 18). In 2012, the withdrawals had decreased in Cook County by 59.2 Mgd, DuPage County by 24.9 Mgd, and Lake County by 5.7 Mgd. Consequently, heads have recovered in 2014 by as much as 250 ft (Figure 19). Despite this recovery, the 2014 heads were still more than 400 ft below predevelopment conditions (Figure 16).

Second, Will, Kendall, and McHenry Counties have all continued to increase their usage of the deep sandstone from 1980 to 2012 (Table 4). Since the sandstone in these counties is overlain by shale, heads have decreased in all three over this time frame by as much as 250 ft in western Joliet (Figure 19). Heads have also decreased in counties where pumping has decreased since 1980. Kane County decreased withdrawals over this time frame by 4.1 Mgd (Table 4), but heads have continued to decrease over much of the county, in particular the southwestern portion, which is closest to the current center of the cone of depression in northeastern Illinois (Figure 19). Pumpage in Waukesha County (Wisconsin) has decreased by 4.0 Mgd since 1980 but heads have decreased by over 150 ft in areas (Table 4 and Figure 19). There are two explanations for this. First, pumping increased in Waukesha County after 1980, but has been decreasing in recent years. Second, the sandstone in this county is overlain by shale, hence groundwater withdrawn from the sandstone is not readily replenished by precipitation. A similar pattern is observed in DeKalb County, where despite a decrease in 1.2 Mgd from 1980 to 2012, heads have decreased by 50 ft in the city of DeKalb (Figure 19).

The third major trend is the fairly consistent withdrawals from areas outside of northeastern Illinois and southeastern Wisconsin (Figure 8 and Table 4). If the sandstone was not overlain by shale (Figure 6), then heads usually did not decrease by more than 25 ft between 1980 and 2014 (Figure 19). The exception to this is at Rockford, where large withdrawals that persisted from 1980 (Figure 17) to 2012 (Figure 10) generally resulted in a 50 to 100 ft decrease in heads (Figure 19). Where shale is present, a 25 to 50 ft decrease in heads is not uncommon, despite the low groundwater demands in areas (i.e., the southwestern portion of the study region). It is noted that a 50-100 ft change in head was observed at three wells along the Illinois River in the southern portion of the study area. It is unclear whether this is a regional trend, as indicated in Figure 19, or a more local phenomenon.

Table 4: Counties in the study area with total groundwater withdrawals in excess of 0.5 Mgd in 2012. Counties with changes in withdrawals from 1980 to 2012 of more than 3 Mgd are bolded (red for withdrawal increases and blue for decreases). Illinois withdrawals are from IWIP and Wisconsin withdrawals were provided by the Wisconsin Water Science Center.

County	State	1980 Withdrawals (Mgd)	2012 Withdrawals (Mgd)	Withdrawal change-1980 to 2012 (Mgd)
WILL	IL	23.9	27.6	**+3.7**
KANE	IL	27.6	23.5	**-4.1**
WINNEBAGO	IL	20.2	23.4	**+3.2**
WAUKESHA	WI	19.5	15.5	**-4.0**
LASALLE	IL	15.7	13.3	-2.4
JEFFERSON	WI	14.9	12.9	-2.0
ROCK	WI	6.4	11.8	**+5.4**
COOK	IL	67.1	7.9	**-59.2**
MCHENRY	IL	4.0	7.7	**+3.8**
KENDALL	IL	1.3	7.6	**+6.4**
GRUNDY	IL	10.9	7.2	**-3.7**
DEKALB	IL	7.8	6.5	-1.2
WALWORTH	WI	3.0	5.5	+2.5
LAKE	IL	11.0	5.4	**-5.7**
OGLE	IL	7.0	5.2	-1.8
GREEN	WI	3.2	4.9	+1.7
LEE	IL	4.0	4.4	+0.4
STEPHENSON	IL	5.0	4.2	-0.8
BOONE	IL	3.3	3.7	+0.4
DUPAGE	IL	28.6	3.7	**-24.9**
RACINE	WI	3.2	3.2	+0.0
HENRY	IL	2.2	3.0	+0.8
JO DAVIESS	IL	2.3	3.0	+0.7
GRANT	WI	3.3	2.8	-0.5
WARREN	IL	3.0	2.5	-0.4
WHITESIDE	IL	3.5	2.4	-1.1
MILWAUKEE	WI	6.8	2.2	**-4.6**
CARROLL	IL	1.5	2.1	+0.6
BUREAU	IL	1.6	1.2	-0.4
LAFAYETTE	WI	1.4	1.1	-0.3
LIVINGSTON	IL	0.1	1.0	+0.9
ROCK ISLAND	IL	0.5	0.6	+0.2
PEORIA	IL	0.7	0.6	-0.1
MARSHALL	IL	0.2	0.5	+0.3

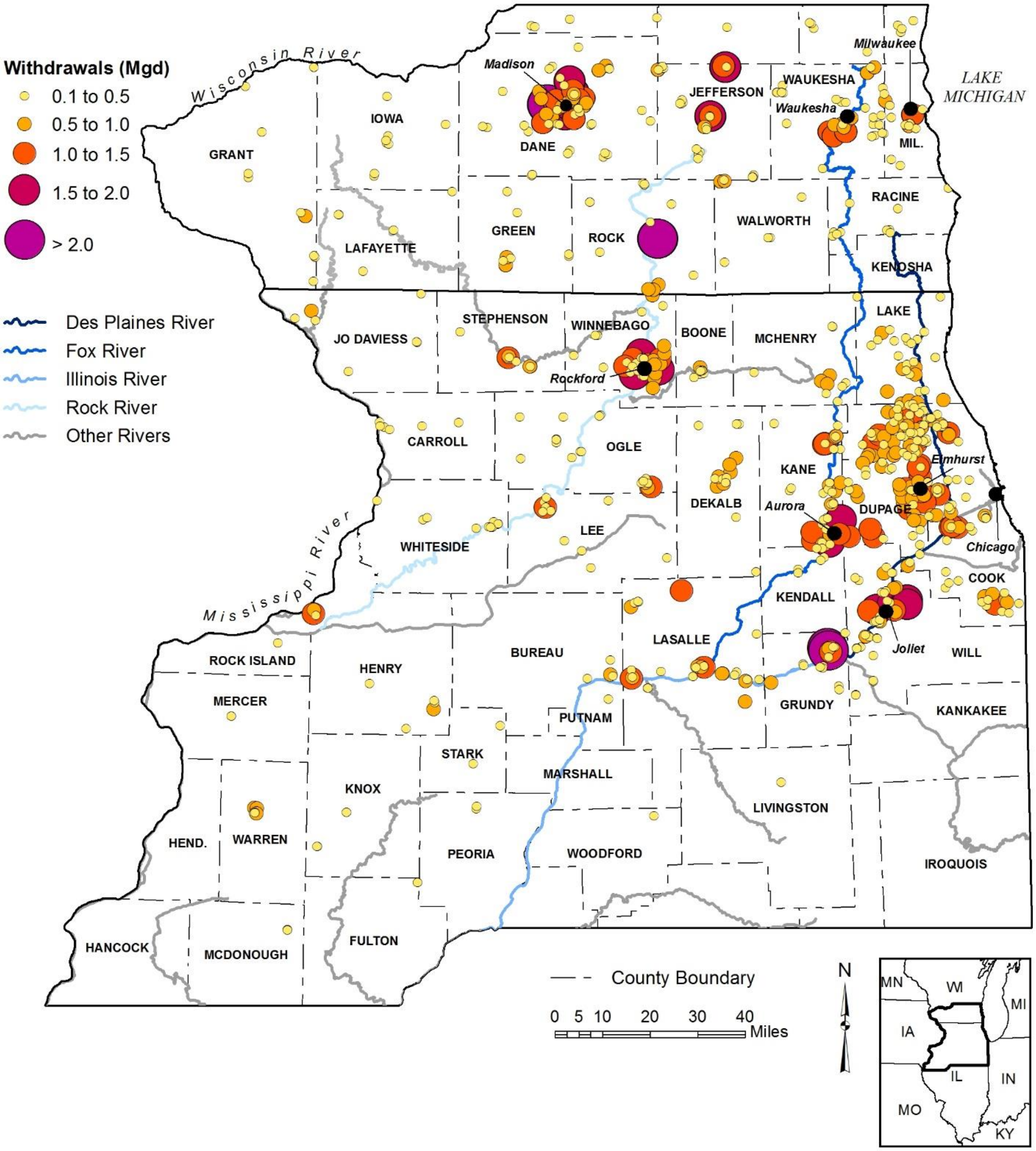

Figure 17: Groundwater withdrawals from the Cambrian-Ordovician sandstone aquifers in 1980. Illinois withdrawals are from IWIP and Wisconsin withdrawals were provided by the Wisconsin Water Science Center.

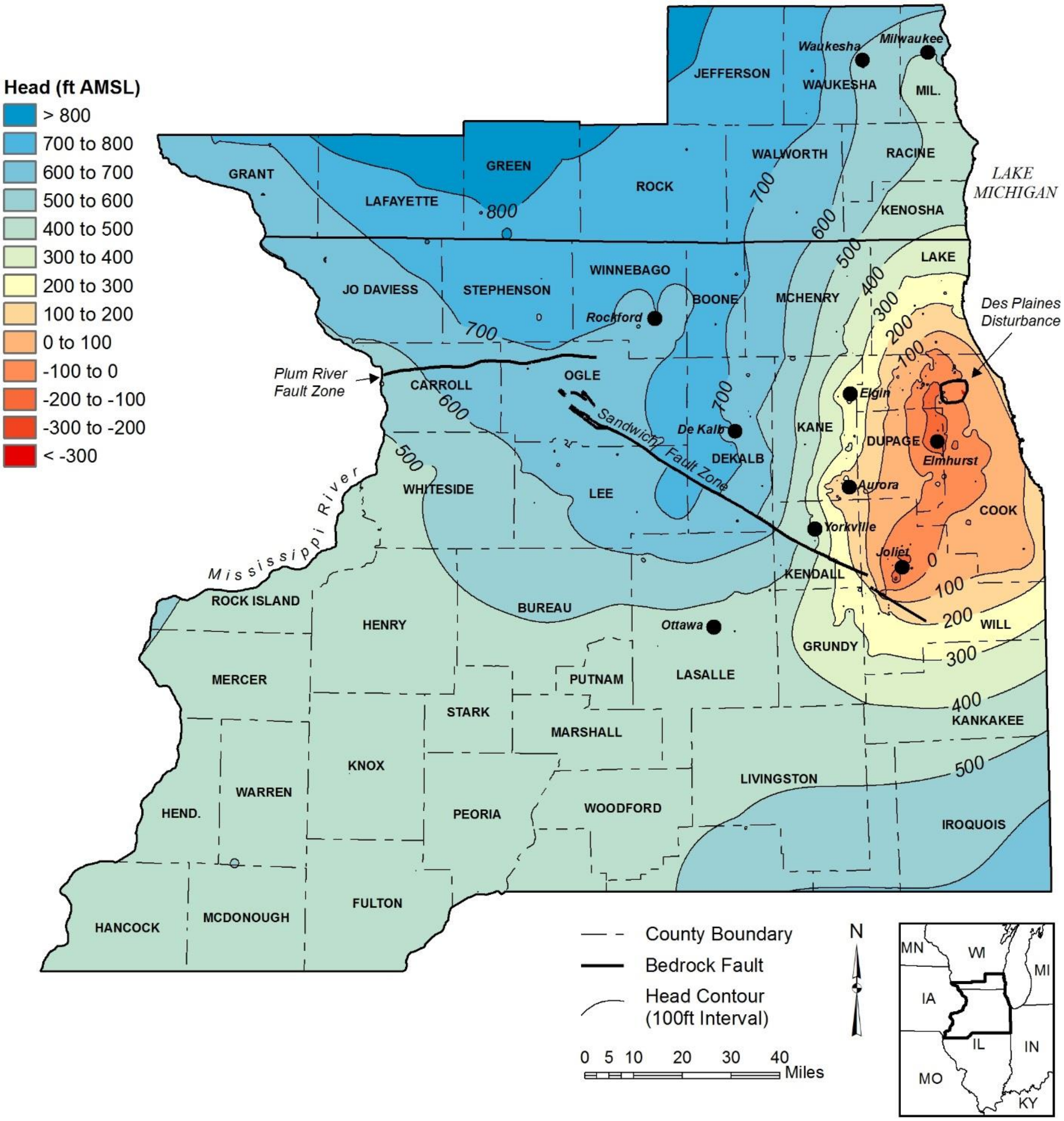

Figure 18: Potentiometric surface of the Cambrian-Ordovician sandstone aquifers in 1980 (100 ft contour).

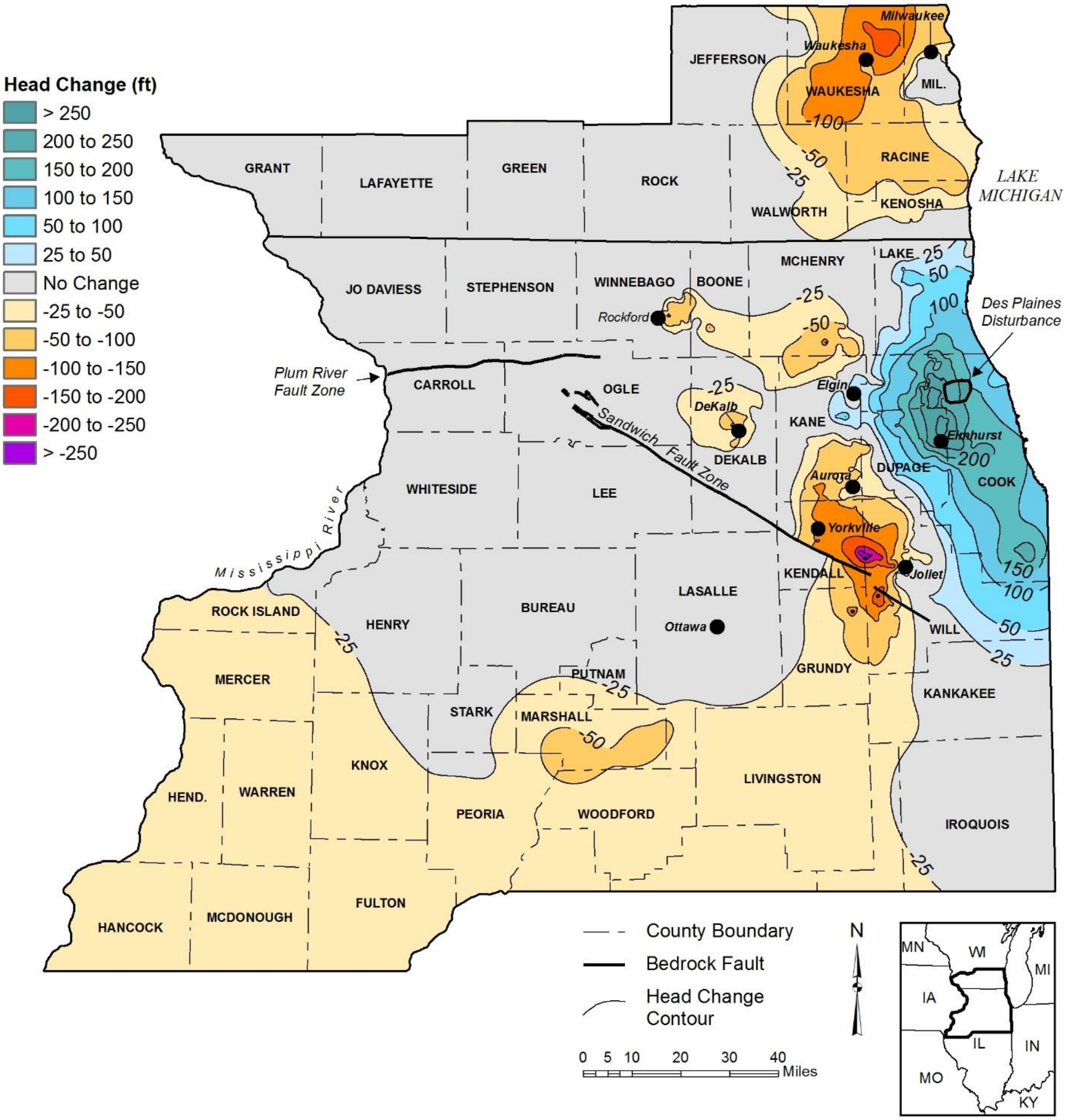

Figure 19: Change in heads from the Cambrian-Ordovician sandstone aquifers between 1980 and 2014.

5.4 Implications for water supply planning regions (WSPRs)

5.4.1 Northwestern Illinois

The highest Cambrian-Ordovician heads observed in the 2014 synoptic measurement in Illinois were in the Northwestern Illinois WSPR (Figure 14). These high heads were primarily the result of relatively high downward leakage of water to the sandstone aquifers but also from connections to surface water bodies. Heads that exceed 600 ft AMSL were generally observed in areas where leakage to sandstone is relatively high due to the absence of shale (see Section 2.3 and Figure 6). In areas where sandstone is at the bedrock surface, only glacial material would deter leakage. Since this glacial material is often composed primarily of sand, leakage rates are relatively high; consequently, heads in excess of 700 ft AMSL were observed.

Another prominent feature in this region is the formation of a cone of depression around Rockford (and to a lesser extent, Belvidere). The drawdown in this area since predevelopment conditions is as much as 100-200 ft (Figure 16), a result of sustained pumping since at least 1980 (Figure 10 and Figure 17). Sandstone wells in Rockford that are near the Rock River generally exhibit very little drawdown, primarily because the sandstone is at or near the bedrock surface in the vicinity of the Rock River (i.e., Rockford wells #1 and #6 in Figure 20). The most drawdown generally occurs to the west of the Rock River, where the sandstone is overlain by carbonates which limit vertical infiltration of water (i.e., Rockford well #30 in Figure 20).

With a few exceptions, no significant head change (>25 ft) has occurred in the western portion of the Northwestern Illinois WSPR since 1980 (Figure 19), which is consistent with the low demand in that region (Figure 10). Furthermore, the sandstone in this area is only sporadically overlain by impermeable shale. More commonly, the sandstone in the western portion of this region is covered by weathered carbonates, which allows for higher rates of leakage. One exception to this is in the western portion of Carroll and Whiteside Counties, where relatively high demand coincides with areas covered by shale (compare Figure 6 to Figure 10), and subsequent head decreases range from 25 to 50 ft.

In Jo Daviess and Carroll Counties, the potentiometric contours bend to the northwest as they approach the Mississippi River, which would suggest a hydrologic connection between the river and sandstone aquifers. This is consistent with observations made by Gannon et al. (2009). More research is required to confirm this observation. In areas south of Carroll County where shale is present above the sandstone (Figure 6), the contours do not indicate that the Cambrian-Ordovician sandstone aquifers have a strong hydrologic link to the Mississippi River.

Also present in this planning region is the Plum River Fault Zone, which runs through Carroll and Ogle County (Figure 14). However, this fault appears to have minimal influence on the heads. The reasons why head differences across this fault are not observed is not immediately clear, although the most likely explanation is that, in contrast to the Sandwich Fault Zone, there are not enough sandstone withdrawals on either side of the fault to create such a difference.

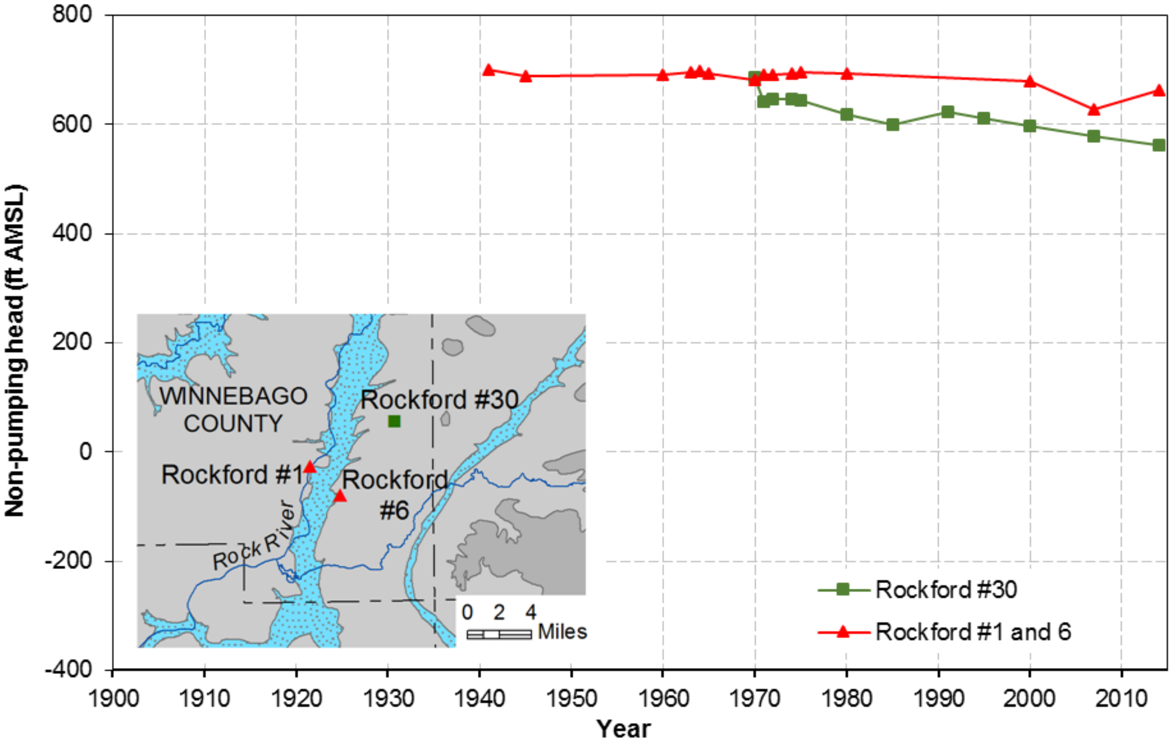

Figure 20: Observed heads at Rockford #6 (1941), #1 (1945-1963), and #30 (1970-2014). See Figure 6 for the inset image legend.

5.4.2 Spoon and La Moine, Middle Illinois, East Central Illinois, and Kankakee

Withdrawals from the Cambrian-Ordovician sandstone aquifers in the Spoon and La Moine Basins WSPR are relatively small, steadily declining from 5 to 3 Mgd since 1980 (Figure 8). However, this area is also largely overlain by shale (Figure 3), and as a result, very little leakage enters the sandstone. Consequently, the head change from 1980 to 2014 is commonly in excess of 25 ft (Figure 19), and drawdown from predevelopment to 2014 is in excess of 100 ft (Figure 16). This decrease appears to be a slow, steady decline, as indicated by the hydrographs for wells in Alexis, Monmouth, and Ipava (Figure 21). There are three possible hypotheses for these regionally persistent, albeit minor, decreases in head over time. First, the small rates withdrawn reported to IWIP may be large enough to cause these decreases. Second, additional wells that are not reported to IWIP may be withdrawing water in this region. Finally, the impact of remote pumping, either in northeastern Illinois, southern Illinois, or Iowa, may be extensive enough to result in such a widespread drawdown. The ISWS will test these hypotheses with a groundwater flow model during water supply planning efforts for the Spoon and La Moine Basins WSPR.

The majority of the Middle Illinois Basin WSPR behaves like the Spoon and La Moine Basins WSPR in that it is mostly covered by shale that prevents leakage to sandstone. Consequently, small head changes (25-50 ft) have been observed since 1980 for most of the region. The exception is LaSalle County, which has the largest water demands from the sandstone in this region but the smallest head change (less than 25 ft) from 1980 to 2014 (Figure 19). The sandstone aquifers used in this area (St. Peter and New Richmond) are near the bedrock surface and receive relatively high rates of leakage to replenish any water withdrawn; hence heads have changed very little in these regions (i.e., two Ottawa wells in Figure 22). In contrast, heads at a nearby industrial facility well where shale overlies sandstone have decreased by nearly 100 ft (Figure 22). It appears that the large sand mining operations in the region are not having a regional impact on heads in the Cambrian-Ordovician sandstone aquifers, although the local impacts were not assessed during the course of this study.

Two wells were measured in the far northern portion of the East Central Illinois Basin WSPR; these wells exhibited similar behavior to wells in the Spoon and La Moine Basins region (25-50 ft decreases since 1980), see Figure 19. To the south, the Cambrian-Ordovician water quality can become too saline for water supply purposes. It is unclear as to how the gradual decreases in head may influence the northward migration of the saline water. The Cambrian-Ordovician sandstone aquifers, in particular the St. Peter Sandstone, could act as a supplemental water source for communities such as Bloomington, whose surface water reservoir was considered "at-risk" during a severe drought (Roadcap et al., 2011). While the salinity in the St. Peter Sandstone may be too high for it to be the sole source of water, groundwater could potentially be mixed with lake water to lower this salinity.

No data points were obtained from the Kankakee River WSPR in 2014. This region no longer uses wells in the Cambrian-Ordovician sandstone aquifers. All contours and head changes are based off of interpolations between the boundary obtained from Feinstein et al. (2005) and measurements from the Northeastern Illinois planning region. These interpolations indicate that heads have not changed by more than 25 ft in this region.

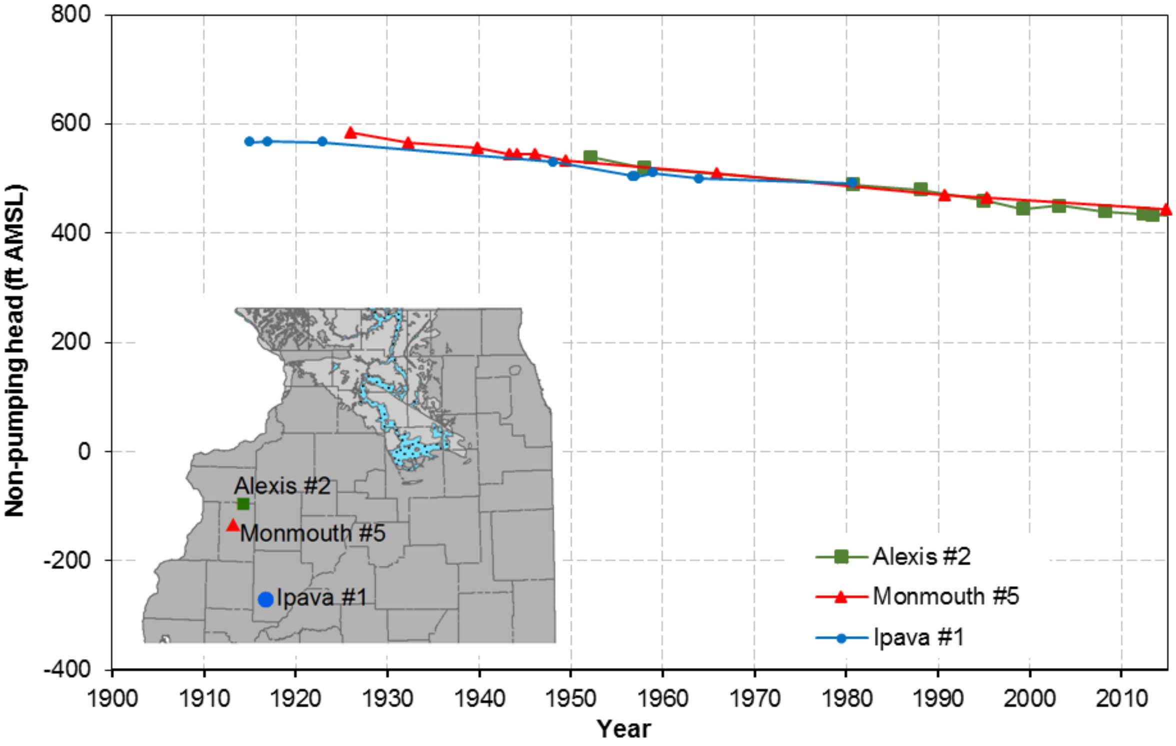

Figure 21: Observed heads at Alexis #2, Monmouth #5, and Ipava #1. See Figure 6 for the inset image legend.

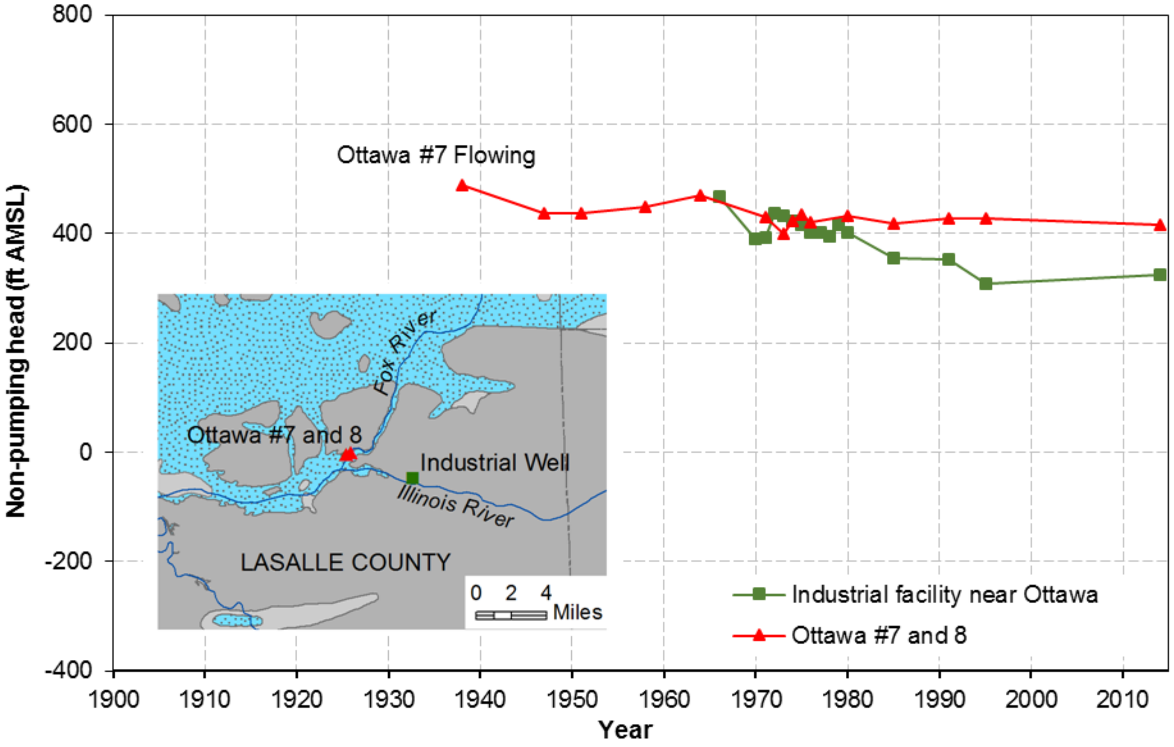

Figure 22: Observed heads at Ottawa #7 (1938-1951) and #8 (1958-2014) and an industrial facility near Ottawa, IL. See Figure 6 for the inset image legend.

5.4.3 Northeastern Illinois

Unlike other water supply planning regions, the demands in the Northeastern Illinois WSPR have fluctuated through time (Figure 8), with heads changing accordingly through time (Figure 23). To capture the impacts of this varied pumping, head contours were developed based on prior synoptic measurements for the following years: 1959, 1966, 1971, 1975, 1980, 1985, 1991, 1995, 2000, 2007, and 2014. The 1959 contours are shown in Figure 24. For the remaining years, maps depicting municipal users of the Cambrian-Ordovician sandstone aquifers, the potentiometric surface, and the head change from the previous potentiometric surface are shown in Figure 25 to Figure 34. Note that these maps do not include DeKalb County, which is a portion of this region that lacks sufficient long-term data to create a potentiometric surface for each year. All maps are based on the raw contouring model results and have not been smoothed beyond the initial QA-QC process. The smoothing process was omitted to highlight local scale impacts that could be related to changes in local withdrawals.

Although synoptic measurements of sandstone heads in the Northeastern Illinois WSPR began in 1959, there is a long history of data records preceding this. Heads in northeastern Illinois in predevelopment conditions were at or near the surface (Figure 23), as indicated both by predevelopment maps and by old drilling records from the late 19th century. Most of the first wells constructed in northeastern Illinois were flowing. However, records from the early part of the 20th century indicate precipitous drops in heads, including at Villa Park well #2 in Cook County (Figure 35) and Joliet well #5 in Will County (Figure 36). In Kane County, the head decrease was more muted before 1950, evident from the less than 25 ft head change from 1915 to 1947 at Aurora #6 (Figure 37). However, heads at this well decreased by 250 between 1947 and 1960, indicating both an increase in withdrawals at Aurora as well as the westward expansion of the northeastern Illinois cone of depression.

In 1959, one large regional cone had formed in the Northeastern Illinois WSPR, with centers at both Joliet and Elmhurst (Figure 24). The period from 1959 to 1966 resulted in the greatest five- to seven-year decrease observed in this study (Figure 25c). This is consistent with the rapid increase in withdrawals from the sandstone aquifers over that period (Figure 8). In 1966, non-pumping heads were approaching mean sea level at Joliet and Elmhurst. This is also evident in the hydrographs for Joliet #1 (Figure 36) and Villa Park #7, which is near Elmhurst (Figure 35). These cones continued to expand until around 1985 (Figure 26b to Figure 29b), with heads approaching -200 ft AMSL at the center of both cones in 1985. A smaller cone of depression was also developing in the Aurora region in 1985 (Figure 29b), with heads approaching 0 ft AMSL at the center. However, there was some variability in the heads observed at Aurora, with well #6 at approximately 100 ft AMSL in 1985 (Figure 37). From 1966 to 1980, there was a clear increasing trend in communities that used the Cambrian-Ordovician sandstone as a primary or partial source of water (Figure 25a to Figure 28a). Head decreases between the synoptic measurements were commonly in excess of 100 ft.

Due to a variety of factors, including concerns over shallow groundwater quality and deep groundwater quantity/quality, many communities began to change their source of water in the 1980s and 1990s (Figure 9). Two consequent head recoveries in the Cambrian-Ordovician sandstones were observed between 1980 and 1985 (Figure 29c). First, heads recovered in northeastern Kane County by more than 150 ft, a result of Elgin switching its primary source of water from the Cambrian-Ordovician sandstones to the Fox River. Second, heads recovered in southeastern Cook County due to many communities switching from the sandstone aquifers to Lake Michigan water.

By 1991, most of the northern communities in Cook County that had previously been using sandstone groundwater had switched to Lake Michigan water (Figure 30a). There was a corresponding recovery in heads of over 150 ft in northern Cook County (Figure 30), as indicated in the hydrograph for Hanover Park #2 (Figure 35). Communities in DuPage and Lake Counties began to switch to Lake Michigan water between 1991 and 1995 (Figure 31a). Consequently, heads recovered over this time period in both counties by as much as 150 ft (Figure 31c). This is indicated in the hydrographs for Villa Park #7 in DuPage County and Wildwood Subdivision #2 in Lake County (Figure 35). Smaller head recoveries also continued in northern Cook County between 1991 and 1995 (Figure 31c and Figure 35c). Furthermore, between 1991 and 1995, Aurora switched to a partial allocation of Fox River water and groundwater from the Cambrian-Ordovician sandstone, resulting in head recovery between 1991 and 1995 (Figure 31c and Figure 37).

Demands in Will County remained relatively consistent during the period where communities in Cook and DuPage Counties went off of the sandstone aquifers. When the more distant communities in northern Cook County switched to Lake Michigan water between 1985 and 1991, the heads in the cone of depression centered on Joliet continued to decrease (Figure 30c). However, when the communities in DuPage County made the switch, the heads at the cone centered on Joliet did not change much (< 50 ft); in fact, they recovered slightly for much of Will County (Figure 31c). Note that while the regional trend from 1991 to 1995 showed an increasing trend in heads at Joliet, this pattern was not exclusively followed by all wells; Joliet #1 showed a gradually decreasing head from 1985 to 1995 (Figure 36).

Between 1995 and 2000, some head recovery continued in Cook and DuPage Counties, although it was muted compared to previous recoveries (Figure 32c). By the year 2000, the northeastern Illinois cone of depression only had one center, Joliet. The growth of this cone between 1995 and 2000 appears to have again been mitigated by head recovery in DuPage County despite continued, and increasing, groundwater withdrawals in the Northeastern Illinois WSPR (Figure 8).

From 2000 to 2007, groundwater withdrawals from the sandstone continued to increase in the Northeastern Illinois WSPR (Figure 8), in particular in Will and Kendall Counties. Only a few communities switched off of the sandstone aquifers over this time frame (Figure 33a). Furthermore, the head recovery in DuPage and Cook Counties had slowed substantially and, in some cases, heads were beginning to decline in these regions (Figure 35c). In other words, the increasing demands in Will and Kendall Counties were no longer counter-balanced by the greatly reduced demands in neighboring counties. As a result, the heads dropped in the northeastern Illinois cone of depression by more than 150 ft in Joliet and Aurora between 2000 and 2007 (Figure 33c, Figure 36, and Figure 37). These large, local decreases are likely exacerbated by the addition of new wells with three common features. First, wells were located in areas where groundwater withdrawals were previously minimal or nonexistent. Second, they were open to only the Ironton-Galesville Sandstone rather than to multiple sandstones. Third, the new wells are located near the Sandwich Fault Zone, which appears to behave as a barrier to flow. Head decreases from 2000 to 2007 were also observed in both McHenry and Lake Counties in excess of 100 ft, although the spatial extent of these changes is small (Figure 33c). Heads did not change significantly in the rest of the area.

Head decreases continued in the Joliet region between 2007 and 2014 by as much as 150 ft (Figure 34c). The current center of the northeastern Illinois cone of depression in Joliet is depicted in Figure 23. The area where heads are less than 0 ft AMSL now covers the majority of northwestern Will County (Figure 34a). The new well in Aurora that led to the large decrease in water levels between 2000 and 2007 is not heavily utilized anymore, resulting in a local head recovery of over 150 ft (Figure 34c).

5.4.3.1 Local hydrographs

Hydrographs for the northeastern Illinois area have been developed to supplement the head change maps. Figure 35 shows the non-pumping heads at Wildwood Subdivision in Lake County, Hanover Park in Cook County, and Villa Park in DuPage County. Heads at these three facilities decreased from predevelopment to the mid-1980s, when many communities began to switch to Lake Michigan water. Heads increased from the mid-1980s to the early 2000s, although they are still hundreds of feet below their predevelopment levels. Heads have remained relatively stable since 2000. Throughout the history of data collection for these three facilities, heads at Wildwood have always been the highest, primarily since this facility is the farthest removed from the center of pumping in northeastern Illinois. Similarly, heads at Villa Park, which is traditionally closest to the center of pumping, have always been the lowest of these three facilities.

Figure 36 shows the decrease in heads at wells in Yorkville and Oswego in Kendall County and Joliet in Will County. Joliet, which is located at the current center of the northeastern Illinois cone of depression, has the lowest heads. Yorkville is the farthest removed of these three facilities from the center of the cone of depression and is also the closest to an area where the sandstone is not overlain by shale; hence Yorkville generally has the highest heads.

Figure 37 shows the non-pumping heads at an industrial facility in McHenry County, the Illinois Youth Center (St. Charles) in central Kane County, and Aurora in southeastern Kane County. While heads have decreased since predevelopment at all three facilities, this decrease appears to have been minimal at the industrial well and more significant at the wells to the south. The lack of decrease at the industrial well is primarily due to its relatively far distance from the center of pumping in northeastern Illinois and its relatively close proximity to the area where sandstone is not overlain by shale. While heads at Aurora are currently hundreds of feet below their predevelopment level, the heads have remained relatively steady since 1980, likely due to Aurora switching to surface water during that time frame.

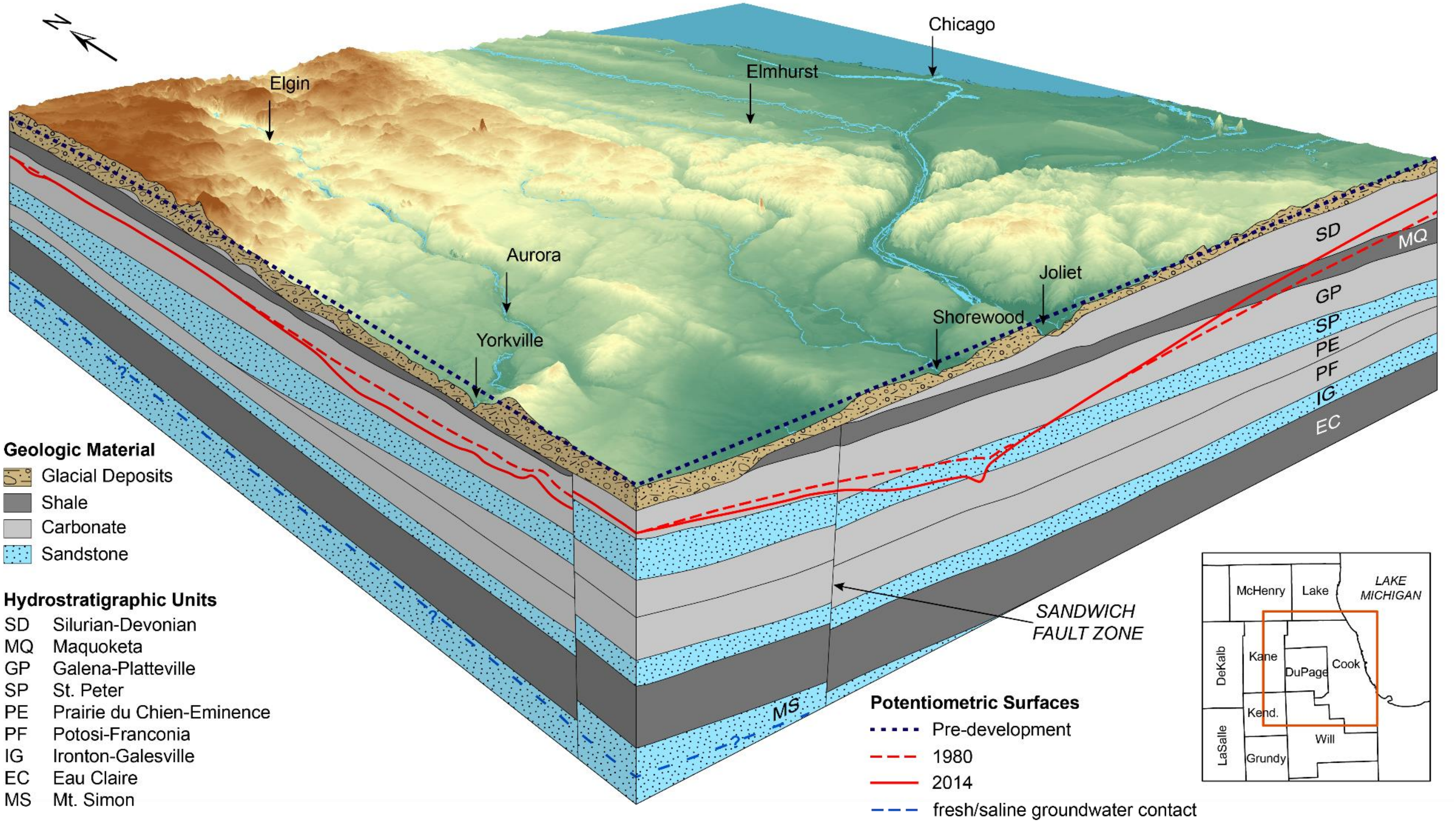

Figure 23: Potentiometric surface of the Cambrian-Ordovician sandstone aquifers for predevelopment, 1980, and 2014 in northeastern Illinois. The left cutaway runs through southern McHenry, Kane, and Kendall Counties. The right cutaway runs through Kendall, Will, and southern Cook Counties

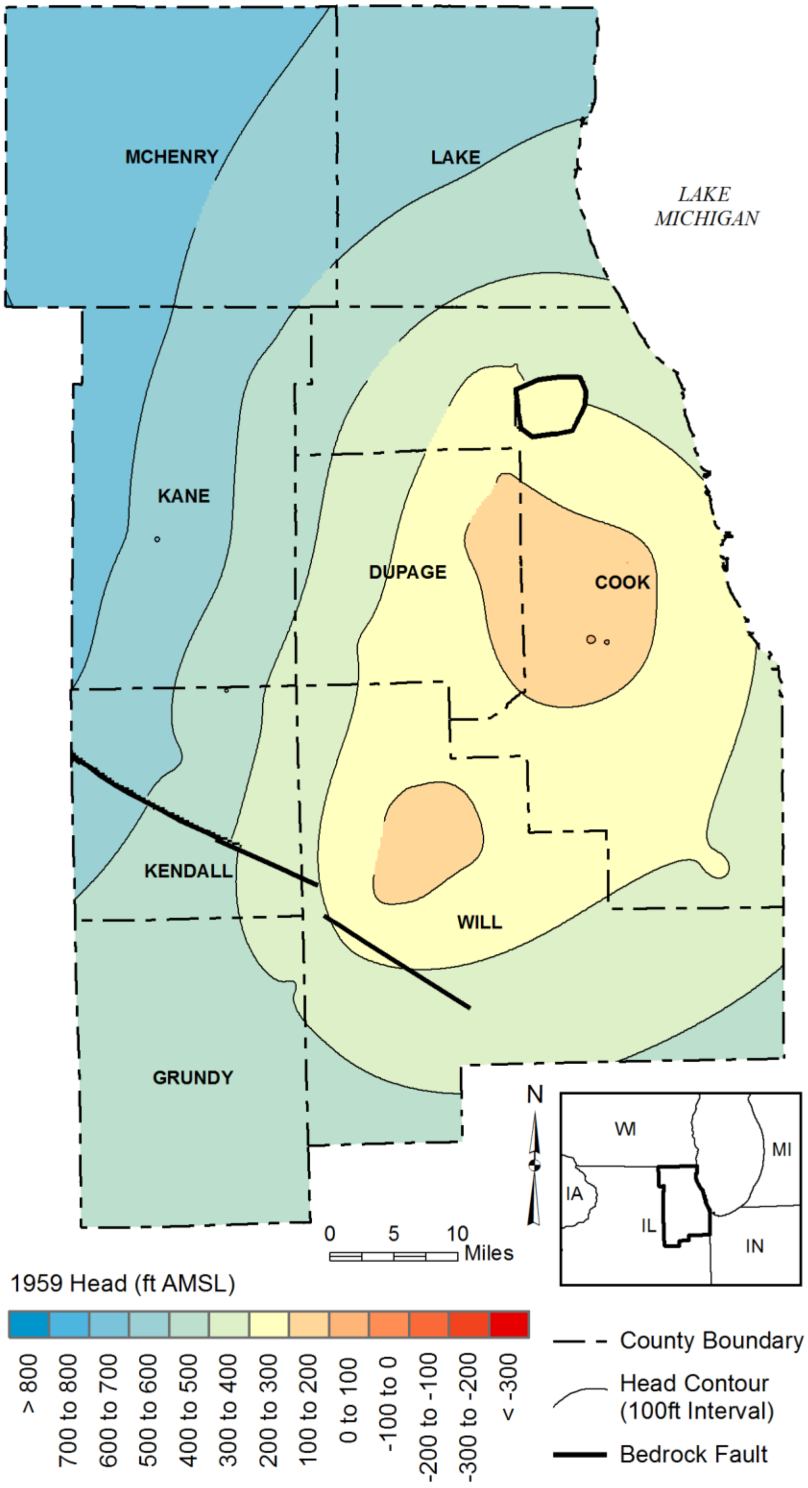

Figure 24: Potentiometric surface of the Cambrian-Ordovician sandstone aquifers in 1959 for the Northeastern Illinois WSPR.

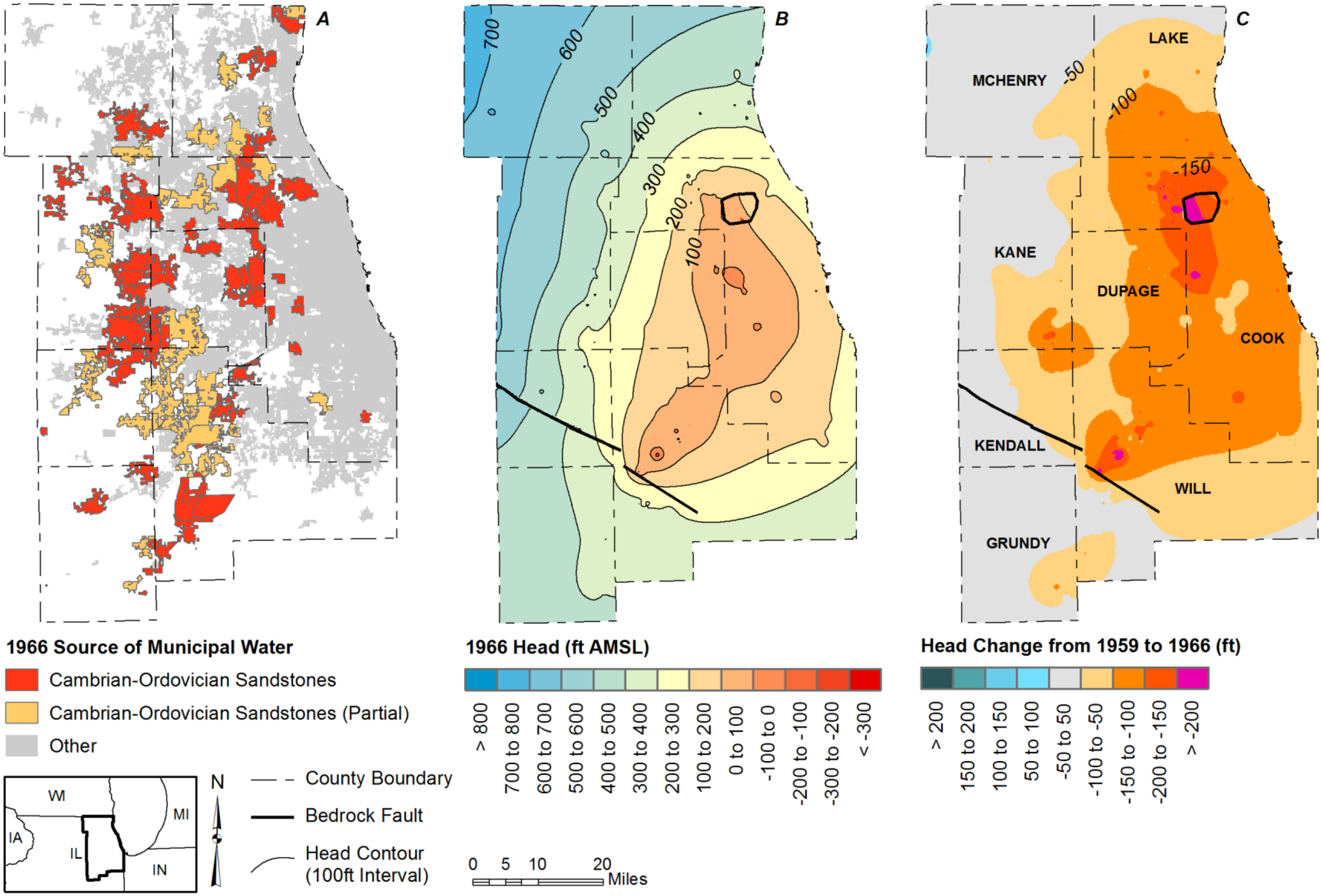

Figure 25: 1966 a) source of water, b) potentiometric surface, and c) head change from 1959 for the Cambrian-Ordovician sandstone aquifers in the Northeastern Illinois WSPR.

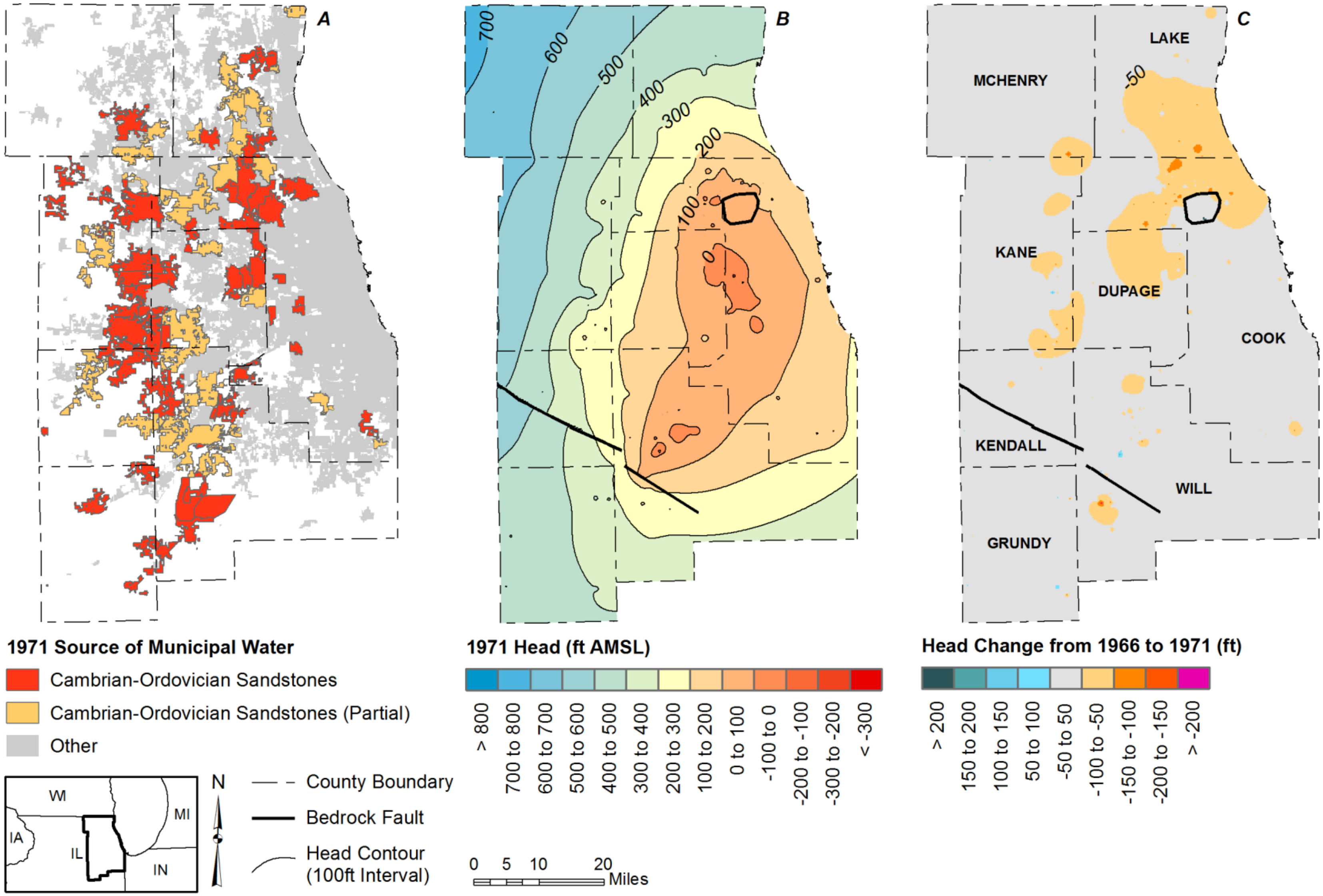

Figure 26: 1971 a) source of water, b) potentiometric surface, and c) head change from 1966 for the Cambrian-Ordovician sandstone aquifers in the Northeastern Illinois WSPR.

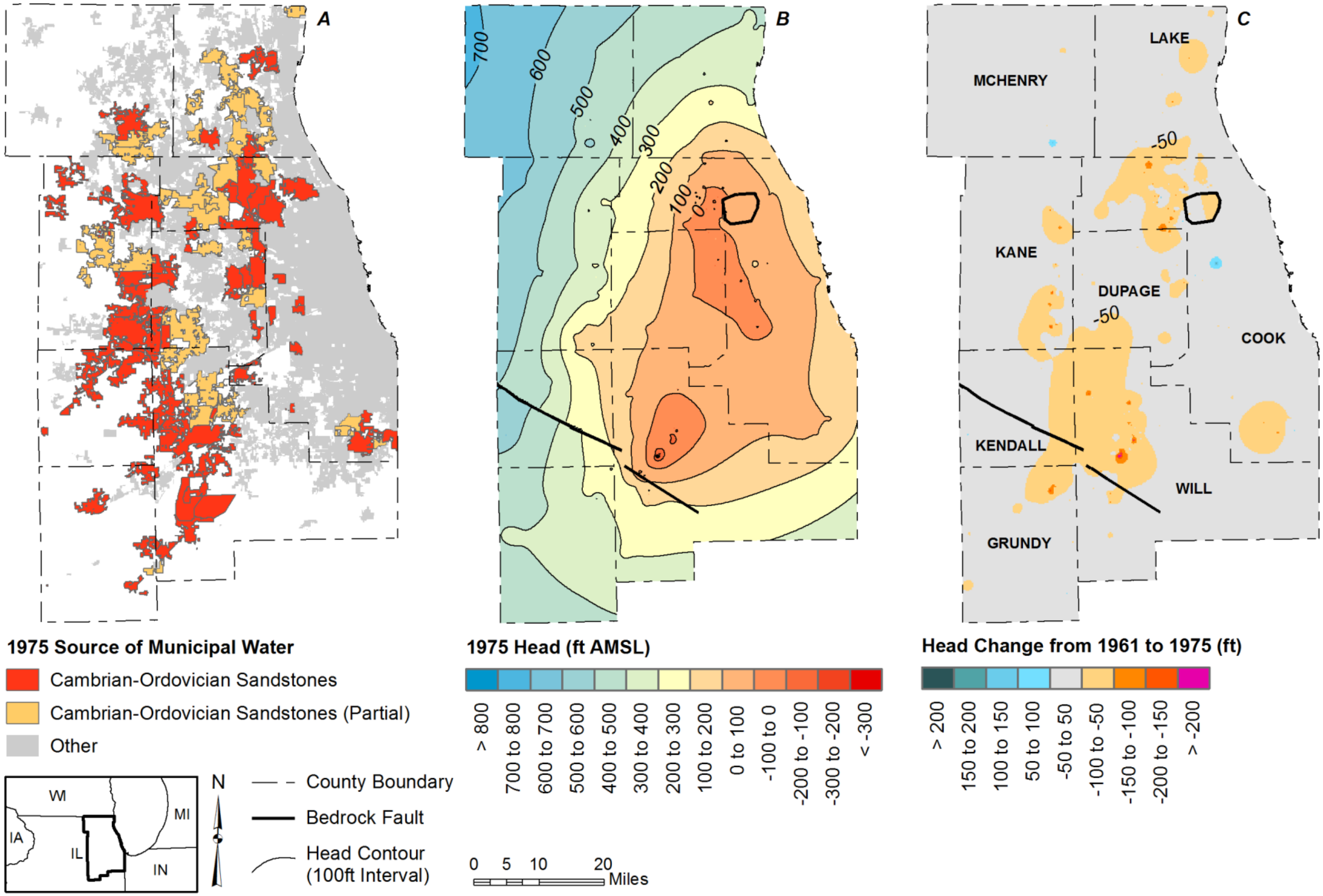

Figure 27: 1975 a) source of water, b) potentiometric surface, and c) head change from 1971 for the Cambrian-Ordovician sandstone aquifers in the Northeastern Illinois WSPR.

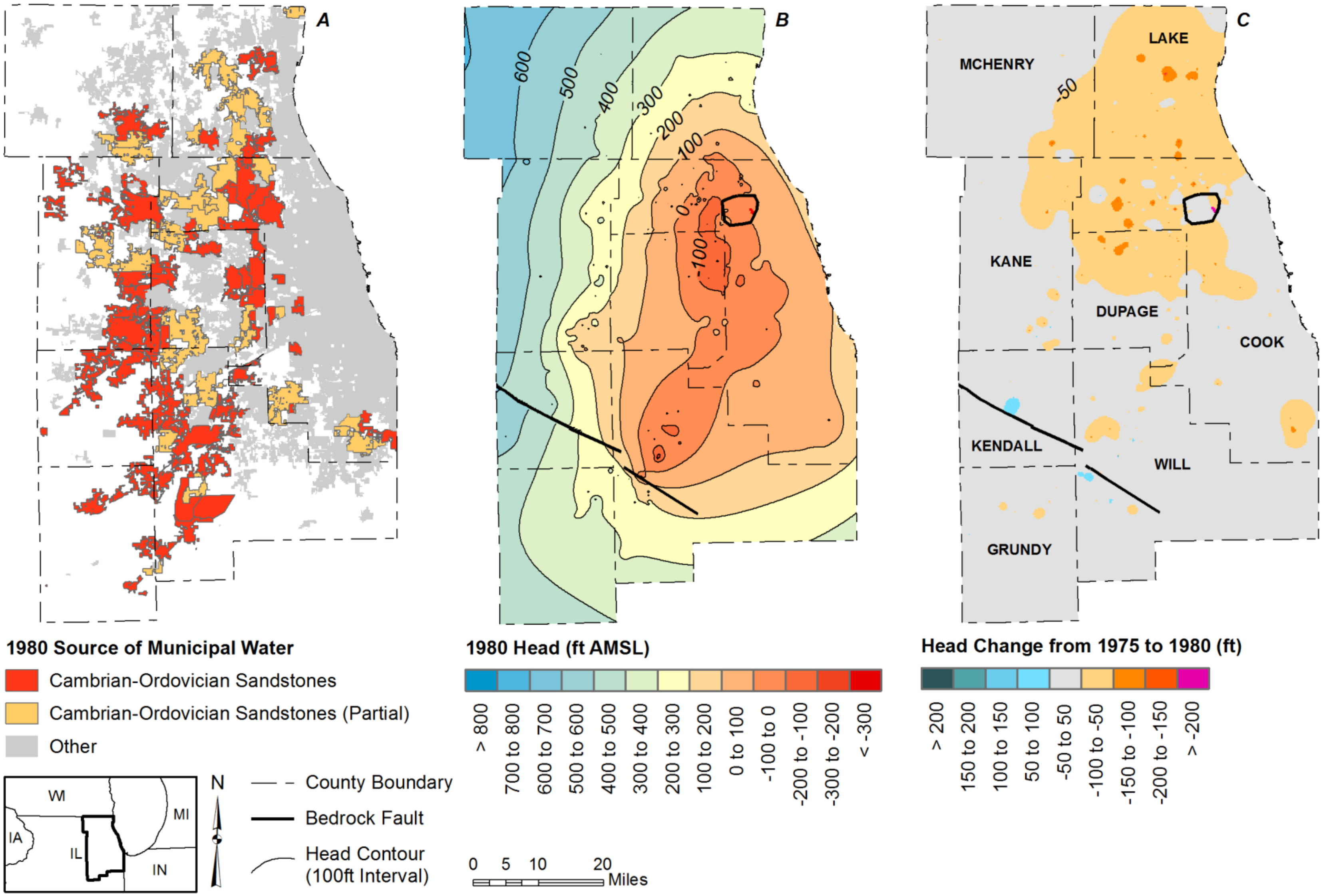

Figure 28: 1980 a) source of water, b) potentiometric surface, and c) head change from 1975 for the Cambrian-Ordovician sandstone aquifers in the Northeastern Illinois WSPR.

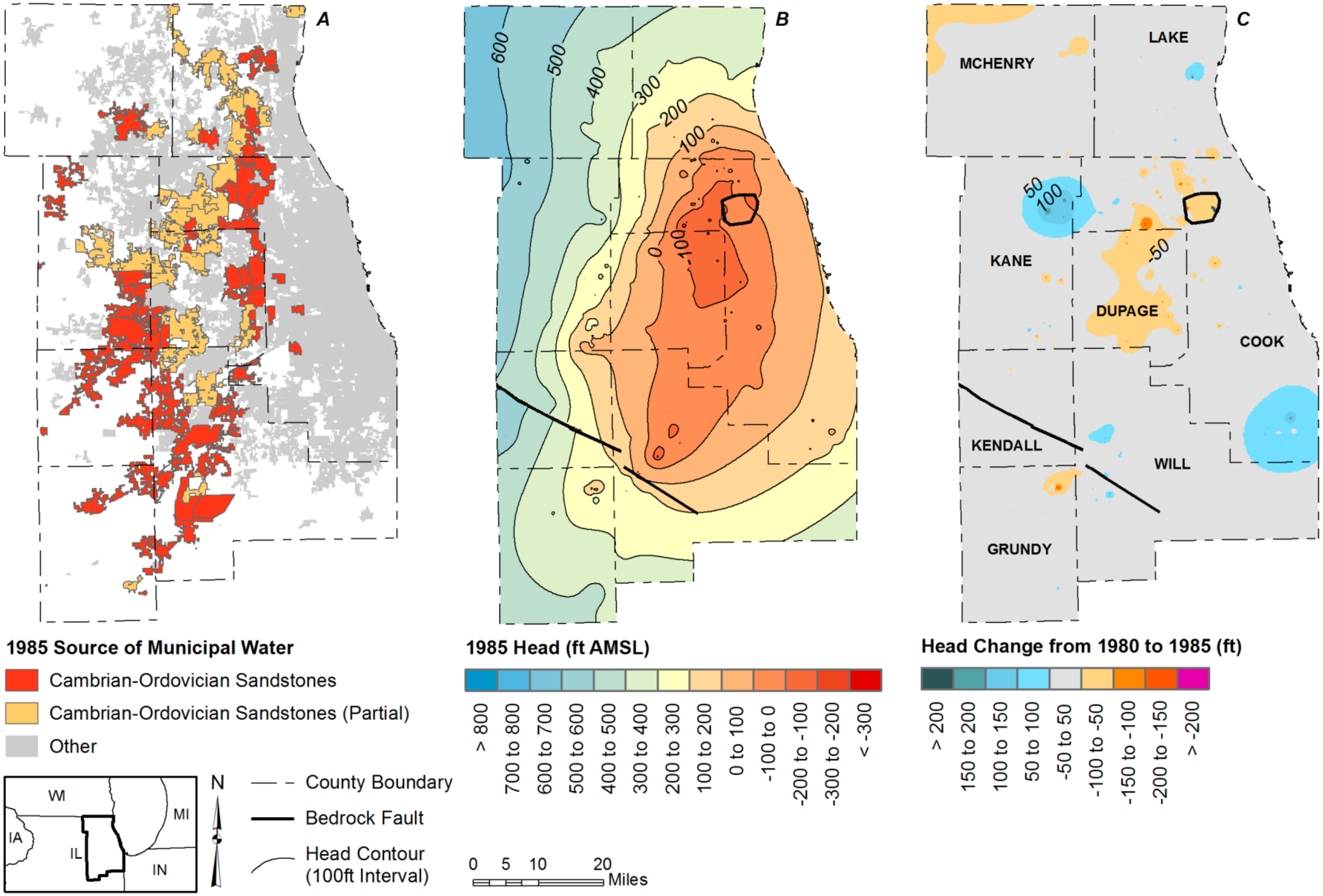

Figure 29: 1985 a) source of water, b) potentiometric surface, and c) head change from 1980 for the Cambrian-Ordovician sandstone aquifers in the Northeastern Illinois WSPR.

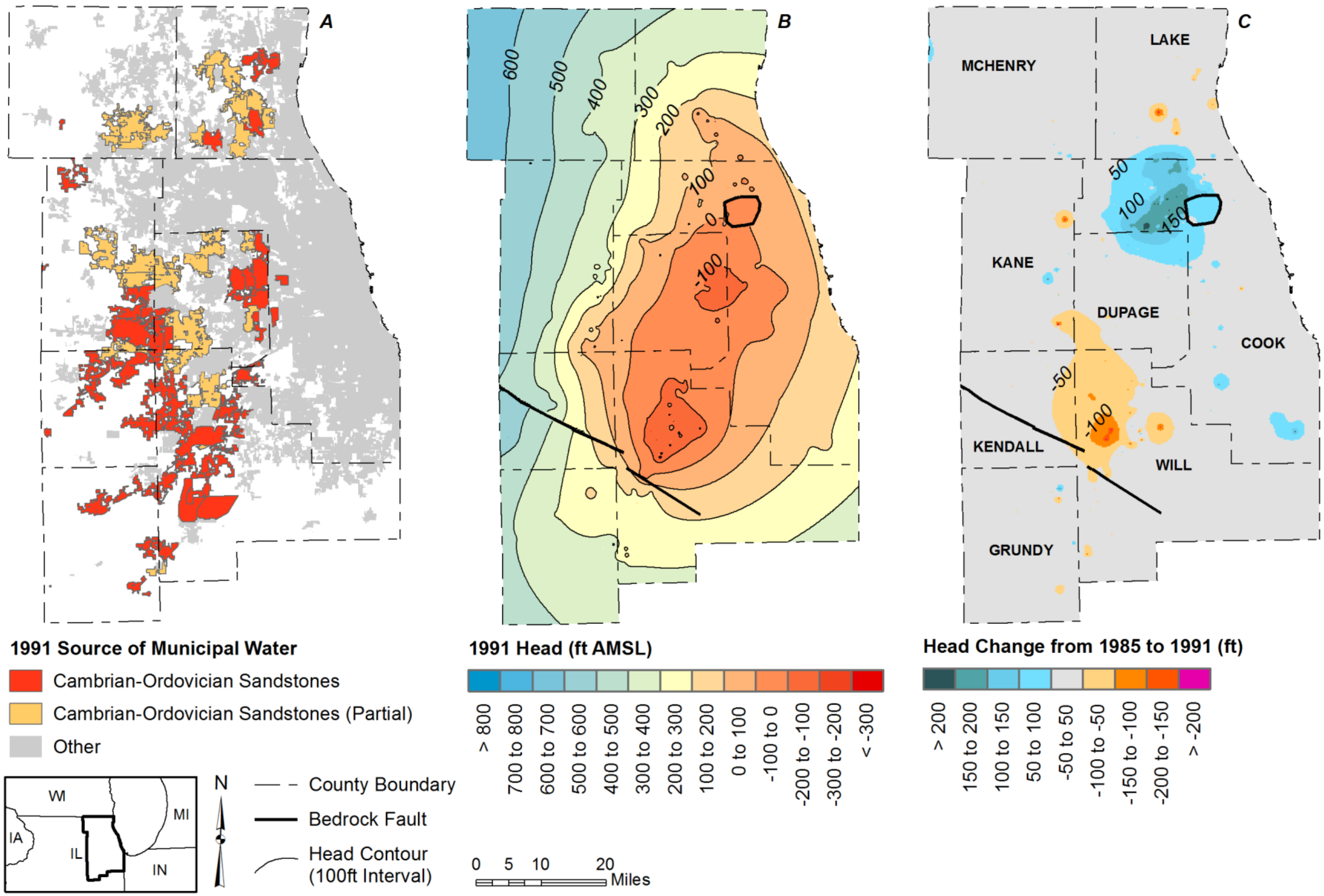

Figure 30: 1991 a) source of water, b) potentiometric surface, and c) head change from 1985 for the Cambrian-Ordovician sandstone aquifers in the Northeastern Illinois WSPR.

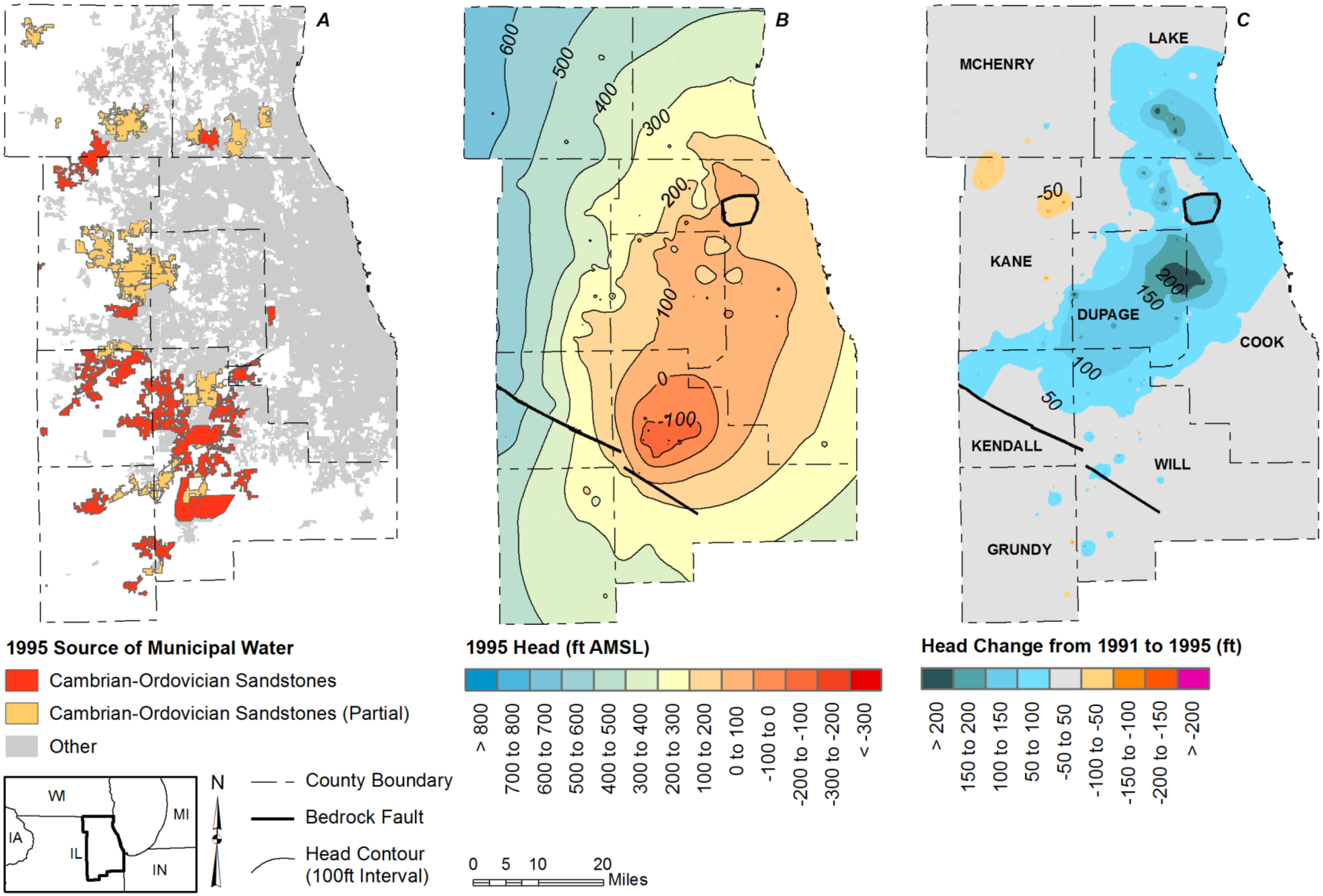

Figure 31: 1995 a) source of water, b) potentiometric surface, and c) head change from 1991 for the Cambrian-Ordovician sandstone aquifers in the Northeastern Illinois WSPR.

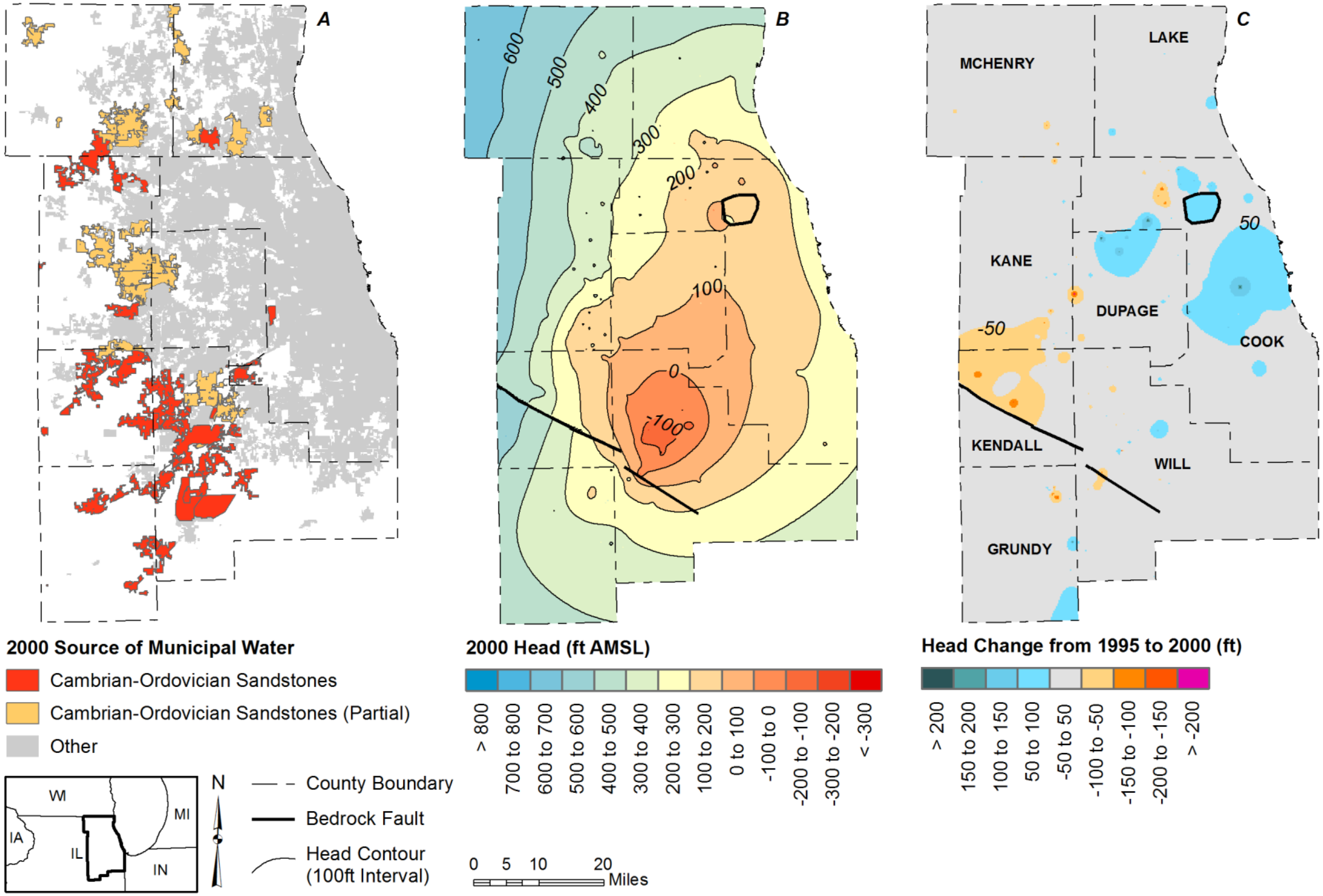

Figure 32: 2000 a) source of water, b) potentiometric surface, and c) head change from 1995 for the Cambrian-Ordovician sandstone aquifers in the Northeastern Illinois WSPR.

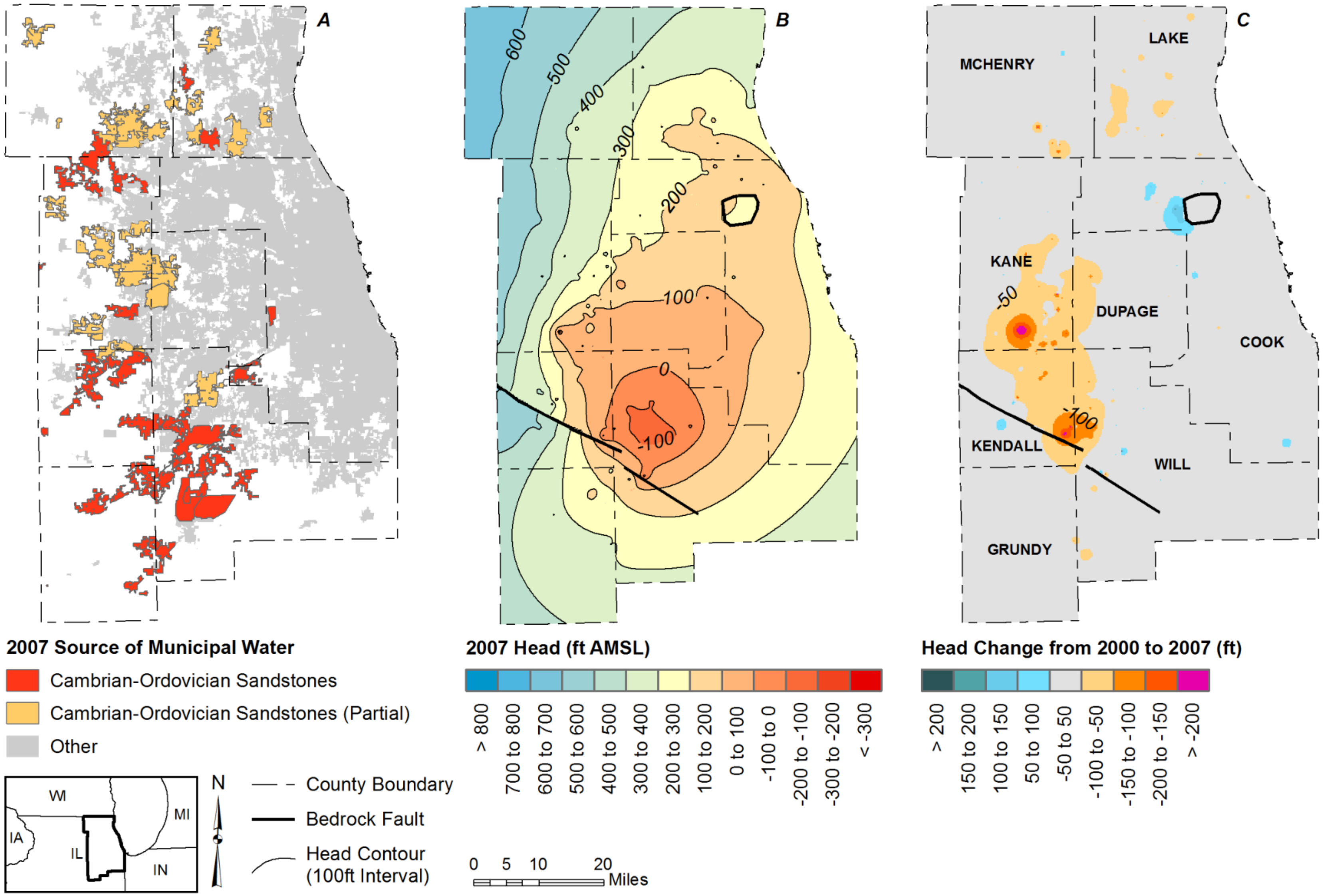

Figure 33: 2007 a) source of water, b) potentiometric surface, and c) head change from 2000 for the Cambrian-Ordovician sandstone aquifers in the Northeastern Illinois WSPR.

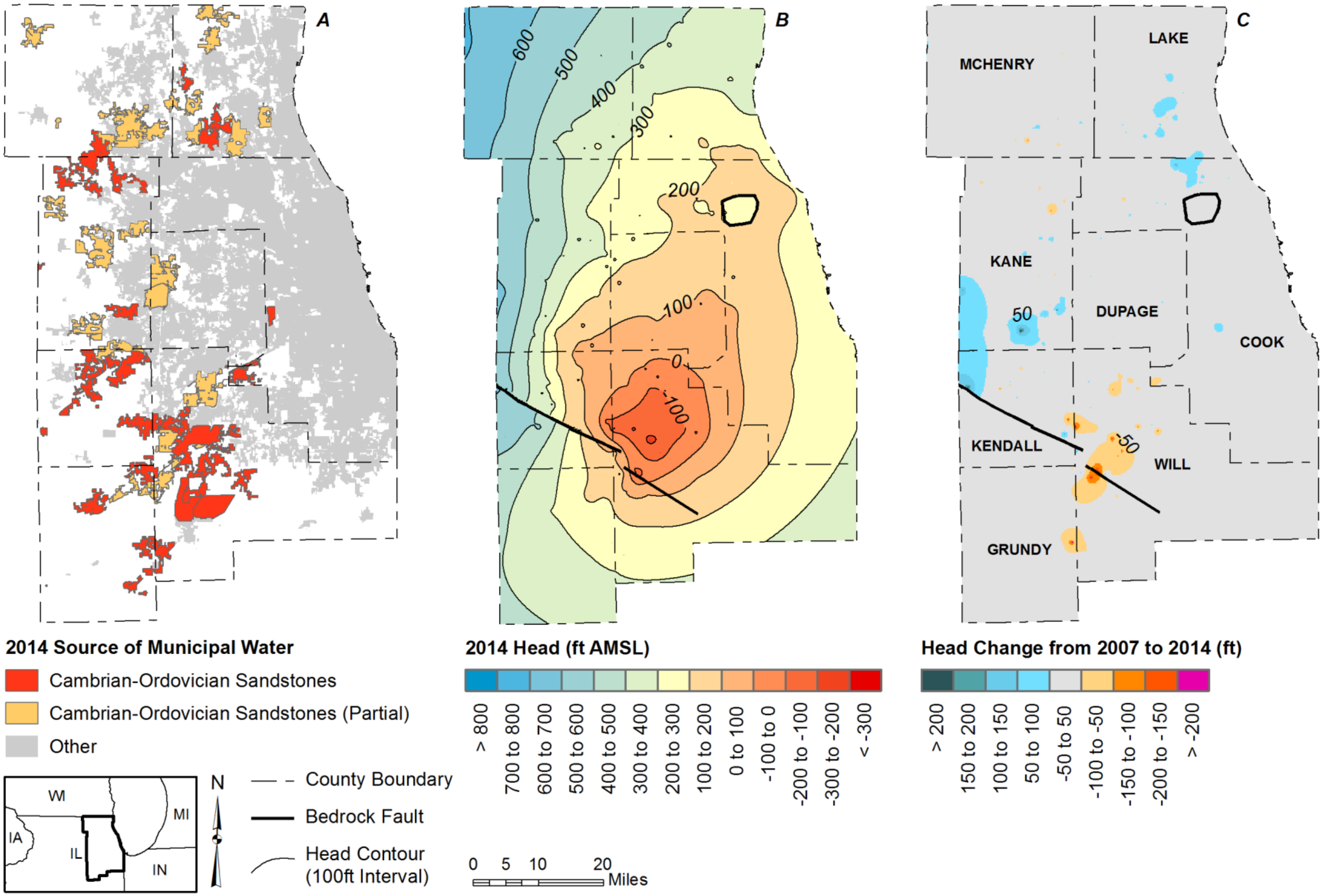

Figure 34: 2014 a) source of water, b) potentiometric surface, and c) head change from 2000 for the Cambrian-Ordovician sandstone aquifers in the Northeastern Illinois WSPR.

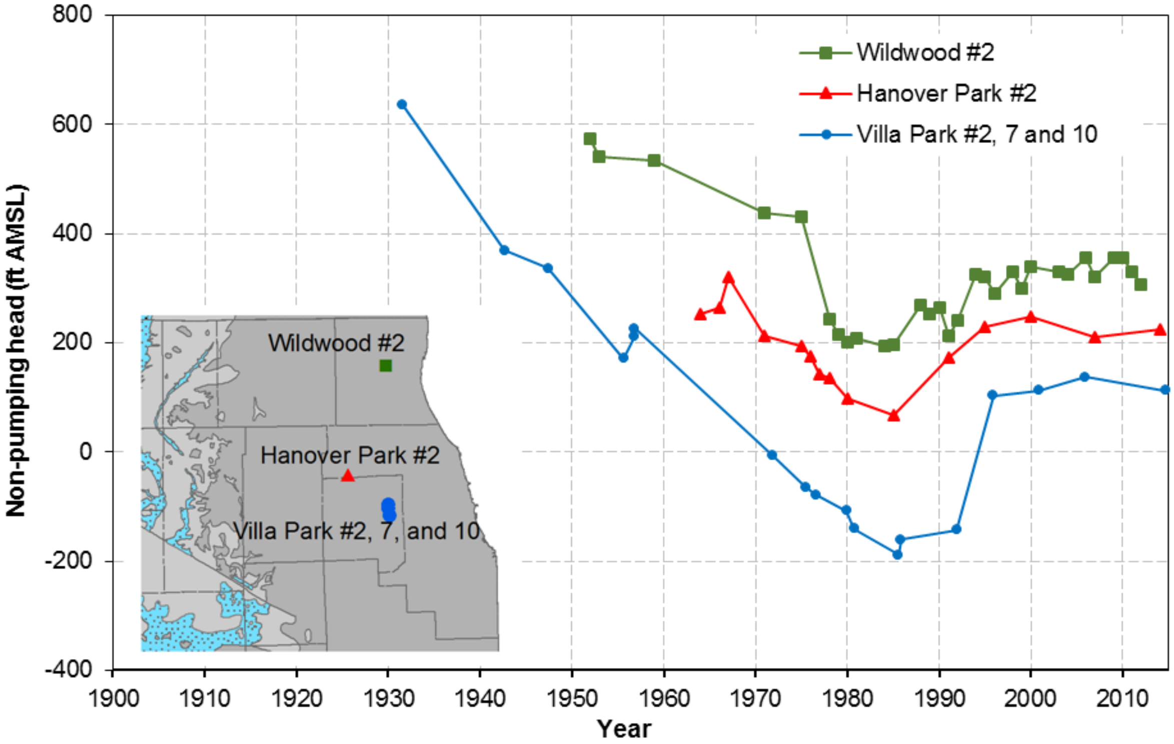

Figure 35: Observed head values for Wildwood #2, Hanover Park #2, and Villa Park #2 (1931-1955), #7 (1956-1995), and #10 (2000-2014). See Figure 6 for the inset image legend.

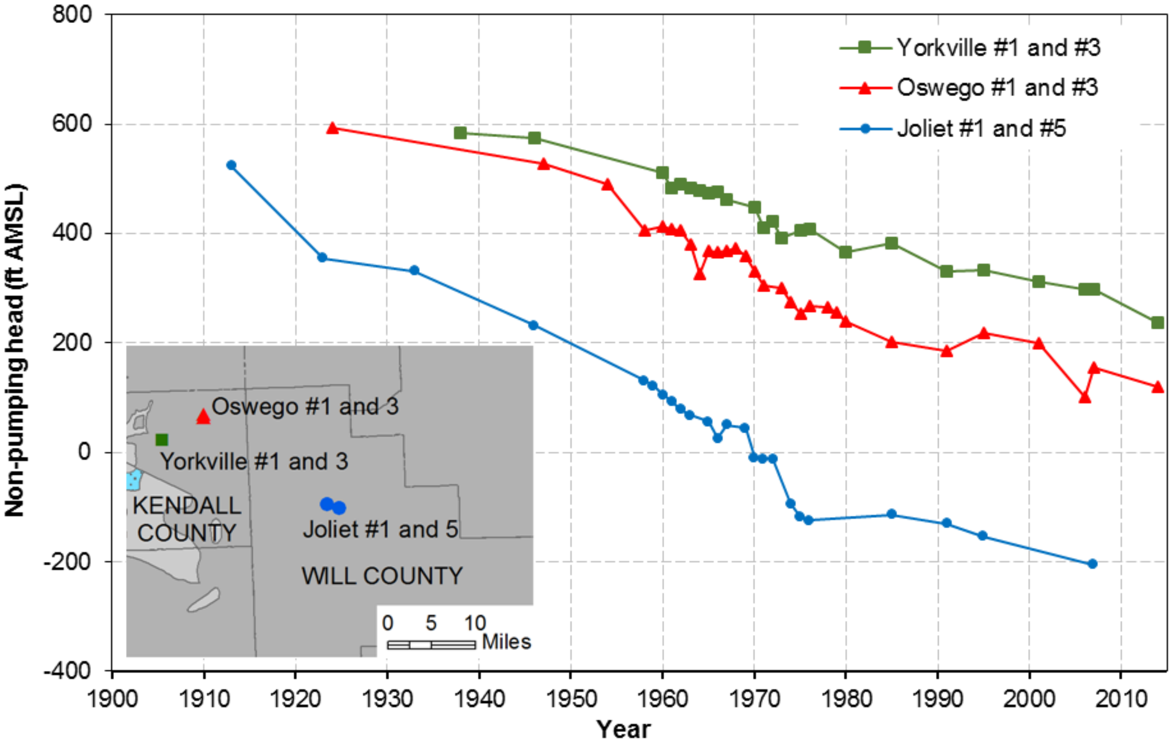

Figure 36: Observed head values for Yorkville #1 (1938-1946) and #3 (1960-2014), Oswego #1 (1924-1958) and #3 (1960-2014), and Joliet #5 (1913-1946) and #1 (1958-2007). See Figure 6 for the inset image legend.

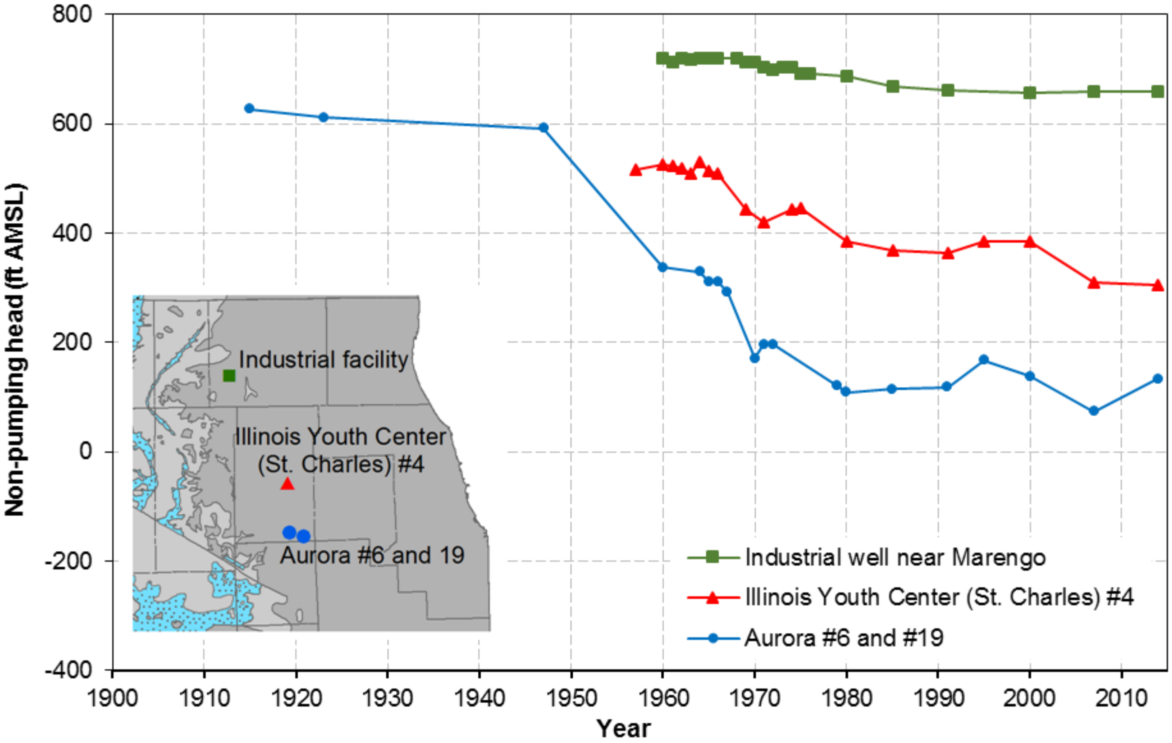

Figure 37: Observed head values for an industrial well near Marengo, IL, Illinois Youth Center (St. Charles) #4, and Aurora #6 (1915-1980) and #19 (1985-2014). See Figure 6 for the inset image legend.

5.4.4 Wisconsin

Similar to northeastern Illinois, shifting sources of water for major communities along Lake Michigan has resulted in changing heads for southeastern Wisconsin. Withdrawals in Waukesha and Milwaukee Counties from the Cambrian-Ordovician sandstone aquifers decreased by, respectively, 4.0 and 4.6 Mgd between 1980 and 2012 (compare Figure 17 to Figure 10, Table 4). Despite this, the cone of depression has shifted westward toward Waukesha, which still had the fourth largest withdrawal within the study area in 2012 (Table 4). The center of the cone has also become deeper through time. In Milwaukee County, the head change from 1980 to 2014 is minimal, while the head decrease in Waukesha County is as much as 200 ft (Figure 19). It is noted that one reason for the large decline in heads in Waukesha County is that pumping increased after 1980, but has been decreasing in recent years (Table 4). Recent recovery in heads has been observed throughout southeastern Wisconsin due to recent decreases in groundwater withdrawals, suggesting that the deepest heads may have already occurred. However, these heads have not recovered to 1980 levels at most wells (except the USGS monitoring well at Waukesha, WI, see Figure 38). This recovery is also observed in the hydrograph for the Richard Bong State Recreational Area, located in southeastern Wisconsin (Figure 38). Where the Cambrian-Ordovician sandstone aquifer is not overlain by shale, head change in Wisconsin has generally been less than 25 ft (Figure 19), as represented by the hydrograph for a well in Green County, WI.

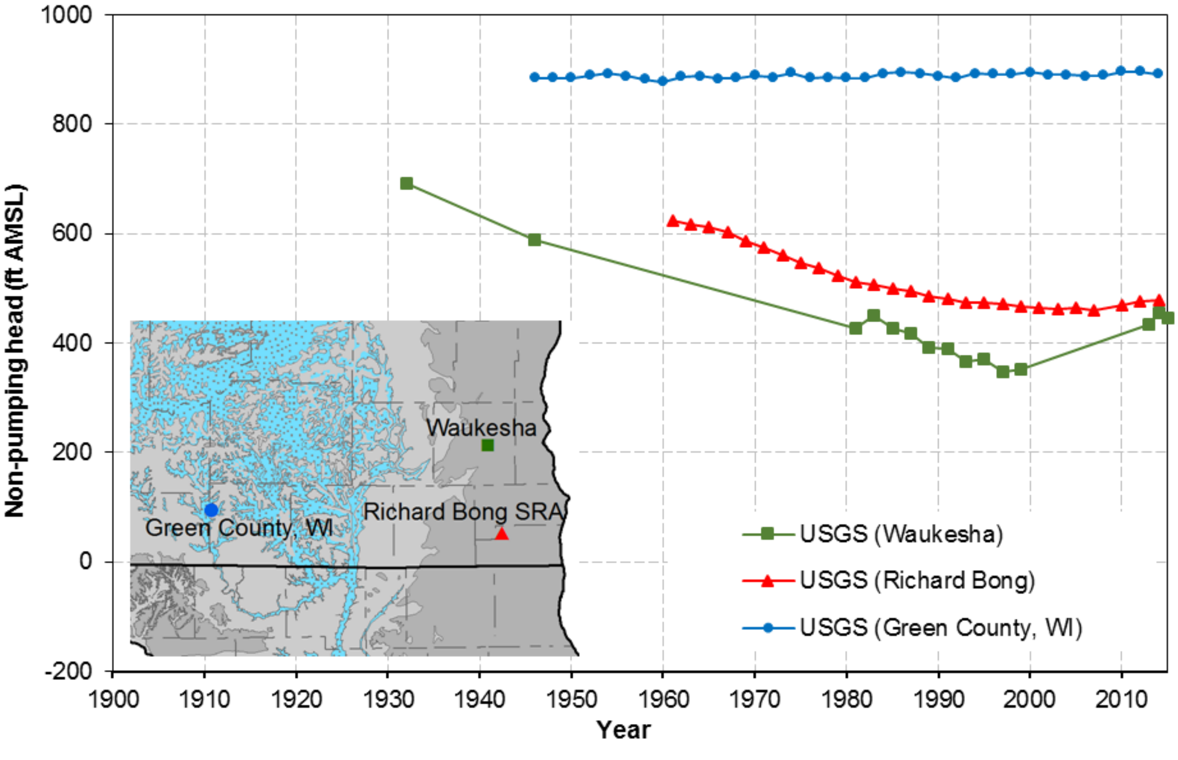

Figure 38: Observed Wisconsin heads at USGS monitoring wells in Waukesha (Site ID 430052088133501), the Richard Bong State Recreational Area (Site ID 423819088090301), and Green County, WI (Site ID 424427089494701). See Figure 6 for the inset image legend.

5.5 Considerations for interpretation of the potentiometric surface

The head contours presented in this study can be used to assess both regional-scale trends in heads and local-scale impacts of pumping. However, a few nuances and caveats must be considered when interpreting these contours on either scale.

5.5.1 Heterogeneity

Sandstone is often conceptualized as a continuous porous medium, yet there are actually fractures and lenses of dolomite, limestone, or shale that can result in local flow complexities. This can have a local impact on the head observed at the well, which may not be consistent with other regional head observations. While many of these observations would have been filtered during our data-screening process, some may remain and cause local high or low points in the contours.

The role of local heterogeneity is particularly important near the Sandwich Fault Zone, where proximity to a fault can greatly impact the heads and drawdowns. There was great variability in the heads within the Sandwich Fault Zone, some of which were filtered for purposes of contouring. For purposes of water supply planning, it is important to understand that the head at a well within this fault zone may not be consistent with the potentiometric surface shown in Figure 14.

5.5.2 Heads in multiple sandstone aquifers

Figure 14 depicts the 2014 potentiometric surface of Cambrian-Ordovician sandstone aquifers. However, the Cambrian-Ordovician is composed of multiple sandstone aquifers which may have different heads at a given location (Hart et al., 2006). Cross-connected wells are a major influence on head separation between sandstones.

5.5.2.1 Cross-connected wells- Conceptual Discussion

Under natural conditions, the St. Peter and Ironton-Galesville Sandstones are separated by two hydrostratigraphic units that, at least in Illinois, function as aquitards (Figure 4), preventing groundwater circulation between the sandstones. However, many wells throughout are open to both sandstones, providing a pathway for flow exchange that bypasses the aquitards. Such wells are referred to as *cross-connected*. Any withdrawal from a well cross-connecting the St. Peter and Ironton-Galesville Sandstones would be satisfied by water from both aquifers (Figure 39a). The head at the well will be the same in both aquifers, but can diverge farther away.

Now consider the impact of casing off the St. Peter Sandstone in an active, high capacity cross-connected well, leaving the well only open to the Ironton-Galesville Sandstone (Figure 39b). If the aquitard was otherwise undisturbed, all demands would be satisfied by water from the Ironton-Galesville Sandstone. Consequently, the head in the St. Peter will stay the same while the head in the Ironton-Galesville will decrease due to the demands.

Finally, consider a well open only to the Ironton-Galesville Sandstone adjacent to an inactive cross-connected well (Figure 39c). The cross-connected well provides a pathway for water to flow from the St. Peter Sandstone to the Ironton-Galesville. Heads will decrease at the production well open only to the Ironton-Galesville, but they will also decrease in the St. Peter Sandstone at the inactive cross-connected well.

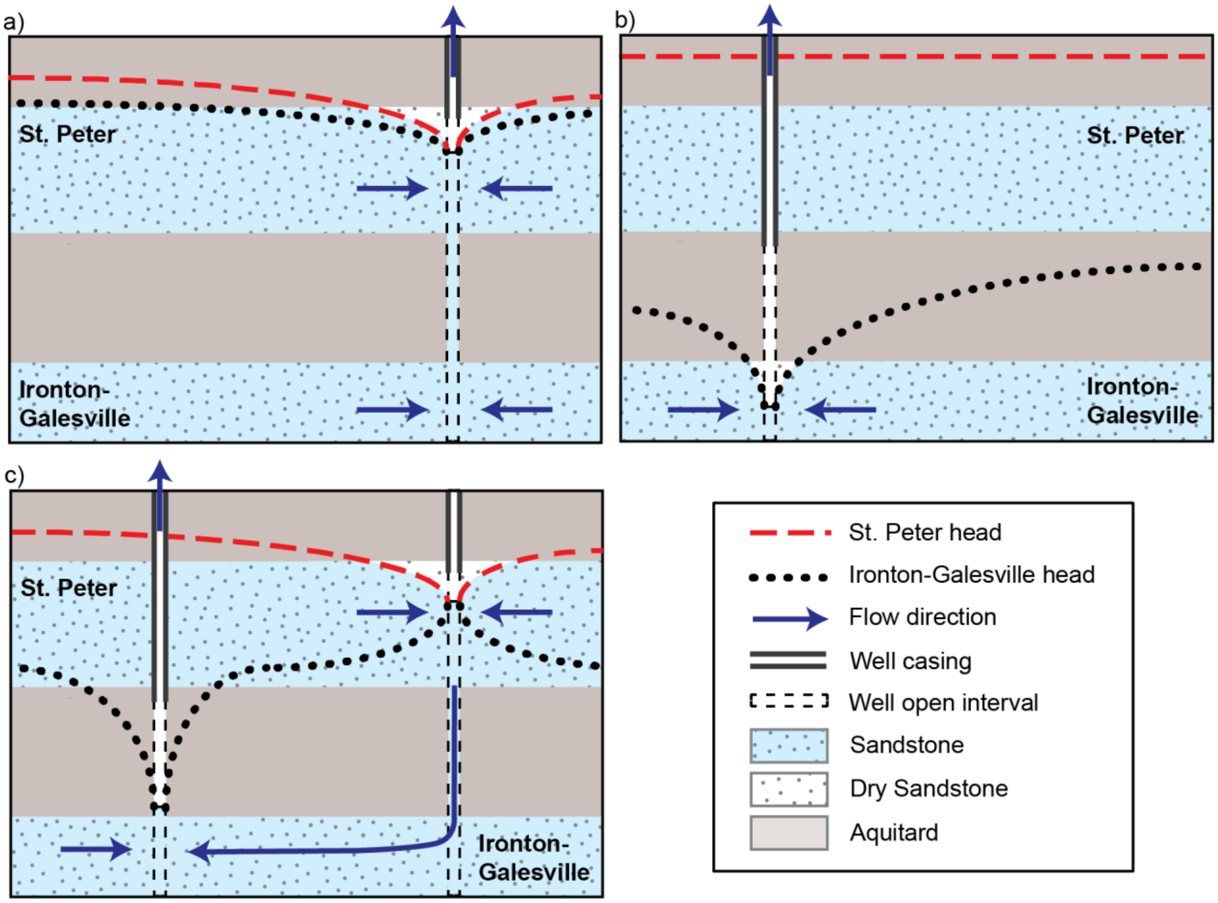

Figure 39: Conceptual diagram of separation of St. Peter and Ironton-Galesville heads when a) the well is cross-connected and b) the well is only open to the Ironton-Galesville. C) Flow through far removed cross connected wells due to the groundwater withdrawals from the Ironton-Galesville.

5.5.2.2 Cross-connected wells: Cambrian-Ordovician sandstone aquifers in Illinois

Head separation within the Cambrian-Ordovician sandstone aquifers of northeastern Illinois has not been considered in previous synoptic measurements (Suter et al., 1959; Burch, 2002), primarily because the density of cross-connected wells in areas of heavy withdrawals prevented any regional separation of St. Peter and Ironton-Galesville heads. In the 2007 synoptic measurement, the largest head difference observed was 60 ft in the Joliet region (Burch, 2008). However, in the 2014 synoptic measurement, this head separation was over 300 ft in this same region. This is primarily due to the proliferation of wells open only to the Ironton-Galesville in western Joliet, an area with few cross-connected wells, resulting in a situation similar to Figure 39c.

In interpreting the 2014 potentiometric contour, it is important to consider the open interval of wells used to generate the contour. These wells can be classified into four types:

1. **St. Peter wells.** These wells are open to the St. Peter Sandstone but not to the Ironton-Galesville Sandstone. The wells may be cross-connected with other sandstone aquifers overlying the Ironton-Galesville.
2. **Ironton-Galesville wells.** These wells are open to the Ironton-Galesville Sandstone but case off the St. Peter. The wells may be cross-connected with other sandstone aquifers underlying the St. Peter.
3. **St. Peter–Ironton-Galesville wells.** These wells are cross-connected between the St. Peter and Ironton-Galesville Sandstones. The wells may also be cross-connected with other sandstone aquifers.
4. **Other sandstone wells.** These wells are only open to the following sandstone aquifers: New Richmond, Jordan, Gunter, Elmhurst, or Mt. Simon. They are not open to the St. Peter or Ironton-Galesville Sandstones.

In western Illinois, the majority of measurements in 2014 were obtained from St. Peter or cross-connected wells (Figure 40). Hence, the potentiometric surface of western Illinois shown in Figure 14 is most accurately viewed as a St. Peter Sandstone surface. However, the few Ironton-Galesville wells in this area had similar heads to the surrounding wells open to the St. Peter, indicating minimal head separation between the sandstones.

In the Northeastern Illinois WSPR, the majority of wells are either Ironton-Galesville or cross-connected wells (Figure 40). Hence, the potentiometric surface in Figure 14 for this region is most accurately viewed as an Ironton-Galesville Sandstone surface. In the vicinity of cross-connected wells, the heads in St. Peter wells were consistent with the Ironton-Galesville potentiometric surface, as had been noted in previous synoptic measurements (Burch, 2002). However, since 2000, many new Ironton-Galesville wells have been constructed in western Joliet, approximately 10-15 miles from the nearest cross-connected well. The resulting head difference is similar to that depicted in Figure 39c, with a large head separation (100-300 ft) between the Ironton-Galesville and St. Peter Sandstones at the point of pumping and a convergence of the heads at the nearest cross-connected well(s). The implication is that withdrawals from a well open only to the Ironton-Galesville Sandstone can be satisfied by water from the St. Peter Sandstone, even if cross-connected wells are a few miles away from the point of withdrawal.

In northeastern Illinois, the preponderance of wells are open to the Ironton-Galesville. St. Peter wells generally have higher heads than Ironton-Galesville or St. Peter-Ironton-Galesville wells, at least in areas with heavy withdrawals. The most desired outcome from this study was to capture the lowest head in the Cambrian-Ordovician sandstone aquifer system at a given point. Hence, for northeastern Illinois, many St. Peter wells were filtered during QA/QC; the resulting potentiometric surface is representative of the Ironton-Galesville Sandstone. It is noted that in the rest of the state, where demands are much lower, the St. Peter wells and Ironton-Galesville wells generally had consistent heads and wells did not have to be filtered because they were open to different units.

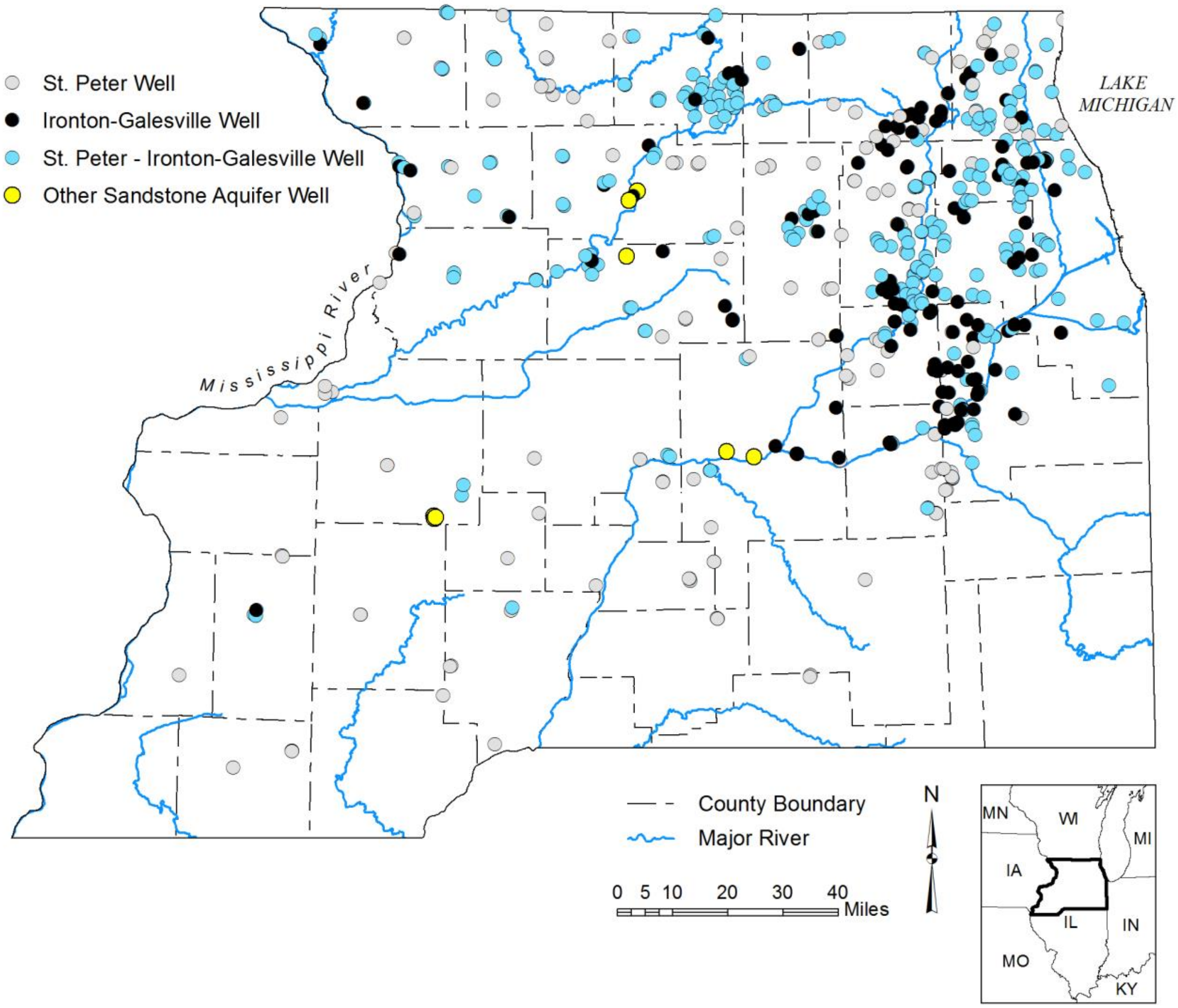

Figure 40: Wells measured in the 2014 synoptic measurement, classified as wells open to the Ironton-Galesville, wells open to the St. Peter, wells open to both the St. Peter and Ironton-Galesville, and wells open to neither (other sandstone aquifer wells).

6 Analysis and applications of the 2014 potentiometric surface

6.1 Three-dimensional groundwater flow model

6.1.1 Previous modeling work

The ISWS has developed a number of models intended to simulate flow in the Cambrian-Ordovician sandstone aquifers for northeastern Illinois (Meyer et al., 2009; Meyer et al., 2013; Roadcap et al., 2013). All of these recent models were developed using MODFLOW-2000 (McDonald and Harbaugh, 1988; Harbaugh et al., 2000), which uses a finite-difference solution to solve groundwater flow. The layers in each model represent a specific hydrostratigraphic unit as shown in Figure 5. To properly represent the three-dimensional shape of each layer, each model was divided into a number of grid cells, each with its own top elevation, bottom elevation, and set of hydrogeologic properties. One of the essential hydrogeologic properties assigned to a model cell was the hydraulic conductivity, which dictates the rate of flow in the horizontal and vertical direction.

Data from previous synoptic measurements were used to compare to the heads simulated by the groundwater flow model. Hydrologic properties were varied until the simulated heads matched the observed heads. For example, in Roadcap et al. (2013), properties were adjusted until the simulated heads matched well with the 2000 observations. To achieve this match, it was necessary to account for the cross-connections between the St. Peter and Ironton-Galesville. This was done by assigning a large vertical hydraulic conductivity zone that forced the simulated heads in the St. Peter and Ironton-Galesville to be similar. In the synoptic measurement for 2000 (Burch 2002), the head difference between these two units was found to be insignificant (< 10 ft in most areas, < 60 ft in the areas of heaviest pumping), so this assumption was appropriate.

6.1.2 Model reconceptualization and calibration

The synoptic measurement of 2014 indicated that the groundwater flow models required revision. In particular, head differences between the St. Peter and Ironton-Galesville Sandstones were observed to be in excess of 300 ft in the Joliet region. This was a new phenomenon due the proliferation of Ironton-Galesville-only wells installed in the western Joliet region starting in 2003. To capture this head difference, a reconceptualization of the connections between the sandstone aquifers was necessary. Instead of a large zone of vertical hydraulic conductivity, it was necessary to assign a high vertical hydraulic conductivity to every model cell where a cross-connecting well was present. These high vertical hydraulic conductivity cells allowed for large rates of exchange between sandstones at the well while preserving the integrity of the aquitard far removed from the cross-connecting wells. The new conceptualization, which was applied to Roadcap et al. (2013), involved adding cross-connecting wells between the shallow aquifers and St. Peter Sandstone (Figure 41a), St. Peter and Ironton-Galesville Sandstones (Figure 41b), and Ironton-Galesville and Mt. Simon Sandstones (Figure 41c). It is noted that specialized MODFLOW packages have been designed to simulate flow through cross-connected wells, in particular Multi-Node Well (Niswonger et al., 2011) and Connected Linear Nodes (Panday et al., 2013). Alternative MODFLOW models were developed using these packages. These results compared favorably with the high vertical hydraulic conductivity zones but required much longer computation time. This is especially prohibitive when developing multiple future scenarios.

As consistent with previous modeling studies, the Sandwich Fault Zone was simulated as a low hydraulic conductivity zone (Meyer et al., 2013; Roadcap et al., 2013). A slightly revised conceptualization of the shape of the fault was developed to restrict lateral flow at the Will and Kendall County border, which was necessary to simulate some of the low heads observed in that region since 2000 (Figure 41d). This mapping is consistent with the observation of fault blocks observed by Kolata et al. (1978). However, local heterogeneity within the fault zone cannot be captured in our groundwater flow model at the current resolution of 2500 ft. This local heterogeneity can be very important for water supply planning efforts near the fault.

The revised groundwater flow model was calibrated to both 2000 and 2014 data (Figure 42). It is noted that the lowest head observations occurred in the year 2014, indicative of the large decreases observed in western Joliet (Figure 33 and Figure 34). The simulated head values were also calibrated against the observations from other synoptic measurements.

6.1.3 Future simulations

Model simulations to 2050 were conducted using two future demand projections developed by Dziegielewski and Chowdhury (2008): baseline and least resource intensive (LRI). These two projections were created using a number of factors, including population, water usage, and economic drivers. A third projection, most resource intensive, was not used in this study due to the large discrepancy between these projections and actual demand from 2005 to 2012. Instead, a third scenario was utilized whereby withdrawals are held constant at 2011 rates until 2050 (henceforth referred to as the constant pumping scenario). The projected demands for these three scenarios are shown in Figure 43.

The hydrographs in Figure 44 to Figure 48 show the simulated future heads for each of these scenarios. For the baseline scenario, the head at Lake in the Hills #11 (Figure 44) falls below the top of the St. Peter. For the LRI and constant pumping scenarios, the head stays within 200 ft of the top of the St. Peter. The heads at Aurora well #19 have remained relatively constant since 1975 (Figure 45), close to the top of the St. Peter Sandstone. The LRI and constant pumping scenarios would continue the historic trend, but heads would fall to 180 ft below the top of the St. Peter in 2050 under the baseline scenario. The 2050 head at Yorkville #3 is highly variable depending on the scenario: 30 ft above the St. Peter in the constant scenario, 102 ft under in the LRI scenario, and below the bottom of the St. Peter in the baseline scenario (Figure 46). At Joliet #10, the head is below the bottom of the St. Peter in 2014 and all 2050 demand projection scenarios (Figure 47). Under the baseline projection demand scenario, the simulated head continues to decrease to 50 ft above the top of the Ironton-Galesville. Finally, at an industrial well near Joliet, just south of the Sandwich Fault Zone, heads are projected to stay at or near the top of the St. Peter in the constant and LRI scenarios, but fall to the bottom of the St. Peter in 2050 in the baseline scenario.

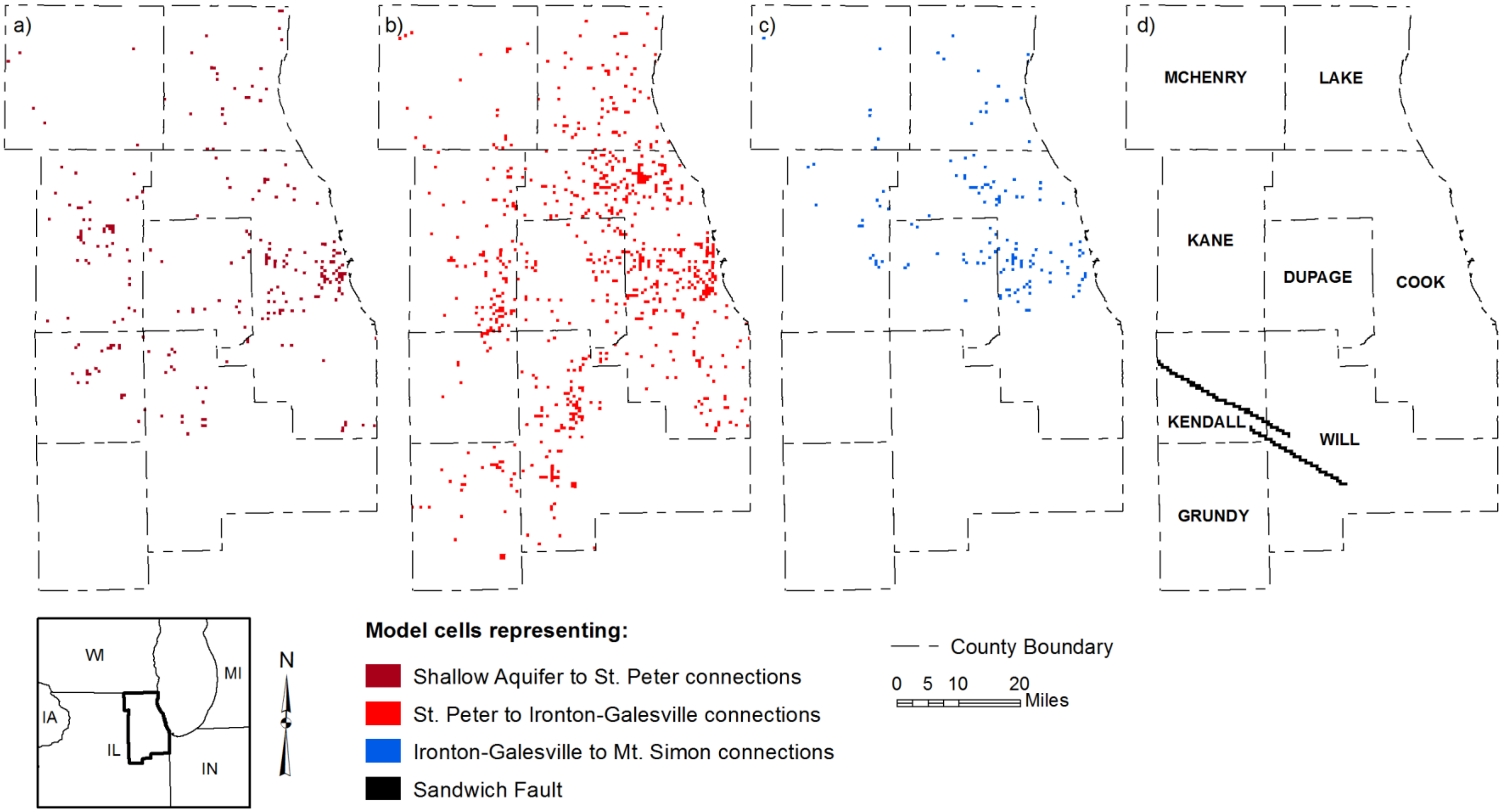

Figure 41: Location of cells assigned a high vertical hydraulic conductivity to simulate cross-connecting wells between a) shallow bedrock and St. Peter Sandstone, b) St. Peter and Ironton-Galesville Sandstones, and c) Ironton-Galesville and Mt. Simon Sandstones. d) Location of cells assigned a low hydraulic conductivity to simulate the Sandwich Fault Zone.

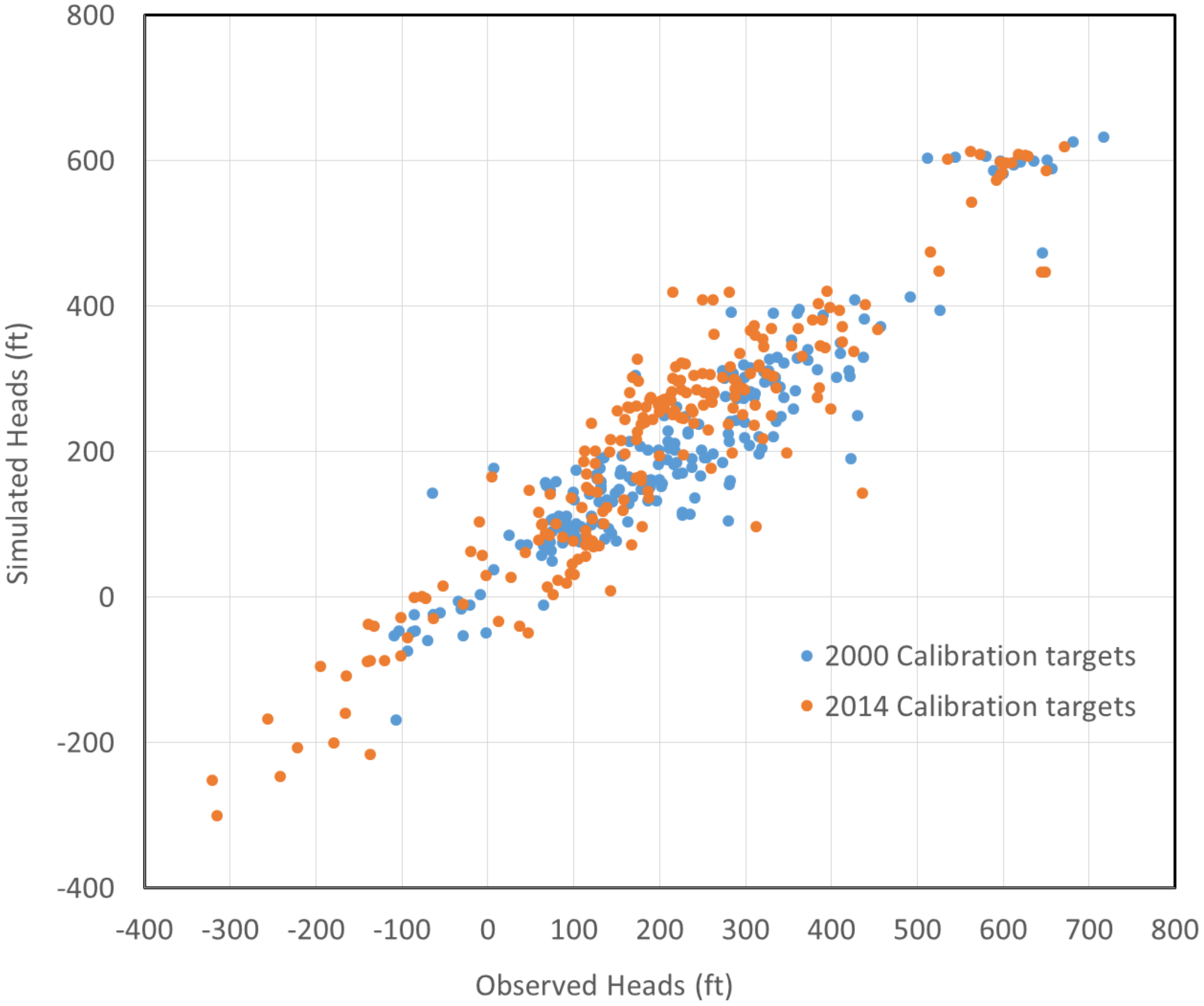

Figure 42: Observed heads obtained from the 2000 and 2014 synoptic measurements plotted against simulated heads from a calibrated groundwater flow model for northeastern Illinois.

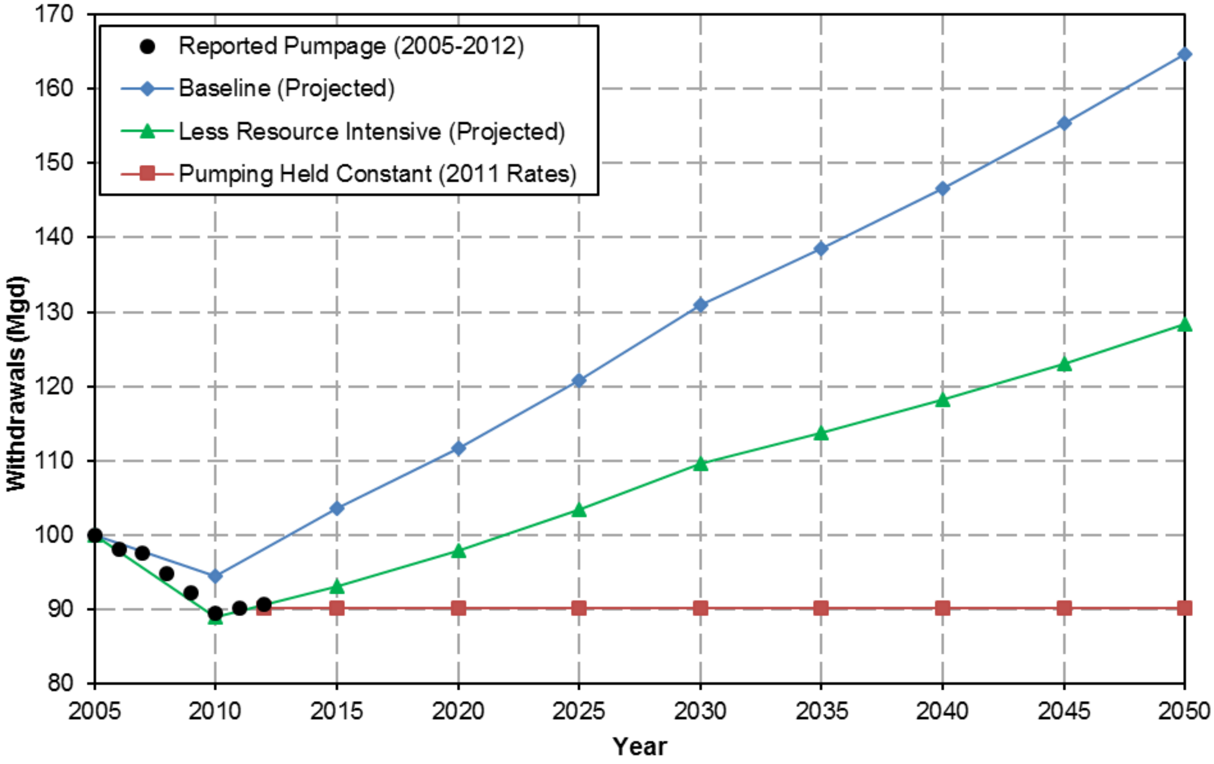

Figure 43: Projected groundwater withdrawals from the Cambrian-Ordovician sandstone aquifers in an eight-county region of northeastern Illinois (Cook, DuPage, Will, Kendall, Kane, McHenry, Lake, Grundy).

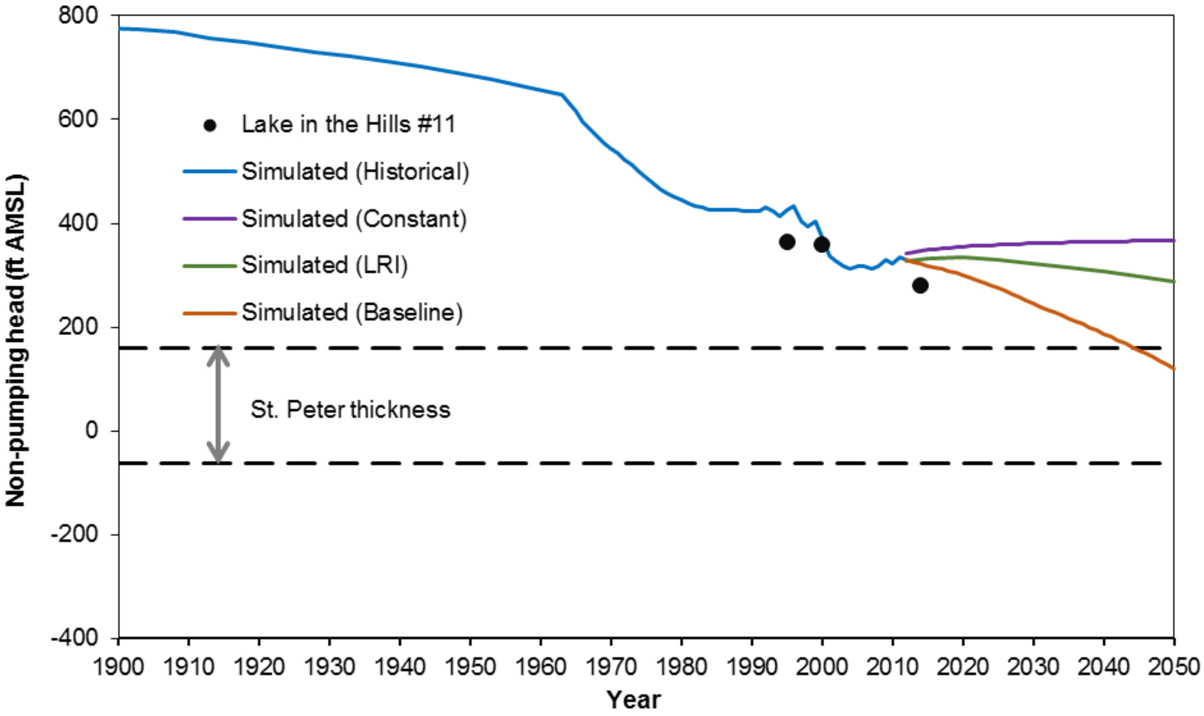

Figure 44: Hydrograph for Lake in the Hills #11, showing observed and simulated values. Future simulations are based off of three scenarios: baseline pumping, least resource intensive, and holding pumping rates constant after 2011.

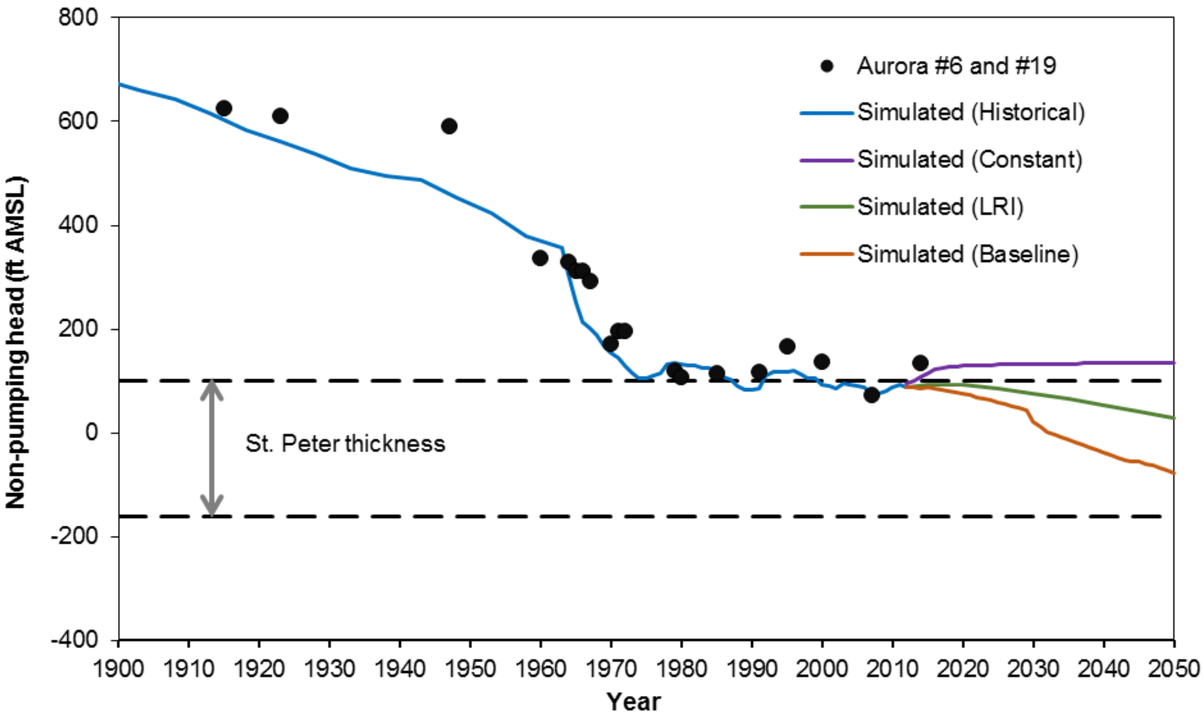

Figure 45: Hydrograph for Aurora #6 (1915-1980) and #19 (1985-2014), showing observed and simulated values. Future simulations are based on three scenarios: baseline pumping, least resource intensive, and holding pumping rates constant after 2011.

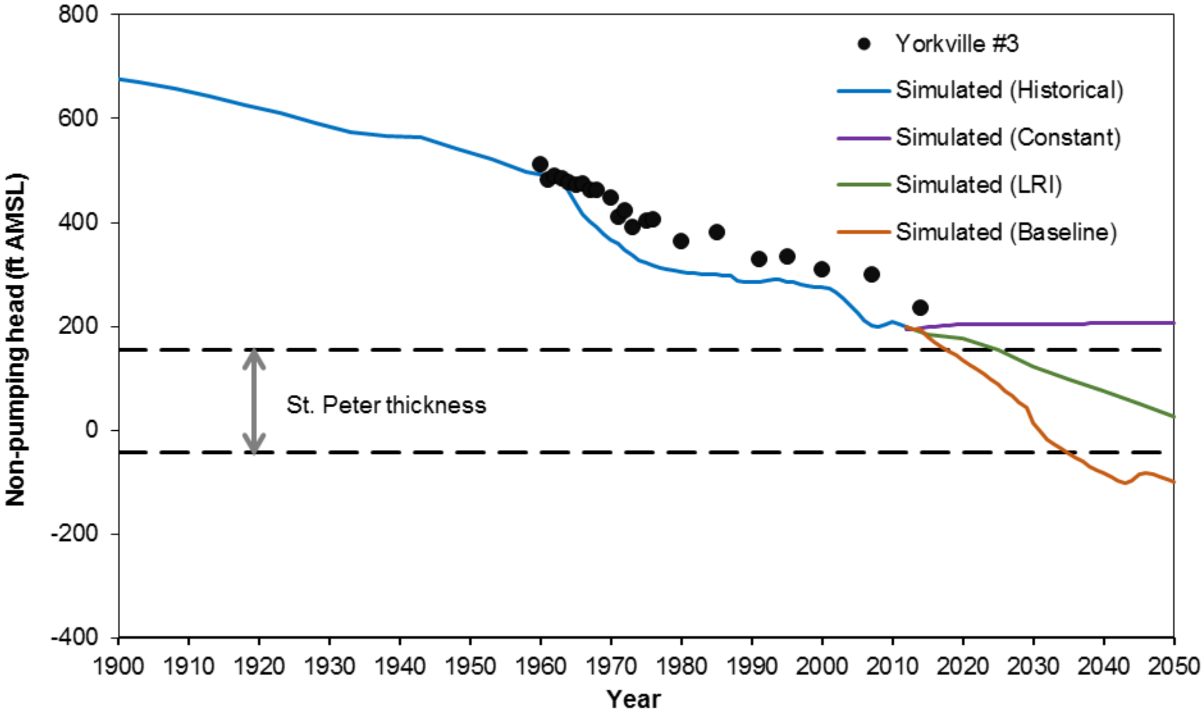

Figure 46: Hydrograph for Yorkville #3, showing observed and simulated values. Future simulations are based on three scenarios: baseline pumping, least resource intensive, and holding pumping rates constant after 2011.

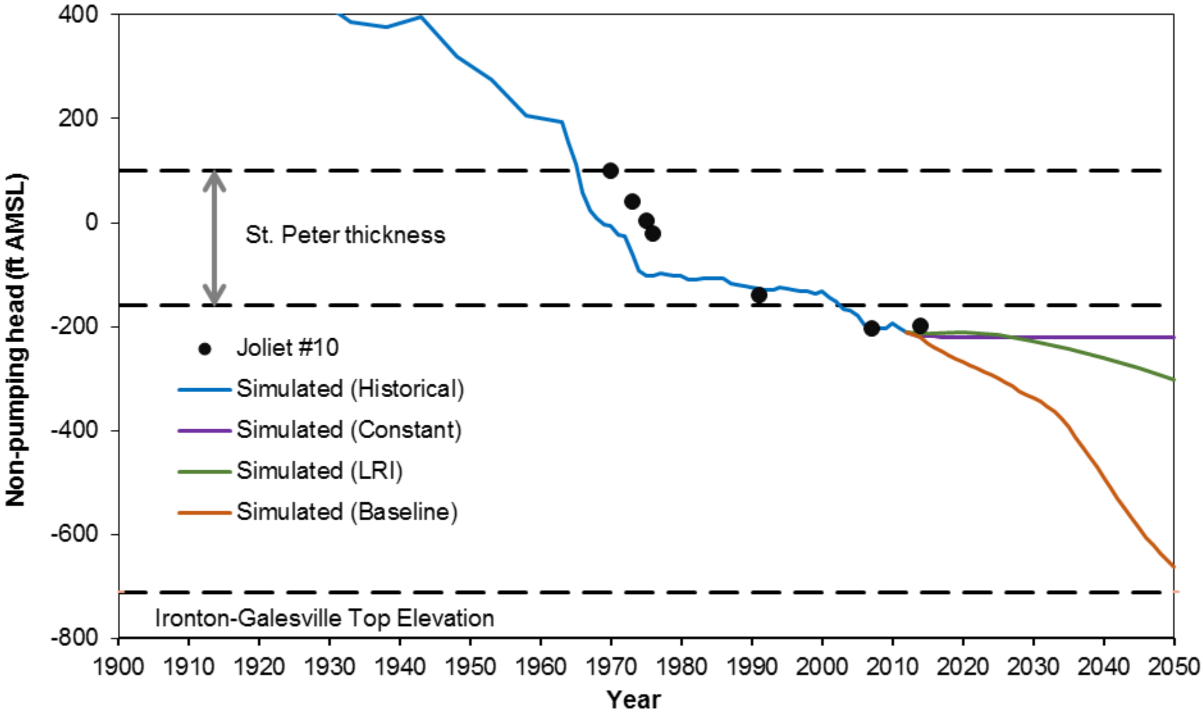

Figure 47: Hydrograph for Joliet #10, showing observed and simulated values. Future simulations are based on three scenarios: baseline pumping, least resource intensive, and holding pumping rates constant after 2011.

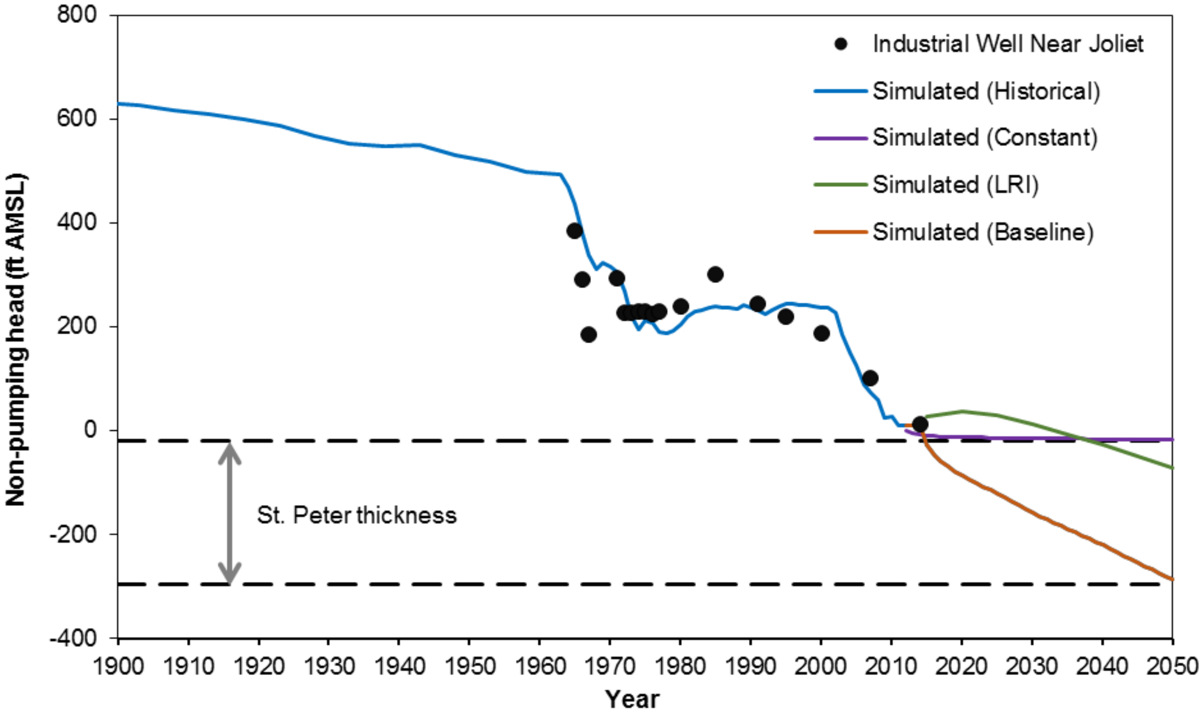

Figure 48: Hydrograph for an industrial well near Joliet, showing observed and simulated values. Future simulations are based on three scenarios: baseline pumping, least resource intensive, and holding pumping rates constant after 2011.

6.2 Desaturation of sandstone aquifers

Partial desaturation of an aquifer can threaten its viability (Meyer et al., 2009; Roadcap et al., 2013). Partial desaturation occurs when an aquifer switches from confined to unconfined, meaning that the head has fallen below the top of the aquifer and pore spaces have started to dewater in response to withdrawals. There are at least three potential negative outcomes of partially desaturating sandstone. First, as the head falls below the upper portion of a sandstone, small-capacity wells penetrating the upper portion of the aquifer may go dry (Figure 49). Second, as the saturated thickness of the aquifer decreases, the transmissivity decreases. Consequently, the well will likely produce less water (Figure 49); as transmissivity continues to decrease, the well may no longer provide economically feasible withdrawals of groundwater. Third, desaturated sandstone will be exposed to oxygen, which will alter redox conditions and potentially have negative water quality effects. Although not observed in Illinois, sandstone exposed to oxygen in Wisconsin has resulted in the release of soluble arsenic (Schreiber et al., 2000). Partial desaturation of the St. Peter Sandstone has been observed at wells both during pumping conditions and when individual wells have been cycled off (Figure 50). At the center of the cone of depression in northeastern Illinois, complete desaturation of the St. Peter Sandstone has been observed (Figure 50).

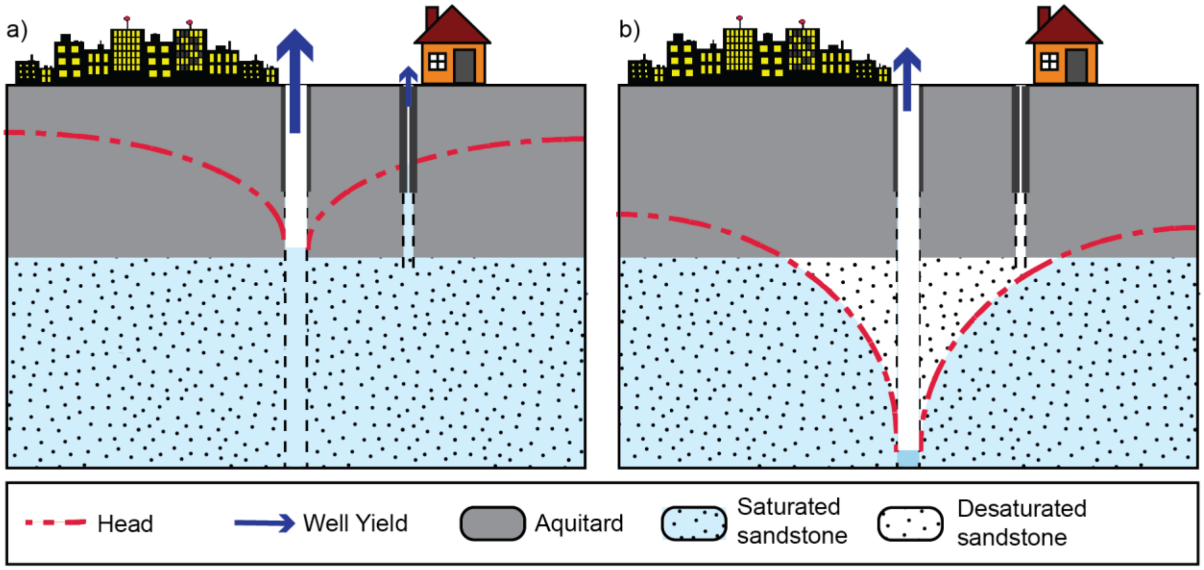

Figure 49: Impacts of desaturation on a sandstone aquifer.

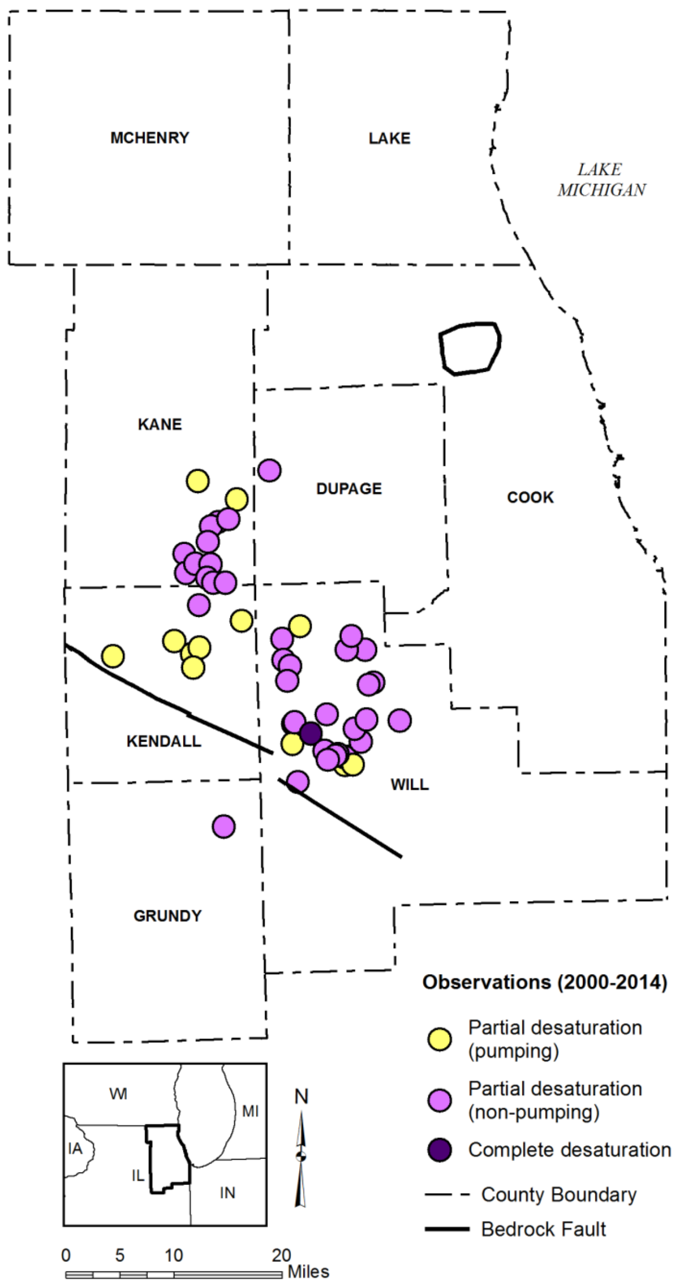

Figure 50: Locations of partial and complete desaturation at residential, public, and industrial wells measured between 2000 and 2014.

6.2.1 Risk of desaturation of the St. Peter Sandstone

The individual sandstone aquifers within the Cambrian-Ordovician in Illinois and Wisconsin are often separated by aquitards (Figure 4). In predevelopment conditions, these aquitards limited groundwater circulation between sandstone aquifers. However, cross-connected wells create pathways for groundwater circulation that bypass the aquitards; consequently, demands from one aquifer may be satisfied by water from other aquifers via these connections (e.g., Figure 39c).

In this study, a potentiometric surface for 2014 was generated that represents the lowest non-pumping head at a given location of the Cambrian-Ordovician sandstone aquifer system, generally the Ironton-Galesville head in northeastern Illinois, as discussed in Section 5.5.2.2. At what point might this lowest head create a risk of desaturation to the other Cambrian-Ordovician sandstone aquifers, in particular the uppermost St. Peter Sandstone? The answer is contingent on withdrawal rates, open intervals of wells, proximity of wells to one another, and proximity of wells to local flow barriers such as the Sandwich Fault Zone. Zones depicting the risk of desaturation can be determined by calculating the difference between the Ironton-Galesville potentiometric surface and the top of each sandstone aquifer within the Cambrian-Ordovician. These risk zones are critical to determine for multiple reasons: 1) understanding the current critical situation, 2) identifying areas where problems may develop under pumping conditions or with future well construction, 3) providing a tool for stakeholders to understand the outcomes from continued withdrawals, and 4) understanding the role that dropping water levels in a deep sandstone aquifer can have on overlying aquifers.

Three risk zones were developed:

- Partial desaturation under pumping conditions: The non-pumping head in the Ironton-Galesville is between 0 and 200 ft above the top of a given sandstone aquifer.
- Partial desaturation under non-pumping conditions: The non-pumping head in the Ironton-Galesville is between 0 and 200 ft below the top of a given sandstone aquifer. The sandstone aquifer may be partially desaturated at or near cross-connected wells with the Ironton-Galesville. New cross-connected wells may result in partial desaturation of the sandstone aquifer.
- Complete desaturation: The non-pumping head in the Ironton-Galesville is more than 200 ft below the top of a given sandstone aquifer. The sandstone aquifer may near complete desaturation at cross-connected wells with the Ironton-Galesville. New cross-connected wells may result in partial or near complete desaturation of the sandstone aquifer.

Consider the conceptual diagram of the St. Peter and Ironton-Galesville Sandstones in Figure 51. When the head in the Ironton-Galesville is within 200 ft of the top of the St. Peter, then the St. Peter Sandstone is at risk of partial desaturation under pumping conditions (Well A in Figure 51). When the Ironton-Galesville head is within 200 ft of the top of the Ironton-

Galesville Sandstone, the St. Peter Sandstone is at risk of complete desaturation and the Ironton-Galesville is at risk of partial desaturation under pumping conditions (Well C in Figure 51).

The location of cross-connected wells are important when assessing where actual desaturation may occur within risk zones. Consider the case of the cross-connected Well B in Figure 51. Without the cross-connected well providing a flow pathway, the St. Peter Sandstone would be completely saturated under non-pumping conditions. However, with the cross-connected well present, the head in the St. Peter decreases and the head in the Ironton-Galesville increases; the net result in this conceptual example is that the St. Peter becomes partially desaturated near the well.

In recent years, the head in the Ironton-Galesville has begun to fall below the bottom of the St. Peter Sandstone (which is on the order of 200 ft thick) near the center of the cone of depression. Cross-connected wells in these areas can potentially lead to nearly complete desaturation of the St. Peter, at least locally. The small amount of water that flows to the cross-connected well will cascade down the wellbore. This is demonstrated with Well D in Figure 51.

6.2.2 2014 risk of desaturation

The 2014 risk of desaturation of the St. Peter Sandstone is shown in Figure 52. The zones depicting risk of complete desaturation of the sandstone are small, occurring within pockets of the Joliet area. These zones are primarily a result of new wells that have been completed within the last ten years that are only open to the Ironton-Galesville Sandstone, which have induced flow from nearby cross-connected wells. The risk zone of partial desaturation under non-pumping conditions extends throughout northwestern Will County and into eastern Kendall County, meaning that the Ironton-Galesville static head is below the top of the St. Peter. The zone depicting risk of partial desaturation under pumping conditions covers large portions of DuPage and Kane Counties as well as small pockets in southern McHenry County. High capacity wells within this zone may result in desaturation of the St. Peter Sandstone under pumping conditions. The risk of desaturation for the St. Peter Sandstone is shown in cross-section for 2014 in Figure 53.

A risk of desaturation map was developed for the Ironton-Galesville. However, all non-pumping heads in the 2014 measurement were over 200 ft above the top of the Ironton-Galesville Sandstone. Hence, as of 2014, no risk zones have developed for this sandstone aquifer throughout northeastern Illinois (Figure 53).

6.2.3 Projected 2050 risk of desaturation

The risk of desaturation was developed for 2050 using each of the three future demand scenarios in both the St. Peter (Figure 54) and Ironton-Galesville (Figure 55). The spatial extent of each risk zone is projected to expand under each of the three scenarios, with the largest increase occurring for baseline (compare Figure 52 with Figure 54a) and the smallest for the constant scenario (compare Figure 52 with Figure 54c), which follows logic since each represent incrementally greater pumpage. In particular, the baseline and LRI scenarios show large increases in the spatial extent of the risk zone for complete desaturation within Kendall County. In the constant scenario, the very high zone remains focused around Joliet. The high risk zone extends throughout the eastern half of Kendall County in all scenarios and also extends into southeastern Kane County. The medium risk zone is present in southern McHenry County in all three scenarios.

Similar to 2014, risk zones are not present for the Ironton-Galesville Sandstone in 2050 for two of the scenarios, LRI and constant (Figure 55b, c). However, in the baseline simulation, the Ironton-Galesville head has decreased to within 200 ft of the top of the Ironton-Galesville Sandstone in the Joliet region and in northeastern Kendall County; hence a risk zone for partial desaturation under pumping conditions has developed (Figure 55a). In very local areas, small risk zones for partial desaturation under non-pumping conditions of the Ironton-Galesville Sandstone have developed. The risk of desaturation for the St. Peter and Ironton-Galesville Sandstones under the baseline projection are shown in Figure 53.

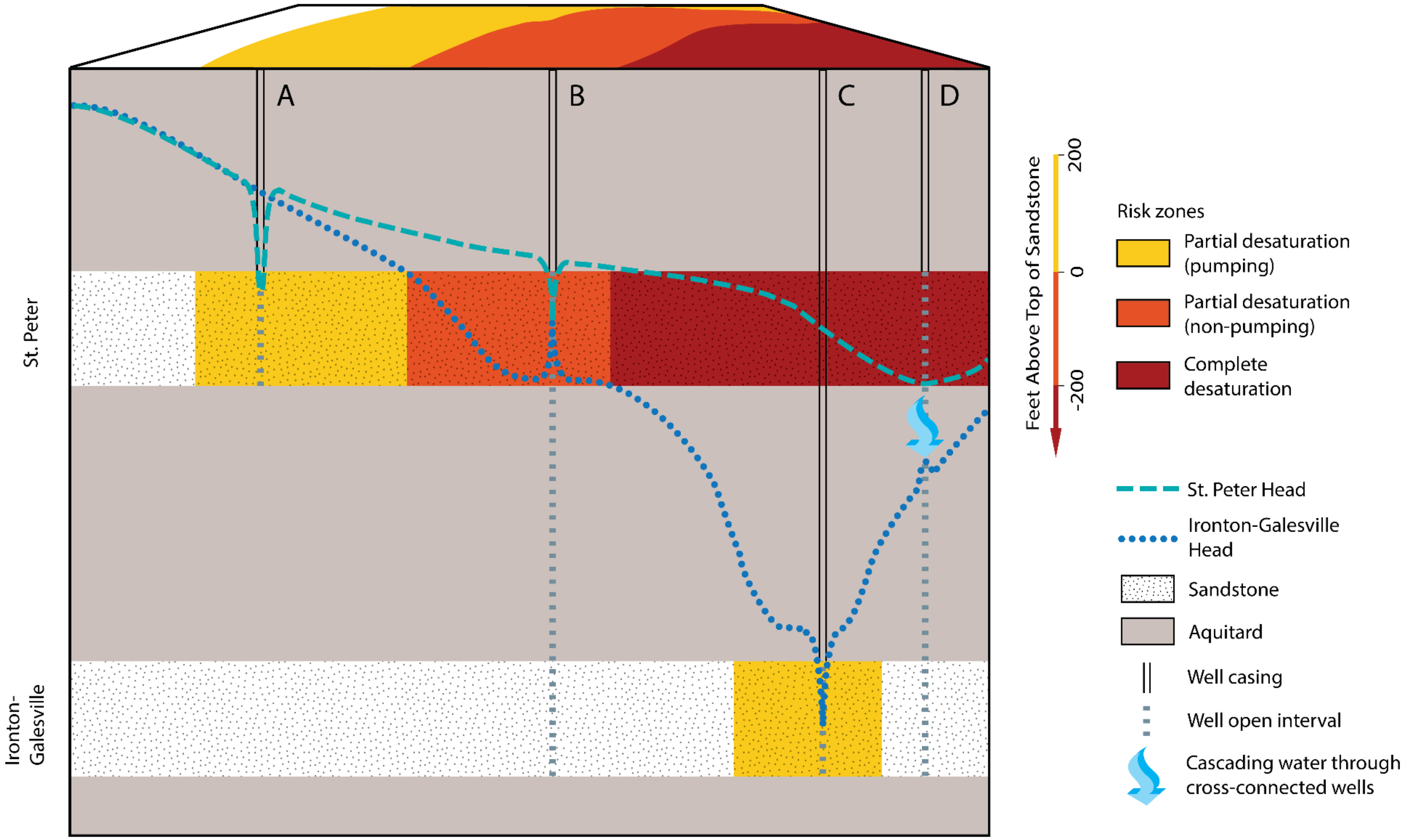

Figure 51: Conceptual diagram showing risk of desaturation to the St. Peter and Ironton-Galesville Sandstones.

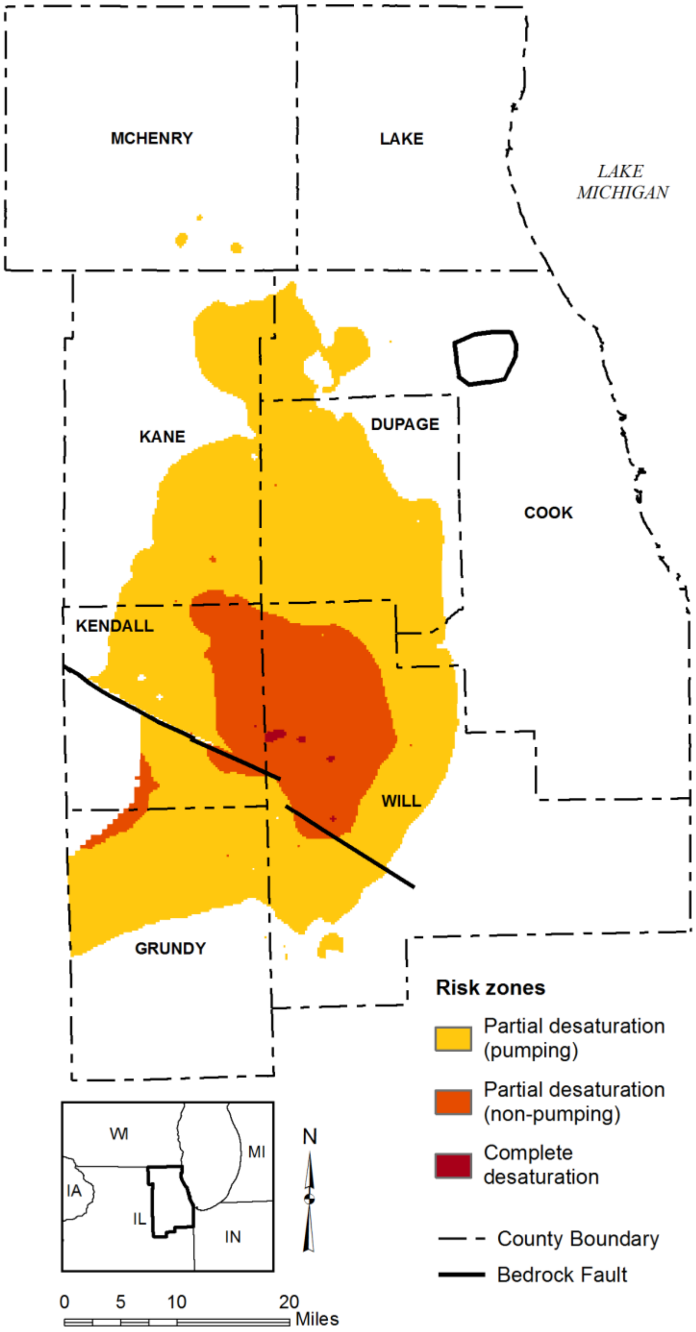

Figure 52: Risk of desaturation of the St. Peter Sandstone in 2014.

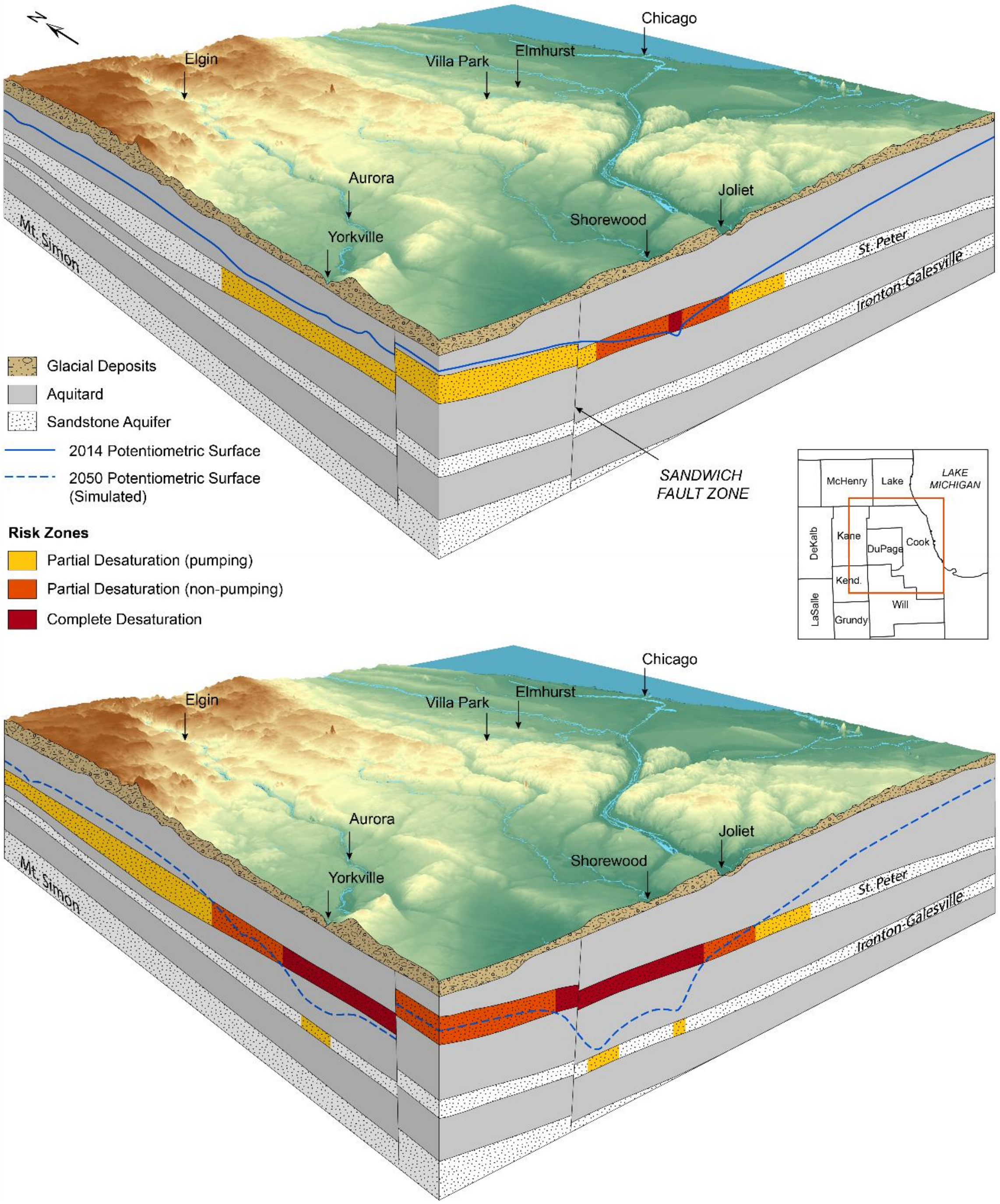

Figure 53: Risk of desaturation in northeastern Illinois in 2014 and 2050 (baseline demand projection). The left cutaway runs through southern McHenry, Kane, and Kendall Counties. The right cutaway runs through Kendall, Will, and southern Cook Counties.

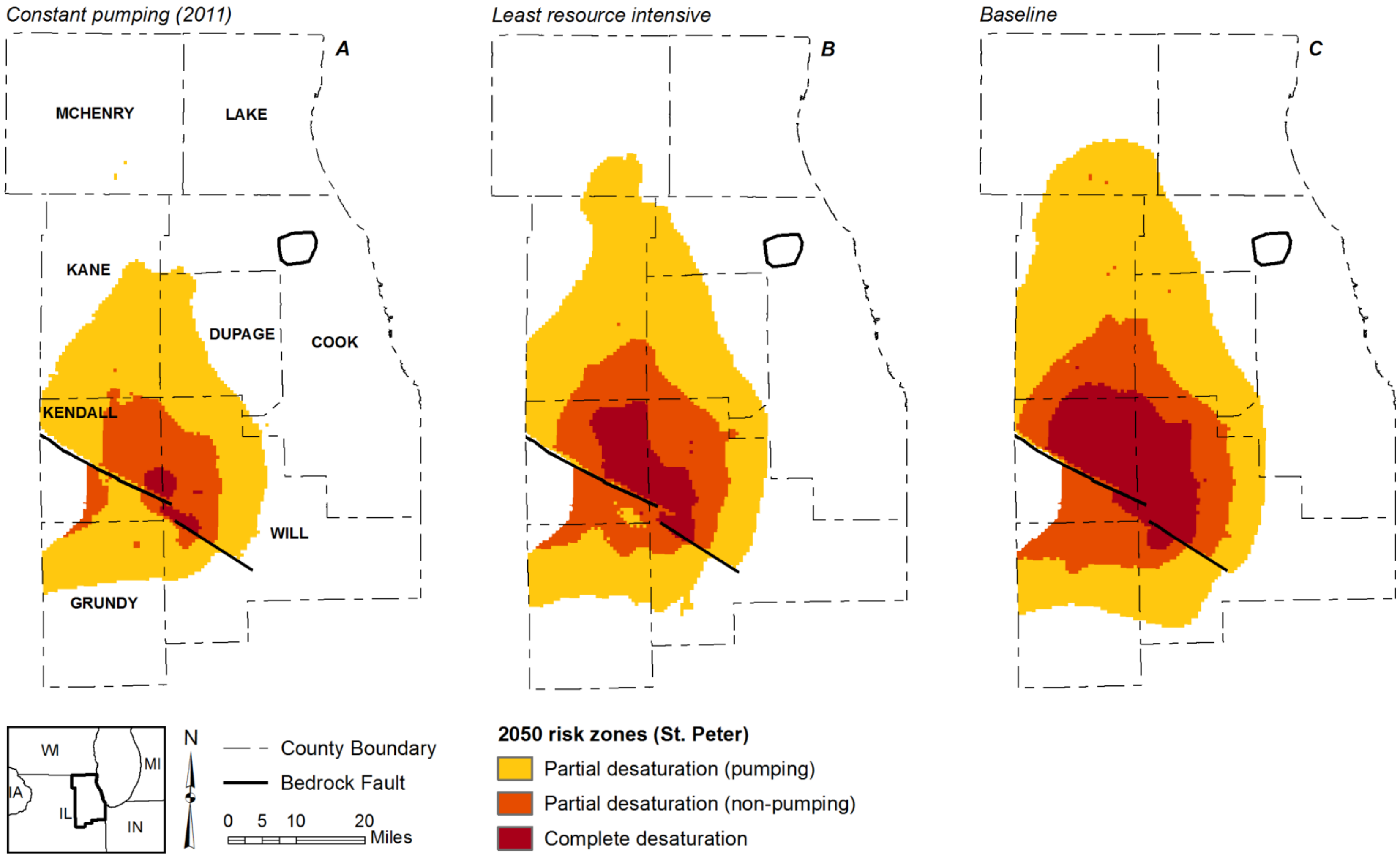

Figure 54: Simulated risk of desaturation in 2050 for the St. Peter Sandstone using three scenarios: a) constant pumping at 2011 rates, b) least resource intensive, and c) baseline.

Figure 55: Simulated risk of desaturation in 2050 for the Ironton-Galesville using three scenarios: a) constant pumping at 2011 rates, b) least resource intensive, and c) baseline.

6.3 Head separation between the Ironton-Galesville and Mt. Simon Sandstones

The Mt. Simon Sandstone is not a productive aquifer in the northern portion of the state due to its high salinity. It underlies the Ironton-Galesville and is separated from it in Illinois by the Eau Claire Unit, which contains large degrees of shale and acts as an aquitard (Figure 4). In the late 19th and early 20th centuries, a few Cambrian-Ordovician wells were completed into the Mt. Simon Sandstone as far south as Will County. In 1898, a cross-connected well between the Ironton-Galesville and Mt. Simon Sandstones was constructed at the American Steel and Wire Co. plant in Joliet (Gobble, 1941). Water from the flowing artesian well had high salinity; hence salt crystals formed where water ponded near the well. The Mt. Simon was immediately plugged to reduce the salinity; but since the well was still flowing after being plugged, it is unclear if a head difference between sandstones was present.

In 1937, another well in the Joliet region was drilled to the Mt. Simon Sandstone at the Stateville Correctional Center (Gobble, 1937). Depth to water was monitored as the well was drilled. The depth to water was 300 ft when the well was drilled into the Ironton-Galesville Sandstone. However, the depth to water decreased to 70 ft when the well was drilled into the Mt. Simon Sandstone. This indicates that a head difference of greater than 230 ft existed between the two sandstones in 1937. The salinity in the well was high, with chloride of 836 ppm and total dissolved solids (TDS) of 1,870 ppm. After the Mt. Simon well was plugged, the salinity decreased, with chloride of 65 ppm and TDS of 461 ppm.

All known connections between the Ironton-Galesville and Mt. Simon Sandstones that previously existed in Will and Kendall Counties have been plugged (Figure 41c). While direct measurements from the Mt. Simon Sandstone are not available in this area since the late 1940s, the groundwater flow model is calibrated to these older observations. Hence, present day heads in the Mt. Simon can be simulated with the groundwater flow model. Due to the lack of cross-connecting wells, the simulated head difference in Will County between the Ironton-Galesville and Mt. Simon Sandstones is as much as 800 ft, with the Mt. Simon heads being the larger of the two (Figure 56). Any newly constructed cross-connected wells between the two sandstones would lead to water from the highly saline Mt. Simon flowing into the Ironton-Galesville. The amount of flow would be largest in areas where the head separation is greatest, and much more than observed in 1937 when the head difference was much less.

The Mt. Simon Sandstone in Wisconsin and the far northern part of Illinois has lower salinity than in the rest of the study area. Presently, wells that cross-connect the Ironton-Galesville and Mt. Simon Sandstones are present throughout Wisconsin and in Lake, McHenry, northern Cook, northern DuPage, and northern Kane Counties.

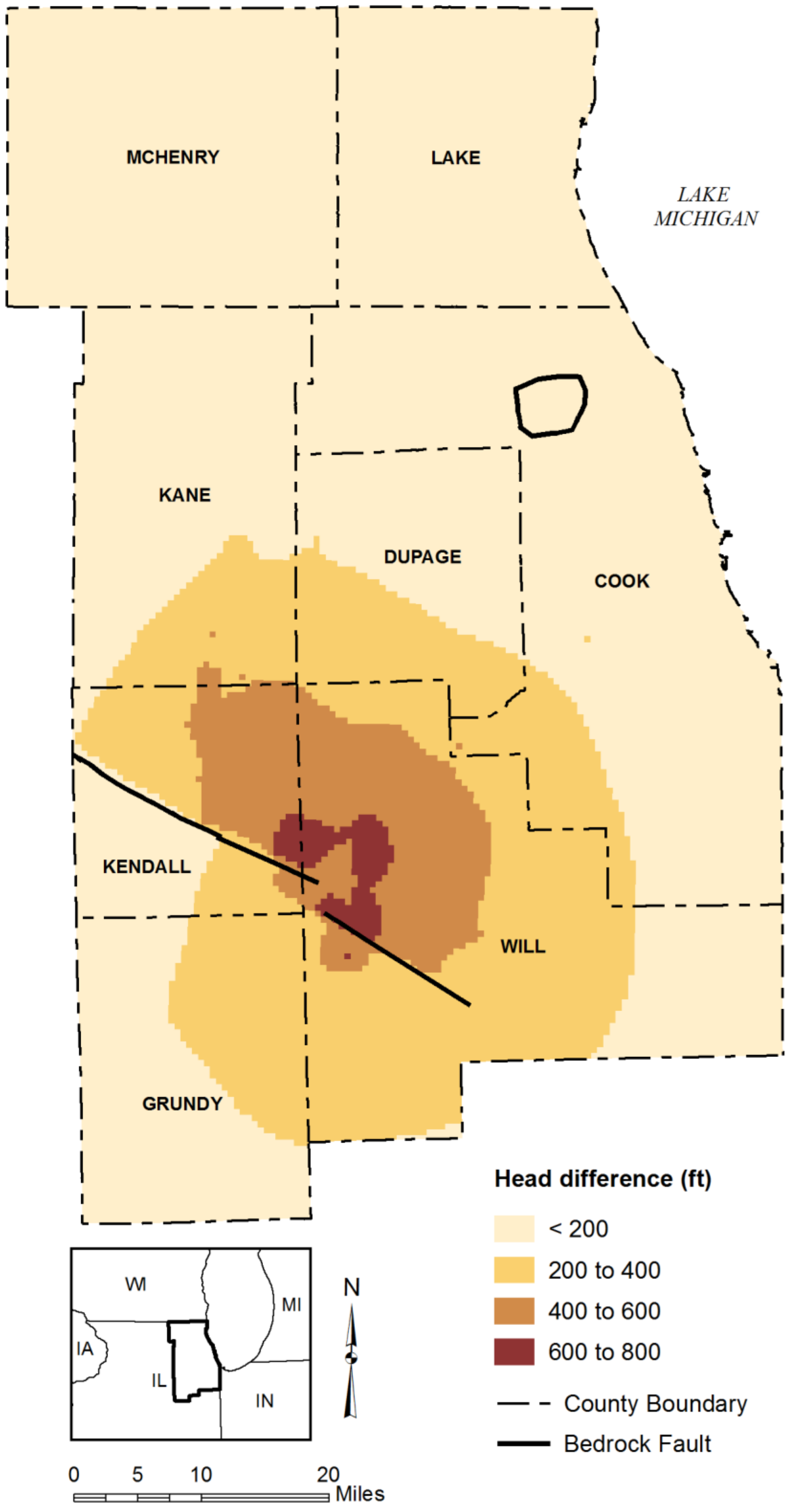

Figure 56: Simulated head difference (ft) in 2014 between the Ironton-Galesville and Mt. Simon Sandstones. Positive values indicate that the Mt. Simon head is greater than the Ironton-Galesville head.

7 Additional water supplies in northern Illinois

7.1 2012 Water demand by alternative source

The following sections show the source of water throughout the study area in Illinois. All withdrawal data presented in the subsequent sections were obtained from IWIP for 2012, which is the most recent complete set of water use data currently compiled by the ISWS. These withdrawal rates are only for public, industrial, and some commercial irrigation supplies. Agricultural irrigation wells are not included because the irrigators have not been required to report to IWIP until 2015. The many thousands of low capacity residential wells are also not included. All withdrawal magnitudes are presented in million gallons per day (Mgd).

7.1.1 Surface water

The surface water withdrawal locations and magnitude of withdrawals are shown in Figure 57. The withdrawals are divided amongst public, irrigation, and self-supplied commercial and industrial uses. The largest withdrawals (>1,000 Mgd) represent largely non-consumptive use of recirculated surface water for cooling, generally for thermoelectric power generation. Most of the mid-size communities using surface water are found in the southern part of the study area where there are insufficient shallow aquifer sources and the Cambrian-Ordovician sandstones are deeply buried or have poor water quality. For drinking water and industrial usages, treatment costs for surface water can be greater than for groundwater because of continually changing chemistry and temperatures. As a result, many communities, especially the smaller ones with access to surface water, will still preferentially utilize the available groundwater sources. Some communities with very limited water resources have been forced to construct long pipelines, such as Galesburg in Knox County, which has a 32-mile pipeline to access groundwater from near the Mississippi River.

The Chicago metropolitan area drew approximately 954 million gallons per day of water from Lake Michigan in 2012, representing about 77 percent of the total 1.24 billion gallons per day used for consumptive purposes in northeastern Illinois. Rivers supplied around 10% (134 Mgd) of the total water used, and groundwater supplied the remaining 13% (165 Mgd). Subtracting out the direct industrial withdrawals from the rivers, the Lake Michigan supply accounted for 85 percent of the water used for public supplies in 2012. Together, the estimates of the potential yield for the various aquifers and rivers in the northeast Illinois total only about 500 Mgd, roughly equal the current use from these sources if evaporative losses of 2.5% (120 Mgd) are assumed for the thermoelectric power plant. Therefore, the continued use of Lake Michigan water is essential to meeting future water needs in the region.

Illinois is limited by a Supreme Court decree to 3,200 cfs from Lake Michigan for all uses. An analysis of the allocation of Lake Michigan water by Meyer et al. (2012) indicates that there is enough water available for additional communities to switch from groundwater to Lake Michigan water. The current distribution network of this water is shown in Figure 58 for the year 2012 with figurative connecting lines from the suppliers to the users. The map is shaded by municipality or Federal facility (Great Lakes and Argonne) so allocations to individual subdivisions or industries are not shown. This figure is an update of a similar figure made by Martin Jaffe of University of Illinois-Chicago for 2000. Note that the service area of Lake Michigan water extends as far west as Kendall County and could expand in the near term to another dozen communities that have lake water allocations that are not in use. Shorewood, 37 miles from the lake, would be the southwestern-most such community. A primary consideration in switching to lake water is the construction cost of additional pipelines through urban areas where such costs are high. While the existing pipeline networks that spread west from the lake are extensive, they might lack the capacity to add additional communities. Also, the City of Chicago has more than doubled water rates per 1,000 gallons from $1.53 in 2008 to $3.81 in 2015 (City of Chicago, 2015).

Lake Michigan water is withdrawn from 14 intakes by the North Shore communities in Lake and northern Cook Counties, four offshore cribs by the City of Chicago, and one intake by the City of Hammond, Indiana. The City of Chicago sells water directly to more than 50 facilities, 18 of which then distribute water further to other facilities. The larger secondary distributers include Oak Park, the DuPage Water Commission, the Northwest Suburban Joint Action Water Agency (JAWA), and the Illinois-American Lake Company via Bedford Park. Some communities are four levels down, such as New Lenox and Mokena, which receive lake water from Chicago via Oak Park via Tinley Park. Arlington Heights and several other communities in north-central Cook County purchase lake water from Evanston. From one intake near Lake Bluff, the Central Lake County JAWA serves a large number of communities with the possibility of additional users hooking on to the system. Hammond distributes water to many suburbs in southern Cook County, although this use counts against the total allocation of Lake Michigan water for Illinois.

Aurora and Elgin, which are still outside of the Lake Michigan service area, obtain a portion of their water supply from the Fox River (Figure 57). Aurora, and to a lesser extent Elgin, supplement Fox River water with groundwater withdrawn from the deep sandstone aquifers. In certain months of the year, due to water quality or low flow concerns in the Fox River, these communities may become more reliant on groundwater. There is additional capacity for further development of water supplies on the Fox River due to an increase in baseflows from effluent discharges over the past several decades (Meyer et al., 2012). The Kankakee River, which supplies water for Kankakee and Wilmington, also has the capacity for additional supplies provided that regulated low-flows on the river are maintained.

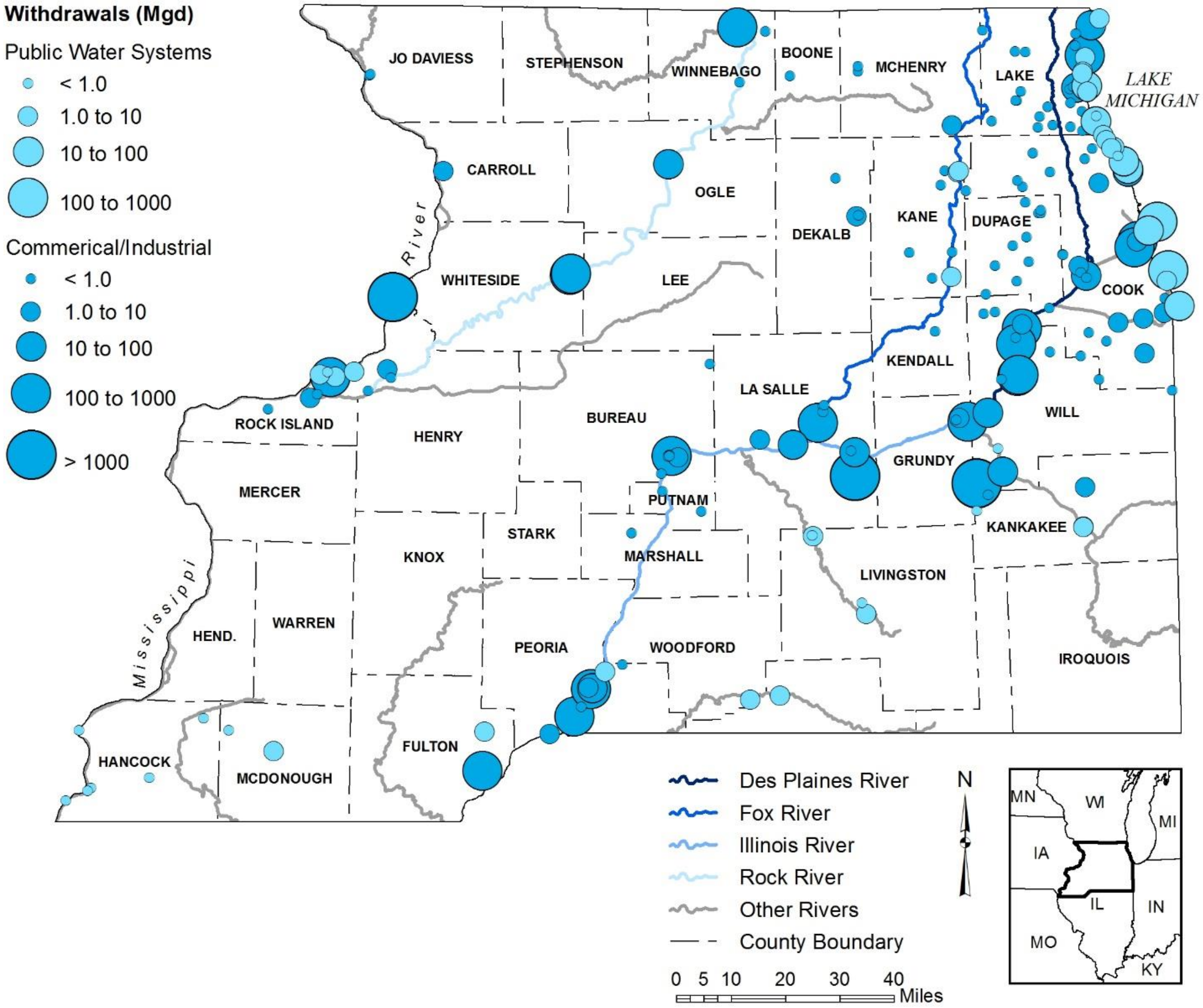

Figure 57: Surface water intakes and magnitude of withdrawals in million gallons per day (Mgd) for public supply, industrial, and commercial irrigation water usages.

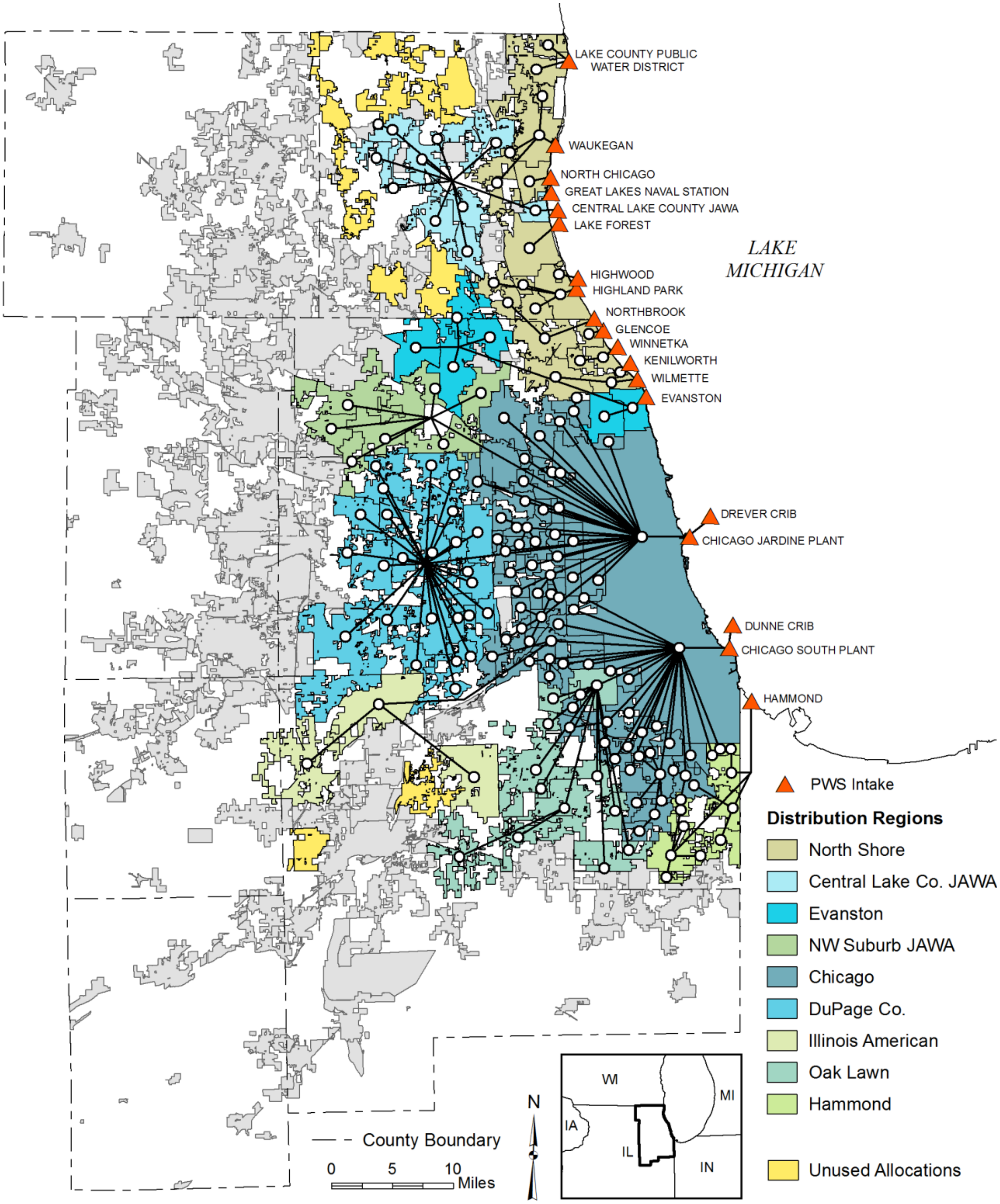

Figure 58: Lake Michigan water distribution network in northeastern Illinois for 2012. Connecting lines are illustrative and do not represent the physical pipelines.

7.1.2 Sand and gravel aquifers

Outwash from melting Pleistocene glaciers left thick sand and gravel deposits in many of the major bedrock valleys of Illinois. These aquifers can be highly permeable and are often at or near the surface where they are hydraulically connected to a stream; hence they can sustainably support very high capacity wells (> 1.5 Mgd). A 30-foot-thick saturated sand and gravel aquifer can have a transmissivity that is easily four times that of the Cambrian-Ordovician sandstone aquifer (10,000 ft^2/d vs 2,200 ft^2/d), although the available drawdown is considerably less (Roadcap et al., 2013). The locations and magnitudes of groundwater withdrawal from sand and gravel aquifers in 2012 are shown in Figure 59, superimposed over the map of major sand and gravel deposits by the ISGS. Further information on the use of the sand and gravels, including potentiometric surface maps, can be found in previous ISWS studies for McHenry County (Meyer, 1998; Meyer et al., 2013), Kane County (Locke and Meyer, 2005; Meyer et al., 2009), the Peoria area (Burch and Kelly, 1993), and the Green River lowland region of Lee, Whiteside, Bureau, and Henry Counties (Burch, 2004). Not shown on Figure 59 are the hundreds of agriculture irrigation wells in the Green River lowlands and the 30 or 40 in McHenry County. The sand and gravel aquifers in Cook and DuPage Counties proved insufficient for significant water supplies but they likely contribute to the water availability in the underlying Silurian-Devonian carbonates. They also support thousands of private wells in Cook and DuPage Counties. Those few wells that fall outside of the major sand and gravel aquifers are likely within very thin lenses of sand and gravel; as a result, the withdrawal rates for these wells generally do not exceed 0.5 Mgd.

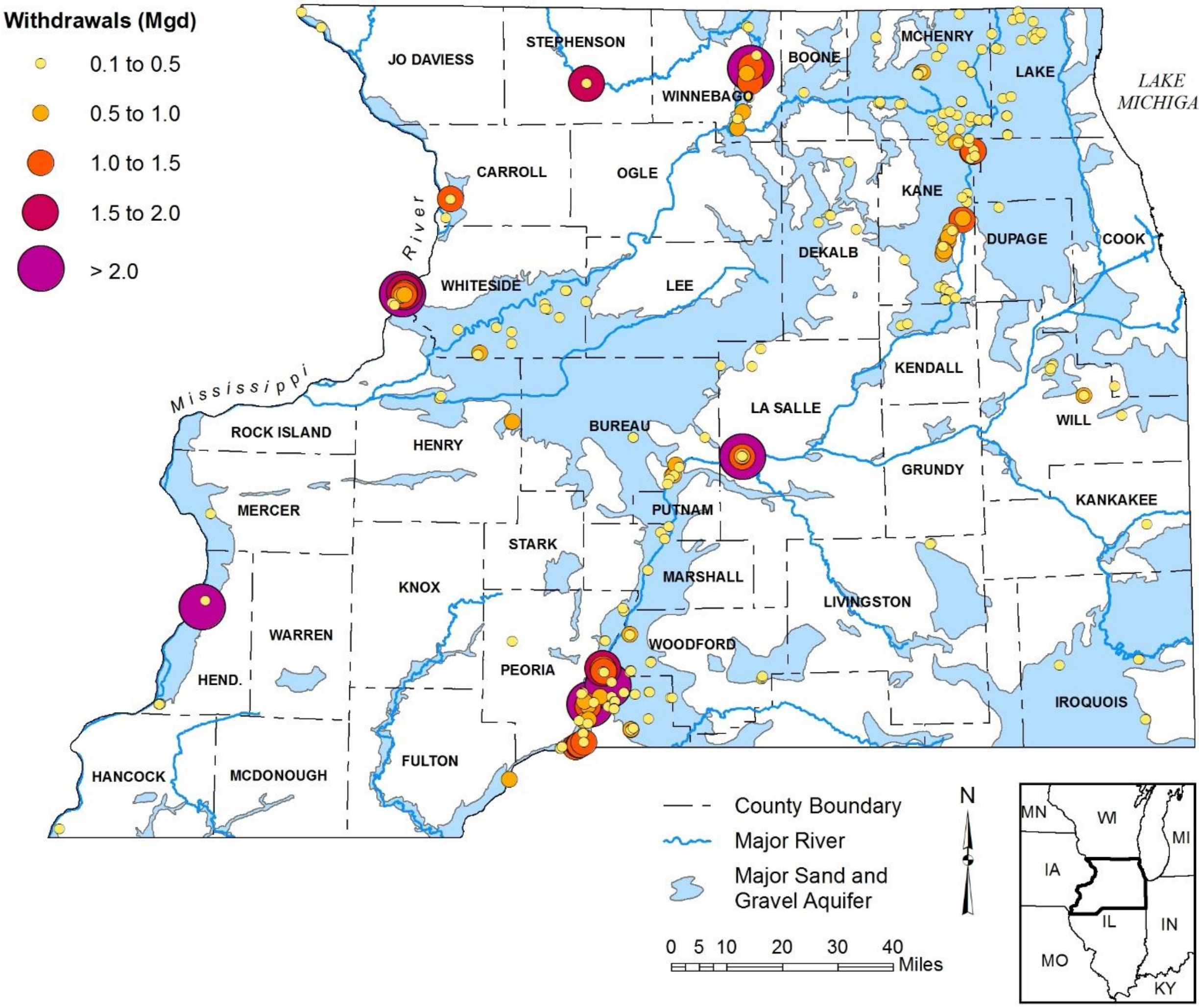

Figure 59: Sand and gravel wells reporting to IWIP within the study area.

7.1.3 Shallow carbonate aquifers

The carbonate bedrock units have been subjected to weathering and dissolution in the geologic past that resulted in the development of significant secondary porosity, especially within the upper 25 to 125 feet of the bedrock surface. Where the carbonates have developed into a productive aquifer is reflected in the distribution of production wells (Figure 60) because the surficial carbonates (Figure 3) are a preferred aquifer to deeply-buried sandstones, absent any water quality problems or overlying sand and gravel aquifers. The Silurian-Devonian carbonates can be highly permeable if a well intersects large dissolution cavities along vertical fractures or bedding plans. Reported transmissivities commonly exceeding 15,000 ft^2/d or, in a few cases 70,000 ft^2/d, at municipal wells in DuPage County (Zeizel et al., 1962) and Will County (Roadcap et al., 1993).

In northeastern Illinois the highly permeable zone in the Silurian-Devonian aquifer follows a band though southwestern Lake, central DuPage, and northeastern Will Counties. This zone corresponds with overlying sand and gravels (Figure 59), higher bedrock elevations, and higher surface elevations along the Valparaiso Moraine. The permeable zone also extends into Kankakee County where the aquifer is used intensively for irrigation (Cravens et al., 1990). The Silurian-Devonian carbonate has much lower transmissivities of less than 130 ft^2/d in central Cook County and historically has never been able to support any sizable withdrawals. The Silurian-Devonian carbonates are also used for water supply in western Illinois where they are overlain by Mississippian shales, suggesting that the units were exposed and weathered between the Devonian and Mississippian Periods. In Woodford and Livingston Counties between the Illinois River and Bloomington, the carbonates are not used because of poor water quality, possibly due the lack of connection to the surface (Figure 5) that would have allowed for flushing with fresh glacial meltwater.

The other carbonate unit that is largely present at the bedrock surface in Illinois is the Galena-Platteville Unit. While it is utilized some by public supplies and industries, it is to a much lesser extent than the Silurian-Devonian. A lack of high capacity wells completed in this unit where it is overlain by the Maquoketa Unit suggest that this unit is not significantly weathered except at the bedrock surface. A few wells are also completed in the Maquoketa Unit (compare Figure 3 with Figure 60), in particular the Fort Atkinson limestone member, which is only at the bedrock surface in a very narrow band in eastern McHenry, Kane, and Kendall Counties.

Groundwater flow directions in the shallow bedrock aquifers of northeastern Illinois generally mimic the surface topography as shown by a potentiometric surface map created from 1,463 water level measurements (Figure 61 and Figure 62). This map covers the area where Silurian-Devonian Unit is at the surface and extends westward to areas where the Maquoketa, Galena-Platteville, and St. Peter units come to the surface (Figure 3). The potentiometric surface map is essentially a composite for the year 2003 that was constructed by piecing together the data used to construct smaller potentiometric surface maps made for other ISWS studies. The measurements for DuPage, Lake, Cook, Will, and Kankakee County were collected in 2002 and 2003 for a potentiometric surface used for the Illinois Environmental Protection Agency's Source Water Protection Program. County-wide groundwater studies provided the measurement data for 2003 in Kane County (Locke and Meyer, 2005), for 2006 in Kendall County (Roadcap et al., 2013), and for 1994 in McHenry County (Meyer, 1998). Meyer et al. (2013) revisited 161 of the McHenry County wells in 2011 but the median water level change was only 2 feet. The Will County data were supplemented with data from the much more extensive 1990 mass measurement (Roadcap et al., 1993), where there was little to no overlap in the data. Water level differences in wells located away from pumping centers that were measured in both 1990 and 2003 had a median difference of only 0.6 feet. An additional 233 surface water elevations were used for the contouring where the bedrock is either exposed along the streams or is connected by a sand and gravel deposit. The contouring was done using the kriging method in the program SURFER©.

Groundwater flow in the region is divided into several flow systems based on the topography and the connections between the aquifer and the streams. The highest heads in the shallow bedrock occur in northern McHenry County and extend southward into western Kane County, dividing eastward groundwater flow towards the Fox River from westward flow towards the Kishwaukee River. This divide generally follows the surface water divide formed by the Marengo Ridge and Woodstock glacial end moraines. Another groundwater divide follows the Valparaiso Moraine though western Lake County, far northwestern Cook, and western DuPage County, dividing a short westward flow path towards the Fox River and a long flow path towards Lake Michigan. The strong skewness of this second divide towards the Fox River suggests that a larger amount of recharge is occurring in this area than in eastern Lake and Cook Counties. The potential for groundwater to discharge to the Des Plaines River in Lake County has not been studied, although the water level elevations in the two systems become equal along some stretches in the northern half of the county. In the southwest region of the mapped area the flow systems become more localized by the Des Plaines, DuPage, and Fox Rivers which cut through the glacial deposits to the bedrock. The groundwater divide underneath the Valparaiso Moraine continues in central Will County where it separates southward flow towards the Kankakee River from northward flow towards the Cal-Sag Channel.

The potentiometric surface is further complicated by permeability changes, pumpage, quarries, and potential connections to the Cambrian-Ordovician sandstones. The steeper hydraulic gradients in central Kane County are likely due to the lower permeability of the Maquoketa Shale that composes the bedrock surface. In Cook and eastern Lake Counties a band of steeper gradients occurs along the 600 foot contour (Figure 62) which may indicate a reduction in permeability within the Silurian-Devonian carbonates. Along and east of this band, very few high capacity wells have been successfully developed, so deep sandstone wells predominate (Figure 10 and Figure 17 and Figure 60).

In central Cook County a wide and shallow cone of depression has formed where the groundwater levels have dropped below the level of the canals and Lake Michigan. Although there are no major pumping wells in the region, other activities that could lower water levels include the dolomite quarries, the deep tunnels for the Tunnel and Reservoir Project (TARP), and the many cross-connected wells with the underlying sandstones (Figure 41a). With a low permeability and a low recharge rate through the thick covering of dense clay tills on the Chicago Lake Plain, the amount of water flowing through to the aquifer is probably very small. Little is known about any connection between the shallow bedrock aquifer and Lake Michigan in Illinois.

A second potentiometric low occurs in central Kendall County along and south of the Sandwich Fault Zone where the Maquoketa and Galena-Platteville Units are at the bedrock surface. Roadcap et al. (2013) postulate that the low could be caused by water moving down the fault zone or down into the underlying St Peter sandstone through cross-connected wells (Figure 41a), whose heads are steeply dropping off towards the east and the center of the cone of depression in the sandstone.

The impact of the stone quarries on groundwater flow patterns is complicated because high water levels are often found in wells near them. In winter time, icicles can be observed high on the quarry walls where groundwater is seeping out of perched zones. The impact of the quarries on the regional potentiometric surface may be limited after the excavation goes below the weathered zone and the secondary permeability drops off. Many of the quarries occur in areas where the permeability may be lower or where leakage from an adjacent stream can prop up groundwater levels. At least five quarries in northeastern Illinois have tunneled downward through the Maquoketa Unit and are mining the underlying Galena Formation. If pumpage from the sandstones were to stop, water levels could recover to the point where the mines would be flooded if they are not actively dewatered; however, the inflow rate through the unweathered Galena dolomite would likely be small.

Changes in pumpage have caused predictable changes in head as communities either increase pumpage or switch sources from the Silurian-Dolomite carbonate aquifer to Lake Michigan or the Cambrian-Ordovician sandstone aquifer. Water levels recovered by more than 50 feet in central DuPage County between the last mass measurement in 1979 (Sasman et al., 1981) and 2003 after many communities switched to receiving Lake Michigan water through the DuPage Water Commission. The individual cones of depression that dotted the 1979 potentiometric surface map have disappeared in towns like Wheaton, Glen Ellyn, Carol Stream, Glendale Heights, Lisle, Downers Grove, and Addison. Water levels declined slightly in western DuPage County where West Chicago still uses groundwater. Similarly in Will County, water levels recovered between 1990 and 2003 in towns that switched to lake water including Bolingbrook, Homer Glen, New Lenox, and Mokena. Further declines in pumping were observed in towns still using groundwater including Crest Hill, Lockport, Frankfort, Steger, and Crete.

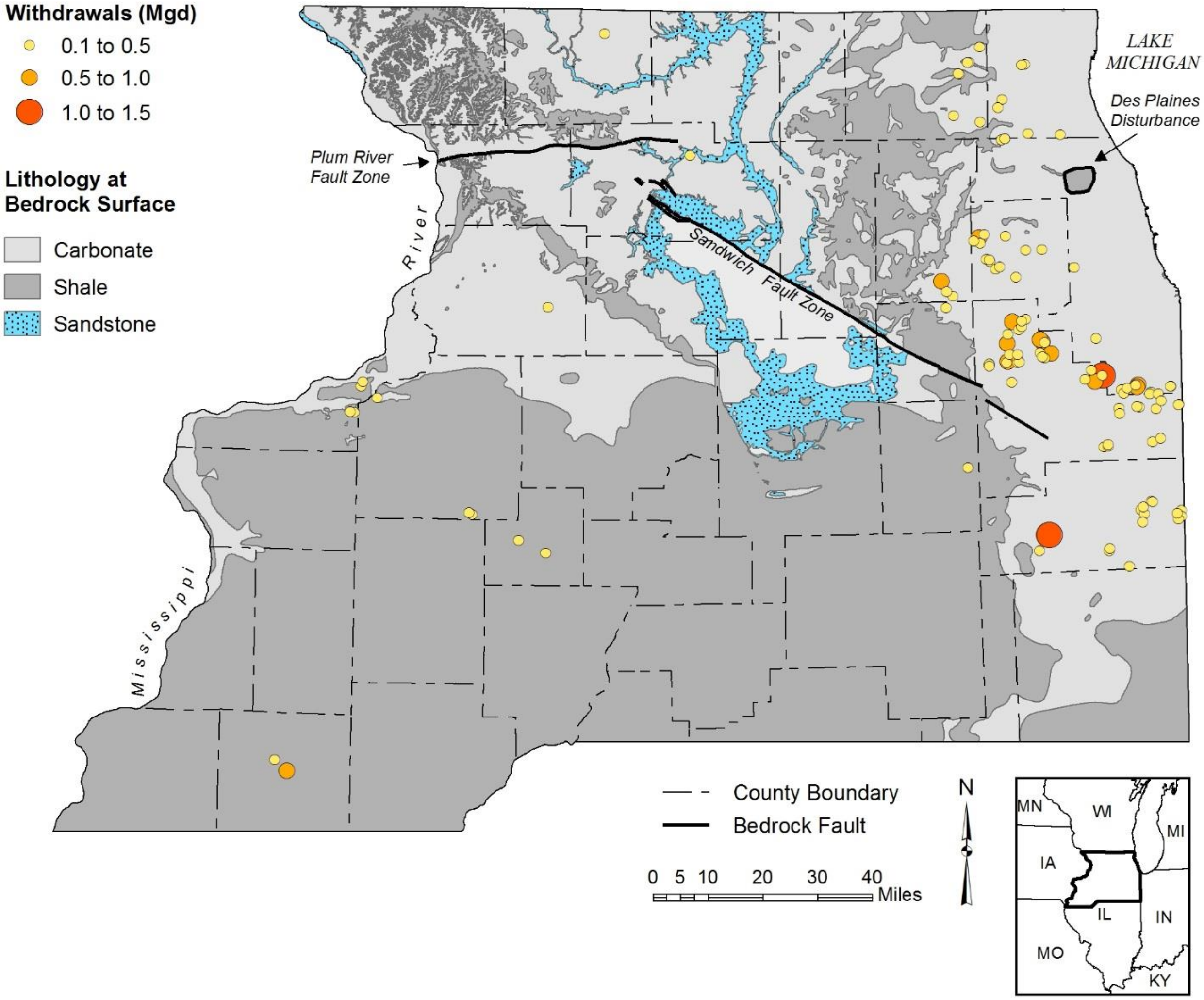

Figure 60: Wells with a primary source of water from carbonate bedrock.

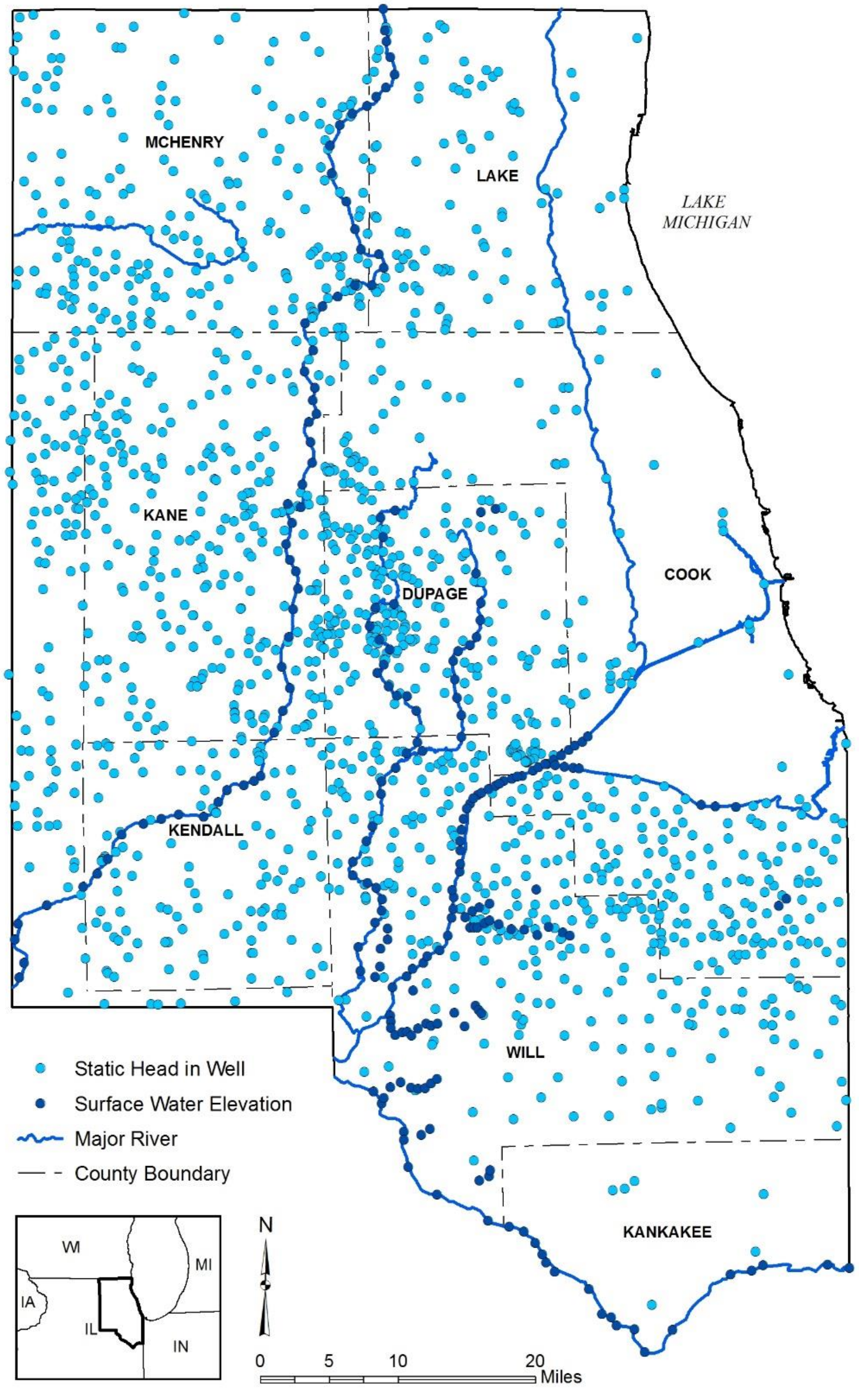

Figure 61: Location of wells and surface water elevations used to construct the shallow bedrock potentiometric surface map for 2003.

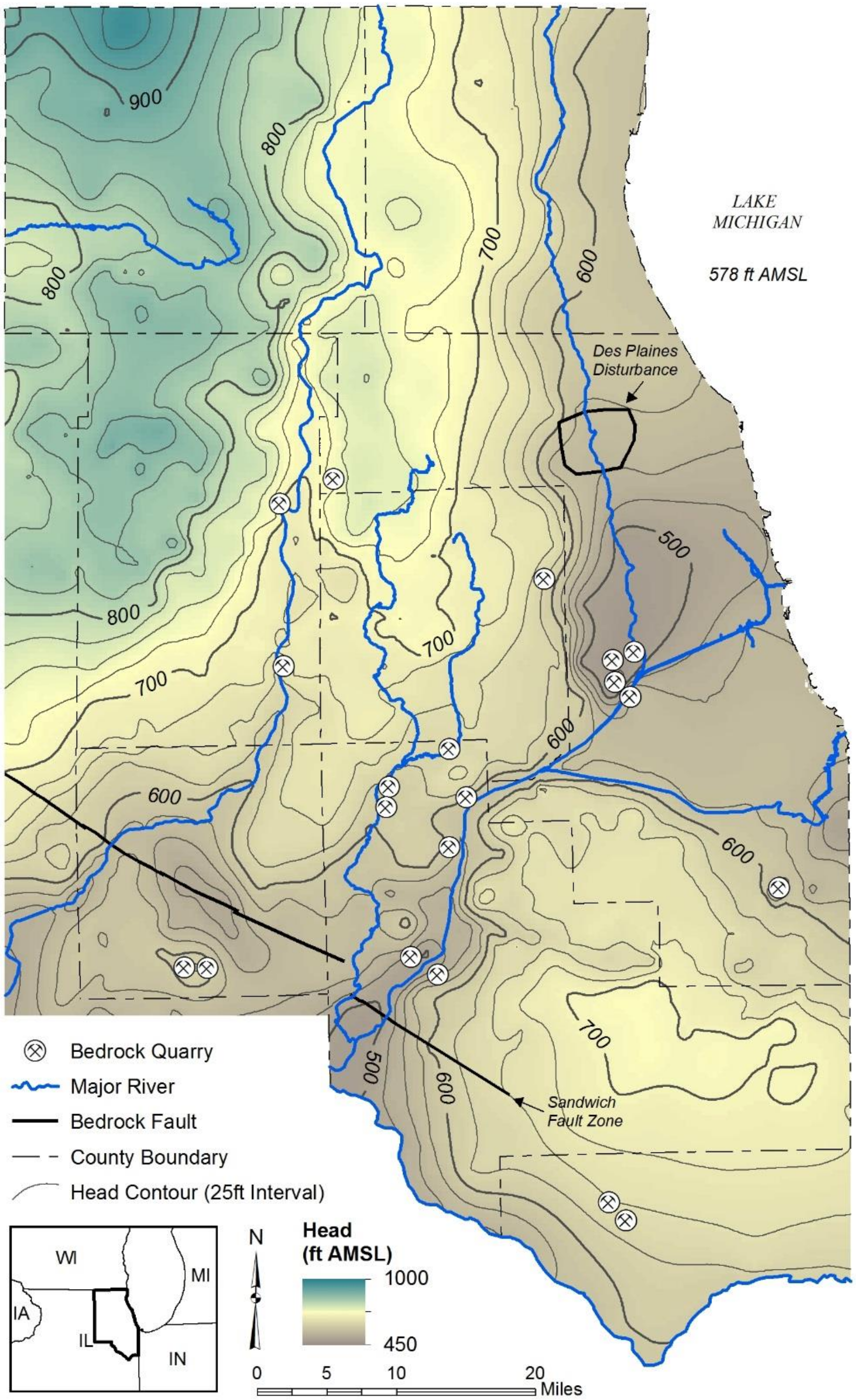

Figure 62: Composite potentiometric surface map of the shallow bedrock aquifers for 2003.

8 Conclusions and recommendations

8.1 Conclusions

The Cambrian-Ordovician sandstone aquifers in Illinois can serve as productive aquifers throughout the northern portion of the state. The factors that can threaten water availability from a sandstone aquifer depend on withdrawals in a region, the material overlying the sandstone, and the water quality within the sandstone. Since all of these factors vary throughout the state, conclusions related to water availability are provided for the following geographic regions: northeastern Illinois/Wisconsin, north-central/northwestern Illinois, and the southern portion of the study region (Figure 2).

8.1.1 Northeastern Illinois/Wisconsin

The largest demands from the Cambrian-Ordovician sandstone aquifers are in northeastern Illinois and southeastern Wisconsin, with water users including municipalities, self-supplied commercial and industrial facilities, and irrigators. Furthermore, the sandstone in this area is generally overlain by shale and unweathered carbonates, both of which serve as aquitards. Consequently, the vertical infiltration of water to the sandstone is limited, meaning that withdrawals from the sandstone are not readily replenished by precipitation. As a result, the heads in the sandstone have fallen by hundreds of feet since predevelopment conditions in northeastern Illinois and southeastern Wisconsin (Figure 16).

When heads fall below the top of a sandstone aquifer, the aquifer becomes unconfined. This is significant because further withdrawals from the aquifer are satisfied by dewatering of pore spaces, a process known as desaturation. Desaturation is a warning sign that the sandstone could be threatened, either immediately (due to water quality concerns) or in the long term (due to continued decrease of heads). Desaturation has been observed in the uppermost sandstone in northeastern Illinois, the St. Peter, and at a number of wells predominantly located in Kane, Kendall, and Will Counties (Figure 50). Partial desaturation of the sandstone aquifer at these wells is often observed when they are pumping but not when they are cycled off. Other wells, however, did experience partial desaturation when they were cycled off, in particular in Kane and Will Counties. Complete desaturation of the St. Peter Sandstone under non-pumping conditions has been observed once, at a well in Joliet. Since this particular well was also open to the Ironton-Galesville Sandstone, it was still able to draw water. However, desaturation could have other implications, including a decrease in pumping capacity. Furthermore, other nearby wells not penetrating only into the shallow St. Peter Sandstone may go dry due to the large decrease in heads.

To assess the risk of desaturation of the St. Peter Sandstone, this report presents risk zones based on the 2014 potentiometric surface (Figure 52). Not every St. Peter well experiences desaturation within these risk zones (although many do). However, all of the wells are at risk of desaturation. There are two primary mechanisms by which these at-risk St. Peter wells could undergo partial or complete desaturation. First, if nearby pumpage increases, then the water level in the St. Peter Sandstone could decrease. These increased withdrawals would not necessarily have to be from wells open to the St. Peter Sandstone. Increased withdrawals from wells only open to the Ironton-Galesville Sandstone may still be satisfied by water from the St. Peter Sandstone if a nearby cross-connected well is present that can act as a conduit for flow circulation between aquifers. Second, a newly constructed cross-connected well, even if not pumping, could work to lower the head in the St. Peter Sandstone and result in desaturation of a well. This is particularly true in Kendall and Will Counties where head separation of more than 300 ft has been observed between the St. Peter and Ironton-Galesville Sandstones. The closer a well is to a newly constructed cross-connected well, the larger the head decline will be. The 2014 risk zones are shown as a cross-section through Will and Kendall Counties in Figure 53.

Future simulations indicate that increases in withdrawals will cause heads to decrease, expanding the risk zone for where partial or complete desaturation of the St. Peter Sandstone may occur (Figure 54). The most severe scenario in this report, the “baseline” scenario, is shown in a cross-sectional view in Figure 53. Under this scenario, the Ironton-Galesville Sandstone at Joliet and Yorkville was simulated to be at risk of desaturation in the year 2050 under both pumping and non-pumping conditions. The Ironton-Galesville Sandstone is the deepest freshwater Cambrian-Ordovician sandstone in Will, Kendall, and southern Kane Counties. Local desaturation of both the Ironton-Galesville and St. Peter Sandstones, as was simulated in the baseline scenario, would force communities and industries in the area to seek alternative water supplies. An additional model simulation was conducted in this report by which withdrawals were held constant at 2011 rates. The risk zones in 2050 changed very little from their measured 2014 delineations under this scenario.

Other water sources are commonly used in northeastern Illinois; in fact, they are usually preferred. Wells constructed in the shallow aquifers, particularly in sand and gravel, are less expensive to construct than deep sandstone wells. Furthermore, while river water is often costly to treat, Elgin and Wilmington rely exclusively on the Fox and Kankakee River, respectively. Aurora also relies on the Fox River and sand and gravel wells to supplement their withdrawals from the Cambrian-Ordovician sandstones. Most communities in Cook, Lake, and DuPage Counties rely on Lake Michigan water, with many switching to this source from the Cambrian-Ordovician sandstones in the 1980s and 1990s. Consequently, heads have increased by over 100 ft in large portions of these three counties (Figure 19). However, heads in the area still remain hundreds of feet below their predevelopment levels (Figure 16), and subsequent large withdrawals from the sandstone in these areas would likely result in rapidly declining heads and widespread desaturation of the sandstone throughout northeastern Illinois.

Many of the stresses in northeastern Illinois are new. In particular, complete desaturation of the St. Peter Sandstone in Will County is just now occurring. As a result, there is not enough historical evidence to define a clear timeline on when wells will no longer be able to withdraw usable quantities of water from this or other sandstones. There is also uncertainty regarding future well construction, both in terms of open intervals and locations. This information is essential to understanding where and when the impacts of future withdrawals will manifest. If the zones depicting risk of desaturation continue to expand, water operators will have to carefully consider drilling practices, both in terms of water quality and long-term water quantity. As desaturation becomes more widespread, many water operators may be forced to seek alternative sources of water, such as surface water or shallow groundwater.

Patterns observed in southeastern Wisconsin are similar to those observed in northeastern Illinois. In particular, the cone of depression surrounding Waukesha has expanded since 1980

(Figure 19). However, due to recent decreases in withdrawals in the region, heads appear to be recovering throughout southwest Wisconsin in the past decade (Figure 38). A close examination of the change in heads in this area may provide insight into the implications of potential water use changes (in particular, reduction in withdrawals from the Cambrian-Ordovician sandstone aquifers) in northeastern Illinois.

8.1.2 North-central/northwestern Illinois

The geology in north-central/northwestern Illinois is much different than in northeastern Illinois. The sandstone in this area is generally not as deep; more importantly, it is not overlain by shale. While aquitards can still overly the sandstone, in the form of low permeable glacial material or unweathered carbonates, these materials generally allow more leakage to the sandstone than shale. Consequently, withdrawals from the sandstone are more readily replenished by precipitation. Even in areas of heavy withdrawals, such as near Rockford, water levels have declined by less than 200 ft from their predevelopment conditions (Figure 16); near the Rock River, the decline may be much less (Figure 20).

Greater rates of infiltration to the sandstone also mean that it is more readily susceptible to contamination than the deep sandstones of northeastern Illinois that are overlain by shale. Many of the sand and gravel aquifers near Rockford have been contaminated by volatile organic compounds (VOCs) (Wehrmann et al., 1988). The lack of drawdown in the sandstones near Rockford, explainable due to the ease with which water can infiltrate to the sandstone, indicates VOCs could also potentially infiltrate to the sandstone.

The sandstones in north-central Illinois appear to be hydrologically connected to surface water features. This was evident during the 2014 synoptic measurement due to the strong similarity between observed heads in a well and nearby stream elevations. In predevelopment conditions, these surface waters were likely groundwater sinks; that is, groundwater flowed into the surface waters. Withdrawals from the sandstone, however, likely have captured much of the water that otherwise would have entered surface waters. Furthermore, as heads decrease (especially under pumping conditions), the surface waters can lose water to the aquifer. As a result, withdrawals in relatively shallow sandstone often lead to reductions in natural groundwater discharge. These reductions have been shown to have negative impacts to stream ecology, especially during dry conditions when the stream relies on groundwater to maintain suitable low flows and temperatures for sensitive species (Meyer et al., 2012).

The concerns related to the Cambrian-Ordovician sandstone aquifers in northwestern and north-central Illinois are much different than those in northeastern Illinois, and as a result require different management strategies. In particular, threats of contamination by a host of soluble constituents or decreases in natural groundwater discharge should be closely monitored.

8.1.3 Southern portion of the study area

Withdrawals from the southern portion of the study area are small compared to the rest of the state (Figure 10). However, the sandstone in this area is overlain by two highly impermeable shale units, the Pennsylvanian-Mississippian and Maquoketa Units. As a result, very little precipitation can replenish water removed from the sandstone. Heads in this area have commonly decreased by over 25 ft since 1980 and by over 100 ft since predevelopment. These changes are much larger than those observed in northwestern Illinois, where shale is absent.

The sandstone in the southern portion of the study area is not at risk of desaturation. It is also not likely at risk of contamination from shallow aquifer contamination; connections to the deep sandstones (natural or anthropogenic) are not present. However, the head reductions in the southern portion of the study region will induce greater flow rates northward. This could result in the highly saline water from southern Illinois moving into the study region. Two communities in the southern portion of the study region with St. Peter Sandstone wells, Chenoa and Minonk, have higher chloride concentrations than wells to the north. Furthermore, in the very southern portion of the study region, the city of Bloomington is currently looking at installing a St. Peter Sandstone well. This would be one of the southernmost Cambrian-Ordovician sandstone aquifer wells used for public water supply purposes in the state. Although chloride concentrations at this new well are expected to be somewhat elevated compared to wells to the north, this groundwater will be diluted with surface water. Further monitoring of the chloride concentration in these southernmost wells is necessary to determine if saline water is flowing northward and at what rate.

Another important question that could provide insight into the hydrogeological properties of the Cambrian-Ordovician sandstone aquifers is why the heads have been decreasing in a regionally consistent manner. Even wells that are separated by as much as 70 miles have had similar decreasing trends throughout time (Figure 21). There are multiple reasons that the heads have been decreasing at this rate. First, the large withdrawals from northeastern Illinois may be decreasing these heads. Second, the decreases may be a response to withdrawals from Iowa. Third, some large withdrawals in the region may not have been reported to IWIP. Finally, the decreases may simply be in response to the small withdrawals from the region. It is most likely that all four of the reasons above are contributing to the decreases in heads.

8.1.4 General conclusions

Illinois has a surplus of water; however, the viability of the Cambrian-Ordovician sandstone aquifers in the state are threatened in areas of northeastern Illinois due to water quantity issues and could be threatened in other portions of the state due to water quality issues. Water supply planning must remain a continuous process, revisiting regions at periodic intervals to capture new issues as they develop. This work will require a combination of monitoring water levels, water chemistry sampling, geologic mapping, and modeling (both groundwater flow and geochemistry). The following section outlines some recommendations for future research of the Cambrian-Ordovician sandstone aquifers.

8.2 Recommendations for future work

The results of the 2014 synoptic measurement have provided information essential to enhance the understanding of the role of cross-connected wells, the impact of shale aquitards, and the role of the Sandwich Fault Zone in dictating regional heads. This study has also allowed the ISWS to develop clear questions that must be answered to better assist communities in determining how best to mitigate demands on the Cambrian-Ordovician sandstone aquifers, if needed. Answering these research questions will help the ISWS understand how to respond to growing communities that consider how to responsibly utilize the Cambrian-Ordovician sandstone as a source of water long into the future.

8.2.1 Recommendations new to this study:

1. The discrete location and open interval of cross-connected wells is essential information to properly understand and simulate groundwater circulation between the sandstone aquifers in the Cambrian-Ordovician system. While this study focused primarily on connections between the St. Peter and Ironton-Galesville Sandstones, a similar analysis for cross-connections between other aquifers was beyond the scope of this study and should be conducted in the future. A water quality study could provide insight into the impact of shallow aquifer or saline Mt. Simon water entering the St. Peter and Ironton-Galesville Sandstones. There are also areas where wells have been deepened in the shallow carbonate bedrock aquifers, which could potentially be related to decreasing water levels in the Cambrian-Ordovician sandstones manifesting via cross-connected wells with these shallower aquifers.
2. Projections of future withdrawals should account for the expected locations and open intervals of new wells. This will require input from communities and industries on their future water use plans, as well as an analysis of trends in well construction. Initial tests indicate that different well configurations can greatly influence future simulations generated with a groundwater flow model.
3. Since the early 1980s, the preponderance of new wells constructed in northeastern Illinois have been open to the Ironton-Galesville and cased through the St. Peter Sandstone. The initial implication of this is that heads in the Ironton-Galesville aquifer drop rapidly while heads in the St. Peter Sandstone are unchanged; the long-term implication, however, is that the heads in the Ironton-Galesville will eventually drop to the point that withdrawals will be satisfied by water from other aquifers via cross-connecting wells. It is recommended that specific areas, including central Will County, Kendall County, southeastern Kane County, and northern Kane/southern McHenry, undergo a more frequent synoptic measurement of heads, as these areas continue to see a proliferation of Ironton-Galesville-only wells. This smaller-scale study could largely be completed with the assistance of water operators in the region, but a few sites must be visited by ISWS personnel. Other regions in northeastern Illinois do not need revisited immediately, but should be measured again at repeated intervals.
4. Groundwater flow models are an essential tool to understanding the physical processes defining flow through the Cambrian-Ordovician sandstone system. Calibration to non-pumping heads in a groundwater flow model is a complicated process; new modeling technologies are improving our ability to do this but at a cost of computational demands. However, these new technologies, which include unstructured grid in MODFLOW (Panday et al., 2013), should still be utilized as much as possible. The ISWS will continue to pursue new technologies in groundwater flow modeling that will enhance our abilities to improve the

existing simulations and better inform communities and industries of the current and future state of the sandstone aquifers.

5. In northern Illinois, the St. Peter Hydrostratigraphic Unit contains the St. Peter Sandstone and the Glenwood Formation. While the sandstone within the St. Peter is most important for the discussions in this paper, shale and dolomite are also present in the Glenwood Formation. We recommend conducting a further study on the implications of these varying lithologies within the St. Peter Unit.
6. The degree of connectedness between the Mississippi River and the Cambrian-Ordovician sandstone is uncertain. This study indicated that in the far northeastern portion of the state, the two were hydrologically connected, but in the southern portion of the study area, this connection was limited. This is consistent with observations made by the USGS (Young, 1992) and the Iowa Department of Natural Resources (Gannon et al., 2009). However, all of these observations have been made through the development of contours. A more sophisticated study, including a combination of water chemistry and flow modeling, is needed to better understand the relationship between the Mississippi River and the sandstone. This will be particularly important in studies of the Northwestern Illinois and Spoon and La Moine Basins Water Supply Planning Regions.
7. The Cambrian-Ordovician to the south of the study area becomes very deep and very saline. However, drawdown from predevelopment on the southern boundary of the study area can be greater than 100 ft. Such drawdown, if accurate, would induce flow of this saline water northward. Additional research is needed to assess if water quality changes have been occurring in the Cambrian-Ordovician sandstone wells in the southern portion of the study area due to the northward migration of saline water.
8. This study offered insight into the regional flow behavior of the Sandwich Fault Zone, Plum River Fault Zone, and the Des Plaines Disturbance. However, these features also have local impacts that cannot be assessed with a potentiometric surface or the existing groundwater flow model. Future work should be focused on better understanding the influence of these faults on horizontal and vertical flow, which can potentially be assessed using water chemistry studies or geophysical techniques.(Young, 1992)
9. The head change of greater than 25 ft in the southern portion of the study area between 1980 and 2014 was unexpected; however, it was also a consistent observation made from the majority of wells measured in this area. The cause of this decrease could be related to withdrawals from northeastern Illinois or Iowa; it could also be related to the smaller withdrawals that have occurred within that area. This gradual decrease in heads could also be a result of withdrawals from a source within the region that is not reported to IWIP. Further investigation is required to assess the true cause of these declines. Included in this recommended study should be a closer inspection of the Marshall County area, where head decreases of more than 50 ft were observed from multiple wells with no distinguishable withdrawals in the area that help to explain why.

8.2.2 Recommendations reinforced by this study from Meyer et al. (2012)

A number of recommendations specific to northeastern Illinois were outlined in Meyer et al. (2012), and many were strongly reinforced by this study. These include recommendations for:

1. Improvement and application of groundwater flow models:

    a. Revision of the existing groundwater flow models to better simulate the interactions of groundwater with streams, in particular the Rock River (which is a potentially important source of water to the Cambrian-Ordovician sandstone).
    b. Revision of the existing groundwater flow models to better simulate shallow aquifer resources, including both sand and gravel and weathered carbonates. This will require geologic mapping of these resources, likely starting with simple assumptions and increasing complexity in necessary regions.
    c. Groundwater withdrawals in southeastern Wisconsin influence heads in northeastern Illinois. Similarly, withdrawals from Iowa will likely influence portions of western Illinois. Improved withdrawal data and representation of geology in these regions will create more realistic model simulations.
    d. Groundwater flow models can simulate when wells in an area may begin to go dry, which is essential information for water supply planners.
    e. Additional future withdrawal scenarios driven by policy and management strategies can provide insight to water supply planners. This can include assessing the impact of certain users switching to an alternative water source, either completely or partially.
    f. Local-scale models can be developed by using the regional models to obtain boundary conditions. This could be particularly important if modeling the local impacts of the Sandwich Fault Zone, the Plum River Fault Zone, or the Des Plaines Disturbance. This modeling would ideally include a geochemical component.
    g. Highly saline water is denser than fresh water, which influences groundwater flow. Density-dependent flow modeling is computationally demanding, but may become necessary if it is determined a significant amount of saline water is flowing or could flow upward from the Mt. Simon or northward from the saline sandstones in the southern portion of the state.
    h. Withdrawals from the shallow aquifers can result in reductions of groundwater discharging to streams (Meyer et al., 2012). The impacts of withdrawals from the sandstone aquifers on natural groundwater discharge will likely be greatest where the sandstone is shallow (i.e., the Rock River) and smallest where the sandstone is deep (i.e., the Fox River). However, this has not been quantified. The rapidly decreasing water levels observed in this study indicate that reductions in natural groundwater discharge should be closely examined. Similarly, for purposes of water supply planning, an allowable reduction of natural groundwater discharge should be determined, which will require input from stream ecologists.

2. Database expansion:
    a. A discrepancy exists between the reported pumpage to the IWIP program and the actual pumpage in Illinois. As a result, starting with the 2013 IWIP data that is being finalized at the time of this report, the ISWS will modify the IWIP database to include one table that includes reported pumpage and a corresponding table that will report estimated pumpage developed using a series of assumptions. These assumptions will be based on strict guidelines which will consider water use trends, facility type, population growth, etc. These guidelines will be documented in the 2013 IWIP report, currently under development.
    b. To help simplify the hydrogeology of the system to the point where reasonable analyses can be conducted, the different geologic strata of Illinois have been combined into a limited number of hydrostratigraphic units. The hydraulic properties assigned to

these units are generally determined by calibration of the existing groundwater flow models. To improve the understanding of properties, a reanalysis of available pumping and slug tests from northern Illinois and surrounding states is necessary. This reanalysis should be conducted using a consistent approach. These tests would be particularly beneficial by assessing wells open to only one unit and far removed from any cross-connecting wells (i.e., a pump test on an isolated Ironton-Galesville well would provide more information in regards to the hydraulic properties of the Ironton-Galesville than would a similar pump test of a St. Peter–Ironton-Galesville well).

3. Monitoring of heads:
    a. The expansion of a long-term monitoring network of the Cambrian-Ordovician sandstone aquifer system would allow for the collection of more data taken at regular intervals. This is important to establish both long-term trends as well as the influence of short-term phenomena (heavy precipitation events, nearby pumping, etc.).
    b. As an alternative to monitoring wells, many facilities have installed real-time telemetry on their production wells. This is particularly common in northeastern Illinois where concerns about rapidly falling heads have prompted the installation of this equipment. The ISWS would benefit from collecting these data at regular intervals and entered in a database. Furthermore, the IWIP program is currently being transitioned into an electronic reporting system, and communities that have obtained multiple head measurements in a year will soon have the ability to communicate these results to the ISWS through IWIP.
4. Release of soluble arsenic:
    a. Desaturation can expose one or more sandstone aquifers to oxygen, which can alter the water chemistry. This is particularly a concern when conditions are such that naturally occurring arsenic can be released in a soluble form. The contact between the Galena-Platteville and the St. Peter Units contains a thin, discontinuous interval of sulfide minerals, known as the sulfide cement horizon (SCH). The SCH has been observed to release arsenic under oxidizing conditions in Wisconsin (Schreiber et al., 2000). The presence and extent of the SCH in Illinois is uncertain. Further research into the potential for arsenic to be released at the SCH in Illinois could be conducted with existing or newly drilled cores; geochemical modeling could also provide insight into where arsenic could potentially be released and at what concentration.

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