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Contract Report 2012-03

Northeastern Illinois Water Supply Planning Investigations:

Opportunities and Challenges of Meeting Water Demand in Northeastern Illinois

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1 Introduction

1.1 Executive Order 2006-01

The availability and sustainability of an adequate and dependable water supply is essential for public, environmental, and economic health. This understanding led to the initiation, under direction of Executive Order 2006-01, of a three-year program for comprehensive regional water supply planning and management in Illinois. Under the framework of the order, the Illinois Department of Natural Resources' Office of Water Resources (IDNR-OWR), in coordination with the Illinois State Water Survey (ISWS), selected two priority water quantity planning areas for pilot planning: a 15-county area in east-central Illinois and an 11-county area in northeastern Illinois. This report focuses on the technical studies in support of water supply planning in the northeastern Illinois region, which includes Boone, Cook, DeKalb, DuPage, Grundy, Kane, Kankakee, Kendall, Lake, McHenry, and Will Counties. These studies highlight the opportunities and challenges of meeting water demand in the region.

Stakeholder water supply planning committees were created in each priority planning area, and each planning committee was tasked with developing regional water supply planning and management recommendations in accordance with existing laws, regulations, and property rights. The Chicago Metropolitan Agency for Planning (CMAP) guided formation of a 35-member grassroots water supply planning group for northeastern Illinois, the Northeastern Illinois Regional Water Supply Planning Group (RWSPG). The ISWS and the Illinois State Geological Survey (ISGS), both within the University of Illinois' Prairie Research Institute, along with the IDNR-OWR, were responsible for providing technical support to the RWSPG and updating and expanding regional water resource information.

The RWSPG was charged with developing a regional plan that clearly describes water supply and demand issues of the region. IDNR-OWR suggested that the regional plan contain at least the following principal components:

- Descriptions of the sources of water available to northeastern Illinois;
- Plausible estimates of how much water may be needed to the year 2050;
- Estimates of the impacts of withdrawing sufficient water to meet demand; and
- Descriptions of options for providing additional sources of water and/or decreasing demand.

The RWSPG was assigned the responsibility of developing water demand scenarios to 2050, which was accomplished via contract with investigators at Southern Illinois University-Carbondale. The purpose of this report is to describe the water resources of northeastern Illinois and summarize the impacts on those resources from increased withdrawals to meet prescribed scenarios of water demand to the year 2050. Time and budget constraints limited the state surveys' assessment of water supply impacts to three principal sources of water: the deep bedrock aquifer that underlies all of the study area; the sand and gravel shallow bedrock aquifer underlying only the Fox River watershed; and the surface waters of the Fox River watershed. The study also took into account surface water supplied from Lake Michigan based on summary information provided by IDNR-OWR. Figure 1 illustrates the planning region.

1.2 Report Structure

The Southern Illinois University Department of Geography developed three scenarios characterizing water demand to 2050 for the RWSPG (Dziegielewski and Chowdhury, 2008). The demand scenarios are summarized in Section 2. Section 3 discusses Illinois' use of Lake Michigan.

The methods, data, and analytical tools used to evaluate the impacts of withdrawals on surface waters of the Fox River watershed and on groundwater are reported in Section 4. Section 4 also includes descriptions of the impacts of the water withdrawal scenarios on these water resources in the region as well as a description of the nature of the water sources. The impacts of drought and possible climate change on Fox watershed surface water availability and the impacts on the environment of increased water withdrawals under drought and possible climate change conditions also are described. In addition, Section 4 describes the regional geology, especially regarding the availability of groundwater (aquifers). Summaries of model results are provided at the end of each modeling discussion.

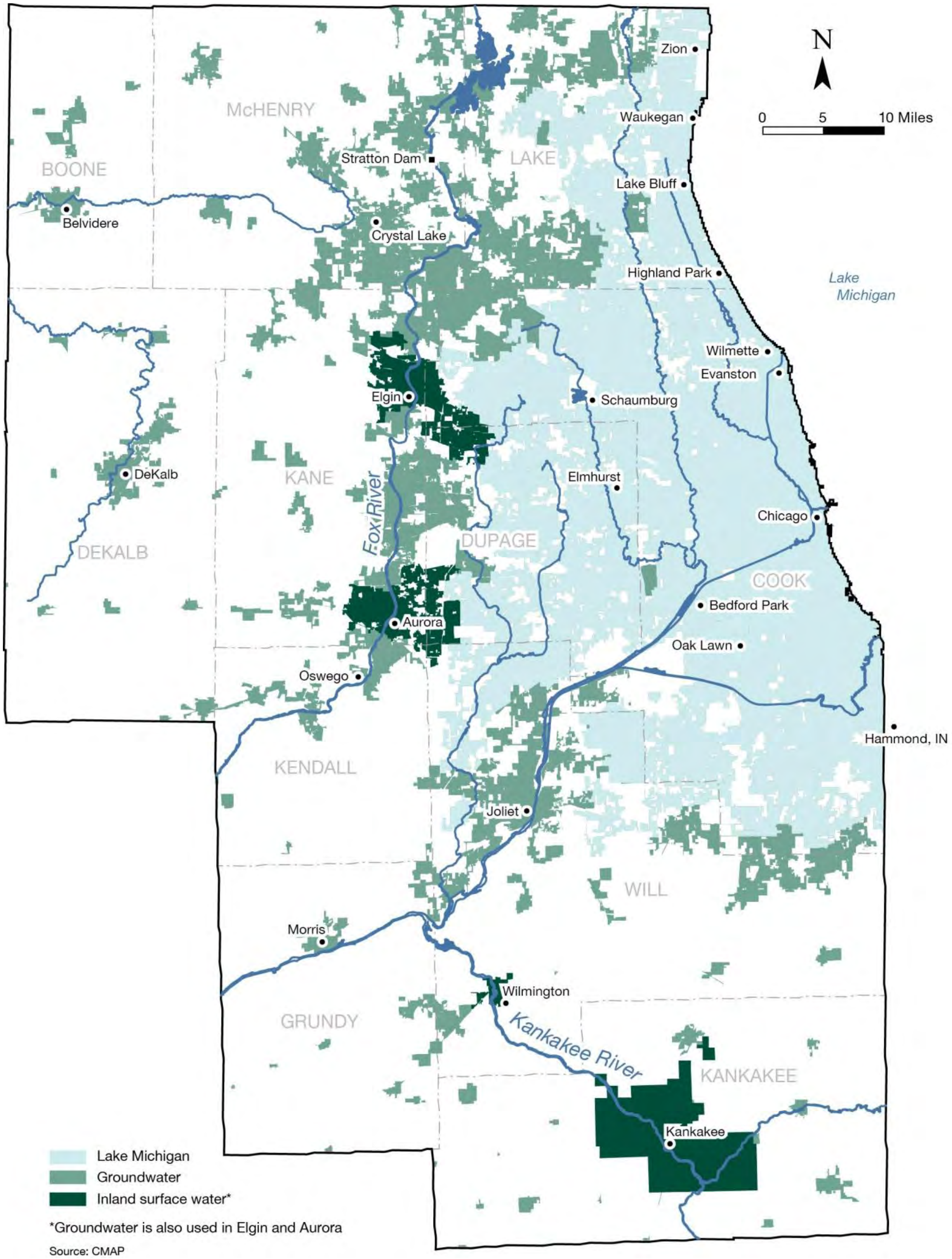
Following a project summary (Section 5), the authors discuss ongoing and future work in Section 6. A glossary of key terms is provided in Section 7, and references are listed in Section 8. As background for those readers unfamiliar with groundwater, a discussion of basic groundwater concepts and terms is provided in Appendix A. A detailed discussion of the regional hydrogeology is found in Appendix B.

1.3 Caveats

The primary focus of the water supply planning initiative is water quantity. Although water quality is not emphasized in this planning effort, water quality issues are reported where existing relevant information is known to the ISWS.

Given the expertise available in the state surveys and the resources and time available to conduct the necessary studies, the following is a list of topics that are important in regional water supply planning and management but are not addressed comprehensively in this report:

- Economics;
- Legal matters;
- Societal and ethical issues and values;
- Water infrastructure;
- Water treatment;
- Water losses;
- Consumptive water use;
- Storm water and floods;
- Utility operations;



*Groundwater is also used in Elgin and Aurora

Source: CMAP

Figure 1. Eleven-county northeastern Illinois water supply planning region and currently utilized community water supply sources (adapted from the Chicago Metropolitan Agency for Planning)

- Conservation and water reuse;
- In-stream water uses (ecosystems, recreation, navigation, etc.); and
- Governance and management.

Surface and groundwater models were developed using the most accurate available knowledge of regional hydrologic conditions. Although the results represent a range of important impacts of the withdrawals simulated in the study, new information and more powerful tools could produce different results from those of this study.

1.4 How Much Water is Available in Northeastern Illinois?

How much water is available to users in northeastern Illinois long-term—that is, the sustainable pumping rate—depends on how water withdrawals affect the environment and what the public considers to be acceptable environmental impacts (Bredehoeft, 2002; Devlin and Sophocleus, 2005). Moreover, these impacts resulting from water withdrawals change constantly as the hydrologic cycle adjusts to climate variability and change, as new wells and surface intakes are put into service and old wells/intakes are taken out of service, and pumping rates at operating wells/intakes rise and fall to meet demands, not only in northeastern Illinois, but especially also in southeastern Wisconsin. Treated effluent that is added to streams increases the availability of water from the receiving streams. Finally, the availability of water is dictated by the price the public is willing to pay for it. If, for example, the expense of desalination of deep groundwater is found to be acceptable, more groundwater will be available. Complicating the issue of expense is the fact that the cost of providing water is constantly changing under the influence of new technologies, a changing economy, and other factors.

Consideration of the numerous impacts of groundwater withdrawals illustrates other complexities involved in computing water availability in a region. Such withdrawals cause the subsurface water pressure (head) in source aquifers to decline, and these head declines, if large enough, may in turn cause water levels in wells to decline (drawdown), possibly resulting in increased pumping expenses and decreased well yields. Head declines may also result in decreased groundwater discharge to streams, possibly leading to reduced stream base flow, reduced water levels in lakes and wetlands, reduced saturated conditions in wetlands, and changes in aquatic habitats and vegetation. In some settings, reduced heads can result in decreased groundwater quality, requiring expensive treatment. Where do scientists, and more importantly the public, draw the line as to what is or is not an acceptable impact?

In this study, instead of generating single-value estimates of water availability, models were employed to simulate the impacts of plausible future pumping conditions. If impacts suggested by the models are considered by stakeholders (in this case, represented by the RWSPG) to be unacceptable or too uncertain, they may recommend to adopt policies and target monitoring and water management efforts to track and mitigate impacts regionally or in specific affected areas, or to conduct additional studies to reduce uncertainty. The models developed for this project are intended to be used for future analysis of other scenarios to test effects of alternative management strategies.

2 Water Withdrawals in 2005 and Future Water Demand to 2050

2.1 Introduction

This chapter summarizes 2005 withdrawals and future withdrawal estimates developed by Dziegielewski and Chowdhury (2008). Subsequent chapters discuss model-simulated impacts of withdrawing water at the estimated rates.

2.1.1 Water Use Sectors

Dziegielewski and Chowdhury (2008) employ five major groups of water users, or water use sectors, in their analysis of water use in northeastern Illinois:

- Public water supplies;
- Self-supplied domestic;
- Self-supplied commerce and industry;
- Self-supplied irrigation and agriculture; and
- Self-supplied electric power generation.

Public water supplies include public and private facilities that provide water for residential use, commerce, and industry and relatively small amounts for irrigation, electric power generation, and other uses. In 2005, public supplies were responsible for 79 percent of water withdrawals in the region (excluding once-through flow in power plants); 74 percent of all public supply withdrawals occurred in Cook County.

In 2005, about 393,000 people in the region obtained water from household wells rather than from public water supply systems. This is the self-supplied domestic sector.

Most water for commerce and industry, electric power generation, and irrigation and agriculture is self-supplied (i.e., facilities operate their own wells and intakes instead of purchasing water from public water supplies). In 2005, 65 percent of all self-supplied withdrawals for commerce and industry were in Cook County. In 2002, 70 percent of all irrigated cropland in the region was in Kankakee and McHenry counties. Irrigation sector withdrawals include those at 352 golf courses that have been built in the region since the 1980s, 239 of these in Cook, DuPage, and Lake Counties.

Twelve large thermoelectric power plants account for more than 95 percent of electricity generation in the region. Much of the water withdrawn for power generation is returned directly to its source, with a small percentage lost to evaporation after being circulated once for cooling in *through-flow power plants*. Dziegielewski and Chowdhury (2008) distinguish this category of power generation water use—referred to in this report as *once-through flow* or, more simply, *through flow*—from *makeup water* pumped by *closed-loop power plants*, which recirculate cooling water. Makeup water is water that is pumped to replace losses and “blowdown” in cooling towers or losses and discharges from perched lakes or ponds. Dziegielewski and Chowdhury (2008) consider makeup water to be a superior estimator of the actual consumptive use of water for power generation compared with the sum of makeup water and once-through flow. Total water use for thermoelectric power generation in 2005 in the region exceeded 4,200 million gallons per day (Mgd), of which only about 52.3 million gallons per day (about 1 percent of the total) was makeup water.

Dziegielewski and Chowdhury (2008) estimated total quantities of water withdrawn from wells, streams, reservoirs, and Lake Michigan. They did not estimate how much water is lost, used, or returned, considering these estimates to be beyond the scope of the project. In this report, the authors calculate average daily withdrawals by dividing available total annual withdrawal data by number of days per year.

2.1.2 Withdrawal Scenarios

The authors use the term *scenarios* for the sets of water withdrawal estimates employed in our analyses (rather than, for example, *predictions* or *projections*) to reflect large uncertainties in estimating future water withdrawals. They advise readers that the scenarios suggest a plausible range of future water withdrawals, but actual future withdrawals may fall outside the range of the scenarios.

2.1.2.1 Scenarios that Assume 1971-2000 Average Climate

Three different combinations of assumptions about future socioeconomic conditions were employed by Dziegielewski and Chowdhury (2008) to develop three different scenarios of future water withdrawals that assume 1971-2000 average climate (Table 1). The low water withdrawal scenario is called the Less Resource Intensive scenario (LRI), and the high withdrawal scenario is called the More Resource Intensive (MRI) scenario. Between these is the Baseline (BL) scenario, referred to as the CT scenario (for Current Trends) in other reports (e.g., Dziegielewski and Chowdhury, 2008; CMAP, 2010). Table 1 provides a qualitative overview of the socioeconomic assumptions on which the three scenarios are based. Additional detail is available in the Northeastern Illinois Regional Water Supply/Demand Plan (CMAP, 2010).

The LRI scenario assumes a population increase of 3,369,313 in 2050, a slow increase in household income, a substantial increase in the price of water, a decrease in irrigated acres, increased water conservation, retirement and non-replacement of three power plants, and a shift of population to Cook and DuPage Counties.

Table 1. Relative Shifts in Socioeconomic Factors Affecting Future Regional Water Demand

Water Demand Factor	*2050 Water Demand Scenario Factor Shift*		
	LRI Scenario	*BL or CT Scenario*	*MRI Scenario*
Population increase	Same as BL	+3,369,313	Same as BL
Household income increase	+	++	+++
Water price increase	++	+	None
Irrigation increase	–	+	++
Water conservation increase	+	~	None
Power plants	-3	-3	+2
Population shift to	Cook and DuPage Counties	None	Kane, Kendall, and McHenry Counties

+ moderate increase; ++ more pronounced increase; +++ dramatic increase;
- decrease; ~ continuation of current situation

The BL scenario assumes the same population increase of 3,369,313 by 2050, a greater increase in household income, a moderate increase in the price of water, an increase in irrigation caused by an increase in the number of golf courses, retirement and non-replacement of three power plants, and a continuation of the historical water conservation trend.

The MRI scenario likewise assumes a population increase of 3,369,313 in 2050, but with a greater increase in household income, no increase in the price of water, even more golf courses, two new power plants, an increase in highly water-consumptive commercial and industrial activities, very little water conservation, and a shift of population to Kane, Kendall, and McHenry Counties.

Climate conditions under the LRI, BL, and MRI scenarios are assumed to be averages for the period 1971 to 2000, and population growth and the percentage of the population employed are assumed to be the same under all three scenarios. Of the factors that differ among the scenarios, the ones accounting for most of the variation in public water supply withdrawals are household income and the price of water. The number of highly water-consumptive commercial and industrial activities and golf courses increases from the LRI scenario, through the BL scenario, to the MRI scenario. Two new power plants are built under the MRI scenario, and three plants are retired under the LRI and BL scenarios.

2.1.2.2 Scenarios that Assume Drought and Climate Change

To illustrate the effect of climate change on water withdrawals, Dziegielewski and Chowdhury (2008) estimated total withdrawals in 2050 under the socioeconomic assumptions of the BL scenario but with altered assumptions pertaining to temperature and precipitation. They defined five different climate change scenarios on the basis of plausible temperature and precipitation departures from the 1971-2000 average conditions assumed to prevail under the BL scenario, and they estimated total withdrawals under each of these scenarios.

To explore the effect of drought, Dziegielewski and Chowdhury (2008) estimated total withdrawals in 2050 under the socioeconomic assumptions of the BL scenario, but substituted an assumed 40 percent reduction from the 1971-2000 average annual precipitation assumed under the BL scenario. This represents fairly severe drought conditions—a 1 in 75 year drought—but not the most severe drought that could occur. Although drought can occur in any year, for purposes of illustration Dziegielewski and Chowdhury assumed this simulated drought to occur in 2050.

2.1.2.3 Future Withdrawals in Indiana and Wisconsin

Future water demand in Indiana and Wisconsin that could affect water availability in northeastern Illinois was estimated by the ISWS. The ISWS created a single scenario of future water demand in Indiana and Wisconsin. This scenario, which also extends to 2050, is based on recent reported pumping and county-level estimates of water demand developed by Dziegielewski et al. (2004).

2.2 Regional Withdrawal Totals

Withdrawals in 2005 (adjusted to average 1971-2000 climate, and excluding withdrawals for power generation) totaled 1,428 Mgd (Figure 2 and Table 2). Under the LRI scenario, withdrawals increase by 93 Mgd or 7 percent above the 2005 climate-adjusted total to 1,521 Mgd in 2050. Under the BL scenario, water withdrawals increase by 530 Mgd, or 37 percent above the 2005 adjusted total to 1,958 Mgd in 2050. Under the MRI scenario, water withdrawals increase by 911 Mgd or 64 percent above the 2005 climate-adjusted total to 2,339 Mgd in 2050. The effects of drought and climate change on withdrawals were estimated by altering the assumptions of the BL scenario pertaining to weather, but retaining all other assumptions of that scenario, hence the bar graphs representing these scenarios are grouped in Figure 2. In a drought with annual precipitation 40 percent below normal, withdrawals in 2050 exceed those of the BL scenario by 128 Mgd, totaling 2,087 Mgd, or 46 percent above the 2005 climate-adjusted

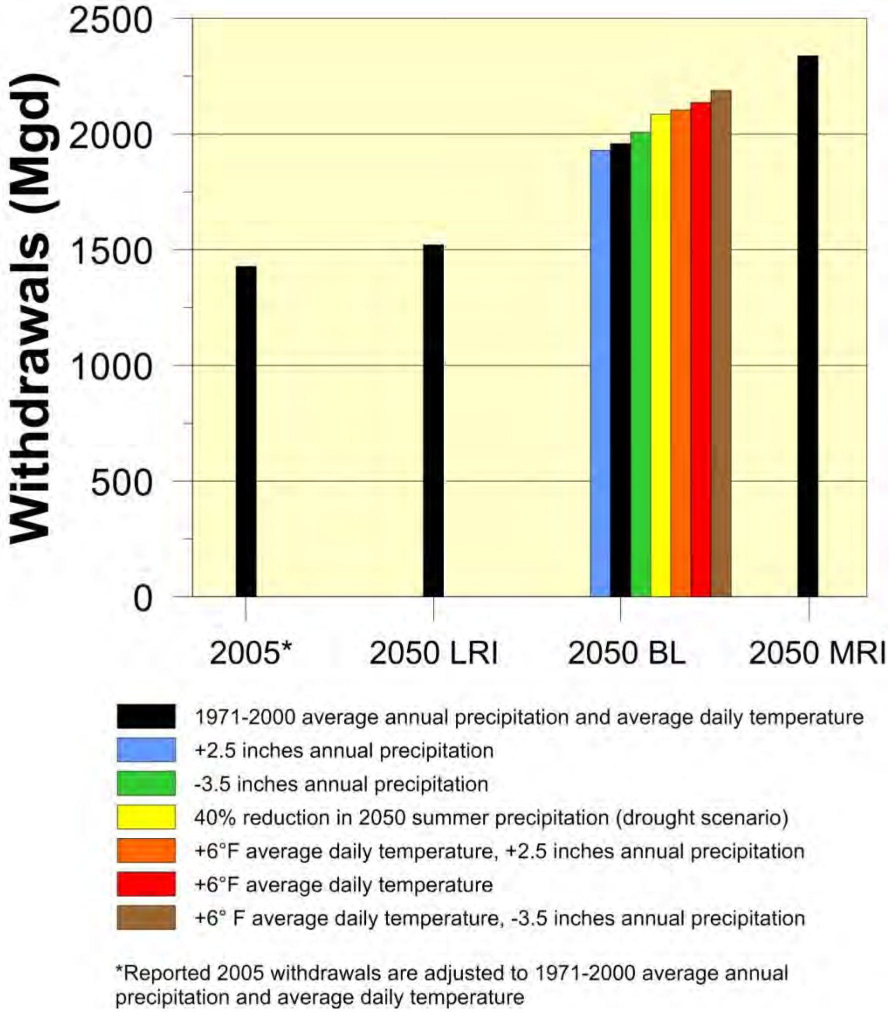


Figure 2. Water withdrawals in the 11-county region in 2005 (adjusted to 1971-2000 average climate) and 2050 for the LRI, BL, and MRI scenarios (which assume 1971-2000 average climate) and for drought and climate change scenarios (which assume departures from 1971-2000 average climate as noted)

total. Estimated total withdrawals under the five climate change scenarios range from 234 Mgd less than those of the BL scenario to 615 Mgd more.

2.3 Withdrawals by Water Use Sector

Table 2 shows withdrawals in 2005 by water use sector; withdrawals in 2050 under the BL, LRI, and MRI scenarios; and withdrawals in 2050 under the drought scenario and five climate change scenarios. Figure 3 illustrates total withdrawals by water use sector (except power generation through flow) in 2005 (adjusted to average 1971-2000 climate) and under the BL, LRI, and MRI scenarios in 2050. Ignoring through flow for power generation, the public supply sector is responsible for most withdrawals in the region (Table 2 and Figure 3).

2.3.1 Withdrawals in 2005

Climate-adjusted public water supply sector withdrawals in 2005 were 1,189 Mgd, self-supplied domestic withdrawals were 32 Mgd, self-supplied commercial and industrial withdrawals were 162 Mgd, and irrigation and agriculture withdrawals were 45 Mgd. About 4,260 Mgd was withdrawn for electric power generation of which about 52 Mgd was makeup water, a plausible estimate of the portion of the power generation withdrawals that is lost to evaporation. About 99 percent of total power generation withdrawals is through flow which is returned to surface waters after use.

2.3.2 LRI Scenario

Table 2 shows that, under the LRI scenario, withdrawals for public water supplies increase 2 percent from the 2005 climate-adjusted total to 1,218 Mgd in 2050. Self-supplied domestic withdrawals increase 17 percent to 37 Mgd. Self-supplied commercial and industrial withdrawals increase 37 percent to 222 Mgd. Irrigation and agriculture withdrawals decrease 2 percent to 44 Mgd. Total power generation withdrawals decrease 40 percent to 2,539 Mgd. Excluding power generation through flow, the overall increase from the climate-adjusted 2005 total is 107 Mgd.

2.3.3 BL Scenario

Under the BL scenario, withdrawals for public water supplies increase 32 percent from the 2005 climate-adjusted total to 1,570 Mgd. Self-supplied domestic withdrawals increase 30 percent to a total of 41 Mgd. Self-supplied commercial and industrial withdrawals increase 80 percent to 292 Mgd. Irrigation and agriculture withdrawals increase 24 percent to 55 Mgd. Total withdrawals for power generation decrease 9 percent to 3,883 Mgd. Excluding power generation through flow, the overall increase from the climate-adjusted 2005 total is 530 Mgd.

2.3.4 MRI Scenario

Under the MRI scenario, withdrawals for public water supplies increase 55 percent from the 2005 climate-adjusted total to 1,837 Mgd. Self-supplied domestic withdrawals increase 55 percent to 49 Mgd. Self-supplied commercial and industrial withdrawals increase 141 percent to 391 Mgd. Irrigation and agriculture withdrawals increase 36 percent to 61 Mgd. Total withdrawals for power generation decrease 8 percent to 3,921 Mgd. Excluding power generation through flow, the overall increase from the climate-adjusted 2005 total is 911 Mgd.

2.3.5 Drought and Climate Change Scenarios

Under the drought scenario, withdrawals in 2050 exclusive of those for power generation total 2,087 Mgd, exceeding the BL scenario withdrawals by 128 Mgd. Under the five climate change scenarios, withdrawals in 2050 exclusive of those for power generation range from 1,930 Mgd (29 Mgd less than BL scenario withdrawals) to 2,188 Mgd (230 Mgd more than BL scenario withdrawals). The effects of drought and climate change on water withdrawals for power generation were not estimated.

2.4 Withdrawals by County

Total 2005 withdrawals for each of the 11 counties in the northeastern Illinois planning region (adjusted to average 1971-2000 climate) and in 2050 under the LRI, BL, and MRI scenarios are shown in Table 3, excluding once-through flows for power generation (Dziegielewski and Chowdhury, 2008). Additional withdrawals will be needed in all counties under the drought scenario and under three of the five climate change scenarios.

2.5 Withdrawals by Source

Sources of water currently utilized in northeastern Illinois include Lake Michigan; inland surface waters of the Chicago Sanitary and Ship Canal (CSSC), the Cal Sag Channel, and the Chicago, Des Plaines, Fox, Illinois, and Kankakee Rivers (only the Fox and Kankakee Rivers are used for public supply); and groundwater. Figure 1 shows public supply sources in the 11-county region, and Table 4 shows total withdrawals from each source in 2005 (adjusted to average 1971-2000 climate) and in 2050 under the LRI, BL, and MRI scenarios, excluding once-through flows for power generation (Dziegielewski and Chowdhury, 2008). While not reflected in Table 4, nearly all of the over 4,200 Mgd withdrawn for electric power generation is once-through withdrawals from surface waters.

Table 4 and Figure 1 show that the principal source of water for the region is Lake Michigan, which provides about 69 percent of all water withdrawn in the 11-county region, excluding once-through flows for power generation. In 2005, Lake Michigan provided about 85 percent of withdrawals for public supply, while inland surface waters and groundwater provided about 3 percent and 13 percent, respectively.

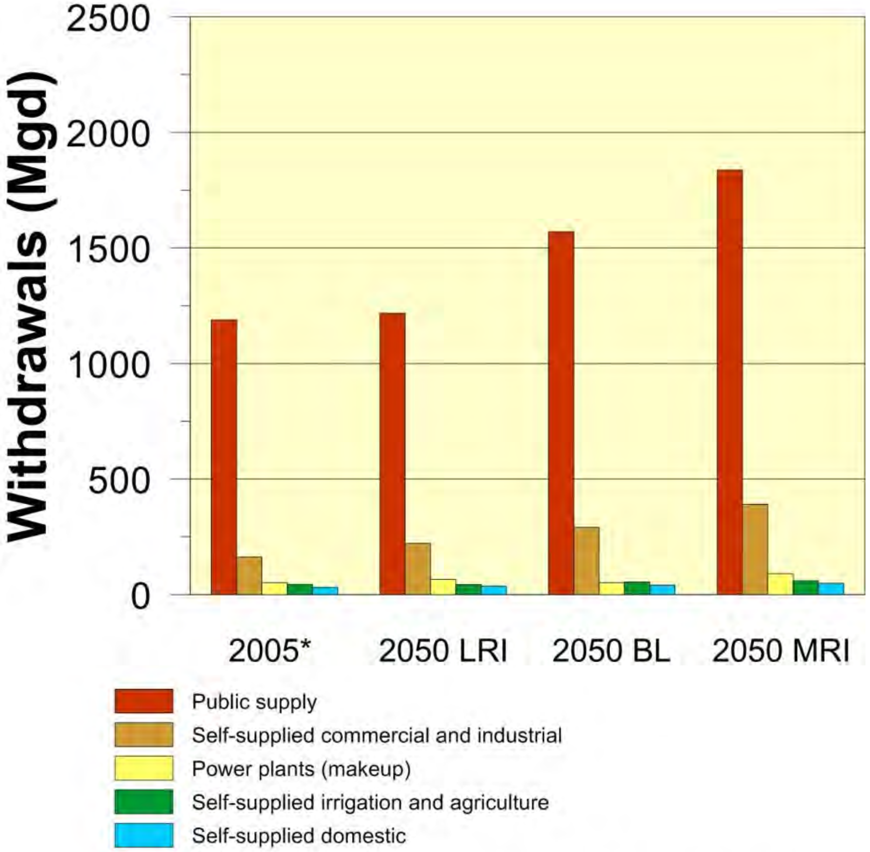
Self-supplied homes rely almost entirely on groundwater. Water for self-supplied commerce and industry is obtained from both surface waters and groundwater; however, significant withdrawals characterized as surface water are pumped by mining operations from sumps and pits for dewatering and for washing and processing of mined aggregate. Approximately 85 percent of water withdrawals for self-supplied irrigation and agriculture originates as groundwater.

Table 2. Reported and Estimated Withdrawals in 11-County Region (Dziegielewski and Chowdhury, 2008) (Mgd)

Water-supply sector or other accounting category		*Reported (2005)*	*1971-2000 average daily temperature and average annual precipitation*				*Drought*[1]	*Climate change*[1]				
			Adjusted (2005)	*BL (2050)*	*LRI (2050)*	*MRI (2050)*	*40% reduction in summer precip. in 2050 (2050)*	*+2.5 inches annual precip. (2050)*	*-3.5 inches annual precip. (2050)*	*+6° F avg daily temp. (2050)*	*+6° F avg daily temp., +2.5 inches annual precip. (2050)*	*+6° F avg daily temp., -3.5 inches annual precip. (2050)*
Public supply		1,255.7	1,189.2	1,570.2	1,217.9	1,837.2	1,649.2	1,552.3	1,600.2	1,702.7	1,683.2	1,735.1
Self-supplied commercial and industrial		191.6	162.4	291.6	222.1	391.4	308	287.8	298.1	328.3	324	335.6
Self-supplied domestic		36.8	31.8	41.2	37.3	49.3	46.8	40.8	43.8	47.1	46	49.4
Irrigation and agriculture		62.0	44.6	55.4	43.8	60.7	82.6	48.6	64.9	58.3	51.5	67.8
Power generation	makeup	52.3	52.3	52.3	66.4	90.8	Not estimated					
	through flow[2]	4,207.2	4,207.2	3,830.2	2,472.3	3,830.2	Not estimated					
TOTAL all sectors		**5,805.6**	**5,687.5**	**5,840.9**	**4,059.8**	**6,259.6**	Not estimated					
TOTAL excluding power generation through-flow		**1,598.4**	**1,480.3**	**2,010.7**	**1,587.5**	**2,429.4**	Not estimated					
TOTAL excluding power generation		**1,546.1**	**1,428.0**	**1,958.4**	**1,521.1**	**2,338.6**	**2,086.6**	**1,929.5**	**2,007.0**	**2,136.4**	**2,104.7**	**2,187.9**

[1] Based on socioeconomic assumptions of BL scenario, with weather and climate assumptions altered from 1971-2000 averages as noted

[2] Largely returned to source



*Reported 2005 withdrawals are adjusted to 1971-2000 average annual precipitation and average daily temperature

Figure 3. Water withdrawals in the 11-county northeastern Illinois planning region, by water use sector in 2005 (adjusted to 1971-2000 average climate) and for the LRI, BL, and MRI scenarios

Under the LRI, BL, and MRI scenarios, the largest percentage increase in total withdrawals is from groundwater sources: +44 percent (+109 Mgd) under the 2050 LRI scenario; +84 percent (+211 Mgd) under the 2050 BL scenario; and +135 percent (+337 Mgd) under the 2050 MRI scenario. Demand for Lake Michigan water decreases 6 percent (-65 Mgd) under the 2050 LRI scenario, but increases 20 percent (+205 Mgd) under the 2050 BL scenario and 37 percent (+379 Mgd) under the 2050 MRI scenario. Demand for river water increases by 30 percent (+63 Mgd) under the 2050 LRI scenario, 54 percent (+115 Mgd) under the 2050 BL scenario, and 110 percent (+233 Mgd) under the 2050 MRI scenario. Under drought and certain climate change conditions the pressure on all water resources would be even greater.

Table 3. Total Withdrawals in Northeastern Illinois, by County (Excluding Through Flow for Power Generation) (Dziegielewski and Chowdhury, 2008) (Mgd)

County	*2005**	*2050 (LRI)*	*2050 (BL)*	*2050 (MRI)*
Boone	7.2	7.9	9.9	111.5
Cook	972.8	915.3	1,171.6	1,340.3
DeKalb	13.8	17.1	21.3	25.4
DuPage	101.2	103.5	124.2	142.2
Grundy	9.2	18.0	22.1	52.4
Kane	52.5	67.8	101.9	135.7
Kankakee	33.6	33.9	40.6	54.0
Kendall	9.5	19.8	31.3	62.3
Lake	91.3	103.1	131.6	160.1
McHenry	38.8	46.7	64.7	100.1
Will	150.5	254.3	291.5	345.2
TOTAL	**1,480.3**	**1,587.5**	**2,010.7**	**2,429.4**

*Adjusted to average 1971-2000 climate

Table 4. 2005 Withdrawals in Northeastern Illinois, by Water Source (Excluding Through Flow for Power Generation) (Dziegielewski and Chowdhury, 2008) (Mgd)

Source	*2005**	*2050 (LRI)*	*2050 (BL)*	*2050 (MRI)*
Lake Michigan	1,018.0	952.9	1,222.7	1,396.9
Inland surface waters	212.2	275.3	327.1	445.0
Groundwater	250.1	359.1	461.0	587.6
TOTAL	**1,480.3**	**1,587.5**	**2010.7**	**2,429.4**

*Adjusted to average 1971-2000 climate

2.6 Use of Water Demand Scenarios in Hydrologic Models

The demand scenario results were incorporated into groundwater and surface water computer models to assess the impacts of withdrawals on the region's water resources. For model input, county sector water demands were disaggregated to withdrawal rates for each well and surface water intake in the region. Indiana and Wisconsin withdrawals also were disaggregated to individual points of withdrawal as described by Meyer et al. (2009). For this initial study, the authors assume that future withdrawals are obtained from the same network of surface intakes and wells in use in 2005. Moreover, they assume that the future distribution of withdrawal rates within a given facility is proportional to its distribution in 2005. For example, if a particular well provided 3 percent of the facility's withdrawals in 2005, they assume that the well provides 3 percent of its withdrawals in 2050. In essence, they assume that water sources and pumping operations remain fixed to reflect 2005 practices. In reality, hundreds of water system managers continually install new withdrawal points, abandon others, and alter pumping operations, their decisions dictated by hydrology, land use, urban growth patterns, economics, politics, and other considerations. The authors highly recommend follow-up modeling studies of plausible future water supply networks that reflect such factors.

Water withdrawal data developed for the water demand study and used in the ISWS models may differ from withdrawal data available to individual facility operators. Although the water demand study used historical data as reported to the ISWS from individual users, the water demand models used variables and factors not necessarily used by individual water facilities in their planning efforts. Therefore, results of this regional planning effort likely differ from individual water users' planning results and are not intended to provide definitive future water withdrawal needs for individual water users. Likewise, these estimates are not a sufficient basis for site-specific infrastructure planning and development. Regional analysis allows for an evaluation of the cumulative environmental impacts of all individual water withdrawals in the region. More detailed site-specific data should be used for site-specific planning and management.

Water withdrawal scenario estimates used in groundwater and surface water models to assess impacts on water resources are average daily withdrawals based upon reported total *annual* withdrawals by each water-using facility. Withdrawals can greatly increase in the summer months primarily due to outdoor water use for agricultural and landscape irrigation (lawn watering). Agricultural and golf course irrigation occurs only during the growing season. Public water system withdrawals during hot, dry summer conditions are commonly twice the average annual rate. Daily water withdrawal rates vary even more from average annual rates than seasonal rates. Water supply system capacities often are designed to meet expected peak daily withdrawal demands. While peak season and peak day demands ought to be considered in determining environmental impacts of withdrawals, only increased seasonal summer demands were examined in groundwater model analyses. Details of the modeled withdrawals applied to the Fox River and the region's aquifers are described in Section 4.

3 Lake Michigan

3.1 Background

3.1.1 History of Illinois' Use of Lake Michigan Water

3.1.1.1 Reversing the Chicago River

As the Chicago area developed, industrial wastes such as animal by-products from the Chicago stockyards, sewage, and excess water from drainage improvements were dumped directly into the Chicago River. With little natural flow, the river became highly contaminated. Since the Chicago River discharged into Lake Michigan, the city's primary water supply, it too became contaminated. As more roads and buildings were constructed, the increase in the impervious area raised the rate and volume of stormwater runoff, resulting in increased flooding.

To solve these problems, the CSSC was constructed to connect the Chicago and Des Plaines Rivers. Completed in 1900, the CSSC allowed the direction of the Chicago River to be reversed, keeping waste and flood waters out of Lake Michigan by sending them into the Mississippi River basin. Built to handle a flow of 10,000 cubic feet per second (cfs) (6,464 Mgd), the initial rate of diversion was about 2,715 Mgd.

A second canal, the North Shore Channel, was completed in 1910 from Lake Michigan at Wilmette south to the North Branch of the Chicago River, increasing the diversion to about 3,878 Mgd. A third canal, the Calumet Sag Channel, was completed in 1922. It connects Lake Michigan to the CSSC through the Grand Calumet River and was constructed to carry sewage from South Chicago, Illinois, and East Chicago, Indiana. Total diversion through the CSSC was increased to about 5,496 Mgd briefly during the 1920s. Figure 4 shows the completed system.

3.1.1.2 Legal Challenges

Starting in 1900, various court actions have affected the operation of the reversal of the Chicago River by Illinois. In 1922 Wisconsin sued Illinois, claiming the Lake diversion was expanded illegally, and sought to halt the diversion entirely. In 1930 the U.S. Supreme Court ordered Illinois to reduce the diversion from the Chicago River into the CSSC to 1,500 cfs (970 Mgd) by 1939. The 1,500 cfs limit was exclusive of Chicago's growing domestic pumpage.

Wisconsin filed suit again in 1958 when three Chicago suburbs obtained state and U.S. Army Corps of Engineers (USACE) permission to tap into Chicago's water supply due to a rapid decline in deep aquifer groundwater levels. In 1967 the U.S. Supreme Court set the Illinois diversion at 3,200 cfs (2,068 Mgd). This limit was based on the Chicago River diversion authorized in 1939, Chicago's domestic water usage, and rainfall from the diverted watershed. A 1980 amendment made technical changes to permit Illinois' effective use and management of the diversion, increasing the accounting averaging period from 5 to 40 years, and adding as a goal the reduction of withdrawals from the deep aquifers. The Supreme Court retained jurisdiction of the case, and all eight Great Lake states, except Indiana, are parties to the case.

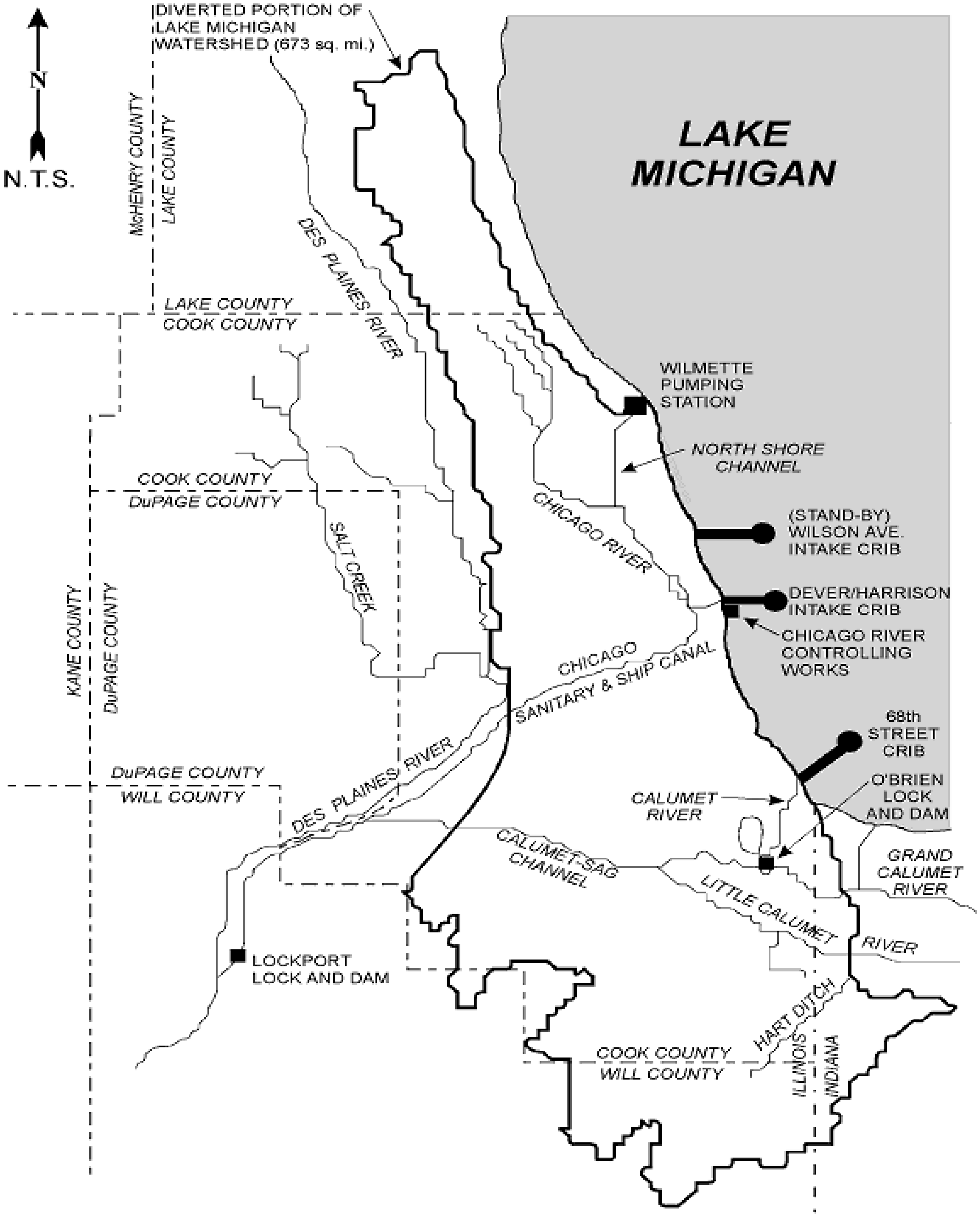


Figure 4. Lake Michigan diversion system at Chicago (from United States Army Corps of Engineers Chicago District. *Lake Michigan Diversion Accounting Water Year 2005 Report*)

3.1.2 Components of Illinois' Lake Michigan Diversion

Diverted water is divided into three major categories: direct diversion, stormwater runoff, and domestic (public water) supply (also referred to as lake pumpage).

3.1.2.1 Direct Diversion

Direct diversion is divided into water diverted for lockage, leakage, navigation, and discretionary use.

Lockage. The amount of lockage diversion depends on the number of times the Chicago River lock at Lake Michigan and the O'Brien lock on the Calumet River are operated, and on Lake Michigan water levels. Federal policy requires the locks to operate on demand. Both locks are among the ten busiest in the country.

Leakage. Leakage occurs through locks, sluice gates, and retaining walls that separate the lake from the Chicago waterway system. Leakage fluctuates considerably, based on lake levels and on the condition of the structures. Leakage was significant in the late 1980s and early 1990s because of high lake levels and faulty seals on the Chicago River lock gates. Leakage through the Chicago River lock at that time was estimated at up to 195 Mgd and was a significant contributor to Illinois' excess diversion. In 2010, the USACE initiated long-awaited rehabilitation of the Chicago River lock gates. Such repairs should reduce leakage flows significantly, especially if lake levels rise.

Navigation. Navigation make-up water is diverted into the Chicago waterway system to maintain adequate depths for safe navigation. Before forecasted storm events, water in the canal system is drawn down as a flood-control measure. If forecasted rainfall is not received, a navigation make-up diversion may be necessary. The navigation make-up allocation is set at 23 Mgd through 2020.

Discretionary Diversion. Water is diverted directly into the Chicago waterway system at the two locks and the Wilmette pumping station in the summer to keep dissolved oxygen levels above standards and to assist in moving water to the Des Plaines River. The discretionary diversion allocation is set at 175 Mgd through 2014, when it will be reduced to 65 Mgd. This reduction of 110 Mgd anticipates that the Metropolitan Water Reclamation District of Greater Chicago's (MWRDGC) Tunnel and Reservoir Project (TARP) Phase II will be operational by 2015. But Phase II may not be finished on schedule since Federal funding has lagged behind requested amounts. When completed, TARP should improve conditions by eliminating the impact of combined sewer overflows, thus reducing the need to flush the waterway with lake water.

3.1.2.2 Stormwater Runoff

Diverted stormwater runoff is runoff from the 673 square mile watershed that drained to the lake prior to the reversal of Chicago River flow (Figure 4). In this document, stormwater runoff also includes other forms of runoff originating from the watershed, including base flow and other runoff from sub-surface sources that contribute to streamflow, all of which are considered as part of the watershed diversion amount. This diversion is measured indirectly, and varies considerably from year to year depending on the amount of precipitation. Based on USACE Diversion Accounting

Reports, stormwater runoff averaged 514 Mgd from 2001 to 2005, 31 percent of average diversion. For the 20-year period 1984–2003, diverted runoff averaged 537 Mgd.

3.1.2.3 Public Supply

A total of 194 public water systems have received Lake Michigan allocation permits from the IDNR-OWR to pump water from Lake Michigan and divert its flow to the Mississippi River basin. Public water system use principally includes household domestic uses, but also includes water purchased for industrial, commercial, and recreational purposes (i.e., not self-supplied) from a public water system with a lake allocation. In 2005 these water systems withdrew a reported 1,076 Mgd from Lake Michigan. Since only 19 public water systems or intergovernmental entities to which they belong have direct access to the lake, most public water systems with allocation permits purchase their water from this small group. There are also a few commercial and industrial permits for low flow allocations. Table 5 provides 2005 (reported and adjusted to 1971-2000 climate) and 2015–2050 scenario projections for Lake Michigan public supply pumpage, as presented in Table ES-7 in Dziegielewski and Chowdhury (2008).

Table 5. Lake Michigan Public Supply Withdrawals (Dziegielewski and Chowdhury, 2008) (Mgd)

Year	*BL*	*LRI*	*MRI*
2005 (Reported)	1,076	1,076	1,076
2005 (Adjusted to 1971-2000 climate)	1,018	1,018	1,018
2015	1,054	931	1,094
2020	1,075	931	1,134
2025	1,098	934	1,176
2030	1,125	939	1,221
2035	1,146	940	1,261
2040	1,170	943	1,304
2045	1,195	947	1,349
2050	1,223	953	1,397

3.2 Future of Lake Michigan Water Availability in Illinois

Central to any discussion concerning long-term availability of water from Lake Michigan is the necessity that Illinois continue its compliance with the U.S. Supreme Court Decree limiting the state's allowable diversion. The decree does not increase Illinois' allowable diversion in the future to meet the needs of a growing region. Therefore, meeting the current and future water supply needs of the existing Lake Michigan water service area and any future expansion of the water service area must not increase Illinois' total diversion above a long-term average of 2,069 Mgd.

Section 3.2 will: (1) briefly summarize the status of the IDNR-OWR review of all current Lake Michigan domestic water allocations, (2) update the estimate of Illinois' current running average diversion and compliance with the U.S. Supreme Court Decree, and (3) review some of the issues/management options that can impact long-term compliance with the decree.

3.2.1 Lake Michigan Water Allocation Review

On July 23, 2008, the IDNR-OWR held a public hearing to enter into the record the final report of its consultant, MWH Americas, Inc. This report contains the final water demand forecasts to the year 2030 for all domestic permittees. Also entered into the record were the compliance plans of all permittees whose unaccounted-for-flows exceeded the IDNR-OWR 8 percent standard, and a list of permittees who did not contest IDNR-OWR proposed revocation of their allocation permit. At this hearing, only two permittees contested the IDNR-OWR proposed decision. Following the hearing, the IDNR-OWR Hearing Officer prepared an Opinion and Order; it was signed by the IDNR Director in December 2008, and new Lake Michigan water allocation permits reflecting the amounts in the order were sent to permittees in February 2009.

IDNR's review of historic water use reveals a general downward trend in water use by Lake Michigan water permittees. This trend was unexpected, since the region has neither been losing population nor experiencing a prolonged period of cool, wet summers, both circumstances that could lead to reduced water use. It is possible that increased energy and water conservation, coupled with higher water prices (from 1995–2005 the average price of Lake Michigan water increased from \$2.99/1,000 gallons to \$3.65/1,000 gallons), accounts for the lower use. This reduced use means that most permittees will see a reduction in their demand/allocation.

Table 6 compares pre-2008 allocations to those approved by the IDNR Director in December 2008. Pre-2008 domestic (public water) allocations for Water Year 2020 total 1,370 Mgd, while allocations for Water Year 2030 total only 1,210 Mgd. This reduction of 160 Mgd may permit Lake Michigan water to as many as 1.16 million additional people, a substantial increase. The reduction of Chicago's allocation accounts for 118 Mgd of the total reduction. Despite this encouraging forecast, Illinois' diversion is determined by actual water use, not by IDNR allocations, so a reduced total domestic allocation does not guarantee that additional lake water is now available for new allocation. However, the forecast illustrates that improving domestic water use efficiency can allow Illinois' limited diversion to supply an expanding population.

IDNR-OWR's 2030 total Lake Michigan water allocation is higher than the 2030 baseline scenario forecast (1,210 Mgd vs.1,125 Mgd) contained in the Regional Water Demand Scenario Report (Dziegielewski and Chowdhury, 2008); however, it is very close to the 2050 baseline forecast of 1,223 Mgd.

3.2.2 Status of Illinois' Diversion

Table 7 shows the latest estimate of Illinois' diversion under the 1980 amended U.S. Supreme Court Decree. This table has been updated to reflect the release of the USACE Report of Illinois' Diversion for Water Year 2007. Since 2005, Illinois' long-term average has dropped and stayed below the Supreme Court limit of 2,068 Mgd; it now stands at 2,049 Mgd. This means that Illinois no longer carries a "water debt." Table 7 also shows estimated diversions for Water Years 2008, 2009, and 2010. The estimated

Table 6. Comparison between Pre-2008 and December 2008 Allocations

Non- Chicago Allocations	*2009*	*2010*	*2015*	*2020*	*2025*	*2030*
Pre-2008						
Number of Permittees	208	208	208	208		
Total Allocations (Mgd)	561.546	567.195	593.783	619.865		
December 2008						
Number of Permittees	198	198	198	198	198	198
Total Allocations (Mgd)	497.900	502.934	524.731	544.787	561.453	577.507

Chicago Allocation	*2009*	*2010*	*2015*	*2020*	*2025*	*2030*
Pre-2008						
Number of Permittees	1	1	1	1		
Total Allocations (Mgd)	737.103	737.103	744.530	750.056		
December 2008						
Number of Permittees	1	1	1	1	1	1
Total Allocations (Mgd)	592.492	594.387	603.861	613.335	622.809	632.282

Total Allocations	*2009*	*2010*	*2015*	*2020*	*2025*	*2030*
Pre-2008						
Number of Permittees	209	209	209	209		
Total Allocations (Mgd)	1,298.649	1,304.298	1,338.313	1,369.921		
December 2008						
Number of Permittees	199	199	199	199	199	199
Total Allocations (Mgd)	1,090.392	1,097.321	1,128.592	1,158.122	1,184.262	1,209.789

diversion for Water Year 2008 is 2,001 Mgd, for Water Year 2009 it is 2,112 Mgd, and for 2010 it is 1,909 Mgd. Except for 2009, and dating back to 1993, all of these years are below the 2,068 Mgd limit. Assuming that these estimates are accurate, when certified, Water Year 2008 will be the 15th consecutive year that Illinois' diversion has been below the court limit. In essence, Illinois is putting water in a "water bank account," which can be used to offset those years in the future if and when Illinois' diversion exceeds the 2,068 Mgd limit. IDNR-OWR believes that establishing a surplus water bank account is an important strategy to ensure its commitment of Lake Michigan water to permittees. First, such a bank account will provide a cushion should Illinois experience conditions similar to those that occurred during the excess diversion years of 1983–1993 (i.e., high precipitation/runoff, high lake levels, and leaking lakefront structures). After 2020, Illinois' 40-year running average diversion must always remain below 2,068 Mgd. The decree does not allow Illinois to have a water debt after that year, so building a surplus water bank account is a wise and necessary course of action. Second, and perhaps more important, a surplus bank account can provide an opportunity to meet additional requests for Lake Michigan water allocation in the future with the expectation that Illinois can continue to comply with the decree.

Table 7. Status of Illinois' Lake Michigan Diversion under the Decree (Mgd)

Accounting Year	*Certified Flow*	*Running Average*	*Cumulative Deviation*
1981	2,007	2,007	61
1982	1,995	2,002	134
1983	2,335	2,113	-133
1984	2,218	2,139	-283
1985	2,244	2,160	-459
1986	2,424	2,204	-815
1987	2,439	2,238	-1,186
1988	2,182	2,230	-1,300
1989	2,183	2,225	-1,415
1990	2,282	2,231	-1,629
1991	2,298	2,237	-1,858
1992	2,203	2,234	-1,993
1993	2,483	2,254	-2,408
1994	1,980	2,234	-2,320
1995	2,066	2,223	-2,318
1996	2,009	2,209	-2,258
1997	2,013	2,197	-2,203
1998	1,978	2,186	-2,112
1999	1,880	2,170	-1,924
2000	1,670	2,144	-1,526
2001	1,744	2,126	-1,202
2002	1,887	2,115	-1,020
2003	1,550	2,090	-502
2004	1,782	2,077	-215
2005	1,791	2,066	62
2006	1,699	2,051	432
2007	2,000	2,049	500
2008[1]	2,001	2,048	567
2009[1]	2,112	2,050	524
2010[2]	1,909	2,046	684

[1] Estimated by IDNR/OWR, based on final approved USGS Lemont discharge values
[2] Estimated by IDNR/OWR, based on provisional USGS Lemont discharge values

Figure 5 illustrates Illinois' diversion for Water Year 2005. Domestic (public supply) pumpage accounted for 59 percent of Illinois' diversion, stormwater runoff accounted for 28 percent, and direct diversion the remaining 13 percent. Stormwater runoff and lockage are two components of diversion that are not currently controllable and together account for approximately 30 percent of Illinois' total diversion.

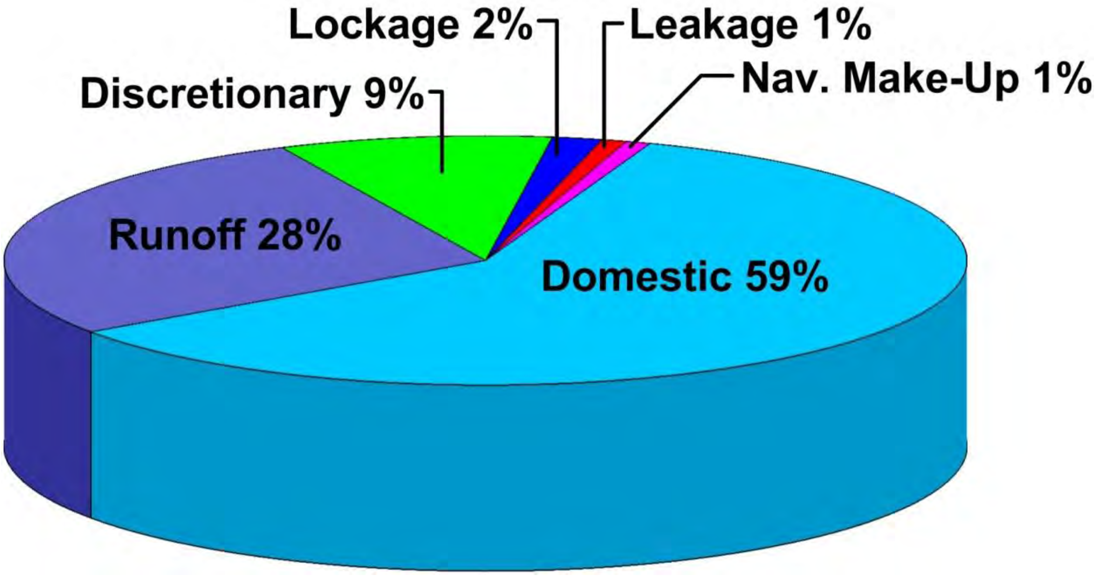


Figure 5. Illinois' Lake Michigan diversion in Water Year 2005

3.2.3 *Long-Term Compliance with the Decree*

How much Lake Michigan water will be available to meet future water supply needs within the current service area and potentially in areas not currently served with lake water? It is not possible to answer this question precisely. Many factors influence Illinois' diversion. These factors can change dramatically over time in ways that are challenging to predict. In addition, there are a number of measures or tools that could be considered, which if implemented, would serve to make more water available for domestic use. The effectiveness of water management measures is challenging to quantify, and a unique set of political, technical, and financial issues will need to be considered. The discussion that follows highlights some of these factors.

3.2.3.1 Climate/Precipitation

Pursuant to the decree, stormwater runoff from the 673 square mile diverted watershed is included as part of Illinois' allowable diversion. Therefore, the frequency and magnitude of precipitation events during a water year will impact diversion. On an approximate 40-year long-term average annual basis, stormwater runoff was estimated by the USACE to be approximately 517 Mgd. This is 25 percent of Illinois' total allowable diversion, so it is very significant, but is highly variable and unpredictable. Estimated stormwater runoff in an extremely wet 1993 was 973 Mgd, but in the drought year of 1988 it was only 336 Mgd. From 1984 to 2003, stormwater runoff averaged 538 Mgd, according to the USACE diversion accounting reports. While this may not seem too far from the 40-year average, if 538 Mgd is more representative of the long-term stormwater runoff average, it means that Illinois has 21 Mgd less water available for domestic water supply needs. Assuming per capita consumption of 125 gallons per capita per day (gpcd), this amount could supply an additional 168,000 people.

Stormwater runoff has increased during the past century, perhaps doubling, due to increased precipitation coupled with urbanization and an associated increase in impervious surfaces in the diverted watershed. Measures have been taken to manage runoff so that less ends up in northeastern Illinois waterways. Stormwater management ordinances in Chicago and other Cook County communities now require new development/redevelopment to store most runoff onsite. Onsite detention, pervious pavement, and green roofs are examples of management measures that, in addition to providing flood control/water quality benefits, will also tend to lower the amount of stormwater runoff from the diverted watershed area. Because diversion accounting as specified by the decree takes place at the outlet of the Chicago Waterway System, every gallon of stormwater runoff that is kept out of the waterway reduces Illinois' diversion by 1 gallon and allows that gallon to be used for other purposes. Though no estimate of stormwater runoff savings has been made, over the long term, the impact could be significant. As a unique example, the recently completed rerouting of the McCormick Place rooftop drainage back to Lake Michigan should reduce diverted stormwater runoff by almost 150,000 gallons per day.

Long-term climate change has the potential to greatly impact this component of Illinois' diversion. Recent data suggest, and many climate change models forecast, significant increases in the magnitude and frequency of high precipitation events (Changnon and Westcott, 2002; Intergovernmental Panel on Climate Change, 2007), which would increase the amount of stormwater runoff. However, an increase in temperature and evapotranspiration would tend to reduce stormwater runoff. Unfortunately, the ultimate impact of these varied effects of climate change on stormwater runoff is unknown, leaving water managers with significant uncertainty in forecasting it.

3.2.3.2 Lake Michigan Water Levels

The level of Lake Michigan has a significant impact on two flow components of direct diversion of Lake Michigan water into the CSSC system: lock operation and lock leakage. Both the Chicago River Lock and the O'Brien Lock on the Calumet River require the diversion of water from Lake Michigan for their operation. The amount of water diverted for lockage is a function of the size of the lock chamber, the head difference between Lake Michigan and the Chicago and Calumet Rivers, and the number of lock operations. The long-term variation in Lake Michigan water levels is around 6 feet, while water levels in the Chicago and Calumet River systems are held relatively constant. The two locks are among the nation's busiest and are operated on an on-demand basis. The amount of water diverted for lockage has varied between 17 and 116 Mgd since 1980, with a 25-year average of 57 Mgd. In Water Year 2005, lockage was 25 Mgd, only 1.6 percent of total diversion for that year. In 1986, lockage was 116 Mgd, accounting for 5.5 percent of total diversion. During that year, Lake Michigan set a new record high water level.

Since water levels on Lake Michigan have been well below average the past several years, the amount of Lake Michigan water diverted for lockage has also been well below normal. Whether this trend will continue, and for how long, is unknown.

Many climate change models suggest that Lake Michigan will experience a 1- to 2-foot water level decline by 2050, but some forecast a water level decline exceeding 5 feet by 2100 (Illinois State Water Survey, 2009). These forecasts suggest that the amount of Lake Michigan diversion needed to operate the lakefront locks should continue to be below historic norms. However, several of these models forecast that above-average Lake Michigan water levels could recur.

The level of Lake Michigan also affects the amount of water that leaks through the structures separating the lake from the river system. This component of diversion has been a significant problem in the past, and numerous efforts have been undertaken to reduce leakage. These efforts include emergency repairs to the Chicago lock by the USACE on several occasions; the emergency elevation of the north/south breakwater by IDNR in 1986; the construction of the Chicago River Turning Basin Wall Project by IDNR in 2000; the upcoming repairs to the headlands areas by IDNR; and maintenance work by the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) at Wilmette.

Determining the amount of water that leaks from Lake Michigan into the waterway system in any given year is problematic. Estimates of leakage have varied greatly over the years, and have been as high as several hundred Mgd during high lake level periods and at times when the Chicago River lock gates failed to seal properly.

All leakage is accounted for as part of Illinois' diversion. After years of waiting for Congressional authorization, the USACE initiated badly needed rehabilitation of the Chicago River lock in 2010. Since the Chicago River lock is at least 16 years past its design life, this rehabilitation project is the most important component of any effort to keep leakage flows to a minimum.

3.2.3.3 Discretionary Diversion

One of the components of direct diversion into the CSSC is discretionary diversion. The purpose of this diversion is to maintain the canal in a reasonably sanitary condition. This component of diversion is managed by the MWRDGC; IDNR-OWR's current allocation for this component is 175 Mgd until Water Year 2015, when it will be reduced to 65 Mgd. This is a reduction of 110 Mgd and reflects the time schedule for the expected completion of the Tunnel and Reservoir Plan (TARP).

The benefits of this massive project to capture combined sewer overflows, in addition to reducing flooding, eliminating backflows to Lake Michigan, and improving water quality in the canal, also extend to enabling IDNR-OWR to direct more of Illinois' authorized diversion to meet future water supply needs. Although the water allocation program must be managed conservatively to maintain compliance with the decree, IDNR-OWR anticipates that a sizable portion of the savings in reducing the discretionary diversion allocation can be held in reserve to meet future water supply needs.

3.2.4 Accounting Issues

The 1967 U.S. Supreme Court Decree, as amended in 1980, contains explicit instructions on how to determine Illinois' diversion. Paragraph 3 of the Decree provides the accounting guidance, including specifying a 40-year running average period to determine compliance with the 3,200 cfs (2,068 Mgd) limit. For the first 39 years (1981–2019), Illinois can accrue a water debt of no more than 2,000 cfs-years (1,293 Mgd-years), and the diversion may exceed 3,680 cfs (2,378 Mgd) during two of those years but must always be less than 3,840 cfs (2,482 Mgd). After 2020, Illinois' running average diversion must always be below 2,068 Mgd and no water debt is allowed. The implication of this is that Illinois must be prepared for high diversion years after 2020 by entering that period with a 40-year running average diversion below 2,068 Mgd. Starting in Water Year 2023, compliance with this requirement will be aided by removal from the 40-year averaging period of the years 1983-1993, when Illinois' diversion exceeded the 2,068 Mgd limit. This will reduce our running average diversion from 2023 to 2034, since those years will no longer count against us. Our cumulative deviation during that 11-year period amounted to about 2,541 Mgd-years. Spread out over a 40-year period that amounts to almost 65 Mgd/year. However, after 2034, the low diversion years (1994–present) will start to drop out, which will tend to increase the running average.

3.2.5 Conclusions

An analysis using assumed values for diversion components was performed to assess the adequacy of Lake Michigan to meet future domestic supply. In this analysis, previously discussed constraints on diversion component amounts were used in combination with component historic averages and the Lake Michigan domestic water supply demand scenarios shown in Table 5 to compute estimates of total lake diversions. The value assumed for stormwater runoff, 537 Mgd, is the 1984–2003 average. Discretionary diversion is held to 65 Mgd based on an imposed IDNR constraint, effective in 2015, which assumes TARP will be fully operational by 2025. The authors also assumed the 25-year average diversion for lockage of 57 Mgd, and the 1997–2007 USACE averages for leakage and navigation of 17 Mgd and 23 Mgd, respectively. Ongoing improvements to the Chicago River lock, expected to be completed in early 2011, should reduce leakage significantly below the 1997–2007 average. While it is uncertain how representative any of the component historic averages are for future decades, particularly given expectations of climate change, these values are the best currently available.

The analysis, summarized in Table 8, Table 9, and Figure 6, suggests that it is likely that Lake Michigan withdrawals can satisfy public system demand through 2050 (or contribute to a water bank), without exceeding the 3,200 cfs (2,068 Mgd) Court limit. Only the 2050 MRI scenario exceeds the Court limit, by 28 Mgd, whereas the 2050 BL and LRI scenarios are 146 and 416 Mgd below the Court limit, respectively. The authors acknowledge that this analysis is simplistic, however, only allowing the public system component of the diversion to vary while holding the other components constant. The other components are not constant, of course, and they could increase above assumed values, potentially causing the Court limit to be exceeded. It is important, therefore, to recognize that all components of the Lake Michigan allocation program are dynamic and all components must be managed wisely to ensure that the court limit is not exceeded.

There is reason to be cautiously optimistic about Lake Michigan water availability for public supply. The state's diversion over the past 14 years has remained consistently below the court limit of 2,068 Mgd. Per capita use appears to be on a slight downward trend, and Lake Michigan water levels remain below the long-term average. In 2015, additional lake water will become available with the reduction in the discretionary diversion allocation. Further, with five additional years of water use data (2006–2010) since Dziegielewski and Chowdhury (2008) completed their study (at the time of their study, complete water withdrawal data were available only through 2005), Lake Michigan public supply pumpage has decreased by 176 Mgd (from 1,076 Mgd in 2005 to 900 Mgd in 2010). This is most likely a result of water conservation measures (e.g., metering, water main replacement), a slow economy, higher than normal withdrawals due to the hot, dry weather experienced in 2005, and the emigration of nearly 200,000 people between 2000 and 2010 from the principal Lake Michigan service area of Cook, DuPage, and Lake Counties, based on U.S. Bureau of Census 2010 data.

Although the Lake Michigan water allocation program must remain flexible to remain in compliance with the Decree, IDNR believes that it can accommodate an increase of about 50–75 Mgd in public water demand without major changes in diversion management policy (while also continuing to satisfy growing water demand within the current Lake Michigan service area). This increase could accommodate any combination of higher-than-expected demand within the existing Lake Michigan service area or expansion of the service area.

Table 8. Estimated Lake Michigan Diversion Components for 2025 (Mgd)

Diversion Component	***Demand Scenarios***		
	LRI	***BL***	***MRI***
Domestic (Public Water) Supply	934	1,098	1,176
Stormwater Runoff	537	537	537
Direct Diversion			
Lockage	57	57	57
Leakage	17	17	17
Navigation	23	23	23
Discretionary	65	65	65
Total	**1,633**	**1,797**	**1,875**

Table 9. Estimated Lake Michigan Diversion Components for 2050 (Mgd)

Diversion Component	*Demand Scenarios*		
	LRI	*BL*	*MRI*
Domestic (Public Water) Supply	953	1,223	1,397
Stormwater Runoff	537	537	537
Direct Diversion			
Lockage	57	57	57
Leakage	17	17	17
Navigation	23	23	23
Discretionary	65	65	65
Total	**1,652**	**1,922**	**2,096**

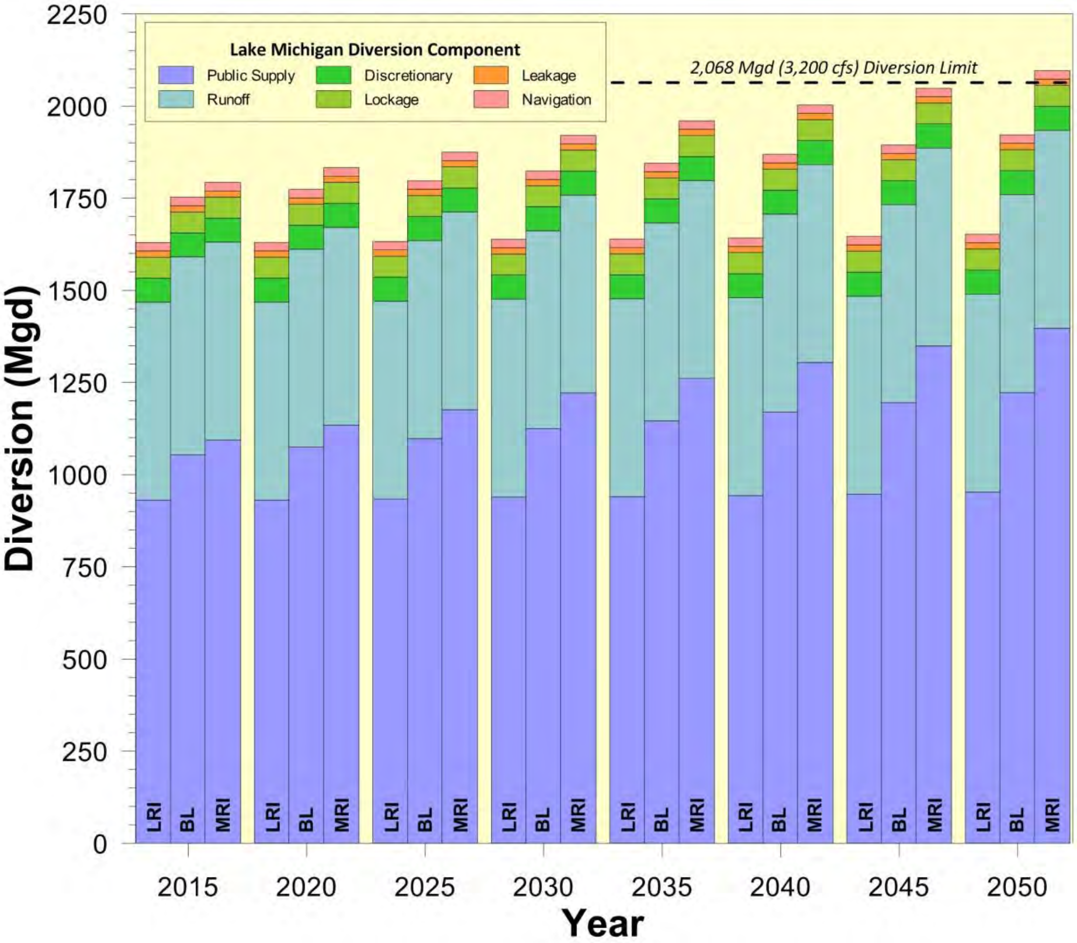


Figure 6. Estimated total Lake Michigan diversion, 2015–2050

4 Inland Surface Waters (Fox River) and Groundwater

4.1 Inland Surface Waters (Fox River)

4.1.1 Introduction

Although water resources development has arguably affected all inland surface waters of the region, Section 4.1 discusses, with limited exceptions, impacts on the Fox River alone. To accommodate the limited time and budget available for this project, the Fox River was selected from among the inland surface waters of the region for this study because it is the subject of prior and ongoing modeling and analysis, because watershed population and water use are rapidly increasing, and because it is already used for water supply by two public water systems, Elgin and Aurora.

Our discussion focuses on impacts to low flow on the Fox River because low flow is a reasonable estimate of both the maximum flow under drought conditions and the minimum flow available to satisfy instream flow needs on the river. Instream flow needs are uses of water within the stream channel that include flow required for aquatic habitat, assimilation of wastewaters, water-based recreation, and stream aesthetics. Management of rivers and streams for instream uses often focuses on maintaining minimum flows, but water quality must also be adequate to support instream uses. Since comprehensive evaluation of the biological, chemical, and socioeconomic factors influencing the flow required for instream uses at a given location is not typically available, managers often specify an arbitrary minimum flow to protect instream uses.

The State of Illinois specifies protected minimum flows only for a small number of streams identified as public waters of Illinois (Figure 7); these consist primarily of the larger navigable rivers in the state. Within the Fox River watershed, only the mainstem Fox River and the Chain of Lakes, near the Wisconsin border, are public waters. Absent detailed analyses for a given stream regarding instream flow needs, IDNR commonly uses the 7-day 10-year low flow value ($Q_{7,\,10}$) as the protected minimum flow for Illinois' public waters, including the Fox River. This means that no new withdrawal from these rivers is permitted if it causes flow to be reduced below the $Q_{7,10}$.

Protection of flow for instream uses on the Fox River requires both maintenance of a minimum flow and minimum water quality. At its lowest flow, effluent from municipal wastewater treatment plants provides much of the flow in the Fox River. The ability of the river to assimilate these effluents and still provide high quality aquatic habitat and recreational opportunities will be a concern in the future, as it is now, particularly because it is expected that effluent discharges to grow with increasing population and water demand. The Fox River studies described in this report address only the quantitative aspects of streamflow availability and use, but an ongoing multi-year study directed by the Fox River Study Group is involved in monitoring and modeling the water quality dynamics of the Fox River. The Fox River Study Group's investigation will greatly improve the scientific basis for managing Fox River water quality to support multiple uses.

Adequacy of streamflow for instream flow needs can be affected not just by river withdrawals, but also by shallow groundwater withdrawals, which can reduce groundwater discharge to the stream and also induce flow directly from the stream into the aquifer (Section 4.2.4.2). Measurable reduction of streamflow due to groundwater

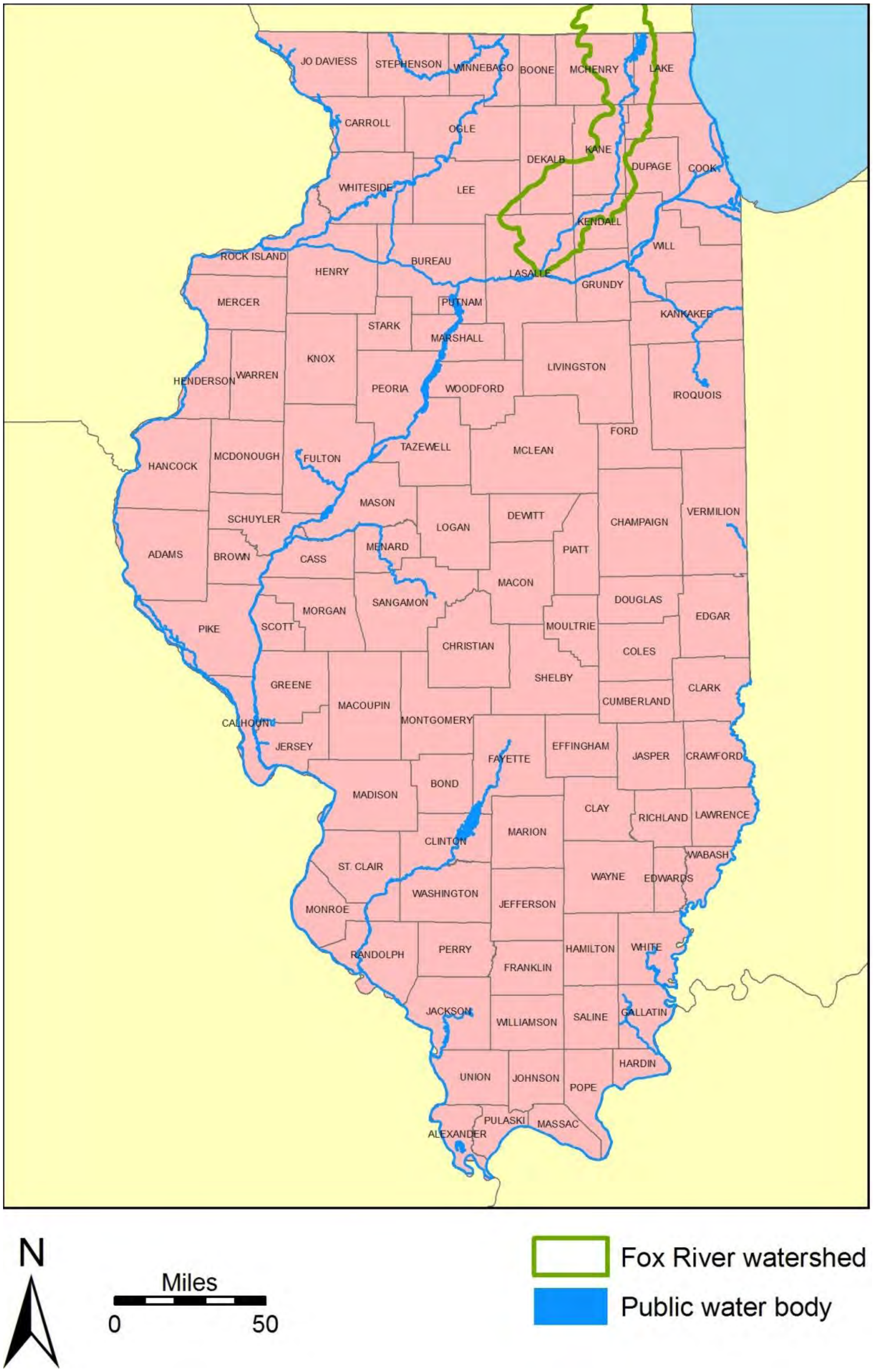


Figure 7. Public waters of Illinois

withdrawals may occur only during very low streamflow conditions accompanying severe droughts. Because the effects of groundwater withdrawals on low flows are diffuse and not directly observable, they could easily go unnoticed. ISWS scientists believe that shallow groundwater withdrawals could threaten instream flows in the Fox River watershed, particularly in tributary streams. On the mainstem Fox River, however, any potential reduction in base flow caused by shallow groundwater withdrawals is more than offset by the release of treated wastewater into the stream (Section 4.1.3), much of which originates from groundwater sources.

4.1.2 Historic and Future Demands

Table 10 shows total inland surface water withdrawals in the planning area for all water use sectors except power generation in 2005 (adjusted to 1971-2000 climate) and 2050 under the BL, LRI, and MRI scenarios (Dziegielewski and Chowdhury, 2008). The totals include withdrawals from the CSSC, the Cal Sag Channel, the Chicago, Des Plaines, Fox, Illinois and Kankakee Rivers, and ponds used in mining.

The industrial/commercial water-use sector is the largest user of inland surface waters in the region, accounting for about 60 percent of climate-adjusted 2005 inland surface water withdrawals. About 80 percent of the climate-adjusted 2005 industrial/commercial inland surface water withdrawals occurred in Cook County, which equals about 50 percent of total climate-adjusted 2005 inland surface water withdrawals.

The power generation sector accounts for about one-quarter of the climate-adjusted 2005 inland surface water withdrawals. That water is used mostly for cooling system make-up water.

The public water supply sector accounts for about 15 percent of the climate-adjusted 2005 inland surface water withdrawals. The sources of these withdrawals are the Kankakee and Fox Rivers, as shown in Table 11. The ISWS has modeled and analyzed the impacts of withdrawals only on the Fox River. An analysis of impacts on other inland surface water sources requires the development of models for those surface waters. The remainder of Section 4.1 addresses only the Fox River watershed.

4.1.3 Factors Affecting Low Flows in the Fox Watershed

Low streamflow conditions in the Fox River watershed were analyzed using a combination of modeling approaches to examine future water supply availability. These models are discussed in Sections 4.1.3.7 and 4.1.4.

Table 10. Future Withdrawals from Inland Surface Waters in 2050 (Dziegielewski and Chowdhury, 2008)

Scenario - Other Surface Waters	*Mgd*	*Change from 2005*	
		Mgd	*%*
2005 (Adjusted to 1971-2000 climate)	212.2		
2050 LRI	275.3	63.1	29.7
2050 BL	327.1	114.9	54.1
2050 MRI	445.0	232.8	109.7

Table 11. Public Water Systems Using Inland Surface Water (Dziegielewski and Chowdhury, 2008)

Public Water System		***Aurora***	***Elgin***	***Kankakee Aqua--IL***	***Wilmington***
County		Kane	Kane	Kankakee	Kankakee
River Source		Fox	Fox	Kankakee	Kankakee
Proportion from River		41%	94%	100%	100%
Quantity from River (Mgd)	***2005 (Adjusted to 1971-2000 climate)***	7.11	13.11	11.95	0.73
	2050 LRI	6.91	18.54	10.90	2.75
	2050 BL	8.87	23.82	14.00	3.61
	2050 MRI	10.58	28.41	21.44	4.27

4.1.3.1 Natural Flows versus Human-Induced Flows

The characteristics of streamflow in any watershed will, over time, vary from earlier conditions because of the cumulative impact of human activities in the region. Like most locations in Illinois, the Fox River watershed has experienced considerable land-use modification since European settlement, including cultivation, drainage modification, urbanization, deforestation, and removal of wetland areas. With the exception of urbanization, most of these modifications occurred in the 1800s prior to any introduction of stream measurements in the region; for this reason, historical stream gaging records do not provide data regarding the impact of these changes. Thus, for the purposes of assessing streamflow conditions within the Fox River watershed, the "natural" or unaltered hydrology is based on the evolved agricultural landscape. It should be noted that the "natural" flow is a calculated amount; for most impacted streams the effect of direct human modifications to their flows must be estimated and then subtracted from the historical flow records.

The driving force in the creation of streamflow is the amount and timing of precipitation. Most rainfall and melted snow will infiltrate into the soil. If the soil is dry, it will retain the water and eventually the water will be used by plants or evaporate back to the atmosphere. However, if the amount of water in the soil exceeds the holding capacity of the soil, the infiltrated water will attempt to move downward–either directly down if the underlying subsoil is not saturated or on a lateral slope as part of the overall subsurface water movement towards the surface drainage. Immediately following rainfall events, the flow of water from the subsurface to the surface drainage can be considerable. But at times of heaviest rainfall, particularly in spring when the ground is frozen or saturated, the rain may not completely infiltrate into the soil and overland flow will occur in addition to the subsurface flow. Lateral flow of shallow groundwater into streams (base flow) occurs all the time into the Fox River and almost all the time into tributary streams. During dry conditions the base flow rate is reduced, even though, during these times, the base flow becomes the sole source of natural flow in the streams.

The Fox River watershed has a high level of natural groundwater contribution to its flow compared to many other watersheds in northeastern Illinois. The major source of the river's low flow is from the northern portions of the watershed, in Wisconsin, and McHenry County, where permeable deposits of shallow sands and gravels provide for a high degree of interaction between groundwater and surface waters. Pockets of shallow, stream-connected sand and gravel deposits are also scattered in other portions of the watershed. Other major rivers in northeastern Illinois that have relatively high base flow contributions to their flows are the Kankakee River (Kankakee and Will Counties) and the Kishwaukee River (McHenry and Boone Counties).

Assessment of the water availability on the Fox River–whether for community supplies or for maintaining water quality and aquatic habitat–is focused on the lowest range of streamflow conditions, conditions that typically occur only during droughts. These low flows almost always occur in late summer or early fall following many months of dry weather, during which time shallow groundwater levels have gradually declined and base flow contribution has been diminished. The lack of rainfall has a cumulative effect on base flow reduction; as a result, the lowest flows do not necessarily coincide with the driest weather conditions but are often related to the duration and persistence of dryness. During the 2005 drought, for example, minimum flows on the Fox River occurred in early September–well after the hottest and driest weather, which occurred early that summer.

For purposes of reference in the remainder of this section, Table 12 shows estimated low, average, and high flows at locations on the Fox River in 2009. Low flow conditions are represented by the minimum 7-day flow that would occur during a 10-year drought, which is used in this report as the index low flow for water supply planning. High flow conditions are exceeded only 2 percent of the time, which is typically slightly less than 2-year flood peak flow. Analysis in this section is focused on low flow during a 10-year drought, but the range of flows that can occur on the river is also instructive. Some results presented in this section are composite values for the entire watershed, represented by the U.S. Geological Survey (USGS) streamgage at Dayton, located in LaSalle County near the Fox River's confluence with the Illinois River. However, the primary focus will be on flow conditions between Stratton Dam and Yorkville, the watershed area of greatest expected growth.

Low flow in the Fox River has varied considerably over the period since 1915 for which daily flow records exist (Figure 8). Throughout the 1930s, 1940s, and 1950s, summer low flows on the Fox River in McHenry and Kane Counties periodically fell below 35 Mgd. In contrast, over the past 40 years, low flows have rarely fallen below 65 Mgd. Four primary factors have had a direct influence on the change in low flow quantity: (1) climate variability, (2) discharge of treated wastewaters into the Fox River, (3) water use withdrawals from the river, and (4) modifications in the gate operations of Stratton Dam, which partially control the outflow of water from the Fox Chain of Lakes in McHenry County. Of these factors, effluent discharges have had the greatest overall impact on low flow amounts along most reaches of the Fox River. Low flows in the Fox River are almost certainly influenced by other factors such as land use changes and flow capture caused by shallow groundwater withdrawals; however, the magnitudes of these

Table 12. Low, Average, and High Flows at Selected Fox River Locations (2009)

Location	*Low flow (Mgd)*	*Average flow (Mgd)*	*High flow (Mgd)*
Wisconsin Border	55	385	1,550
Stratton Dam	60	560	2,130
Algonquin	70	640	2,390
Aurora	100	820	3,260
Yorkville	120	905	3,550
Dayton	155	1,365	5,260

influences are usually not sufficiently large such that they can be directly observed or extracted from the hydrologic records.

4.1.3.2 Climate Variability

Records show considerable long-term variability in Illinois climate and streamflow. Figure 9 shows precipitation and streamflow in the Fox River basin since 1900, as 10-year moving averages. The precipitation and streamflow values plotted in Figure 9 represent the approximate mid-point of the 10 years being averaged; for example, the value for 1995 represents the average for the 10 years from 1990 to 1999; the value for 1996 represents the average for the 10 years from 1991 to 2000; and so forth. Streamflows in Figure 9 are taken from the Fox River at Dayton (1915–2006) representing the composite flow conditions from the entire Fox River watershed. Average streamflows are expressed in inches of water spread uniformly over the entire watershed, such that in this manner they can be directly compared with the precipitation for the concurrent period. Figure 9 shows that the precipitation and streamflow in the Fox River watershed since 1970 have been considerably higher than at any other time in the twentieth century. Figure 9 also shows that 10-year average streamflow is closely correlated with concurrent precipitation, with a correlation coefficient (r) of 0.922.

Table 13 compares the average precipitation and streamflow for four separate periods of record at the Dayton gage: 1915–2006, the period of record for the gage; 1930–1964, an extended period of low precipitation and streamflow; 1970–1996, an extended period of high precipitation and streamflow; and 1948–2006, a base period often used by the ISWS for streamflow analyses because many long-term gages have records dating back to around 1948. For all periods, the difference between the average precipitation and streamflow is roughly 24 inches per year, which is the average amount of water returned to the atmosphere through evapotranspiration (evaporation and plant transpiration). Average streamflow during the wettest period, 1970–1996, is 66 percent greater than average streamflow during the driest period, 1930–1964. Average streamflow during the base period of 1948–2006 is roughly 10 percent greater than streamflow during the entire 91-year gaging record, 1915–2006.

The longest precipitation records for the Upper Mississippi River Basin, which begin in the mid-1800s, indicate that wet periods existed in the 1800s that may have been comparable to conditions from 1970 to 1995 (Figure 10). When viewed in this longer context (as shown in Figure 10), there is considerable variability in the precipitation record, but no overall long-term increasing or decreasing trend (Knapp, 2005). Because there is such a strong correlation between average precipitation and streamflow over the

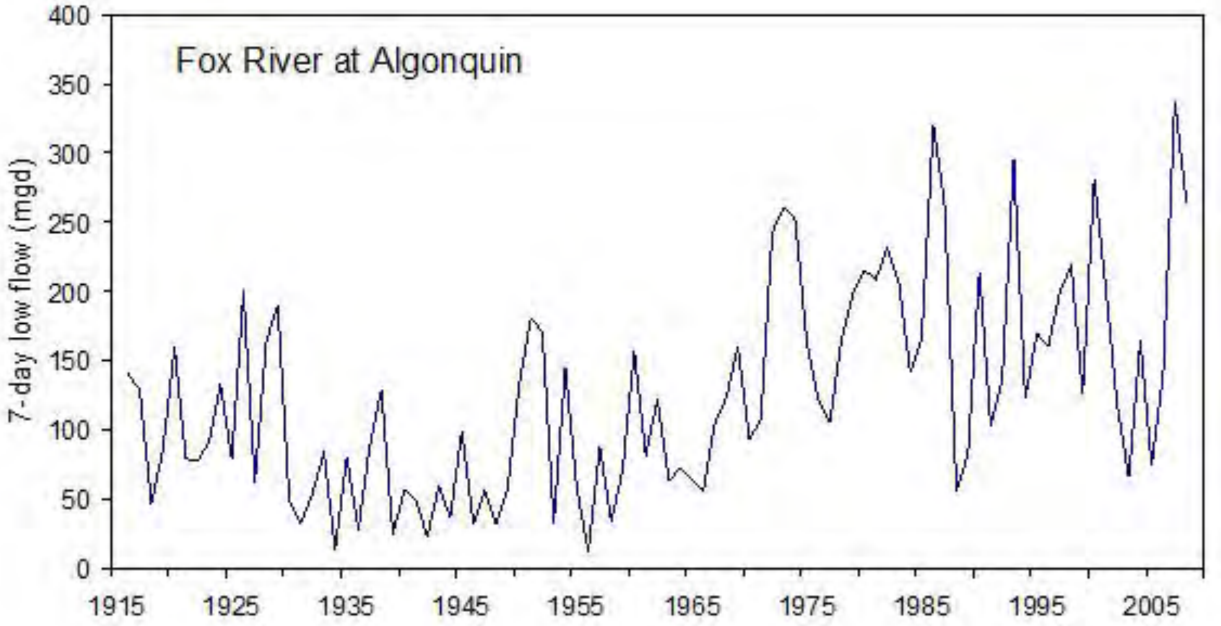


Figure 8. Annual low flows, Fox River at Algonquin

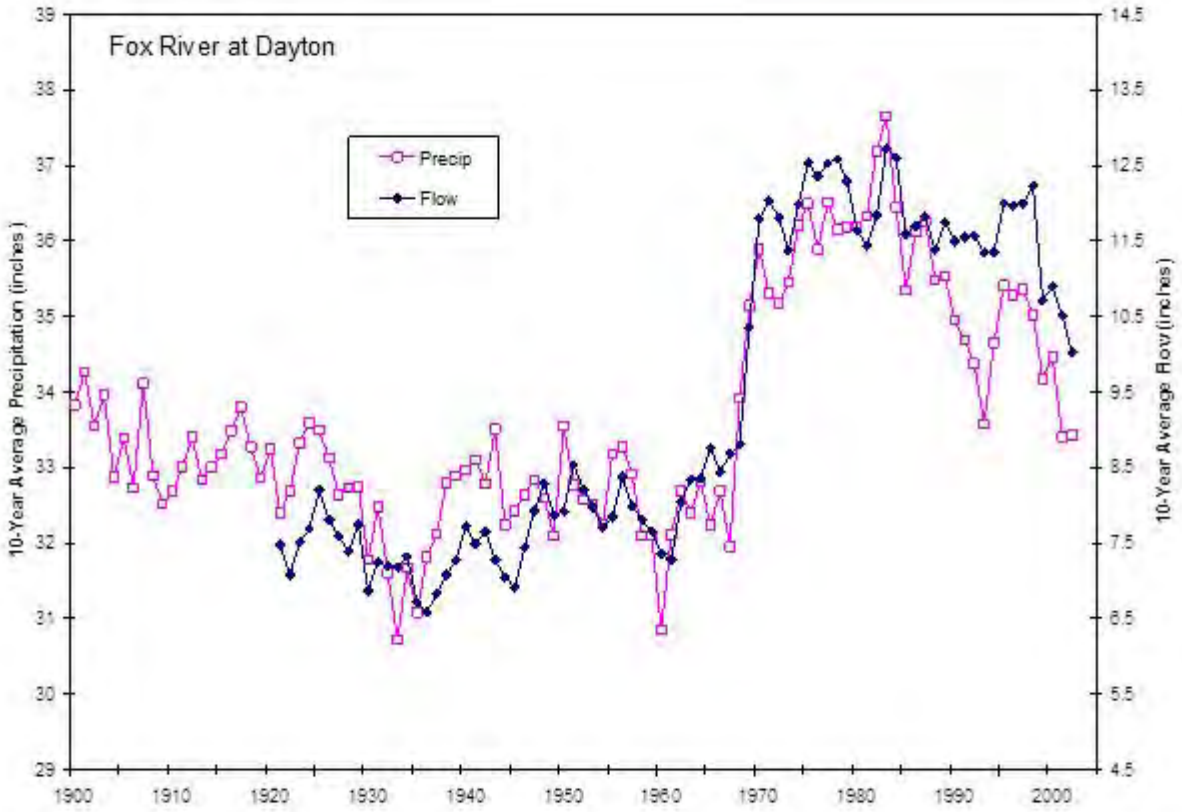


Figure 9. Comparison of 10-year average annual precipitation in the Fox River basin (1900–2006) and streamflow measured for the Fox River at Dayton (1915–2006)

Table 13. Comparison of Average Precipitation and Average Streamflow, Fox River at Dayton

Years	*Average Precipitation (inches/year)*	*Average Streamflow (inches/year)*	*Estimated Evapotranspiration (inches/year)*
1915-2006	33.6	9.3	24.3
1930-1964	31.9	7.3	24.6
1970-1996	35.9	12.1	23.8
1948-2006	34.2	10.3	23.9

period covered by the historical records, it is reasonable to assume that the mid-1800s experienced high streamflows. Therefore, observed increases in streamflow in the Fox River basin (and much of the Upper Midwest) during the twentieth century may reflect long-term climatic and hydrologic variability instead of an increasing trend.

4.1.3.3 Effluent Discharges

Effluent discharges in Illinois and Wisconsin, the great majority coming from municipal wastewater treatment plants, released an average of 138 Mgd to the Fox River and its tributaries during 2005. These discharges collectively account for as much as 10 percent of the entire (average) flow in many reaches of the river, even when losses from other factors are considered. The two largest water reclamation districts, serving Aurora, Elgin, and neighboring communities, account for nearly 40 percent of the total effluent discharge; the Waukesha, WI, region accounts for nearly 15 percent.

Table 14 shows statistics describing changes in effluent discharge to the Fox River watershed since 1970. Average effluent discharge is roughly tied to average water use, although some effluent is attributable to storm water and other wet-weather accumulations of water in sewer systems. In general, a 50 percent increase in a community’s water use roughly corresponds to a 50 percent increase in its effluent.

In addition to collecting wastewaters from domestic, commercial, and industrial users, sanitary sewers also accumulate water during wet periods, primarily as a result of leaks from groundwater and inflow from storm water. As a result, the highest effluent discharges from wastewater treatment plants do not occur in the summer when water use is highest, but instead during wet periods, typically in the spring. The amount of effluent during particularly wet periods can be more than 50 percent greater than the average; in contrast, high flows in the Fox River may be 300 percent greater than the average flow. Thus, although effluent amounts are greater when streamflows are high, they compose a comparatively smaller fraction of the overall streamflow.

The effluent amount tends to be lower during dry periods, with the lowest municipal effluent amounts typically 65 to 70 percent of the average effluent. In contrast, low flow in the Fox River can be as little as 10 percent of the average flow. Thus, although effluent amounts are less when streamflows are low, they compose a much larger fraction of overall streamflow. During extremely low streamflow conditions on the Fox River, such as the lowest 7-day period during a 10-year drought (the 7-day 10-year low flow or $Q_{7,10}$), the total effluent amount discharged to the Fox watershed’s streams is expected to be roughly 84 Mgd. This low flow effluent amount substantially elevates

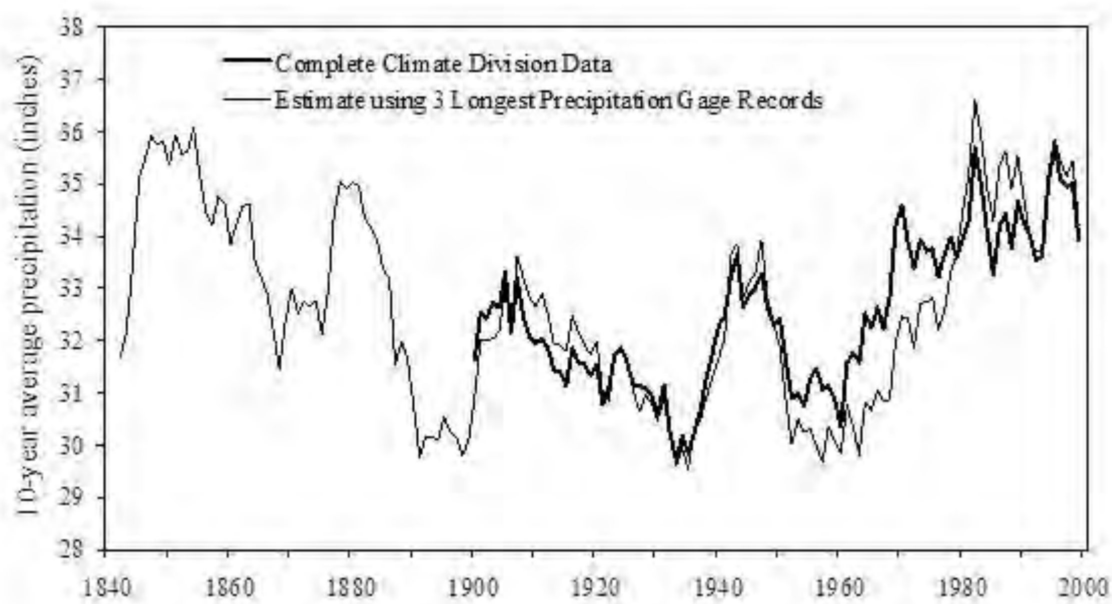


Figure 10. Estimated 10-year average watershed precipitation for the Upper Mississippi River Basin, 1840–2000 (from Knapp, 2005)

low flows in the Fox River. In comparison, the watershed's natural base flow contribution during such a low flow period is estimated to be 120 Mgd. Table 15 lists the general distribution of effluent discharges along selected reaches of the river during low flow conditions.

4.1.3.4 Water Supply Withdrawals

For the past 100 years, almost all of the water used in the Fox watershed was obtained from groundwater sources. But in 1983, Elgin's public water system began withdrawing from the Fox River, and, except for one year, over 90 percent of Elgin's water was obtained from the river during the period 1991–2005. Aurora began withdrawing water from the Fox River in 1992. The river supplied 50 to 60 percent of Aurora's water use from 1992 to 2003, but in 2004 and 2005 the withdrawal was reduced to less than 50 percent of the city's water use. Total Fox River withdrawals by the two water systems have remained fairly steady since 1992, averaging 19.8 Mgd from 1992 to 2005. A smaller amount is withdrawn from the Fox River by the Fermi National Accelerator Laboratory, but this withdrawal is not continuous and its operation ceases when Fox River flow drops below 195 Mgd.

Community water use typically follows a seasonal cycle. From November through April, community water use typically varies little. For most communities, this base level of water use remains fairly consistent from year to year. Monthly water use typically begins to rise in May, reaches a maximum in July, and recedes during the fall. Although several warm-season activities cause water use to rise in summer, lawn and

Table 14. Fox River Watershed Wastewater Effluent Amount for Average and Low-Flow Conditions, 1970–2005

Statistic	*1970*	*1984*	*2005*
Average effluent (Mgd)	Not available	100	138
Low-flow 7-day effluent (Mgd)	46	66	84

Table 15. Distribution of Low-Flow Effluent Discharges Along the Fox River (2005)

Reach	*Effluent (Mgd)*
Upstream of Stratton Dam	24
Stratton Dam to South Elgin	31
South Elgin to Yorkville	27
Downstream of Yorkville	2
TOTAL	**84**

landscape watering (or irrigation) is the most influential factor. Summer water use may vary considerably between years, with higher use during periods of low precipitation. For most communities in Kane County, for example, the highest recorded water use occurred in June or July during the 2005 drought. The timing of the lowest streamflow in late August or September occurs when water use is typically above average, but these streamflows do not coincide with the period of greatest water use. Based on records from the 2005 drought, total withdrawals from the Fox River during the lowest flow conditions are only about 10 percent greater than the annual average, as opposed to the high summer water use rates.

Although this section focuses on the impact of direct withdrawals on streamflows, groundwater withdrawals by shallow wells also may reduce the natural contribution of shallow groundwater to streams, thus indirectly impacting low streamflows. Such impacts are probably localized and are not usually detected by flow monitoring except by strategically located measurements during very low flow conditions. Well impacts on shallow groundwater-surface water interactions may be one of the greatest threats to instream flows in the Fox River's tributary streams. The establishment of streamflow gages or low flow measurements on selected high-quality tributaries, in advance of groundwater development, would help detect impacts of shallow groundwater use on base flows.

4.1.3.5 Gate Operations of Stratton Dam

Stratton Dam (previously named McHenry Dam) is located in Moraine Hills State Park, southeast of the City of McHenry (Figure 1). It was originally constructed in 1907 to raise and regulate the level of water in the Fox Chain of Lakes for navigation by motor boats (State of Illinois Rivers and Lakes Commission, 1915). The original dam included flashboards that could raise the water an additional 3 feet. The dam was reconstructed in 1942 in its current form with adjustable gates to control the outflow, and has been owned and operated by the State of Illinois since that time. There are no known records of the operation of the dam prior to 1942.

Low flows in the reach of the Fox River immediately downstream of Stratton Dam are predominantly controlled by releases from the dam. Two different changes in the dam's operation policy, in 1965 and 1988, have resulted in an overall increase in its flow releases during dry periods. Low flows measured at the USGS gage at Algonquin, located 17 miles downstream of Stratton Dam, reflect the impact of these operation changes (Table 16).

The current 10-year low flow release at Stratton Dam, 60 Mgd, is roughly equivalent to the natural 10-year low flow as estimated by the ISWS (Knapp, 1988). Although the operation at the dam is the main factor determining the amount of low flow downstream, the ability to maintain the current minimum flow release without causing noticeable drawdown in the Chain of Lakes is possible because of increases in inflows to the lakes provided by upstream effluent discharges. Without the additional flow provided by these effluents, the minimum release from the dam during drought conditions would need to be noticeably less than the natural inflow rate in order to maintain the recreational pool, as was the condition prior to 1988. Analysis by Knapp (1988) indicated that the frequency and magnitude of low water levels in the Chain of Lakes was decreasing as a result of the increasing amount of wastewater effluent being discharged by communities upstream of the lakes. This finding was influential in bringing about the 1988 increase in Stratton Dam's minimum low flow release to its current level. The 1988 study also suggested that if water use and effluent growth continued as expected, the frequency and magnitude of lake drawdown would continue to decrease, and an additional increase in the minimum low flow release might be acceptable sometime in the future.

This trend could be interrupted in the future, however, if some Wisconsin communities are able to obtain their water supply from Lake Michigan and, as a result, are required to return their treated wastewater to the Lake Michigan watershed. Effluent discharges upstream of Stratton Dam added roughly 24 Mgd to the river's flow during low flow conditions in 2005. The effluent originates as groundwater. Roughly half this total amount (12 Mgd) comes from water use near Waukesha, WI, where several communities straddle the Great Lakes watershed divide and as such may be considered for potential exemptions to the Great Lakes Compact's ban on inter-basin diversions. It is not known how likely exemptions are to be granted in the future, but if they are granted, part or all of the 12 Mgd effluent amount would be routed to Lake Michigan, reducing the low flows in the Fox River (upstream of Stratton Dam) by the same amount. Such an action could potentially reduce the effluent inflow into the Chain of Lakes to pre-1988 conditions; however, it is not envisioned that such a condition would lead to a reversal of the 1988 decision to increase the minimum flow release from Stratton Dam. In either case, effluent discharge amounts from other communities upstream of Stratton Dam would be expected to grow, eventually making up for the loss of Waukesha's effluent if that were to occur.

Table 16. Lowest Observed 7-Day and 31-Day Low Flows in the Fox River at Algonquin

Prior to 1965

Rank	*Year*	*7-day lowflow (Mgd)*	*Year*	*31-day low flow (Mgd)*
1	1956	12	1934	20
2	1934	14	1956	21
3	1942	23	1936	34
4	1939	28	1939	36
5	1936	32	1931	41
6	1948	32	1958	43
7	1946	33	1948	45
8	1953	34	1946	45
9	1931	37	1944	55
10	1958	47	1918	59

Since 1965

Rank	*Year*	*7-day low flow (Mgd)*	*Year*	*31-day low flow (Mgd)*
1	1988	56	1965	74
2	1966	56	1966	78
3	1965	64	2003	81
4	2003	66	1988	83
5	2005	74	2005	86

Current

Statistic	*Year*	*7-day low flow (Mgd)*	*Year*	*31-day low flow (Mgd)*
10-year low flow	Current	70	Current	84
50-year low flow	Current	54	Current	59

4.1.3.6 Composite Effect of Human Influences on Low Flows

Figure 11 shows the overall impact of human influences on low flow in the Fox River along a reach from near Crystal Lake downstream to Yorkville, comparing the present-day (2005) 10-year low flow to estimated natural or unaltered flow during a 10-year drought. In the upstream (northern) portion of this reach, the present-day 10-year low flow slightly exceeds the estimated unaltered flow, which is controlled by low flow releases from Stratton Dam. Downstream, the unaltered flow gradually increases through natural accretion of base flow to the Fox River and its tributaries. In contrast, the present-day flow progressively gains considerable additional flow from effluent discharged by groundwater-using public water systems. “Dips” or decreases in the present-day flow mark withdrawals, with subsequent effluent discharge, by Elgin and Aurora. At the downstream (southern) end of this reach at Yorkville, the present-day low flow is 35 Mgd greater than the unaltered flow. This 35 Mgd net increase in low flows is roughly

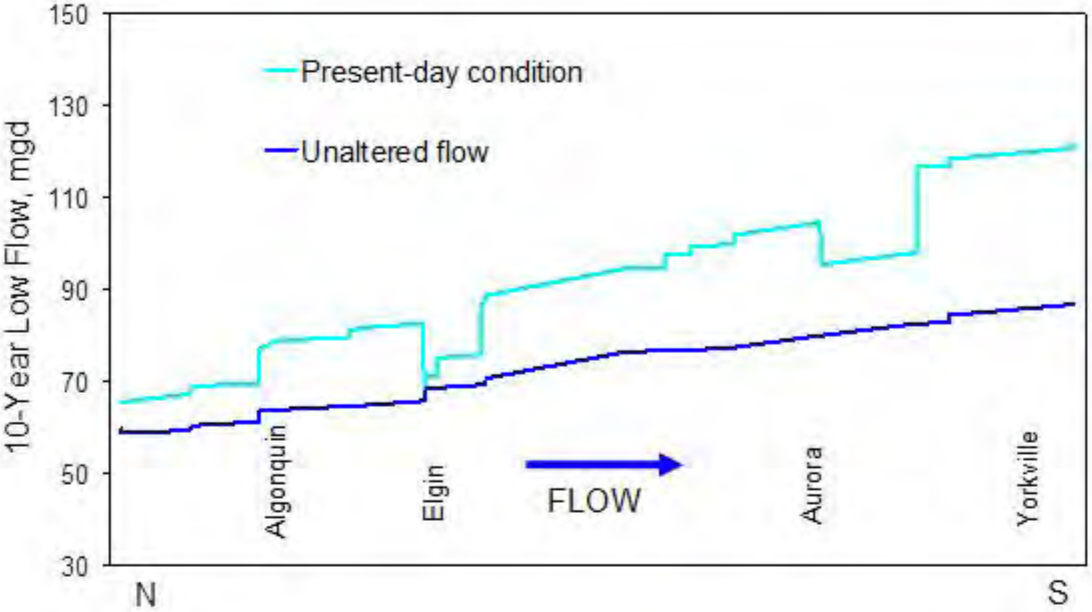


Figure 11. Ten-year low flow under unaltered conditions and approximate 2005 (present-day) conditions, Fox River from near Crystal Lake to Yorkville

equivalent to the difference between the effluent discharges (+58 Mgd) and water supply withdrawals (–24 Mgd) on the river between Stratton Dam and Yorkville.

4.1.3.7 Impacts of 2050 Water Demand Scenarios on Streamflow

As mentioned above, low flow conditions in the Fox River have historically been impacted by climate variability or change, effluent discharges, water supply withdrawals, and the operation of Stratton Dam. These same factors have the potential to change future low flow conditions. For this study, two models were prepared by the ISWS to analyze potential changes in water availability from the Fox River and its tributaries. The first model, the Fox River Surface Water Accounting Model (FRSWAM), was developed to estimate impacts of existing and future water use on the Fox River, including both effluent discharges (from both surface and groundwater sources) and water supply withdrawals. This model provides an update of streamflow frequency assessments of the Fox River previously conducted by the ISWS and documented by Knapp (1988), Knapp and Myers (1999), and Knapp et al. (2007). These previous model development studies on which the current model is based were supported by IDNR-OWR and Kane County. Predictions of the FRSWAM assume that future climate will resemble the historical climate. The FRSWAM is essentially the same surface water accounting model used by Knapp et al. (2007), but the authors of the present study have expanded the model to provide results for the entire Illinois portion of the Fox River watershed. The second model, a watershed model discussed in Section 4.1.4, was developed primarily to analyze potential climate change impacts.

A note on the uncertainty of flow estimates is warranted. The low flow estimates for the Fox River have a standard error of roughly 10 to 15 percent. The relatively high level of accuracy for the flow estimates for the Fox River is provided by (1) the presence of four USGS continuous flow monitoring gages on the river, three of which have long-term records, and (2) the river having a stable channel, such that there is not much variability in the channel condition at each gage during the periods between periodic flow measurements when flows must be estimated using river stage readings. Low flow estimates for ungaged tributary streams typically are very small values that have standard errors in excess of 50 percent. Flow statistics for ungaged sites are estimated using equations based on selected watershed characteristics and observations from regional gaging stations. Whereas such transfer equations typically have standard errors of estimate of 20 to 25 percent for most streamflow conditions, the relative error increases when the flow magnitude is very small.

2050 Water Demand. Impacts in 2050 were estimated for the BL, LRI, and MRI scenarios described in Section 2.1.2: Table 17 lists the percent change in Fox watershed water use from 2005 to 2050 under these scenarios. Changes in effluent discharge for all communities are assumed to be proportional to growth in water use as listed in Table 17.

All community water supply systems in the watershed currently obtain water exclusively from groundwater sources except Elgin and Aurora, which obtain part of their water from the Fox River. Thus, except where noted in the following sections, Elgin and Aurora would continue to operate the only surface water withdrawals in the watershed, with projected increases in surface water withdrawals under the 2050 BL scenario of 82 and 25 percent, respectively.

Potential Change in the Waukesha Water Source and Impacts Upstream of Stratton Dam. The principal exception in the 2050 growth scenarios regarding water supply sources is for the groundwater withdrawals that supply Waukesha, WI, and surrounding communities. As mentioned previously, several communities near Waukesha straddle the Great Lakes watershed divide and as such may be considered for potential exemptions to the Great Lakes Compact's ban on inter-basin diversions. Two possibilities are considered:

- If no exemptions are granted, regardless of where the Waukesha region obtains its future water, it is assumed that the region's water use will grow at the rates specified in Table 17, with proportional increases in effluent discharges to the Fox River. The resulting flow increases in the Fox River could be substantial; for example, increased inflows into the Chain of Lakes could range from +12 Mgd under the LRI scenario to +52 Mgd under the MRI scenario. With such levels of additional inflow to the Chain of Lakes, it is expected that at some point the minimum flow releases from Stratton Dam also would be increased.
- If exemptions were eventually granted, some existing effluent discharges to the Fox River would cease, decreasing low flows in the Fox River upstream of Stratton Dam. Under this alternative, the authors assume that the entire Waukesha region will be granted exemptions and will obtain water supplies from Lake Michigan. However, it is possible that exemptions could be granted only for some of these communities.

The second alternative is the more conservative for planning purposes in Illinois, because it does not rely on Wisconsin facilities to create additional water availability for potential downstream use by Illinois; as a result, the full Lake Michigan exemption alternative is used when evaluating impacts of the 2050 water demand scenarios. With the simulated diversion to Lake Michigan of effluent from communities near Waukesha, the 2050 LRI scenario would result in a net 6 Mgd reduction of inflow to the Chain of Lakes. Such a decrease in inflow would not be expected to impact the Stratton Dam operation policy or the magnitude of low flow releases from the dam. In contrast, if water use in other communities upstream of Stratton Dam grows at the largest MRI rate, the additional 2050 inflows into the Chain of Lakes may be sufficient to sustain a larger minimum flow release from the dam, even with the assumed diversion of Waukesha effluents to Lake Michigan (Table 18). Under the MRI scenario, the authors assume that the minimum flow release from Stratton Dam increases by 10 Mgd, corresponding to an incremental increase in the minimum gate opening at the dam. As noted earlier, if the Waukesha region does not obtain water from Lake Michigan and continues to release its effluents into the Fox River, the 2050 $Q_{7,10}$ inflow into the Chain of Lakes will increase by an even larger amount.

Figure 12 shows the modeled impact in 2050 of the BL scenario on low flows in the Fox River, again along a reach extending from near Crystal Lake downstream to Yorkville. Similar results are shown in Figures 13 and Figure 14 for the LRI and MRI scenarios, respectively. The modeling results show that low flow in the Illinois portion of the Fox River, and the proportion of low flow originating as effluent, will continue to increase. The increase in effluent more than offsets the expected increase in withdrawals at Elgin and Aurora.

Potential for Water Supply Withdrawals. The modeled scenarios discussed above do not examine the possibility that new withdrawals from the Fox River could provide water to additional communities. Instream flow guidelines used by IDNR specify that new withdrawals should not cause flow in the Fox River to fall below the $Q_{7,\ 10}$, which is shown in Figure 12 to Figure 15 as the present-day (2005) low flow. Additional water could be obtained from the Fox River if IDNR revised its guidelines to fix the protected flow level at the present-day $Q_{7,\ 10}$ so that the protected flow would not change even as additional effluent increases actual low flow.

Figure 12 to Figure 15 show locations on the Fox River downstream of Elgin where the projected 2050 low flow is greater than present-day low flow by more than 10 Mgd, allowing development of a new 10-Mgd withdrawal under a management policy that fixes the protected low flow at its present-day condition. For example, Figure 15 shows projected low flow on the Fox River, assuming the BL scenario, if two additional river withdrawals are developed near St. Charles and Yorkville by 2050. In this example, the hypothetical withdrawals at St. Charles and Yorkville total 15 and 10 Mgd, respectively. The authors have selected 8- to 10-Mgd as a rough threshold for a new surface water supply in acknowledgment of the economies of scale associated with surface water treatment costs. The feasibility of water supply withdrawals from the river would, of course, also involve evaluating potential impacts related to water quality and aquatic ecosystem diversity. Downstream locations in Kane and Kendall Counties might be able to support an 8- to10-Mgd withdrawal far in advance of 2050. For example,

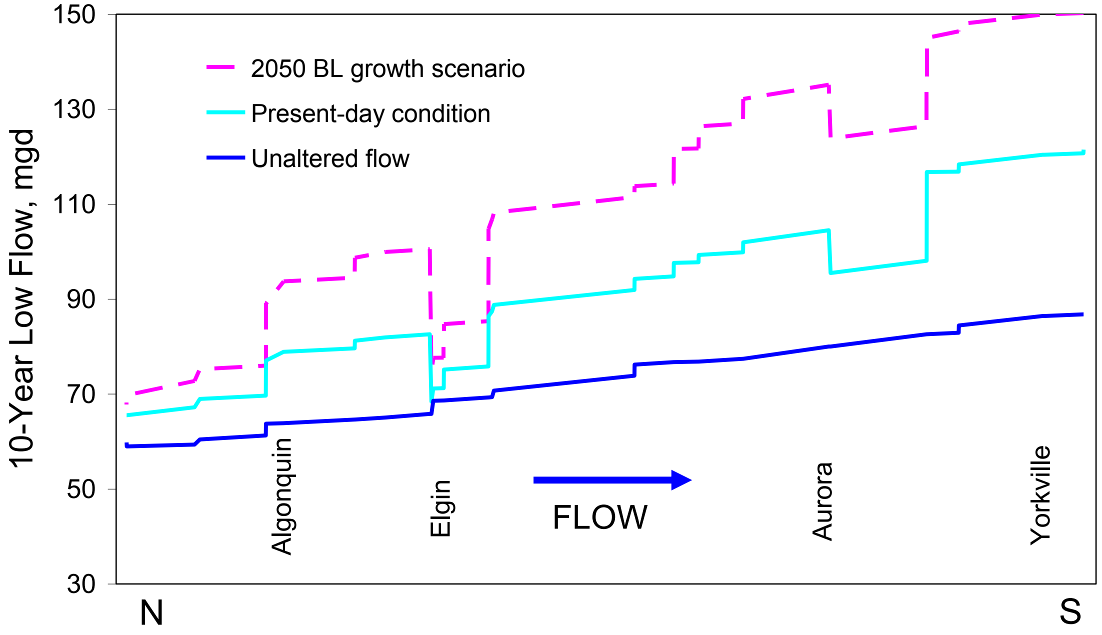


Figure 12. Ten-year low flow under unaltered conditions, approximate 2005 (present-day) conditions, and conditions in 2050 (BL scenario), Fox River from near Crystal Lake to Yorkville

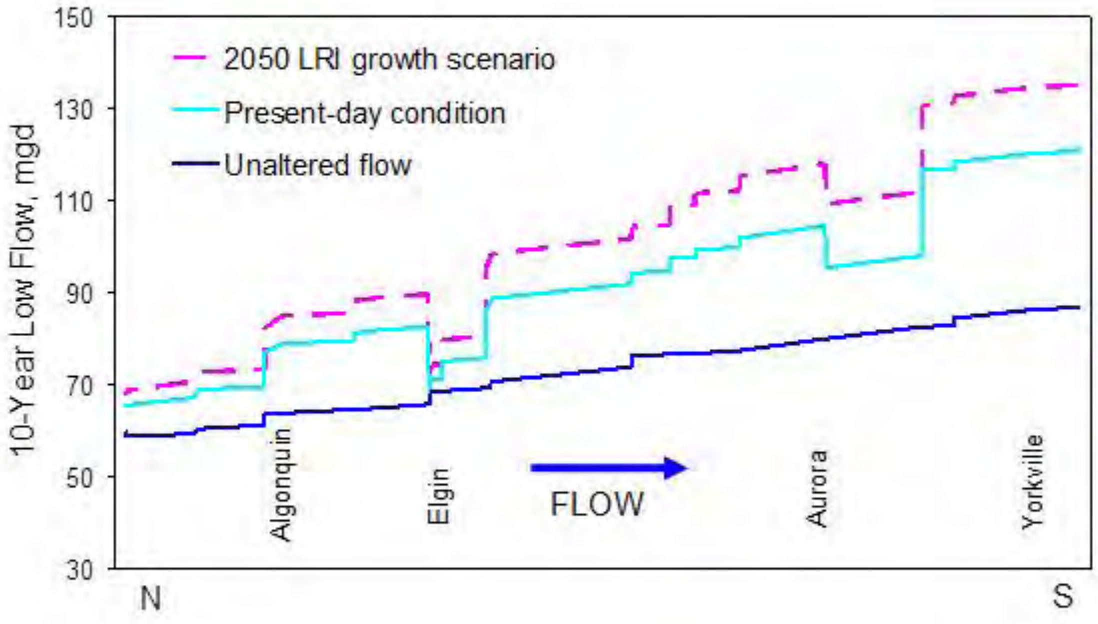


Figure 13. Ten-year low flow under unaltered conditions, approximate 2005 (present-day) conditions, and conditions in 2050 (LRI scenario), Fox River from near Crystal Lake to Yorkville

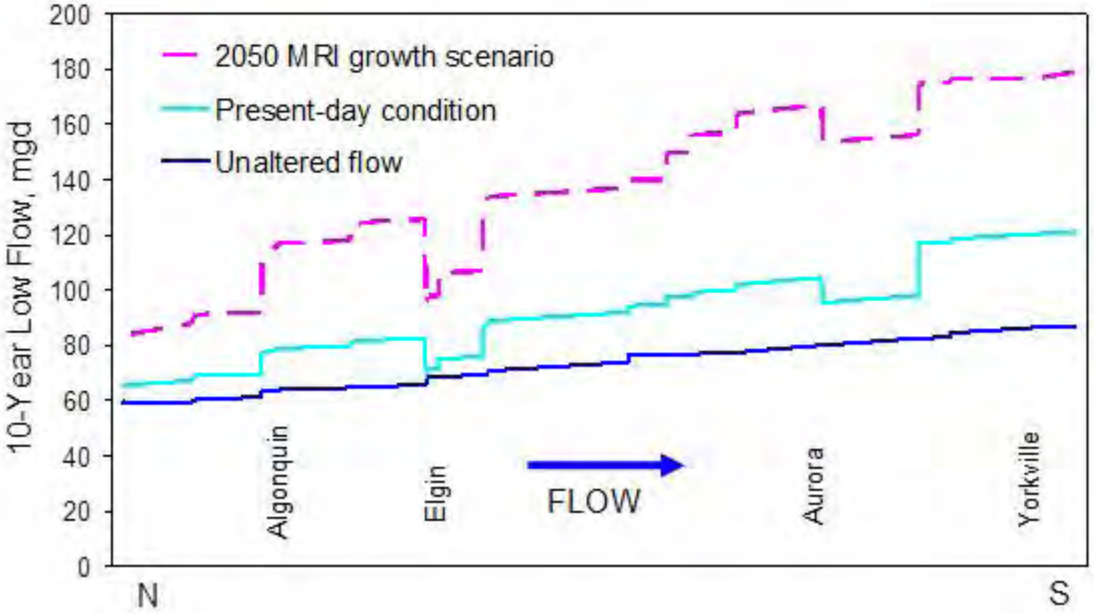


Figure 14. Ten-year low flow under unaltered conditions, approximate 2005 (present-day) conditions, and conditions in 2050 (MRI scenario), Fox River from near Crystal Lake to Yorkville

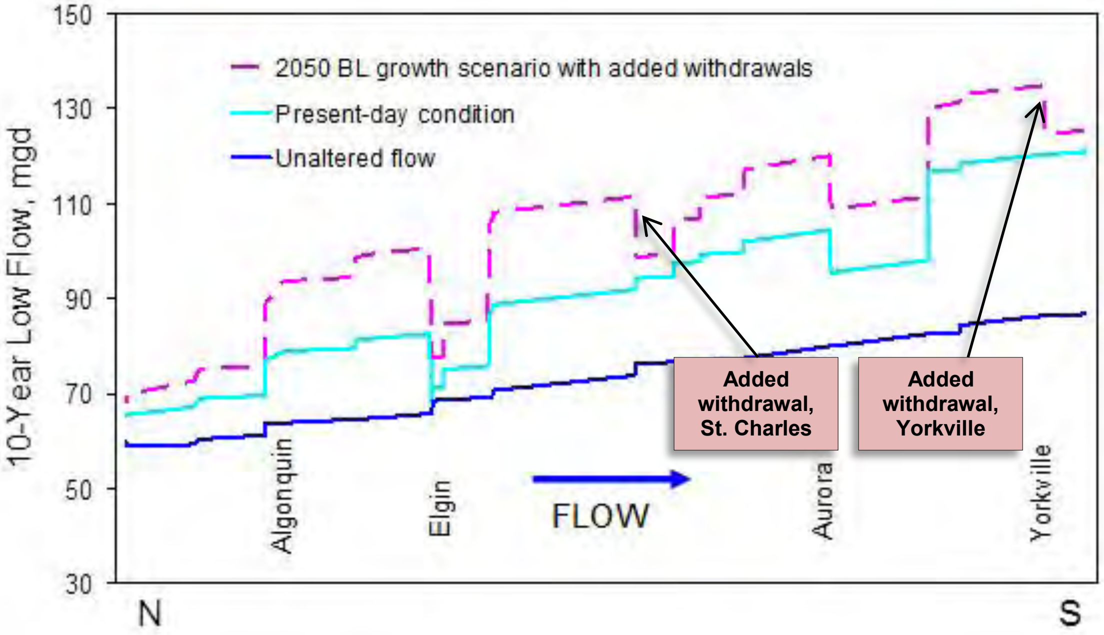


Figure 15. Ten-year low flow under unaltered conditions, approximate 2005 (present-day) conditions, and conditions in 2050 (BL scenario) with added withdrawals near St. Charles and Yorkville, Fox River from near Crystal Lake to Yorkville. The total low flow withdrawal in this example is 25 Mgd

Table 17. Change in Water Demand, 2005–2050 (Percent)[1]

Location	*Scenario*		
	LRI	*BL*	*MRI*
Elgin (Fox River WRD)	41	82	117
Aurora (Fox Metro WRD)	-3	25	49
Crystal Lake	-10	16	38
Oswego	151	223	285
DeKalb County	46	88	124
Remainder of Kane County	45	145	229
Remainder of Kendall County	359	804	1,280
Lake County	45	86	121
Remainder of McHenry County	39	121	238
Waukesha County, WI[2]	45	132	238
Walworth County, WI	45	147	238

[1] Percent growth values in Illinois were calculated using 2005 water use estimates, adjusted to 1971-2000 climate, and 2050 water demand estimates developed by Dziegielewski and Chowdhury (2008). Percent growth values for Wisconsin were assumed to be equal to the McHenry County values, except for the BL scenario, which is from the Southeastern Wisconsin Regional Planning Commission (2007).

[2] Percent growth for Waukesha County is for remaining communities outside the immediate vicinity of Waukesha City.

Table 18. Impacts on Low Flow Immediately Upstream and Downstream of Stratton Dam, Assuming the Waukesha, WI Region Obtains its Water Supply from Lake Michigan

	Scenario		
	LRI	*BL*	*MRI*
	Change in $Q_{7,10}$ (Mgd)		
Inflow to Chain of Lakes	-6	+2	+12
Minimum release from Stratton Dam	0	0	+10

if the projected difference between the 2050 low flow and present-day low flow is 20 Mgd, as it is at any location downstream of St. Charles in the BL scenario (Figure 12), then a 10-Mgd difference might exist by 2025 to 2030, thus allowing a 10-Mgd withdrawal. Similarly, if the projected difference between the 2050 low flow and present-day low flow is 30 Mgd, such as near Yorkville in the BL scenario, then a 10-Mgd withdrawal might be feasible near Yorkville by 2020. These possibilities require a change in the IDNR-specified minimum protected flow, as discussed in the preceding paragraph.

A new river withdrawal would affect the availability of flow for other withdrawals both upstream and downstream. For example, if a 10-Mgd withdrawal was developed at Yorkville in 2020, it would affect the feasibility of a withdrawal upstream because that subsequent withdrawal could cause the existing Yorkville withdrawal to no longer satisfy its $Q_{7,10}$ protected low flow. Similarly, a 10-Mgd river withdrawal located upstream of Elgin would not be desirable under either of the BL and LRI scenarios because it would then cause the Elgin withdrawal to no longer satisfy the $Q_{7,10}$ protected low flow. Such a withdrawal upstream of Elgin could potentially be developed only under the MRI scenario because of that scenario's higher effluent discharge in the upper watershed and its impact on Stratton Dam releases.

The potential for river withdrawals varies with water demand, as illustrated by Figure 16 and Figure 17, which show examples of hypothetical withdrawals under the LRI and MRI scenarios, respectively. In the LRI scenario, only one river withdrawal could be developed by 2050, whereas in the MRI scenario, three to four such withdrawals could be developed.

Table 19 shows the estimated maximum amount of direct river withdrawals, excluding the projected demand of Elgin and Aurora, which could be developed over the Kane and Kendall County reaches of the Fox River. This maximum value is equal to the projected increase in the $Q_{7,10}$ low flow at the downstream end of this reach of the river in Kendall County under each scenario. The maximum withdrawal is compared to the total projected water demand growth in the two counties for each scenario, again removing the projected growth for Elgin and Aurora. For most scenarios, roughly 50 percent of the projected water demand growth could be supplied by river withdrawals (assuming that IDNR fixes the protected flow level to its current value). Under the MRI scenario, it is possible that a river withdrawal could be developed in McHenry or Lake Counties, which would reduce the maximum potential withdrawal in Kane and Kendall Counties.

The modeled 2050 scenarios do not examine the impact of potential water reuse within the watershed or the switch in water source from groundwater to surface water. Water reuse at any location will reduce the discharge of wastewater effluent to receiving streams. The impact of water reuse is similar in many ways to the impact of a river withdrawal, in that both effectively (1) reduce the low flow quantity in the river, and (2) relieve the dependence on groundwater supplies. If substantial water reuse occurs in the watershed, projected increases in low streamflows on the Fox River, as shown in Figure 12 to Figure 15 may not be realized. Thus water reuse also reduces the maximum potential withdrawal from the river. Note that the current use of the Fox River for water supply by Elgin and Aurora is essentially a type of reuse, as a good portion of the available low flow in the river originates from upstream effluents. Further, if a community was to switch from a groundwater source to the Fox River, there would be no net effluent addition to flow as now occurs from that community. However, a switch by communities reliant on shallow wells from groundwater to surface water would also reduce the capture of streamflow by wells, restoring natural groundwater discharge and increasing base flow.

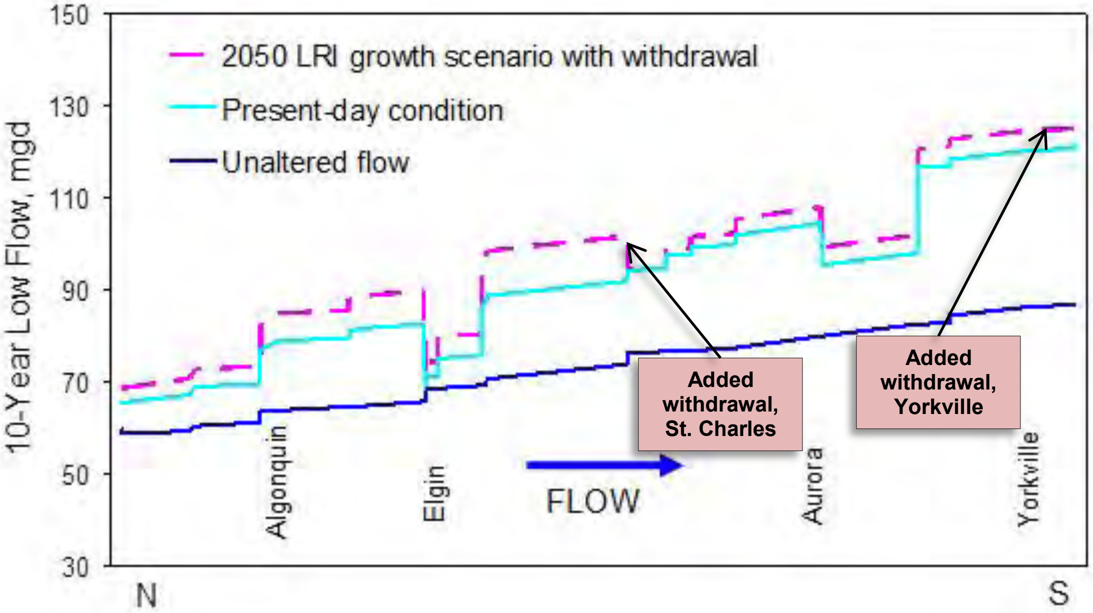


Figure 16. Ten-year low flow under unaltered conditions, approximate 2005 (present-day) conditions, and conditions in 2050 (LRI scenario) with added withdrawals near St. Charles and Yorkville, Fox River from near Crystal Lake to Yorkville. The total low flow withdrawal in this example is 10 Mgd

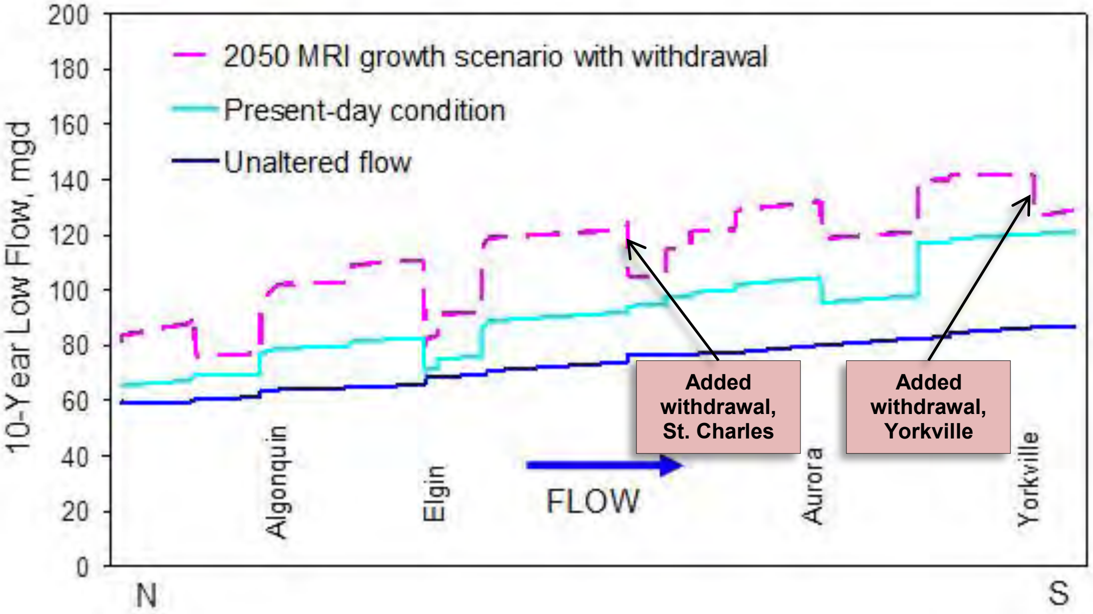


Figure 17. Ten-year low flow under unaltered conditions, approximate 2005 (present-day) conditions, and conditions in 2050 (MRI scenario) with added withdrawals near St. Charles and Yorkville, Fox River from near Crystal Lake to Yorkville. The total low flow withdrawal in this example is 50 Mgd.

Table 19. Comparison of Maximum Potential River Withdrawals to Projected Water Demand Growth by 2050 in Kane and Kendall Counties (excluding Elgin and Aurora)

	2050 water demand scenario		
	LRI	***BL***	***MRI***
Maximum amount of potential new river withdrawals (Mgd)	14	29	58
Total projected water demand growth (Mgd)	19	57	105

Finally, the authors note that the development of a river withdrawal water supply system is available at any location and year if off-channel storage or other supplemental supply sources are created at the same time. The supplemental supply must be capable of providing water during very low flow conditions when use of the river withdrawal would cause the streamflow to fall below the protected flow level.

Off-channel storage was not assessed for this project due to time and budget constraints. The assessment of off-channel storage is less a matter of scientific research and more a matter of land-use decision making. With regard to off-channel storage, the principal issue in northeastern Illinois is whether to set aside relatively large tracts of land for water storage, a challenge in an urban environment where the land may be desired for numerous other uses.

Off-channel storage of water can employ an existing structure, such as an abandoned quarry or gravel pit (provided it is engineered to retain water), or a newly constructed depression developed using cut-and-fill earthmoving. Earthmoving is expensive, although the expense can be lessened if the storage volume uses an existing depression (or valley or quarry/pit) in the landscape.

The volume of water needed in an off-channel reservoir can be considerable and depends upon the characteristics of the streamflow during a severe drought as well as water demand. Low flow in the Fox River in northern Kane County is very much related to the operation of Stratton Dam. During the low water levels that would occur in the Chain of Lakes during a severe 50-year drought, the gates at the dam would likely be set at the minimum release level for two to three consecutive months. An off-channel storage facility located downstream of Stratton Dam, designed as a primary supplemental supply for 90 consecutive days, would need to store 276 acre-feet of water for every Mgd of average water use during the 90-day period. Reservoir capacity would also need to provide for losses from evaporation and groundwater seepage. A 10 Mgd supply, for example, would require at least 2,760 acre-feet of water, equivalent to a 160-acre lake (a quarter-section) at least 17 feet deep.

4.1.4 Potential Impacts of Climate Change on Fox River Flows

The authors prepared a hydrologic simulation model of the Fox River watershed to assess potential impacts of climate change on flows in the Fox River. The model was developed using the Soil and Water Assessment Tool (SWAT), a standard watershed model used by hydrologists to simulate the hydrologic processes and streamflows within large watersheds. Model development and calibration is described in a separate report (Bekele and Knapp, 2009). They refer to this model as the Fox River Watershed Model.

With the Fox River Watershed Model, one can not only simulate historical streamflow, but also streamflow resulting from hypothetical combinations of environmental conditions. For example, it is possible to use climatic input from different time periods combined with the current land cover and water withdrawal conditions (the authors represent current land cover and water withdrawals with 2005 data). The modeler can answer questions such as "What would streamflows be like if the worst drought of record were to occur with today's level of development?" or "What would streamflows be like if climate change caused temperatures to increase in the future, assuming other factors remain constant?"

The Fox River Watershed Model thus allows the authors to alter basic assumptions about the hydrology of the Fox River Basin. This is in contrast to the Fox River Surface Water Accounting Model (presented in the previous section), which predicts the impacts of changing water use on Fox River flows, but is limited to conditions in which the underlying hydrology of the watershed (including climatic conditions) remains unchanged. There is a trade-off in model accuracy. The Fox River Surface Water Accounting Model provides much better accuracy in estimating absolute flows based on restricted assumptions, whereas the Fox River Watershed Model is more flexible but limited in its ability to predict absolute flows resulting from specific events. Although the Fox River Watershed Model cannot precisely estimate streamflows under selected climate scenarios, flows estimated for different scenarios can be compared to indicate relative effects of modeled environmental changes.

4.1.4.1 Selected Climate Change Scenarios

For modeling the effects of climate change, the 1971–2000 climate record and 2005 land use and water use for the Fox River watershed were taken as baseline conditions. Eight hypothetical climate scenarios, based on a combination of potential changes in total annual precipitation and annual average temperature, were analyzed:

- Scenario I. A 5-inch increase in annual precipitation.
- Scenario II. A 5-inch decrease in annual precipitation.
- Scenario III. A 3°F increase in annual average temperature.
- Scenario IV. A 3°F increase in annual average temperature combined with a 5-inch increase in annual precipitation.
- Scenario V. A 3°F increase in annual average temperature combined with a 5-inch decrease in annual precipitation.
- Scenario VI. A 6°F increase in annual average temperature.
- Scenario VII. A 6°F increase in annual average temperature combined with a 5-inch increase in annual precipitation.
- Scenario VIII. A 6°F increase in annual average temperature combined with a 5-inch decrease in annual precipitation.

All simulated changes in temperature and precipitation are relative to the mean annual average temperature and average annual precipitation for the period 1971–2000.

There is considerable variability in the predictions of climate models, with each model considered to have equal credibility. As described earlier, the lowest (below the 5th percentile) and highest (above the 95th percentile) projections of temperature and precipitation have been eliminated, so that the remaining range of scenarios encompasses the middle 90 percent of all climate model results.

The 6°F temperature increase in Scenarios VI, VII, and VIII is the maximum projected increase (threshold for the upper 5th percentile) in Illinois temperatures by 2050 as indicated by a variety of climate models. Although many climate models suggest smaller increases in Illinois' air temperature by 2050, the great majority of credible models show some increase. The 3°F temperature increase of Scenarios III, IV, and V represents either (1) the maximum projected increase by 2025 or (2) a middle-of-the-road projection of temperature change expected by 2050. For these scenarios, temperature increases are expected to occur uniformly over all 12 months. Warmer climatic conditions will probably reduce water availability in the landscape, as more water will be returned to the atmosphere through evaporation and plant transpiration. Even if precipitation is unchanged, the authors expect that climatic warming will cause streamflow to decrease under most conditions.

Roughly half of the climate models suggests an increase in precipitation by 2050, whereas the other half suggests a decrease. The 5-inch decrease or 5-inch increase in average annual precipitation of Scenarios I, II, IV, V, VII, and VIII roughly represents the outer 5th and 95th percentile range of climate model results, and no change in precipitation (Scenarios III, and VI) represents more of a middle-of-the-road climate model prediction of future precipitation.

4.1.4.2 Other Simulation Scenarios

A ninth scenario, based on climate data from 1931 to 1960, a period that had several severe droughts, was simulated for comparison of the streamflow effects of historic extreme climate with those of the hypothetical scenarios:

- Scenario IX. Precipitation and temperature similar to 1931 to 1960.

The average temperature of northeastern Illinois in 1931–1960 was roughly 0.8°F warmer than in 1971–2000, and the 1931–1960 average annual precipitation was 3.8 inches less than that in 1971–2000. Scenario II is the most comparable of the hypothetical scenarios to the 1931-1960 climate approximated by Scenario IX.

4.1.4.3 Flow Simulation Results

Table 20 shows, for each of three long-term Fox River streamgage locations, eight selected streamflow statistics characterizing simulated flows under the nine scenarios and under the 1971-2000 baseline conditions. As discussed earlier, these are not strict predictions, but they can be compared to ascertain relative impacts. The New Munster, WI gage is located upstream of the Fox Chain of Lakes and represents collective flow changes within the Wisconsin portion of the Fox River watershed. The Algonquin gage is located immediately upstream (north) of Kane County, and the Dayton gage is located upstream of the mouth of the Fox River near Ottawa.

Table 21 to Table 24 illustrate results of the watershed modeling in a second format. Table 21 arranges the eight simulated climate scenarios, together with the 1971-

2000 baseline condition (BL Scenario), in a grid representing increasing temperature from left to right and increasing precipitation from bottom to top. Simulation results are shown in Table 22 to Table 24 as percent changes, relative to the baseline condition, in three selected flow statistics (mean annual flow, minimum annual flow, and $Q_{7,10}$). To further simplify the presentation, the values given in Table 22 to Table 24 represent the composite change in flows for the three Fox River gaging locations (New Munster, Algonquin, and Dayton). In many cases, the percent changes for the three locations are similar, although the New Munster values tend to have a slightly greater percent difference and the Algonquin values tend to show a smaller percent difference.

The estimates in Table 22 to Table 24 suggest the following conclusions regarding future streamflow:

- The change in the mean annual flow (Table 22) ranges from -36 to +35 percent. The change in mean flow is much more sensitive to changes in annual precipitation than to temperature increases.
- The change in the minimum annual flow (Table 23) ranges from -34 to +45 percent. The percent change is roughly similar to the change in the mean annual flow, except for the three scenarios incorporating a precipitation increase (top row). The minimum annual flow appears to be less sensitive to temperature than mean annual flow. Precipitation, not temperature, may be the limiting factor in the driest years when determining the total amount of evapotranspiration that occurs from the land surface, which is one of the major determinants in the water budget.
- The percentage change in $Q_{7,10}$ (Table 24) ranges from -20 to +16, which is less than the ranges of change in mean and minimum annual flow. The reduced range may be explained in part because the existing low flows are augmented by effluent discharges, and the effluent portion of the flow has not been modified in these climate change simulations. However, even when the effects of effluent and other factors are removed from the analysis, the percent change in the remaining “natural” low flows in the Fox River is still less than that of the average and minimum annual flows. The authors conclude that natural base flow (i.e., the groundwater contribution to the streamflow) is affected less by climate variation than other components of streamflow (i.e., primarily the surface runoff component).

The results also generally indicate that flow is more sensitive to changes in average precipitation than to changes in temperature. As shown in Table 20 and Table 22 to Table 24, the decrease in flow associated with an average annual precipitation decrease of 5 inches is typically more than double that associated in a temperature increase of 6^{o}F, except for the extreme high and low flow conditions. Low flows (Table 24) show comparatively greater sensitivity to changes in temperature.

The changes in $Q_{7,10}$ shown in Table 24 provide the most pertinent numbers for looking at the water supply impacts of climate change in the Fox River watershed. The -20 to +16 percent range of changes in low flow is equivalent to roughly a ±12 Mgd change in $Q_{7,10}$ in northern Kane County and ±20 Mgd change in Kendall County. This is compared to the 2050 baseline projected change in low flows as a result of increased water demand, which generally ranges from +20 to +30 Mgd in the same reach.

Comparison to the 1931–1960 Historical Climate (Scenario IX). As noted previously, the 30 years from 1931 to 1960 were drier and somewhat hotter than the baseline 1971–2000 condition. Use of the watershed model allows us to compare hydrologic conditions from these two historical periods while keeping other factors such as water use and land use constant at 2005 values. Comparison of the Fox River Watershed Model results for 1931–1960 and 1971–2000 shows that mean annual flow during the 1931–1960 period was roughly 17 percent less than during the 1971–2000 period (Table 25). The flow simulations also show that 1931–1960 climate would result in substantially lower minimum annual flow (-30 to -21 percent compared to the 1971–2000 baseline), but less difference (-13 to +2 percent) in $Q_{7,\ 10}$.

4.1.4.4 Discussion

Some climate change literature has warned of the possibility that both drought and floods could worsen as a result of climate change. The hydrologic simulations they have examined for this study suggest that this would not be the case. The simulations suggest that the entire flow regime would get either consistently wetter or consistently drier as a result of climate change. Worsening of both floods and droughts would require substantial redistribution of precipitation throughout the year, with a defined wet season and an increase in heavy precipitation events occurring within an overall drier climate. The climate models as a group do not indicate that such redistribution is likely. In addition, the historical climate record strongly indicates that heavy precipitation events occur less frequently during drier climatic episodes.

Most scenario simulations suggest that flood magnitudes would decrease as a result of temperature increases. Flood magnitudes are consistently higher only in Scenario I, in which there is a precipitation increase but no associated temperature increase. High flows in the northern portion of the watershed upstream of New Munster (Table 20) are particularly affected by increases in temperature, presumably because higher temperatures limit the accumulation of a snowpack during winter. Historically, many of the largest floods in the upper portion of the Fox River watershed have occurred in early spring and often have a significant snowmelt contribution.

The authors emphasize that the simulation results shown in Table 22 to Table 24 represent a broad range of potential climate conditions from the 5th to 95th percentiles in climate model predictions, with the corner boxes in these tables representing the more extreme scenarios. Many climate model results fall closer to the center portion of this range, with the center box in Table 22 to Table 24 representing the most likely of the presented scenarios.

Under the hottest and driest climate scenario (Scenario VIII), with a temperature increase of 6^{o} F and an annual precipitation reduction of 5 inches, the reduction of the $Q_{7,10}$ is estimated to be 20 percent. Again, in contrast, the 2005 water uses in the Fox River watershed driven by effluent discharges are estimated to increase the Fox River low flows in most locations by 25 to 30 percent. Thus the most extreme climate scenario appears to have less of an impact than current water use. The impact of additional water use growth on low flows is further examined in Section 4.1.5.

4.1.5 Combined Impacts of 2050 Water Demand and Climate Change

Table 26 shows the estimated change in the $Q_{7,10}$ on the Fox River at two locations, Algonquin and Yorkville, based on various combinations of the 2050 water demand projections and climate change scenarios. A diagram similar to Table 21 to Table 24 is provided for the eight climate and baseline scenarios, but each climate scenario box shows combined results for the three 2050 water demand scenarios, e.g., baseline (BL), less resource intensive (LRI), and more resource intensive (MRI). As before, each scenario assumes that wastewater effluents from the Waukesha region are no longer discharged to the Fox River, thus reducing inflow to the Fox River from Wisconsin. Most climate scenarios, taken alone, project a decrease in Fox River low flows (Table 24), but in most of the combined scenarios low flows increase because of projected increases in groundwater withdrawals and wastewater effluents. Simulated low flow increases at Algonquin are not great (except for the MRI scenario) because (1) the authors assume that Waukesha effluents are no longer discharged to the Fox River, (2) most of the remaining projected water demand growth is located downstream of Algonquin, and (3) storage in the Chain of Lakes and the operation of Stratton Dam buffers upstream impacts. In contrast, a substantial increase in low flow at Yorkville occurs for most scenario combinations because of projected increases in groundwater withdrawals and effluent discharges in the Kane and Kendall County areas. Projected increases in low flow for most scenario combinations further substantiate the conclusion, presented earlier, that additional surface water withdrawals from the Fox River might be able to supply up to half of the increasing water demand. A few scenario combinations exist for which low flows may not be sufficient to supply additional river withdrawals and still maintain Fox River protected flows, i.e., if future water demand grows at a low rate (LRI) while the climate also becomes either substantially hotter or drier. At the same time, with growth at the LRI rate, it is more likely that new surface water withdrawals may not be needed to meet increases in future water use. Indeed, projected increased water demand in Kane and Kendall Counties is not met in 7 of the 9 LRI scenarios at Yorkville. At Algonquin, water demand in Kane and Kendall Counties is not met in any of the 9 LRI scenarios. The highest additional quantities of streamflow for water withdrawals while maintaining Fox River protected flows occur under the MRI scenario when groundwater withdrawals and effluent discharges also are highest. If the LRI scenario is the preferred target for water supply management in the region, they emphasize that benefits from reduced groundwater withdrawals must be balanced against less surface water availability resulting from reduced groundwater effluent.

To summarize, projected increases in low flows for most scenario combinations further support the conclusion that additional surface water withdrawals from the Fox River might be able to meet up to half of the prescribed increasing water demands in major portions of the Fox River basin, such as the Kane-Kendall County region. Instream flow considerations dictate that the river would likely not be able to provide water via direct withdrawals to users upstream of Kane County. Surface water users there will likely require off-channel storage. In all such analyses, they assume that all used water (effluent) is returned to the Fox River after use.

Table 20. Statistics of Simulated Flow for Each Climate Scenario (Mgd)

Fox River at New Munster, WI

Scenario	*Change in Avg. Annual T (ºF)*	*Change in Annual Precip. (in.)*	*Min. daily flow*	$Q_{7,10}$	*90% low flow*	*50% Flow*	*Mean Flow*	*10% high flow*	*1% high flow*	*Max. daily flow*
Baseline			34	43	98	266	352	736	1,410	2,954
I	0	+5	35	50	130	381	480	987	1,769	3,590
II	0	-5	33	39	79	178	258	542	1,158	2,529
III	+3	0	32	39	92	246	328	677	1,247	2,116
IV	+3	+5	33	46	121	359	449	906	1,591	2,592
V	+3	-5	32	37	74	171	241	505	1,033	1,808
VI	+6	0	31	37	87	236	308	626	1,189	1,980
VII	+6	+5	32	39	112	334	421	853	1,505	2,414
VIII	+6	-5	31	35	67	165	227	467	966	1,610
IX	See Section 4.1.4.2		36	41	83	215	294	602	1,432	2,636

Fox River at Algonquin

Scenario	*Change in Avg. Annual T (ºF)*	*Change in Annual Precip. (in.)*	*Min. daily flow*	$Q_{7,10}$	*90% low flow*	*50% flow*	*Mean Flow*	*10% high flow*	*1% high flow*	*Max. daily flow*
Baseline			50	66	158	434	601	1,248	2,616	4,166
I	0	+5	52	74	222	642	823	1,779	2,844	4,765
II	0	-5	48	59	116	287	430	927	2,285	3,890
III	+3	0	48	63	145	418	565	1,175	2,355	4,018
IV	+3	+5	49	69	204	610	776	1,558	2,613	4,063
V	+3	-5	47	58	104	281	406	890	2,004	3,968
VI	+6	0	46	56	137	399	533	1,106	2,261	3,995
VII	+6	+5	47	66	195	581	732	1,472	2,525	4,109
VIII	+6	-5	45	53	99	268	385	838	1,679	3,981
IX	See Section 4.1.4.2		61	69	122	362	498	1,011	2,428	4,335

Fox River at Dayton

Scenario	*Change in Avg. Annual T (ºF)*	*Change in Annual Precip. (in.)*	*Min. daily flow*	$Q_{7,10}$	*90% low flow*	*50% Flow*	*Mean Flow*	*10% high flow*	*1% high flow*	*Max. daily flow*
Baseline			119	167	341	923	1,240	2,534	4,889	14,783
I	0	+5	151	200	454	1,313	1,664	3,369	5,752	16,662
II	0	-5	112	148	263	622	913	1,907	4,211	12,274
III	+3	0	111	158	321	873	1,156	2,346	4,325	14,403
IV	+3	+5	129	178	420	1,262	1,559	3,115	5,145	16,286
V	+3	-5	107	140	246	593	853	1,788	3,692	11,938
VI	+6	0	111	148	304	825	1,077	2,144	4,211	14,081
VII	+6	+5	117	166	397	1,178	1,455	2,910	4,967	15,908
VIII	+6	-5	103	130	235	569	798	1,667	3,550	11,654
IX	See Section 4.1.4.2		143	179	286	734	1,000	2,013	4,639	10,881

Table 21. Climate Scenarios Arranged to Show Relative Changes in Temperature and Precipitation

Annual Temperature Difference from 1971-2000 Mean (ºF)

COOLER ↔ **WARMER**

Annual Precipitation Difference from 1971-2000 Mean (inches)		0	+3	+6
WETTER	+5	Scenario I	Scenario IV	Scenario VII
↕	0	BL Scenario	Scenario III	Scenario VI
DRIER	-5	Scenario II	Scenario V	Scenario VIII

Table 22. Potential Change in Mean Annual Flow under Simulated Climate Scenarios (Percent Difference from 1971–2000 Conditions)

Annual Temperature Difference from 1971-2000 Mean (ºF)

COOLER ↔ **WARMER**

Annual Precipitation Difference from 1971-2000 Mean (inches)		0	+3	+6
WETTER	+5	+35	+27	+19
↕	0	0	-7	-12
DRIER	-5	-27	-32	-36

Table 23. Potential Change in Minimum Annual Flow under Simulated Climate Scenarios (Percent Difference from 1971–2000 Conditions)

Annual Temperature Difference from 1971-2000 Mean (ºF)

COOLER ↔ **WARMER**

Annual Precipitation Difference from 1971-2000 Mean (inches)		0	+3	+6
WETTER	+5	+45	+45	+35
↕	0	0	-2	-7
DRIER	-5	-32	-34	-33

Table 24. Potential Change in $Q_{7,10}$ under Simulated Climate Scenarios (Percent Difference from 1971–2000 Conditions)

Annual Temperature Difference from 1971-2000 Mean (ºF)

Annual Precipitation Difference from 1971-2000 Mean (inches)

Annual Precipitation Difference from 1971-2000 Mean (inches)		COOLER 0	+3	WARMER +6
WETTER	+5	+16	+6	-3
	0	0	-7	-13
DRIER	-5	-11	-15	-20

Table 25. Difference in Simulated Flow for 1931–1960 Conditions (Percent Difference from 1971–2000 Conditions)

Statistic	*New Munster, WI*	*Algonquin*	*Dayton*
Mean Annual Flow	-16	-17	-19
Minimum Annual Flow	-30	-24	-21
$Q_{7,10}$	-13	-2	+3

Table 26. Potential Change in $Q_{7,10}$ under Combinations of Simulated Climate and Water Demand Scenarios (Percent Change, 2005–2050)

a. Algonquin

Annual Temperature Difference from 1971-2000 Mean (ºF)

COOLER ⟷ **WARMER**

Annual Precipitation Difference from 1971-2000 Mean (inches)

		0	+3	+6
WETTER	+5	LRI: +11 BL: +13 MRI: +29	LRI: +7 BL: +9 MRI: +25	LRI: +4 BL: +6 MRI: +22
	0	LRI: +4 BL: +6 MRI: +22	LRI: +1 BL: +3 MRI: +19	LRI: -6 BL: -4 MRI: +12
DRIER	-5	LRI: -3 BL: -1 MRI: +15	LRI: -5 BL: -3 MRI: +13	LRI: -9 BL: -7 MRI: +9

b. Yorkville

Annual Temperature Difference from 1971-2000 Mean (ºF)

COOLER ⟷ **WARMER**

Annual Precipitation Difference from 1971-2000 Mean (inches)

		0	+3	+6
WETTER	+5	LRI: +30 BL: +46 MRI: +74	LRI: +20 BL: +36 MRI: +64	LRI: +13 BL: +29 MRI: +57
	0	LRI: +14 BL: +30 MRI: +58	LRI: +9 BL: +25 MRI: +53	LRI: +1 BL: +17 MRI: +45
DRIER	-5	LRI: +3 BL: +19 MRI: +47	LRI: -1 BL: +15 MRI: +43	LRI: -7 BL: +8 MRI: +37

4.2 Groundwater

4.2.1 Introduction

This section discusses results from computer-based simulations (modeling) of groundwater flow in the deep aquifers supplying the northeastern Illinois water supply planning region and in the shallow aquifers of the Illinois part of the Fox River watershed. In 2002, the Kane County Board commissioned the state surveys to conduct a broad assessment of groundwater and surface water resources in support of water supply planning efforts within Kane County (Meyer et al., 2009). The objectives of that study were to clarify the relationships between aquifers and streams and to quantify the effects of current and future groundwater development. The study assimilated a wide variety of newly collected and archived hydrogeologic data into models or computer programs that simulate groundwater flow. The regional groundwater flow model developed for Kane County formed the principal basis of a regional model for this planning study, which was developed by revising and recalibrating the Kane County regional model. This section discusses the development, application, and results of simulations using this revised computer model to evaluate the impacts from historical and possible future groundwater pumping scenarios. As background for readers unfamiliar with groundwater, Appendix A introduces basic groundwater terminology and concepts.

4.2.1.1 Generalized Geologic Setting

Groundwater sources available to northeastern Illinois (Figure 18) include the deep aquifers—layers consisting principally of sandstone that are, for purposes of this study, referred to as the Ancell Unit, Ironton-Galesville Unit, and Mt. Simon Unit—and the shallow aquifers, bedrock units lying above the deep aquifers and unconsolidated sand and gravel aquifers contained within the Quaternary Unit, which consists of glacial drift and lesser amounts of postglacial materials (Figure 18). In northeastern Illinois, the Mt. Simon Unit is used far less than the Ancell and Ironton-Galesville Units because of the expense of drilling to it and because deeper portions of the Mt. Simon contain water that is too salty for most uses. The shallow aquifers include the Shallow Bedrock Aquifer (a layer of weathered dolomite encompassing about the uppermost 25 to 125 feet of bedrock) and several discontinuous layers of unconsolidated sand and gravel contained in the Quaternary Unit overlying the Shallow Bedrock Aquifer. Appendix B summarizes the hydrogeologic setting of northeastern Illinois.

In most of northeastern Illinois, the shallow and deep aquifers are separated by a laterally extensive, relatively impermeable interval underlying the Shallow Bedrock Aquifer. Because this interval limits vertical leakage of water to the deep aquifers, it is called a *confining unit*. For purposes of this study, the terms *shallow* and *deep* are extended to other parts of the regional model domain despite the fact that they do not necessarily accurately describe the positions of the materials in these areas. For example, in southern Wisconsin and in Illinois southwest of the Sandwich Fault, rocks above the Ancell formation have been removed by erosion, but the authors still refer to the Ancell and underlying aquifers as "deep aquifers" despite their shallow position.

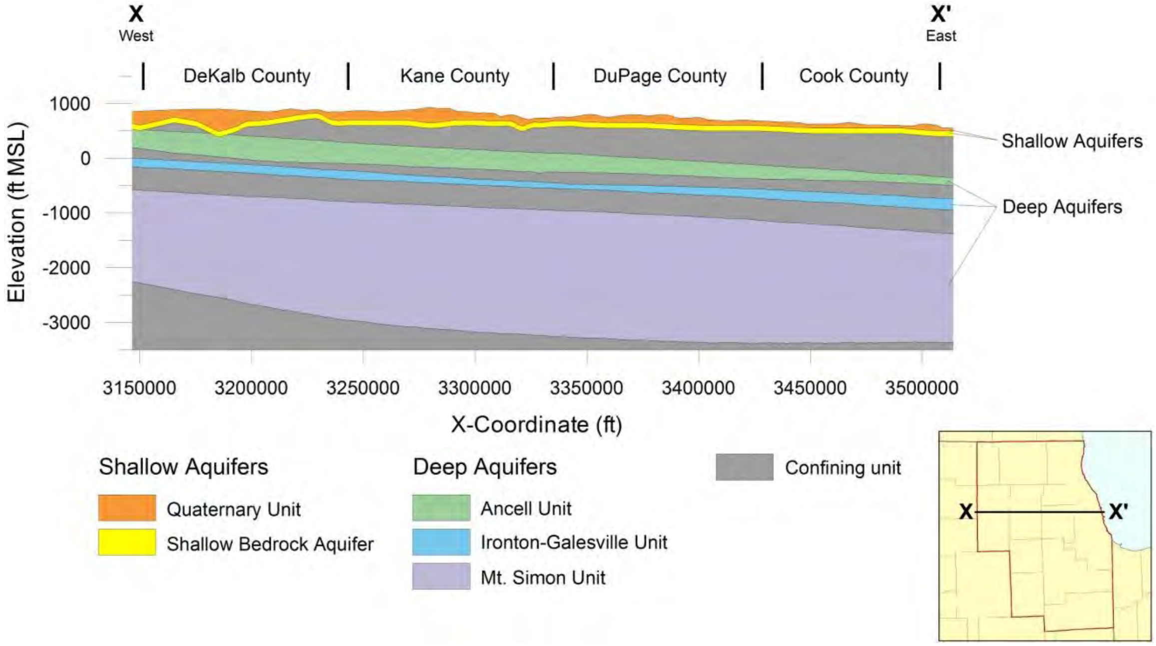


Figure 18. East-west cross-section showing regional hydrostratigraphic units

For convenience in discussing groundwater withdrawals in the region, this report extends the distinction between the shallow and deep aquifers to distinguish between *shallow units* and *deep units,* and between *shallow wells* and *deep wells*. The shallow units are those overlying the Ancell Unit, and the deep units are the Ancell Unit and units underlying the Ancell (Figure 18). In practice, withdrawals from the shallow units are distributed between the Quaternary Units and the units constituting the Shallow Bedrock Aquifer (weathered portions of the Silurian-Devonian Carbonate, Maquoketa, and Galena-Platteville Units). Wells drilled into deep units are sometimes left open to all overlying units, so withdrawals from deep wells can also include withdrawals from shallow units. For purposes of this study, shallow wells are those open *only* to the shallow units. Deep wells are open to the deep units but also may be open to the shallow units. Withdrawals from deep wells open to the shallow aquifers in the 11-county northeastern Illinois area have generally declined since 1964. In 2005, withdrawals from these wells constituted only about 3 percent of total groundwater withdrawals in the region (Figure 19).

4.2.2 Groundwater Flow Model

Understanding the relationships among groundwater resources, the relationship between groundwater and surface waters, and their response to withdrawals requires a quantitative approach that assimilates the available observations and knowledge, computes flow rates and water levels, and projects these into the future for alternative water-withdrawal scenarios. For the present study, these requirements are met using a computer model of groundwater flow, which is a set of interrelated mathematical

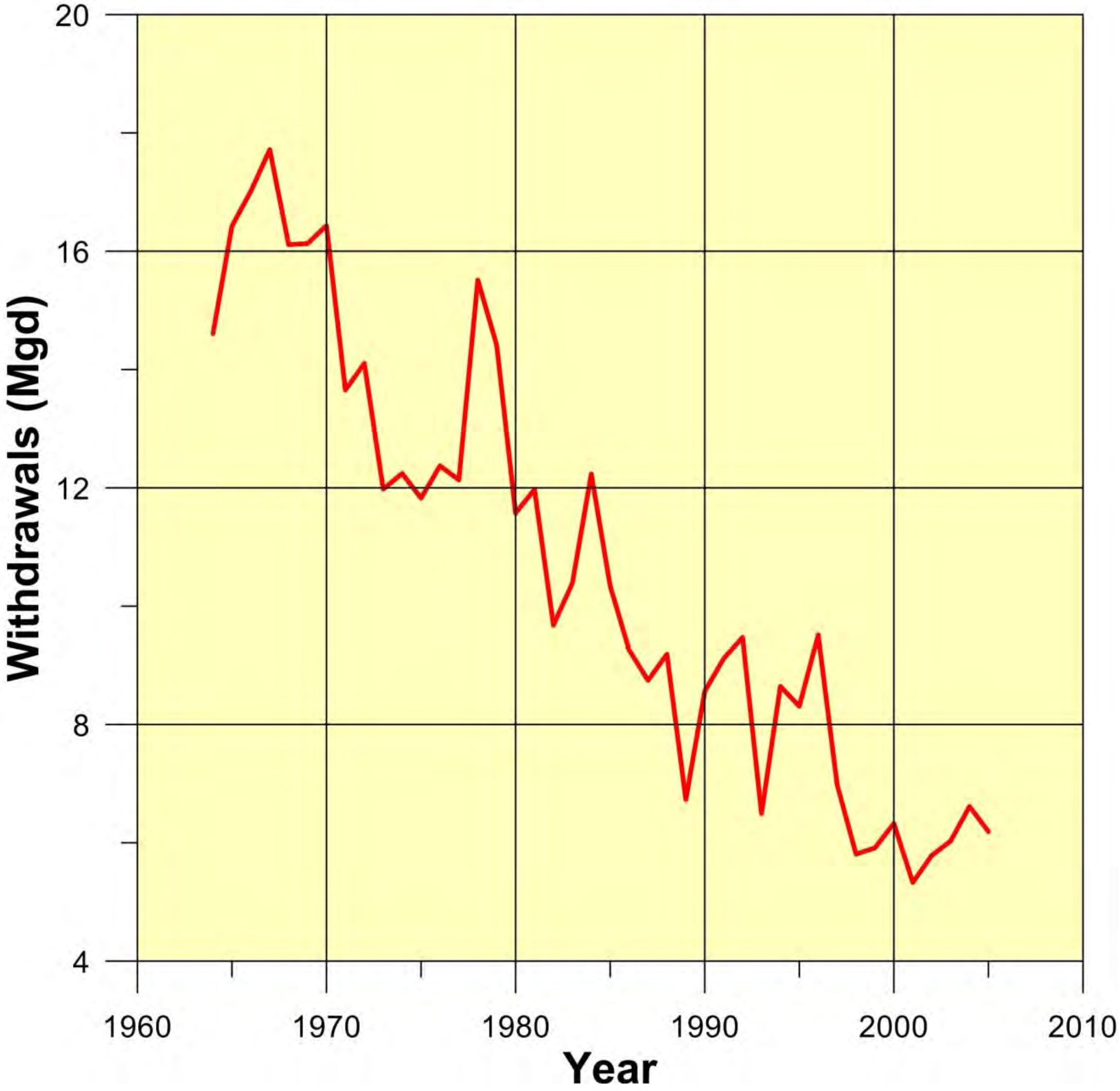


Figure 19. Withdrawals from deep wells open to the shallow aquifers in northeastern Illinois, 1964–2005

equations that represent aquifers, wells, and streams, solved using a computer program. The model developed for this study uses the finite-difference method, a mathematical technique which divides the aquifer into a grid of blocks to solve the equations representing groundwater flow through porous media.

The groundwater flow model of this study uses MODFLOW 2000, a computer code developed by the U.S. Geological Survey (McDonald and Harbaugh, 1988). MODFLOW 2000 reads data files describing the area of interest, sets up the equations representing groundwater flow, pumping, and the interactions of groundwater and surface water, and solves for the estimated hydraulic head and flow. MODFLOW 2000 can simulate s*teady-state conditions*, in which hydraulic head and groundwater flow no longer change because they are at equilibrium with the distribution and rates of water inflow and outflow. MODFLOW 2000 can also simulate *transient conditions*, where heads and fluxes change with time as they adjust to new pumping wells, or changes in withdrawal rates, recharge, river levels, etc. If stresses do not change, steady-state conditions will eventually be reached as a new equilibrium is reestablished.

So that the model accurately reflects existing research on hydrogeological conditions within the model domain, data employed to characterize layer elevations, parameters, and boundary conditions are based to the extent possible on a wide range of published and unpublished observations. Parameters such as hydraulic conductivity and recharge rates are specified on a zoned basis.

The groundwater flow model simulates all major current and historic groundwater withdrawals in northeastern Illinois and the surrounding areas which could plausibly influence groundwater flow in northeastern Illinois. Flows into and out of major surface-water features are represented using the MODFLOW river and drain packages; the drain package also is used to simulate agricultural and urban drainage systems.

4.2.2.1 Resolution

The groundwater flow model used in this study was developed by revising the 20-layer regional model developed for Kane County (Meyer et al., 2009) to 22 layers to accept a more detailed 5-layer representation of the Quaternary deposits within a polygonal area surrounding the Illinois portion of the Fox River watershed (Fox River watershed geologic mapping domain in Figure 20). The resulting 22-layer model simulates groundwater flow in all geological materials from land surface down to the crystalline Precambrian basement (Table 27). This includes both the shallow and deep aquifers in a large portion of Illinois, Indiana, Michigan, Wisconsin, and Lake Michigan (Figure 20). The model employs a variable resolution, its highest resolution area being a rectangular nearfield covering all of northeastern Illinois, where cells have horizontal dimensions of 2,500 feet (Figure 21 and Figure 22). The regional model is most accurate and precise within the detailed nearfield region that encompasses northeastern Illinois. The extent of the regional model permits simulating distant influences on flow in the deep aquifers, including the pumping and recharge in Wisconsin and discharge to the Illinois River near LaSalle. The Quaternary deposits (the unconsolidated deposits above bedrock) are most accurately represented within the Fox River Watershed Geologic Mapping Domain (Figure 20).

Model layers represent major hydrostratigraphic units in northeastern Illinois, but representation of the Quaternary deposits differs between the Fox River watershed geologic mapping domain and other areas (Table 27). Hydrostratigraphic units in northeastern Illinois and in the Fox River watershed geologic mapping domain are described in Appendix B. In some cases, more than one layer is employed to represent a single hydrostratigraphic unit (Table 27). More than one layer is employed to more accurately represent hydraulic variability within a unit, if necessary, and to provide for future refinement of the model. With the exception of the Quaternary Unit, in instances wherein a hydrostratigraphic unit is represented by more than one model layer, the thickness of each model layer is $1/x$ of the thickness of the hydrostratigraphic unit, where x is the number of model layers used to represent the hydrostratigraphic unit. Outside the

Fox River Watershed Geologic Mapping Domain, the thickness of each of the five layers devoted to the Quaternary is, likewise, 1/5 of the total thickness of the Quaternary Unit. Within the Fox River Watershed Geologic Mapping Domain, five individual Quaternary hydrostratigraphic units were mapped (Table 27 and Appendix B), and mapped thicknesses were employed for model layers representing each of these units.

The hydrogeologic framework of the groundwater flow model (that is, the hydrogeological model consisting of estimates of top and bottom elevation for each of the 22 model layers) was developed by computer processing of data from a wide variety of published and unpublished sources. For bedrock units (model layers 6-22) and for the Quaternary Unit *outside* of the Fox River Watershed Geologic Mapping Domain, sources and processing techniques are discussed by Meyer et al. (2009), except that the Quaternary Unit for the present study was divided into five layers of equal thickness as opposed to the three discussed by Meyer et al. For areas *within* the Fox River Watershed Geologic Mapping Domain, geologic data for the bedrock surface and overlying Quaternary deposits were compiled from a range of completed and ongoing high-, moderate-, and low-resolution mapping. Three-dimensional interpolated surfaces from high-resolution studies by Dey et al. (2007) (Kane County area), the Central Great Lakes Geologic Mapping Coalition (Lake County), and Ed Smith of the ISGS (personal communication) (Kendall County) were incorporated directly into the model. Interpreted surface-contours and cross section data were used from previous moderate-resolution mapping efforts in McHenry County (Curry et al., 1997; Wickham et al., 1988) and DeKalb County (Vaiden et al., 2004; Wickham et al., 1988).

4.2.2.2 Uncertainty and Model Calibration

Uncertainty in models of natural systems arises from our inability to understand, measure, or completely represent all the features of the true systems (Gorelick, 1997). Uncertainties in groundwater models may be categorized as either *parameter uncertainty* or *conceptual uncertainty* (Neuman and Wierenga, 2003). *Parameter uncertainties* reflect our imperfect knowledge of both the input parameters of the model (hydraulic conductivity, recharge, pumping rates, aquifer geometry, etc.) and the variables the model simulates (hydraulic heads and flow rates). For example, field studies yield estimates of hydraulic conductivity, but hydraulic conductivity varies by location such that a complete characterization is impossible. Further, field studies of hydraulic conductivity are plagued by scale effects and simple measurement errors. Calibrating model results to field observations can reduce the uncertainty of the input hydraulic conductivity, but the observations themselves also include errors such that the calibrated values retain uncertainty. That is, input parameters for the model can only be known within a range of values justified by field studies and calibration. *Conceptual uncertainties* arise from our imperfect knowledge of the processes governing the modeled system, which forces us to make assumptions regarding what processes to include in the model. In practice, conceptual models are based on expert judgment and can be evaluated to quantify the possible impact of conceptual uncertainties. For example, this study assumes that the dominant groundwater flow processes for this system are saturated, isothermal flow, driven by hydraulic gradients at relatively low velocities. The effects of salinity, temperature, and flow through unsaturated zones are not included because these

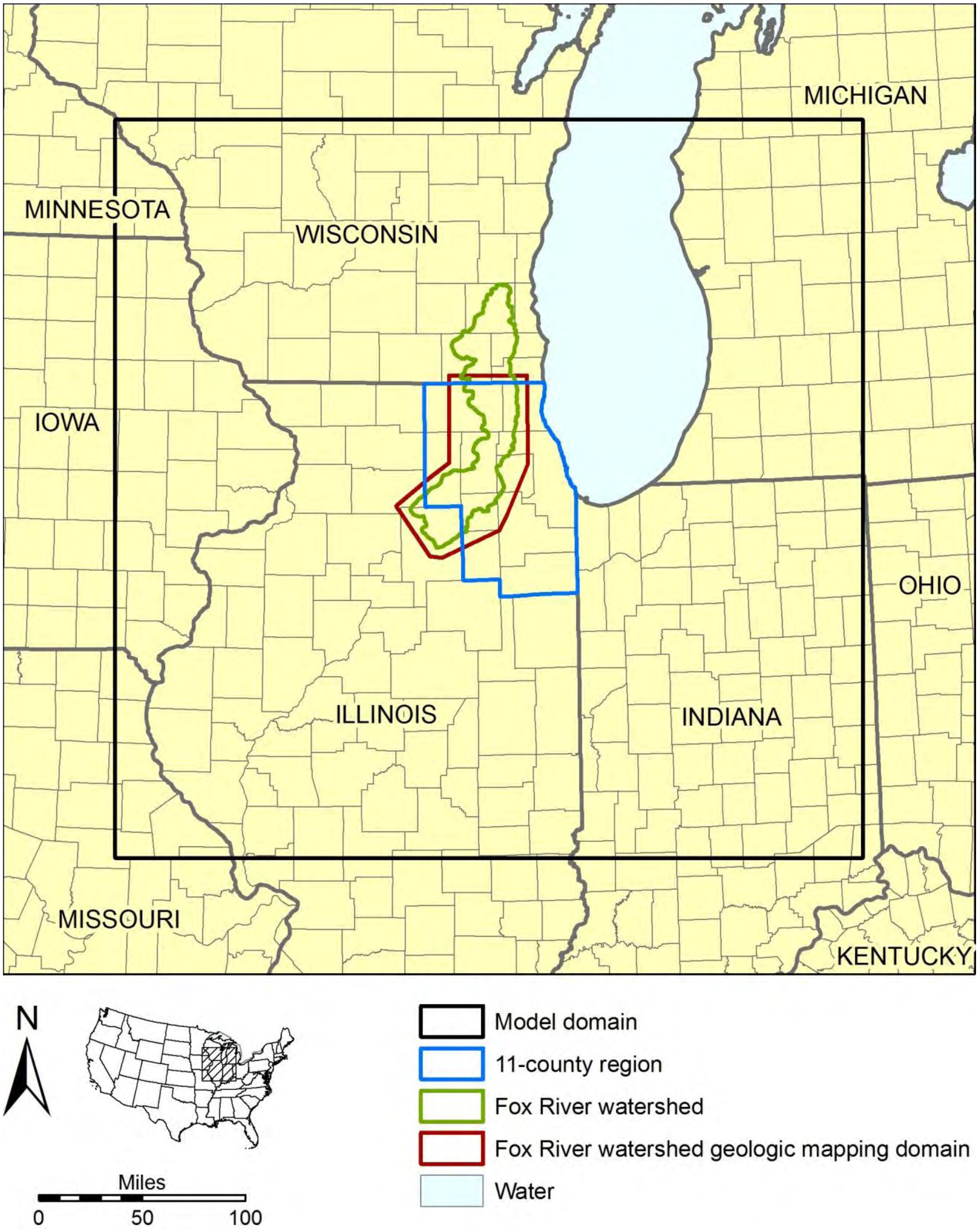


Figure 20. Northeastern Illinois regional groundwater flow model domain, Fox River watershed outline, and Fox River watershed geologic model domain

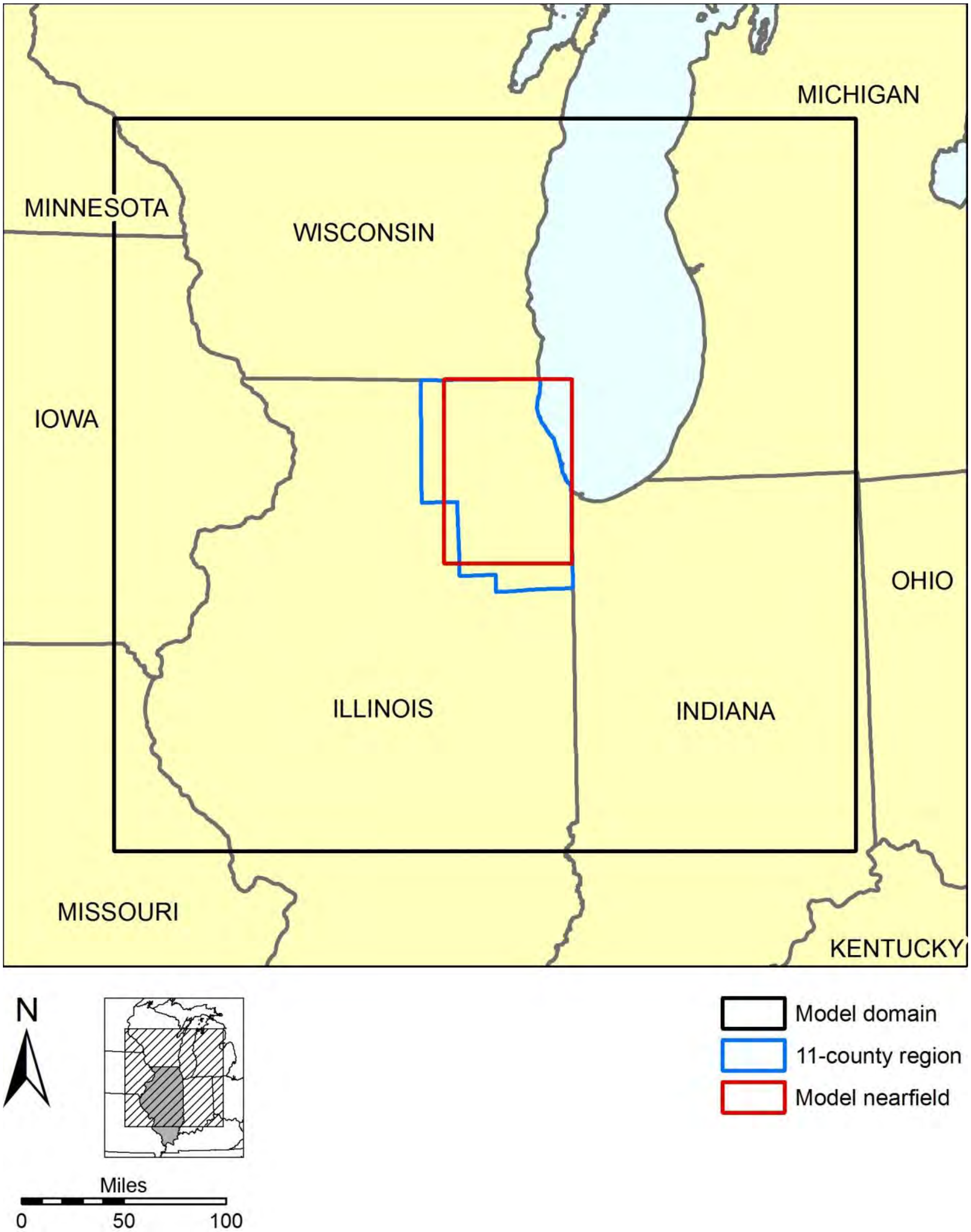


Figure 21. Domain and nearfield of the northeastern Illinois regional groundwater flow model

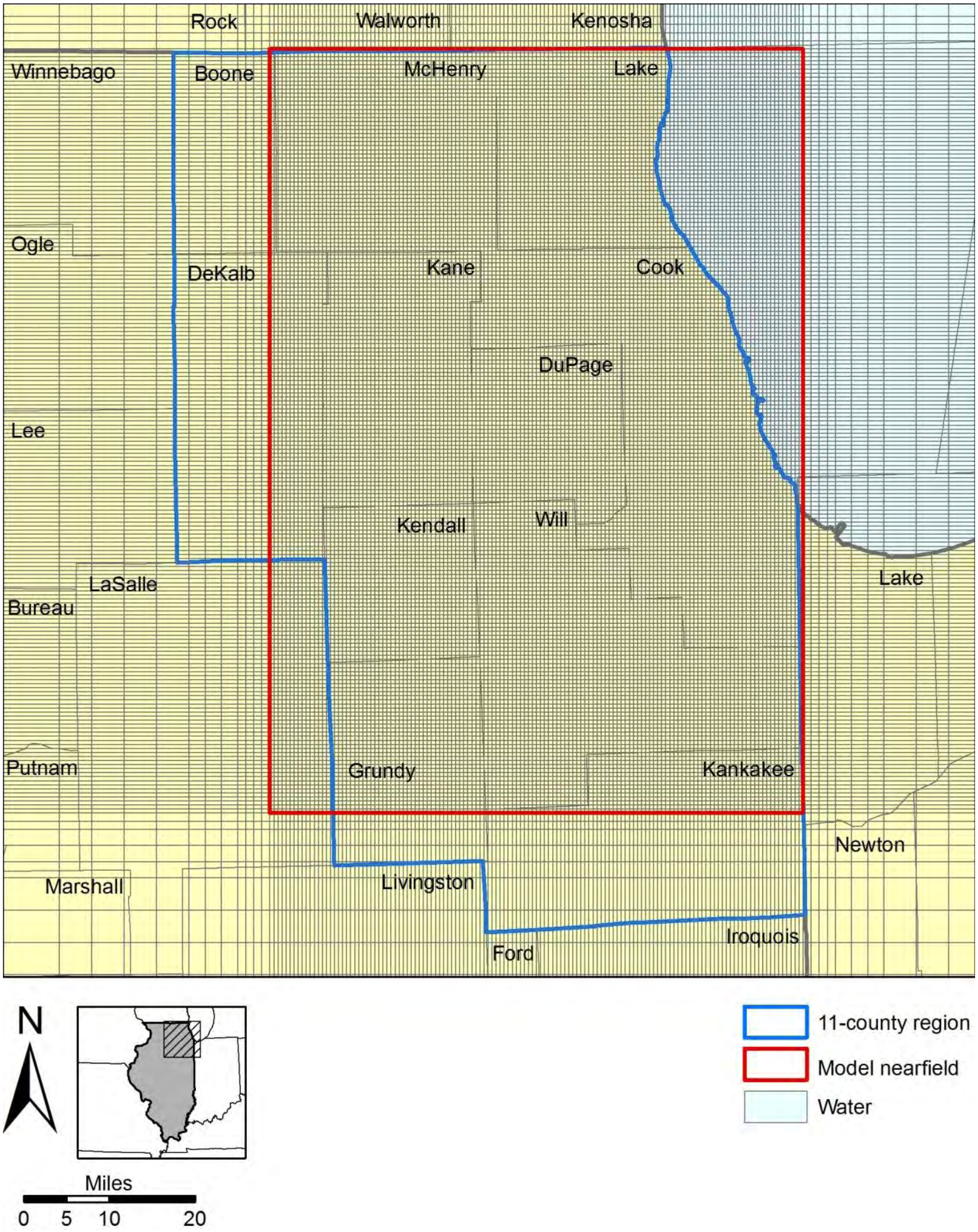


Figure 22. Detail of nearfield grid of northeastern Illinois regional flow model

Table 27. Layer Scheme of the Northeastern Illinois Regional Groundwater Flow Model

HYDROSTRATIGRAPHIC UNIT		*MODEL LAYER*
Other Areas	*Fox River Watershed Geologic Mapping Domain*	
Quaternary Unit	Quaternary Fine-Grained Unit 1	1
	Quaternary Coarse-Grained Unit 1	2
	Quaternary Fine-Grained Unit 2	3
	Quaternary Fine-Grained Unit 3	4
	Quaternary Coarse-Grained Unit 2	5
Upper Bedrock Unit		6
Silurian-Devonian Carbonate Unit		7
		8
		9
Maquoketa Unit		10
		11
Galena-Platteville Unit		12
		13
Ancell Unit		14
Prairie du Chien-Eminence Unit		15
Potosi-Franconia Unit		16
Ironton-Galesville Unit		17
Eau Claire Unit		18
Mt. Simon Unit		19
		20
		21
		22

processes are generally believed to have minor influences on the aquifers of this system (Feinstein et al., 2005a; Feinstein et al., 2005b; Mandle and Kontis, 1992). The impact of these conceptual uncertainties on the model can be quantified by ancillary calculations, but evaluating conceptual model uncertainty is an area of ongoing research (Neuman and Wierenga, 2003). It is important to note that both categories of uncertainty are present in the model of this study, and cannot be avoided; in short, “With any model, we get uncertainty for free” (Gorelick, 1997).

The groundwater flow model used for this study, which employs a conceptual model developed from expert judgment and calibrated model parameters, represents the authors’ best understanding of the system and, as such, might be termed an *expected-case model*. However, reasonable variations of the expected-case model (employing plausible, but different, conceptual models and parameters that depart from those used in the expected-case model but that are within plausible ranges dictated by parameter uncertainties) will yield a range of plausible predictions rather than a single prediction.

Calculating model uncertainty can be computationally intensive, and communication of model uncertainty is frequently challenging. The formal approach to uncertainty analysis would be to develop a number of models that include not just the expected case, but plausible variations reflecting conceptual and parameter uncertainties, and to use the collective model results to determine the probabilities of these predictions and summarize their range using, for example, confidence intervals. Such estimates could then be used by decision-makers to assess the reliability of model predictions and rationally evaluate the risks associated with management alternatives (Pappenberger and Beven, 2006). This approach would allow computation of a range of results (head and groundwater discharge to streams, for example) for each point within a three-dimensional model domain and would permit probabilities to be assigned to the results. Although such results would be ideal for planning purposes in that they would fully acknowledge parameter and conceptual uncertainty, the current technology for assigning probabilities to detailed groundwater models requires repeating the simulation many times (a so-called Monte Carlo analysis), a computationally intensive exercise that, given the complexity of the model developed for this study, is well beyond the project scope. An alternative is to create a limited set of simulations that bound the range of plausible predictions using the most sensitive parameters and assumptions (Walker et al., 2003). This study employs such an approach to examine model uncertainty, using three separate simulations of future pumping, a parameter to which groundwater flow models are highly sensitive. Whereas Monte Carlo analysis allows a potentially large number of results for each point within a model domain, the approach used in the present study permits only three results for each point. Unlike Monte Carlo analysis, the approach used here, although it qualitatively expresses the reliability of model predictions for use in evaluating management alternatives, does not permit computation of the probability of a result.

Groundwater flow models undergo a process of calibration in which system geometry and properties, initial and boundary conditions, and stresses are adjusted so that model simulations are as realistic as possible (Hill and Tiedeman, 2007). The model employed for this study was calibrated using an automated procedure for parameter estimation, also known in groundwater modeling as the inverse solution. Automated estimation of parameters runs the model many times, adjusting parameter values within ranges of user-specified plausible ranges until model simulations approximate a set of observations of head and groundwater discharge referred to as calibration targets. Although this report does not discuss in detail the calibration of the groundwater flow model, the procedure was very much like that employed to calibrate the regional groundwater flow model used in the ISWS modeling study for Kane County and described by Meyer et al. (2009).

Estimation of calibration target uncertainty provides a means by which the quality of the calibration and the accuracy of the model can be judged, since the accuracy of the model-simulated heads and flows can be no better than that of the calibration targets. Calibration target uncertainty is the result of measurement errors, unmodeled temporal and spatial variability, and other factors (Anderson and Woessner, 2002). Application of an approach for estimating calibration target errors is described by Meyer et al. (2009) for the calibration targets employed in developing the models used in the ISWS modeling study for Kane County (see their Appendix E). The calibration target errors calculated by Meyer et al. (2009) and discussed in the following paragraphs for the present modeling study are estimates of the accuracy of the targets as predictors of model-simulated values.

Conversely, they are estimates of the error of the model-simulated values as predictors of the target values. They are not estimates of the accuracy of the targets as predictors of the actual field values. Thus, a modeler can use these estimates of calibration target uncertainty as an indicator of when to cease the calibration process. That is, calibration can be terminated when the error of the simulated values is less than the calibration target error. The approach used by Meyer et al. (2009) was followed to generate calibration target error estimates for the present study.

For deep head calibration targets, the results of the analysis are no different from those of the Kane County study; that is, the deep head calibration targets are estimated to have a maximum uncertainty of ±200 feet. The greatest source of the uncertainty is the long open interval of the wells that are the sources of these deep head targets. These wells are open to many different subsurface units, and heads vary continuously along these long open intervals, so the water level in the well is not representative of the head at specific points along the borehole. The ±200-foot maximum uncertainty means that the calibration target value may be as much as 200 feet different from the simulated head, principally because the simulated value is calculated at a single point in the deep aquifers at the *x, y* location of the calibration target. Simulated heads in individual deep hydrostratigraphic units and actual heads in these units (which are rarely measured since most deep wells are open to multiple units) also disagree because the model does not simulate interformational transfer of groundwater along boreholes. In most parts of the region, groundwater would be transferred downward from the Ancell Unit to the Ironton-Galesville, causing actual heads in the Ancell to be lower than simulated heads and actual heads in the Ironton-Galesville to be higher than simulated heads. Interformational transfers of groundwater along boreholes are discussed further in Section 4.2.4.4.

For the present modeling study, the shallow head calibration targets are estimated to have an uncertainty of ±68 feet. The greatest source of the shallow head target uncertainty is unmodeled heterogeneity in the shallow subsurface. The 68-foot uncertainty of the shallow head targets means that any one target may be as much as 68 feet different from the simulated value, mainly because the simulated value does not reflect actual subsurface heterogeneity. The uncertainty of these shallow head calibration targets is greater for the present model than for the local-scale model of the Kane County area, described by Meyer et al. (2009), for which the shallow head targets were estimated to have an uncertainty of ±29 feet. The principal reason for this difference is that the modeled area for the present study (the Fox watershed) is significantly larger than that of the Kane County local-scale model (Kane County itself).

Calibration targets for flux were developed from streamgaging records and the Illinois Streamflow Assessment Model (Knapp et al., 2007) for watersheds within the modeled domain. The flux targets represent the long-term average of total groundwater discharge, or base flow, to streams and drains within the watershed. The target values are estimated as the arithmetic average of Q_{80} and Q_{50} (Meyer et al., 2009). Flux target uncertainty is dependent on the uncertainty of estimates of flow. Due to the controlled release at Stratton Dam and the addition of effluent discharges, flux targets for the Fox River were not used. Low flow estimates for ungaged tributary streams were determined to have a standard error from 12 to 27 percent depending on whether the watershed upstream of the flux target was underlain by low or high permeability subsoils.

Watershed target low flow estimates range from 2 to 76 cfs with errors ranging from 0.4 to 21 cfs. The median flux target error at nearfield targets is 1.8 cfs, while the median flux target error at farfield targets is 21.3 cfs (see Meyer et al., 2009, Appendix E).

To restate, assumptions made in the process of simplifying a complex hydrogeologic environment *and* uncertainty in the data being used to calibrate the model give rise to inherent model uncertainty. As an acknowledgment of the limitations in accuracy and comprehensiveness of the observations used for model development, the model results are best used as a screening tool to provide a sense of the locations and magnitudes of groundwater pumping impacts. The outcomes and trends in the results provide insight to the ability of the region's groundwater resources to meet potential future water demands.

4.2.2.3 Simulated Groundwater Withdrawals

Historical Pumping. Historical groundwater withdrawal data were compiled for approximately 8,300 wells (Figure 23 and Figure 24) and for an additional seven "pumping centers" representing pre-1964 withdrawals from deep wells in northeastern Illinois (Figure 25). Withdrawals from all of these wells and pumping centers were simulated in the regional groundwater flow model.

The withdrawal data, which include well locations and source interval determinations in addition to annual withdrawal rates, cover much of Illinois and parts of Indiana and Wisconsin adjacent to northeastern Illinois. Although the geographic, hydrogeologic, and temporal scope of the withdrawals represented in the model is not comprehensive, the authors believe that the compiled data represent the major influences on groundwater flow in the regional model nearfield of northeastern Illinois. Withdrawals were selectively omitted for several reasons: (1) inclusion of a truly comprehensive representation of groundwater withdrawals would strain computational resources and add significantly to computation time; (2) withdrawals at distant locations, at low rates, in the distant past, and from rapidly recharged aquifers would have little impact on present groundwater flow in the model nearfield; (3) making assumptions regarding locations, rates, timing, and hydrostratigraphic sources of withdrawals in the absence of readily available data from existing databases would strain the project budget and schedule. Thus, existing databases of groundwater withdrawals in the regional model domain were reviewed, and if omissions in these databases were judged to be significant to modeling groundwater flow in the model nearfield, withdrawal data were assumed in order to address the omissions. A detailed description of the data sources and processing used in compiling the withdrawal database is included in Meyer et al. (2009).

The geographic scope of the withdrawals simulated in the regional model includes central and northern Illinois and Indiana and southern Wisconsin. Withdrawals in Michigan are not represented. Withdrawals from deep wells in Illinois and Indiana are sometimes omitted owing to irregular availability of historical withdrawal data, as discussed in Meyer et al. (2009). Because it is unlikely that withdrawals from distant shallow wells would affect heads in the regional model nearfield, shallow wells in Illinois and Indiana are represented only if they are located within USGS hydrologic units in the immediate vicinity of northeastern Illinois. This area is referred to as the shallow aquifer withdrawal accounting region (SAWAR). This means that shallow wells within only very small portions of the 11-county planning region, if indeed any are present, were not included in the regional model (Figure 21 and Figure 22).

Pre-1964 withdrawals in Illinois and Indiana from shallow wells within the SAWAR are not represented, and withdrawals from 1964 through 2005 are irregularly represented. Shallow well withdrawals in Illinois during the period 1964–1979 are represented only for the portion of the SAWAR within the following counties: Boone, Cook, DeKalb, DuPage, Grundy, Kane, Kankakee, Kendall, Lake, LaSalle, Lee, McHenry, Ogle, Will, and Winnebago. Shallow well withdrawals within the entire Illinois portion of the SAWAR are represented in the model for the period 1980–2005. Shallow well withdrawals within the Indiana portion of the SAWAR are represented in the model only for the period 1985–2005. Shallow wells in southeastern Wisconsin are represented for the period 1864–2005. Data from other parts of Wisconsin are not available. A total of about 6,400 shallow wells are simulated in the model.

Deep wells represented in the regional model are illustrated in Figure 24. The time period represented by these withdrawals differs by state. Withdrawals from deep wells in Illinois are represented for the period 1864–2005. Deep wells active during the period 1864–1963 are represented by seven idealized pumping centers (Figure 25), with pumping totals at these seven centers aggregated to represent the significant deep well withdrawals of northeastern Illinois. Wells active during the period 1964–2003 are represented individually. Deep well withdrawals during the period 1964–1979 in Illinois that are represented in the regional model are limited to wells located in the following 20 northern Illinois counties: Boone, Carroll, Cook, DeKalb, DuPage, Grundy, Jo Daviess, Kane, Kankakee, Kendall, Lake, LaSalle, Lee, McHenry, Ogle, Rock Island, Stephenson, Whiteside, Will, and Winnebago. Most deep well withdrawals in the state occur within this area. Deep well withdrawals from Illinois wells during the period 1980–2005 are represented in the entire portion of Illinois within the regional model domain. A total of 1,900 deep wells are simulated in the groundwater flow model.

Because mineralized water from deep wells in Indiana is unacceptable for most uses, the deep units are largely unused there. Only a single deep well in Indiana is represented in the model; this is the only deep well included in a database of groundwater withdrawals obtained from the Indiana Department of Natural Resources (personal communication, Mark Basch, 2002). The withdrawal record for this well covers the period 1985–2005. Deep wells in southeastern Wisconsin are represented for the period 1864–2005 in this dataset. Data from other parts of Wisconsin are not available.

The sources of historical Illinois withdrawal data employed in this study are hardcopy records on file at the ISWS (covering the period 1964–1979); an electronic database, maintained by the ISWS, of withdrawal data compiled largely from owner-reported withdrawal measurements and estimates (covering the period 1980–2005); and estimates for years of non-reporting to the ISWS by facility owners (also covering the period 1980–2005). Pre-1964 withdrawal data were obtained as an electronic file from Stephen L. Burch of the Illinois State Water Survey (ISWS) (personal communication, 2002). Data derived from this source represent withdrawals from deep wells that were active during the pre-1964 period. As mentioned, pumping activity is represented by

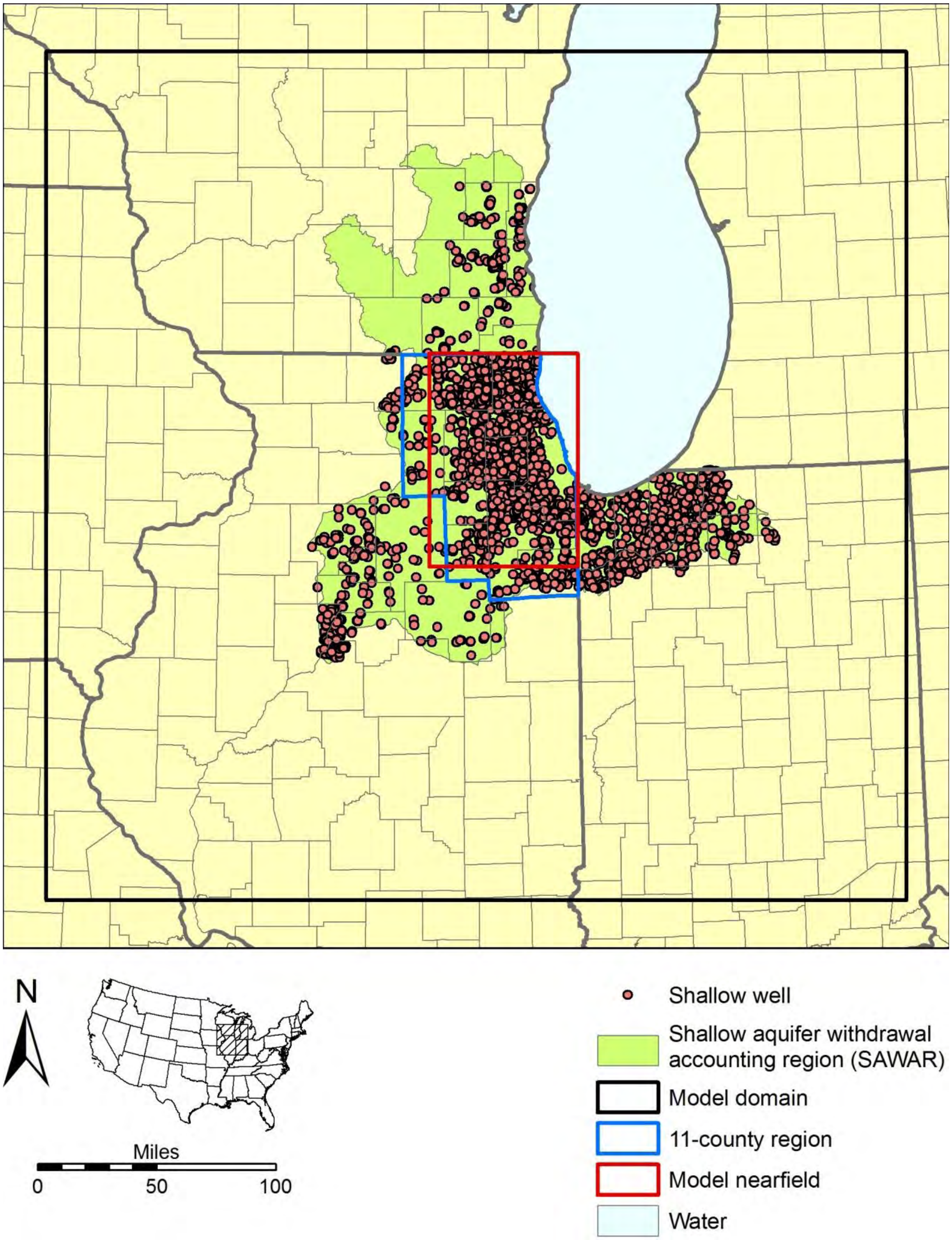


Figure 23. Shallow wells represented in the northeastern Illinois regional groundwater flow model

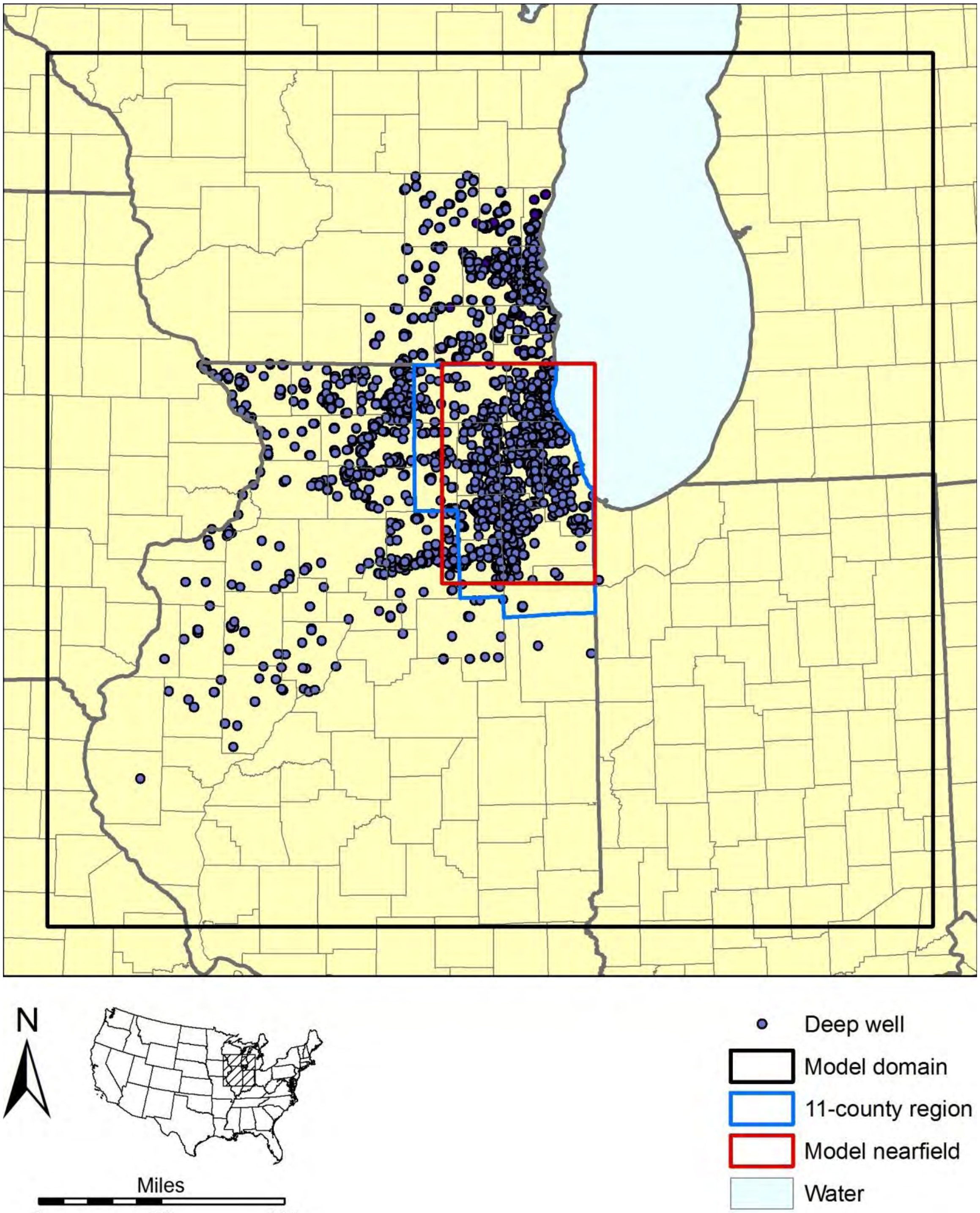


Figure 24. Deep wells represented in the northeastern Illinois regional groundwater flow model

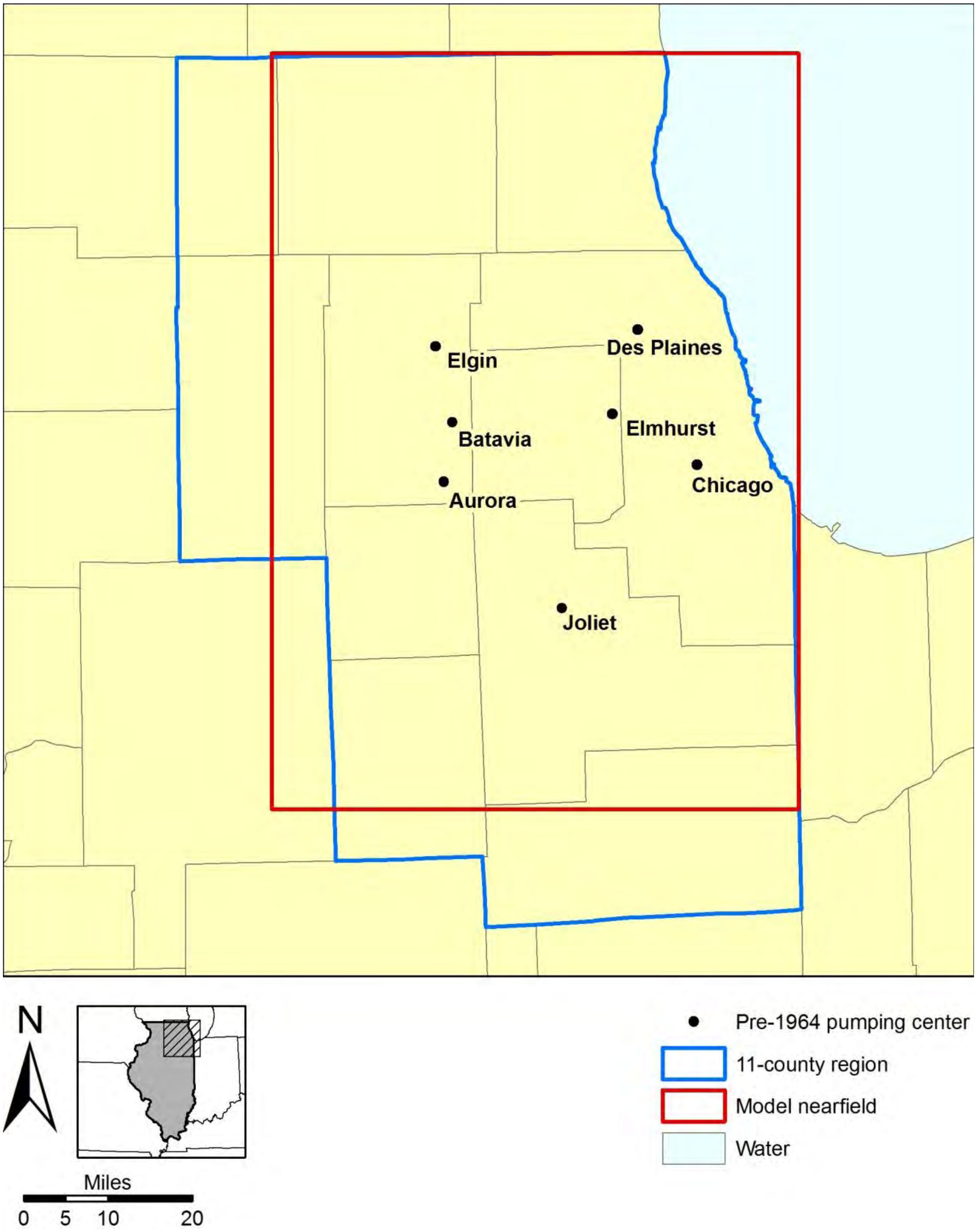


Figure 25. Historic aggregated deep aquifer pumping centers (after Suter et al., 1959)

seven idealized pumping centers (Figure 25), equivalent to aggregated total deep well withdrawals in northeastern Illinois. They were employed in previous modeling studies by Burch (1991) and Prickett and Lonnquist (1971). Aggregation for the Chicago pumping center was especially significant, as for example, pumpage at this center alone amounted to as much as 35 Mgd in the 1920s (Suter et al., 1959). As will be discussed in the next section, this created some mathematical irregularities in the model results.

The completeness of this dataset is not known, but it is based on sources that sought, and continue to seek, to document withdrawals from all community and non-community public water system wells, wells supplying commercial and industrial facilities having a pump capacity greater than 50 gallons per minute (gpm), and irrigation wells having a pump capacity greater than 50 gpm. As such, the authors believe the data are a reasonably complete representation of groundwater withdrawals in the region. Estimates are included for wells during years when it is probable that the wells were in use, but withdrawal data were not collected. The accuracy of the data is not known, but it is likely that the reported measurements are accurate to within ±10 percent of the actual value (United States Department of the Interior Bureau of Reclamation, 1997). The sources, processing, and uncertainty of the withdrawal data are discussed in detail in Meyer et al. (2009).

Groundwater withdrawals in northeastern Illinois have declined since the 1980s, largely as a consequence of public water systems in Cook, DuPage, and Lake Counties shifting from groundwater to Lake Michigan as a water source, but also because of improvements in efficiency, reduction of leakage, and deindustrialization (Figure 26). The largest annual declines in total groundwater withdrawals occurred in the early 1990s, when many groundwater-using public systems in DuPage County shifted to Lake Michigan water. Declines in withdrawals from deep wells have been greater than those from shallow wells, primarily because many public water systems that switched to Lake Michigan relied heavily on deep wells. Comparison of the distribution of pumping in 1985 (Figure 27, Figure 28, and Figure 29) and 2005 (Figure 30, Figure 31, and Figure 32) shows the effects of the shift to Lake Michigan by many suburban public water systems during the intervening years. The overall spatial effect of this shift has been to push the band of groundwater withdrawals farther west and south as pipelines deliver Lake Michigan water to inland areas at progressively greater distances from the lake. Withdrawals from the shallow units in 2005 are concentrated within a corridor extending from the Indiana boundary in Will County northwestward through the Fox River Valley of Kane County and extreme northwestern Cook County and northward into McHenry County (Figure 30 and Figure 31). In the southern part of the corridor, the source of these shallow withdrawals is predominantly the shallow bedrock aquifer (Will, southern Cook, and DuPage Counties), but large amounts of groundwater are withdrawn from Quaternary sand and gravel aquifers in the northern part of the corridor (east-central and northeastern Kane County and McHenry County). Principal areas of withdrawals from the deep units remaining in 2005 are (1) the industrial corridor along the Chicago Sanitary and Ship Canal and Des Plaines River, (2) the Fox River Valley area of southeastern Kane County, and (3) southeastern McHenry County (Figure 32).

Future Pumping. Three scenarios were simulated for the period 2005 to 2050, although the model may be adapted to simulate a wide range of other scenarios. Modeled

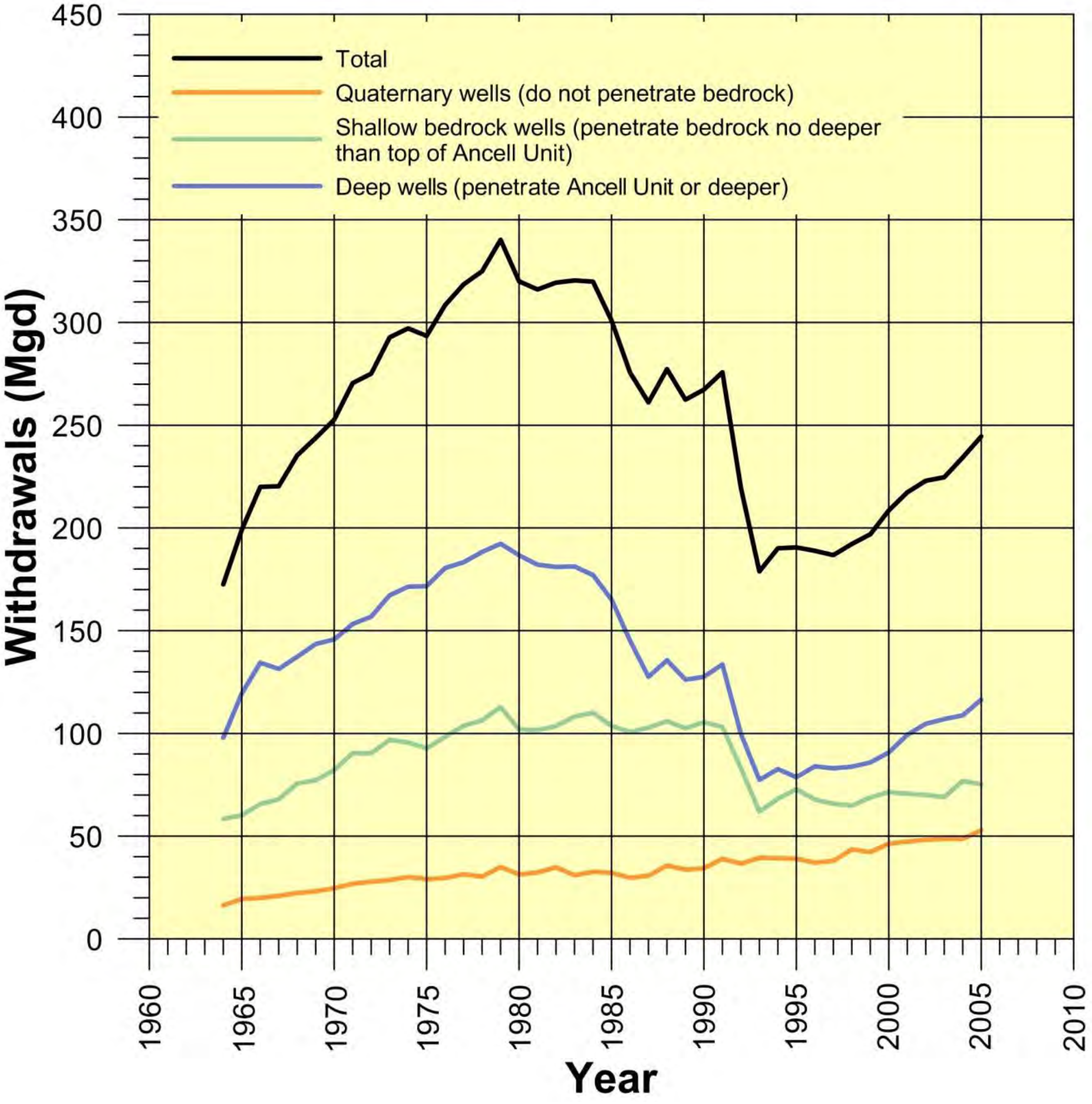


Figure 26. Simulated groundwater withdrawals in 11-county area, 1964–2005

withdrawals for this investigation were based on the BL, LRI, and MRI water demand scenarios developed by Dziegielewski and Chowdhury (2008) and described previously (Section 2.1.2). These county-level demands were disaggregated to individual points of withdrawal (wells) by Dziegielewski and Chowdhury and provided to ISWS scientists for use as model input.

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

- Because the authors did not wish to speculate or dictate new well locations and source aquifers, no new points of withdrawal were added beyond those wells operating in 2005. Instead, all additional future demands were assigned to those existing points.

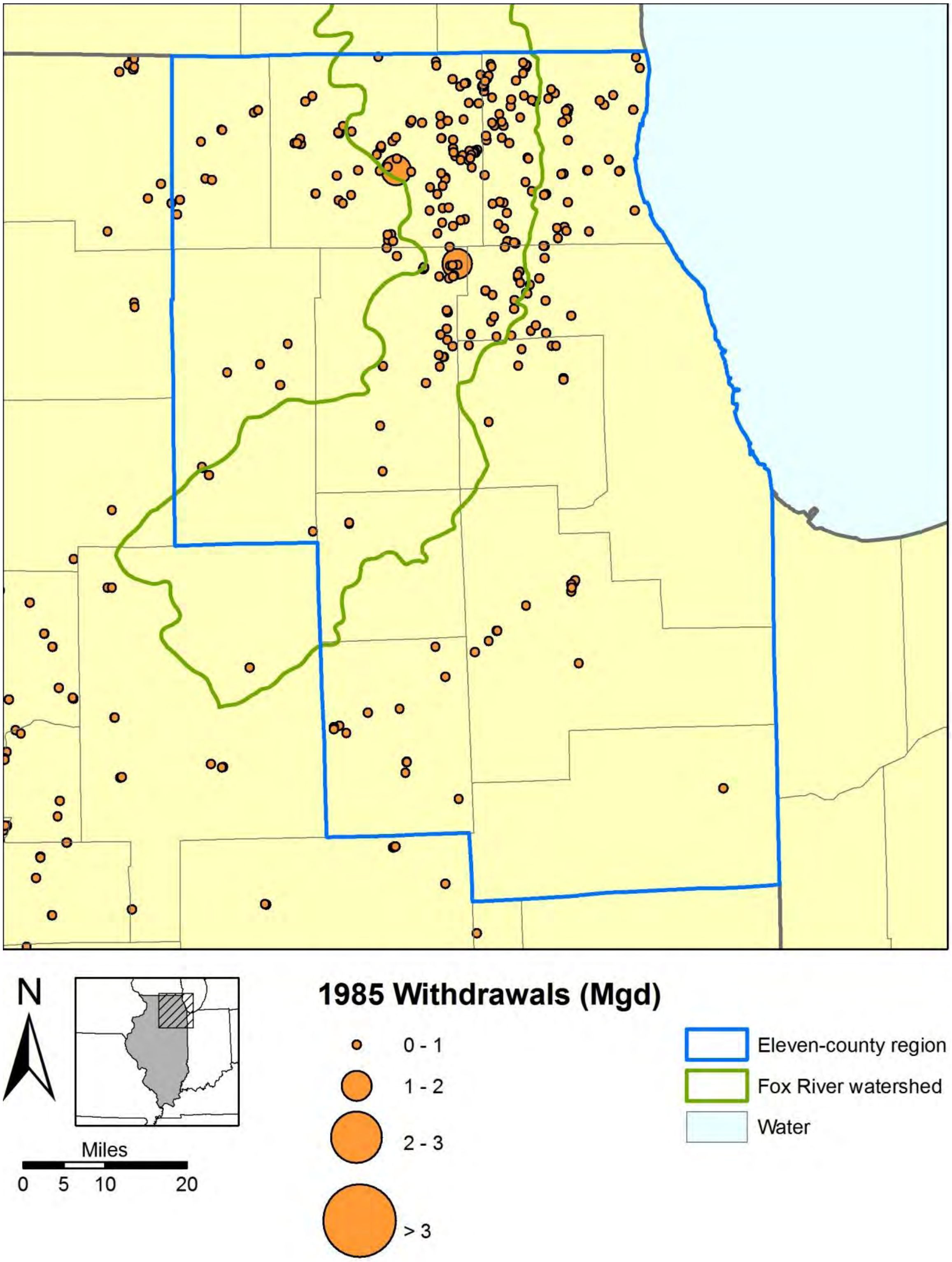


Figure 27. Simulated 1985 withdrawals from Quaternary Unit wells in northeastern Illinois

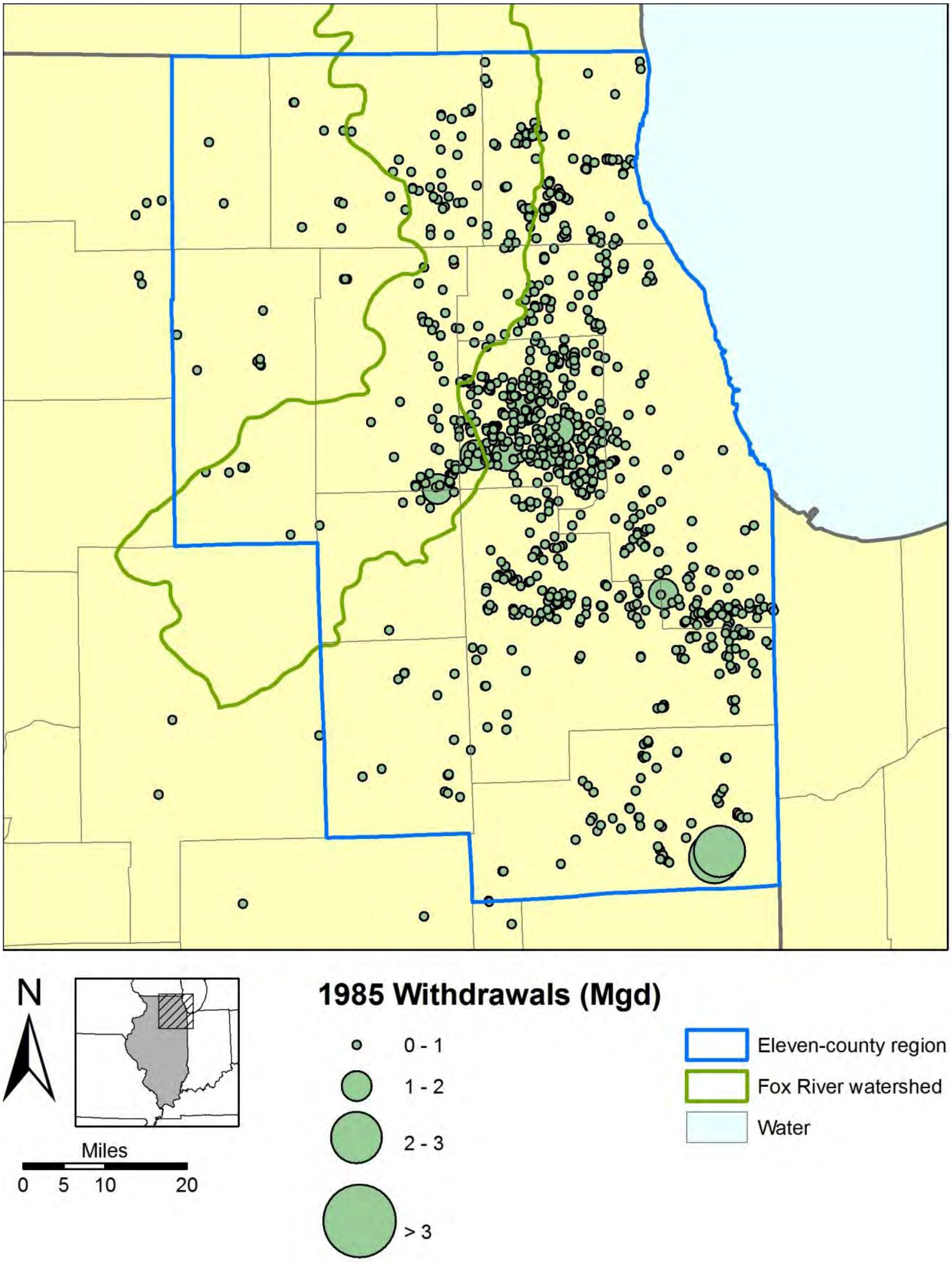


Figure 28. Simulated 1985 withdrawals from shallow bedrock wells in northeastern Illinois

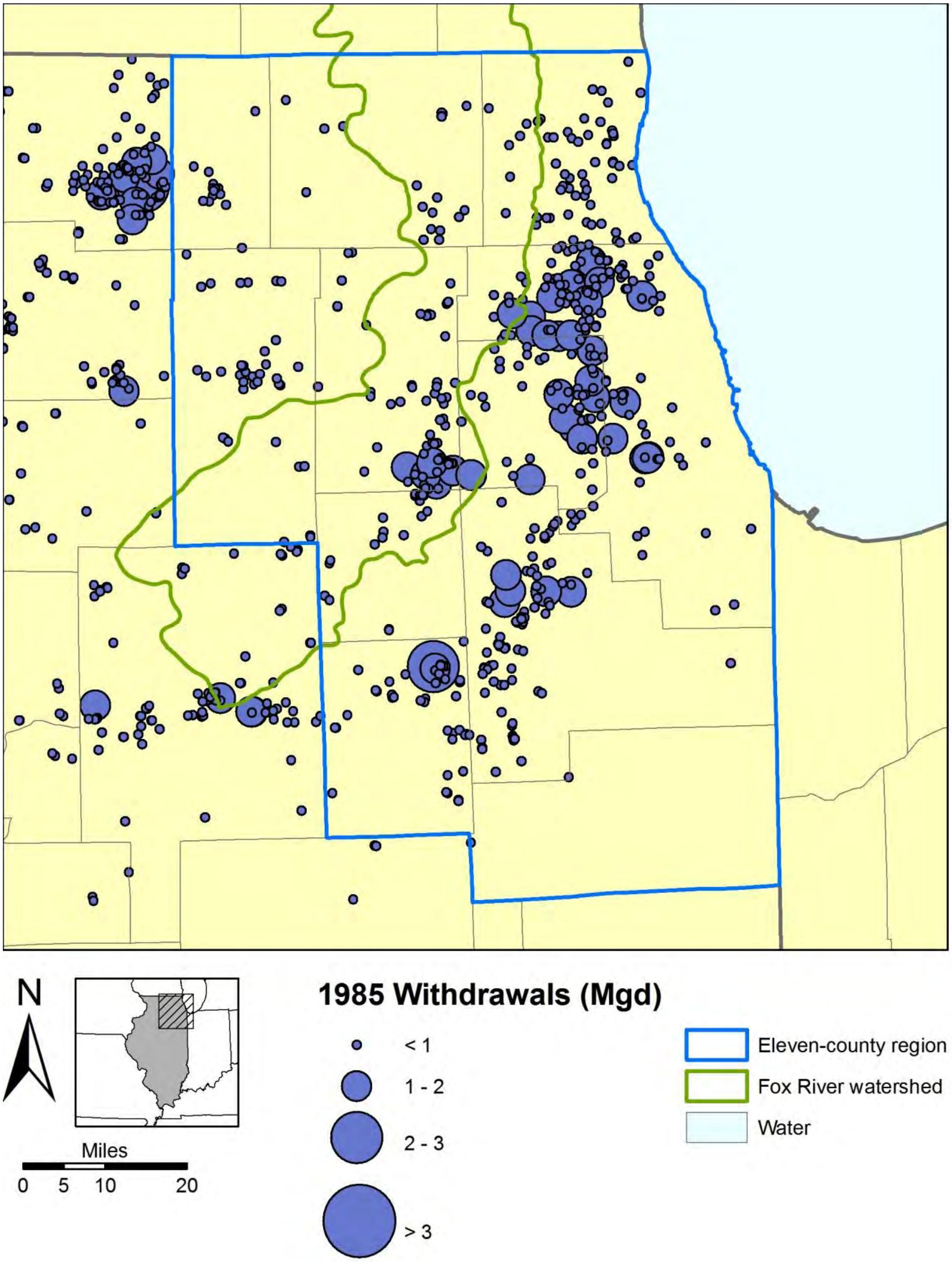


Figure 29. Simulated 1985 withdrawals from deep wells in northeastern Illinois

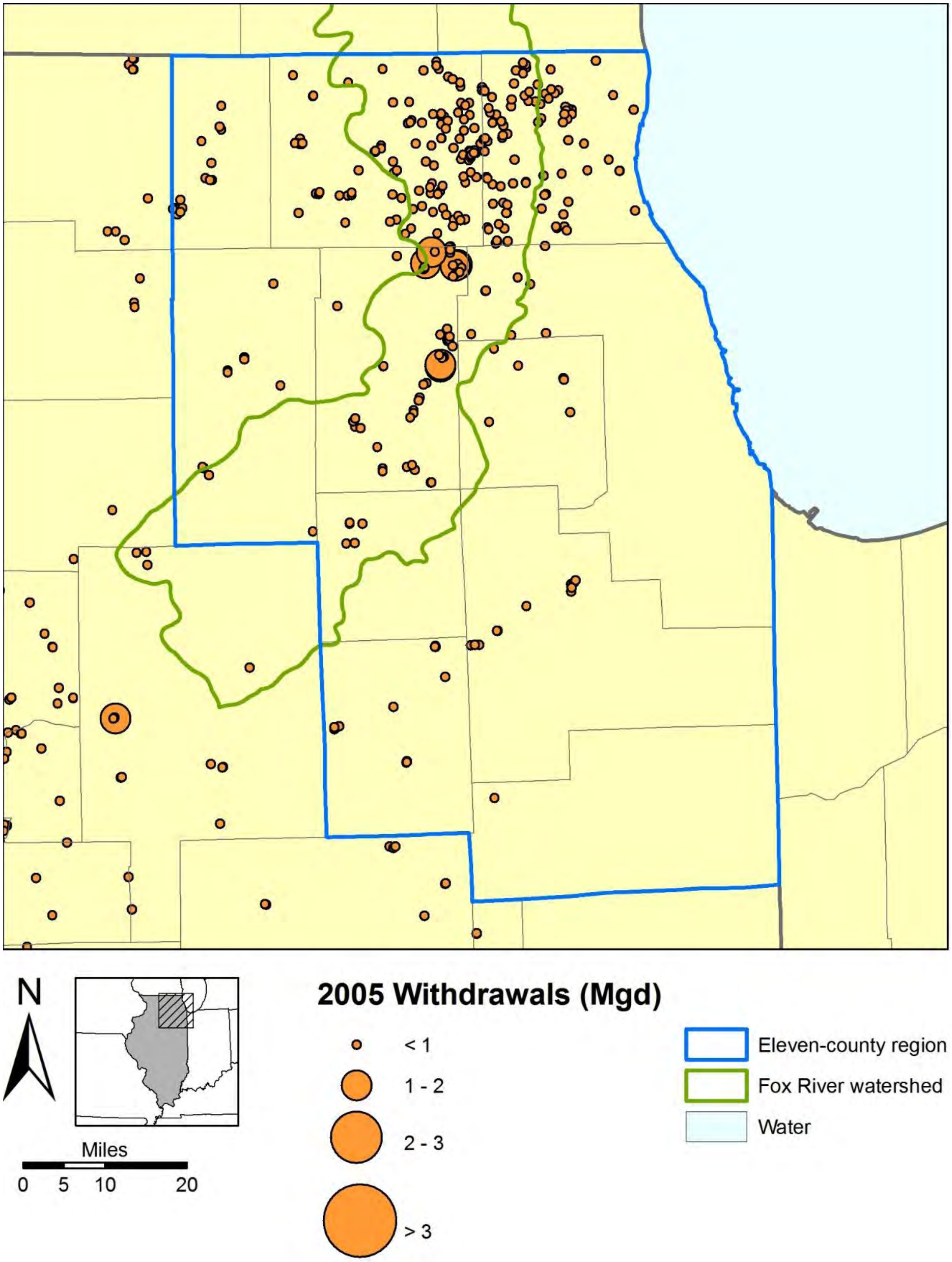


Figure 30. Simulated 2005 withdrawals from Quaternary Unit wells in northeastern Illinois

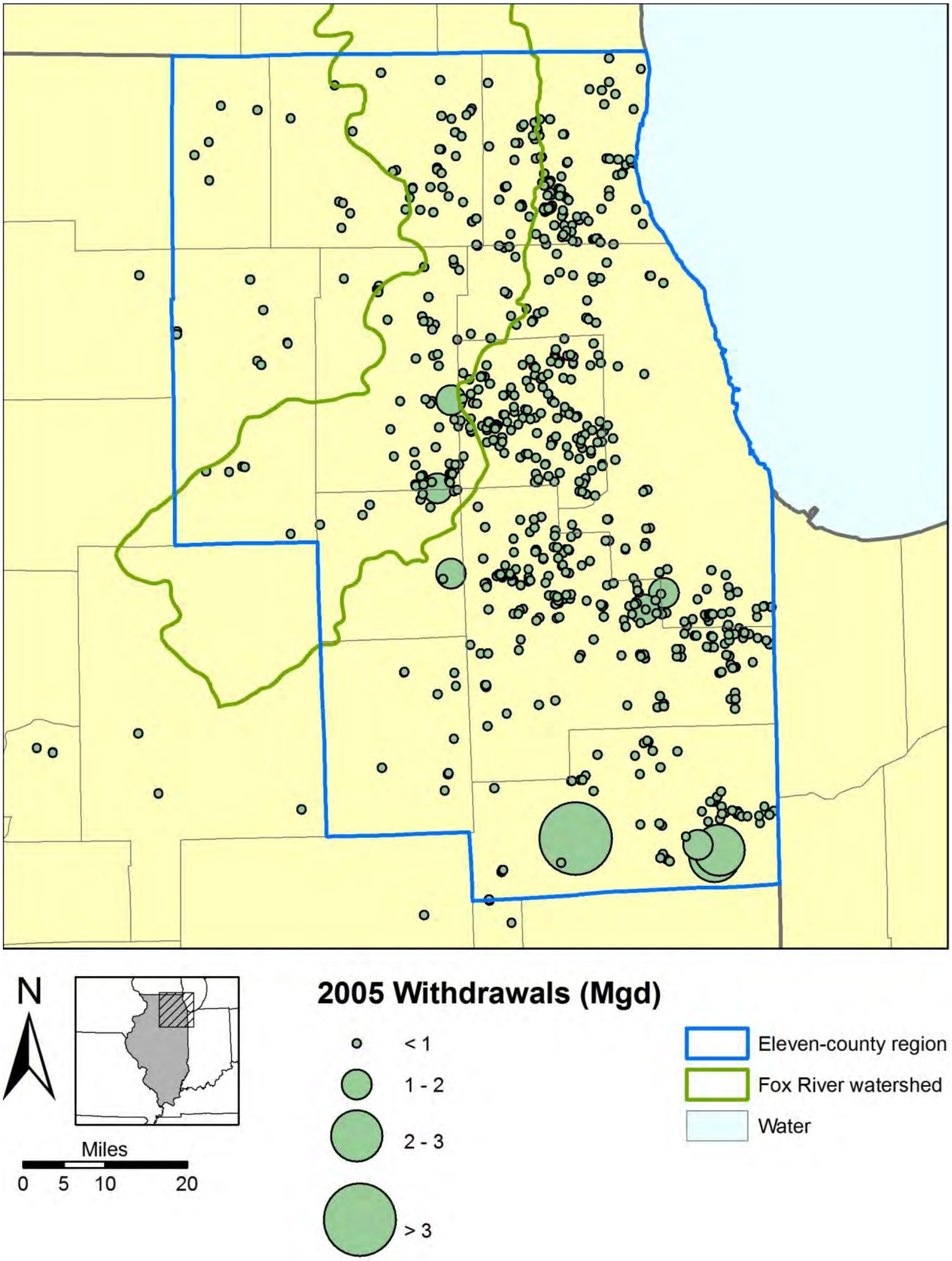


Figure 31. Simulated 2005 withdrawals from shallow bedrock wells in northeastern Illinois

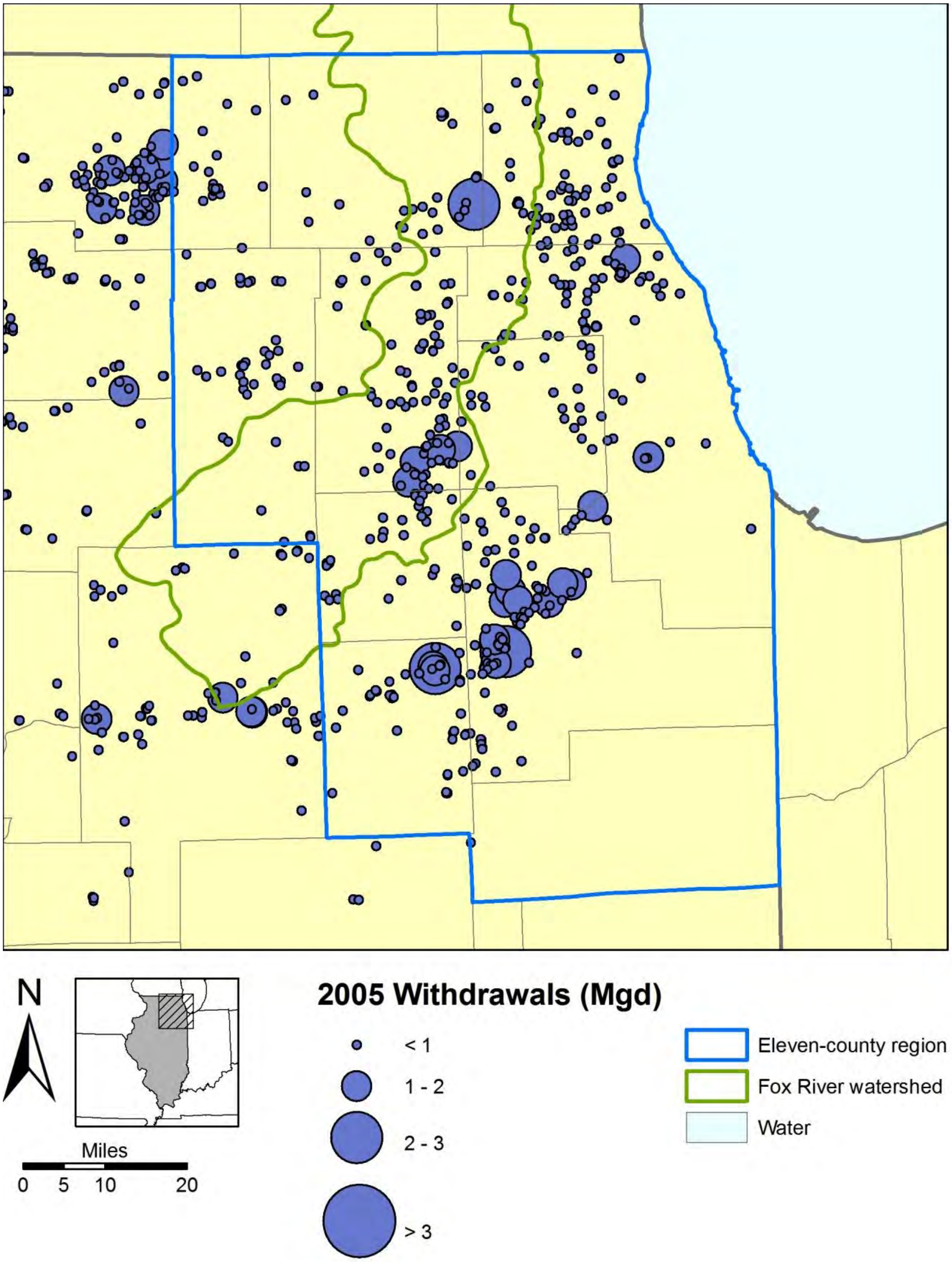


Figure 32. Simulated 2005 withdrawals from deep wells in northeastern Illinois

- Actual future withdrawals will be distributed between existing wells and new wells, the latter at locations and open to source aquifers not known to the authors and not simulated in the model. Model estimates of future pumping impacts will differ from actual future impacts accordingly, since the model cannot predict impacts where it is not designed to simulate pumping. Strategic siting of new wells could distribute withdrawals so as to reduce impacts below model-simulated levels in the most affected areas.
- Assignment of future (post-2005) pumping reflects facility pumping operations in 2005. For example, Crystal Lake withdrew about 4.30 Mgd of groundwater in 2005; about 10.4 percent of this total (0.45 Mgd) was pumped from well 11 at that facility. Under the BL scenario, Dziegiewski and Chowdhury (2008) estimated that Crystal Lake would pump a total of about 5.22 Mgd in 2050. For purposes of model simulation, the authors assigned 10.4 percent of that total (0.54 Mgd) to well 11, reflecting the proportion pumped from the well in 2005. The authors employed the same convention for the post-2005 period for each of the three scenarios. Although the convention cannot reflect actual evolution of the regional well network–which will be a product of numerous decisions by hundreds of managers, in response to a range of factors, and perhaps without knowledge of management decisions made by other facilities in the region–it was necessary owing to time and budget constraints of this initial assessment. Nevertheless, the modeling results based on it permit identification of problematic areas for priority follow-up investigation.
- Although assigning additional future demand to existing public and industrial/commercial wells exceeded some actual well pumping capacities (based on 24-hour operation at the well pump's rated capacity), the addition of new wells to accommodate such exceedances would typically occur within the grid spacing of the flow model nearfield (2,500 feet), thus essentially adding that demand to the same model cell anyway.
- Future agriculture/irrigation demands were not assigned to wells if they exceeded the well pumping capacity. Future agriculture/irrigation withdrawals were assigned to existing agriculture/irrigation wells, but additional withdrawals were limited at the pumping capacity of the well (based on 24-hour constant operation at the well pump's rated capacity). In some cases, this meant not all the county agriculture/irrigation demand could be allocated. Depending on the demand scenario, from 14.5 to 22 Mgd in 2050 irrigation demand across the 11 counties was unallocated (Table 28 to Table 30).
- This irrigation well pumping capacity assumption was violated during model simulations when model stress periods were divided into ⅓-year increments to allow simulation of increased irrigation demand during the growing season. To do this, irrigation wells were "turned off" in the first and last thirds of the year and "turned on" at three times their assigned annual rate during the middle third of the year.
- Domestic self-supplied withdrawals (i.e., rural domestic wells) were not simulated. This amounted to from 37.3 to 49.3 Mgd in 2050 demand across the 11-county region (Table 28 to Table 30). Since these wells are predominantly completed in the shallow aquifers and return the groundwater pumped from them to the shallow units via septic

systems, it is likely that this circulation of water will not have significant impacts on groundwater availability in the region.

Simulated withdrawals in the 11-county region increase between 2005 and 2050 with 2050 totals ranging from 327 to 532 Mgd, depending on demand scenario (Figure 33, Table 28 to Table 30). Unsimulated demand based on the projections of Dziegielewski and Chowdhury (2008) includes irrigation demand ranging from 14.5 to 22.0 Mgd in 2050 and domestic demand ranging from 37.3 to 49.3 Mgd. The sources of projected withdrawals reflect the 2005 proportionality, with roughly a 50/50 split between the deep and shallow aquifers (shallow aquifers including the shallow bedrock and Quaternary aquifers combined). Projected withdrawals from the deep aquifers in 2050 in the 11-county area total 197 and 251 Mgd under the BL and MRI scenarios, respectively, rates that are higher than the peak historical withdrawal rate from the deep aquifers of about 190 Mgd (Figure 34), a rate known to produce rapidly falling heads in some deep wells. For comparison, the spatial distributions of withdrawals in 2050 for the three aquifers under each scenario are shown in Figure 35 to Figure 46.

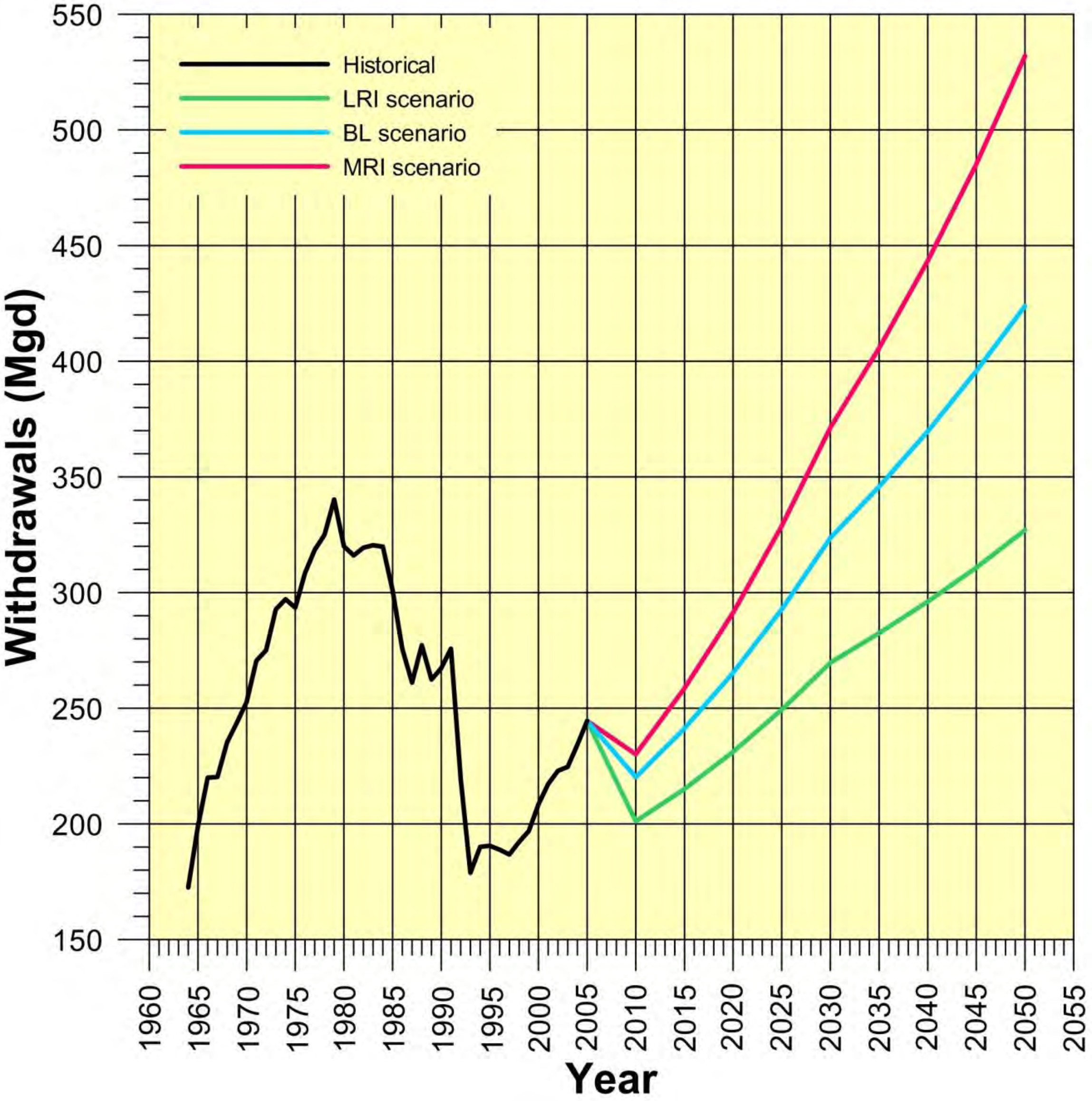


Figure 33. Total simulated groundwater withdrawals in 11-county region, 1964–2050

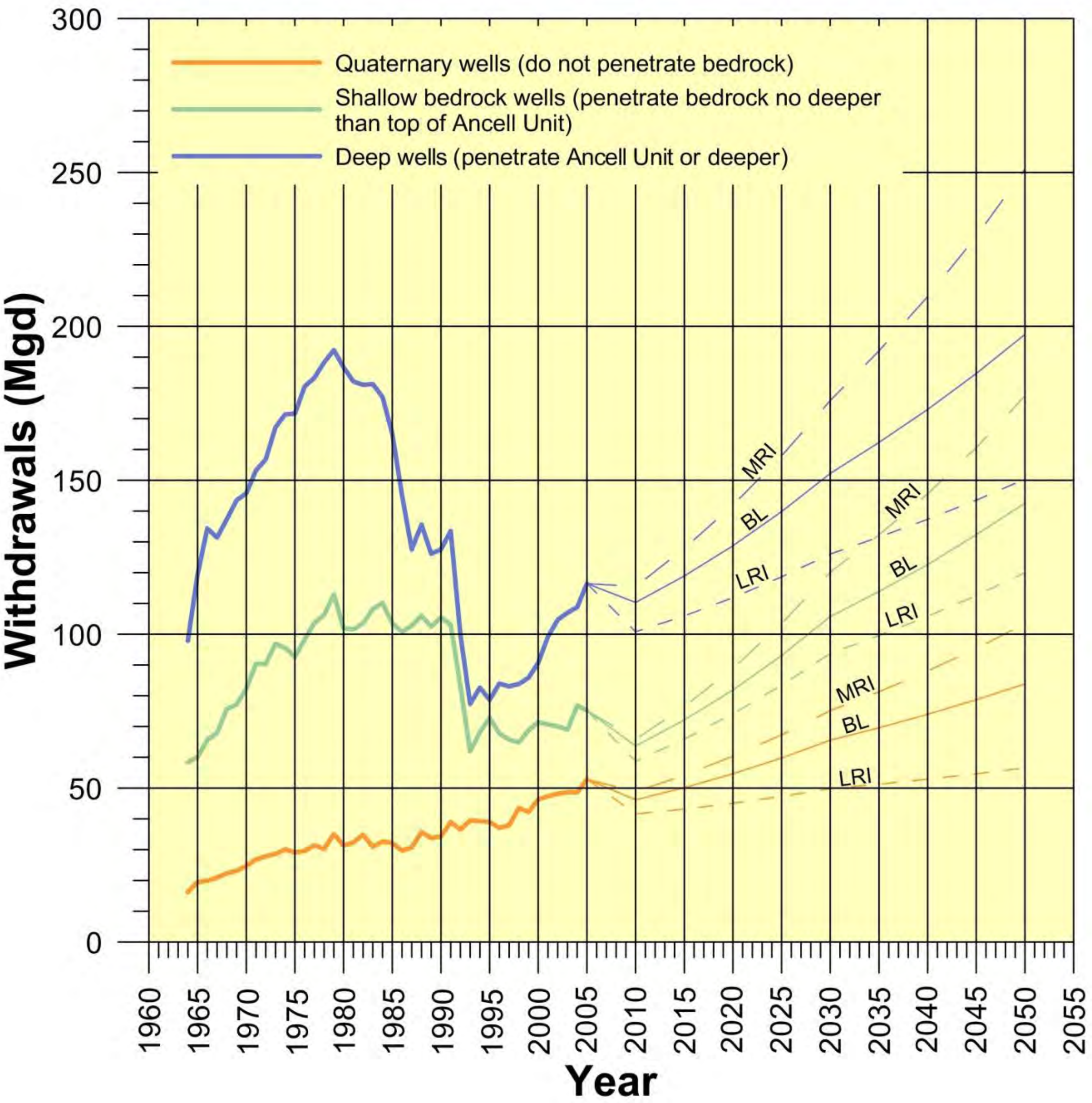


Figure 34. Simulated groundwater withdrawals in 11-county area by aquifer group and scenario, 1964–2050

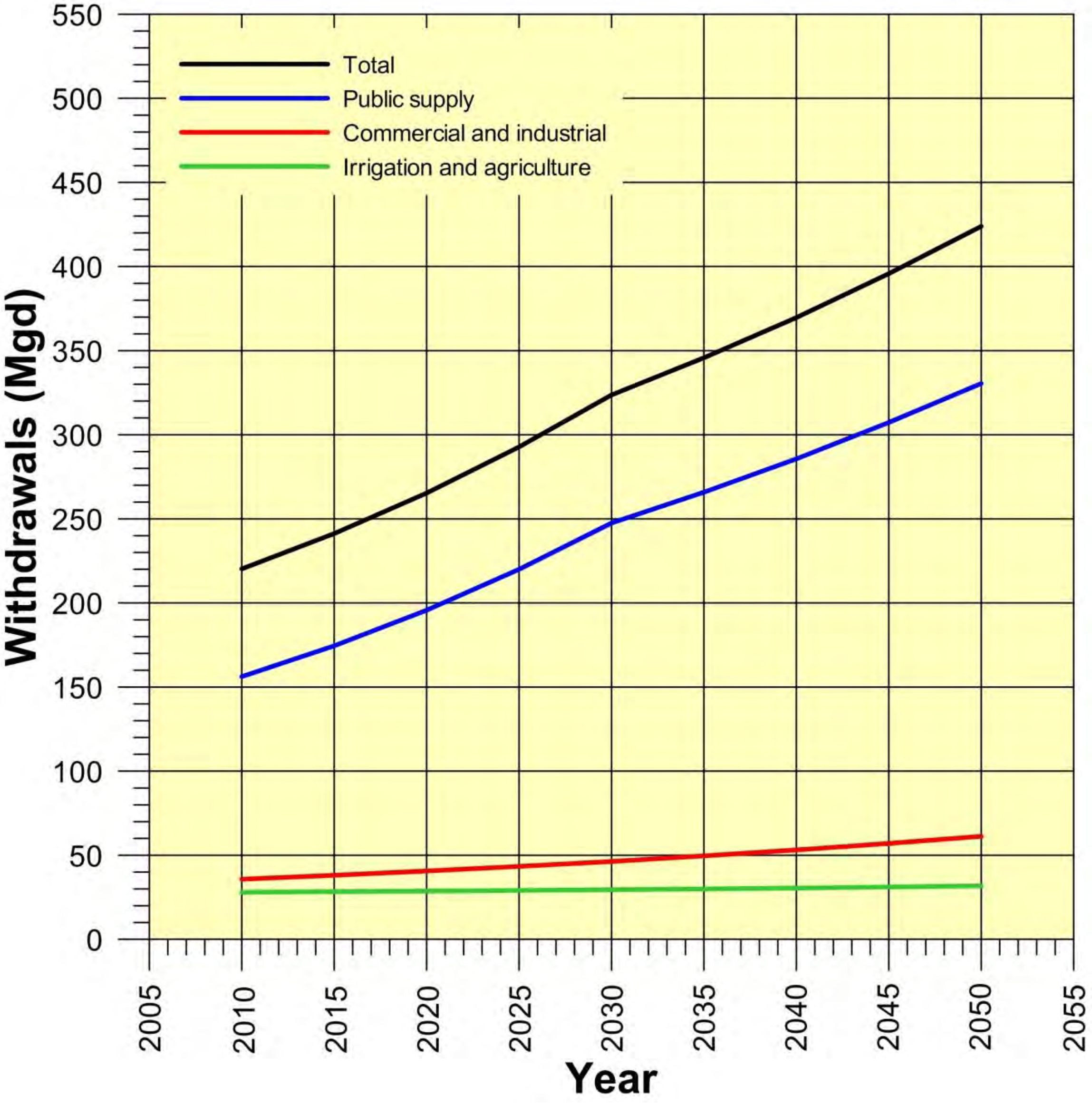


Figure 35. Projected groundwater withdrawals in 11-county area subdivided by water use sector, BL scenario

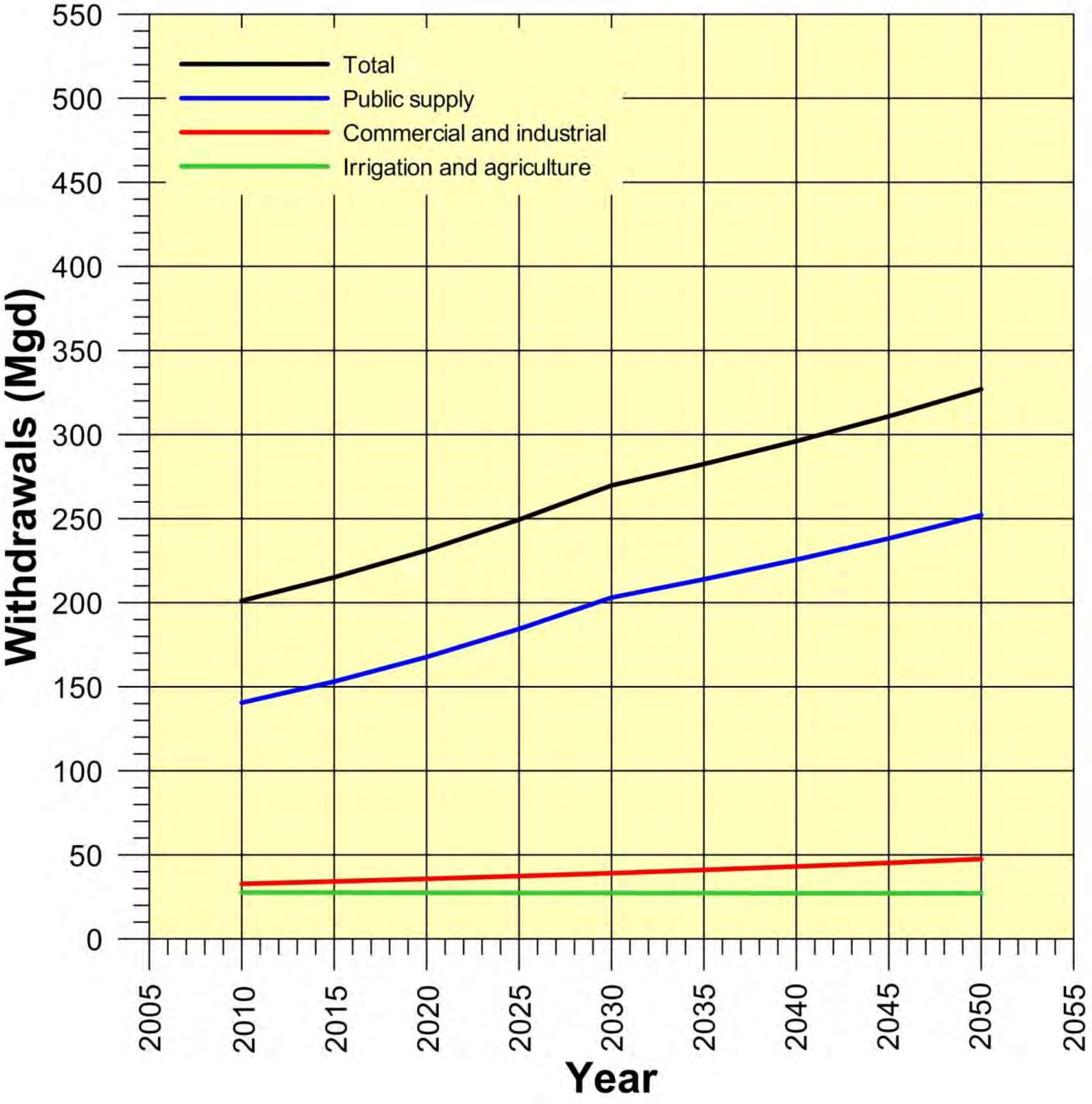


Figure 36. Projected groundwater withdrawals in 11-county area subdivided by water use sector, LRI scenario

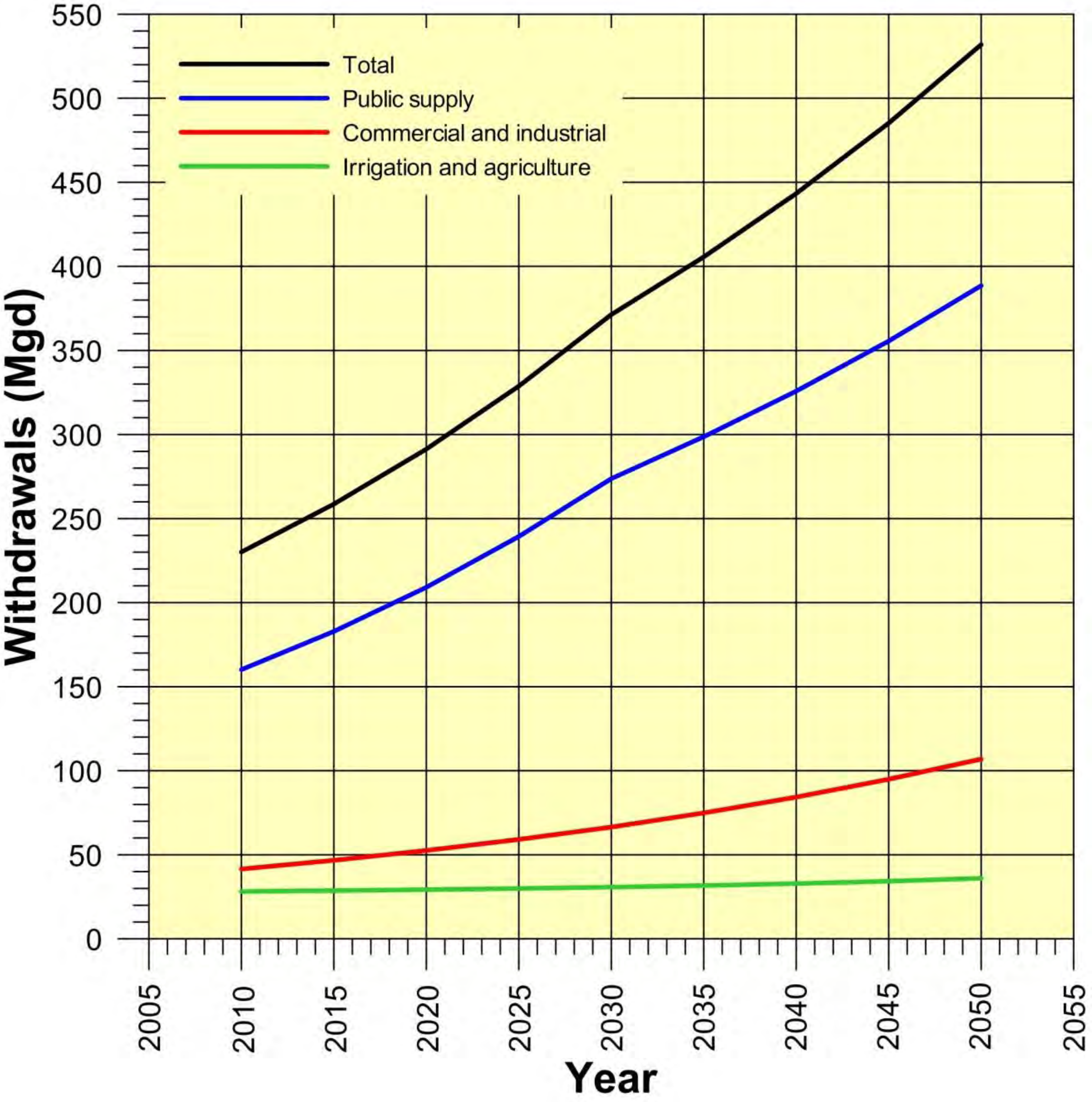


Figure 37. Projected groundwater withdrawals in 11-county area subdivided by water use sector, MRI scenario

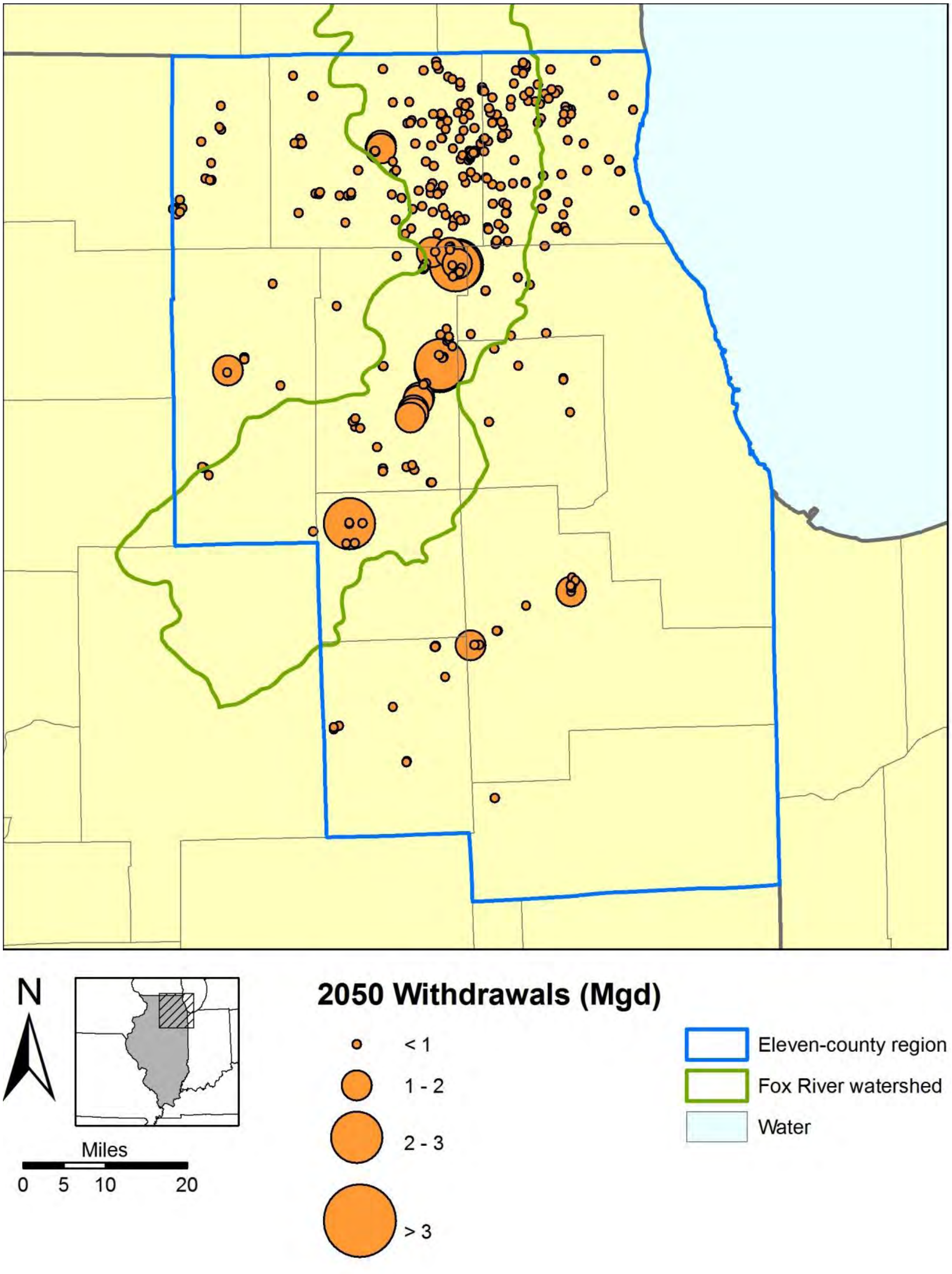


Figure 38. Simulated 2050 withdrawals from Quaternary Unit wells in northeastern Illinois, BL scenario

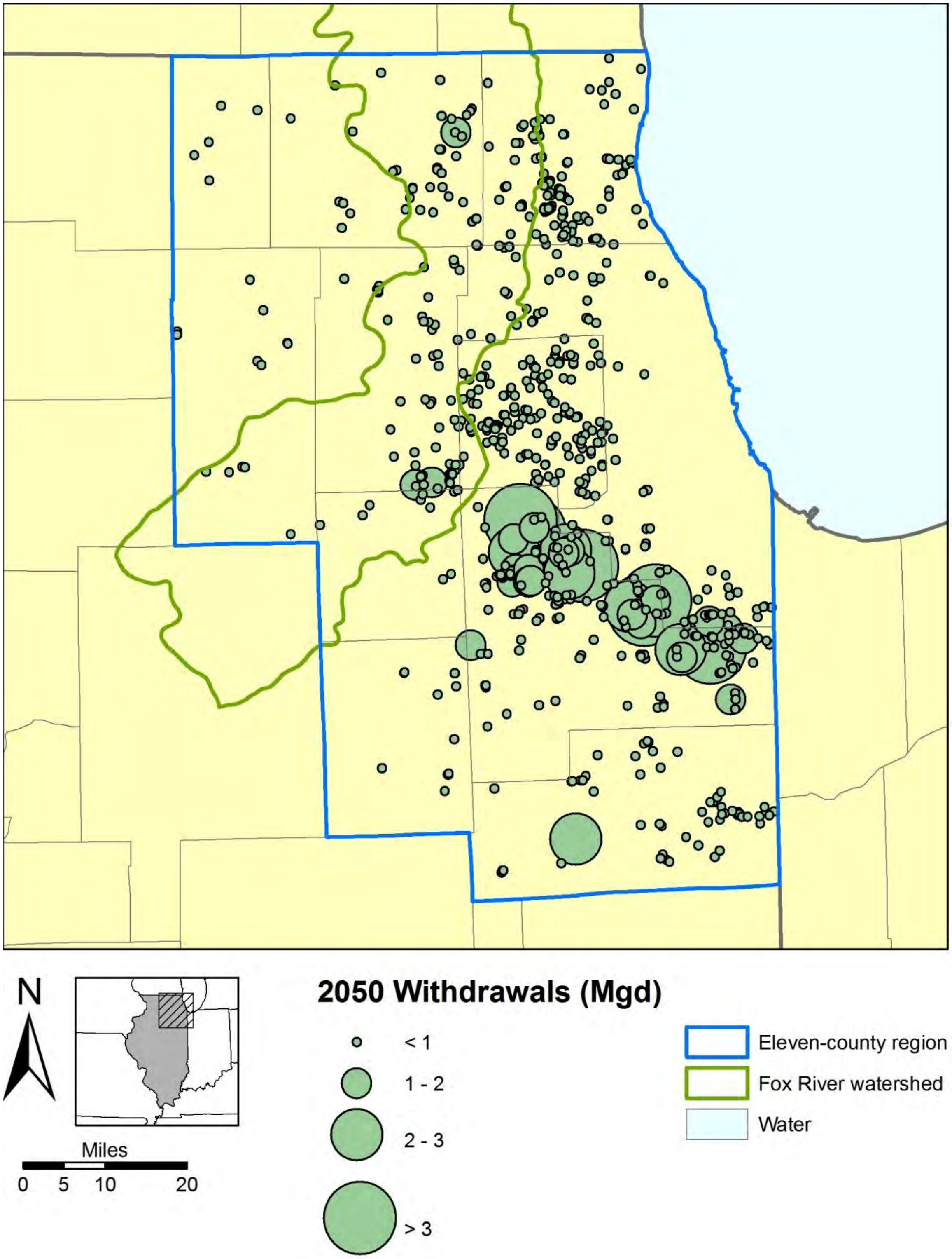


Figure 39. Simulated 2050 withdrawals from shallow bedrock wells in northeastern Illinois, BL scenario

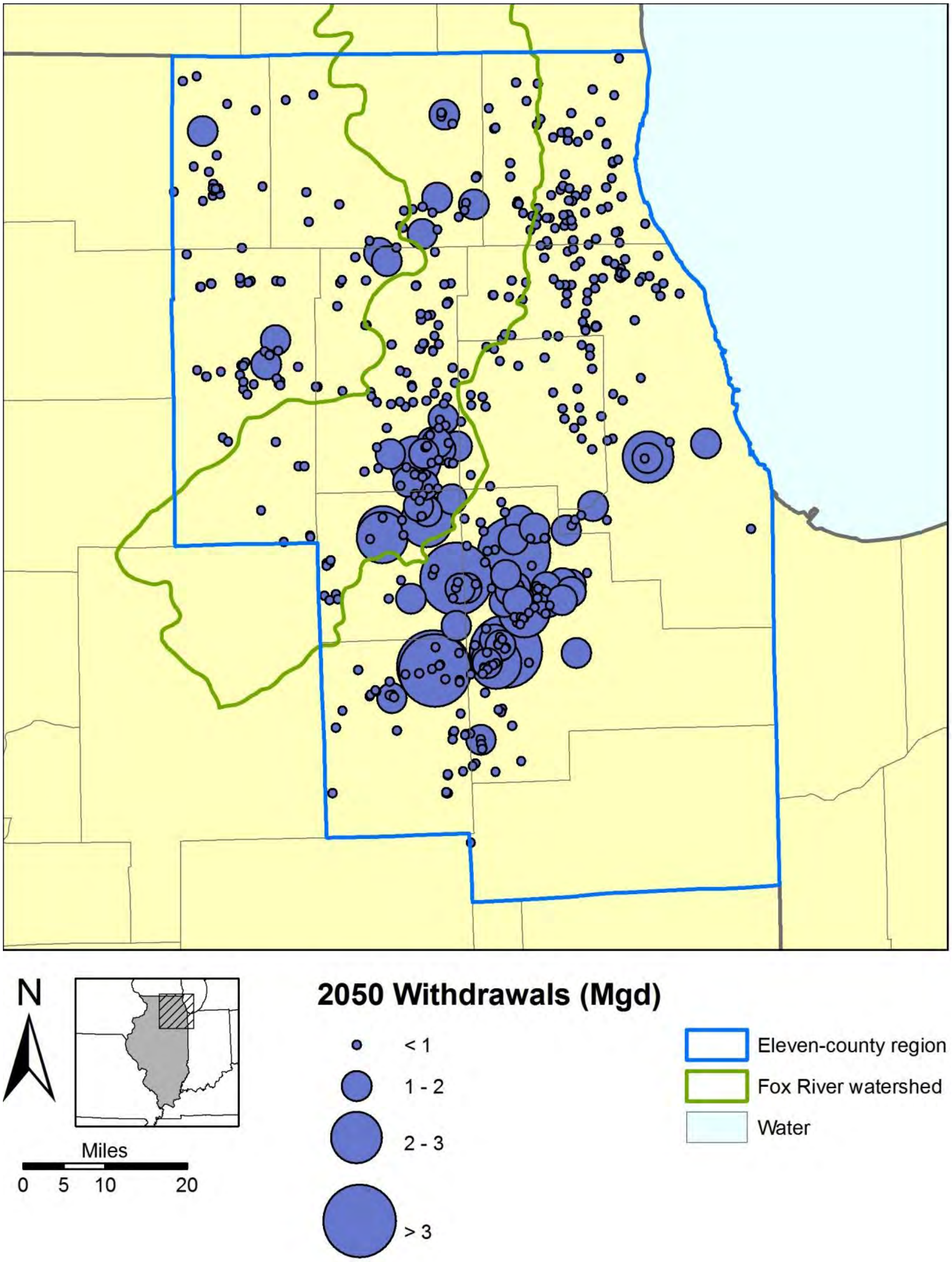


Figure 40. Simulated 2050 withdrawals from deep wells in northeastern Illinois, BL scenario

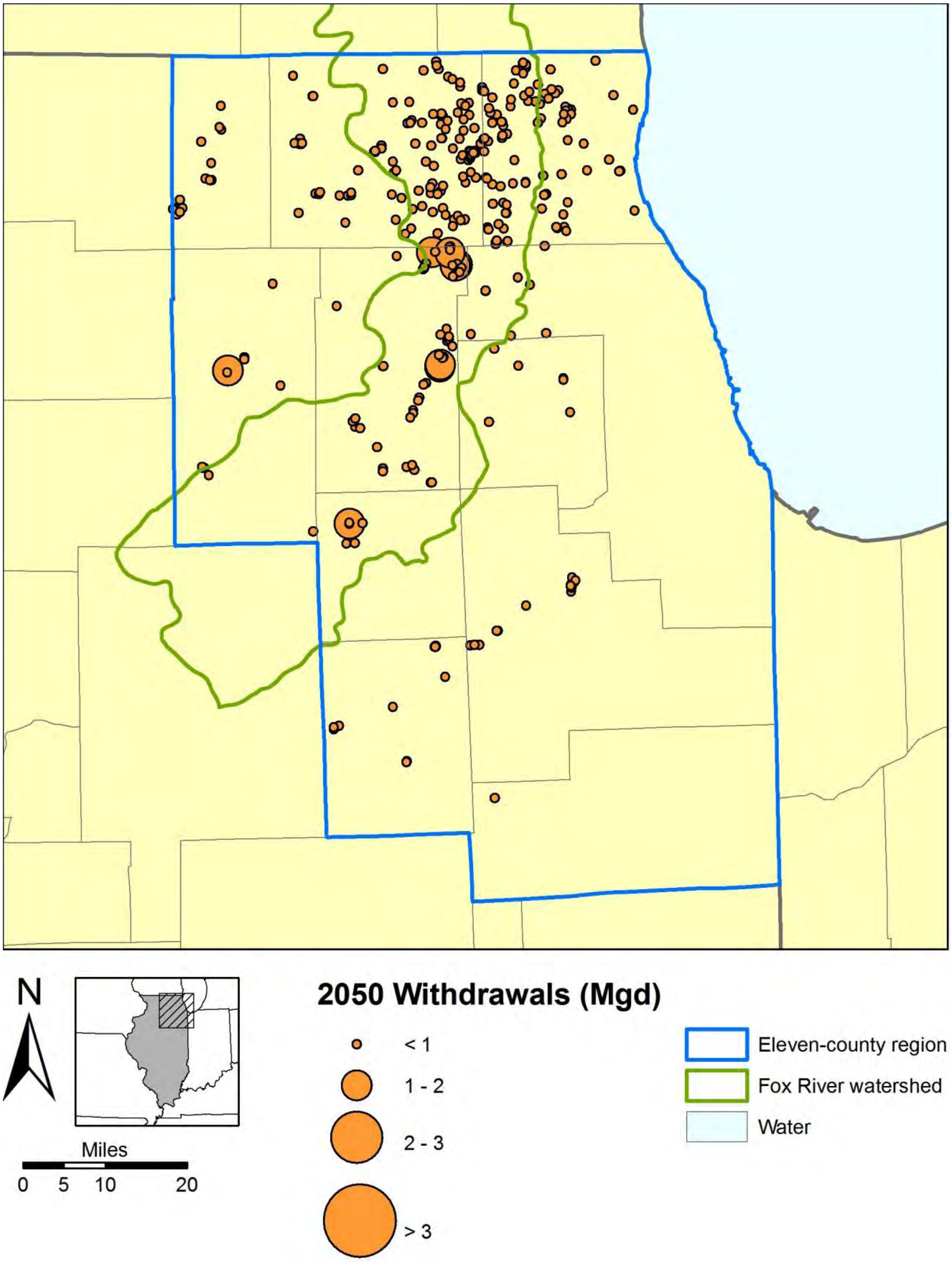


Figure 41. Simulated 2050 withdrawals from Quaternary Unit wells in northeastern Illinois, LRI scenario

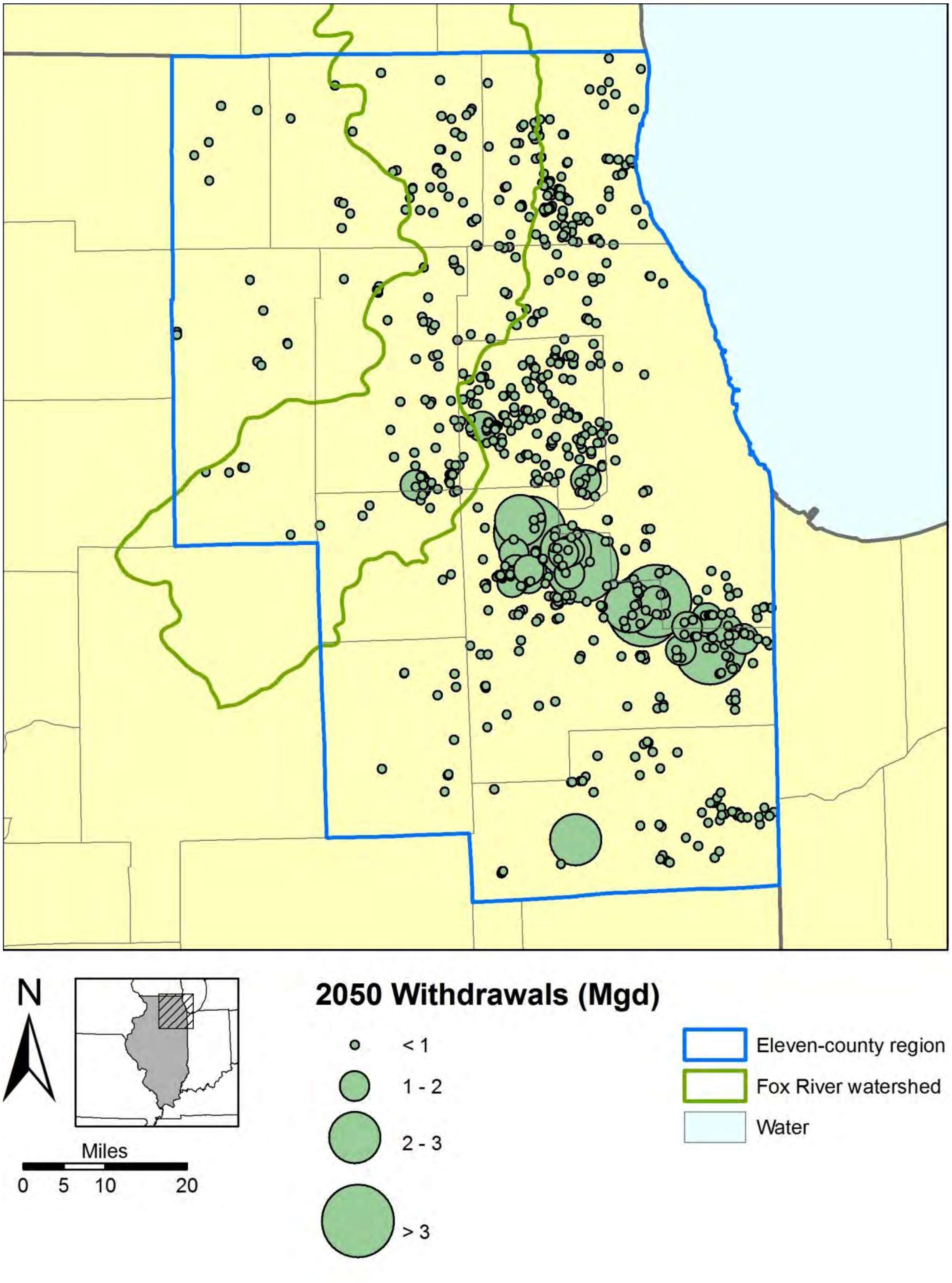


Figure 42. Simulated 2050 withdrawals from shallow bedrock wells in northeastern Illinois, LRI scenario

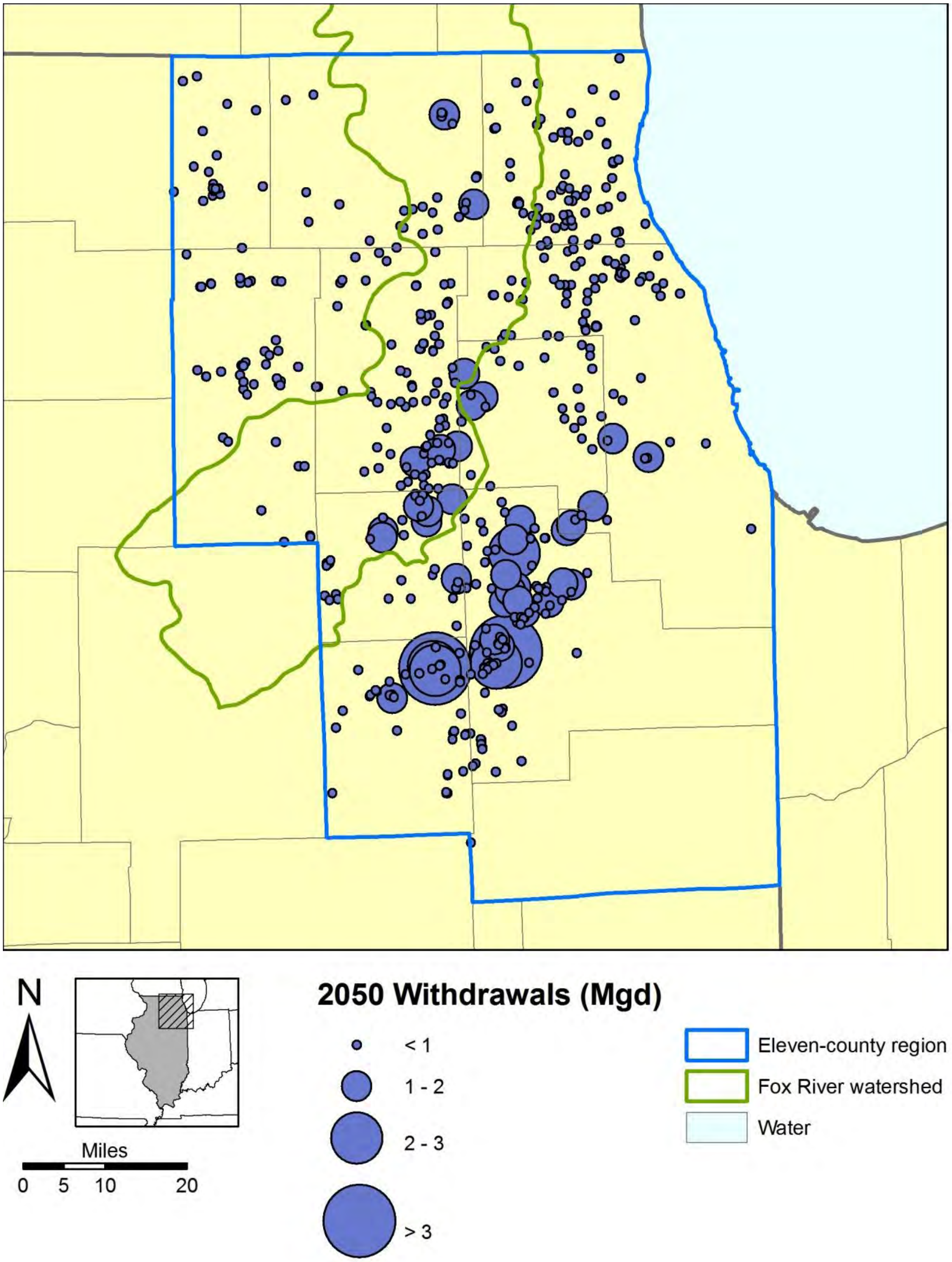


Figure 43. Simulated 2050 withdrawals from deep wells in northeastern Illinois, LRI scenario

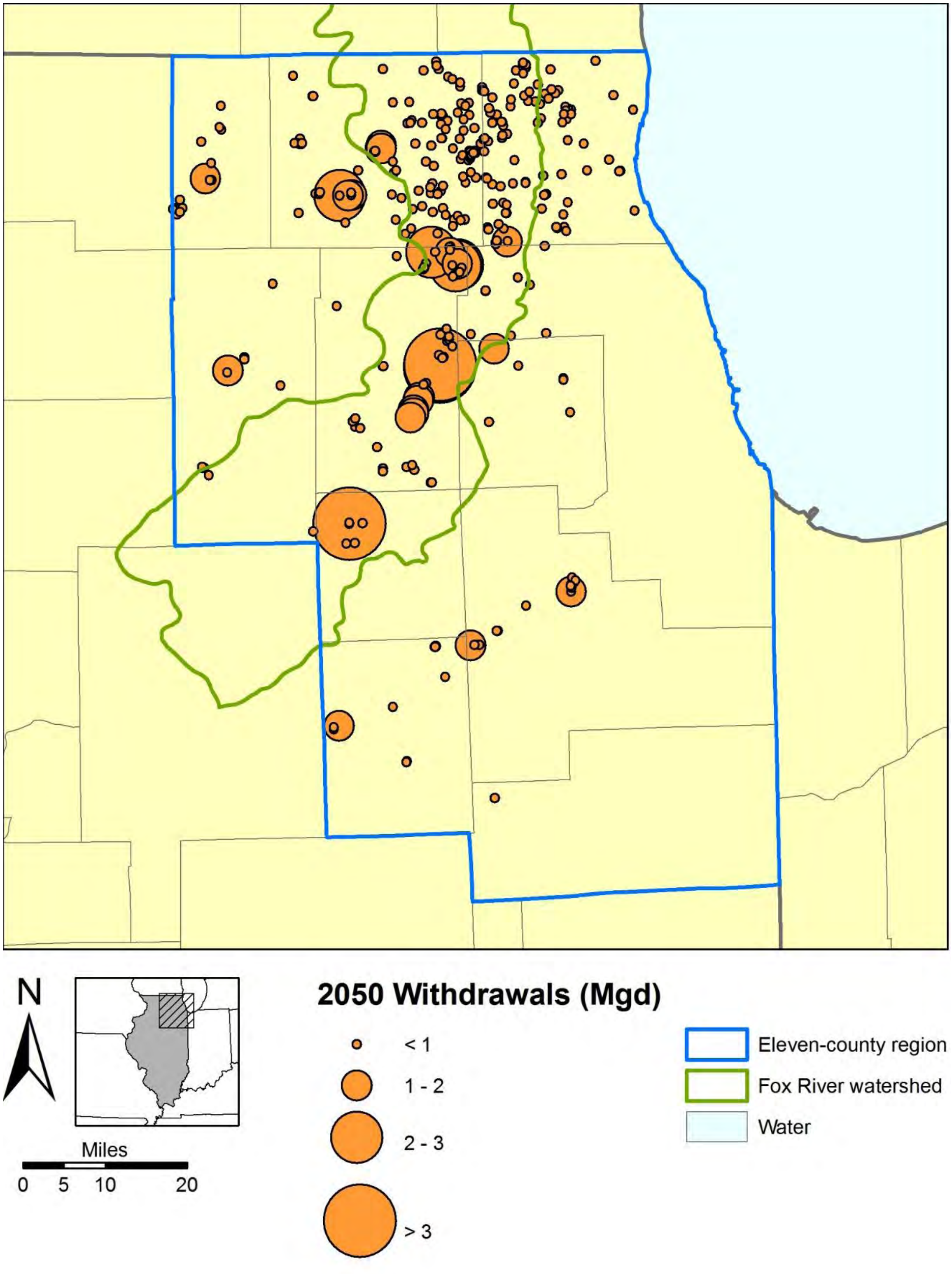


Figure 44. Simulated 2050 withdrawals from Quaternary Unit wells in northeastern Illinois, MRI scenario

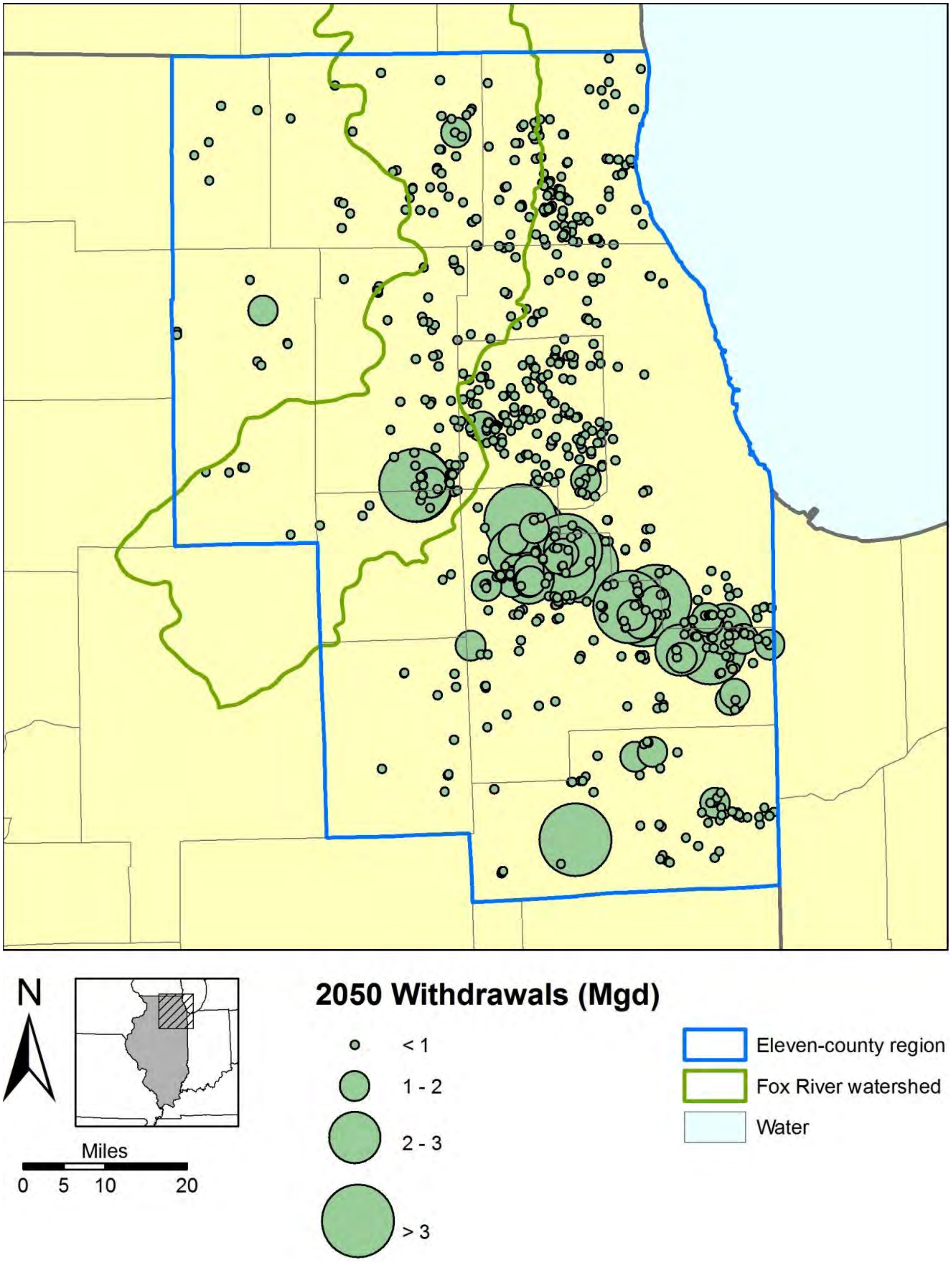


Figure 45. Simulated 2050 withdrawals from shallow bedrock wells in northeastern Illinois, MRI scenario

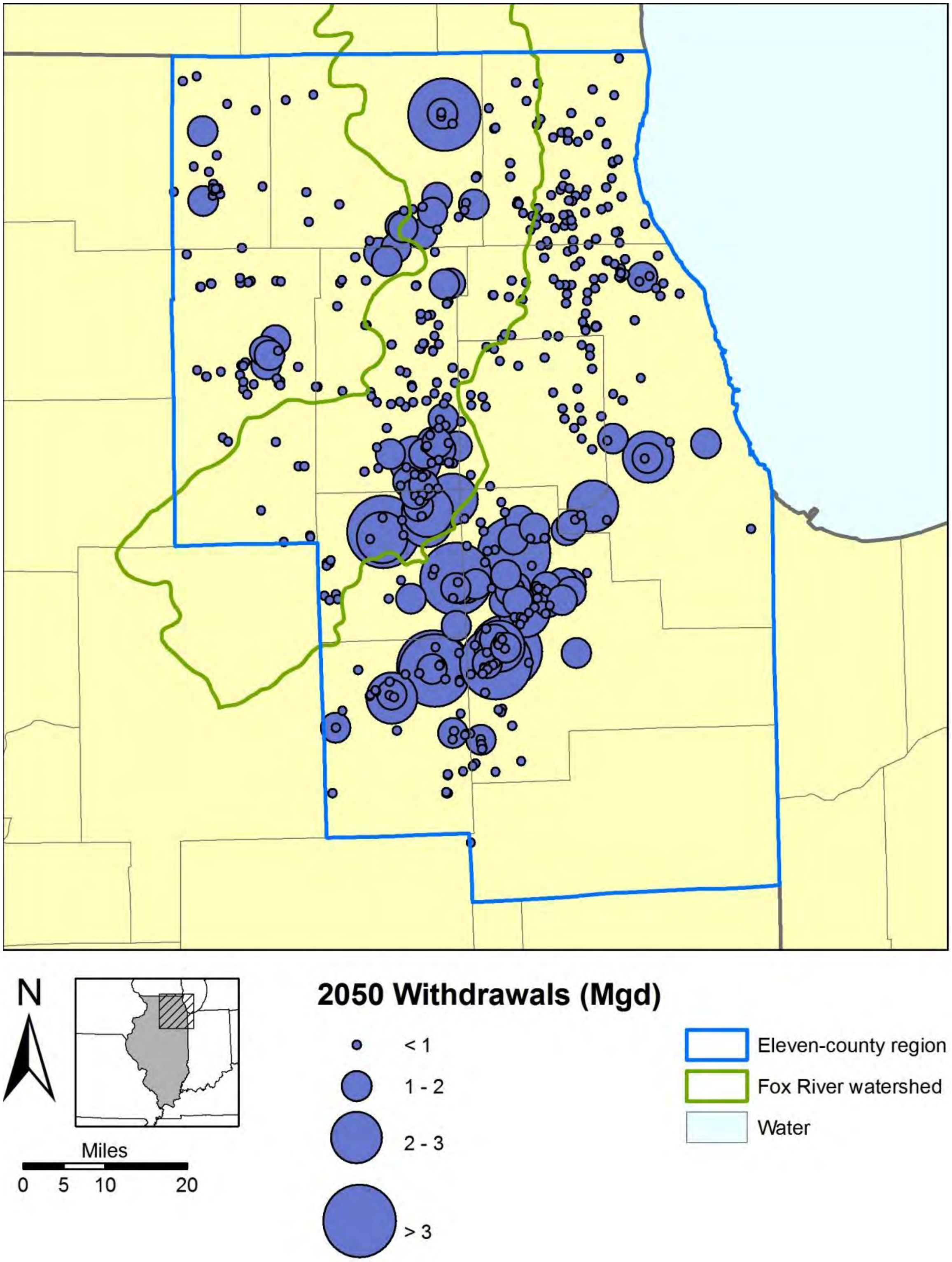


Figure 46. Simulated 2050 withdrawals from deep wells in northeastern Illinois, MRI scenario

Table 28. Withdrawals Allocated to Wells (and Left Unallocated), BL Scenario, 2010–2050 (Mgd)

Year	*Public Supply*	*Industrial/ Commercial*	*Agriculture/ Irrigation*	*Total Allocated*	*Unallocated Ag/Irrigation*	*Unallocated Domestic*
2010	156.18	35.74	27.99	220.23	15.25	33.37
2015	174.50	38.08	28.33	241.24	15.94	34.71
2020	195.69	40.63	28.68	265.33	16.49	35.93
2025	220.00	43.36	29.07	292.77	17.19	37.04
2030	247.50	46.29	29.51	323.64	17.93	38.08
2035	265.83	49.62	29.96	345.77	18.51	38.94
2040	285.66	53.14	30.50	369.66	19.30	39.71
2045	307.31	57.01	31.11	395.80	20.13	40.45
2050	330.49	61.25	31.79	423.90	21.01	41.17

Table 29. Withdrawals Allocated to Wells (and Left Unallocated), LRI Scenario, 2010–2050 (Mgd)

Year	*Public Supply*	*Industrial/ Commercial*	*Agriculture/ Irrigation*	*Total Allocated*	*Unallocated Ag/Irrigation*	*Unallocated Domestic*
2010	140.49	32.73	27.59	201.13	14.63	31.65
2015	153.09	34.18	27.51	215.09	14.67	32.70
2020	167.70	35.72	27.42	231.15	14.55	33.62
2025	184.39	37.37	27.35	249.41	14.56	34.46
2030	203.04	39.09	27.29	269.71	14.58	35.23
2035	213.92	41.03	27.21	282.45	14.42	35.83
2040	225.57	43.05	27.16	296.07	14.43	36.36
2045	238.21	45.22	27.13	310.84	14.44	36.85
2050	252.04	47.54	27.10	326.97	14.47	37.32

Table 30. Withdrawals Allocated to Wells (and Left Unallocated), MRI Scenario, 2010–2050 (Mgd)

Year	*Public Supply*	*Industrial/ Commercial*	*Agriculture/ Irrigation*	*Total Allocated*	*Unallocated Ag/Irrigation*	*Unallocated Domestic*
2010	160.13	41.51	28.15	230.13	15.32	37.04
2015	182.89	46.71	28.69	258.63	16.10	39.00
2020	209.13	52.56	29.27	291.32	16.74	40.80
2025	239.33	59.14	29.96	328.79	17.54	42.50
2030	273.73	66.46	30.76	371.33	18.39	44.10
2035	298.68	74.90	31.70	405.66	19.09	45.50
2040	325.82	84.31	32.85	443.39	20.01	46.80
2045	355.61	94.94	34.27	485.24	20.99	48.07
2050	388.55	106.93	36.03	531.97	22.04	49.31

4.2.3 Comparison with Local-Scale Model of Meyer et al. (2009)

For a previous modeling study, Meyer et al. (2009) developed a local-scale groundwater flow model covering the shallow subsurface of Kane County and adjacent townships. Since the highly-resolved portion of the regional flow model of this study (the Illinois portion of the Fox watershed) and the Kane County local-scale flow model are so similar, a reader familiar with both models may question the difference in model results (results published here and results published by Meyer et al., 2009). The authors devote this section of the report to comparing inputs to the two flow models. The comparison is summarized in Table 31.

As discussed in Section 4.2.2.1, the representation of the Quaternary Unit in the present regional groundwater flow model is most highly resolved, and therefore most accurate, within the Fox River watershed geologic mapping domain (Figure 20). This region was chosen specifically for shallow aquifer flow modeling because (1) highly-detailed geologic mapping information for the Quaternary Unit is not available across the entire domain of the present regional model (or even the 11-county study area); (2) detailed geologic mapping information for the Quaternary Unit within the Illinois portion of the Fox River watershed was largely available; and (3) the Fox River watershed generally encompasses the most rapidly growing area within the 11-county study area and is the most highly dependent on the Quaternary Unit aquifers within the 11 counties. The authors elected not to directly employ the local-scale model of Kane County for the present study, despite its use of highly-resolved Quaternary layers because (a) it would not provide results for the entire Fox River watershed, and (b) it would prove cumbersome to use in concert with additional modeling covering the remainder of the Fox watershed. For reasons further described below, the Kane County local-scale model and the regional-scale model of this study rely on different input data and, therefore, provide different results. The authors believe the Kane County local-scale model provides more precise simulations of shallow groundwater flow within its domain than the regional model of this study, and it could, with updated future pumping scenario data, provide more accurate results for Kane County than those included in the present study.

The geographic domains of the two flow models differ greatly, the model of this study covering much of the upper Midwest and the local-scale model of Meyer et al. (2009) covering only Kane County and adjacent townships of surrounding counties (Figure 47). The areas of greatest accuracy of the two models are much more similar, however, and they overlap to a great extent since most of Kane County lies within the Fox River watershed and, conversely, a large portion of the Fox River watershed is contained within Kane County.

For the area of overlap, the same shallow geological model was the basis for both flow models. This geological model was developed originally for Kane County (Dey et al., 2007) and was incorporated into the shallow geological model of the Illinois portion of the Fox watershed developed for the present study. The local-scale flow model of the Kane County area is more highly resolved, both horizontally and vertically, than the flow model developed for the present study, and principally for this reason the authors of the present report believe the Kane County local-scale flow model to be more accurate. The local-scale Kane County flow model employs square cells that measure 660 by 660 feet; whereas the flow model of the present study uses square cells that measure 2,500 by

Table 31. Comparison of Shallow Groundwater Modeling of Illinois Portion of the Fox River Watershed (This Study) with Local-Scale Model of Kane County Area (Meyer et al., 2009)

Model characteristic	*Present study*	*Kane County local-scale flow model (Meyer et al., 2009)*
Model domain (Figure 47)	Multiple-state area centered on northeastern Illinois	Kane County and bordering areas within about 6 miles of Kane County
Area of greatest accuracy for simulation of shallow groundwater flow (Figure 47)	Fox River watershed in Illinois	Kane County
Horizontal grid resolution	Maximum resolution Δx=2,500 feet, Δy=2,500 feet Minimum resolution Δx=20,000 feet, Δy=2,500 feet (Figure 48)	Δx=660 feet, Δy=660 feet
Vertical resolution	Quaternary represented by 5 layers	Quaternary represented by 14 layers
Geological modeling of area of greatest accuracy for simulation of shallow groundwater flow	The portion overlapping the Kane County local-scale model domain (Meyer et al., 2009) is based largely on the same geological model (Dey et al., 2007) used to develop the Kane County local-scale model	Developed by ISGS from borehole data, geophysical data, and previous analysis and mapping (Dey et al., 2007)
Simulation of boundary flow to/from area of greatest accuracy for simulation of shallow groundwater flow	Flows to/from the Illinois portion of the Fox watershed are integral to the regional model covering much of the upper Midwest. As such, flows to/from the area of greatest model accuracy reflect transient changes in pumping within the entire region.	Flows to/from Kane County are linked, using the approach of telescopic mesh refinement, to a separate regional model covering much of the upper Midwest.
Simulation of historical withdrawals	1864-2005	1964-2003
Simulation of future withdrawals (Figure 50)	2006-2050; three scenarios (BL, LRI, MRI) developed specifically for the 11-county study area by Dziegielewski and Chowdhury (2008)	2004-2050; two scenarios (low pumping, high pumping) developed from estimates for the entire Midwest by Dziegielewski et al. (2004, 2005)

2,500 feet (Figure 48) in its most highly-resolved area. This most highly-resolved part of the model occupies about 77 percent of the Illinois portion of the Fox River watershed; however, model cells of the present flow model increase to dimensions of 20,000 feet in the *x* direction and 2,500 feet in the *y* direction in the southwestern part of the Fox River watershed. On the basis of the larger cell size, the present model is presumed to be less accurate in this area. The vertical resolution of the Kane County local-scale flow model is also greater than the flow model of the present study. The Kane County local-scale flow model represents the Quaternary materials with 14 layers, whereas to reduce computational intensity, the flow model of the present study uses only 5 Quaternary layers.

The local-scale Kane County flow model depends on the approach of telescopic mesh refinement (TMR) to simulate the effects of pumping from outside its domain. This was necessary because, unlike the present flow model, the Kane County local-scale flow model is not contained within the larger regional flow model that simulated all other withdrawals within the larger model domain (as described earlier in Section 4.2.2.1, the regional flow model domains are the same). The TMR approach, as applied to the Kane County local-scale flow model, used 2002 fluxes computed from the regional-scale model developed for that project for model cells bordering the local-scale model domain, and applied these fluxes to cells of the local domain. By using TMR, the local model responded to regional pumping stresses outside of the local model domain.

Meyer et al. (2009) simulated markedly different scenarios of future pumping than those used in the present study. The scenarios simulated by Meyer et al. (2009) differ from those simulated in the present study because they rely on different statistical models of water use in the region, and the statistical modeling that is the basis of the scenarios modeled in the present study employs updated data. The scenarios employed by Meyer et al. (2009), based on estimates of future water developed by Dziegielweski et al. (2004, 2005), project significantly less water use in the 11-county region than even the LRI scenario of the present study (Figure 49). The high-pumping scenario of Meyer et al. (2009) projects total groundwater pumping of about 311 Mgd in the region in 2050, while the LRI, BL, and MRI scenarios of the present investigation project groundwater withdrawals of about 327, 424, and 532 Mgd, respectively, in 2050.

Figure 50 compares these scenarios only for withdrawals within the Kane County local model domain (i.e., the accounting only includes shallow withdrawals). The accounting in Figure 50 shows better agreement between the scenarios than does the accounting for the 11-county area shown in Figure 49, but readers should note that the withdrawal projections are not identical. Historical withdrawals are simulated in the Kane County local-scale model until 2003, but they are simulated in the model of the present study until 2005.

In summary, the Kane County local-scale flow model is more highly resolved and therefore should provide more accurate results within Kane County, but its use is more computationally intensive. Further, because it uses TMR, it is separated from the regional flow model, and fluxes between it and the regional model are not seamlessly integrated. Because of these differences, updated pumping scenarios (with higher withdrawals) have not been run on the Kane County model. The highly-resolved portion of the present flow model, on the other hand, is not as detailed (nor as accurate) as the Kane County model,

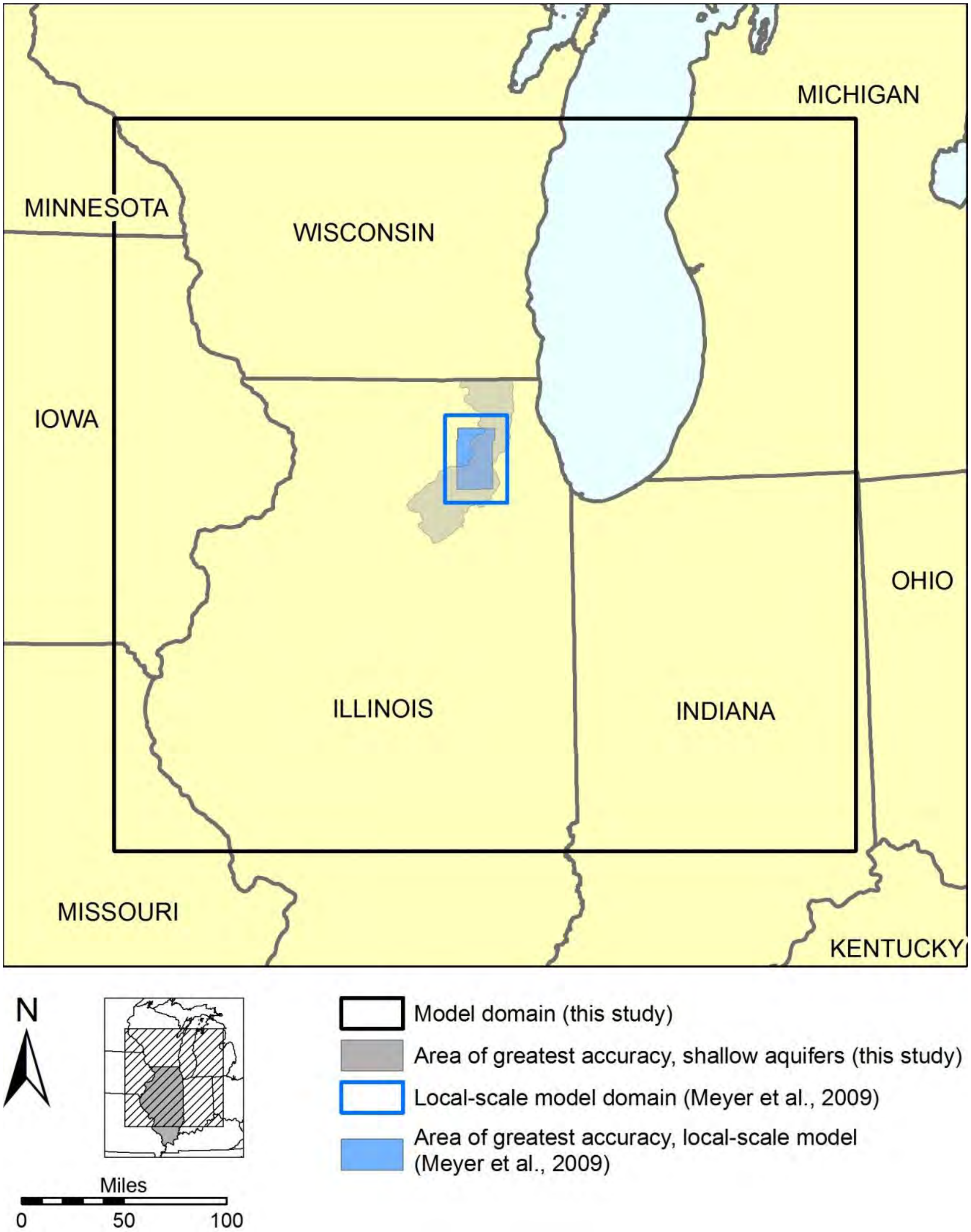


Figure 47. Model domains and areas of greatest model accuracy for the shallow aquifers for the model of the present study and the Kane County local-scale model of Meyer et al. (2009)

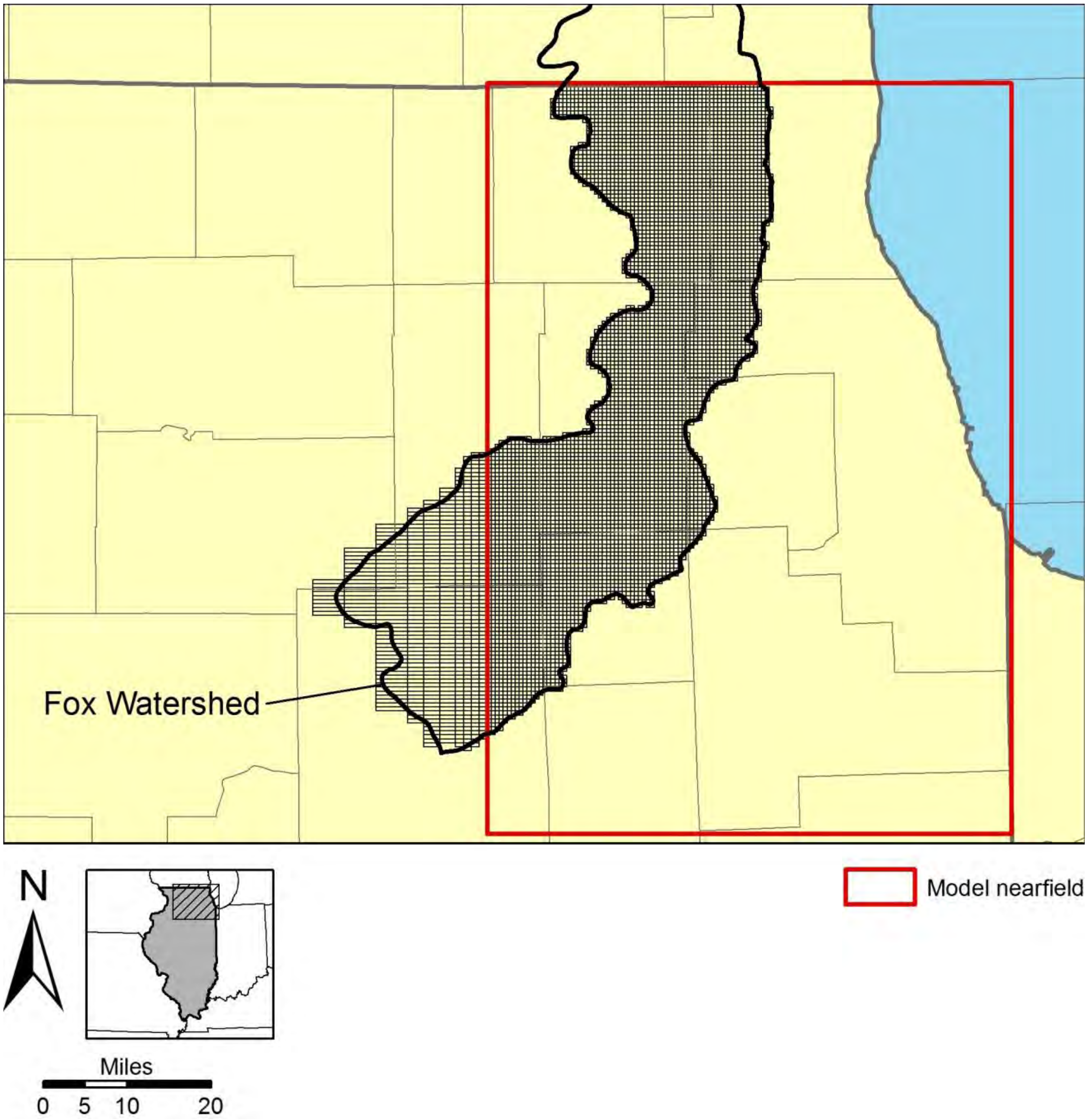


Figure 48. Model cells in the area of greatest model accuracy for the shallow aquifers, showing increasing cell size in the southwestern part of the Fox River watershed

but encompasses a larger area, is an integral part of the regional flow model, and includes updated future pumping scenarios developed specifically for this study.

4.2.4 Model Results

This section discusses results of model simulations of historical groundwater conditions and estimated future groundwater pumping conditions (demand scenarios). The modeling of historical conditions simulates pumping between 1864 (when large-scale pumping is considered to have begun in northeastern Illinois) and the present. It is a

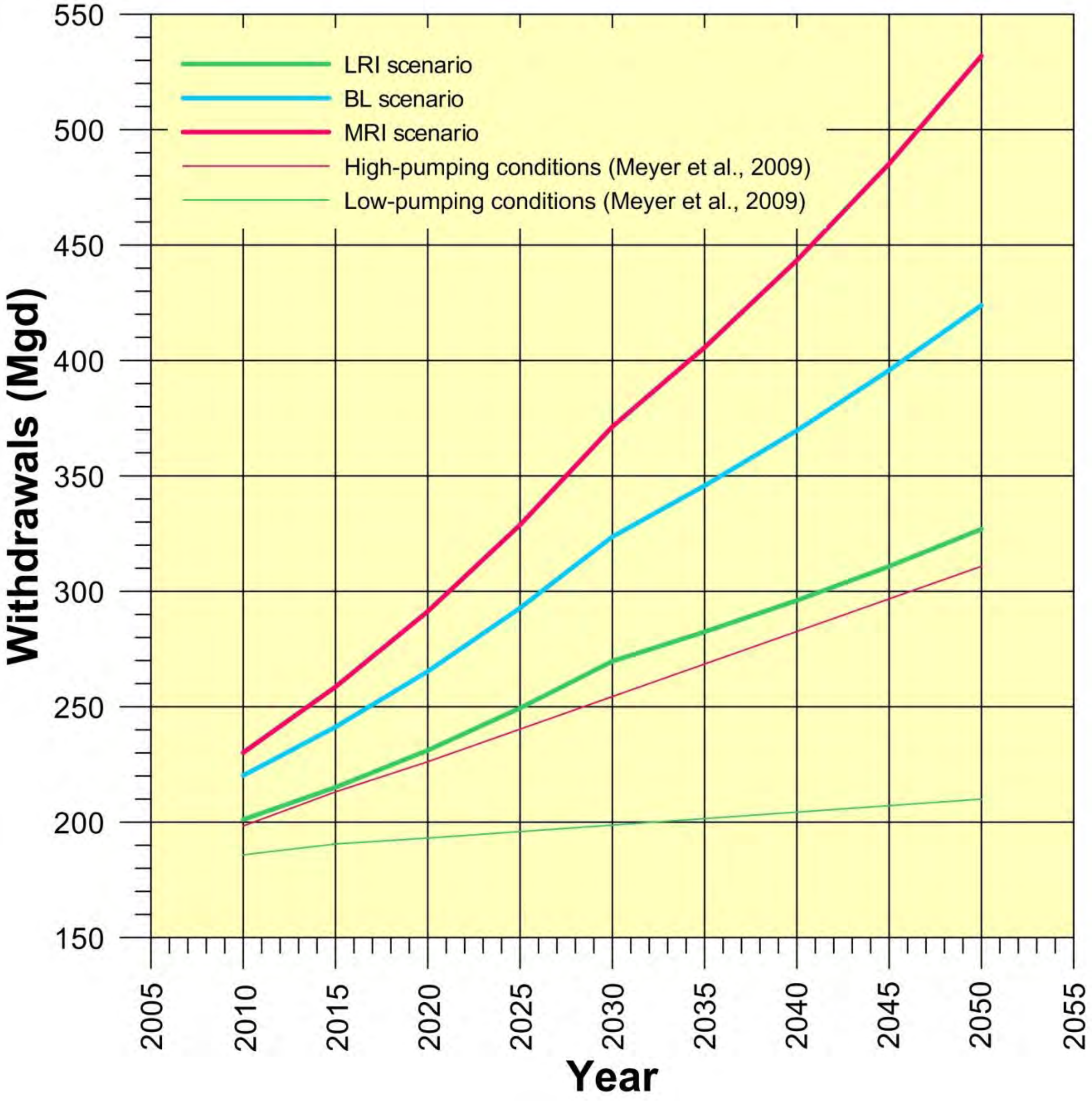


Figure 49. Scenarios of future groundwater withdrawals employed in this study and by Meyer et al. (2009) (plotted totals are for the 11-county northeastern Illinois area)

transient simulation in which pumping for each well represented in the model is varied annually. The locations of shallow and deep wells simulated in the model are shown in Figure 23 and Figure 24. Only the pumping rates of these are changed from year to year in the simulations; all other parameters remain constant through time. The simulations provide insight into the principal influences on groundwater flow in the region and permit characterization of past, present, and future pumping impacts.

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

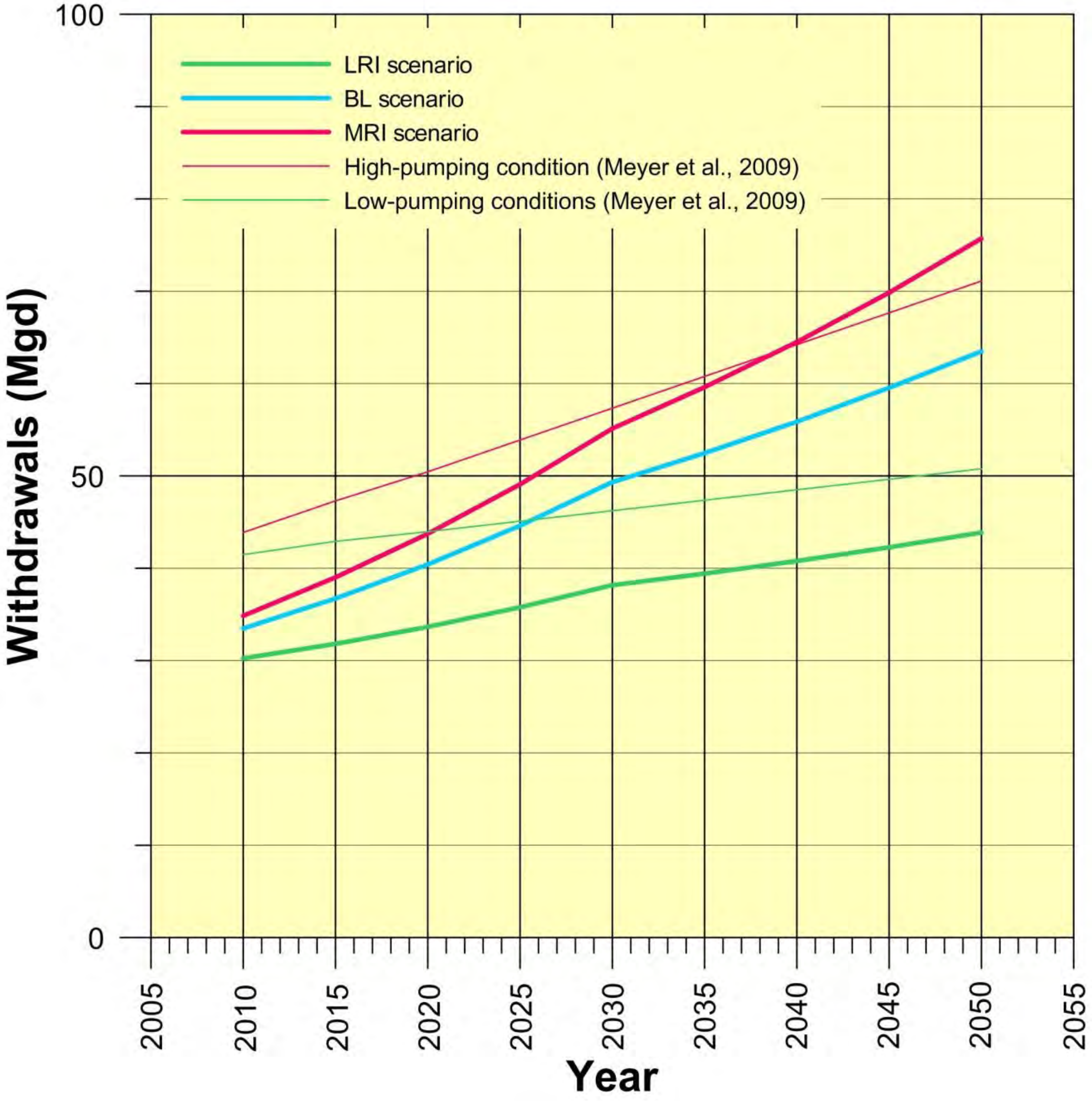


Figure 50. Scenarios of future groundwater withdrawals employed in this study and by Meyer et al. (2009) (plotted totals are for the Kane County local flow model domain)

- Simulated drawdown in the basal Quaternary deposits (model layer 5),
- Simulated drawdown in the Shallow Bedrock Aquifer (model layer 7),
- Simulated drawdown in the Ancell Unit (model layer 14),
- Simulated drawdown in the Ironton-Galesville Unit (model layer 17),
- Simulated available head above the top of the Ancell Unit,
- Simulated available head above the top of the Ironton-Galesville Unit,
- Temporal change in simulated heads (i.e., hydrographs of water levels), and
- Temporal change in natural groundwater discharge to streams.

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

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

Automatic termination of withdrawals can, to a limited degree, lead to unexpected and conflicting output. For example, termination of withdrawals due to desaturation under higher-pumping scenarios, with consequent head recovery, may lead to output that shows less drawdown under higher-pumping conditions than under lower-pumping conditions. However, the authors believe that such conflicting output affects only limited areas and limited periods of simulation. Output affected by automatic termination of withdrawals may reflect a computational cycle in which (1) a model cell/layer desaturates, (2) withdrawals from the desaturated cell/layer are turned off, (3) the model unit resaturates in response to cessation of withdrawals, (4) withdrawals are restarted, and (5) the model unit again desaturates, starting the cycle again. In some cases, this problem may be a result of assigning excessive pumping to an existing well location rather than spreading the added demand to new locations and source aquifers. In other cases, this problem may be a result of dividing a single aquifer unit into too many layers (e.g., as shown in Table 27, in this model the Silurian-Devonian Carbonate Unit is split into three layers, and drawdown cannot extend too deeply into a unit before withdrawals are curtailed). Investigation of the specific locations, wells, and timing of the automatic termination of simulated withdrawals is recommended for future analysis.

4.2.4.1 Model Analysis of the Shallow Aquifers

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

In general, transient simulations show that drawdown in the shallow aquifers is much more scattered and of lesser magnitude than in the deep aquifers in areas where the latter aquifers are confined by the relatively impermeable Maquoketa and Upper Bedrock

Units, which include all but the western edge of northeastern Illinois, principally in Boone, DeKalb, and Kendall Counties (see Figure 51 and Section 4.2.1.1). Simulated shallow aquifer drawdown in most of the Fox watershed area is less than 5 feet from 1985 to 2050 (Figure 52 to Figure 67). This difference is attributable to availability of replacement water to the aquifers (i.e., water entering the aquifers to replace groundwater withdrawn through wells). In northeastern Illinois, the relatively impermeable Maquoketa and Upper Bedrock Units, where present, greatly limit leakage into the deep aquifers from above, so replacement water for these aquifers is derived principally by slow, lateral movement from north-central Illinois where this relatively impermeable cover is absent.

In contrast, confining units above the bedrock are discontinuous and variable in thickness and permeability, and drawdown in the shallow aquifers is consequently reduced by higher rates of leakage into them. Higher leakage also reduces drawdown in the deep aquifers in areas lacking the relatively impermeable cover of the Maquoketa and Upper Bedrock Units. The authors emphasize that shallow aquitards have been mapped in detail only in limited portions of the Fox River watershed. For both the shallow and deep aquifers, some of the replacement water originates as captured streamflow, which is a consequence of (1) diversion of recharge into wells that would otherwise discharge to a stream and (2) leakage of water from stream channels in response to pumping. Although streamflow capture generally reduces drawdown, the reduced drawdown comes at the cost of diminished groundwater discharge to streams.

Figure 52 and Figure 53 show drawdown in the lowermost Quaternary layer (Quaternary Coarse-Grained Unit 2) and the Shallow Bedrock Aquifer within the Fox River watershed at the end of the 1985 irrigation season. Of most significance is a relatively broad cone of depression in both aquifers in central DuPage and northwestern Cook Counties. This is a result of withdrawals principally from the Shallow Bedrock Aquifer, which cause heads to decline both in the Shallow Bedrock and in the overlying, hydraulically connected Quaternary sand and gravel aquifers. Another cone of depression (30–40 feet deep) is evident in the shallow aquifers at Woodstock (central McHenry County), and smaller cones are present in the vicinity of South Elgin and St. Charles (east-central Kane County).

Owing to Lake Michigan allocations and resulting reduction in groundwater pumping that occurred in the late 1980s and early 1990s, by 2005 the broad cone of depression in DuPage and Cook Counties has disappeared (Figure 54 and Figure 55). In 2005, areas of significant shallow aquifer drawdown within the Fox River watershed cover large areas of northeastern Kane County and southeastern McHenry County. These are a collective response to pumping of wells operated by the Villages of Algonquin, Carpentersville, East Dundee, Lake in the Hills, and the City of Crystal Lake. The most severe drawdown in this area exceeds 50 feet and occurs in the Crystal Lake area. Less drawdown, from 30 to 50 feet, occurs at Woodstock, Algonquin, and Carpentersville. Widespread drawdown does not appear in the Crystal Lake, Algonquin, and Carpentersville areas in the simulation of 1985 conditions. Increasing drawdown also appears at South Elgin and along a St. Charles-Geneva-Batavia corridor. Another shallow, but broad, cone of depression appears in the basal Quaternary sand and gravel aquifer in south central DeKalb County. In 2005, this cone appears essentially unchanged from 1985, and in all future demand scenarios as well. It is probably a result of a

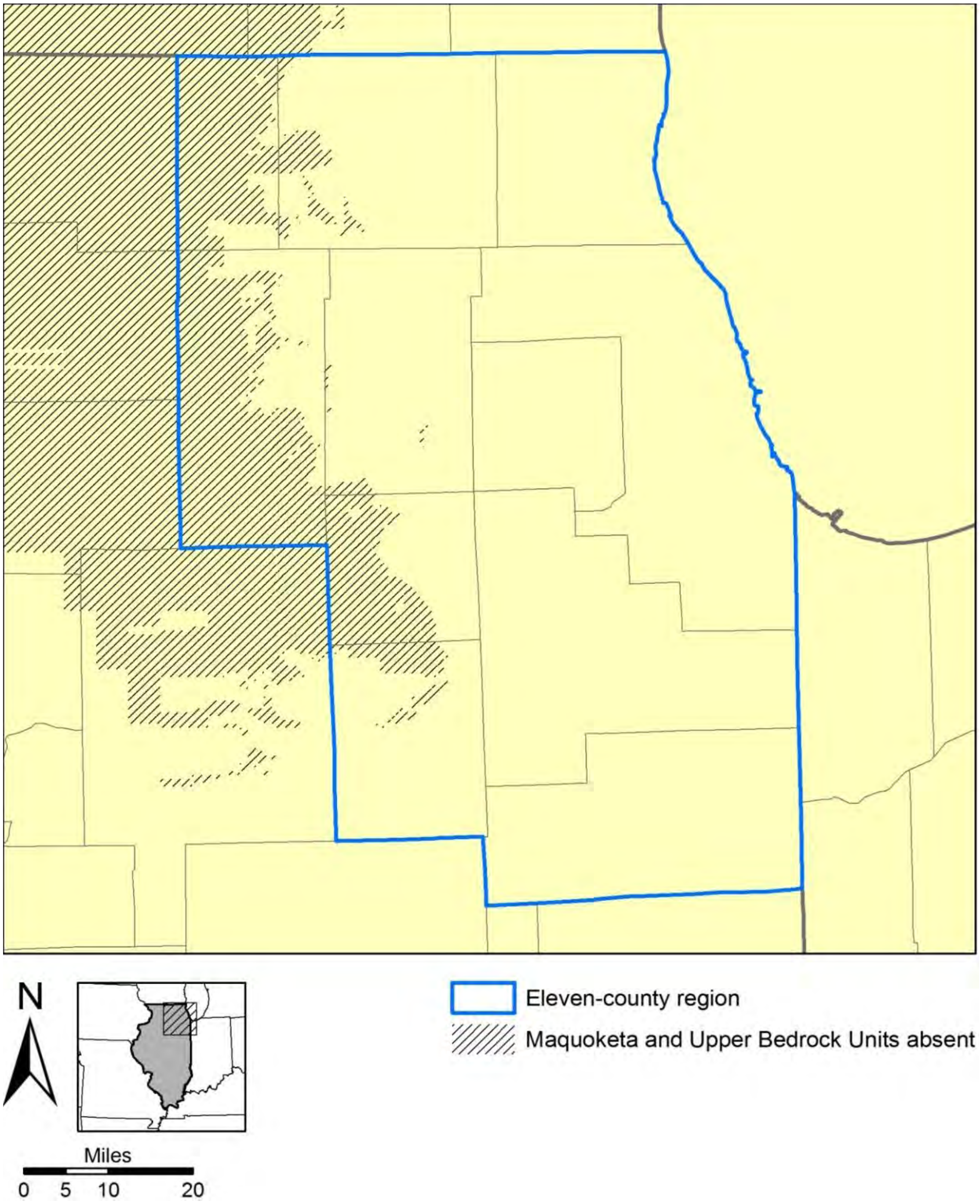


Figure 51. Area of absence of Maquoketa and Upper Bedrock Units, which together form the principal confining unit overlying the deep aquifers in the northeastern Illinois region

commercial facility pumping from so-called “deep” bedrock aquifers that, in this area, are located immediately beneath the Quaternary. Note that our convention in this report is to refer to these units, despite their shallow position in southern DeKalb County, as *deep*

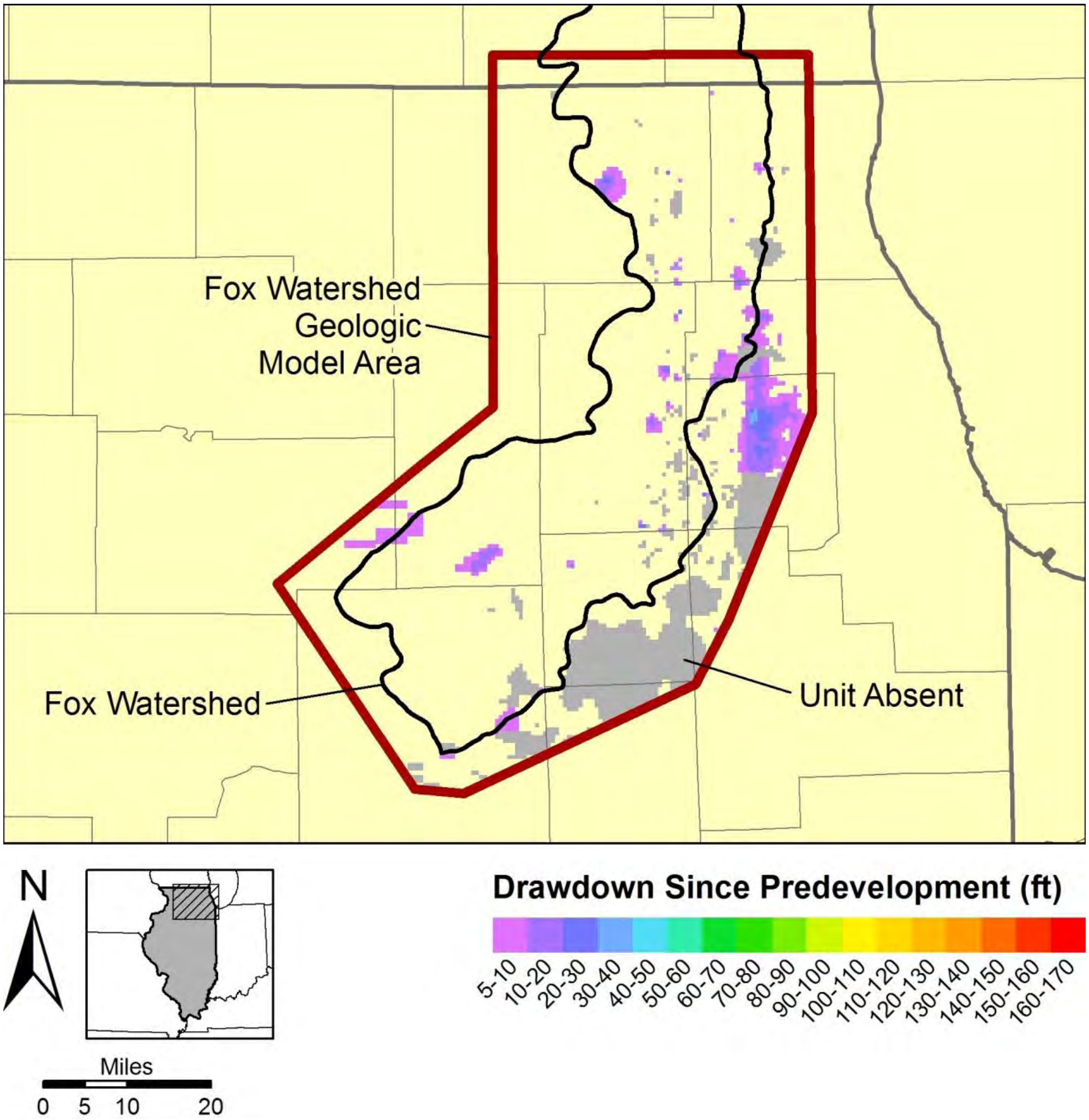


Figure 52. Drawdown in Quaternary Coarse-Grained Unit 2 in the Fox Watershed Geologic Model Area at the end of the 1985 summer irrigation season

aquifers (Section 4.2.1.1).

Simulations of future pumping scenarios suggest that areas of significant shallow aquifer drawdown present in 2005 (Figure 54 and Figure 55) will expand and deepen by 2025 (Figure 56 to Figure 61) and continue to do so to 2050 (Figure 62 to Figure 67), depending upon the demand scenario. These include the previously mentioned Woodstock (40–50 feet drawdown deepening to 70–80 feet), southeastern McHenry-northeastern Kane County (e.g., Crystal Lake , 120 feet drawdown, deepening to 135 feet; Algonquin, 100 feet drawdown, deepening to 150 feet), and South Elgin and St. Charles-Geneva-Batavia (20–30 feet drawdown, deepening to 40–50 feet) areas. In the

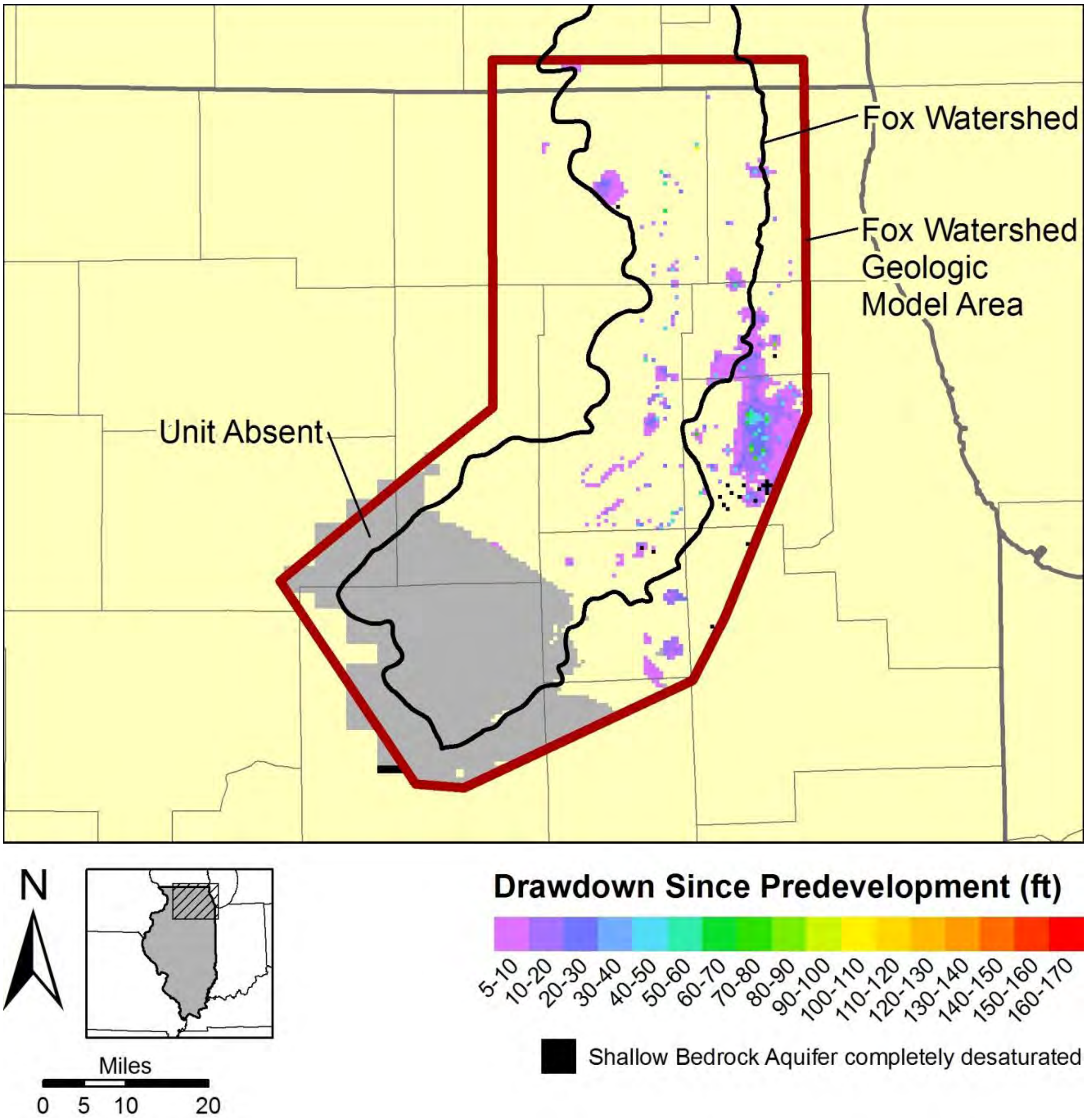


Figure 1. Drawdown in the Shallow Bedrock Aquifer in the Fox Watershed Geologic Model Area at the end of the 1985 summer irrigation season

2025 BL and MRI scenarios and all 2050 scenarios, a small cone is present at Plano in northwestern Kendall County.

Drawdown may also be shown in plots of head vs. time, or hydrographs; locations of simulated hydrographs are shown in Figure 68. Figure 69, for example, is a hydrograph illustrating simulated heads at Crystal Lake, an area where the model suggests significant shallow aquifer drawdown. The figure shows simulated historical heads and simulated future heads in the coarse-grained layer at the base of the Quaternary

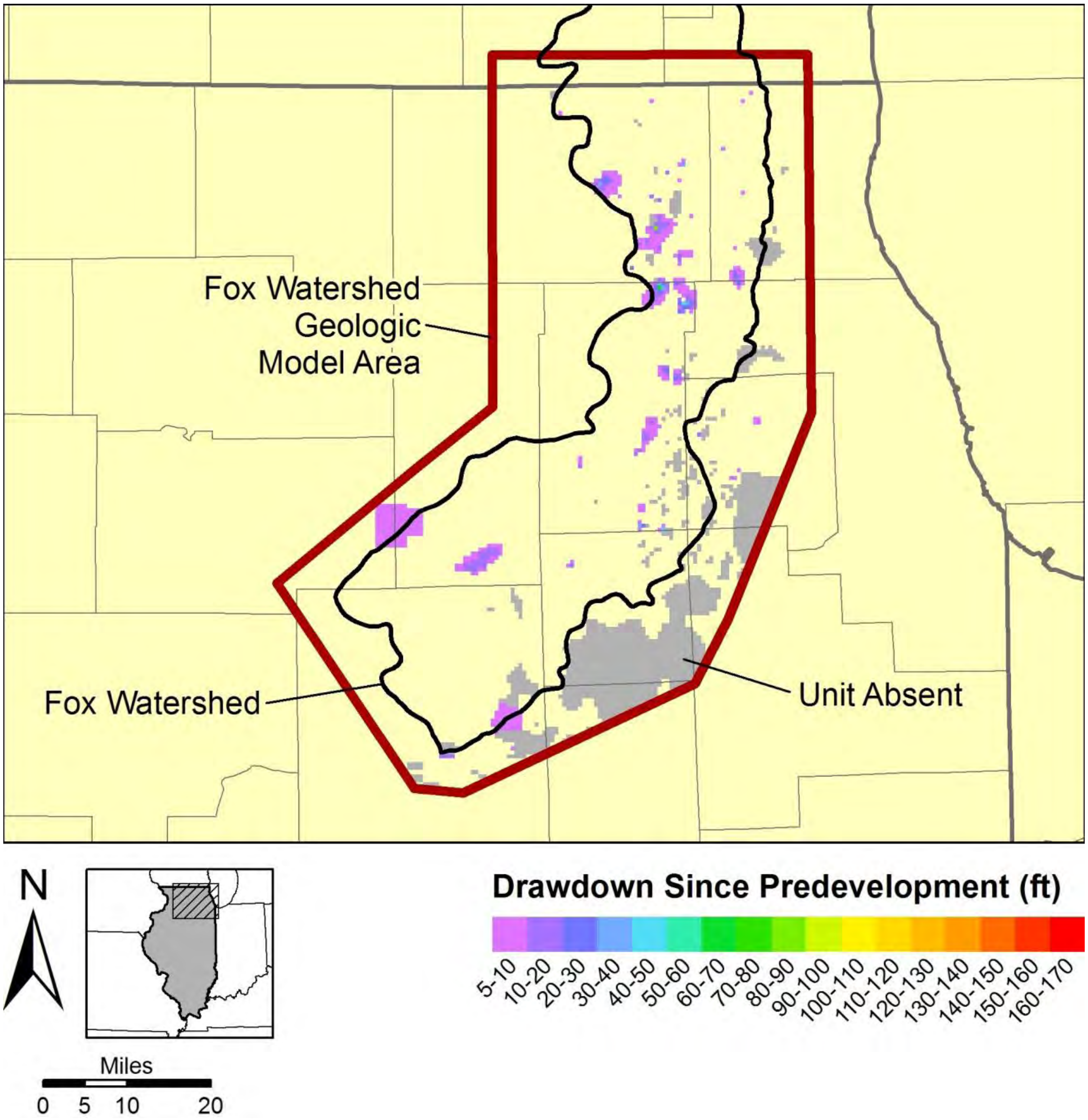


Figure 54. Drawdown in Quaternary Coarse-Grained Unit 2 in the Fox Watershed Geologic Model Area at the end of the 2005 summer irrigation season

(model layer 5) for each of the three demand scenarios introduced in Section 2.1.2 (LRI, BL, and MRI). A dashed horizontal line shows the approximate elevation of the top of the basal Quaternary layer at the hydrograph location and shows that the aquifer remains saturated at Crystal Lake through 2050 for all simulated pumping scenarios.

One engineering rule-of-thumb is to avoid drawing water levels below the aquifer top, converting groundwater conditions from confined to unconfined. In this situation, known as desaturation, air can come into contact with the groundwater and aquifer

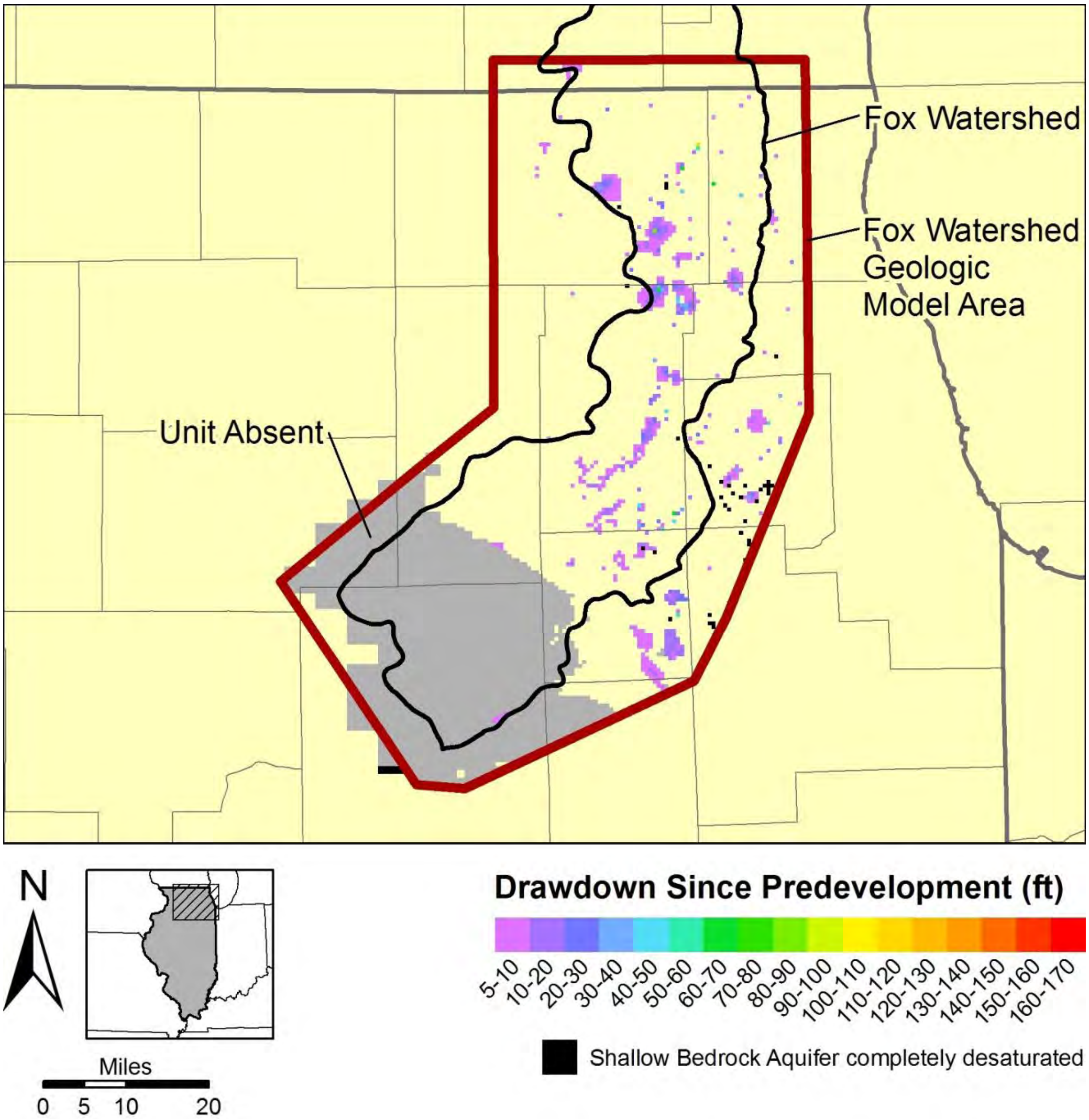


Figure 55. Drawdown in Shallow Bedrock Aquifer in the Fox Watershed Geologic Model Area at the end of the 2005 summer irrigation season

materials, resulting in precipitation of minerals that can clog well screens and reduce aquifer porosity. In most of the Fox watershed, simulated heads remain above the top of the aquifer to 2050, even under the MRI scenario, but in some areas of significant shallow aquifer drawdown, the model suggests that heads may decline below the top of the aquifer. In other areas, downward trends suggest that heads could fall below the top of the aquifer after 2050, especially under the BL and MRI scenarios, even if this critical horizon is not reached before 2050 (e.g., drawdown trend for MRI scenario in Figure 69).

While desaturation may not result in clogging of well screens and aquifers, being dependent on local conditions, a second, more universally applicable, rule-of-thumb

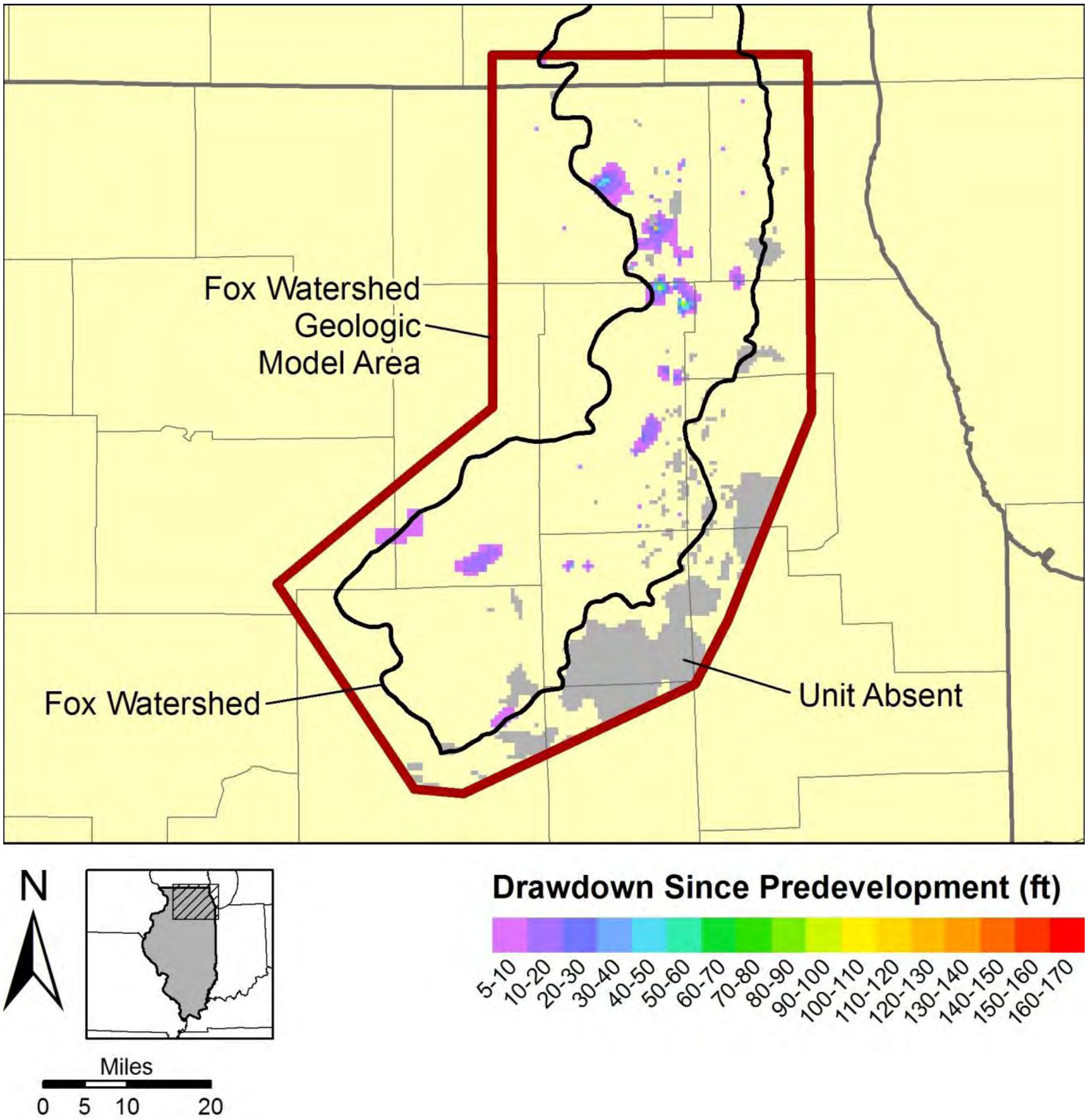


Figure 56. Drawdown in Quaternary Coarse-Grained Unit 2 in the Fox Watershed Geologic Model Area at the end of the 2025 summer irrigation season, BL scenario

instructs well operators to avoid dewatering more than one-third of the aquifer saturated thickness. Exceeding that limitation significantly reduces the transmissivity of the aquifer and causes drawdown to disproportionately increase.

Readers may question the value of the simulated shallow head estimates in view of the fact that the authors estimate shallow head calibration target uncertainty and model uncertainty at ±68 feet (Section 4.2.2.2). First, however, the exercise of identifying the available data and synthesizing a model from them permits identification of data shortcomings and formulation of strategies for addressing them, testing a conceptual

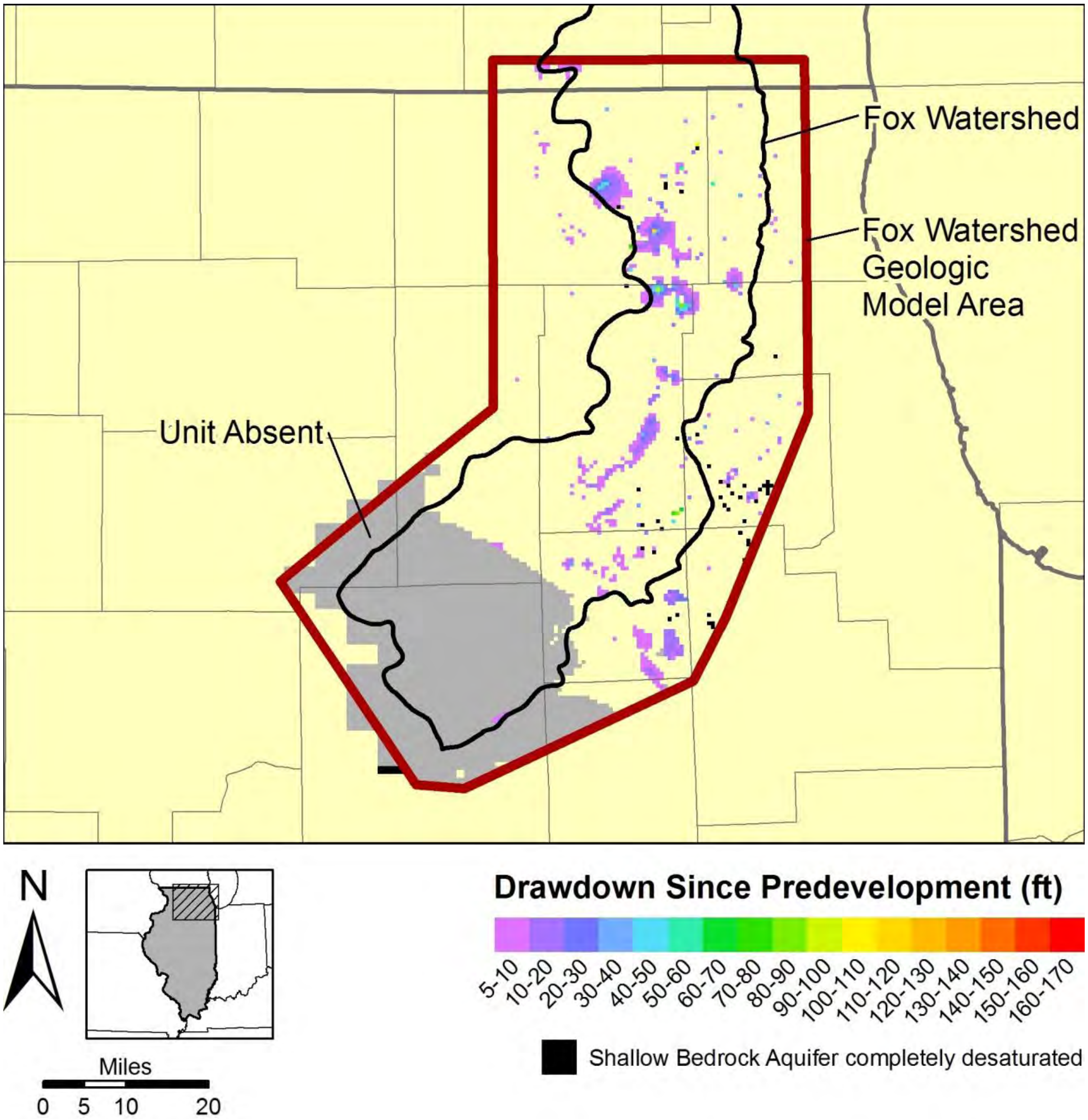


Figure 57. Drawdown in Shallow Bedrock Aquifer in the Fox Watershed Geologic Model Area at the end of the 2025 summer irrigation season, BL scenario

model of groundwater flow, and establishment of a modeling framework for future analysis. Second, the magnitudes and spatial distribution of the simulated head, despite uncertainty, represent a best guess of historical and future heads and as such are of value as a screening tool illustrating likely areas of unacceptable head decline.

The calibration target uncertainty estimation process shows that about 98 percent of the shallow head calibration target variance is a consequence of unmodeled heterogeneity, a component of error that may be reduced significantly by improving the database of pumping test results and other data that are the basis for model representation of hydraulic conductivity. The superior shallow head target uncertainty of the local-scale

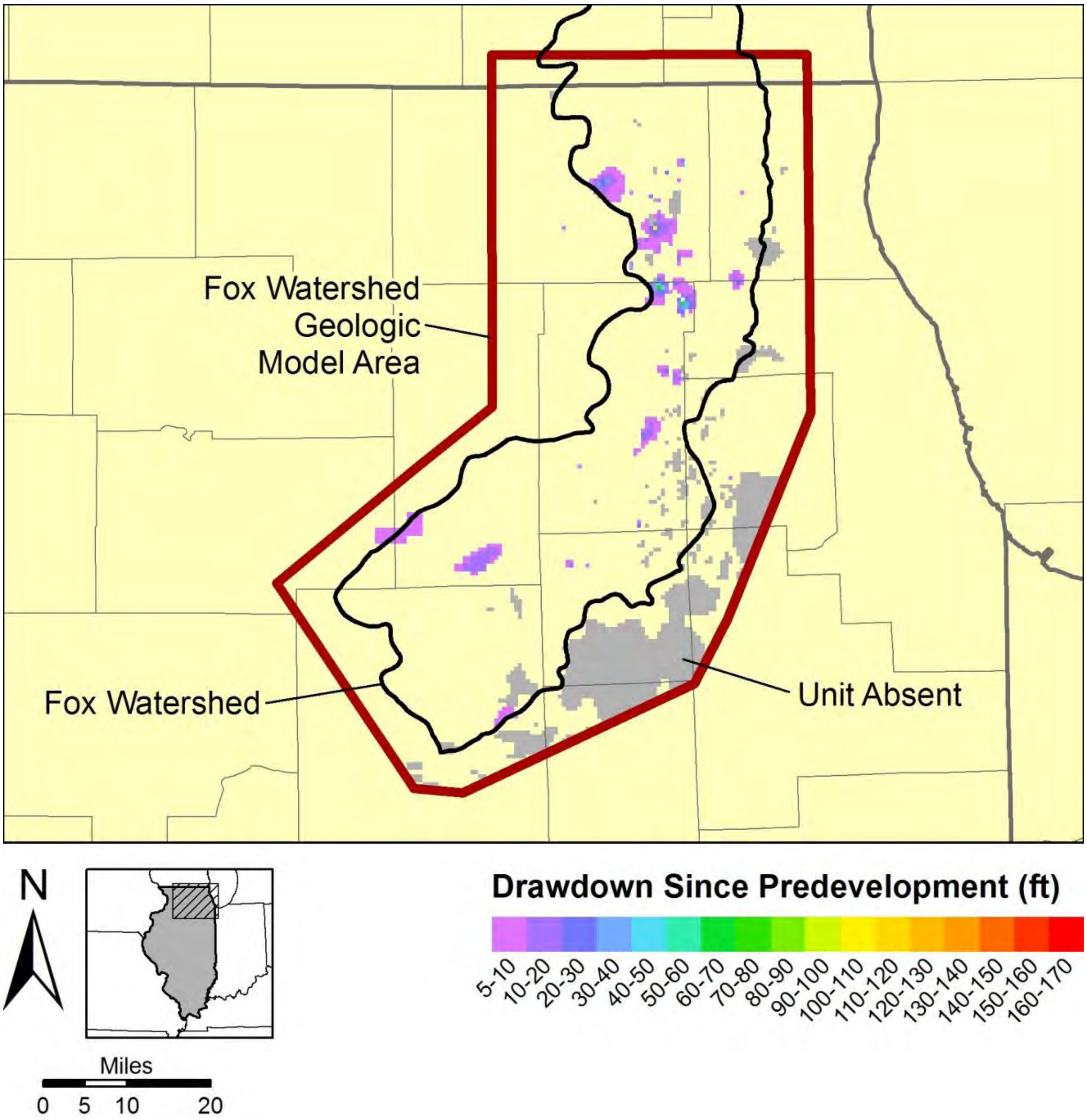


Figure 58. Drawdown in Quaternary Coarse-Grained Unit 2 in the Fox Watershed Geologic Model Area at the end of the 2025 summer irrigation season, LRI scenario

model developed for Kane County, estimated by Meyer et al. (2009) at ±29 feet, is almost exclusively a reflection of the improved characterization of heterogeneity featured by that model. Such areas might be targets for monitoring, more detailed study, and/or specialized management.

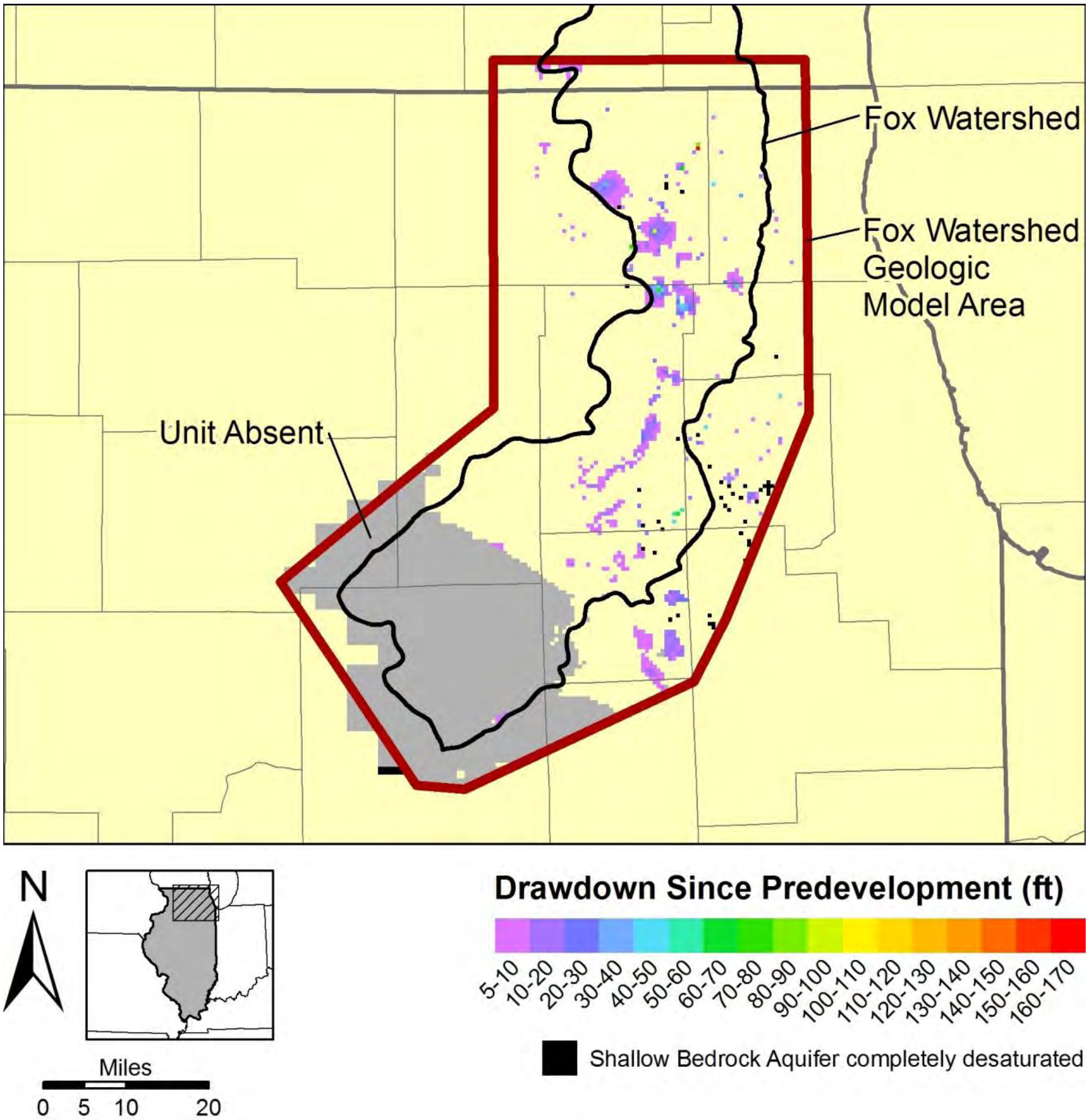


Figure 59. Drawdown in Shallow Bedrock Aquifer in the Fox Watershed Geologic Model Area at the end of the 2025 summer irrigation season, LRI scenario

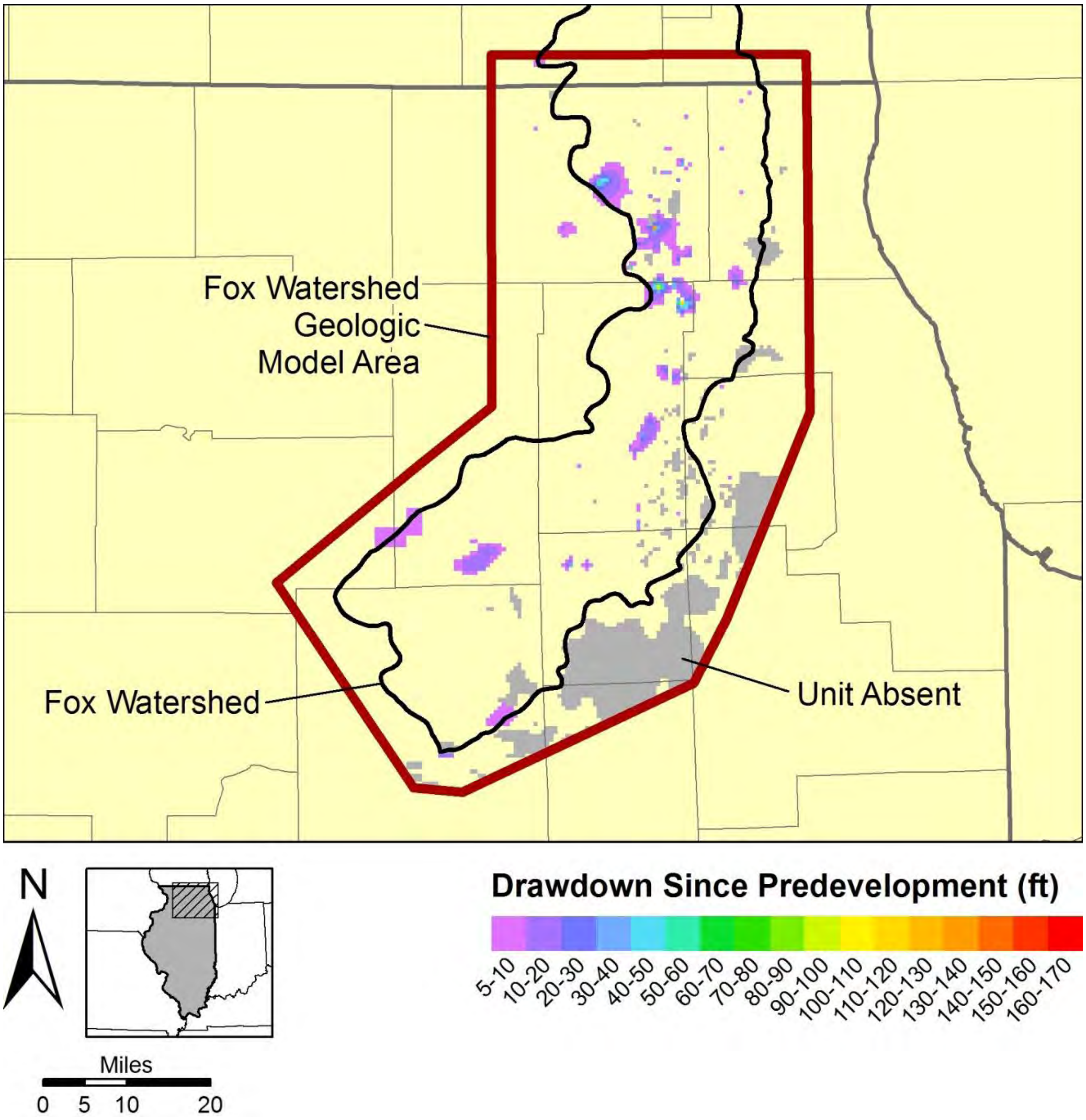


Figure 60. Drawdown in Quaternary Coarse-Grained Unit 2 in the Fox Watershed Geologic Model Area at the end of the 2025 summer irrigation season, MRI scenario

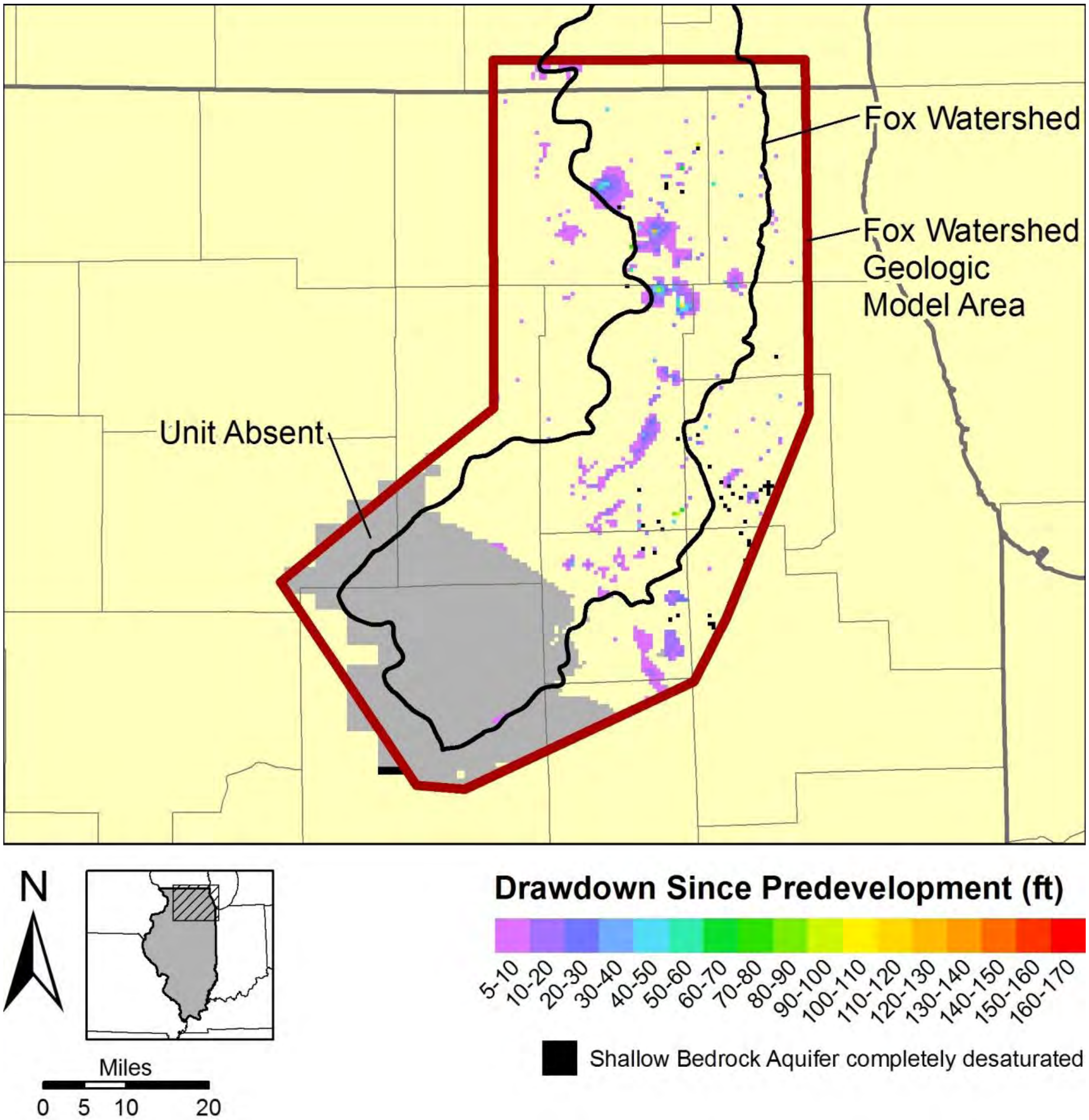


Figure 61. Drawdown in Shallow Bedrock Aquifer in the Fox Watershed Geologic Model Area at the end of the 2025 summer irrigation season, MRI scenario

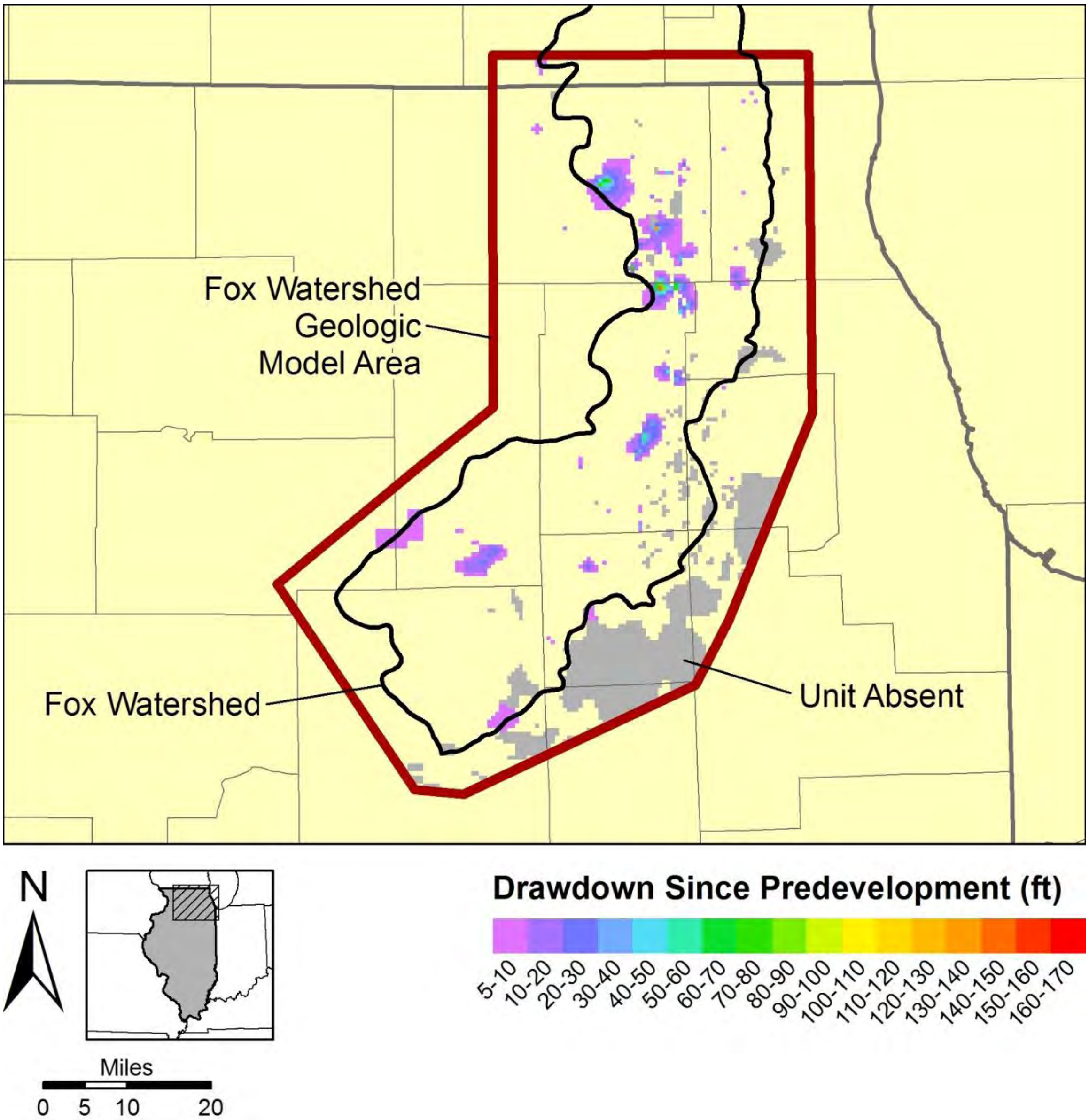


Figure 62. Drawdown in Quaternary Coarse-Grained Unit 2 in the Fox Watershed Geologic Model Area at the end of the 2050 summer irrigation season, BL scenario

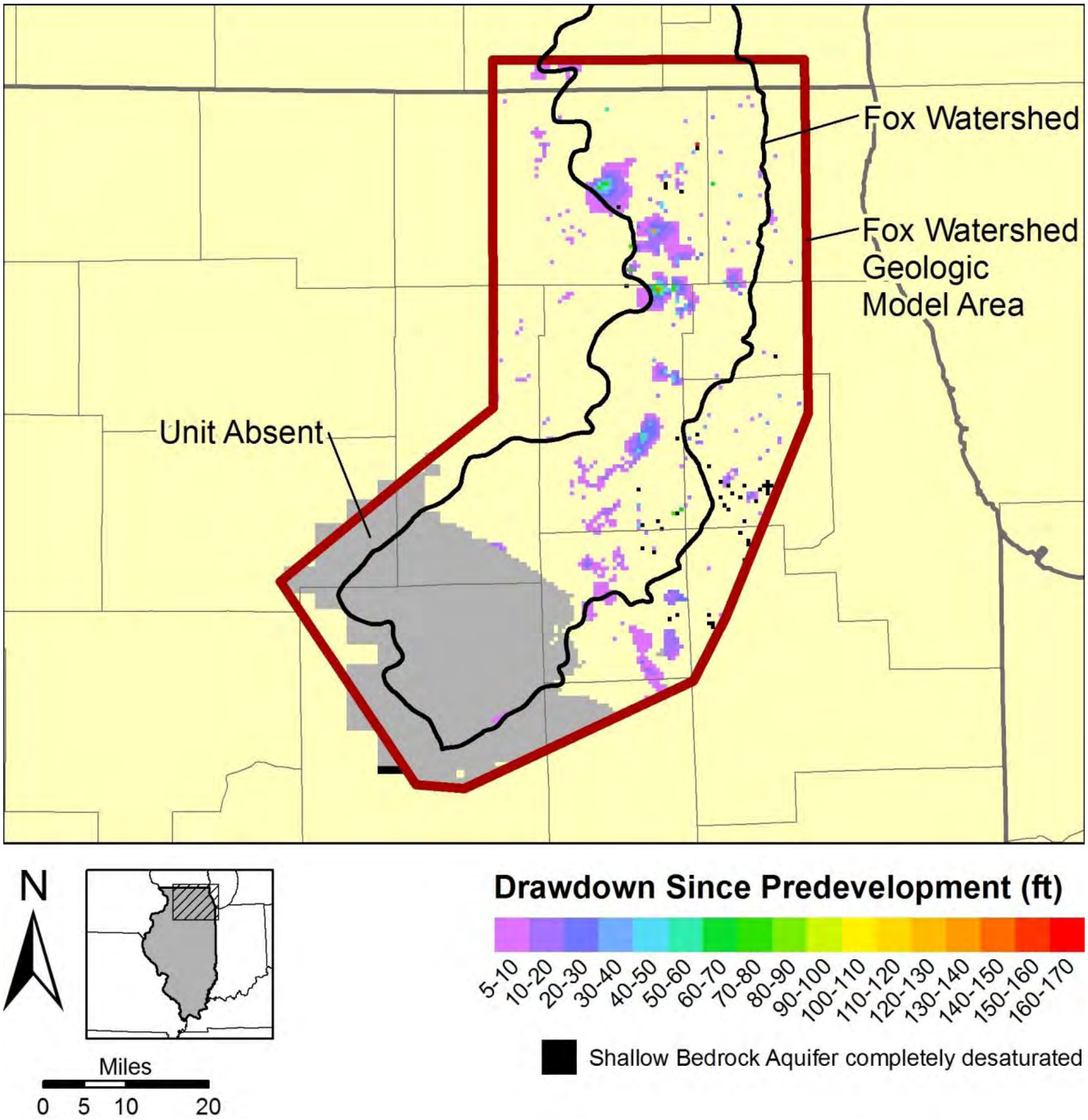


Figure 63. Drawdown in Shallow Bedrock Aquifer in the Fox Watershed Geologic Model Area at the end of the 2050 summer irrigation season, BL scenario

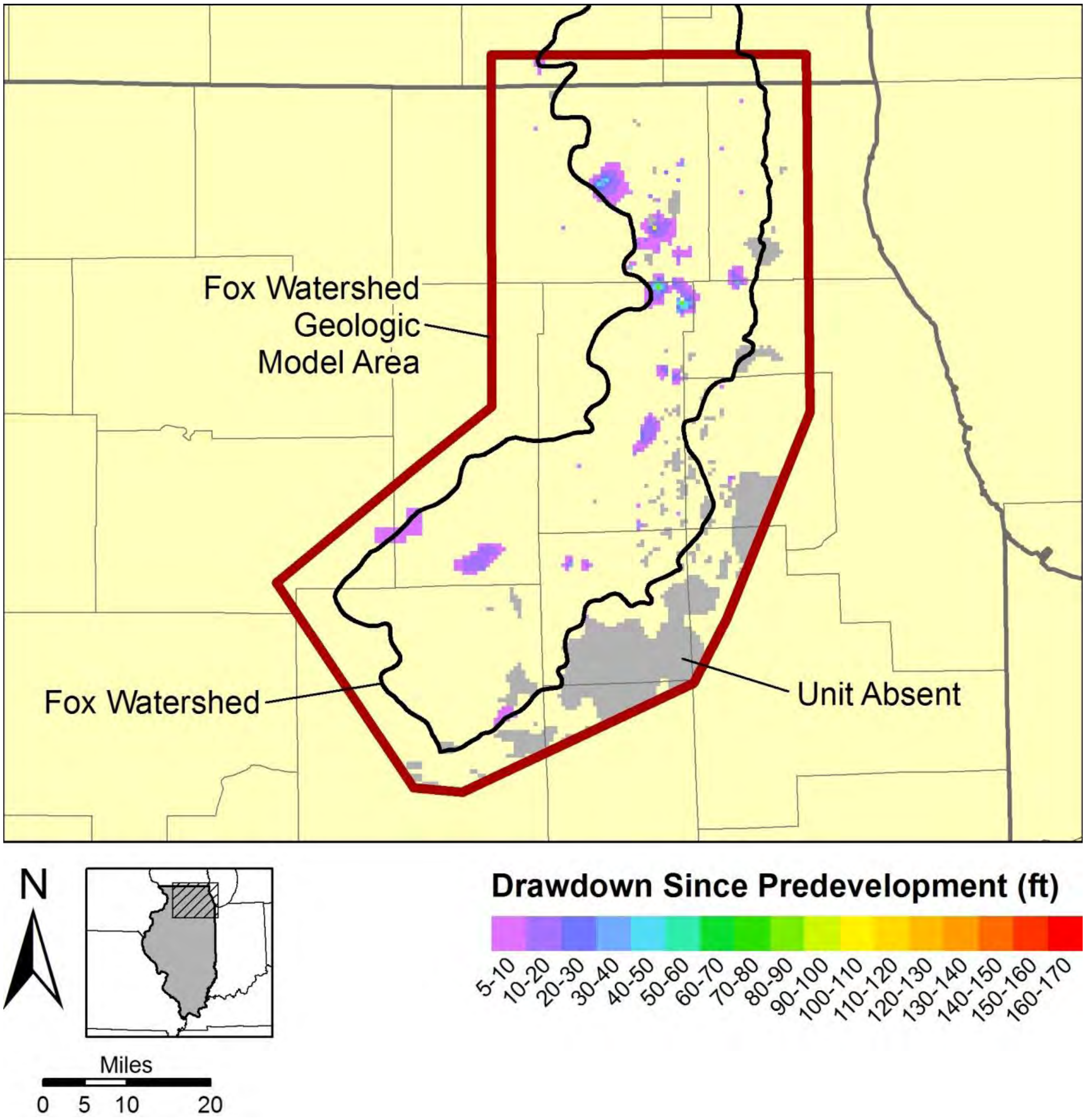


Figure 64. Drawdown in Quaternary Coarse-Grained Unit 2 in the Fox Watershed Geologic Model Area at the end of the 2050 summer irrigation season, LRI scenario

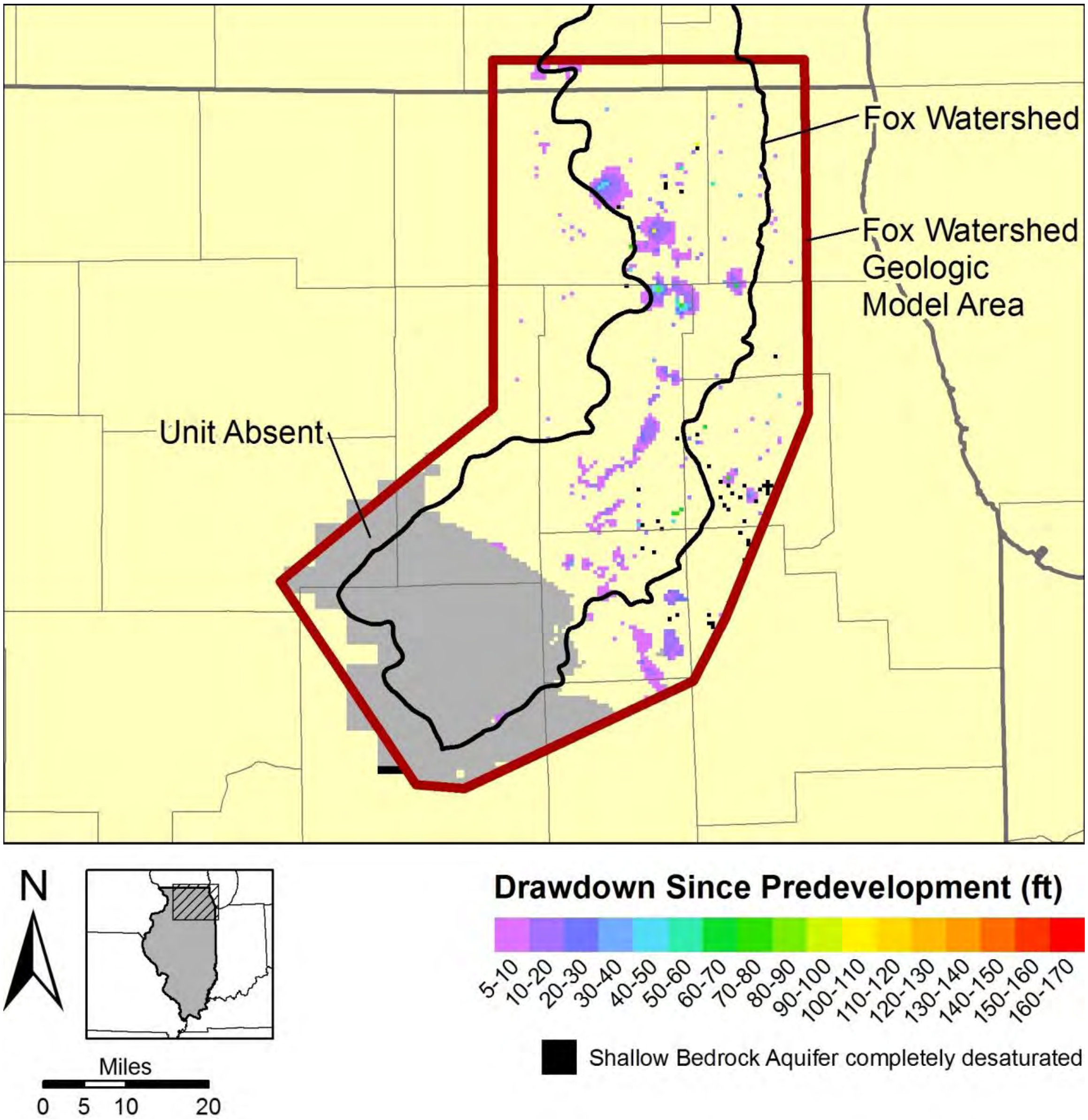


Figure 65. Drawdown in Shallow Bedrock Aquifer in the Fox Watershed Geologic Model Area at the end of the 2050 summer irrigation season, LRI scenario

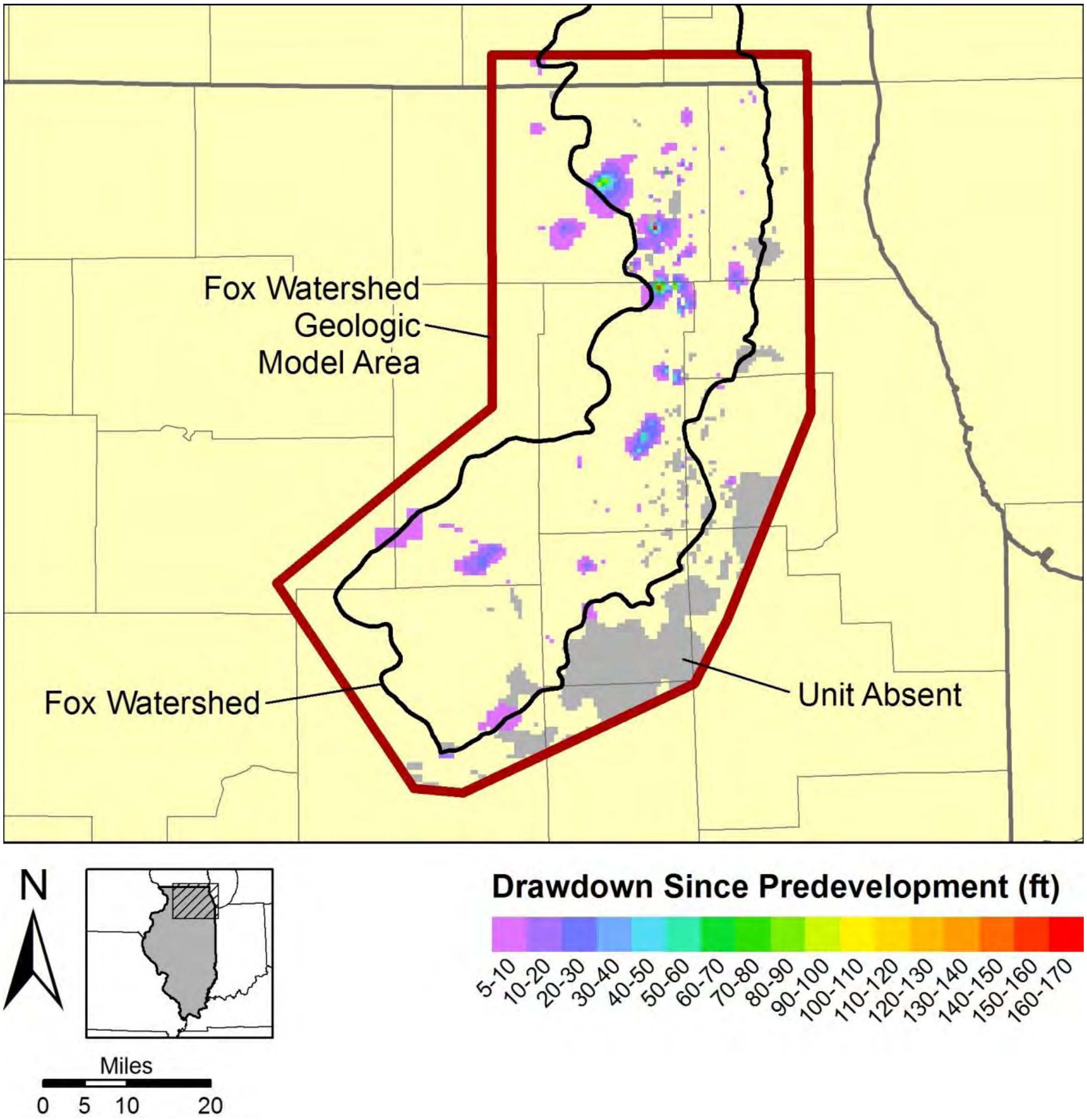


Figure 66. Drawdown in Quaternary Coarse-Grained Unit 2 in the Fox Watershed Geologic Model Area at the end of the 2050 summer irrigation season, MRI scenario

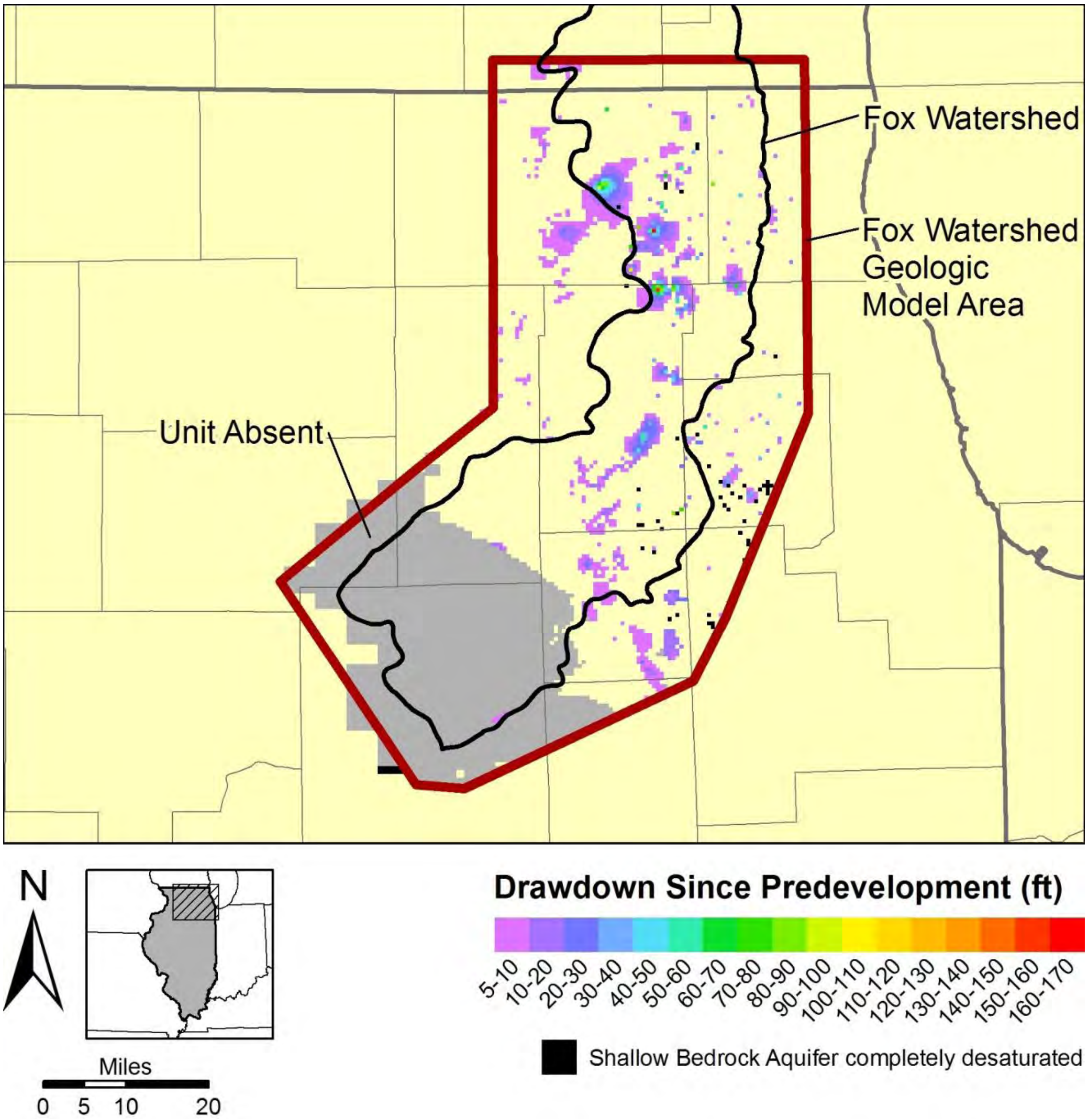


Figure 67. Drawdown in Shallow Bedrock Aquifer in the Fox Watershed Geologic Model Area at the end of the 2050 summer irrigation season, MRI scenario

Figure 68. Locations of simulated hydrographs shown in this report

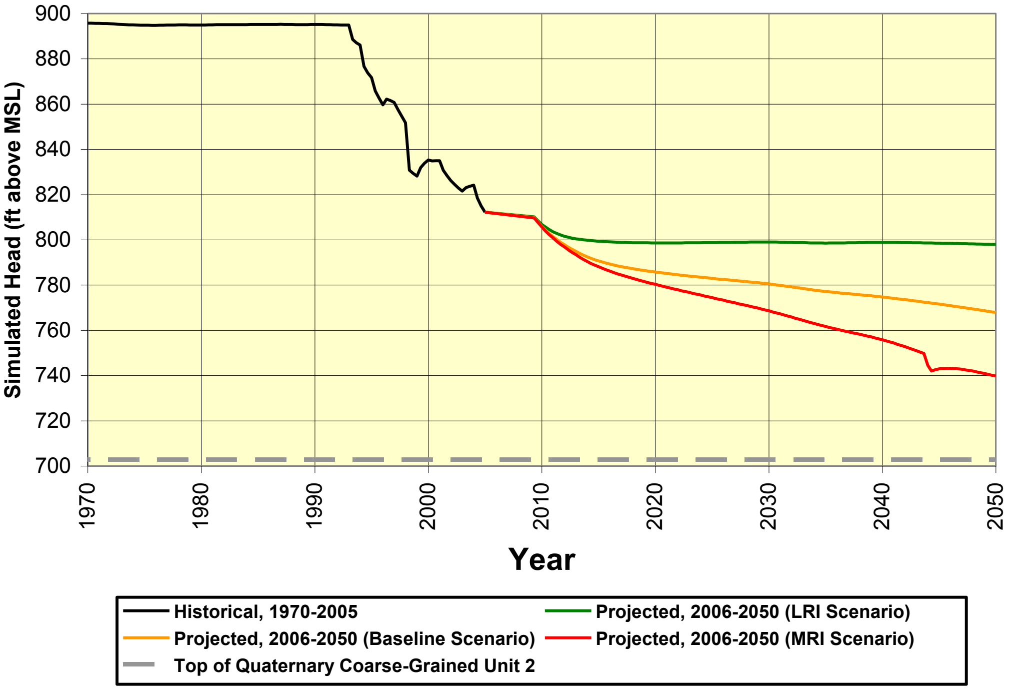


Figure 69. Simulated heads in Quaternary Coarse-Grained Unit 2 near the center of the Crystal Lake pumping center

4.2.4.2 Model Analysis of Natural Groundwater Discharge to Streams

Drawdown is reduced through capture of streamflow, so drawdown in the shallow aquifers, while significant in limited areas, is not as widespread as in the deep aquifers (see discussion in following sections). Although observational data have not actually shown such impacts, model simulations suggest that pumping from shallow wells with resultant capture of streamflow can significantly reduce natural groundwater discharge to streams (the source of stream base flow) in some areas. Streamflow capture occurs by two mechanisms: (1) by diversion into shallow wells of recharge that would otherwise discharge to streams, (2) by directly inducing streamflow to leak from stream channels. Model analysis suggests that natural groundwater discharge to streams in the Illinois portion of the Fox River basin declined from predevelopment rates by 8 and 10 percent in 1985 and 2005, respectively, reflecting increased pumping of shallow groundwater in the basin. These reductions are not evenly distributed across the Fox River watershed, however, because local hydrogeology and pumping are irregularly distributed. Results of analysis for pumping conditions in 1985 and 2005 for numerous Fox River watershed sub-basins (Figure 70) are shown in Table 32, Figure 71, and Figure 72. From pre-development (pre-1864) to 1985, simulated groundwater discharge to streams decreased from 2 to 33 percent (Figure 71). From pre-development to 2005 simulated groundwater discharge to streams decreased from 2 to 36 percent (Figure 72). In both 1985 and 2005, the greatest simulated reductions occurred in the Flint Creek sub-basin in northwestern Cook and southwestern Lake Counties, reflecting the reliance of the sub-basin on shallow

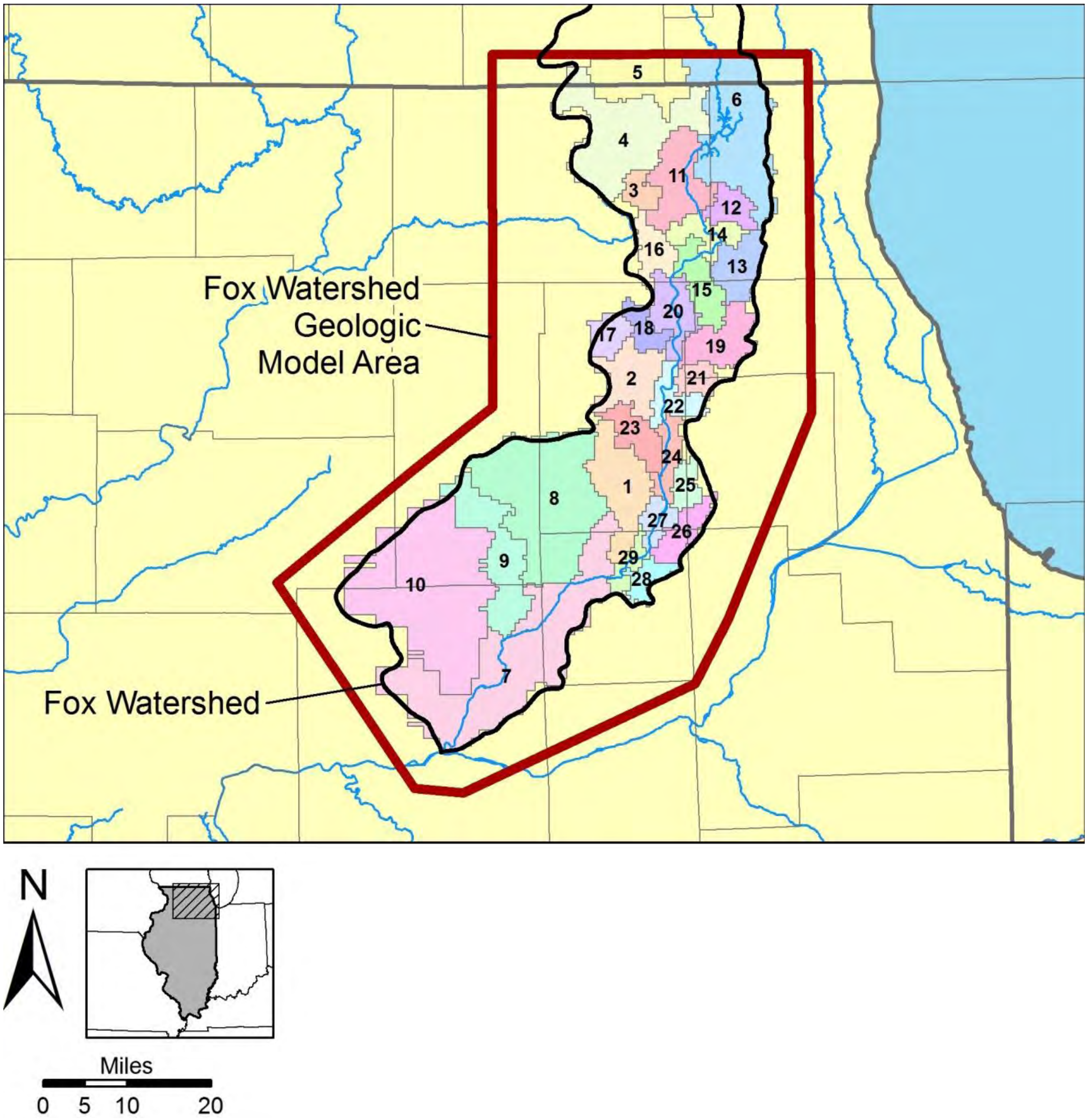


Figure 70. Fox watershed sub-basins used for accounting of natural groundwater discharge

groundwater for water supplies. Comparison of the 1985 and 2005 maps reflects the shift in public water systems in northwestern Cook County from locally-derived shallow groundwater to Lake Michigan as a water source. Simulated natural groundwater discharge to Brewster Creek and Poplar Creek was reduced by 13 and 31 percent in 1985, respectively, but the reductions fell to only 8 and 3 percent in 2005. Post-1985 increases in pumping of shallow groundwater accompanying suburban development are evident in the greater reduction of natural groundwater discharge in sub-basins in Kane and McHenry Counties, most notably those of Mill Creek and the Crystal Lake Outlet.

🟧	1 East Run-Blackberry Creek; Lake Run-Blackberry Creek
🟧	2 Otter Creek-Ferson Creek; Ferson Creek
🟧	3 Boone Creek
🟩	4 Town of Alden; Headwaters Nippersink Creek; Nippersink Creek; Carr Harrison Cemetery-Nippersink Creek; Greenwood-Nippersink Creek; Wonder Lake-Nippersink Creek; City of Woodstock
🟨	5 West Branch North Branch Nippersink Creek-North Branch Nippersink Creek; North Branch Nippersink Creek
🟦	6 Hoosier Creek; Spring Brook-Fox River; Palmer Creek-Fox River; Bassett Creek-Fox River; Channel Lake; Nippersink Lake-Fox River; Sequoit Creek; Pistakee Lake-Fox River; Squaw Creek; Headwaters Squaw Creek
🟥	7 Hollenback Creek-Fox River; Rob Roy Creek; Clear Creek-Fox River; Roods Creek-Fox River; Mission Creek-Fox River; Outlet Buck Creek; Headwaters Buck Creek; Brumbach Creek-Fox River; Goose Creek-Fox River
🟩	8 Squaw Grove-Little Rock Creek; Town of Sandwich-Little Rock Creek; West Branch Big Rock Creek; East Branch Big Rock Creek; Welch Creek; Headwaters Little Rock Creek; Big Rock Creek
🟩	9 Buck Creek-Somonauk Creek; Headwaters Somonauk Creek; Outlet Somonauk Creek; Parris Lake-Somonauk Creek
🟪	10 Town of Meridan; Sutphens Run; Town of Leland-Little Indian Creek; Little Indian Creek; Paw Paw Run-Indian Creek; Town of Shabbona-Little Indian Creek; Town of Rollo-Indian Creek; Crookedleg Creek; Earl Cemetery-Indian Creek
🟥	11 Griswold Lake-Fox River
🟪	12 Cotton Creek
🟦	13 Flint Creek
🟨	14 Cary Creek-Fox River
🟩	15 Spring Creek-Fox River
🟧	16 Crystal Lake Outlet
🟪	17 Headwaters Tyler Creek
🟦	18 Tyler Creek
🟥	19 Poplar Creek
🟪	20 Jelkes Creek-Fox River
🟥	21 Brewster Creek
🟦	22 Norton Creek-Fox River
🟥	23 Mill Creek
🟧	24 Town of Geneva-Fox River
🟩	25 Town of Aurora
🟪	26 Waubonsie Creek
🟦	27 Mastodon Lake-Fox River
🟦	28 Morgan Creek
🟩	29 Town of Oswego-Fox River

Figure 70. Fox watershed sub-basins used for accounting of natural groundwater discharge (Continued)

The results of a similar analysis completed for Kane County with a more detailed local model of the Kane County area (Meyer et al., 2009) show that by 2003, reductions in natural groundwater discharge to streams were much greater than that shown for 2005 with the regional model employed for the present study (Figure 72). For example, the detailed local model suggests a 68 percent reduction in groundwater discharge to Mill Creek upstream of Batavia, while this study's regional results suggest only a 33 percent reduction. This is probably a result of differences in model detail. The authors of the present study believe that the local Kane County flow model (Meyer et al., 2009), which is much more detailed, is more accurate than the model used in this study.

A comparison of the absolute base flow reductions with other streamflow data discussed in Section 4.1 shows the scale of these reductions. Average and low-flow effluent in the Fox River totaled 138 and 84 Mgd, respectively, in 2005 (Table 14). Total base flow reduction in the Illinois portion of the Fox watershed in 2005 is estimated at 61 Mgd (Table 32), 56 percent less than average effluent and 27 percent less than low-flow effluent. This comparison does not account for reduction in natural groundwater discharge due to pumping in Wisconsin (although regulation of Fox River flow by Stratton Dam may reduce or eliminate this effect), but it suggests that effluent more than compensates for the reduction in natural groundwater discharge due to pumping in the Fox watershed. This comparison does not address water quality differences between natural groundwater discharge and effluent, however, and it only considers the total estimated reduction of natural groundwater discharge with effluent at the mouth of the Fox River. With regard to the last point, since many wastewater treatment plants discharge effluent directly into the Fox River, tributary streams may be more severely affected by reductions in natural groundwater discharge than the mainstem Fox River. Reductions in base flow may also critically affect Fox River flow in reaches between a community's intake and effluent discharge point where flow is aberrantly low.

Modeling the effects of climate change (Section 4.1.4) provides another opportunity to understand the scale of the base flow reduction ascribed to groundwater pumping. The reduction due to pumping—estimated at 61 Mgd at the mouth of the Fox River in 2005— is comparable to the reduction in median simulated Fox River flow at Dayton (also near the mouth of the Fox River) caused by a 3ºF increase in temperature from 1971–2000 recorded values (78 Mgd) (see Scenario III results in Table 20). In other words, the modeling suggests the reduction in base flow at Dayton in 2005 is similar to the reduction that would occur given a 3ºF increase in temperature and *no* pumping of groundwater in the region. It is noteworthy that the simulated reduction in base flow is much less than the 292 Mgd simulated reduction in Fox River median flow at Dayton that occurred from 1931 to 1960, an unusually hot, dry period. Simulation of future pumping scenarios suggests that natural groundwater discharge in the Illinois portion of the Fox River basin could be reduced to rates that are 9 to 11 percent less than predevelopment rates in 2025 (Figure 73 to Figure 75, Table 33 to Table 35) and 10 to 14 percent less than predevelopment rates in 2050 (Figure 76 to Figure 78, Table 33 to Table 35). The pattern of reductions within the Fox River watershed resembles the 2005 pattern. The greatest reductions occur in the Crystal Lake Outlet sub-basin, where model simulations suggest reductions of 37 to 47 percent in 2025 and 40 to 62 percent in 2050, depending on the pumping scenario. Other significant reductions occur in the Mill Creek sub-basin, where model simulation suggests reductions of 32 to 41 percent in 2025 and 37 to 56 percent in 2050, and Flint Creek sub-basin, where reductions are estimated at 32 to 37 percent in 2025 and 41 to 50 percent in 2050.

The groundwater flow model results suggest that total reduction in base flow at the mouth of the Fox River will range from 59 to 70 Mgd in 2025 and 67 to 87 Mgd in 2050, depending on the scenario (Table 33 to Table 35). These totals are similar or less than total low-flow effluent in 2005 (84 Mgd), but they are much less than average effluent in 2005 (138 Mgd) (Table 14). The simulated base flow reduction does not account for reduction in base flow due to groundwater pumping in Wisconsin, but regulation of Fox River flow by Stratton Dam may reduce or eliminate this effect. Since effluent in the Fox River will increase as water withdrawals in the watershed increase (Section 4.1.3.7), the data suggest that effluent will more than compensate for reductions in base flow in the Fox River, but streamflow may be noticeably reduced in tributary streams upstream of effluent discharge points and in reaches of the Fox River between a community's intake and effluent discharge point. As mentioned previously, the authors did not explore potential effects of water quality differences between natural groundwater discharge and effluent on overall Fox River water quality.

Of the scenarios simulated to estimate climate variability effects on Fox River flow, the scale of the simulated base flow reductions most closely resembles the 78 Mgd reduction in median flow at Dayton resulting from a 3ºF increase in temperature from 1971 to 2000 recorded values (78 Mgd) (see Scenario III results in Table 20). In other words, the modeling suggests the reduction in base flow at Dayton in 2025 and 2050 is similar to the reduction that would occur given a 3ºF increase in temperature and *no* pumping of groundwater in the region. The simulated reductions are considerably less than the 292 Mgd simulated reduction in Fox River median flow at Dayton that occurred during the period from 1931 to 1960.

Given the approach employed to model groundwater discharge to streams and the scarcity of available observations of historical streamflow, verification of the reductions in streamflow suggested by the model is a fruitful area for future study. The simulated reductions in groundwater discharge suggested by the modeling of this study are both annualized and aggregated along stream reaches. As such, they may not be observable or easily recognized at specific points along a stream or during all periods of the year. Further, model calibration was based on estimates of average annual groundwater discharge (based on the mean of Q_{50} and Q_{80}), not groundwater discharge under low flow, or drought, conditions (e.g., $Q_{7,10}$). Therefore, the discharge reductions presented in Figure 71 to Figure 78 (and Table 32 to Table 35) may not reflect reductions under low flow conditions.

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

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

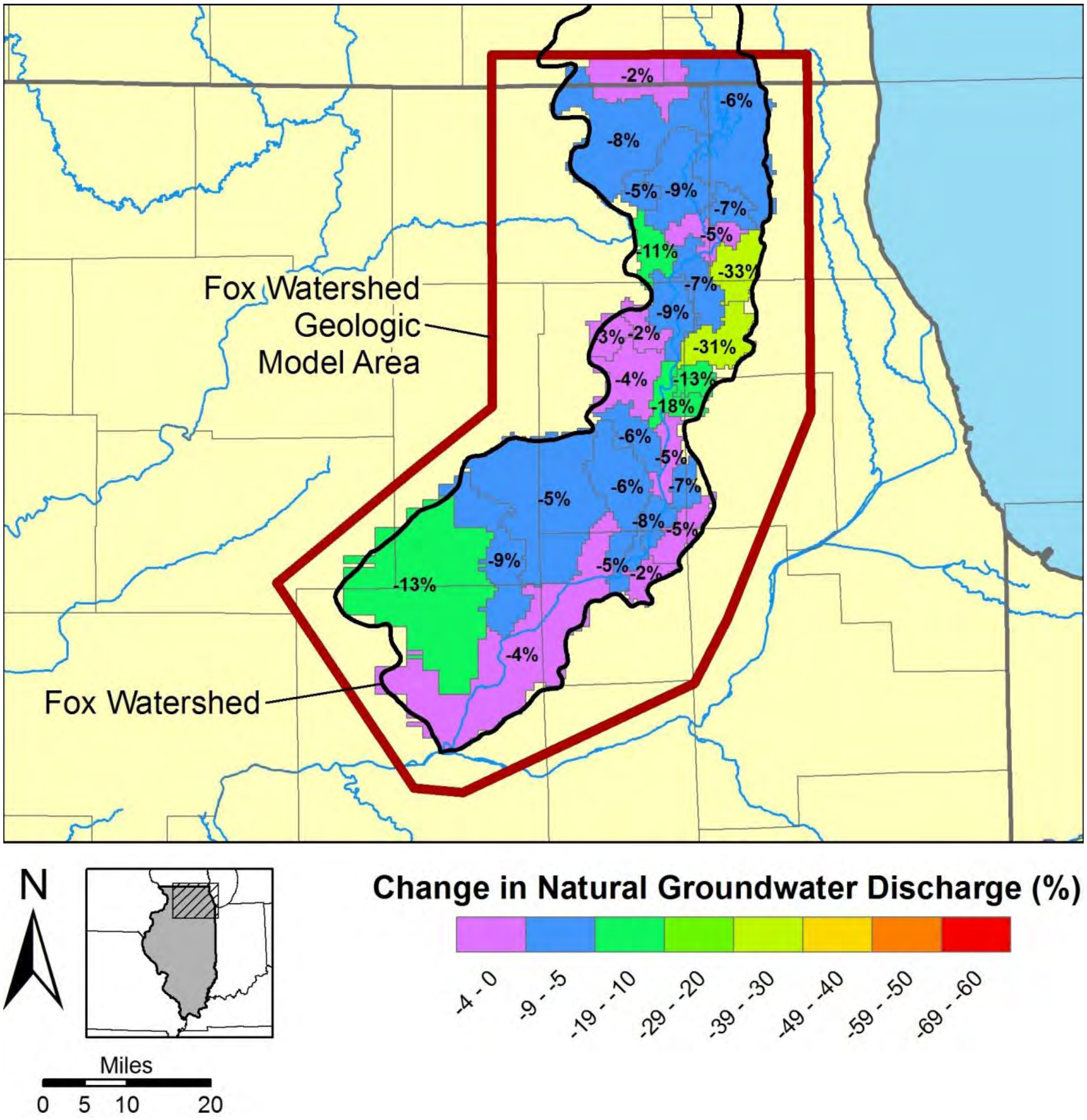


Figure 71. Change in natural groundwater discharge (pre-development to 1985) in the Fox watershed caused by pumping, by stream reach

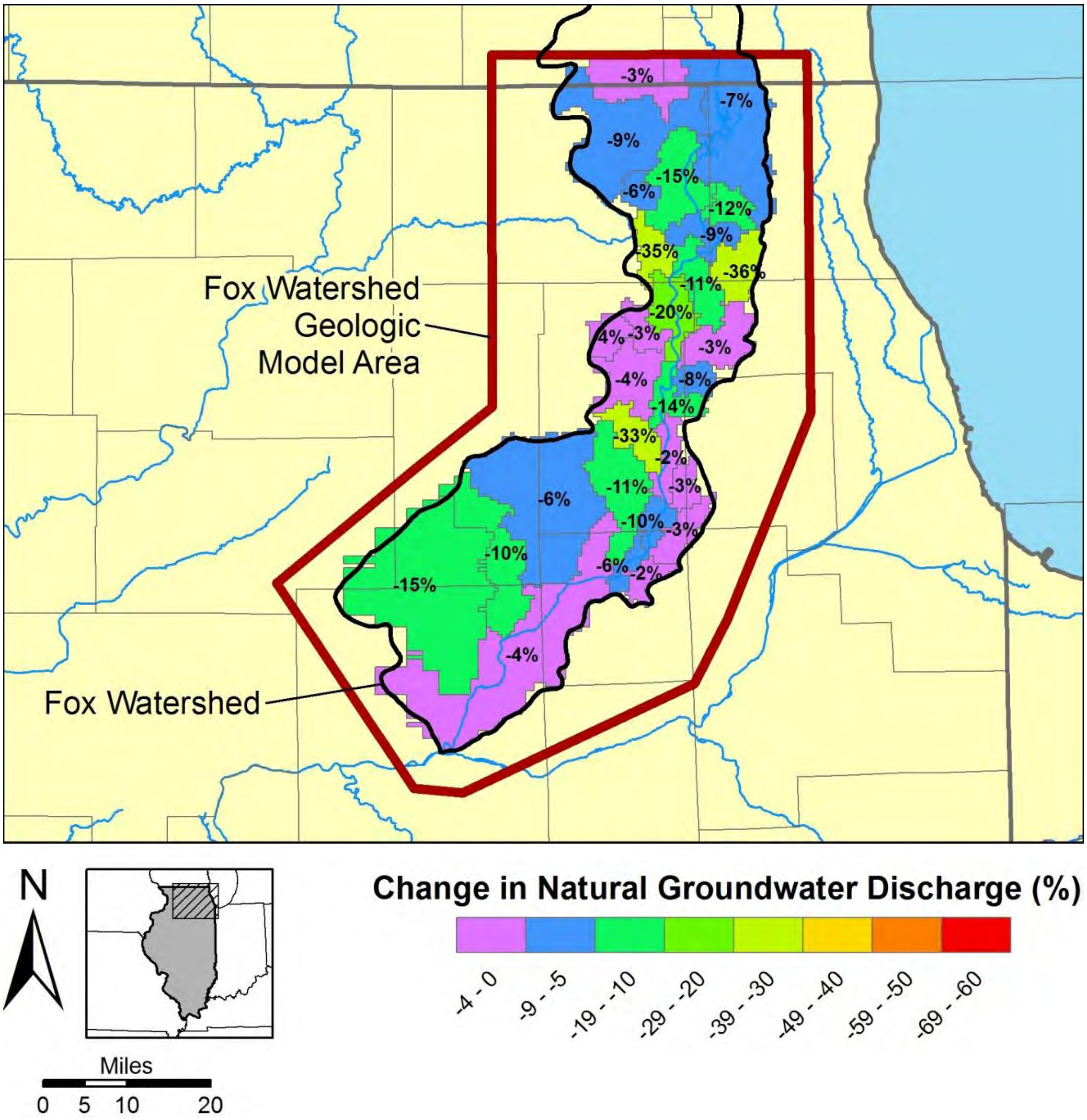


Figure 72. Change in natural groundwater discharge (pre-development to 2005) in the Fox watershed caused by pumping, by stream reach

Table 32. Simulated Natural Groundwater Discharge in Fox Watershed Sub-Basins

ID (Figure 70)	*Sub-Basin*	*Predevelopment (Mgd)*	*1985*			*2005*		
				Change Since Predevelopment			*Change Since Predevelopment*	
			Mgd	*Mgd*	*%*	*Mgd*	*Mgd*	*%*
1	East Run-Blackberry Creek; Lake Run-Blackberry Creek	26	24	-2	-6%	23	-3	-11%
2	Otter Creek-Ferson Creek; Ferson Creek	15	15	-1	-4%	15	-1	-4%
3	Boone Creek	7	7	0	-5%	7	0	-6%
4	Town of Alden; Headwaters Nippersink Creek; Nippersink Creek; Carr Harrison Cemetery-Nippersink Creek; Greenwood-Nippersink Creek; Wonder Lake-Nippersink Creek; City of Woodstock	35	32	-3	-8%	32	-3	-9%
5	West Branch North Branch Nippersink Creek-North Branch Nippersink Creek; North Branch Nippersink Creek	25	24	-1	-2%	24	-1	-3%
6	Hoosier Creek; Spring Brook-Fox River; Palmer Creek-Fox River; Bassett Creek-Fox River; Channel Lake; Nippersink Lake-Fox River; Sequoit Creek; Pistakee Lake-Fox River; Squaw Creek; Headwaters Squaw Creek	78	73	-5	-6%	73	-6	-7%
7	Hollenback Creek-Fox River; Rob Roy Creek; Clear Creek-Fox River; Roods Creek-Fox River; Mission Creek-Fox River; Outlet Buck Creek; Headwaters Buck Creek; Brumbach Creek-Fox River; Goose Creek-Fox River	82	78	-4	-4%	79	-3	-4%
8	Squaw Grove-Little Rock Creek; Town of Sandwich-Little Rock Creek; West Branch Big Rock Creek; East Branch Big Rock Creek; Welch Creek; Headwaters Little Rock Creek; Big Rock Creek	66	62	-4	-5%	62	-4	-6%
9	Buck Creek-Somonauk Creek; Headwaters Somonauk Creek; Outlet Somonauk Creek; Parris Lake-Somonauk Creek	28	25	-3	-9%	25	-3	-10%
10	Town of Meridan; Sutphens Run; Town of Leland-Little Indian Creek; Little Indian Creek; Paw Paw Run-Indian Creek; Town of Shabbona-Little Indian Creek; Town of Rollo-Indian Creek; Crookedleg Creek; East Cemetery-Indian Creek	104	90	-14	-13%	89	-15	-15%
11	Griswold Lake-Fox River	22	20	-2	-9%	18	-3	-15%
12	Cotton Creek	8	7	-1	-7%	7	-1	-12%
13	Flint Creek	6	4	-2	-33%	4	-2	-36%
14	Cary Creek-Fox River	13	13	-1	-5%	12	-1	-9%

Table 32. Simulated Natural Groundwater Discharge in Fox Watershed Sub-Basins (Concluded)

ID (Figure 70)	***Sub-Basin***	***Predevelopment (Mgd)***	***1985***			***2005***		
				Change Since Predevelopment			***Change Since Predevelopment***	
			Mgd	***Mgd***	***%***	***Mgd***	***Mgd***	***%***
15	Spring Creek-Fox River	15	14	-1	-7%	13	-2	-11%
16	Crystal Lake Outlet	6	6	-1	-11%	4	-2	-35%
17	Headwaters Tyler Creek	4	4	0	-3%	4	0	-4%
18	Tyler Creek	5	5	0	-2%	5	0	-3%
19	Poplar Creek	11	8	-3	-31%	11	0	-3%
20	Jelkes Creek-Fox River	16	14	-1	-9%	12	-3	-20%
21	Brewster Creek	4	4	-1	-13%	4	0	-8%
22	Norton Creek-Fox River	11	9	-2	-18%	9	-2	-14%
23	Mill Creek	10	9	-1	-6%	7	-3	-33%
24	Town of Geneva-Fox River	9	8	0	-5%	9	0	-2%
25	Town of Aurora	5	5	0	-7%	5	0	-3%
26	Waubonsie Creek	9	9	0	-5%	9	0	-3%
27	Mastodon Lake-Fox River	7	6	-1	-8%	6	-1	-10%
28	Morgan Creek	6	6	0	-2%	6	0	-2%
29	Town of Oswego-Fox River	5	5	0	-5%	5	0	-6%
	Total	**639**	**587**	**-52**	**-8%**	**578**	**-61**	**-10%**

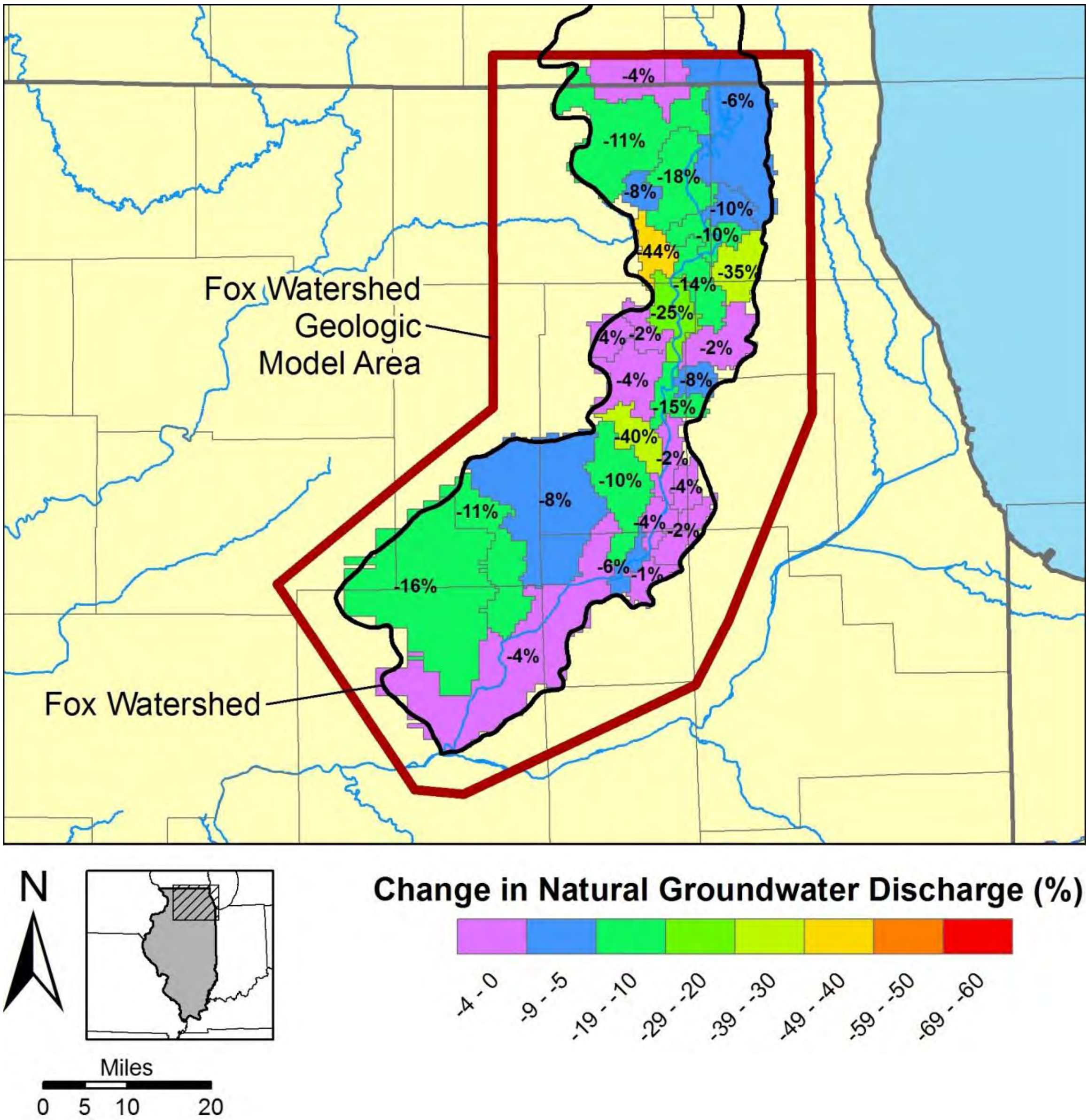


Figure 73. Change in natural groundwater discharge (pre-development to 2025) in the Fox watershed caused by pumping, BL scenario, by stream reach

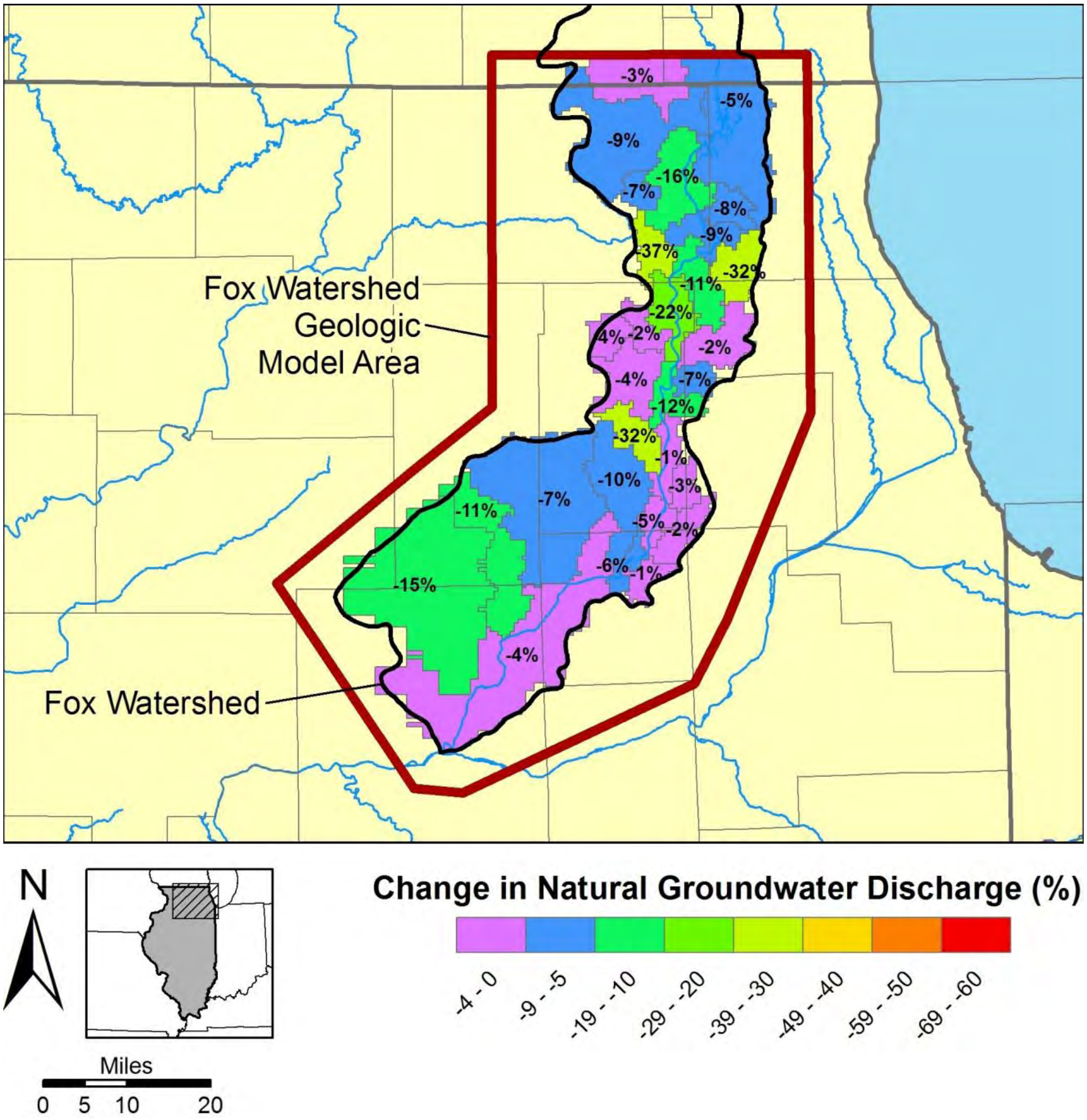


Figure 74. Change in natural groundwater discharge (pre-development to 2025) in the Fox watershed caused by pumping, LRI scenario, by stream reach

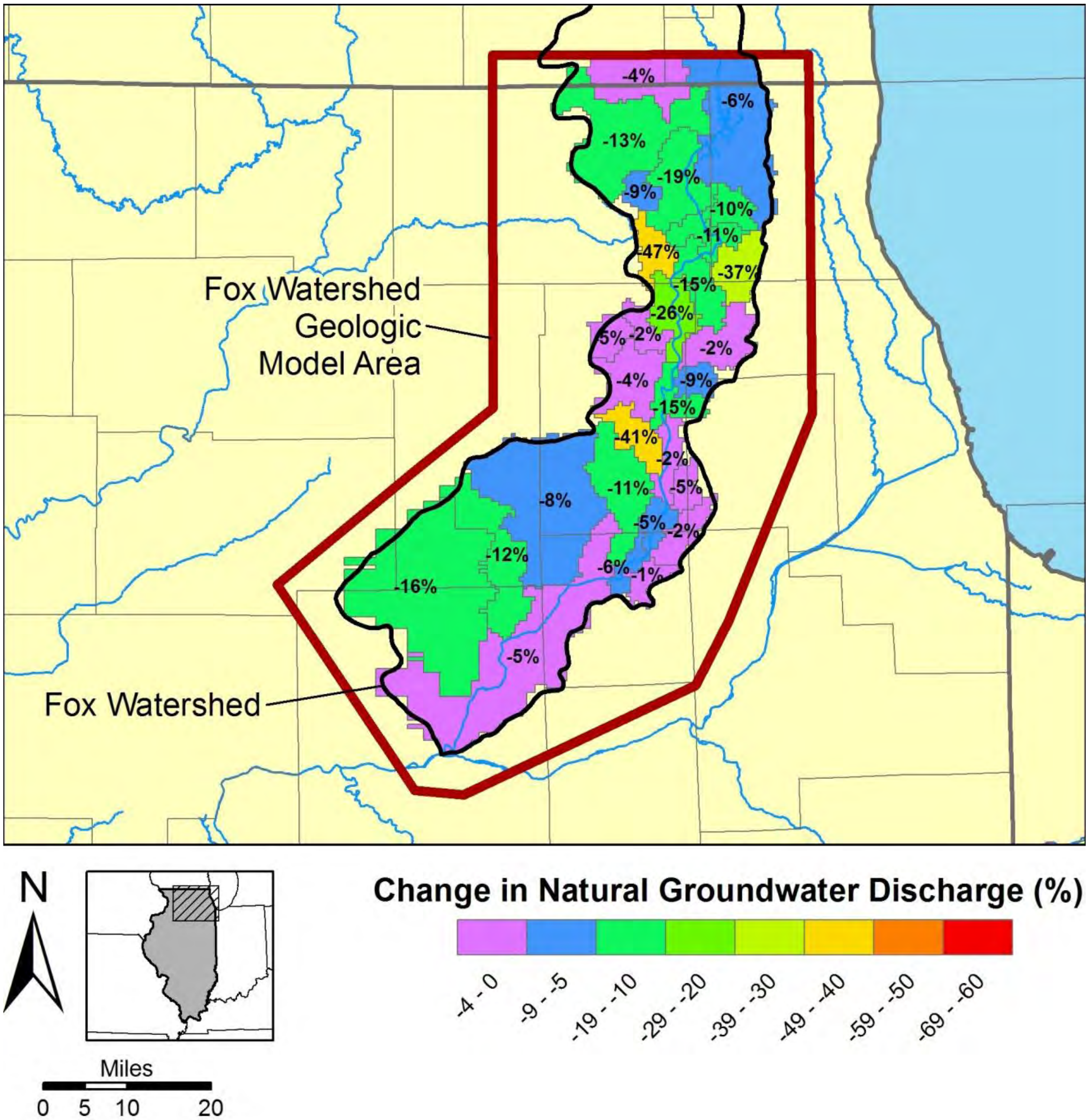


Figure 75. Change in natural groundwater discharge (pre-development to 2025) in the Fox watershed caused by pumping, MRI scenario, by stream reach

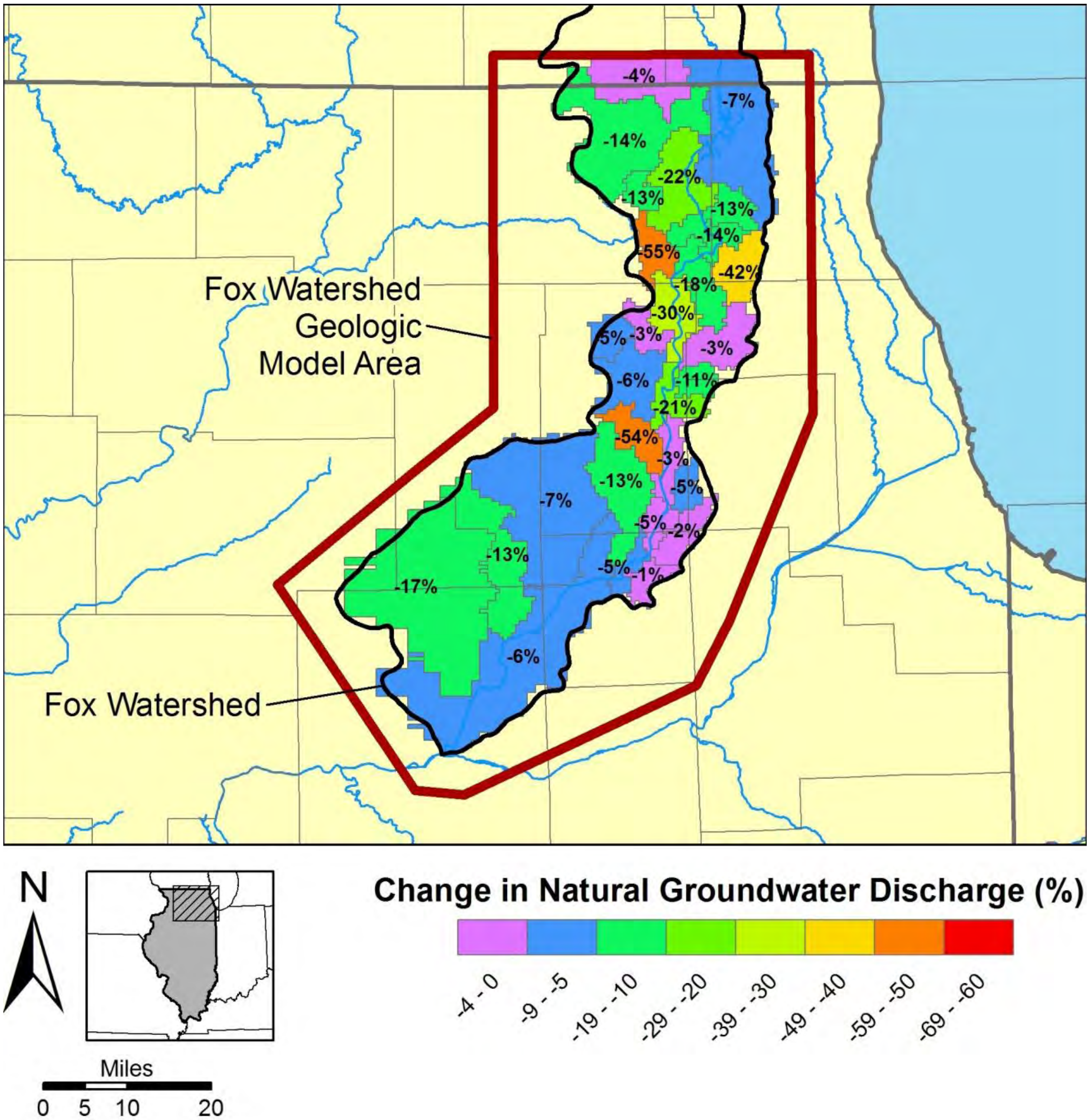


Figure 76. Change in natural groundwater discharge (pre-development to 2050) in the Fox watershed caused by pumping, BL scenario, by stream reach

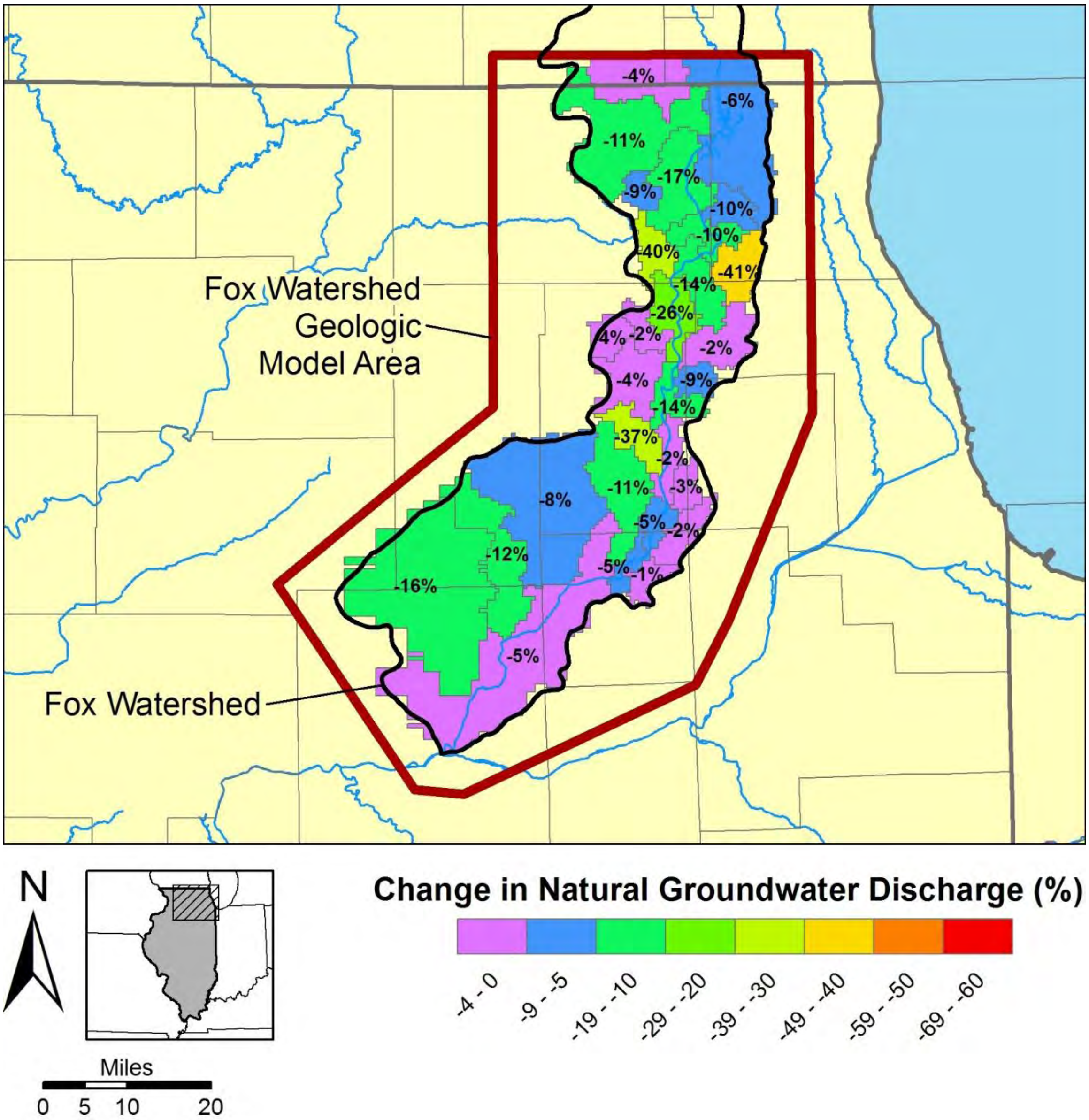


Figure 77. Change in natural groundwater discharge (pre-development to 2050) in the Fox watershed caused by pumping, LRI scenario, by stream reach

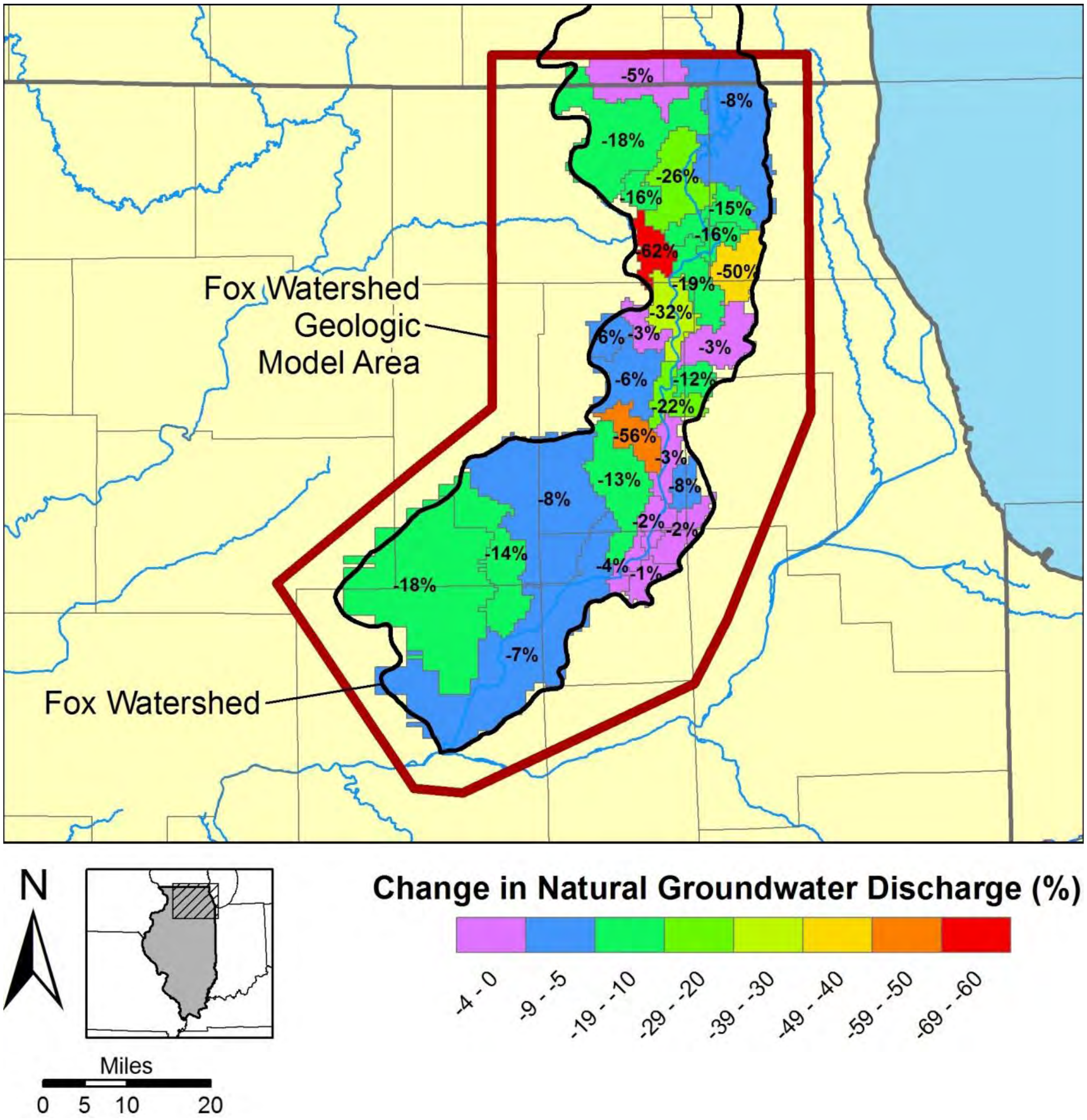


Figure 78. Change in natural groundwater discharge (pre-development to 2050) in the Fox watershed caused by pumping, MRI scenario, by stream reach

Table 33. Simulated Natural Groundwater Discharge in Fox Watershed Sub-Basins, BL Scenario

ID (Figure 70)	*Sub-Basin*	*Predevelopment (Mgd)*	*2025*			*2050*		
				Change Since Predevelopment			*Change Since Predevelopment*	
			Mgd	*Mgd*	*%*	*Mgd*	*Mgd*	*%*
1	East Run-Blackberry Creek; Lake Run-Blackberry Creek	26	23	-3	-10%	23	-3	-13%
2	Otter Creek-Ferson Creek; Ferson Creek	15	15	-1	-4%	14	-1	-6%
3	Boone Creek	7	7	-1	-8%	6	-1	-13%
4	Town of Alden; Headwaters Nippersink Creek; Nippersink Creek; Carr Harrison Cemetery-Nippersink Creek; Greenwood-Nippersink Creek; Wonder Lake-Nippersink Creek; City of Woodstock	35	31	-4	-11%	30	-5	-14%
5	West Branch North Branch Nippersink Creek-North Branch Nippersink Creek; North Branch Nippersink Creek	25	24	-1	-4%	24	-1	-4%
6	Hoosier Creek; Spring Brook-Fox River; Palmer Creek-Fox River; Bassett Creek-Fox River; Channel Lake; Nippersink Lake-Fox River; Sequoit Creek; Pistakee Lake-Fox River; Squaw Creek; Headwaters Squaw Creek	78	74	-4	-6%	73	-6	-7%
7	Hollenback Creek-Fox River; Rob Roy Creek; Clear Creek-Fox River; Roods Creek-Fox River; Mission Creek-Fox River; Outlet Buck Creek; Headwaters Buck Creek; Brumbach Creek-Fox River; Goose Creek-Fox River	82	78	-4	-4%	77	-5	-6%
8	Squaw Grove-Little Rock Creek; Town of Sandwich-Little Rock Creek; West Branch Big Rock Creek; East Branch Big Rock Creek; Welch Creek; Headwaters Little Rock Creek; Big Rock Creek	66	61	-5	-8%	61	-5	-7%
9	Buck Creek-Somonauk Creek; Headwaters Somonauk Creek; Outlet Somonauk Creek; Parris Lake-Somonauk Creek	28	25	-3	-11%	24	-4	-13%
10	Town of Meridan; Sutphens Run; Town of Leland-Little Indian Creek; Little Indian Creek; Paw Paw Run-Indian Creek; Town of Shabbona-Little Indian Creek; Town of Rollo-Indian Creek; Crookedleg Creek; East Cemetery-Indian Creek	104	88	-16	-16%	86	-18	-17%
11	Griswold Lake-Fox River	22	18	-4	-18%	17	-5	-22%
12	Cotton Creek	8	7	-1	-10%	7	-1	-13%
13	Flint Creek	6	4	-2	-35%	4	-3	-42%
14	Cary Creek-Fox River	13	12	-1	-10%	12	-2	-14%

Table 33. Simulated Natural Groundwater Discharge in Fox Watershed Sub-Basins, BL Scenario (Concluded)

ID (Figure 70)	***Sub-Basin***	***Predevelopment (Mgd)***	***2025***			***2050***		
				Change Since Predevelopment			***Change Since Predevelopment***	
			Mgd	***Mgd***	***%***	***Mgd***	***Mgd***	***%***
15	Spring Creek-Fox River	15	13	-2	-14%	12	-3	-18%
16	Crystal Lake Outlet	6	4	-3	-44%	3	-4	-55%
17	Headwaters Tyler Creek	4	4	0	-4%	4	0	-5%
18	Tyler Creek	5	5	0	-2%	5	0	-3%
19	Poplar Creek	11	11	0	-2%	11	0	-3%
20	Jelkes Creek-Fox River	16	12	-4	-25%	11	-5	-30%
21	Brewster Creek	4	4	0	-8%	4	0	-11%
22	Norton Creek-Fox River	11	9	-2	-15%	9	-2	-21%
23	Mill Creek	10	6	-4	-40%	5	-5	-54%
24	Town of Geneva-Fox River	9	9	0	-2%	9	0	-3%
25	Town of Aurora	5	5	0	-4%	5	0	-5%
26	Waubonsie Creek	9	9	0	-2%	9	0	-2%
27	Mastodon Lake-Fox River	7	6	0	-4%	6	0	-5%
28	Morgan Creek	6	6	0	-1%	6	0	-1%
29	Town of Oswego-Fox River	5	5	0	-6%	5	0	-5%
	Total	**639**	**573**	**-66**	**-10%**	**560**	**-79**	**-12%**

Table 34. Simulated Natural Groundwater Discharge in Fox Watershed Sub-Basins, LRI Scenario

ID (Figure 70)	Sub-Basin	Predevelopment (Mgd)	2025			2050		
				Change Since Predevelopment			Change Since Predevelopment	
			Mgd	Mgd	%	Mgd	Mgd	%
1	East Run-Blackberry Creek; Lake Run-Blackberry Creek	26	23	-3	-10%	23	-3	-11%
2	Otter Creek-Ferson Creek; Ferson Creek	15	15	-1	-4%	15	-1	-4%
3	Boone Creek	7	7	-1	-7%	7	-1	-9%
4	Town of Alden; Headwaters Nippersink Creek; Nippersink Creek; Carr Harrison Cemetery-Nippersink Creek; Greenwood-Nippersink Creek; Wonder Lake-Nippersink Creek; City of Woodstock	35	32	-3	-9%	31	-4	-11%
5	West Branch North Branch Nippersink Creek-North Branch Nippersink Creek; North Branch Nippersink Creek	25	24	-1	-3%	24	-1	-4%
6	Hoosier Creek; Spring Brook-Fox River; Palmer Creek-Fox River; Bassett Creek-Fox River; Channel Lake; Nippersink Lake-Fox River; Sequoit Creek; Pistakee Lake-Fox River; Squaw Creek; Headwaters Squaw Creek	78	74	-4	-5%	74	-4	-6%
7	Hollenback Creek-Fox River; Rob Roy Creek; Clear Creek-Fox River; Roods Creek-Fox River; Mission Creek-Fox River; Outlet Buck Creek; Headwaters Buck Creek; Brumbach Creek-Fox River; Goose Creek-Fox River	82	79	-3	-4%	78	-4	-5%
8	Squaw Grove-Little Rock Creek; Town of Sandwich-Little Rock Creek; West Branch Big Rock Creek; East Branch Big Rock Creek; Welch Creek; Headwaters Little Rock Creek; Big Rock Creek	66	62	-4	-7%	60	-6	-8%
9	Buck Creek-Somonauk Creek; Headwaters Somonauk Creek; Outlet Somonauk Creek; Parris Lake-Somonauk Creek	28	25	-3	-11%	25	-3	-12%
10	Town of Meridan; Sutphens Run; Town of Leland-Little Indian Creek; Little Indian Creek; Paw Paw Run-Indian Creek; Town of Shabbona-Little Indian Creek; Town of Rollo-Indian Creek; Crookedleg Creek; East Cemetery-Indian Creek	104	89	-16	-15%	88	-16	-16%
11	Griswold Lake-Fox River	22	18	-3	-16%	18	-4	-17%
12	Cotton Creek	8	7	-1	-8%	7	-1	-10%
13	Flint Creek	6	4	-2	-32%	4	-3	-41%
14	Cary Creek-Fox River	13	12	-1	-9%	12	-1	-10%

Table 34. Simulated Natural Groundwater Discharge in Fox Watershed Sub-Basins, LRI Scenario (Concluded)

ID (Figure 70)	*Sub-Basin*	*Predevelopment (Mgd)*	*2025*			*2050*		
				Change Since Predevelopment			*Change Since Predevelopment*	
			Mgd	*Mgd*	*%*	*Mgd*	*Mgd*	*%*
15	Spring Creek-Fox River	15	13	-2	-11%	13	-2	-14%
16	Crystal Lake Outlet	6	4	-2	-37%	4	-3	-40%
17	Headwaters Tyler Creek	4	4	0	-4%	4	0	-4%
18	Tyler Creek	5	5	0	-2%	5	0	-2%
19	Poplar Creek	11	11	0	-2%	11	0	-2%
20	Jelkes Creek-Fox River	16	12	-3	-22%	11	-4	-26%
21	Brewster Creek	4	4	0	-7%	4	0	-9%
22	Norton Creek-Fox River	11	10	-1	-12%	9	-2	-14%
23	Mill Creek	10	7	-3	-32%	6	-4	-37%
24	Town of Geneva-Fox River	9	9	0	-1%	9	0	-2%
25	Town of Aurora	5	5	0	-3%	5	0	-3%
26	Waubonsie Creek	9	9	0	-2%	9	0	-2%
27	Mastodon Lake-Fox River	7	6	0	-5%	6	0	-5%
28	Morgan Creek	6	6	0	-1%	6	0	-1%
29	Town of Oswego-Fox River	5	5	0	-6%	5	0	-5%
	Total	**639**	**580**	**-59**	**-9%**	**572**	**-67**	**-10%**

Table 35. Simulated Natural Groundwater Discharge in Fox Watershed Sub-Basins, MRI Scenario

ID (Figure 70)	*Sub-Basin*	*Predevelopment (Mgd)*	*2025*			*2050*		
				Change Since Predevelopment			*Change Since Predevelopment*	
			Mgd	*Mgd*	*%*	*Mgd*	*Mgd*	*%*
1	East Run-Blackberry Creek; Lake Run-Blackberry Creek	26	23	-3	-11%	23	-3	-13%
2	Otter Creek-Ferson Creek; Ferson Creek	15	15	-1	-4%	14	-1	-6%
3	Boone Creek	7	7	-1	-9%	6	-1	-16%
4	Town of Alden; Headwaters Nippersink Creek; Nippersink Creek; Carr Harrison Cemetery-Nippersink Creek; Greenwood-Nippersink Creek; Wonder Lake-Nippersink Creek; City of Woodstock	35	31	-4	-13%	29	-6	-18%
5	West Branch North Branch Nippersink Creek-North Branch Nippersink Creek; North Branch Nippersink Creek	25	24	-1	-4%	23	-1	-5%
6	Hoosier Creek; Spring Brook-Fox River; Palmer Creek-Fox River; Bassett Creek-Fox River; Channel Lake; Nippersink Lake-Fox River; Sequoit Creek; Pistakee Lake-Fox River; Squaw Creek; Headwaters Squaw Creek	78	73	-5	-6%	72	-6	-8%
7	Hollenback Creek-Fox River; Rob Roy Creek; Clear Creek-Fox River; Roods Creek-Fox River; Mission Creek-Fox River; Outlet Buck Creek; Headwaters Buck Creek; Brumbach Creek-Fox River; Goose Creek-Fox River	82	78	-4	-5%	76	-6	-7%
8	Squaw Grove-Little Rock Creek; Town of Sandwich-Little Rock Creek; West Branch Big Rock Creek; East Branch Big Rock Creek; Welch Creek; Headwaters Little Rock Creek; Big Rock Creek	66	61	-5	-8%	61	-5	-8%
9	Buck Creek-Somonauk Creek; Headwaters Somonauk Creek; Outlet Somonauk Creek; Parris Lake-Somonauk Creek	28	25	-3	-12%	24	-4	-14%
10	Town of Meridan; Sutphens Run; Town of Leland-Little Indian Creek; Little Indian Creek; Paw Paw Run-Indian Creek; Town of Shabbona-Little Indian Creek; Town of Rollo-Indian Creek; Crookedleg Creek; East Cemetery-Indian Creek	104	87	-17	-16%	85	-19	-18%
11	Griswold Lake-Fox River	22	18	-4	-19%	16	-6	-26%
12	Cotton Creek	8	7	-1	-10%	6	-1	-15%
13	Flint Creek	6	4	-2	-37%	3	-3	-50%
14	Cary Creek-Fox River	13	12	-2	-11%	11	-2	-16%

Table 35. Simulated Natural Groundwater Discharge in Fox Watershed Sub-Basins, MRI Scenario (Concluded)

ID (Figure 70)	*Sub-Basin*	*Predevelopment (Mgd)*	*2025*			*2050*		
				Change Since Predevelopment			*Change Since Predevelopment*	
			Mgd	*Mgd*	*%*	*Mgd*	*Mgd*	*%*
15	Spring Creek-Fox River	15	12	-2	-15%	12	-3	-19%
16	Crystal Lake Outlet	6	3	-3	-47%	2	-4	-62%
17	Headwaters Tyler Creek	4	4	0	-5%	4	0	-6%
18	Tyler Creek	5	5	0	-2%	5	0	-3%
19	Poplar Creek	11	11	0	-2%	11	0	-3%
20	Jelkes Creek-Fox River	16	12	-4	-26%	11	-5	-32%
21	Brewster Creek	4	4	0	-9%	4	-1	-12%
22	Norton Creek-Fox River	11	9	-2	-15%	9	-2	-22%
23	Mill Creek	10	6	-4	-41%	4	-5	-56%
24	Town of Geneva-Fox River	9	9	0	-2%	9	0	-3%
25	Town of Aurora	5	5	0	-5%	5	0	-8%
26	Waubonsie Creek	9	9	0	-2%	9	0	-2%
27	Mastodon Lake-Fox River	7	6	0	-5%	7	0	-2%
28	Morgan Creek	6	6	0	-1%	6	0	-1%
29	Town of Oswego-Fox River	5	5	0	-6%	5	0	-4%
	Total	**639**	**569**	**-70**	**-11%**	**552**	**-87**	**-14%**

4.2.4.3 Model Analysis of the Deep Bedrock Aquifers

Introduction. In most of northeastern Illinois, exchange of water between the shallow and deep aquifers is greatly limited by relatively impermeable rocks of the Maquoketa and Upper Bedrock Units overlying the deep aquifers. Circulation within the deep aquifers thus occurs on a regional scale, with most recharge into the aquifers occurring in Boone and DeKalb Counties, where the impermeable rocks are absent. Under predevelopment conditions, groundwater in the deep aquifers underlying northeastern Illinois slowly discharged upward into the shallow units, and ultimately to surface waters—primarily the upper Illinois River and lower Fox River, with some diffuse upward leakage to Lake Michigan. Presently, discharge of deep groundwater in the region is dominated by flow to wells. As described in Section 4.2.4.1, drawdown in the deep aquifers in the area of confinement by the Maquoketa and Upper Bedrock Units is widespread and of much greater magnitude than in the shallow aquifers. The relatively impermeable Maquoketa and Upper Bedrock Units, where present, greatly limit leakage into the deep aquifers from above, so replacement water for these aquifers is derived principally by slow, lateral movement from north-central Illinois where this relatively impermeable cover is absent. The slow lateral movement of water from north-central Illinois cannot keep pace with rates of withdrawal in the area of confinement, so deep well withdrawals are derived from reduction in aquifer storage, and cones of depression deepen and widen. Section 4.2.4.3 includes a complete discussion of pumping impacts on the Ancell Unit followed by a similar treatment of the Ironton-Galesville Unit.

Uncertainty. Observed water levels in deep wells are composites of the heads in all units intercepted by the open borehole of the well. The model simulates individual model layers, however, and thus, the model-simulated heads are not equal to the composite water levels measured in typical multiple-aquifer deep northeastern Illinois wells. Compare, for example, the simulated heads in the Ancell and Ironton-Galesville Units at the end of the summer irrigation season in 2000 (Figure 79 and Figure 80) with the composite heads measured in deep wells in northeastern Illinois by Burch (2008) in fall 2000 (Figure 81). For the most part, the observed head (Figure 81) falls between the simulated aquifer heads (Figure 79 and Figure 80). The authors attribute a portion of the disagreement between the simulated heads in model layers and the observed water levels to uncertainty in the head measurements used for model calibration estimated in the model nearfield at ±200 feet (Section 4.2.2.2). The model could be greatly improved if widespread observations of formation-specific heads, rather than composite heads, became available; these would be employed for model calibration and/or verification.

Much of the remaining difference between observed composite water levels and simulated heads in intercepted aquifers may be attributable to interformational transfer of groundwater, via open boreholes, between deep aquifers. This effect is not simulated by the regional model, and although a detailed analysis of its effects is beyond the scope of the project, the authors can offer a speculative, qualitative assessment of the effect of these transfers on deep aquifer head. Since most deep wells in northeastern Illinois are open only to the Ancell and Ironton-Galesville Units, not the deeper Mt. Simon Unit (Table 36), model-simulated heads suggest that the transfer of water along most deep boreholes is downward, from the Ancell Unit (with higher simulated head) to the Ironton-Galesville (with lower simulated head). This transfer is equivalent to constantly pumping water from the Ancell Unit into the Ironton-Galesville. With the influence of unsimulated downward transfers of groundwater in the thousands of deep wells in northeastern Illinois, then, actual heads are likely to be lower in the Ancell and higher in the Ironton-Galesville than the heads simulated with the regional model.

Maps illustrating simulated head, available head, and drawdown in deep aquifers, particularly in maps of Ironton-Galesville results, display desaturated model cells that are incongruously surrounded by heads that do not indicate a cone of depression. The authors believe these desaturated cells are an artifact of the model design that erroneously does not permit them to resaturate after historically high withdrawals have ceased and that does not simulate interformational transfers of groundwater via boreholes. The map of simulated Ironton-Galesville heads following the 2000 summer irrigation season (Figure 80) shows several such desaturated cells, the most pronounced example being a roughly circular block of cells in central Cook County. This block developed as a consequence of concentrated pumping assigned to the Chicago pumping center, one of seven pumping centers used to simulate pumping during the period 1864 to 1963. Aggregation at the Chicago pumping center is especially significant, amounting to as much as 35 Mgd during the 1920s (Suter et al., 1959). Individual desaturated cells are additionally scattered across Kane, DuPage, and Cook Counties; these may be related to the Aurora, Des Plaines, and Elmhurst pumping centers or to individual wells pumped at high rates that may or may not still be operating. Exploration of the parameters controlling the cell-resaturation algorithm, directed at correcting this apparently erroneous cell desaturation problem, is ongoing. For the present, overall model results (e.g., drawdowns) are not affected, as evidenced by the fact that patterns of head and drawdown in cells adjacent to the desaturated cells follow regional patterns, suggesting that the surrounding cells are completely resaturated. While the maps included in this report contain these anomalies, the reader is advised to disregard them.

Ancell Unit. Figure 82 shows drawdown in the Ancell Unit at the end of the 1985 irrigation season. The most striking feature of this map is the deep cone of depression beneath eastern DuPage and northwestern Cook Counties, where drawdown exceeded 850 feet in the 100+ years since pumping began. By 2005 (Figure 83), the cone of depression was greatly reduced as a result of decreases in deep bedrock withdrawals when Lake Michigan water became available to that area (see also Figure 29, Figure 32, and Figure 34, which show the temporal and spatial changes in deep withdrawals). Smaller cones appear in extreme northeastern Cook County, apparently from golf course irrigation withdrawals.

By 2025, drawdown for all three demand scenarios is more apparent in the Aurora and Joliet areas of southeastern Kane and northern Will Counties (Figure 84 to Figure 86). The cone of depression in eastern DuPage and northwestern Cook Counties, despite reduced withdrawals in that area, persists and is testament to the very slow rates of vertical leakage into the Ancell as well as the slow rates of horizontal movement within the unit. By 2050, the drawdown pattern established in 2025 has continued to grow (Figure 87 to Figure 89). Note that maps of simulated Ancell Unit drawdown in 2025 and 2050 include widely scattered desaturated cells that are likely artifacts of model design as discussed above.

Hydrographs illustrate temporal changes in simulated Ancell Unit heads at Lake in the Hills, Maple Park, Shorewood, St. Charles, Oswego, Aurora, and Montgomery (locations shown in Figure 68). The Ancell Unit hydrographs include simulated historical heads and simulated future heads, the future heads being shown for each of the three demand scenarios introduced in Section 2.1.2 (LRI, BL, and MRI). A horizontal line shows the approximate elevation of the top of the Ancell Unit at each location. At Maple Park and Lake in the Hills, 2050 water levels remain 300 feet or more above the top of the Ancell for all three demand scenarios (Figure 90). By 2050, heads fall to less than 100 feet above the top of the Ancell at Shorewood and St. Charles (Figure 91). Heads fall to the top of the Ancell or below at Oswego, Aurora, and Montgomery (Figure 92 and Figure 93), falling to the top at Aurora and Montgomery by 2040 for the BL and MRI scenarios.

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

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

Because of the potential problems caused by drawdown of Ancell heads, maps were developed to show the available simulated head above the top of the Ancell. In these maps (Figure 94 to Figure 102), available head refers to the difference between Ancell Unit head and the top of the Ancell. Areas having less than 200 feet of available head (shaded in Figure 94 to Figure 102) might be considered for monitoring or as priority planning areas. Note, however, that available Ancell Unit head was commonly less than 200 feet under predevelopment conditions in the western part of the region covered by these figures owing to the shallow position of the Ancell in that region. Although simulated Ancell Unit head remained above the top of the Ancell Unit in both 1985 and 2005 (Figure 95 and Figure 96), available Ancell head has declined to less than 100 feet in areas of heavy pumping from deep aquifers. These areas include eastern DuPage and northwestern Cook Counties (in 1985) and the Aurora area of southeastern Kane County (in 2005). Model simulations show that the Aurora and Joliet areas of diminished available head (centered in southeastern Kane and west-central Will Counties, respectively) continue to grow through 2025 (Figure 97 to Figure 99) to 2050 (Figure 100 to Figure 102), with heads in some model simulations falling below the top of the Ancell in those two areas. Widely scattered, probably largely erroneously desaturated cells are shaded black in the maps of available Ancell Unit simulated head. Note that the erroneous nature of the apparent desaturation is suggested by the lack of reduced available head surrounding the desaturated cells.

Table 36. Source Aquifers of Deep Wells in 11-County Region, 1964–2005

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

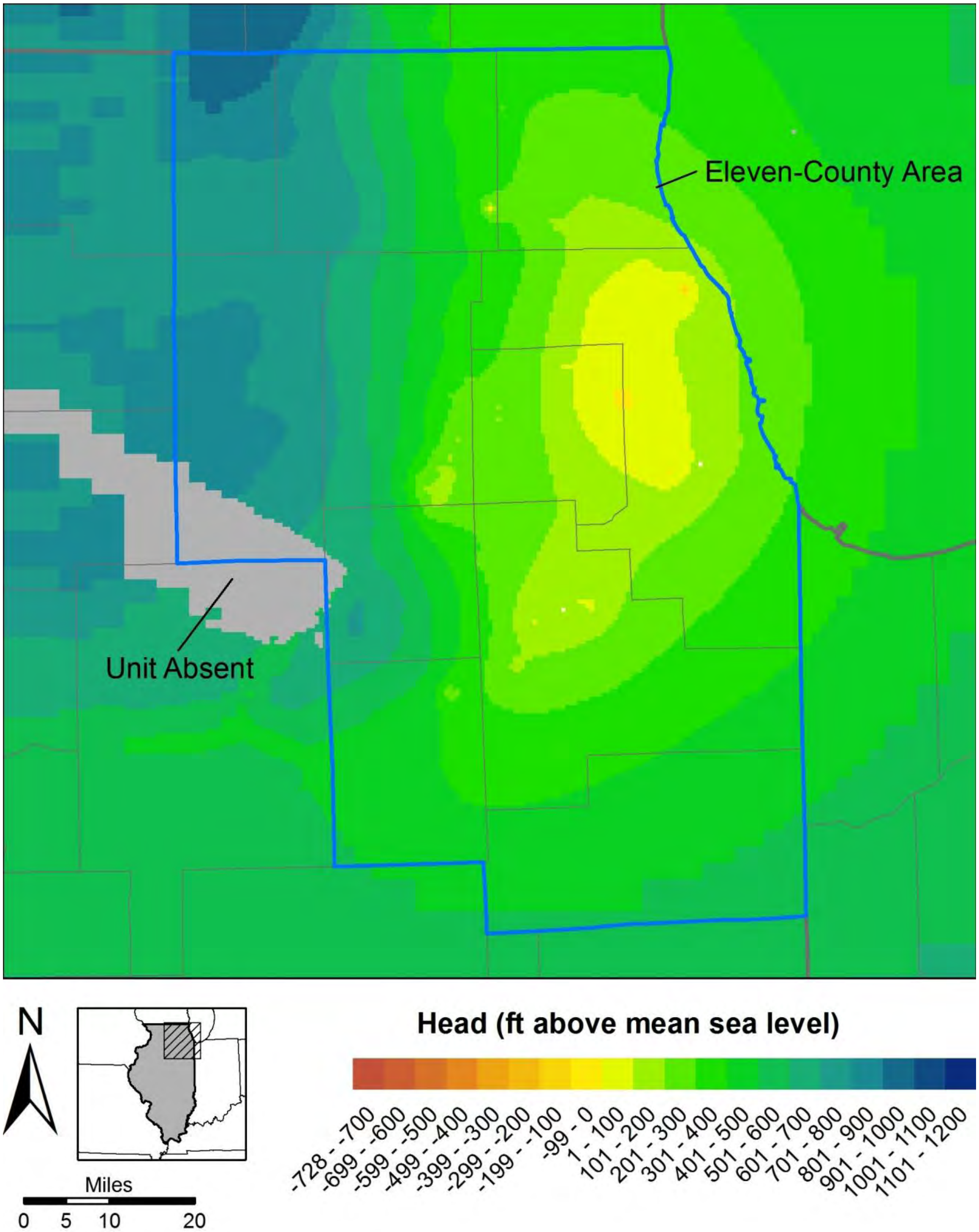


Figure 79. Simulated head in the Ancell Unit at end of summer irrigation season, 2000

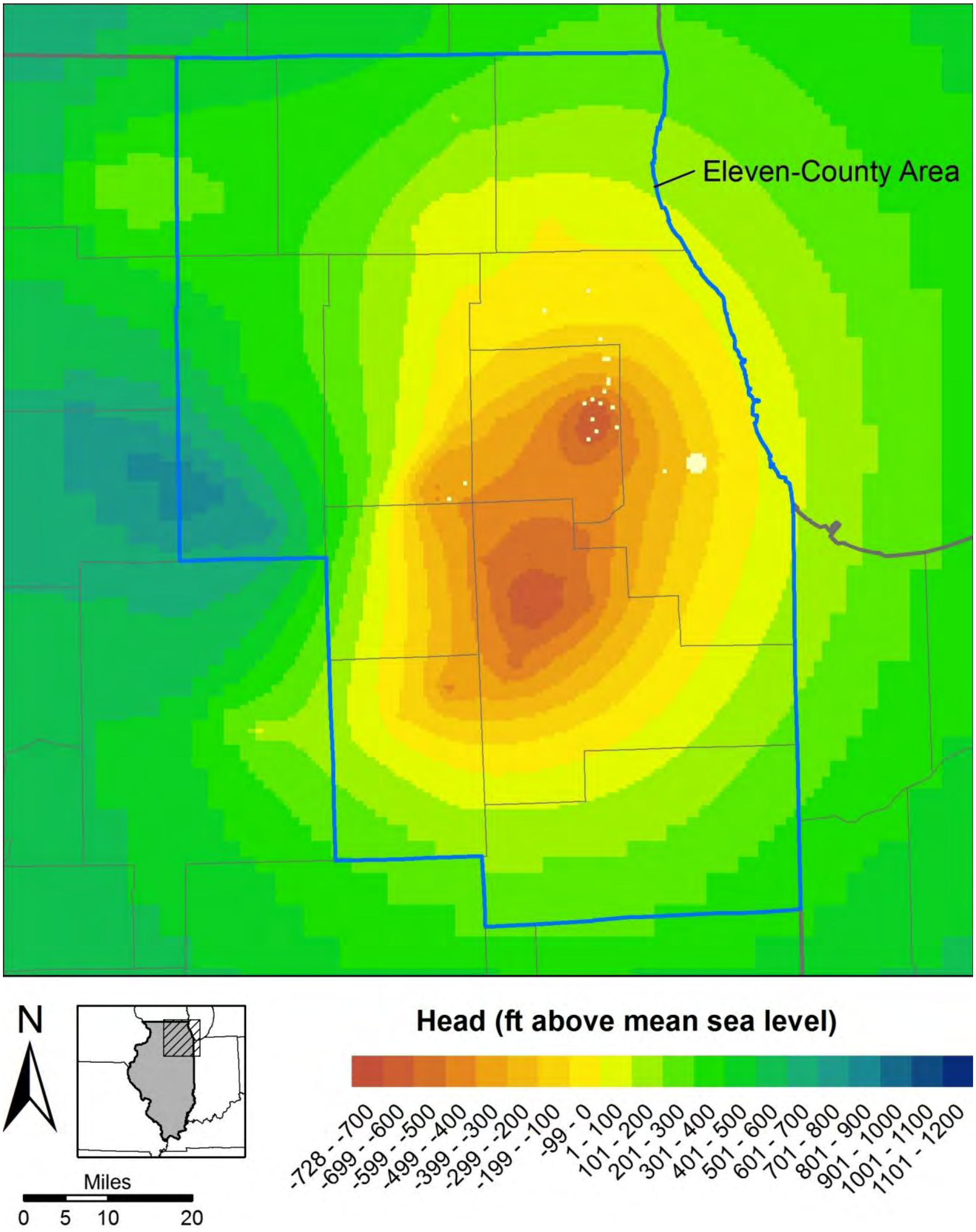


Figure 80. Simulated head in the Ironton-Galesville Unit at end of summer irrigation season, 2000

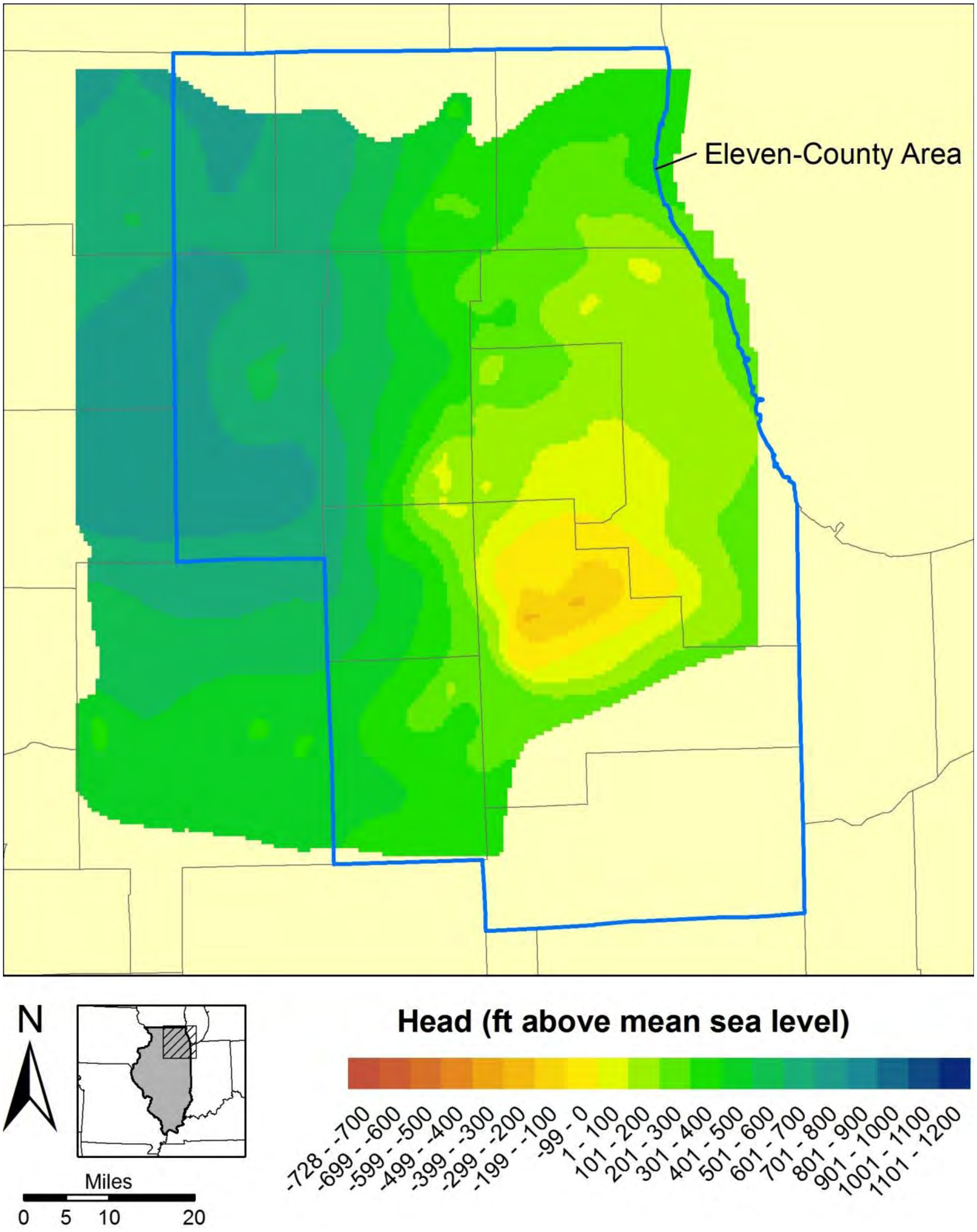


Figure 81. Observed composite head in deep wells, fall 2000 (based on Burch, 2008)

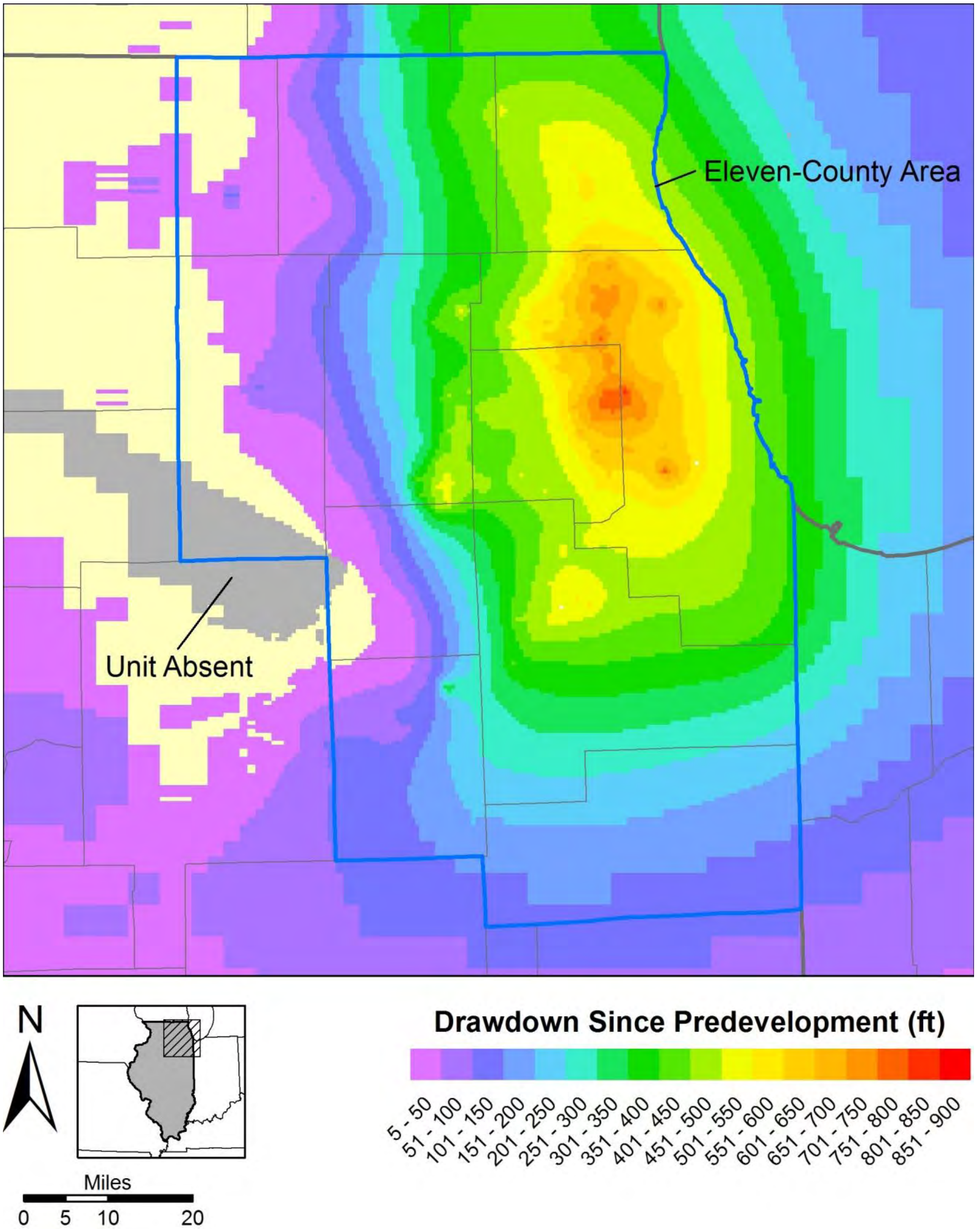


Figure 82. Simulated drawdown in the Ancell Unit, end of summer irrigation season, 1985

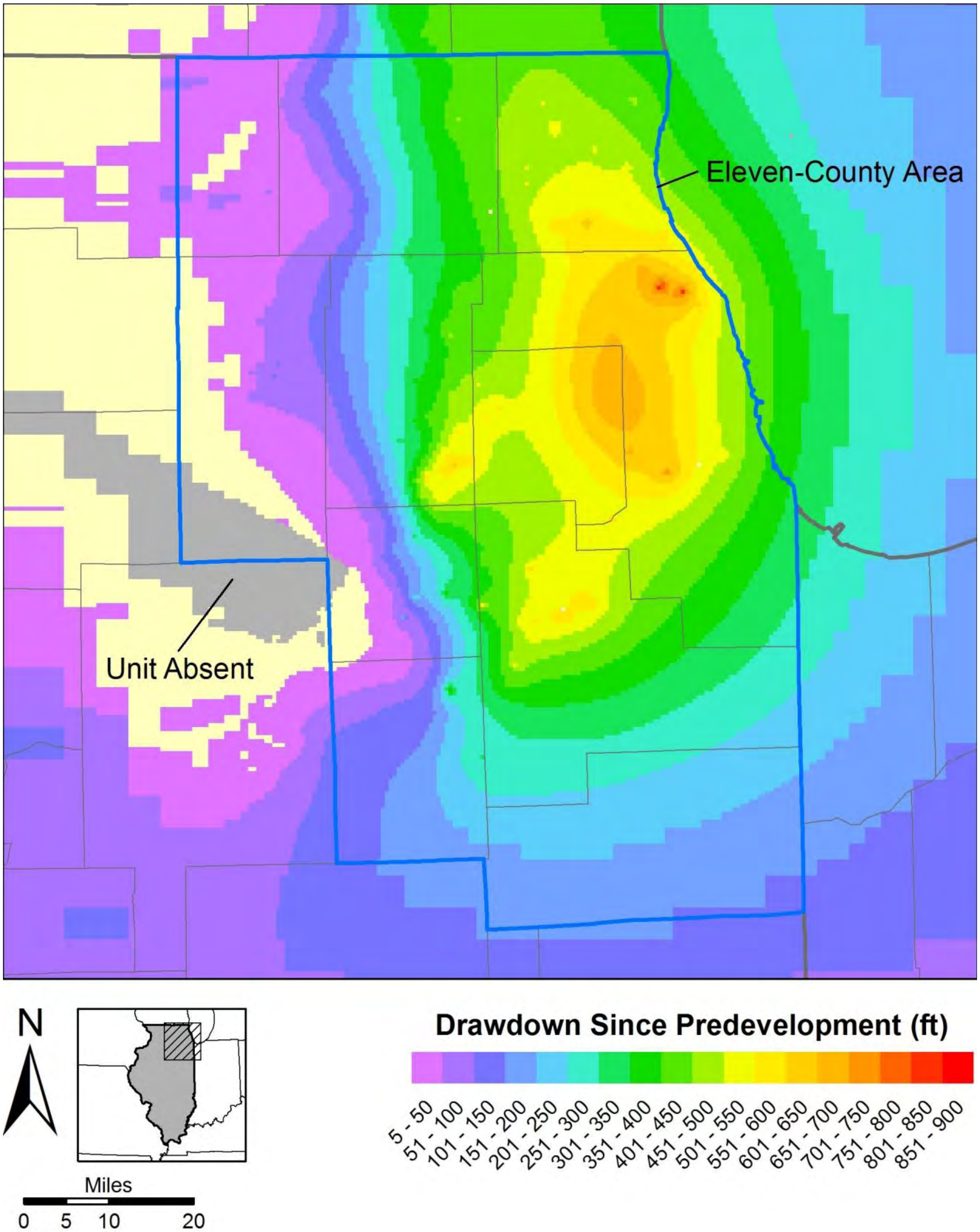


Figure 83. Simulated drawdown in the Ancell Unit, end of summer irrigation season, 2005

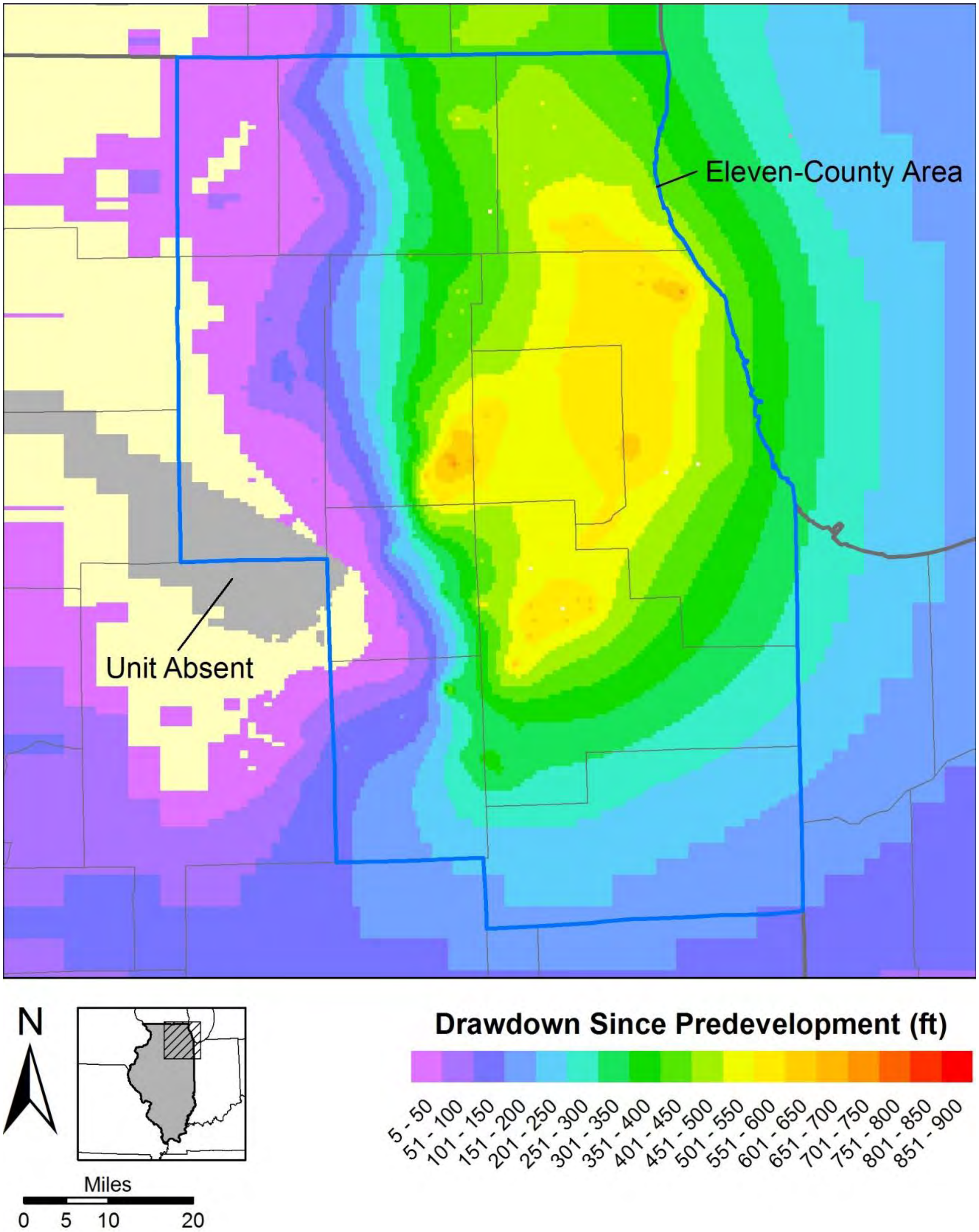


Figure 84. Simulated drawdown in the Ancell Unit, end of 2025 summer irrigation season, BL scenario

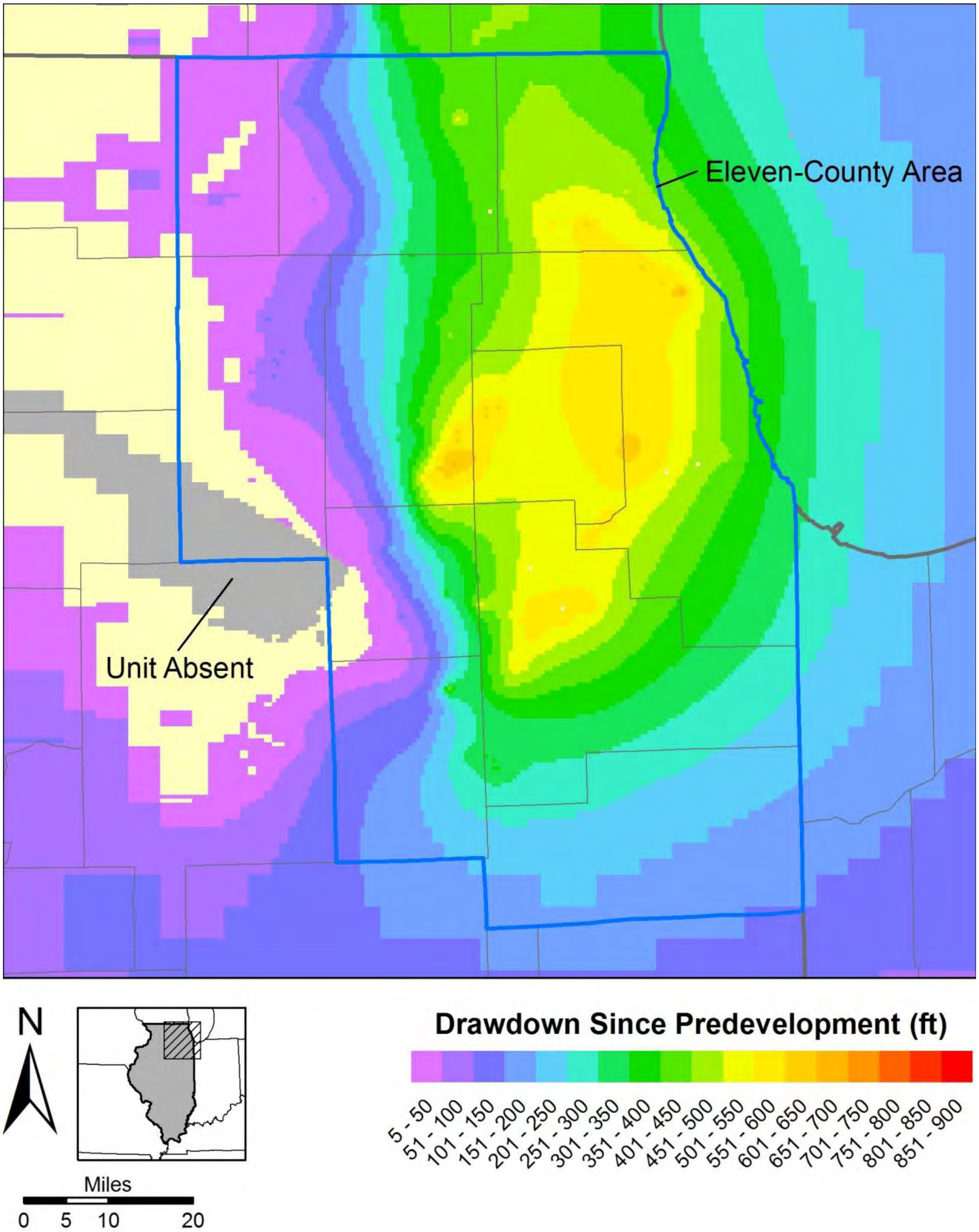


Figure 85. Simulated drawdown in the Ancell Unit, end of 2025 summer irrigation season, LRI scenario

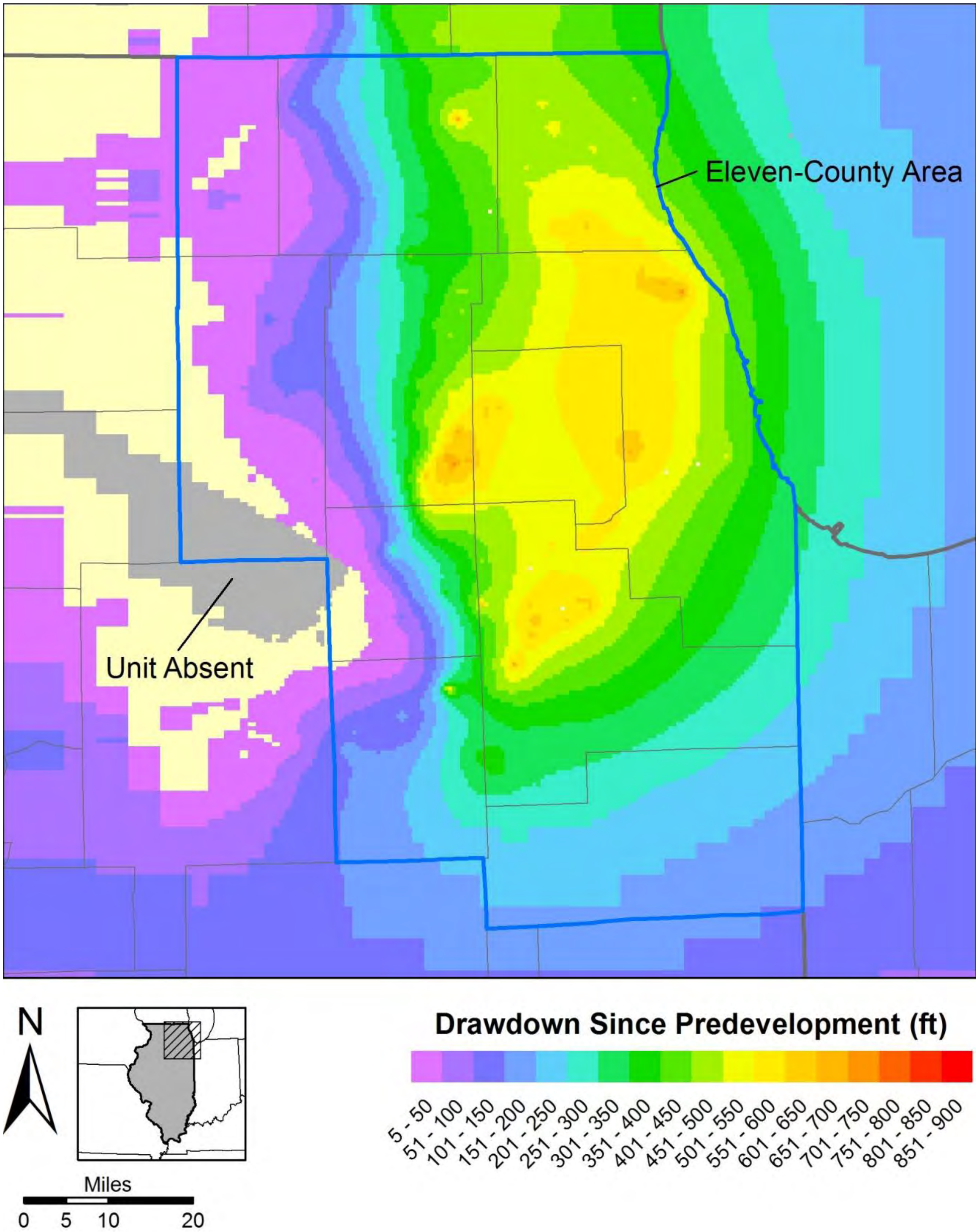


Figure 86. Simulated drawdown in the Ancell Unit, end of 2025 summer irrigation season, MRI scenario

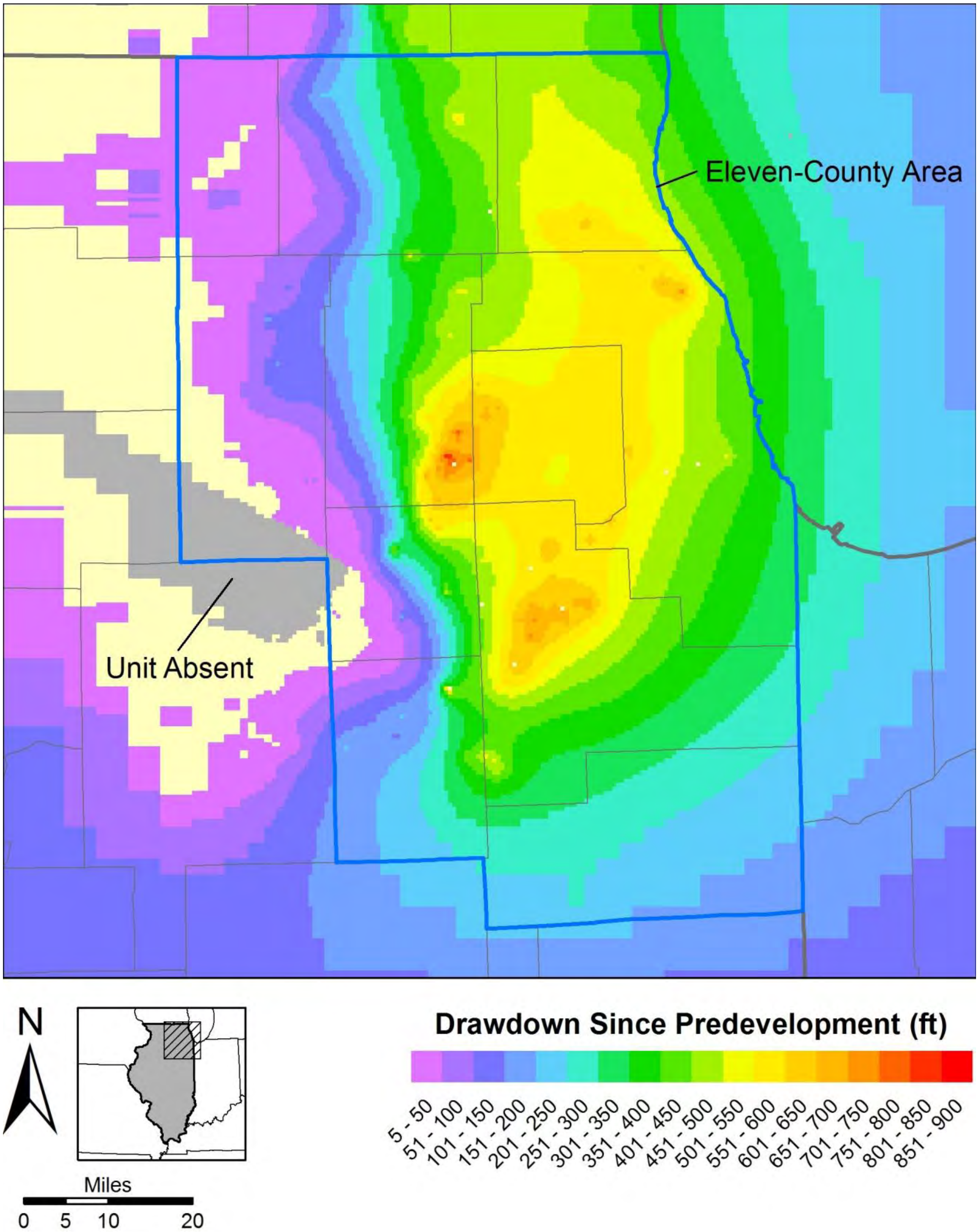


Figure 87. Simulated drawdown in the Ancell Unit, end of 2050 summer irrigation season, BL scenario

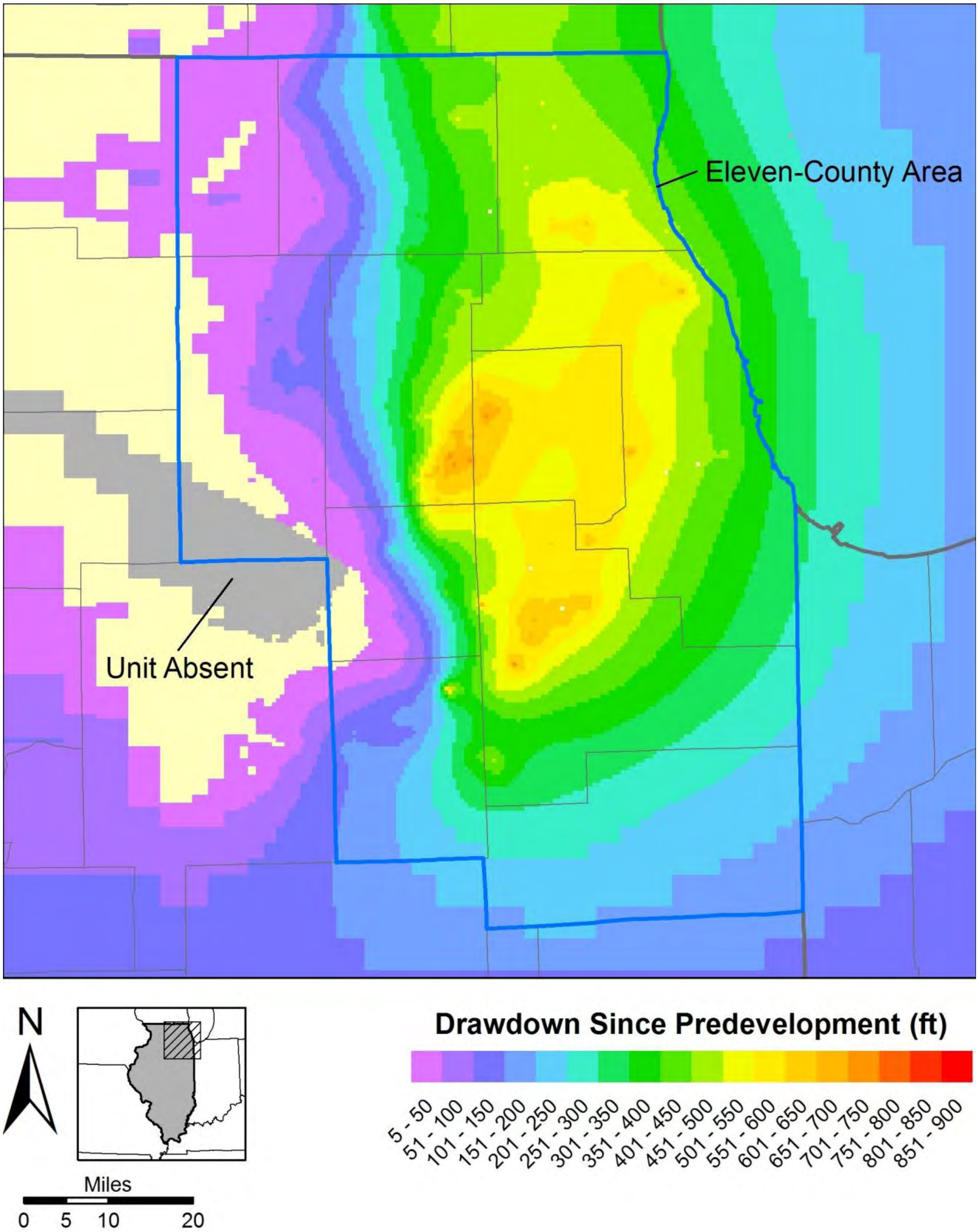


Figure 88. Simulated drawdown in the Ancell Unit, end of 2050 summer irrigation season, LRI scenario

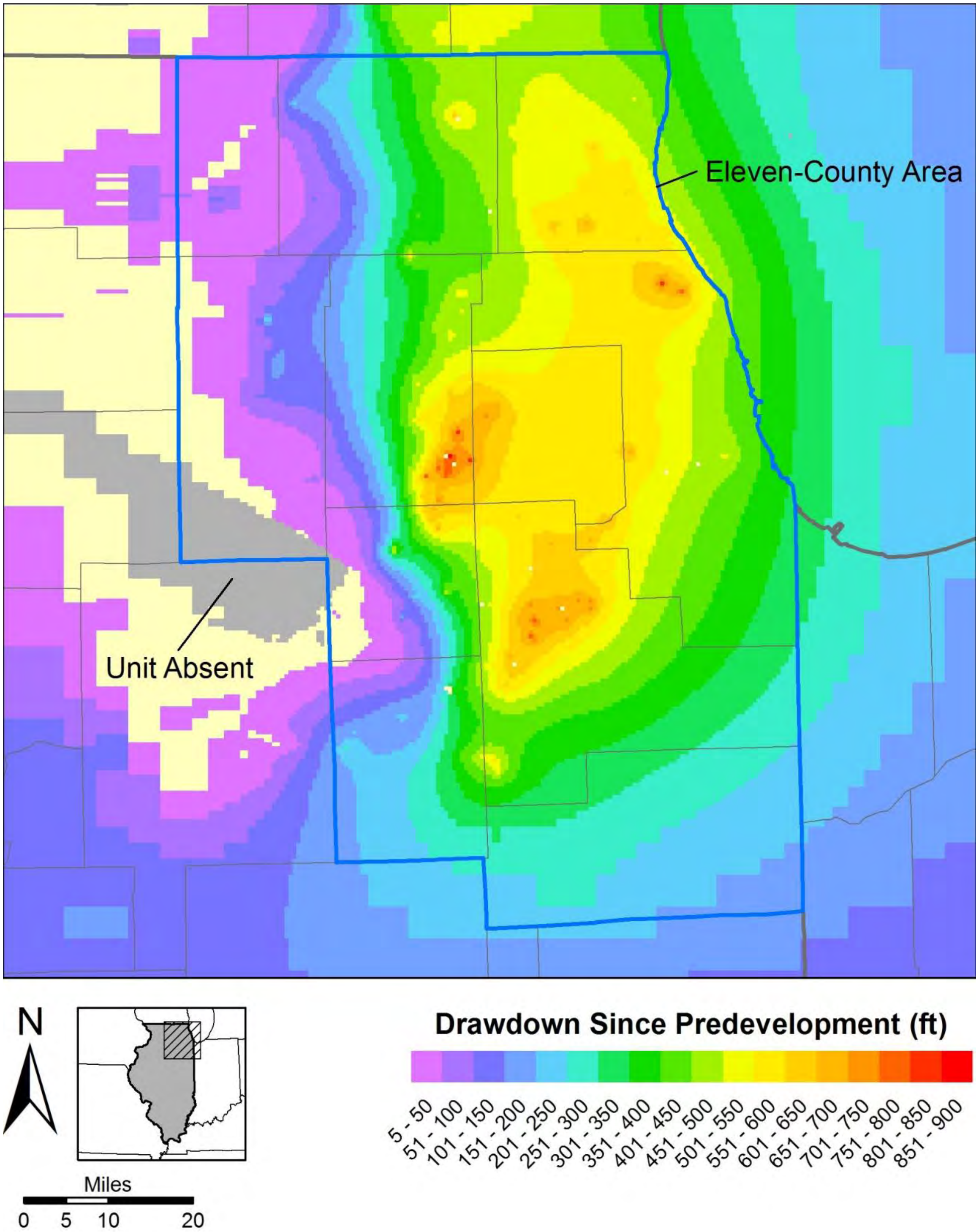


Figure 89. Simulated drawdown in the Ancell Unit, end of 2050 summer irrigation season, MRI scenario

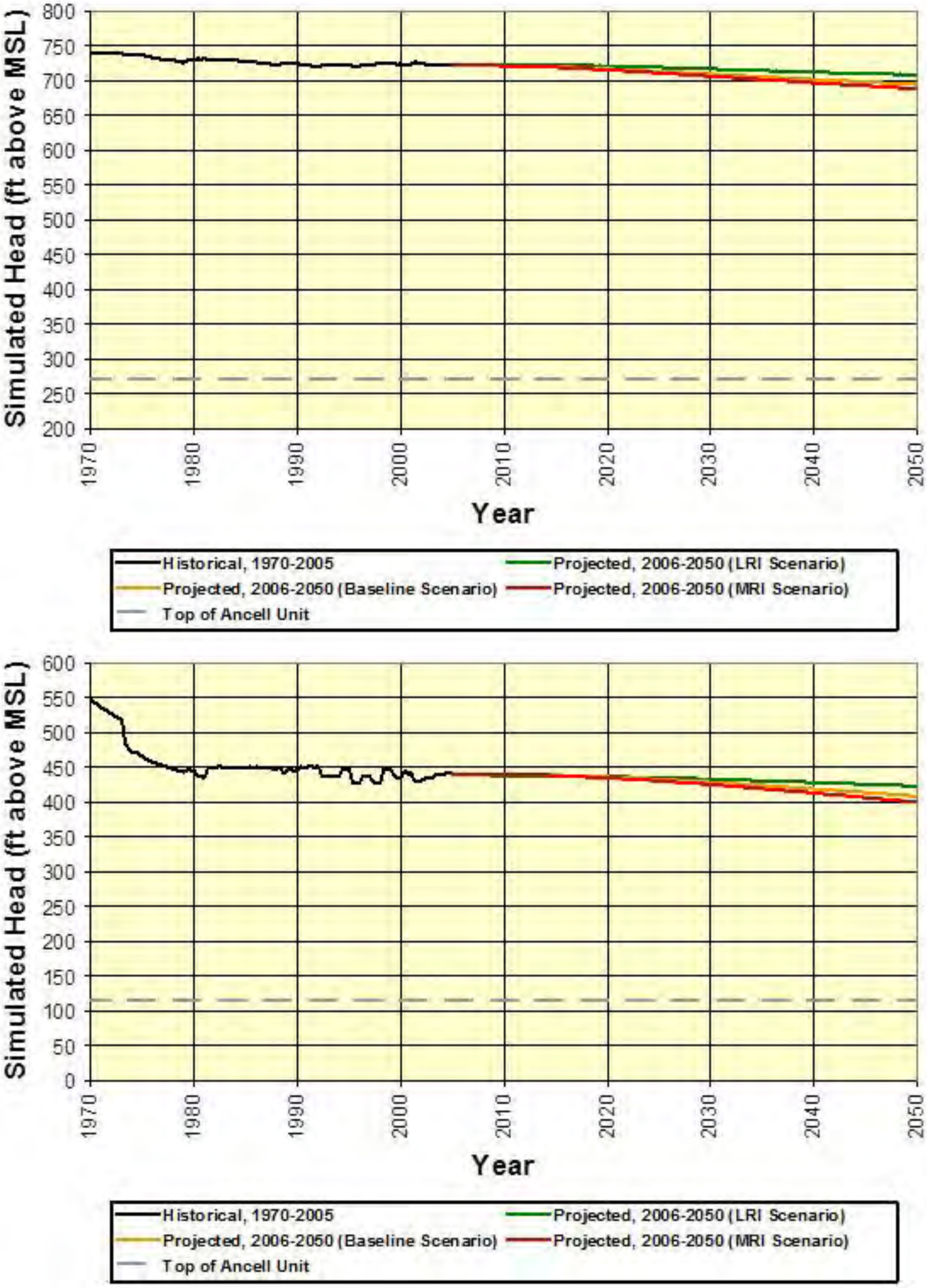


Figure 90. Simulated heads in the Ancell Unit at Maple Park (top) and Lake in the Hills (bottom)

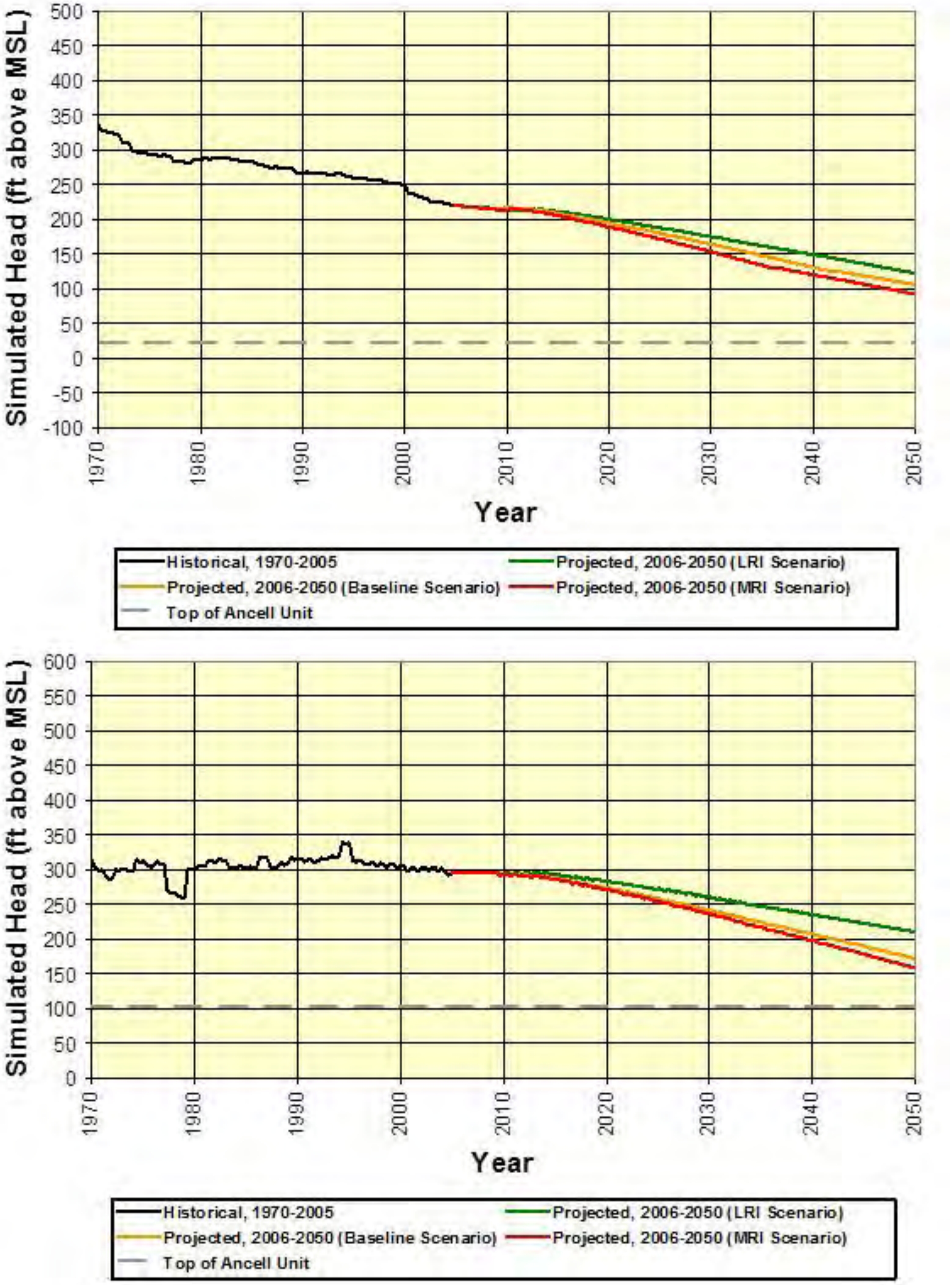
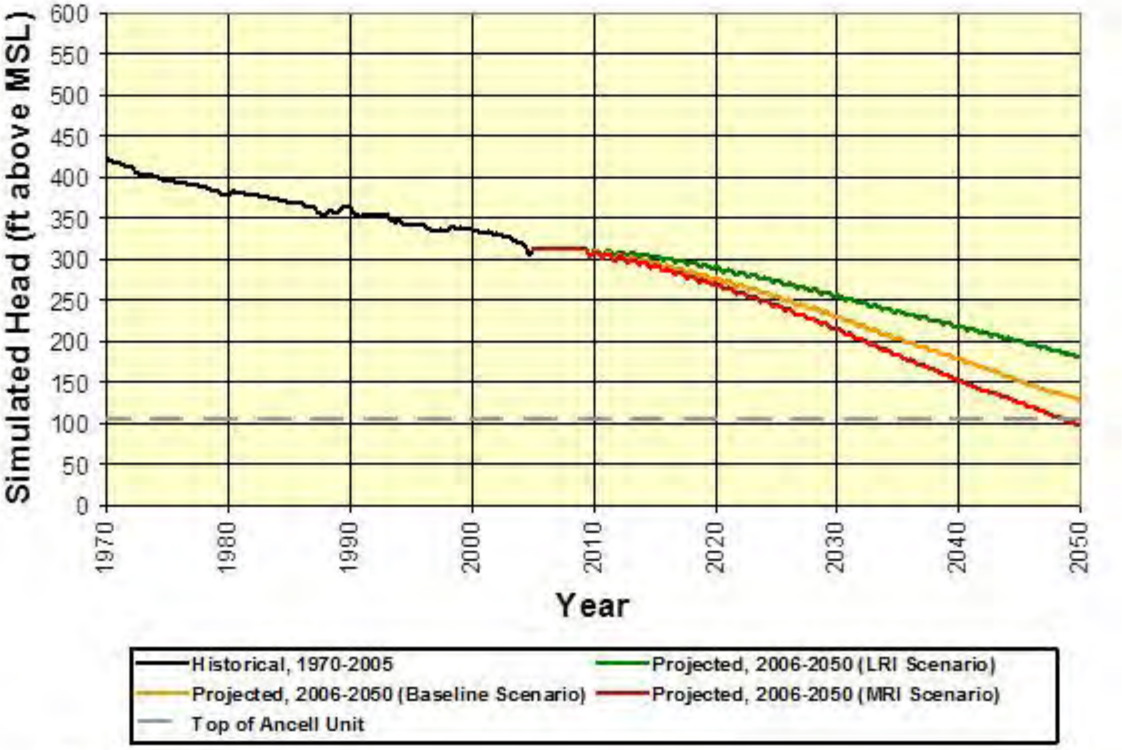


Figure 91. Simulated heads in the Ancell Unit at Shorewood (top) and St. Charles (bottom)



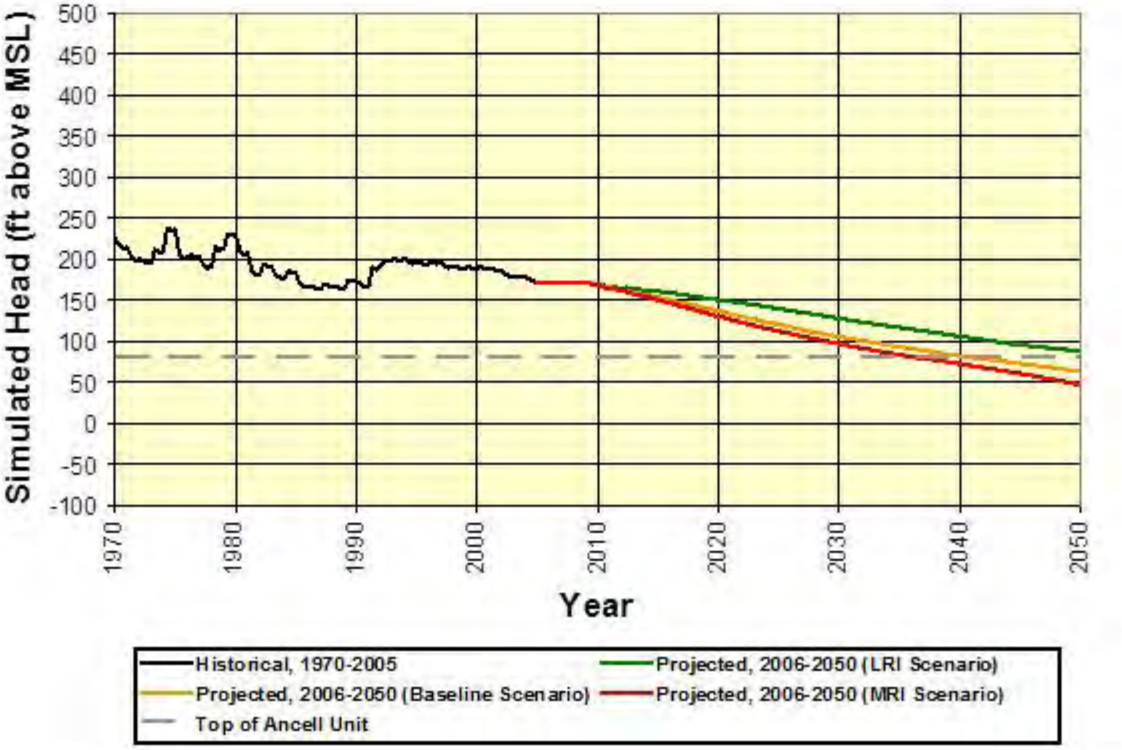


Figure 92. Simulated heads in the Ancell Unit at Oswego (top) and Aurora (bottom)

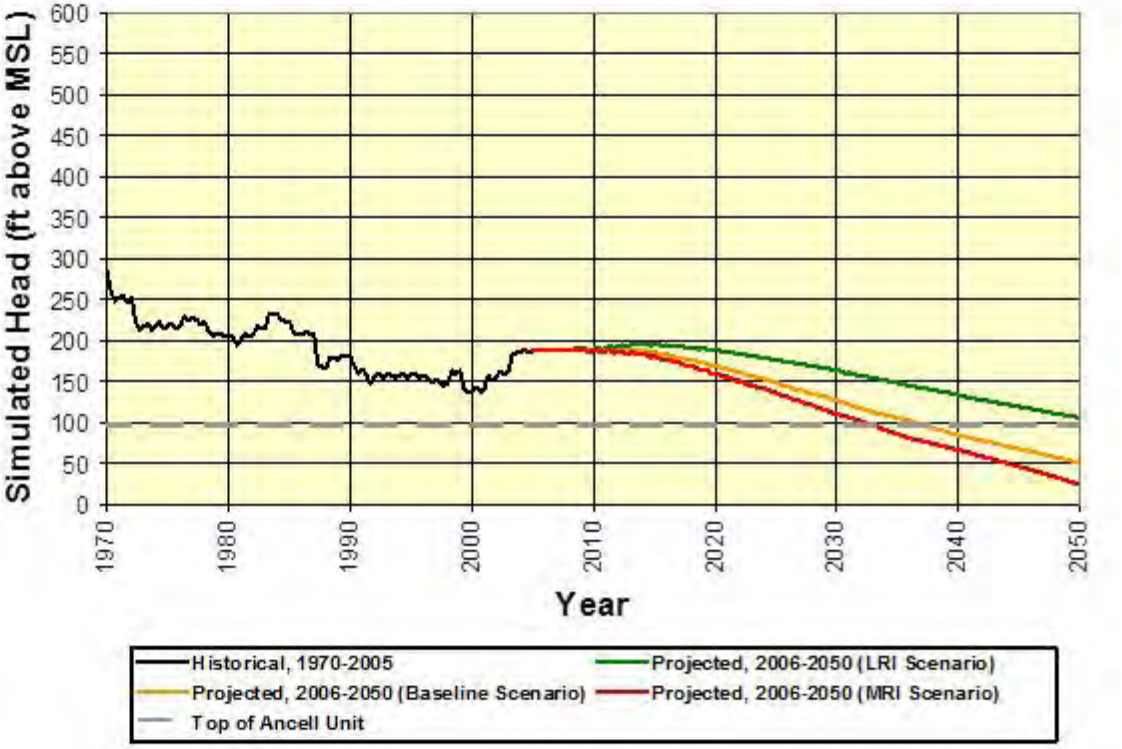


Figure 93. Simulated heads in the Ancell Unit at Montgomery

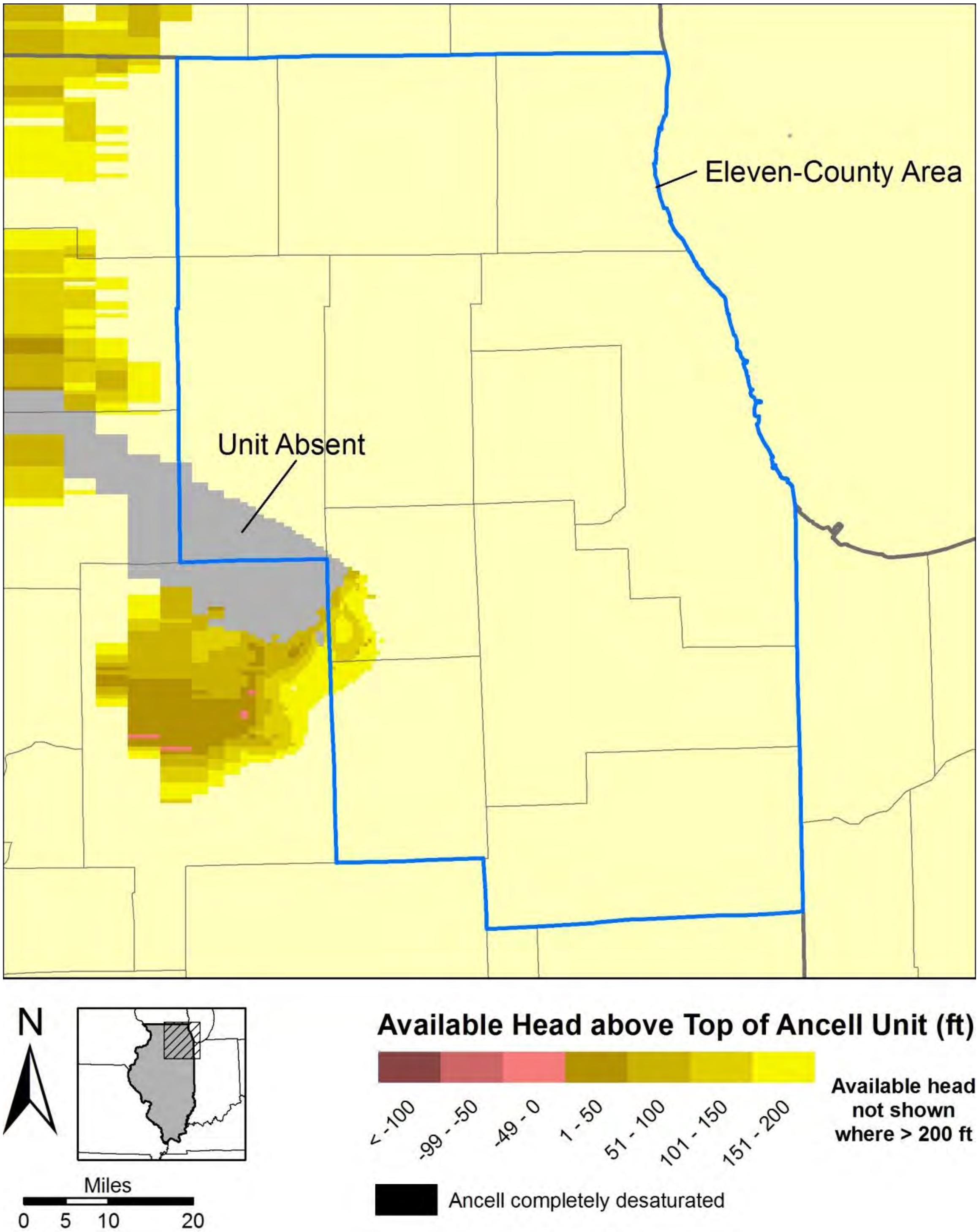


Figure 94. Available simulated Ancell Unit head above the top of Ancell Unit under predevelopment conditions. Available head is not shaded where greater than 200 feet.

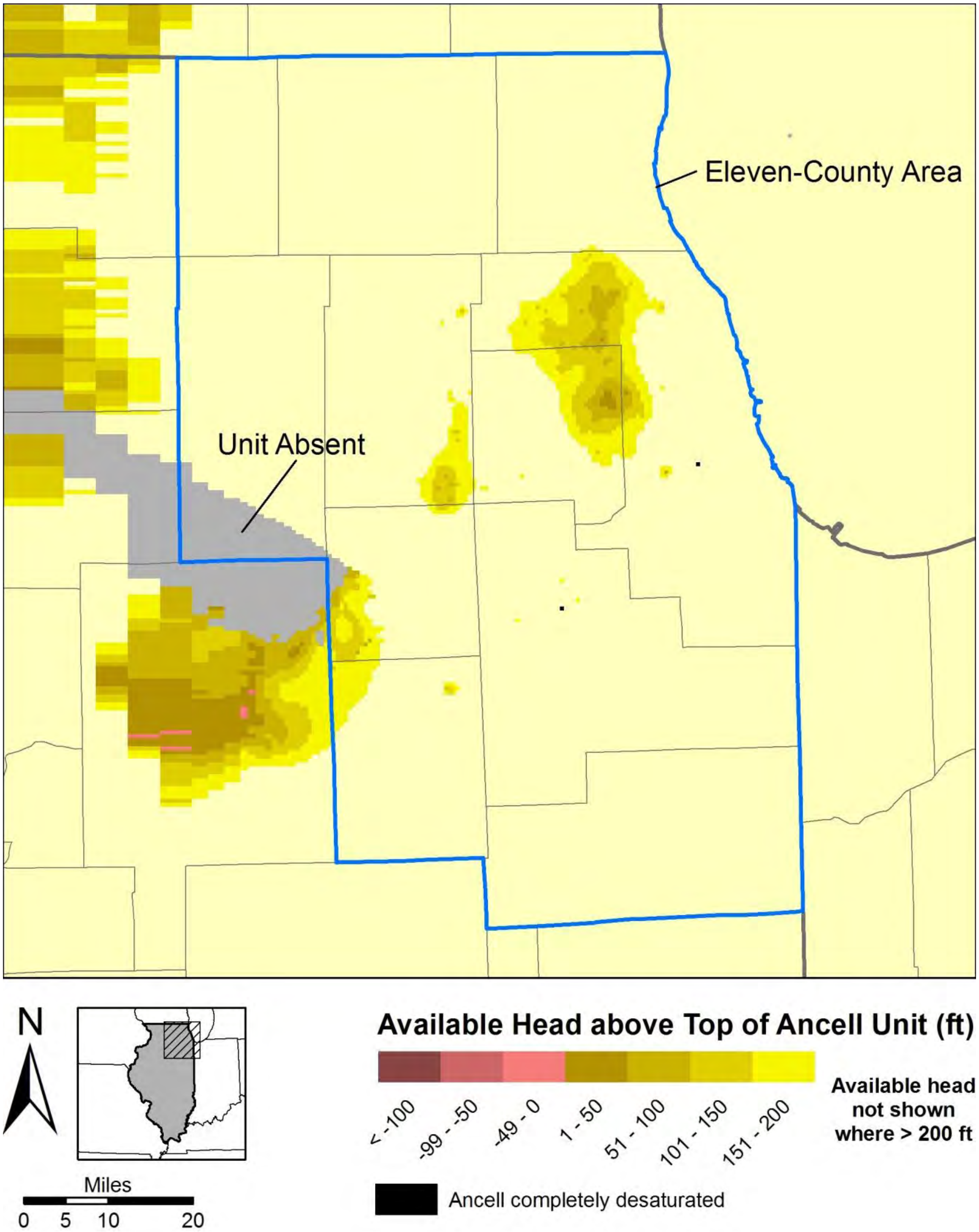


Figure 95. Available simulated Ancell Unit head above the top of Ancell Unit, end of 1985 summer irrigation season. Available head is not shaded where greater than 200 feet.

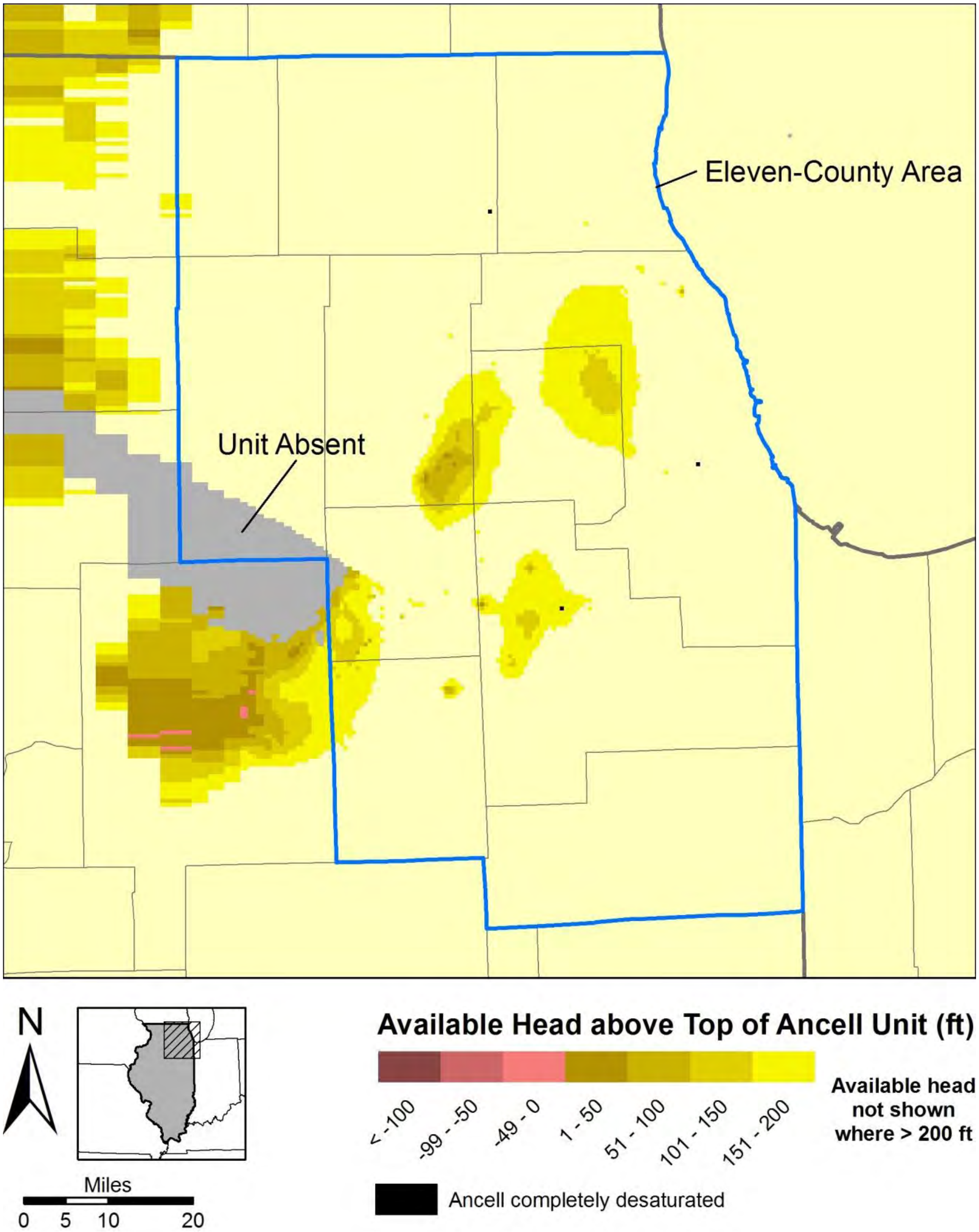


Figure 96. Available simulated Ancell Unit head above the top of Ancell Unit, end of 2005 summer irrigation season. Available head is not shaded where greater than 200 feet.

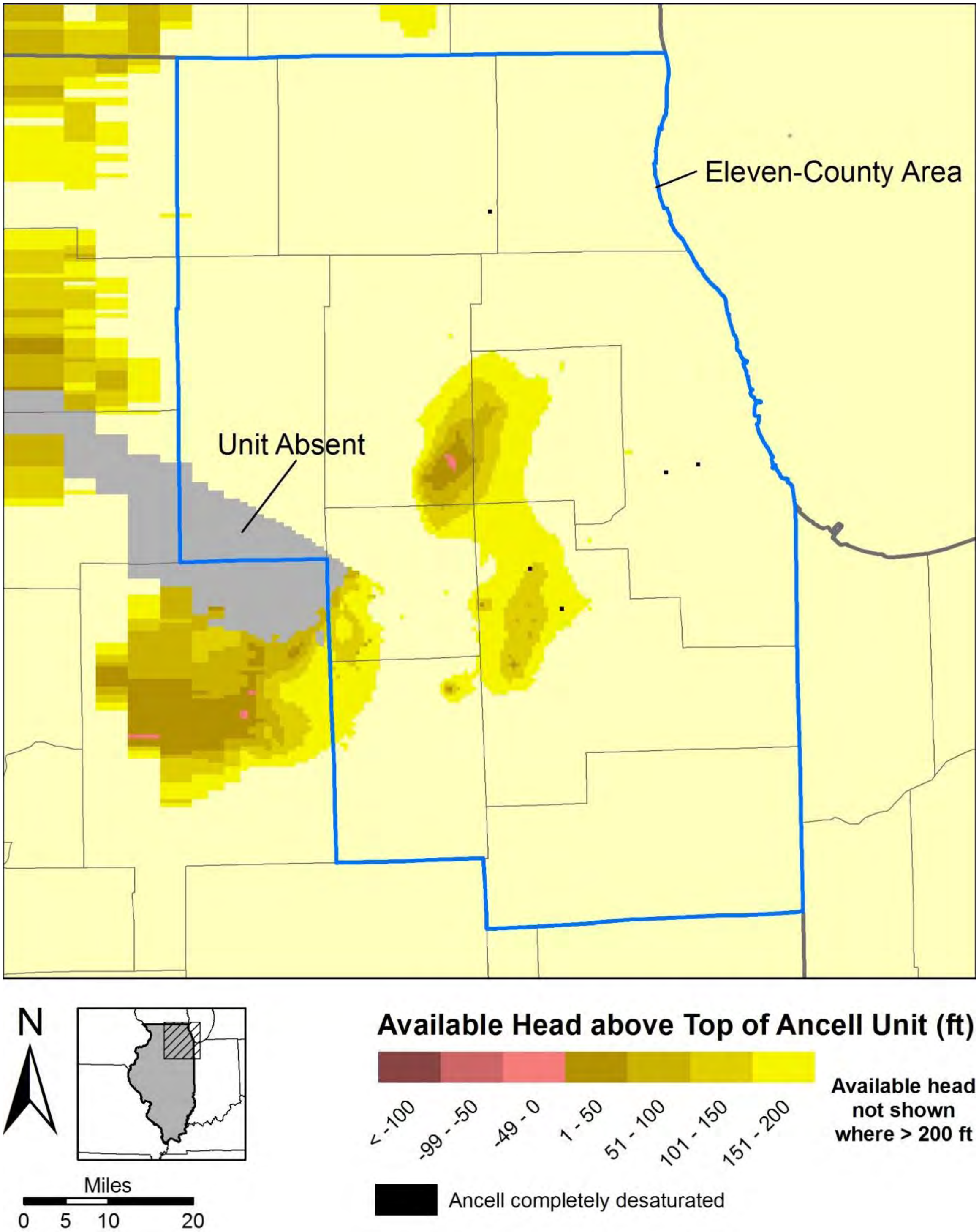


Figure 97. Available simulated Ancell Unit head above the top of Ancell Unit, end of 2025 summer irrigation season, BL scenario. Available head is not shaded where greater than 200 feet.

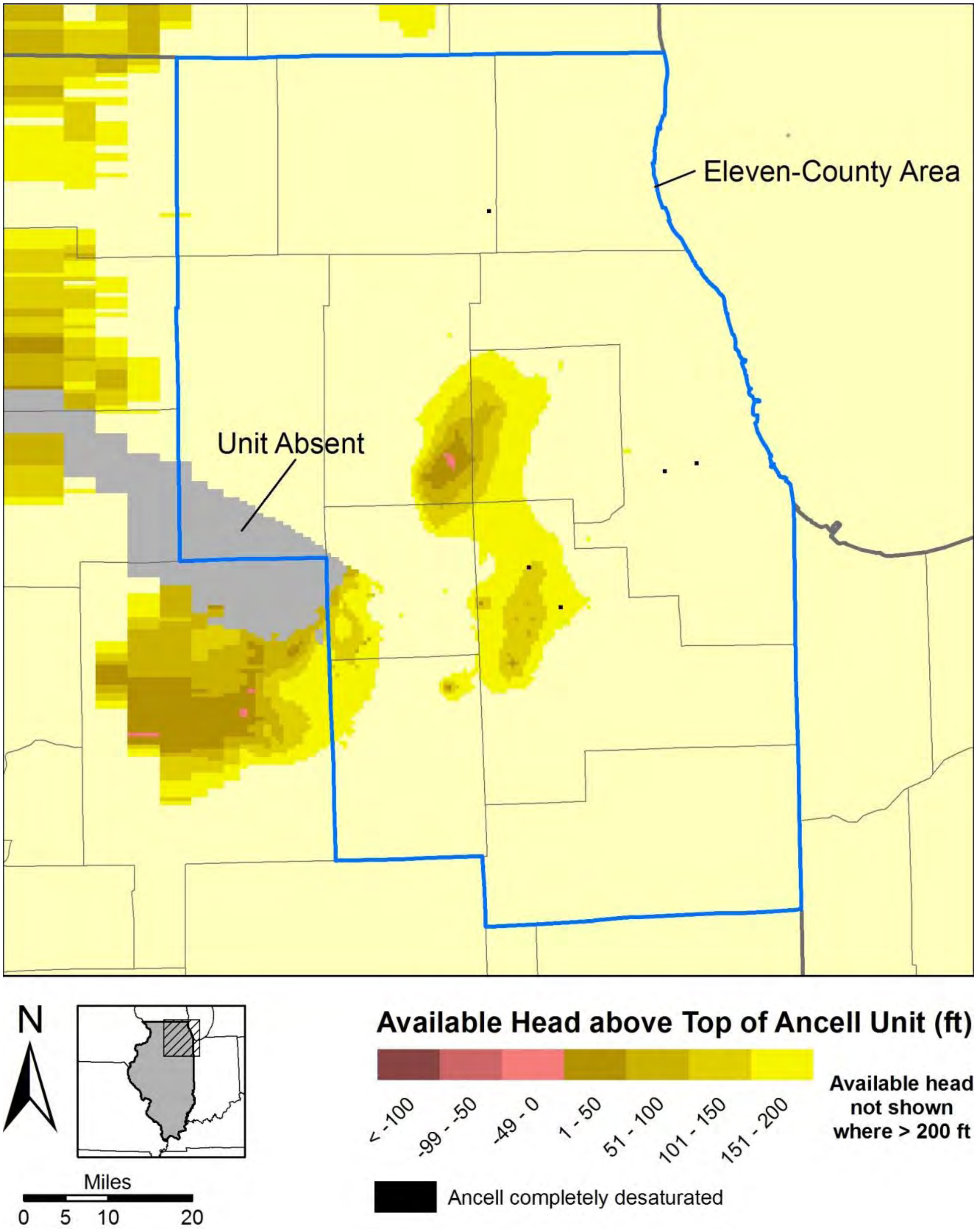


Figure 98. Available simulated Ancell Unit head above the top of Ancell Unit, end of 2025 summer irrigation season, LRI scenario. Available head is not shaded where greater than 200 feet.

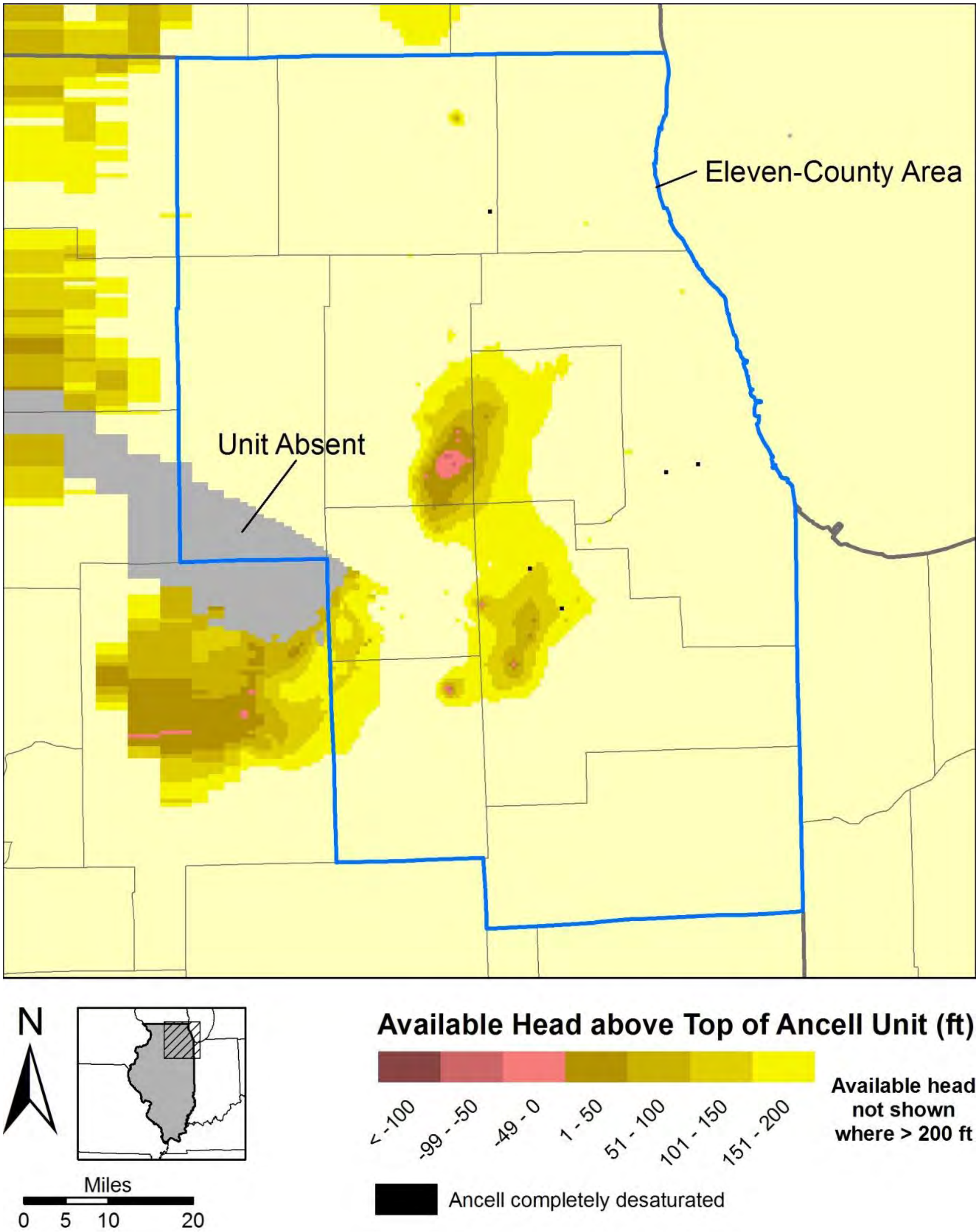


Figure 99. Available simulated Ancell Unit head above the top of Ancell Unit, end of 2025 summer irrigation season, MRI scenario. Available head is not shaded where greater than 200 feet.

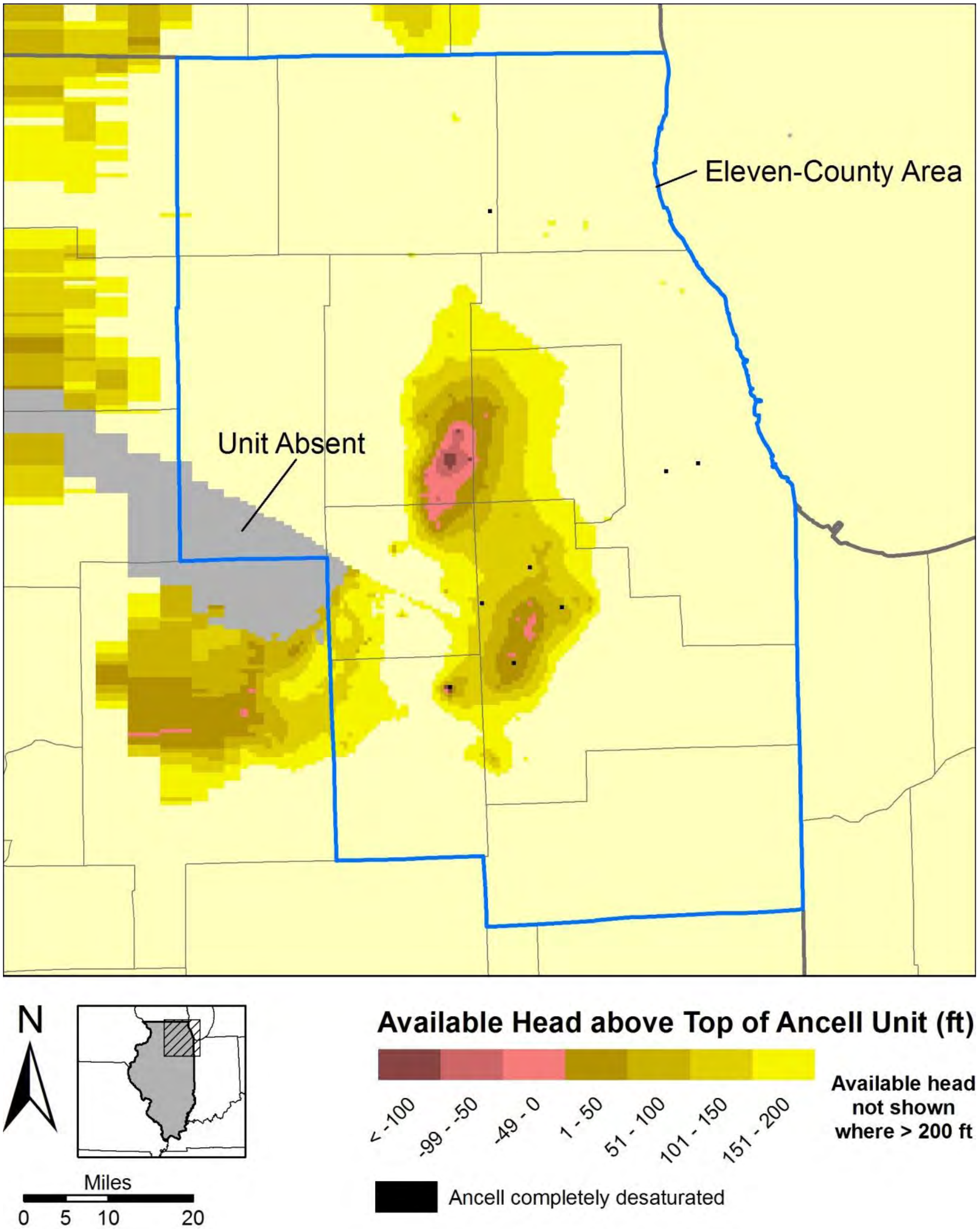


Figure 100. Available simulated Ancell Unit head above the top of Ancell Unit, end of 2050 summer irrigation season, BL scenario. Available head is not shaded where greater than 200 feet.

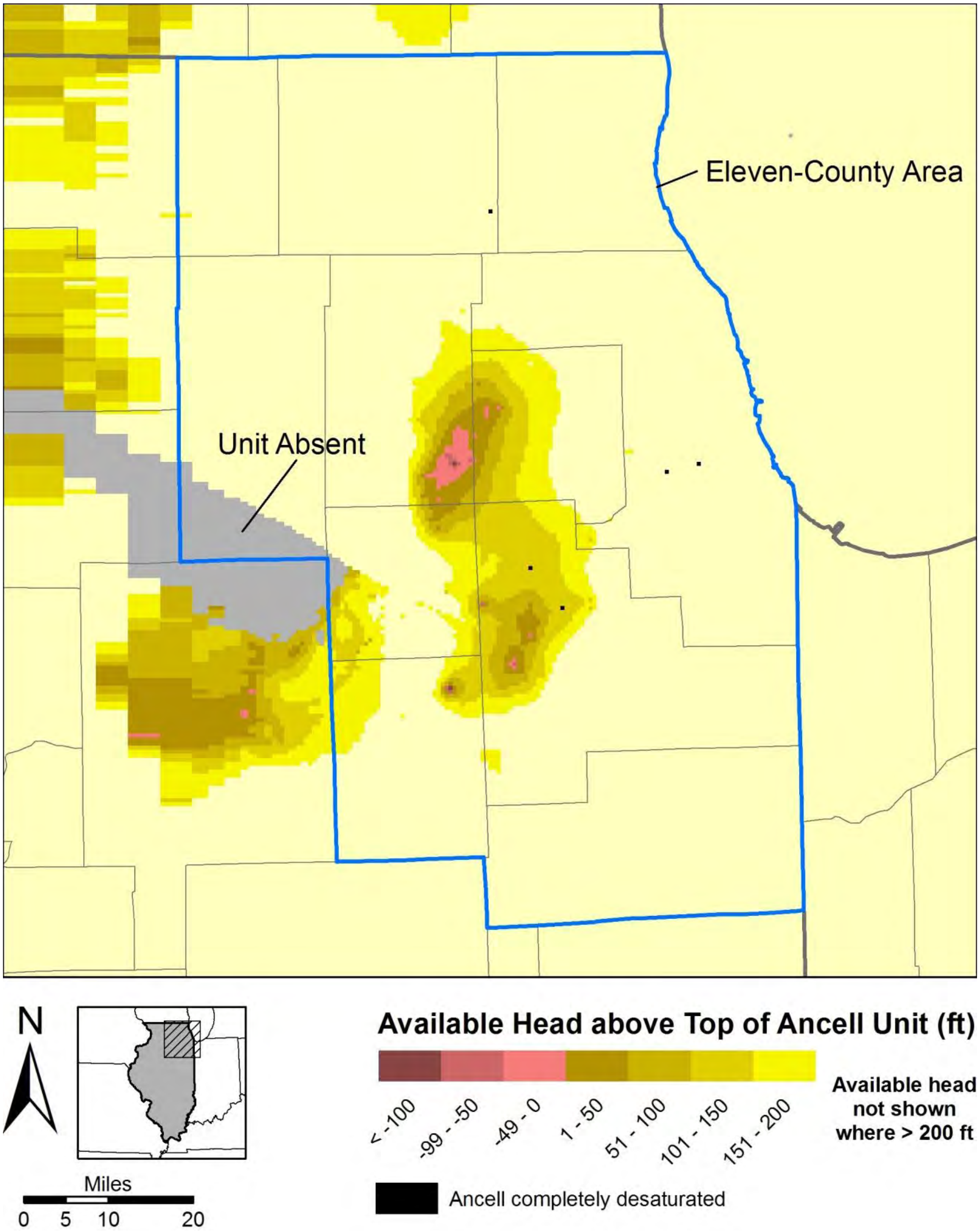


Figure 101. Available simulated Ancell Unit head above the top of Ancell Unit, end of 2050 summer irrigation season, LRI scenario. Available head is not shaded where greater than 200 feet.

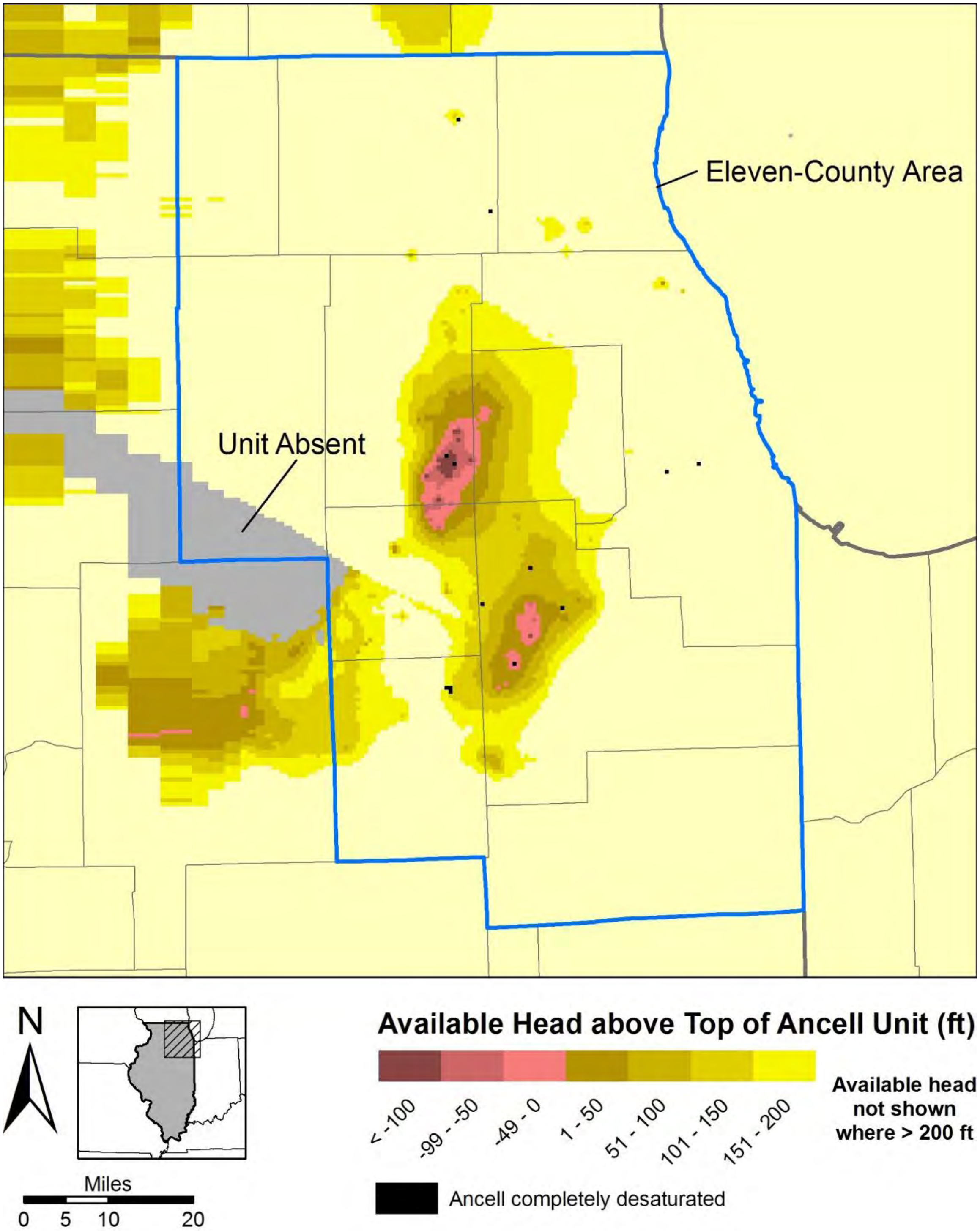


Figure 102. Available simulated Ancell Unit head above the top of Ancell Unit, end of 2050 summer irrigation season, MRI scenario. Available head is not shaded where greater than 200 feet.

Ironton-Galesville Unit. The authors advise readers that simulated Ironton-Galesville heads are probably not as accurate as the simulated Ancell Unit heads owing to lack of formation-specific head observations for use in model calibration and verification (page 148), nonsimulation of interformational transfer of groundwater via open boreholes (page 148 and Section 4.2.4.4), termination of withdrawals when cells become desaturated (page 107), and difficulties in controlling cell resaturation (page 149). Improvement of the regional model to reduce error originating from these problems is ongoing.

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

Further study is needed to determine how interformational transfer of groundwater via boreholes open to the Ancell and the Ironton Galesville Units affects heads. The simulations discussed in this report assume no interformational transfer, and the simulated Ironton-Galesville heads at Joliet are as much as 900 feet below the simulated Ancell heads. Yet measurements by Burch (2002) at Joliet and Nicholas et al. (1987) at Zion suggest that head differences between the two aquifers are less than 60 feet. In their lower-resolution flow model of the deep aquifers, Mandle and Kontis (1992) used an algorithm developed by Bennett et al. (1982) to simulate interformational transfers of groundwater which resulted in nearly equal modeled heads in the two units. This complicated algorithm has yet to be coded into MODFLOW.

Automatic termination of withdrawals from wells open to the Ironton-Galesville, caused by complete desaturation of the unit, as well as persistent desaturated conditions indicative of cell resaturation problems, may compound and reflect model uncertainties brought about by the lack of Ironton-Galesville head calibration targets and/or non-simulation of interformational transfers of groundwater. For example, termination of withdrawals from the Ironton-Galesville, as well as failure of desaturated model cells to resaturate, may occur because the calibration procedure, poorly constrained owing to a lack of Ironton-Galesville head calibration targets, selects hydraulic parameters that cause the Ironton-Galesville to desaturate. Termination of withdrawals and poor cell resaturation may also reflect non-simulation of interformational transfers of groundwater, which would contribute groundwater to the Ironton-Galesville and thereby offset desaturation.

Because multiple sources of uncertainty affect the simulated Ironton-Galesville heads, the authors illustrate and discuss results only for the historical period ending in 2005 and for the BL scenario from 2006 to 2050. The authors do not cover the LRI and MRI results for the Ironton-Galesville as it is likely that the sources of uncertainty discussed above affect the simulated heads as much or more than differences in pumping rates between the BL, LRI, and MRI scenarios.

Simulated Ironton-Galesville drawdown at the close of the 1985 irrigation season exceeds 1400 feet in eastern DuPage and northern Will Counties (Figure 103). By 2005

(Figure 104), the cone of depression is reduced in size as a result of reductions in deep bedrock withdrawals when Lake Michigan water became available to DuPage County and northwestern Cook County (Figure 26, Figure 29, Figure 32, and Figure 34 show temporal and spatial changes in deep bedrock withdrawals). The deepest part of the cone persists, however, in the Joliet area of Will County, with significant drawdown extending into the Aurora area of southeastern Kane County. By 2025, the cone of depression centered in Will County expands (Figure 105), and by 2050, the drawdown pattern established in 2025 expands northward up the Fox River valley (Figure 106).

Note that sporadically-present unshaded areas in maps of simulated Ironton-Galesville drawdown (Figure 103 to Figure 106), most commonly single model cells that are barely visible in the figures, may represent model cells that were not resaturated following desaturation accompanying historical high pumping rates (page 149). The desaturation is probably of this erroneous long-term type where the unshaded cells are not surrounded by a concentric pattern of increasing drawdown. Most obvious is the group of unshaded (and therefore desaturated) cells in Cook County representing the 1864-1963 Chicago pumping center (see Figure 25). Efforts to correct the resaturation issue are ongoing.

Hydrographs for model cells near Maple Park, Lake in the Hills, St. Charles, Aurora, Shorewood, Oswego, and Montgomery (locations shown in Figure 68) illustrate temporal changes in simulated Ironton-Galesville heads. At Maple Park (Figure 107 top), simulated heads remain over 400 feet above the top of the Ironton-Galesville. At Lake in the Hills (Figure 107 bottom), Ironton-Galesville heads fall to within 250 feet of the Ironton-Galesville. The hydrograph at St. Charles (Figure 108 top) is similar to Lake In The Hills, although heads are roughly 100 feet lower than at Lake in the Hills. Heads fall into the Ironton-Galesville by 2030 at Aurora (Figure 108 bottom), but readers should note that heads were comparably low in the Aurora area in the mid- to late-1980s, before Lake Michigan allocations relieved pumping stresses on the deep aquifers. Heads also fall to near or below the top of the Ironton-Galesville at Shorewood, Oswego, and Montgomery (Figure 108 to Figure 110) before 2025. At Oswego and Montgomery (Figure 109 and Figure 110), model simulations suggest that the Ironton-Galesville becomes completely desaturated before 2050; heads declining precipitously after 2030 are due to a reduction in aquifer transmissivity.

The authors caution readers about the desaturation of the Ironton-Galesville at Montgomery and Oswego suggested by the model simulations. The authors believe the Ironton-Galesville would not become completely desaturated as the model suggests, because wells at these and similar locations of precipitous head decline would fail or would be turned off before heads decline to the point of complete desaturation. Still, the locations of model-simulated Ironton-Galesville desaturation—despite model uncertainties, simplifications, and assumptions—strongly suggest areas for priority consideration in future monitoring and water-supply planning.

Likewise, areas where available Ironton-Galesville head is less than 200 feet (Figure 111 to Figure 114) might be considered as priorities for monitoring and planning. Figure 111 to Figure 114 show sporadically-present black areas representing model cells that were not resaturated after being completely desaturated by historical high pumping rates. These cells are unshaded in maps of simulated Ironton-Galesville drawdown (Figure 103 to Figure 106) and are discussed above.

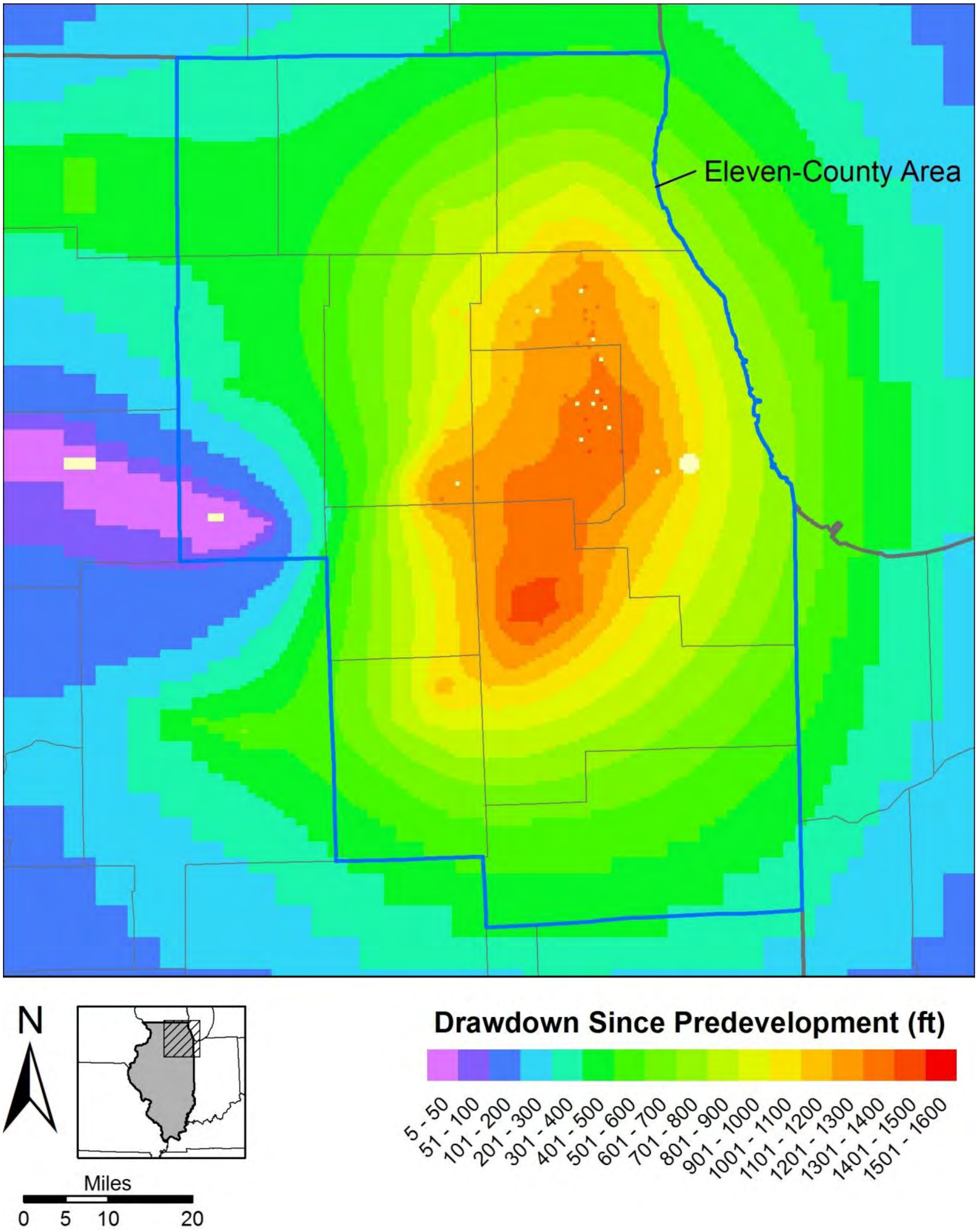


Figure 103. Simulated drawdown in the Ironton-Galesville Unit, end of summer irrigation season, 1985

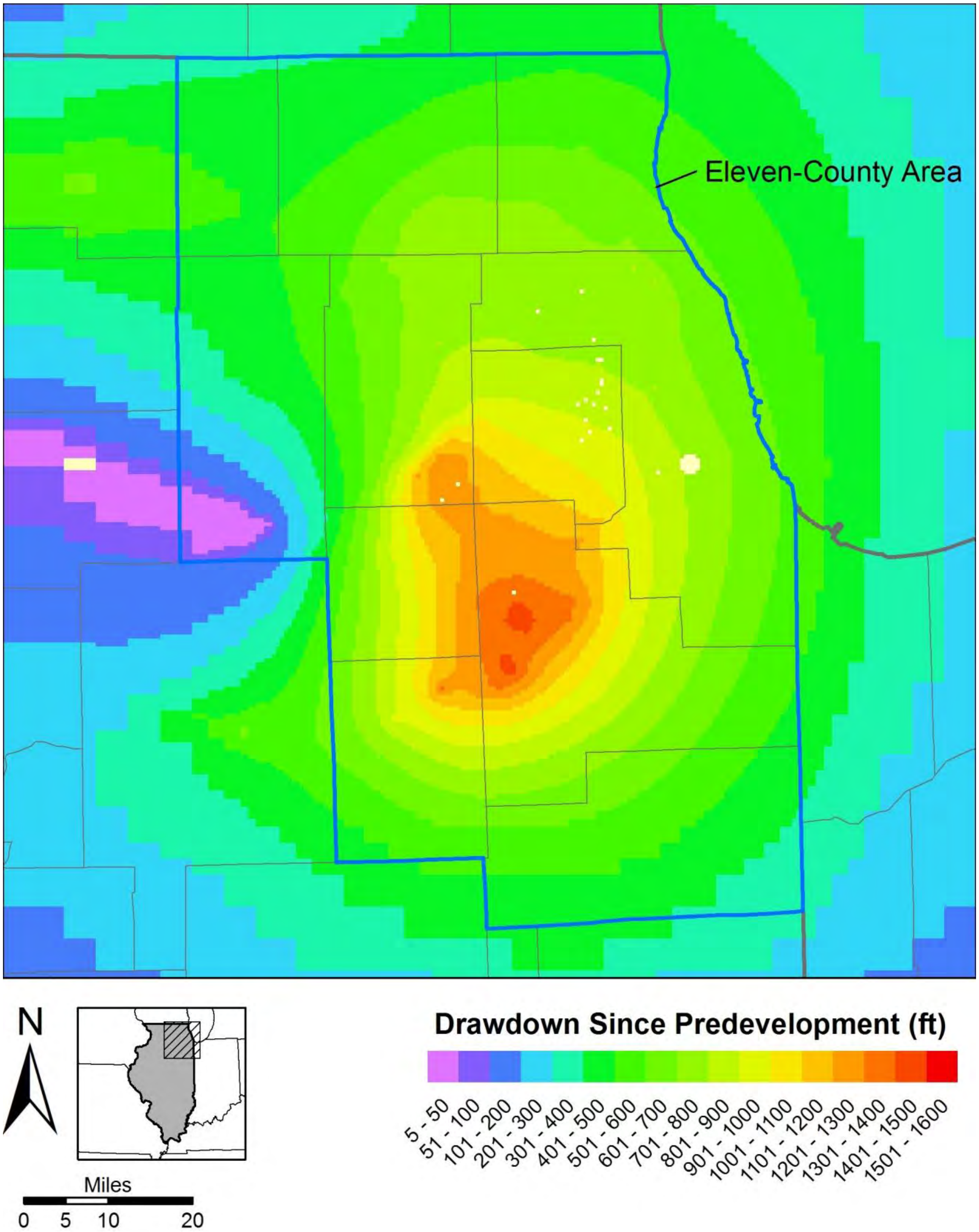


Figure 104. Simulated drawdown in the Ironton-Galesville Unit, end of summer irrigation season, 2005

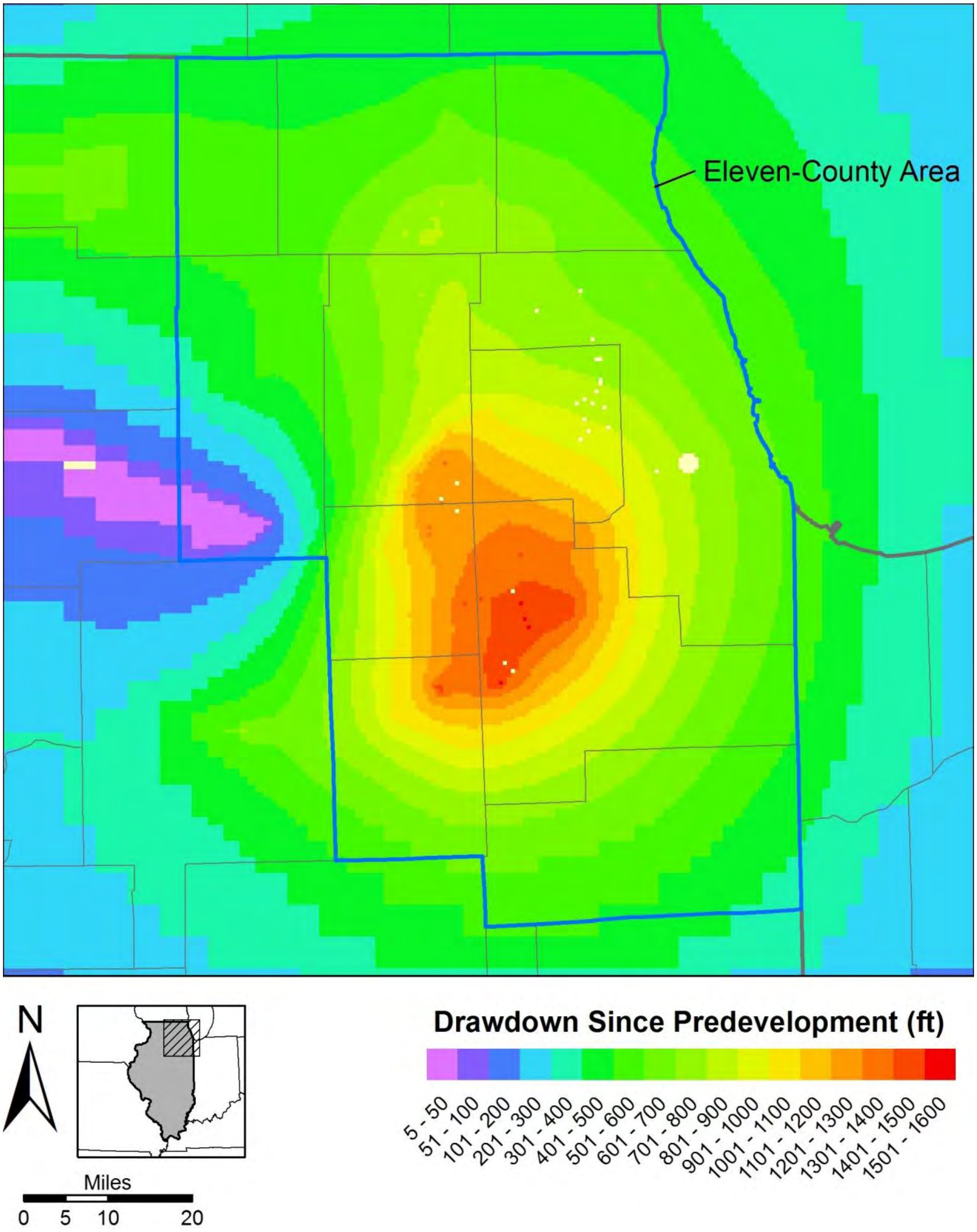


Figure 105. Simulated drawdown in the Ironton-Galesville Unit, end of 2025 summer irrigation season, BL scenario

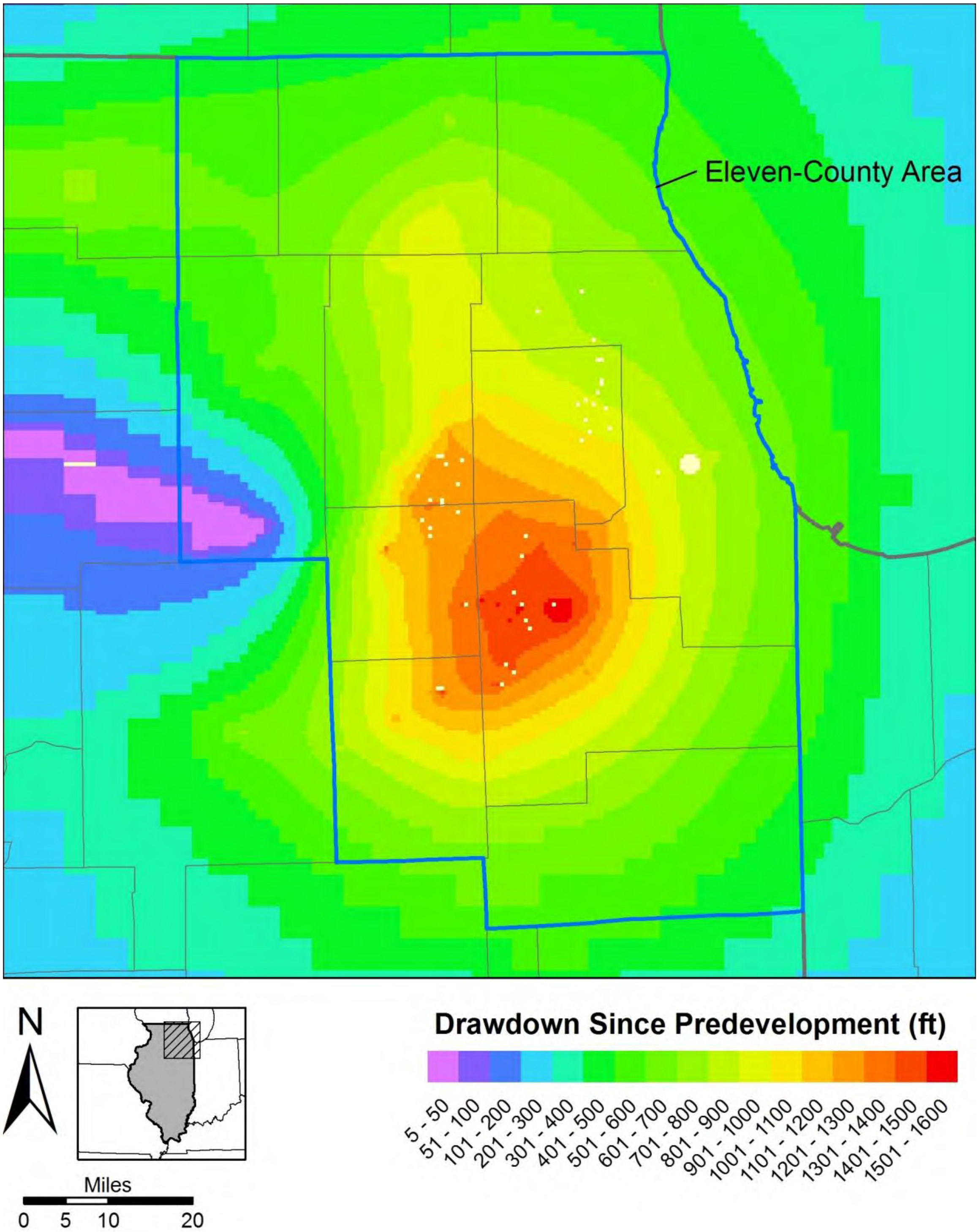


Figure 106. Simulated drawdown in the Ironton-Galesville Unit, end of 2050 summer irrigation season, BL scenario

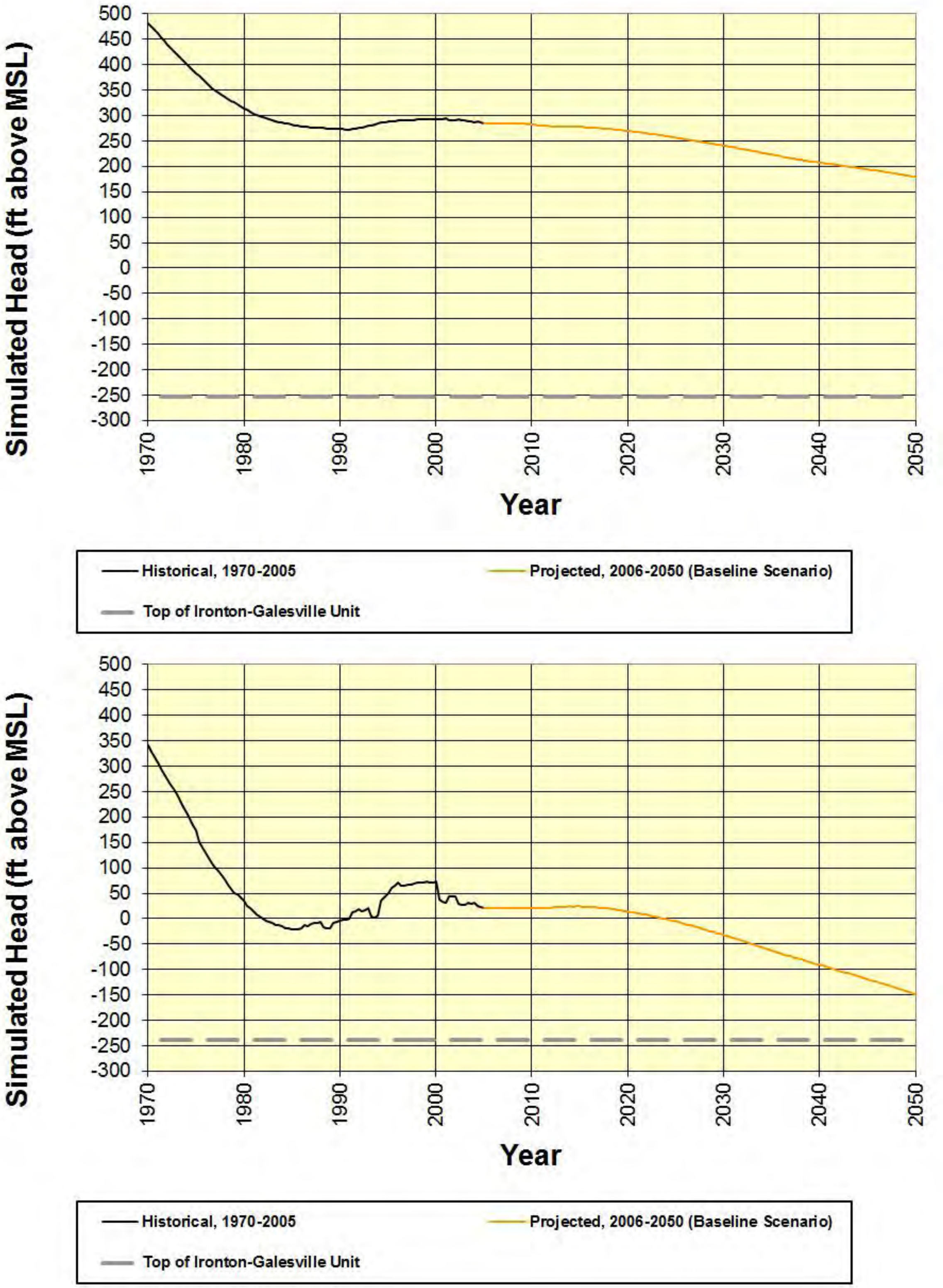


Figure 107. Simulated heads in the Ironton-Galesville Unit at Maple Park (top) and Lake in the Hills (bottom)

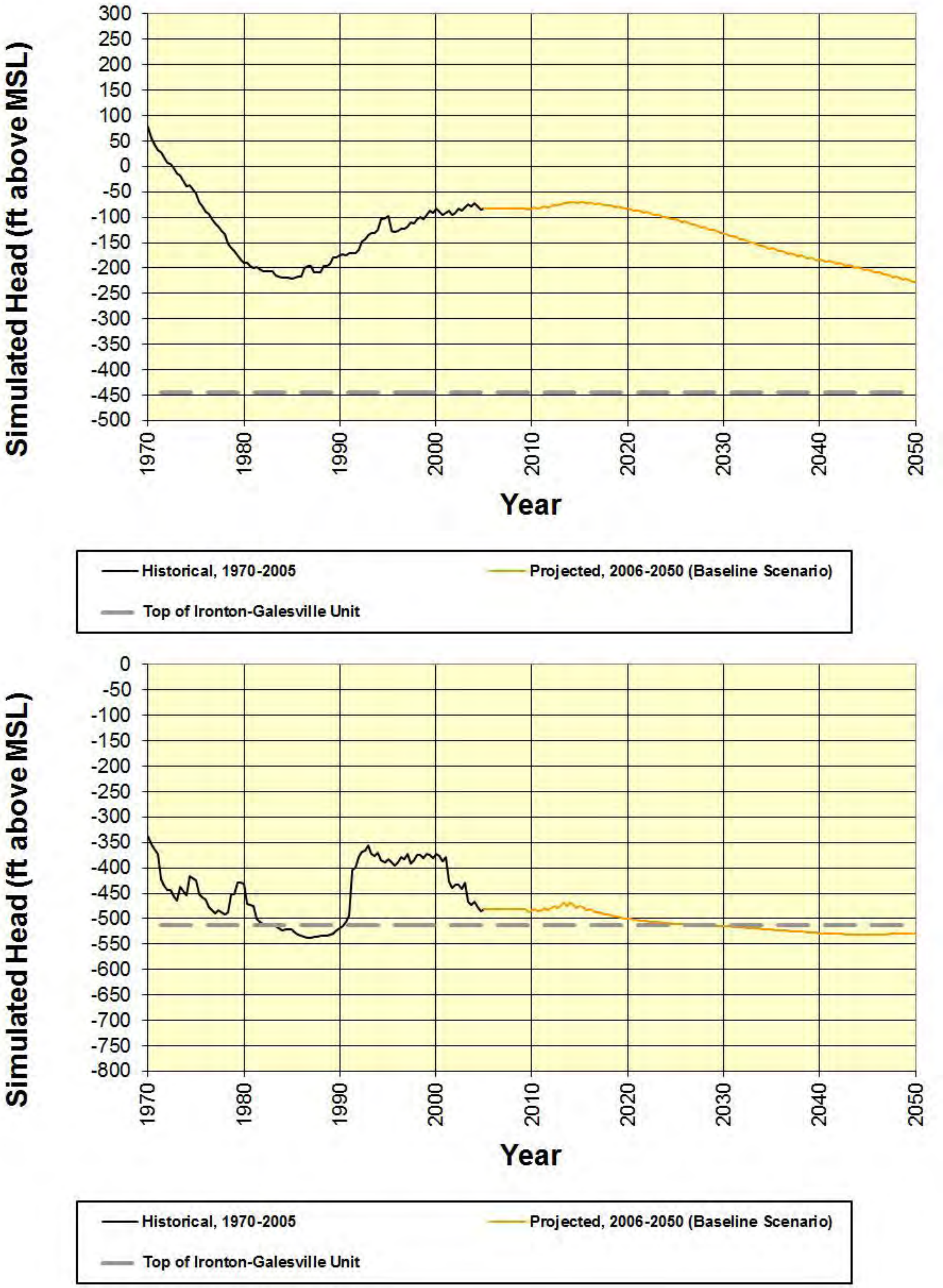


Figure 108. Simulated heads in the Ironton-Galesville Unit at St. Charles (top) and Aurora (bottom)

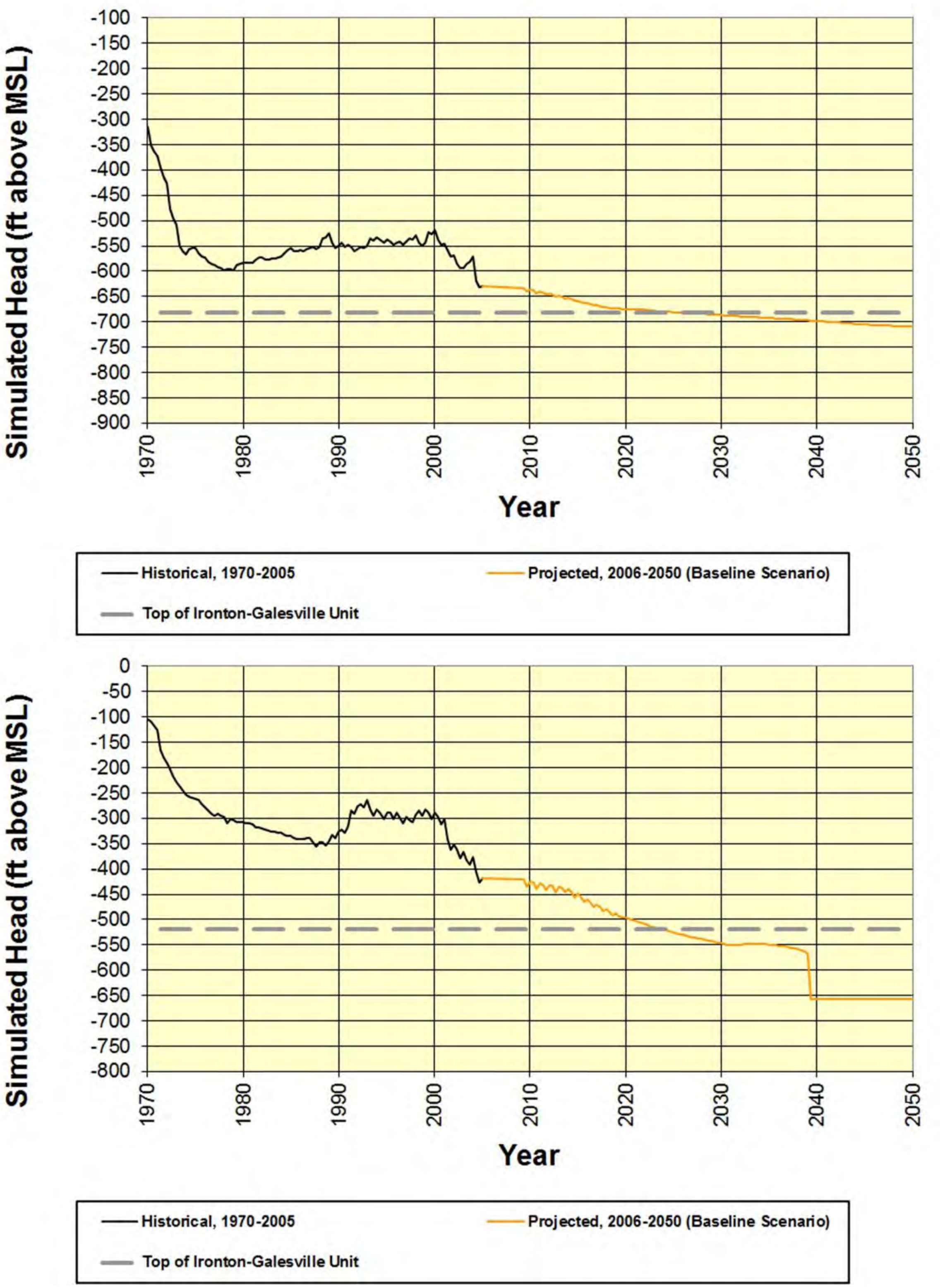


Figure 109. Simulated heads in the Ironton-Galesville Unit at Shorewood (top) and Oswego (bottom)

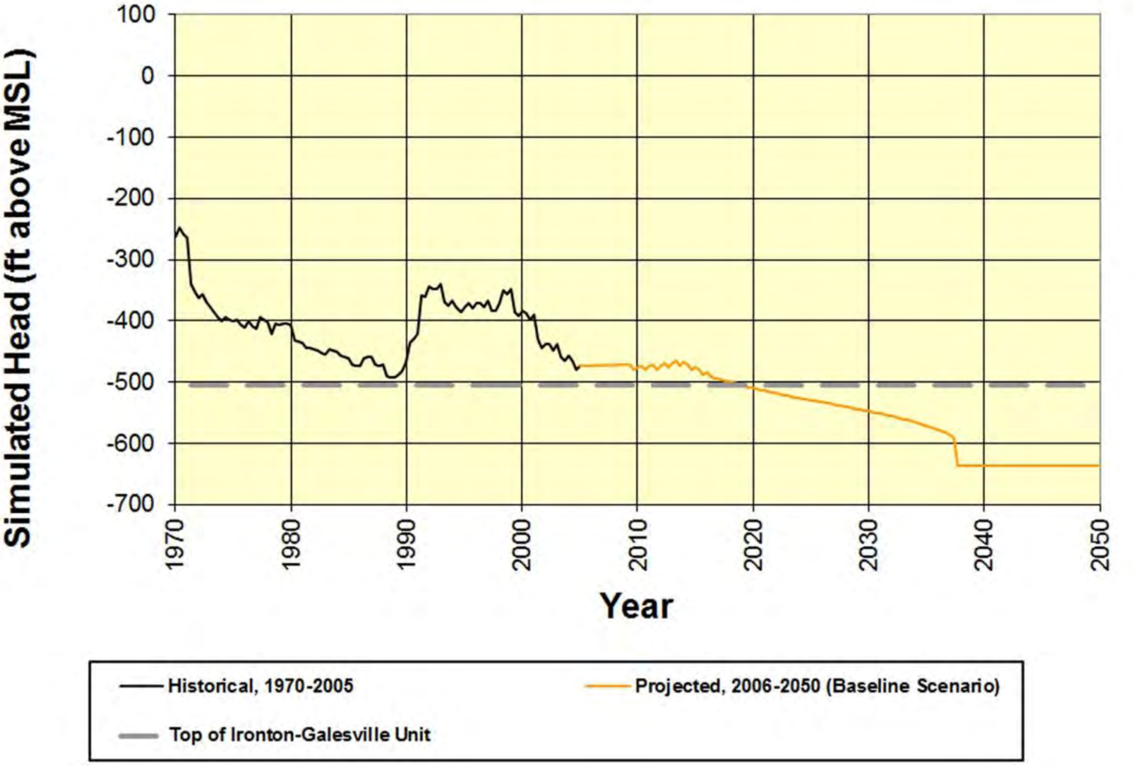


Figure 110. Simulated heads in the Ironton-Galesville Unit at Montgomery

In 1985, available simulated head was near or below the top of the Ironton-Galesville in a broad area of eastern DuPage and northwestern Cook Counties (Figure 111). By 2005, available Ironton-Galesville head recovered in those areas, but declined to within 100 feet of the top of the unit in southeastern Kane and northwestern Will Counties (Figure 112). Model simulations show that the Aurora and Joliet areas of diminished available head continue to grow through 2025 (Figure 113) and 2050 (Figure 114), with heads falling below the top of the Ironton-Galesville in those two areas. Reduced available head also affects southeastern McHenry County in the 2050 BL scenario (Figure 114).

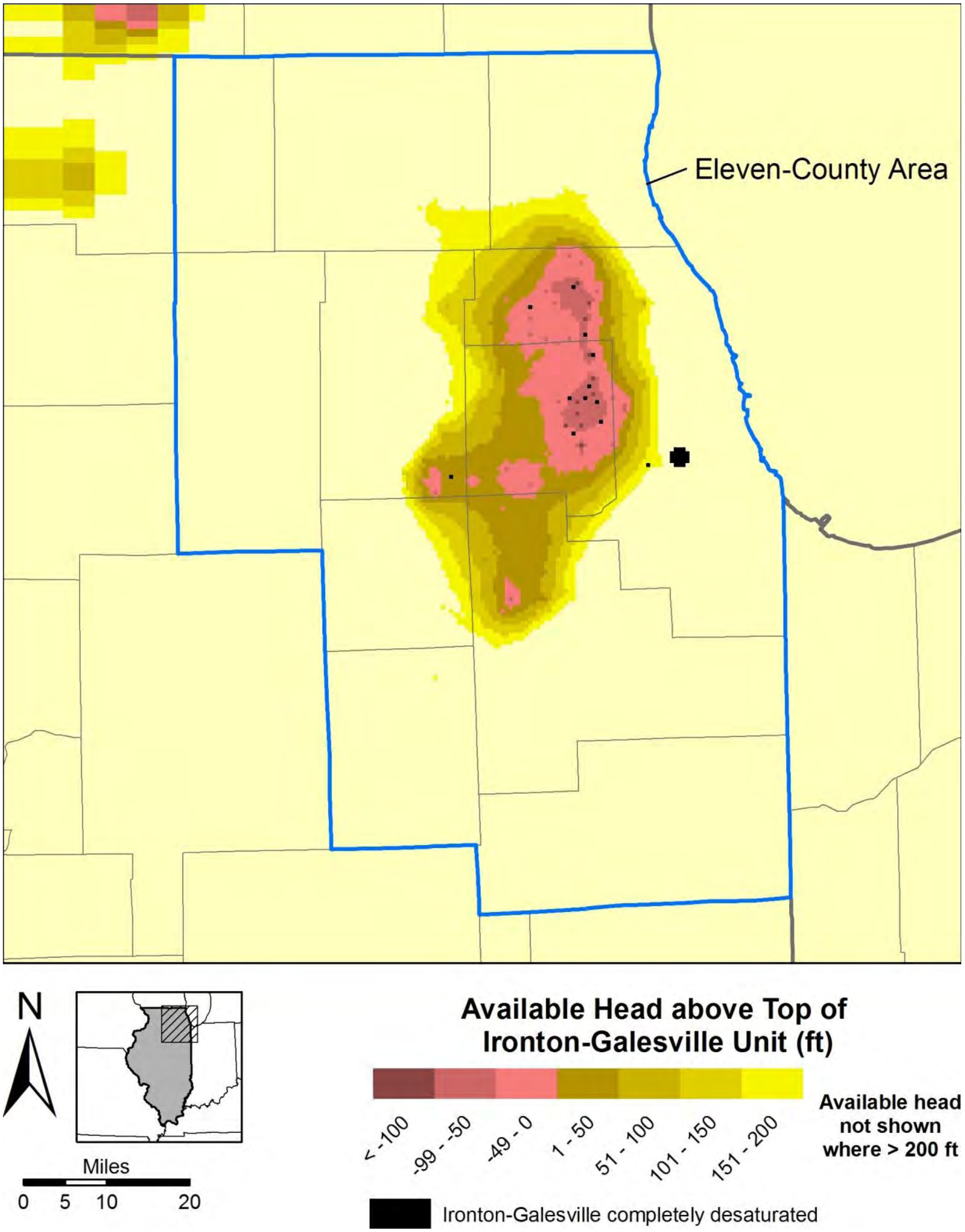


Figure 111. Available simulated Ironton-Galesville Unit head above the top of Ironton-Galesville Unit, end of 1985 summer irrigation season. Available head is not shaded where greater than 200 feet.

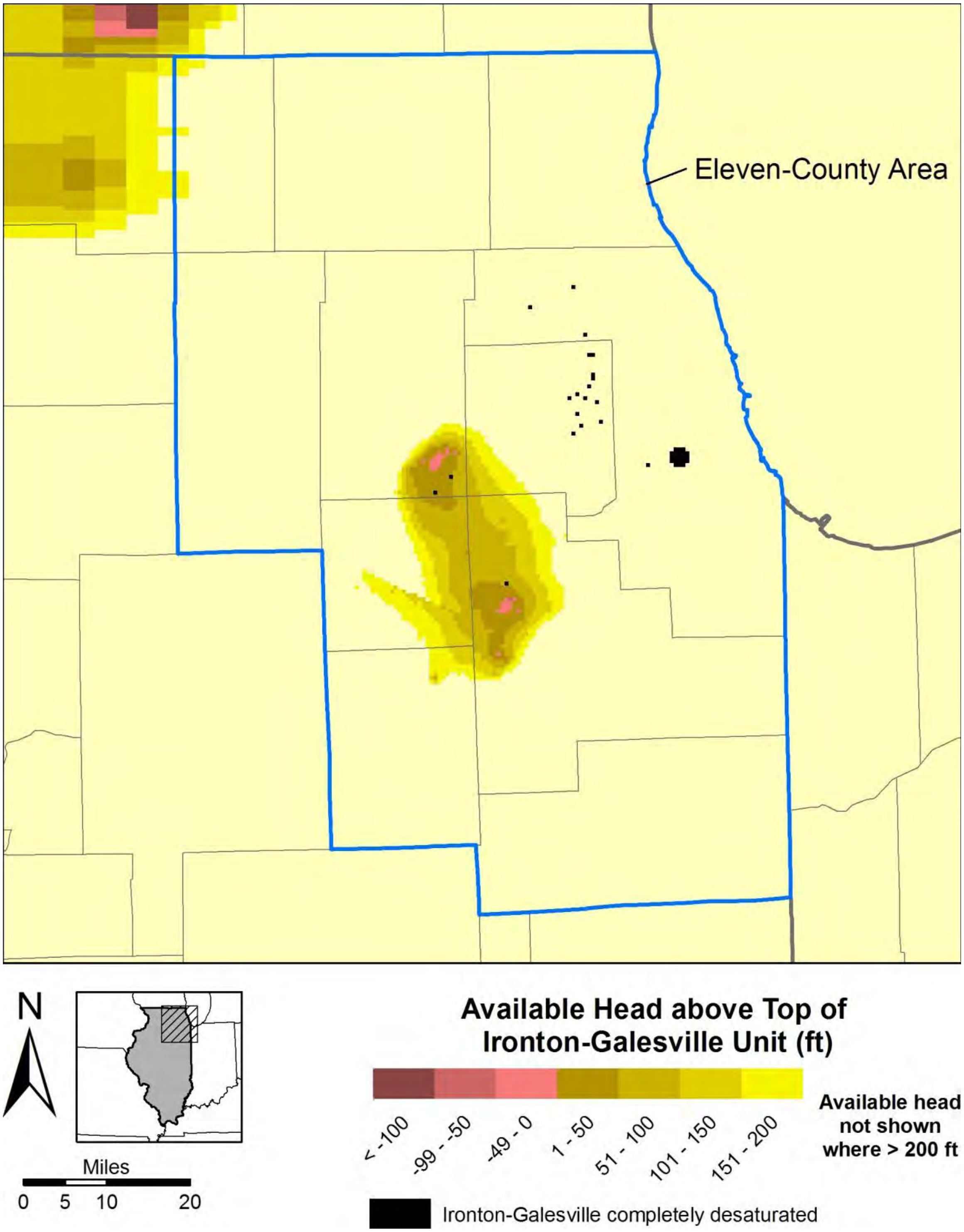


Figure 112. Available simulated Ironton-Galesville Unit head above the top of Ironton-Galesville Unit, end of 2005 summer irrigation season. Available head is not shaded where greater than 200 feet.

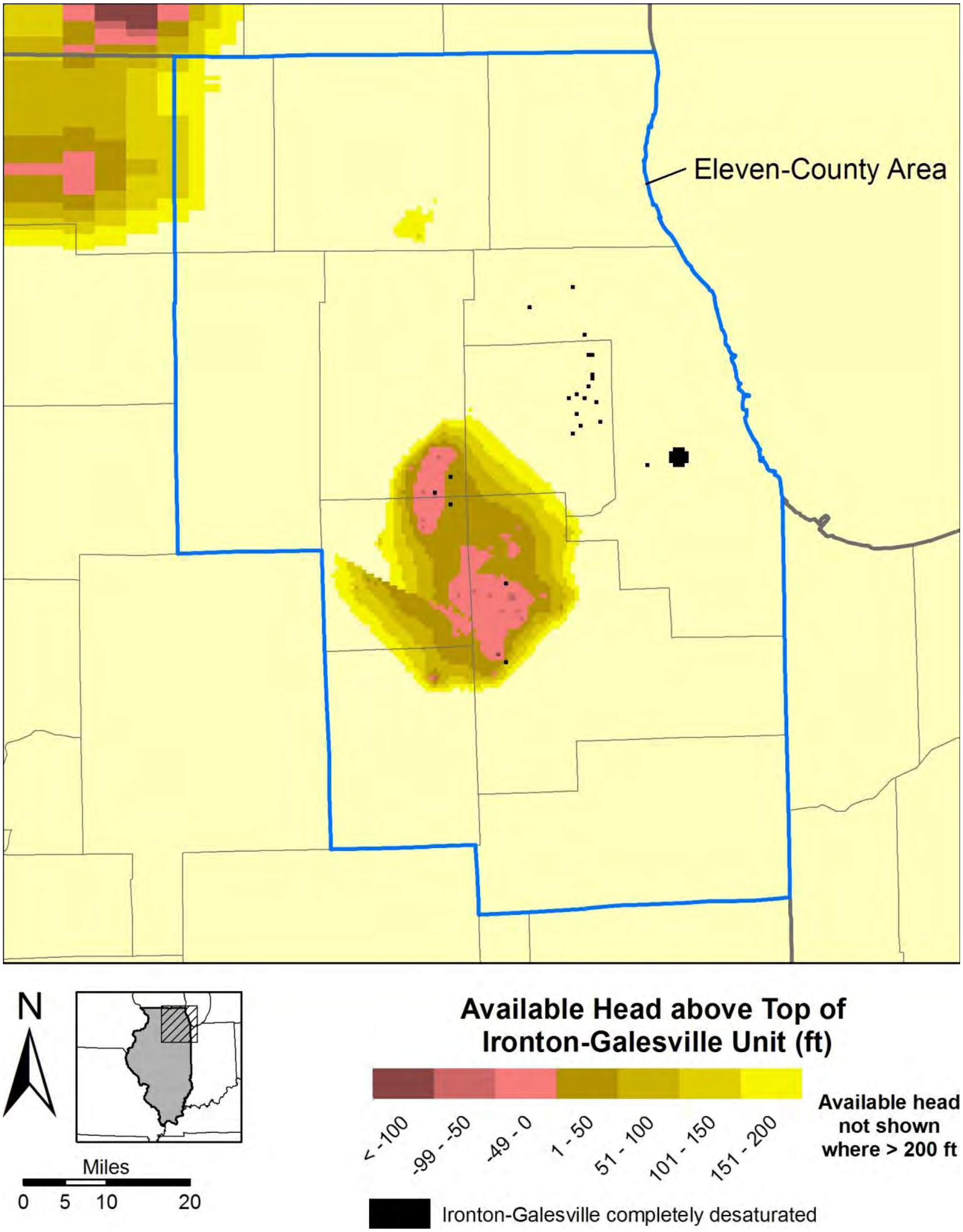


Figure 113. Available simulated Ironton-Galesville Unit head above the top of Ironton-Galesville Unit, end of 2025 summer irrigation season, BL scenario. Available head is not shaded where greater than 200 feet.

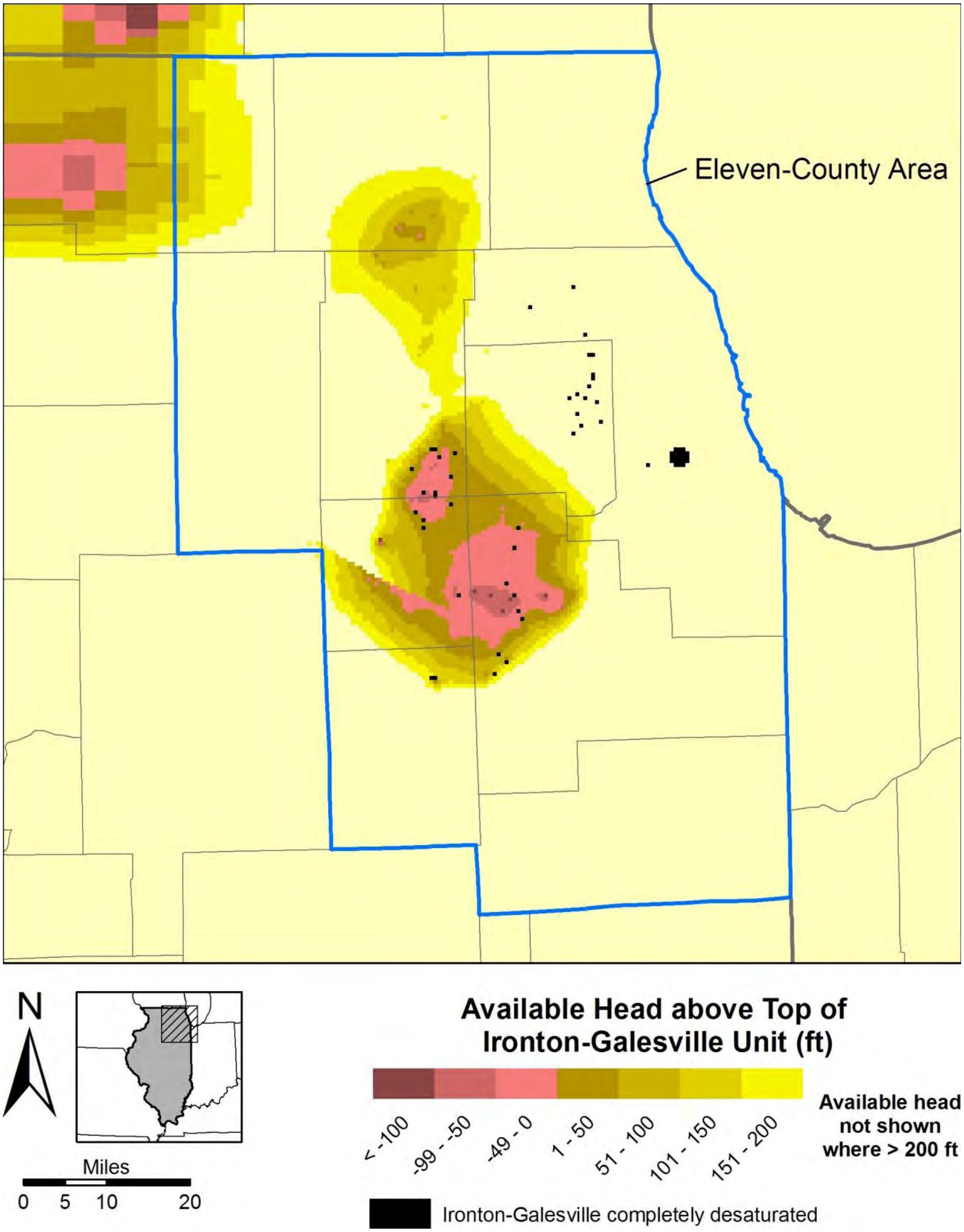


Figure 114. Available simulated Ironton-Galesville Unit head above the top of Ironton-Galesville Unit, end of 2050 summer irrigation season, BL scenario. Available head is not shaded where greater than 200 feet.

4.2.4.4 Comparison of Observed and Simulated Deep Available Heads

Mapping of *observed* available deep composite head above the top of the Ancell Unit (Figure 115), based on 2007 potentiometric surface mapping by Burch (2008), differs significantly from the 2005 simulated available head shown in Figure 96. A map of available observed deep composite head *above the top of the Ironton-Galesville* is not included in this report, because nowhere in northeastern Illinois is the 2007 available observed deep composite head above the top of the Ironton-Galesville less than 200 feet, the threshold value for shading of available head used in this report.

The available observed deep composite heads indicate that the observed deep composite head in northeastern Illinois is lower than the simulated Ancell Unit head and higher than the simulated Ironton-Galesville head. This relationship is corroborated by heads observed by the USGS in discrete, packed-off intervals in a deep test well at Zion, Lake County, Illinois (Nicholas et al., 1987). The USGS drilled this test well in 1980 to a depth of 3,475 feet, penetrating 40 feet of Precambrian granite. Portions of the Zion well were isolated from the rest of the open interval of the well using packers so that heads could be measured in the isolated intervals. This is the only well in the model nearfield from which such data are available. Observed and simulated heads at the Zion well are shown in Table 37. The data show that the range of observed heads in the deep aquifers at Zion is far less than that of the simulated heads. The lesser range of observed deep aquifer heads is qualitatively consistent with interformational transfer of groundwater between deep aquifers via boreholes open to more than one of these aquifers, a flow of groundwater that our model does not simulate (see page 148). It is likely that interformational transfers between deep aquifers have occurred since wells were initially installed in the deep aquifers in northeastern Illinois during the mid-nineteenth century. Of the 1,200 deep wells in the 11-county area active during the period 1964–2005, 675 (56 percent) are or were open to more than one of the principal deep aquifers (the Ancell, Ironton-Galesville, and Mt. Simon Units) (Table 36). In most instances (558 wells), these wells are or were open to the Ancell and Ironton-Galesville Units, not the Mt. Simon Unit.

Still, since the magnitude of the residuals at the Zion location, which range from 2 feet (layer 14) to 153 feet (layer 22), is also consistent with the calibration target errors calculated for nearfield wells (see Section 4.2.2.2 and Appendix E in Meyer et al., 2009), the residuals at Zion may simply reflect the components considered in the calculation of head calibration target error. These error components include unmodeled temporal variability, measurement error, errors due to vertical averaging over long piezometer intervals (not including the effect of interformational borehole transfers of groundwater), unmodeled heterogeneity, and interpolation error. The residuals between the observed and simulated heads at Zion suggest that the regional model accuracy is greatest for model layer 14, and the accuracy declines downward.

Heads in the deep aquifers are probably also influenced by downward transfers of groundwater from shallow aquifers along boreholes open to both shallow and deep aquifers, but such wells are less numerous than are deep wells open to more than one deep aquifer. Pumping records at the ISWS indicate that 183 of the 1,200 deep wells used in the 11-county area from 1964 to 2005 (15 percent) are or were open to the shallow aquifers as well as the deep ones. These transfers of water would have the effect of

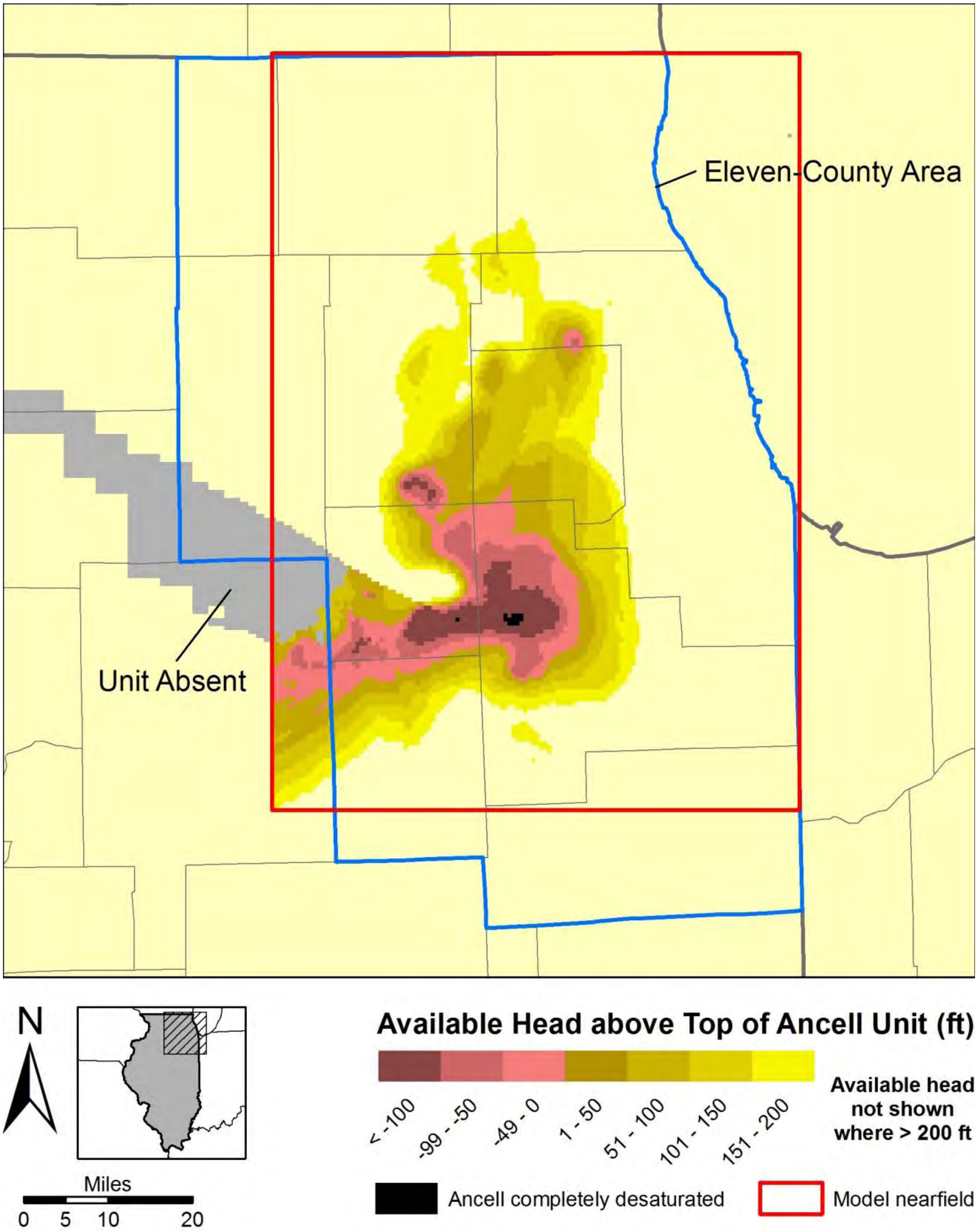


Figure 115. Available observed composite deep well head in 2007, not shown in area outside groundwater flow model nearfield, based on mapping by Burch (2008). Available head is not shaded where greater than 200 feet.

Table 37. Comparison of Simulated Heads and Observed Heads at USGS Zion Test Well

Model Layer	Median Simulated Head in 1982 (ft above MSL)	Median Observed Head in 1982 (ft above MSL)	Residual (ft)
14	372	370	-2
17	268	366	98
19	270	373	103
22	272	425	153

reducing heads in the shallow aquifers and increasing heads in the deep aquifers to which they are open. Most of these (110 wells) are not open to the Ironton-Galesville and Mt. Simon Unit, but are instead open to the shallow aquifers together with the Ancell Unit. Thus, of the deep aquifers, the Ancell Unit is the most affected by these transfers of groundwater from the shallow aquifers.

4.2.4.5 Summary of Model Results

Modeling of historical groundwater conditions simulates pumping between 1864 (when large-scale pumping is considered to have begun in northeastern Illinois) and 2005, while the modeling of future conditions extends from 2006 through 2050. The modeling consists of transient simulations in which pumping for each represented well is varied annually. Only the pumping rates of the wells are changed from year to year in the historical and future pumping simulations; all other parameters (e.g., recharge, hydraulic conductivity, stream characteristics, and drainage parameters) remain constant through time.

As an acknowledgment of the limitations in accuracy and comprehensiveness of the observations used for model development, the authors recommend that model results be used as a screening tool providing a sense of the locations and magnitudes of groundwater pumping impacts. The results are useful for identifying areas for further data collection and analysis and to provide a basis for formulating management policy directed toward reducing impacts in areas affected to a degree that is judged unacceptable by stakeholders. As values for model calibration, the authors estimate deep head targets to have an accuracy of only about ±200 feet; shallow head targets are only accurate to within about ±68 feet. The authors can confirm modeled heads only to be within the head target accuracy. The authors also caution readers that reductions in groundwater discharge to streams suggested by the modeling may not be observable or easily recognized. Few data are available to verify the reductions, and analysis of existing data is lacking. Moreover, reductions in natural groundwater discharge suggested by this study, all of which result from simulated increases in groundwater withdrawal, may be masked by hydrologic factors that are not simulated by the groundwater flow modeling of this study. Some of these unsimulated processes could, in fact, offset the simulated reductions.

The results of the groundwater simulations and their implications are briefly summarized below. Recommendations for additional work are included in Section 6.

- In general, model simulations show that drawdown in the deep aquifers is much greater than in the shallow aquifers, this difference reflecting (1) the great depth of the deep aquifers and the high potentiometric heads historically contained within them, and (2) the much greater availability of replacement water to the shallow aquifers—i.e., water entering the aquifers to replace groundwater withdrawn through wells. In northeastern Illinois, relatively impermeable confining units overlie the deep aquifers and greatly limit leakage into the aquifers from above, and the low transmissivity of the deep aquifers limits eastward movement of replacement water from north-central Illinois, where the relatively impermeable cover is absent. In contrast, replacement water enters the shallow aquifers much more readily, and these comparatively higher rates of leakage function to reduce drawdown.
- Simulated heads in the deep aquifers reflect overlapping cones of depression resulting from significant pumping in the Chicago and Milwaukee areas since the mid-nineteenth century. The simulated head distributions approximate maps of measured deep well heads (e.g., Burch, 2008). Differences between observed deep well heads and simulated heads in individual deep aquifers reflect scale effects, estimated parameters and boundary conditions, calibration target uncertainty, termination of pumping by the model upon complete cell desaturation, and unmodeled interformational transfer of groundwater through boreholes open to multiple aquifers.
- Model simulations suggest that, in 2005, over 500 feet of drawdown and over 1,100 feet of drawdown have occurred in the Ancell and Ironton-Galesville Units, respectively, in southeastern Kane County and northern Will County since pumping began (Figure 83). These units are the two principal deep aquifers in the region. Drawdown causes water levels in wells open to these aquifers to decline, decreasing well yields, increasing pumping expenses and, in extreme cases, causing water-supply interruptions that can only be addressed by replacement of the wells or lowering of pumps.
- Drawdown also could lead to increases in salinity of deep well water as well as increases in concentrations of radium, barium, and arsenic. For example, the modeling suggests some desaturation (draining of pore spaces) of rock units immediately overlying the Ancell Unit aquifer. Historical experience in Wisconsin has shown this dewatering can lead to elevated arsenic concentrations in water from deep wells (Schreiber et al., 2000). Kelly and Meyer (2005) explored for trends in water quality in groundwater derived from deep wells in northeastern Illinois. They found that, although the available data did not support the existence of such trends in most areas, data from the two largest deep bedrock pumping centers—Joliet and Aurora—did suggest increasing mineralization.
- Modeling shows that significant shallow aquifer drawdown affected many locations in the Fox River watershed in 2005, but drawdown in the shallow aquifers is not as widespread as in the deep aquifers, and drawdown magnitude is much less. The lesser drawdown in the shallow aquifers reflects increased availability of replacement water for water withdrawn from shallow wells relative to deep wells. The largest cones of depression surround public water system wells supplying Algonquin, Carpentersville, East Dundee, Lake in the Hills, Woodstock, Geneva, Batavia, South Elgin, St. Charles, and Crystal Lake.

- Computer simulation of plausible scenarios of future pumping suggests that additional drawdown, reduction in stream base flow, and changes in the quality of groundwater withdrawn from deep wells are all possible in parts of the 11-county study area before 2050.
- Model simulation of future pumping suggests deep aquifer heads will continue to recover to a limited degree in eastern parts of northeastern Illinois, where many water systems abandoned deep wells in the 1980s and 1990s. The combination of continued head declines in the Joliet—Aurora area and continued head recovery in Cook and DuPage Counties shifts the deepest parts of the Chicago area cone of depression west-southwest to the Joliet—Aurora area.
- Simulation of future pumping suggests that where recovery of Ironton-Galesville heads began in the 1980s, the rates of recovery will decrease to zero, and heads will begin to decline again before 2050.
- Simulation of future pumping suggests partial to complete desaturation (draining of pore spaces) will affect parts of the Ancell and Ironton-Galesville Units by 2050. Desaturation will lead to a decline in well yield and increasing pumping expenses. Deep wells in the areas of partial to full desaturation of the Ancell Unit also may be vulnerable to increases in arsenic, barium, and radium concentrations that, left untreated, may be harmful to human health. Comparison of observed 2007 water levels in deep wells with the elevation of the top of the Ancell Unit suggests that desaturation of the Ancell Unit may already be occurring in the southern part of the 11-county region. The early occurrence of this desaturation in comparison with model output may reflect the inability of the model to simulate downward transfer of water from the Ancell Unit through boreholes open to multiple deep units.
- Simulation of future pumping suggests that areas of drawdown exceeding 5 feet in the shallow aquifers present in 2005 will expand by 2050. Under some scenarios, drawdown also occurs in areas near Plano (northwestern Kendall County) and Marengo (western McHenry County).
- Model simulations suggest that, as of 2005, pumping has reduced natural groundwater discharge within the Illinois portion of the Fox River watershed by about 10 percent, meaning that less groundwater presently discharges by natural seepage into streams of the Fox watershed than under predevelopment conditions. The reduction may not be recognizable from flow measurements on the Fox River because effluent more than compensates for the reduced natural groundwater discharge; however, flow in tributary streams not receiving effluent discharges may be noticeably reduced. Few streamflow data are available to verify the reductions, and analysis of existing data is lacking. Moreover, reductions in natural groundwater discharge suggested by this study, all of which result from simulated increases in groundwater withdrawal, may be masked by hydrologic factors that are not simulated by the groundwater flow modeling of this study. Unmodeled processes, notably leakage from buried pipe networks and climate variability, could alter these simulated base flow reductions. Future impacts are likely to increase with increases in shallow aquifer pumping. The total reduction in natural groundwater discharge in the Fox watershed caused by groundwater pumping (61 Mgd) is comparable to the reduction in median Fox River flow at Dayton that would be caused by an increase in temperature of 3ºF from 1971–2000 recorded values (78 Mgd).

- Within the Illinois portion of the Fox River watershed, the greatest reduction in simulated natural groundwater discharge in 2005 is in the watershed of Flint Creek in northwestern Cook County and southwestern Lake County, where groundwater discharge is reduced by about 36 percent from predevelopment rates.
- Model simulations suggest that natural groundwater discharge within the Illinois portion of the Fox River watershed will likely decline to rates in 2050 that are 9 to 12 percent below predevelopment rates. The greatest reductions occur in the watershed of the Crystal Lake Outlet, where model simulations suggest reductions of 40 to 62 percent in 2050, depending on the pumping scenario. Other significant reductions occur in the watersheds of Mill Creek, where model simulation suggests reductions of 37 to 56 percent in 2050, and Flint Creek, where reductions are estimated at 41 to 50 percent in 2050.

5 Project Summary

The authors conducted an analysis of the impacts of increased water withdrawals to meet prescribed scenarios of water demand to the year 2050 for an 11-county area of northeastern Illinois that includes Boone, Cook, DeKalb, DuPage, Grundy, Kane, Kankakee, Kendall, Lake, McHenry, and Will Counties. Excluding once-through flows for electric power generation, the region may require 1,588 to 2,429 Mgd of water in 2050, an increase of 107 to 949 Mgd (7 to 64 percent) from the estimated 2005 withdrawal, corrected to 1971-2000 average climate, of 1,480 Mgd. Sources of water investigated for this study include Lake Michigan, the Fox River, shallow aquifers within the Fox River basin, and deep aquifers underlying the entire region. Excluded from the current analyses were other inland surface waters, most notably the Kankakee River, and shallow aquifers lying outside the Fox River basin, such as those shallow bedrock and sand/gravel aquifers supplying eastern Lake County.

Lake Michigan, which provided about 85 percent of all water used for public water systems in 2005 (1,063 Mgd), will probably continue to supply most of the region's water to 2050. Analysis using assumed and historical values for lake diversion components suggests Lake Michigan can continue to meet additional public supply demand or contribute to a water bank, the total diversion exceeding the 3,200 cfs (2,068 Mgd) limit, decreed by the U.S. Supreme Court, only in the final years under the MRI scenario. However, assumed values employed in the analysis, which are based on historical averages, may not be representative of future decades. Under the MRI scenario, Illinois' total diversion exceeds the Court limit by about 30 Mgd in 2050, but it is 145 Mgd below the Court limit under the BL scenario. IDNR believes that Illinois' Lake Michigan water allocation program can remain in compliance with the Court decree and still accommodate an increase of 50 to 75 Mgd in domestic water supply allocation without major policy changes in diversion management (while also continuing to accommodate the growing water demand within the current Lake Michigan service area). This additional supply could accommodate higher than expected demand within the existing Lake Michigan service area or expansion of the service area.

Although the Fox River supplies water to only two public water systems, those of Elgin and Aurora, effluent discharges to the Fox will continue to grow in proportion to community growth (and concomitant increases in water use) throughout the Fox River watershed. Our analysis suggests that, depending on the demand scenario, the Fox River could accommodate projected 2050 demand by Elgin and Aurora as well 14 to 58 Mgd in additional withdrawals, assuming that IDNR fixes the protected low-flow level at approximately its current value so that it does not continue to increase with increasing effluent. Further analysis of simulated low-flow reductions caused by shallow groundwater pumping is needed to assess whether such reductions would conflict with new points of river withdrawals. If captured streamflow is returned to the Fox River as effluent, however, the overall impact to Fox River water availability is probably minimal.

In general, regional groundwater flow model simulations show that drawdown in the deep bedrock aquifers is much greater than in the shallow aquifers, this difference reflecting the availability of replacement water to the aquifers—i.e., water entering the aquifers to replace groundwater withdrawn through wells. In northeastern Illinois, relatively impermeable confining units overlie the deep aquifers and greatly limit leakage into the aquifers from above, so replacement water to these aquifers is derived principally by slow lateral movement from north-central Illinois, where the relatively impermeable cover is absent. In contrast, low-permeability materials do not as greatly limit entry of replacement water into the shallow aquifers, and drawdown in these aquifers is thus offset by higher rates of leakage into the aquifers and by captured streamflow.

Computer simulations of plausible scenarios of future pumping suggest that significant additional drawdown, reduction in stream base flow, and changes in the quality of groundwater withdrawn from deep wells are all possible in parts of the 11-county study area before 2050. Regional model simulations suggest heads will continue to recover to a limited degree in eastern parts of northeastern Illinois, where many water systems abandoned deep wells in the 1980s and 1990s. The combination of continued head declines in the Joliet - Aurora area and continued head recovery in Cook and DuPage Counties shifts the deepest parts of the Chicago area cone of depression west-southwest to the Joliet - Aurora area. Modeling suggests limited areas of partial to complete desaturation (draining of pore spaces) of the Ancell Unit by 2050. Deep wells in the areas where the Ancell Unit head is near to the top of the Ancell, and where the Ancell Unit is partially desaturated, may be vulnerable to increases in arsenic, barium, and radium concentrations that, left untreated, may be harmful to human health. Partial desaturation of the Ancell Unit will also lead to declines in well yield and increasing pumping expenses. Modeling also suggests desaturation of portions of the Ironton-Galesville may occur before 2050, which would contribute to further declines in well yields and increases in pumping costs.

Even with model uncertainties, the results, together with historical experience, suggest that demand assigned to the deep aquifers under the assumptions of this study will, over time, have severe impacts. Projected withdrawals from the deep aquifers in 2050 in the 11-county area total 197 and 251 Mgd under the BL and MRI scenarios, respectively. These rates that are higher than the area's peak historical withdrawal rate from the deep aquifers of about 190 Mgd, a rate known to cause rapidly falling heads in some deep wells. Our model simulations, which terminate in 2050, suggest that the assigned withdrawals under all scenarios result in some degree of mining of the deep aquifers. *Groundwater mining* refers to withdrawal of groundwater at rates exceeding rates of movement of replacement water to the locations of the withdrawals, either by leakage or by lateral flow, and it results in continued drawdown in the mined aquifer. Mining can continue, but doing so limits the future viability of the deep aquifers, because eventually the cost of constructing and operating a deep well will exceed benefits derived in the form of a usable water supply. Future research in support of water supply planning in northeastern Illinois might be directed toward identifying areas of groundwater mining, determining when the mined aquifers cannot yield groundwater economically to accommodate forecasted pumping, developing revised pumping forecasts that extend aquifer and well viability, and providing guidance to water systems seeking to shift from dependence on a mined aquifer to a source having greater long-term viability.

In general, model simulations show that drawdown in the shallow aquifers is much more scattered and of lesser magnitude than in the deep aquifers. However, pumping from shallow aquifers has the effect of reducing discharge to wetlands and surface waters. Model analysis suggests that natural groundwater discharge to streams in the Illinois portion of the Fox River basin declined by 10 percent from predevelopment rates to 2005, and may decline as much as 14 percent basin-wide under the 2050 MRI scenario, reflecting increased pumping of shallow groundwater in the basin.

The results of this study should be looked at with some optimism. Our analysis suggests that the Fox River and Lake Michigan can accommodate demand from existing public water system recipients in Elgin, Aurora, and the Lake Michigan service area to 2050 and that additional water is available from both sources to satisfy demand elsewhere. Water may also be available from other inland water sources not examined for this study (e.g., the Kankakee River and shallow aquifers outside the Fox River basin), but these resources should be scientifically assessed in further studies. The present study identifies locations of potential water shortages that, with planning, can be offset by shifting demand to other sources and/or by reducing demand through such approaches as water conservation and reuse. Moreover, the present study has developed modeling tools and approaches that can be employed to simulate a range of alternative demand scenarios in support of an ongoing water supply planning effort in the region. There is time (from 10 to 30 years depending on the community) to pursue source and management alternatives, but since major construction projects and regional management plans take time to implement, planners should act now.

6 Ongoing and Future Work

6.1 Introduction

Section 6 enumerates research tasks that would extend the support for water supply planning in northeastern Illinois begun by the efforts described in this report. Possibilities fall into several categories: (1) revision of the existing hydrologic models (Section 6.2), (2) studies that employ the existing models, possibly with revisions (Section 6.3), (3) database expansion and improvement (Section 6.4), and (4) monitoring (Section 6.5). Considerable overlap between these categories exists, and efforts in one category may contribute to others. For example, data acquired through monitoring constitute an expansion and improvement of the existing database and may be employed in models for characterization of boundary conditions and calibration. Some of these tasks, particularly those relating to model improvement, are already underway at the ISWS.

6.2 Revision of Existing Models

- Surface-water modeling capabilities should be expanded to include other watersheds in the region where assessment of surface water availability, or of the effects of watershed modification, is needed. Highest priorities for this effort are in the Kishwaukee and Kankakee watersheds.
- Integrated surface-groundwater hydrologic models would more accurately simulate flow interactions between streams and aquifers than the separate groundwater and surface-water models employed for the present project. Simulation of streamflow capture by wells could be added to the FRSWAM, for example, so that the model can estimate low flows that take into account reduction of natural groundwater discharge. An effort to integrate surface water and groundwater models would require supporting field studies of groundwater/surface-water interactions, as listed in Section 6.4.1.
- Revising the groundwater flow model so that surface water and drained conditions are represented as boundary conditions in the lower Rock River watershed, west of the area where surface water and drained conditions are represented in the current model, would provide more accurate simulations in western parts of the 11-county region. The lower Rock River watershed influences groundwater availability at pumping centers in the more urbanized areas to the east because the lack of Maquoketa and Upper Bedrock Unit cover in much of the watershed permits comparatively high rates of leakage to the deep aquifers (Figure 51). In addition, representation of the lower Rock River watershed as constant head cells in the present regional-scale model forces simulated streamflow to higher-than-observed rates at some locations in the model nearfield.
- The nearfield of the groundwater flow model would need to be expanded only slightly to include the entire 11-county area. The resulting model would offer higher-resolution results for areas of Boone, DeKalb, LaSalle, Grundy, and Kankakee Counties not presently included in the nearfield.
- Detailed groundwater flow modeling of the shallow aquifers, limited to the Illinois portion of the Fox River watershed in the present study, could to be expanded to

include other parts of northeastern Illinois, thus providing a more comprehensive understanding of the effects of pumping on shallow aquifers and streamflow outside the Fox River watershed.

- Groundwater flow modeling of southeastern Wisconsin (Feinstein et al., 2005a; Feinstein et al., 2005b) could be employed to refine the hydraulic conductivity zonation of layers 1 to 5 (the Quaternary Unit) and thereby reflect thick sand and gravel deposits in southeastern Wisconsin. This would probably improve simulation accuracy in the northern part of the regional model nearfield, along the Illinois-Wisconsin boundary, particularly in the shallow units.
- The existing groundwater flow model could be revised to simulate interformational transfer of groundwater via open boreholes. Numerous such boreholes exist in northeastern Illinois, and transfers of groundwater, most notably between the Ancell and Ironton-Galesville Units, have likely affected heads in the region (page 148 and Section 4.2.4.4). Such effects are not simulated by the present model.
- The groundwater flow model used in this study incorporates an implicit assumption that groundwater flow is dominated by flow within the saturated portions of the aquifers, ignoring flow through unsaturated zones. This assumption is justified by the relatively low flow rates through unsaturated material, and is a common assumption for studies of aquifers in humid regions. However, modeling downward flow through the desaturated units, using available MODFLOW modules, may improve model accuracy.
- Groundwater flow model improvements should be made to allow re-wetting of desaturated cells that is readily apparent in current model output long after pumping in dewatered cells has ceased (page 149).
- Transient simulations conducted using the groundwater flow model are affected by cessation of withdrawals from units as they become desaturated during model runs (page 107). That is, when a unit becomes completely desaturated, the modeling software automatically terminates withdrawals from the desaturated cells rather than reassigning the withdrawals to another unit. Further model development could be directed toward identifying the contexts in which this effect is unrealistic and following up by adjusting resaturation parameters, revising model layering, and modifying other model characteristics to reduce the effect.

6.3 Modeling Studies

6.3.1 Applications

- Water supply planners could benefit from an accounting process to identify where and when the modeling software has automatically reduced simulated withdrawals to zero as described on page 62. Such accounting could provide insight on the water demand that cannot be accommodated by existing wells.
- The hydrologic models developed for this project could be employed for simulation of additional scenarios in northeastern Illinois and consequent formulation of policy and management strategies for water resources in the region.
- Scenarios simulated for this project cover a range of possible future developments, but other scenarios are possible, and additional scenarios might be developed with input from individual communities. Foremost among these is assessing the effects of

shifting deep aquifer withdrawals to alternative water sources. As discussed (page 75), the present study assumes a pumping network that reflects the 2005 network both in terms of geographic distribution and distribution of pumping rates among facility points of withdrawal.

- Groundwater simulations could be conducted for extended periods to evaluate transient effects beyond the mid-twenty-first century (the time horizon employed for transient simulations conducted for this project).
- The groundwater flow model can be adapted to simulate climate change effects that have already been simulated for the Fox River (Section 4.1.4). Climate change is likely to affect groundwater recharge rates as well as groundwater demand.
- If required for more detailed local studies, the groundwater flow model can be used to provide boundary fluxes for future high-resolution inset models. Such model integration, accomplished using the approach of telescopic mesh refinement, permits distant influences on groundwater flow to be represented in a rational and non-arbitrary manner in the inset models.

6.3.2 Research

- Future investigations could be directed toward understanding the complex relationship of Illinois' Lake Michigan diversion components under scenarios of climate change. Since Lake Michigan is a water resource of paramount importance to the northeastern Illinois, such research is central to water supply planning in the region. Climatically-induced changes in lake level can have a significant effect on the direct diversion component of Illinois' limited diversion of water from the lake. Climate also affects the stormwater component of Illinois' diversion.
- The groundwater flow model employed in the present study could be used to estimate changes in groundwater exchange with Lake Michigan resulting from historical and future groundwater pumping in the region. Lake Michigan receives groundwater discharge directly or indirectly via tributary streams and, depending on local conditions, provides recharge. The interaction of the Great Lakes with groundwater is acknowledged by U.S. and Canadian Great Lake states and provinces in its 2001 Great Lakes Charter Annex (International Joint Commission, 2001), which includes protection of groundwater quantity and quality as vital for preservation of the lakes. Groundwater flow modeling indicates that total direct and indirect groundwater discharge to Lake Michigan in the seven counties of southeastern Wisconsin in 2000 was about 91.5 percent of the predevelopment rate (Feinstein et al., 2005b).
- Water supply planning efforts in northeastern Illinois could benefit from both surface water and groundwater modeling of the Kankakee River watershed. The shallow aquifers and surface waters of the Illinois portion of the Kankakee River watershed are the source of significant withdrawals in the 11-county region of northeastern Illinois, and they could provide water to rapidly-growing south suburban locations, including Joliet. Together, the public water systems of Kankakee and Wilmington withdraw over 13 Mgd (reported 2005 total) from the Kankakee River, and this total is projected to exceed 17 Mgd in 2050 (BL scenario), an increase of over 38 percent. Owing to the availability of a productive Shallow Bedrock Aquifer, shallow groundwater withdrawals in the watershed total over 18 Mgd; these are forecasted to increase to over 19 Mgd in 2050 (BL scenario).

- By employing modeling codes not used in the present project that explicitly simulate saline water density, more accurate groundwater flow modeling can be developed that reflects the hydraulic effects of density barriers to flow and indicates the potential for saline water to enter deep wells in northeastern Illinois. Saline water is present in lower portions of the Mt. Simon Unit and in downdip areas of the important deep aquifers, including the Ancell Unit, Ironton-Galesville Unit, and Mt. Simon Unit. Because it is denser than fresh water, this saline water influences groundwater circulation. Deep saline groundwater is also a concern because pumping in northeastern Illinois could eventually induce saline water into deep wells, reducing groundwater quality and limiting use of the deep groundwater. Density-dependent modeling is computationally demanding. Preliminary simulations could be developed using available head data and groundwater quality data from the Mt. Simon Unit and downdip portions of other bedrock units, which are scarce, but these simulations will be limited in accuracy until additional head and groundwater quality data became available. Acquisition of these additional data is recommended in Section 6.4.
- Although observations of the hydraulic character of the Sandwich Fault Zone are not available (see Section 6.4), preliminary models could be calibrated, using the existing regional-scale model together with assumed values of hydraulic conductivity representative of either a high- or low-permeability fault zone, to test the effects on groundwater circulation in the region. The hydraulic character of the Sandwich Fault Zone is not likely to be as simple as it is currently represented in the groundwater flow model, which treats it simply as a planar displacement feature juxtaposing model layers having differing hydraulic properties but with no unique intrinsic hydraulic properties of its own. It is conceivable, however, that rocks within the fault zone could have either higher or lower hydraulic conductivity than surrounding rocks, owing to fracturing (which would increase permeability) and mineral precipitation within fractures (which would decrease permeability). Acquisition of additional data on the hydraulic properties of the Sandwich Fault Zone might provide a rational justification for one or the other representation of the fault zone (simple displacement feature versus high- or low-permeability zone); such acquisition is recommended in Section 6.4.
- Investigation of the effects of urbanization on groundwater circulation and on groundwater/surface-water interactions, and incorporation of these effects into computer models, could be a valuable contribution to water resources management in northeastern Illinois. Groundwater simulations suggest that withdrawals have appreciably reduced natural groundwater discharge to many streams in the Fox River watershed. The extent to which these reductions are offset by other changes within the watershed is not well understood, however. It is possible that while shallow aquifer pumping has reduced groundwater contribution to streams from predevelopment rates, other effects of urbanization (e.g., leaking infrastructure, lawn watering, land application of effluent) may have added to stream baseflows (Meyer, 2005).
- An optimization study employing the existing groundwater and surface-water models could be conducted to characterize scenarios of water resources development associated with the fewest penalties in the form of head reduction, water quality degradation, infrastructure cost, or other negative outcomes.

- Comparison of different models of the same locations and aquifers can inform discussions of model accuracy and help identify data shortcomings. Toward this end, the modeling results for the Fox watershed shallow aquifers from this study, including model output pertaining to changes in natural groundwater discharge, should be compared to that of the local-scale shallow groundwater model developed for Kane County by Meyer et al. (2009). To make the comparison meaningful, however, it will first be necessary to run the local-scale Kane County model with the same pumping scenarios (BL, LRI, and MRI) employed in the present study.

6.4 Database Expansion and Improvement

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

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

6.4.1 Hydraulic Properties and Boundary Conditions

- The most significant need for database expansion and improvement is for compilation of comprehensive, accurate withdrawal data. Analysis of alternative scenarios of future pumping (Section 4) clearly shows that pumping rate uncertainty is responsible for much of the uncertainty in possible outcomes. This also applies to simulations of aquifer history, where the groundwater simulations display changes in drawdown distribution and magnitude that are solely a function of the assumed distribution of pumping. Historic pumping simulated by the models is limited in accuracy. For example, pre-1964 shallow pumping in Illinois is not simulated, and pre-1964 pumping from deep wells in Illinois is aggregated to seven fictitious pumping centers.

Model results for the Ironton-Galesville Unit particularly show the impact of aggregating historic pumping to a single Chicago pumping center (page 176).

- The limited accuracy of the simulated historic pumping is largely due to the lack of readily available data, but it might be possible to fill gaps in the record with assumptions or with withdrawal data from historic pumping records discovered through organized research. Both efforts would require research using hardcopy records, possibly at several local and state facilities. Improvement of the database of historic pumping would be of greatest value in simulating groundwater flow in the deep units, because, in comparison with shallow groundwater flow, deep groundwater flow requires significant time to reach a steady state following changes in pumping rates and locations.
- Simulation accuracy could be enhanced by improving existing withdrawal databases, which might also involve changes in institutional/governmental requirements for reporting of groundwater withdrawals. In general, regional groundwater flow modeling in the urban corridor surrounding southern Lake Michigan, which covers an area extending from Michigan through Indiana and Illinois to Wisconsin, would benefit from a consistent approach to withdrawal measurement, reporting, and data compilation by all states surrounding the lake.
- Better data on irrigation and self-supplied domestic withdrawals would improve data completeness for simulation of groundwater flow conditions. Domestic self-supplied withdrawals were estimated by Dziegielewski and Chowdhury (2008) by estimating differences between county population and county population served by public water systems. Often, the estimate of the population served by public water systems exceeded the total county population. This led to highly uncertain estimates of domestic self-supplied demand. The widespread distribution of thousands of low-capacity wells pumping from numerous aquifers led us to not include domestic self-supplied withdrawals in the regional model. Some assessment of these water-use sectors could be added to the scope of the ISWS Illinois Water Inventory Program (IWIP), which collects water withdrawal data statewide. The passage of Senate Bill 2184 into law as Public Act 096-0222 mandates reporting to IWIP of water withdrawals exceeding 100,000 gallons per day with a five-year window for irrigators to report either individually or as a group (e.g., within a water authority or county). Continued funding for IWIP is critical to any future water supply planning efforts in this region and elsewhere in Illinois.
- More accurate modeling of streamflow capture by groundwater pumping, whether in the context of a groundwater flow model or integrated groundwater and surface-water models, will require field studies of groundwater/surface-water interactions to provide supporting data.
- As a parameter in most groundwater flow models to which shallow heads and streamflow are highly sensitive, groundwater recharge is a significant subject for additional study, yet accurate measurement of recharge is problematic and a subject of active research (National Research Council, 2004). Recharge rates employed in the groundwater flow model are based on watershed-scale estimates that do not portray the local variability arising from such factors as vegetation, land cover, slope, and geology. Studies directed toward detailed characterization of recharge rates in the region would be of considerable value in future modeling studies, including

improvement of the model employed in this study. Further, current research into climate variability suggests that the climatic factors affecting recharge might be dramatically different in the future, yet the relationship between climate and recharge is not clear. Reducing uncertainties in recharge and discharge—or at least understanding their impact on model predictions—will require continued monitoring and analysis of streamflow, groundwater levels, and soil moisture to assess the temporal variability of the water table.

- Future groundwater flow modeling in the region would benefit from systematic research on the hydraulic properties of all the modeled units, aquifers and aquitards alike. This research would logically include an effort devoted to reanalysis, using a consistent approach, of available pumping and slug tests from the multi-state region surrounding northeastern Illinois.
- Groundwater flow modeling would be improved by field studies of hydraulic properties of units that are, at best, poorly understood hydraulically. For example, the aquitard consisting of unweathered Silurian-Devonian Carbonate Unit, Maquoketa Unit, and Galena-Platteville Unit underlying the Shallow Bedrock Aquifer exerts significant control on groundwater circulation within the major deep aquifers of northeastern Illinois (the Ancell, Ironton-Galesville, and Mt. Simon Units), yet the hydraulic character of this interval is poorly known. And despite its use as an aquifer, little is known about the hydraulic characteristics of the Ironton-Galesville, because most tested wells open to the aquifer are also open to the Ancell Unit. Testing of such wells does not permit computation of hydraulic properties specific to the Ironton-Galesville.
- The groundwater flow model would benefit from field studies to improve characterization of the hydraulic properties of the Sandwich Fault Zone. Such studies might provide justification for one of the conceptual models of the fault zone discussed in Section 6.3.2 (simple planar displacement, high conductivity zone, or low conductivity zone), or they might suggest another conceptual model entirely.
- Additional field studies would provide observations to support groundwater flow modeling of the shallow materials. Comparatively few high-quality pumping tests of the shallow materials in northeastern Illinois exist, and many units have not been tested. Diamicton units, for example, exert major influence on shallow groundwater movement, yet their hydraulic characteristics are not well understood. In general, the spatial variability of the hydraulic conductivity of the vitally important sand and gravel aquifers is not well known and is only suggested by differences in well productivity. The horizontal and vertical distributions of hydraulic conductivity of the widely used Shallow Bedrock Aquifer are poorly documented by available high-quality pumping tests, which are sparsely distributed, influenced by overlying sand and gravel aquifers, and are from wells open to bedrock intervals that frequently extend downward into the underlying aquitard.
- With the exception of pumping rates, the hydraulic parameters and boundary conditions in the groundwater flow model do not change with time, and they reflect modern conditions (roughly those of the late twentieth century). Yet land cover changes associated with settlement, agricultural development, and urbanization have exerted significant hydrologic impacts, and more accurate model simulations might be possible if the models portrayed historically accurate changes in such

characteristics as recharge rates and drained areas, both of which have probably changed as the region has developed. Such an effort would require research into land cover/land use changes and estimation of hydraulic characteristics of historic land cover/land use regimes.

- The locations and characteristics of drained areas in the groundwater flow model are poorly known and, for this project, are based on soils and urban-area mapping and on general assumptions regarding agricultural and urban drainage systems in the region. The actual locations of the many drainage systems are not documented, and the locations and characteristics of agricultural drains are, in particular, debatable. Future modeling would benefit from mapping of both agricultural and urban drainage systems and field studies to support accurate characterization of these systems.
- As discussed in Section 6.3.2, the effect of saline water in downdip areas and in the Mt. Simon Unit is not simulated directly in the groundwater flow model. The accuracy of additional modeling to simulate these effects would be severely limited without acquisition of groundwater quality data from the downdip areas and from the Mt. Simon Unit. These data could also be useful in accurately simulating the effects of the Sandwich Fault Zone on groundwater flow in the region. Some newly acquired water-quality data from current studies of carbon sequestration by the ISGS might be useful for modeling the effects of salinity in the Sandwich Fault Zone.

6.4.2 Geological Models

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

6.4.3 Calibration Data

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

- There is no alternative to employing speculative predevelopment heads for steady-state calibration of the groundwater flow model under nonpumping conditions, but head data for transient verification of the model under pumping conditions could be improved and could reduce model uncertainty discussed on page 68. These data were collected from a sparse network of active or retired supply wells frequently open to numerous hydrostratigraphic units, giving them a very low level of reliability for calibration. In addition, collection of water-level data from the wells occurred sporadically, and some of the wells served as water supply wells during the time the water-level data were collected, limiting their usefulness for model calibration. Future model development would greatly benefit from systematic, long-term collection of head data from a network of dedicated observation wells open to single hydrostratigraphic units and not subject to pumping. Installation, protection, and measurement of monitoring wells are relatively inexpensive for the shallow, unconsolidated aquifers, but can be very expensive for the deep aquifers. Here, collaborating with owners of existing deep wells may permit converting old wells into monitoring wells at a minimal cost. Heads in these wells should be observed at least quarterly to permit use of the data for transient model calibration and/or verification. Long-term, rather than sporadic, monitoring of water levels in these observation wells would be critical for the data to be most useful for model calibration and/or verification, requiring a commitment to the effort from monitoring authorities. Moreover, the wells in such a network would probably need to be constructed, at considerable expense, as it is unlikely that a suitable number of retired deep water supply wells, open to single hydrostratigraphic units, will ever become available for use as observation wells in the region. It is practical for water supply purposes to leave deep wells open to all rocks underlying the Maquoketa Unit.
- Synoptic studies involving low flow measurements at multiple locations along suspect stream reaches are needed to identify specific locations where the stream may be losing flow to groundwater. Such measurements might be targeted to streams where decreasing low flow trends, such as Blackberry Creek in Kane County, were identified (Knapp et al., 2007). This type of synoptic study is most effective when streams are experiencing their very lowest flow conditions.

6.4.4 Sulfide-Cement Horizon

Research suggests that reduction of heads to a position near the contact of the Galena-Platteville and Ancell Units has led to increased arsenic concentrations in groundwater pumped from deep wells in northeastern Wisconsin (Schreiber et al., 2000). The source of the arsenic may be a thin interval of sulfide minerals, the sulfide-cement horizon (SCH), at the contact between the Galena-Platteville and Ancell, which releases arsenic under oxidizing conditions. Although preliminary studies suggest that the SCH is present in Illinois (Lasemi, ISGS, personal communication, 2005), there is a need for more comprehensive study to verify the presence of the SCH in Illinois and confirm that the SCH contains arsenic that can be liberated as a consequence of declining heads. This could be done using existing core being stored by the ISGS and in concert with local drillers as new wells are drilled. Combined geochemical and flow modeling could help determine how much arsenic is released and how the concentration would be diluted by water from other formations.

6.5 Monitoring

Monitoring is essential for early identification of problematic trends and establishes a database of historic heads that is irreplaceable for model calibration.

- Monitoring of heads would ideally employ dedicated observation wells located throughout the 11-county region and should include wells in areas of significant future simulated drawdown. Water levels in these wells should be measured on at least a quarterly basis, but, if the wells are instrumented with digital dataloggers, water levels could be measured much more frequently (with less frequent on-site visits). The authors recommend a newly constructed network, because such wells could be rationally located, could be constructed and logged using standard and consistent methods, and would be unhindered by the confounding effects of pump operation that occur when using active water supply wells. Although a dedicated network of deep observation wells open to single hydrostratigraphic units and located in areas of significant simulated drawdown is also recommended, construction of such a network is likely to be cost-prohibitive. Lacking such a network, existing monitoring of the deep aquifers should be continued on the five-year basis employed historically by the ISWS and enhanced with more frequent and additional monitoring of selected wells. Owners of deep wells slated for sealing or abandonment might maintain the wells for observation purposes. Coordinated measurement of water levels in deep wells in both Illinois and Wisconsin would provide for interstate mapping of heads in the region. Additionally, observation wells could be sampled periodically to permit tracking of water quality trends.
- Enhanced gaging of streamflow is recommended to improve (1) understanding of base flow, (2) the role of effluent in offsetting reduction in natural groundwater discharge, (3) stream-aquifer interactions, and (4) aquatic ecosystem function. Because long-term records are needed to identify flow trends, the authors advise that new stream gages be installed on tributary streams that are both known to have strong surface-groundwater interactions and in locations expected to have future growth in water use from shallow groundwater sources. Monitoring of streams projected to incur significant simulated base flow reduction, such as Mill Creek, is particularly advisable.

7 Glossary

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

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

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

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

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

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

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

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

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

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

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

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

confining bed: See *aquitard*

confining unit: See *aquitard*

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

hydraulic gradient: See *head gradient*

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

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

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

interference: See *well interference*

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

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

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

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

lithostratigraphy: *Stratigraphy* based on *lithology*.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

8 References

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Appendix A. Groundwater Concepts

A.1. Aquifers and Confining Beds

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

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

A.2. Potentiometric Surface Maps

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

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

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

A.3. Hydraulic Properties

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

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

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

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

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

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

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

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

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

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

A.4. Groundwater Recharge and Discharge

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

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

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

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

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

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

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

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

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

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

A.5. Effects of Pumping

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

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

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

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

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

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

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

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

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

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

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

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

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

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Appendix B. Generalized Hydrogeologic Setting

B.1. Introduction

This appendix summarizes the hydrogeologic setting of the 11-county northeastern Illinois planning area (Section B.2, blue outline in Figure B-1), with greater detail on the shallow Quaternary hydrogeology of the Fox River watershed geologic mapping domain (Section B.3, red outline in Figure B-1), a priority area for shallow groundwater flow modeling for this study. The discussion employs hydrostratigraphic nomenclature developed to facilitate groundwater flow modeling. The hydrostratigraphic units introduced in this appendix (Table B-1) are the basis for the layers in the groundwater flow model employed in this project (Section 4.2.2), with each hydrostratigraphic unit typically represented by one to five model layers.

The aquifers available to northeastern Illinois include a set of *deep aquifers* and a set of *shallow aquifers* (Figure 18). The deep aquifers consist of layers of consolidated Paleozoic bedrock, primarily sandstone—the Ancell Unit, Ironton-Galesville Unit, and Mt. Simon Unit. In northeastern Illinois, the Mt. Simon Unit is used far less than the Ancell and Ironton-Galesville Units because of the expense of drilling to it and because deeper portions of the Mt. Simon contain water that is too salty for most uses. The shallow aquifers include the Shallow Bedrock Aquifer (a layer of weathered dolomite encompassing about the uppermost 25 to 125 feet of bedrock) and unconsolidated sand and gravel aquifers contained in the Quaternary Unit, consisting mainly of glacial drift, overlying the Shallow Bedrock Aquifer. The hydrogeologic framework of northeastern Illinois exerts major control on groundwater flow and availability in the region. Both the deep and shallow aquifers can be highly productive and are commonly used for domestic and municipal water supplies. Discharge from the shallow aquifers sustains flow in perennial streams and maintains water levels in wetlands throughout the region.

B.2. Generalized Hydrogeologic Setting of Northeastern Illinois

Paleozoic sedimentary rocks overlie crystalline Precambrian basement throughout the 11-county area of northeastern Illinois. These rocks dip gently off the combined Wisconsin and Kankakee Arches into the Michigan Basin to the northeast and the Illinois Basin to the south. However, the Sandwich Fault Zone displaces the Paleozoic rocks in Kendall and southern DeKalb counties. In addition, the Des Plaines Disturbance (interpreted as an impact structure) adds local structural complexity to the otherwise gently dipping Paleozoic sedimentary rocks in northeastern Illinois (Dietz, 1947; Emrich and Bergstrom, 1962).

Each hydrostratigraphic unit described in this appendix may not be present everywhere in northeastern Illinois, and unit thicknesses may vary considerably. In addition, the units are lithologically and hydraulically heterogeneous.

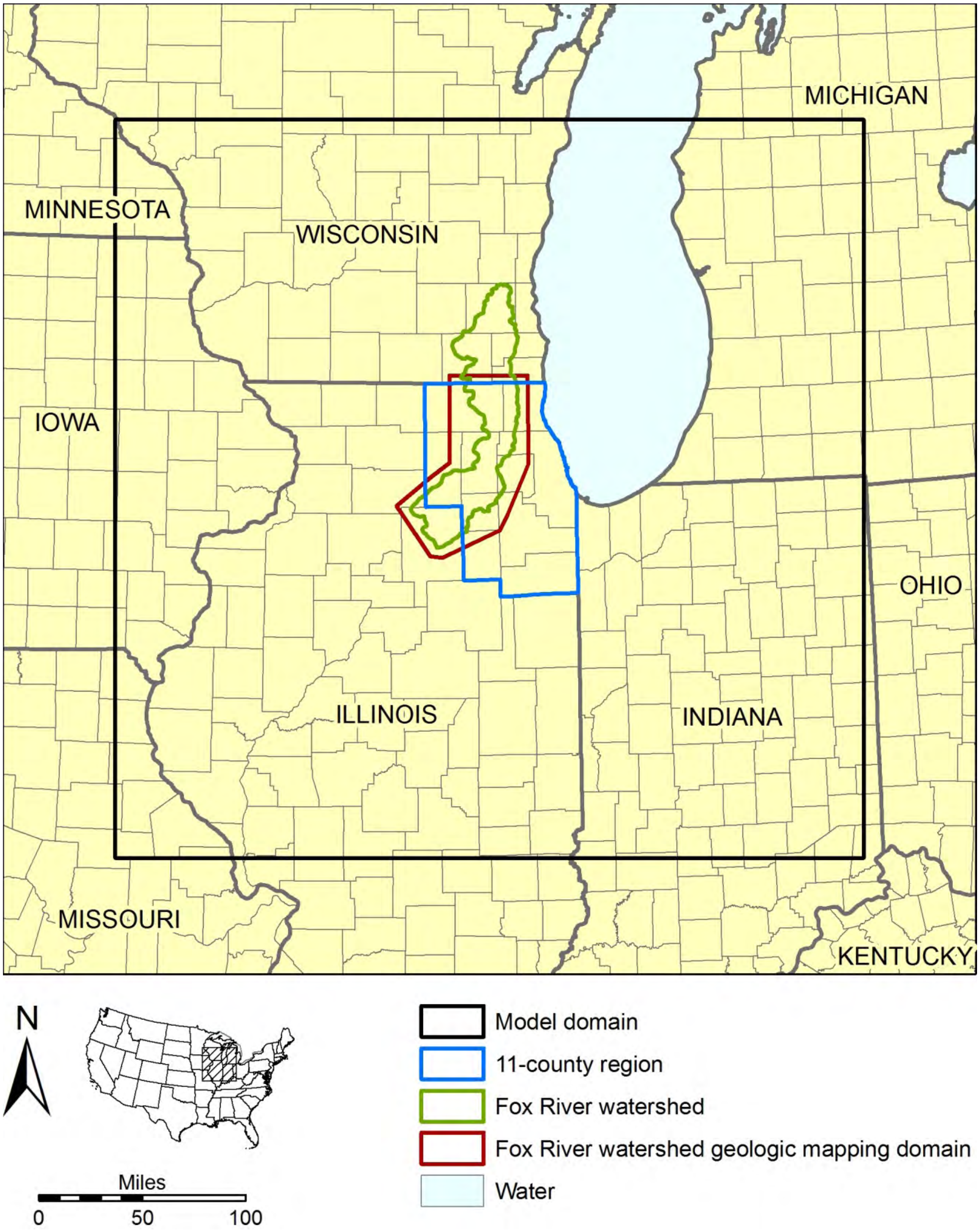

Figure B-1. Index map showing areas discussed

Table B-1. Hydrostratigraphic Nomenclature*

Other Areas	Fox River Watershed Geologic Mapping Domain
Quaternary Unit	Quaternary Fine-Grained Unit 1
	Quaternary Coarse-Grained Unit 1
	Quaternary Fine-Grained Unit 2
	Quaternary Fine-Grained Unit 3
	Quaternary Coarse-Grained Unit 2
Upper Bedrock Unit	
Silurian-Devonian Carbonate Unit	
Maquoketa Unit	
Galena-Platteville Unit	
Ancell Unit	
Prairie du Chien-Eminence Unit	
Potosi-Franconia Unit	
Ironton-Galesville Unit	
Eau Claire Unit	
Mt. Simon Unit	

*Units are progressively younger upward

The Precambrian rocks underlying the Paleozoic sedimentary rocks of northeastern Illinois, which are 3,000 to 5,000 feet below land surface, are poorly understood, but they are typically interpreted to be relatively impermeable igneous plutonic and metamorphic rocks (Cannon et al., 1997; Catacosinos and Daniels, 1991; Catacosinos et al., 1990; McGinnis, 1966; Nicholas et al., 1987). Quaternary sediments, mostly glacial drift, cover the Paleozoic rocks in most of the study area. More detailed summaries and studies of the regional character and extent of Paleozoic bedrock units have been widely cited (Visocky et al., 1985; Willman et al., 1975). The following paragraphs summarize the major bedrock units, based on hydrostratigraphic nomenclature developed for the groundwater flow model employed in this project (Table B-1), and their hydrogeologic character in northeastern Illinois.

B.2.1. Mt. Simon Unit

The lowermost water-yielding rocks in northeastern Illinois—the Mt. Simon Sandstone and, directly overlying the Mt. Simon, the Elmhurst Sandstone Member of the Eau Claire Formation—are grouped as the *Mt. Simon Unit*. Use of these Cambrian sandstones for water supply is limited in northeastern Illinois by high salinity (Visocky et al., 1985). The Mt. Simon Unit may reach thicknesses of 1200 and 3000 feet in McHenry County and Will County, respectively.

B.2.2. Eau Claire Unit

The upper two members of the Cambrian Eau Claire Formation, here grouped as the *Eau Claire Unit*, consist of finer-grained shale, siltstone, and dolomite that act collectively as a confining unit separating the Mt. Simon Unit, an aquifer, from another aquifer, the Ironton-Galesville Unit.

B.2.3. Ironton-Galesville Unit

The *Ironton-Galesville Unit*, consisting of the Cambrian Ironton and Galesville Sandstones, overlies the Eau Clare Formation and is continuous throughout northeastern Illinois (Visocky et al., 1985). This unit is typically 150 to 225 feet thick and is thickest in the southeast portion of northeastern Illinois. The Ironton-Galesville is the most productive of the deep aquifer units and is often used in combination with the overlying Ancell Group sandstones, referred to in this report as the Ancell Unit (Meyer et al., 2009).

B.2.4. Potosi-Franconia Unit and Prairie du Chien-Eminence Unit

The *Potosi-Franconia Unit* (Franconia Formation and overlying Potosi Dolomite, both Cambrian) and the *Prairie du Chien-Eminence Unit* (Cambrian Eminence Formation, and overlying Ordovician Prairie du Chien Group) sequentially overly the Ironton-Galesville Unit. Both units consist predominantly of fine-grained siliciclastic sediments and dolomite with lenses of sandstone. Generally, these units are considered an aquitard, but sandstones contained within them sometimes function as aquifers. Where these rocks make up the bedrock surface, secondary porosity permits small groundwater supplies to be obtained (Meyer et al., 2009).

B.2.5. Ancell Unit

The *Ancell Unit* of this report consists of the Ordovician Ancell Group. In northeastern Illinois, the Ancell Unit consists of the Glenwood Formation (sandstone, dolomite, and shale) and the St. Peter Sandstone. Where the St. Peter Sandstone is present in northern Illinois, it is an important aquifer supplying many large municipal wells, often in combination with the Ironton-Galesville sandstones.

B.2.6. Galena-Platteville Unit and Maquoketa Unit

The Galena-Platteville and Maquoketa Units function as a confining unit for the Ancell Unit aquifer in the study area. The *Galena-Platteville Unit*, consisting of the Ordovician Platteville and Galena Groups, is predominantly pure limestone and dolomite, while the *Maquoketa Unit* consists of dolomitic shale and argillaceous dolomite and limestone assigned to the Ordovician Maquoketa Group. Within 25 to 125 feet of the bedrock surface, secondary porosity—a product of weathering and dissolution of the rock materials—is present within the Galena-Platteville and Maquoketa Units (as well as the overlying Silurian-Devonian Carbonate Unit); the units may function as an aquifer known as the *Shallow Bedrock Aquifer* (Csallany and Walton, 1963; Dey et al., 2007b; Meyer et al., 2009). In most of the 11-county area, however, the Galena-Platteville and Maquoketa Units function as a confining unit.

B.2.7. Silurian-Devonian Carbonate Unit

Carbonates deposited during the Silurian and Lower through Middle Devonian are represented by the *Silurian-Devonian Carbonate Unit*. The Silurian System consists largely of dolomite, but lesser amounts of shale are present, and the dolomites may be argillaceous, silty, and clean. Devonian rocks do not extend into northeastern Illinois, where the Silurian-Devonian Carbonate Unit is composed entirely of Silurian dolomites. Secondary porosity in the 25–125 feet of the Silurian-Devonian Carbonate Unit underlying the bedrock surface—which, together with the 25–125 feet of the Galena-Platteville and Maquoketa Units underlying the bedrock surface, forms the *Shallow Bedrock Aquifer* (Csallany and Walton, 1963; Dey et al., 2007b; Meyer et al., 2009)—provides small to moderately large quantities of groundwater to wells in northeastern Illinois. Where it is overlain by younger rocks of the Upper Bedrock Unit, so that it is absent from the interval of secondary porosity development near the bedrock surface, the Silurian-Devonian Carbonate Unit is most accurately characterized as an aquitard.

B.2.8. Upper Bedrock Unit

The Upper Bedrock Unit contains Upper Devonian through Cretaceous rocks of variable lithology. This unit is absent from all of the 11-county area except southwestern Will County and southern Grundy County. Although this sequence includes both aquifers and confining units in areas remote from northeastern Illinois, the overall hydrologic effect of the sequence for the underlying units is one of a confining unit, owing to the presence of widespread, relatively impermeable fine siliciclastic materials within it.

B.2.9. Quaternary Unit

Quaternary deposits, consisting largely of unconsolidated diamicton, sand, gravel, clay, and silt, are assigned to the *Quaternary Unit*. Most of these materials were deposited during glaciation of the area during the Pleistocene, but post-glacial sand, lacustrine clays and silts, and anthropogenic fill are present in some areas. Where thick and laterally extensive, sand and gravel deposits within the Quaternary Unit can provide large groundwater supplies, but diamicton, clay, and silt beds function as aquitards. In the next section, the Quaternary Unit is subdivided and described in greater detail for the Fox River watershed geologic mapping domain.

B.3. Quaternary Hydrogeologic Setting of Fox River Watershed Geologic Mapping Domain

The topography and shallow hydrogeology of northeastern Illinois are, to a large extent, a product of glaciations during the Quaternary period, which encompasses the last 2.6 million years of earth history. Particularly influential has been the last 25,000 years of the Quaternary, which may be termed the last Ice Age. Between 25,000 and 14,000 years ago, glaciers advanced into northeastern Illinois at least five separate times. The distribution, thickness, and character of major glacial stratigraphic units often reflect the positions of former glacier margins, which are frequently marked by moraines. In northeastern Illinois, those ice margins were often regionally north-south trending boundaries formed from glacial advances and retreats out of the Lake Michigan Basin (Figure B-2). Thus, major changes in the distribution and character of glacial units are most abrupt along east-to-west transects. Sediments associated with glacial environments include fine-grained diamictons (mixed clay, silt, sand, and gravel), fine-grained lake sediments (primarily clay and silt), and coarse-grained meltwater deposits (primarily sand and gravel). The distribution of the Quaternary materials has been affected to some extent by post-glacial erosion and redistribution of sediments by modern streams. Many detailed studies of Quaternary deposits in northeastern Illinois are available (e.g., Curry et al., 1997; Dey et al., 2007b; Hansel and Johnson, 1996; Vaiden et al., 2004).

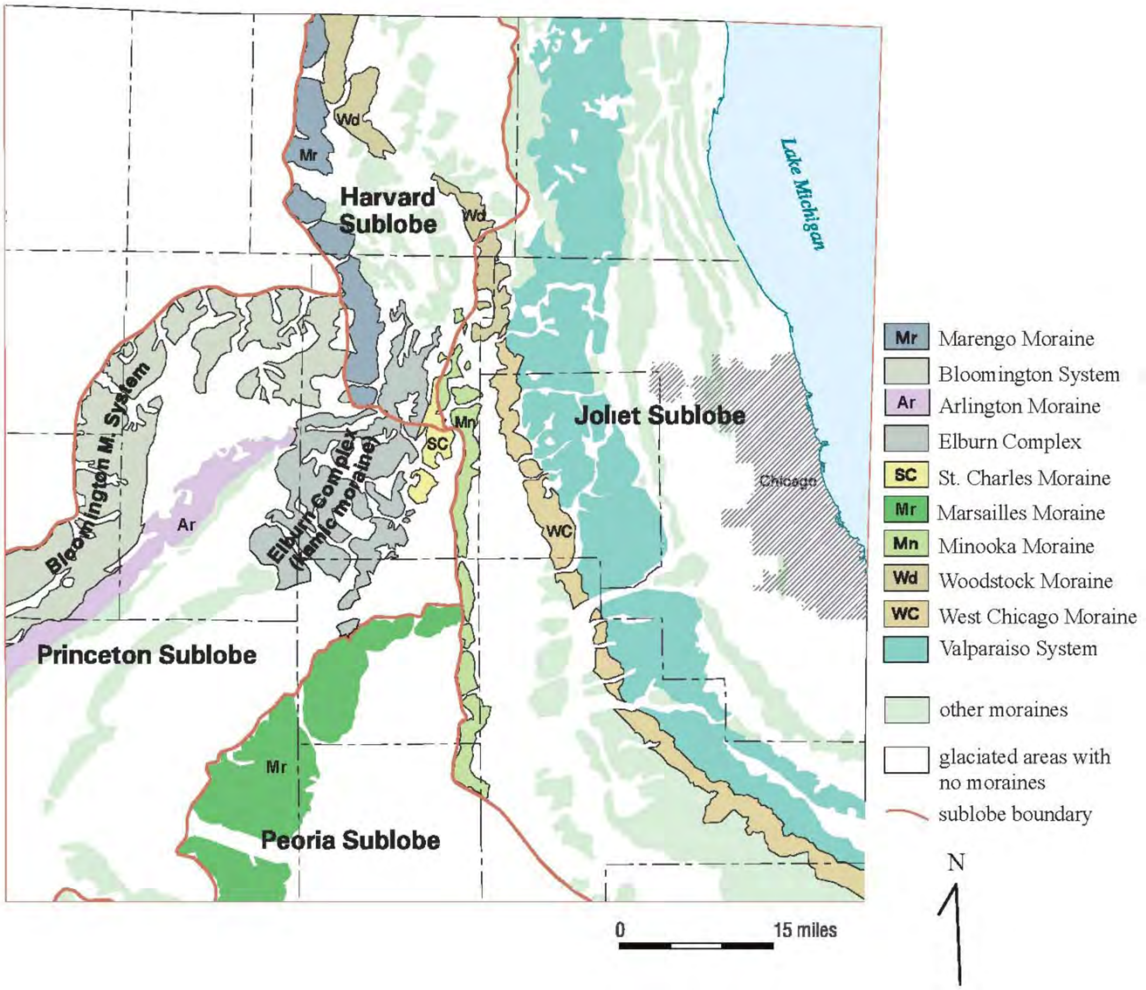

Figure B-2. Major Wisconsin Episode moraines in northeastern Illinois (modified from Dey et al., 2007b)

A schematic cross section of the Quaternary lithostratigraphic units in northeastern Illinois is shown in Figure B-3. Cross sections showing the distribution of the lithostratigraphic units are shown in Figure B-5, with cross section locations shown in Figure B-4. These lithostratigraphic units are simplified into five hydrostratigraphic units for purposes of groundwater flow modeling, and this hydrostratigraphic classification (Table B-1) is the basis for the unit descriptions in Section B.3.1 to Section B.3.5. The effect of representing the complex Quaternary lithostratigraphy using the simplified hydrostratigraphic classification is shown by comparing the lithostratigraphic cross sections in Figure B-5 with those in Figure B-6, which use the hydrostratigraphic classification to represent the same materials along the same lines of section.

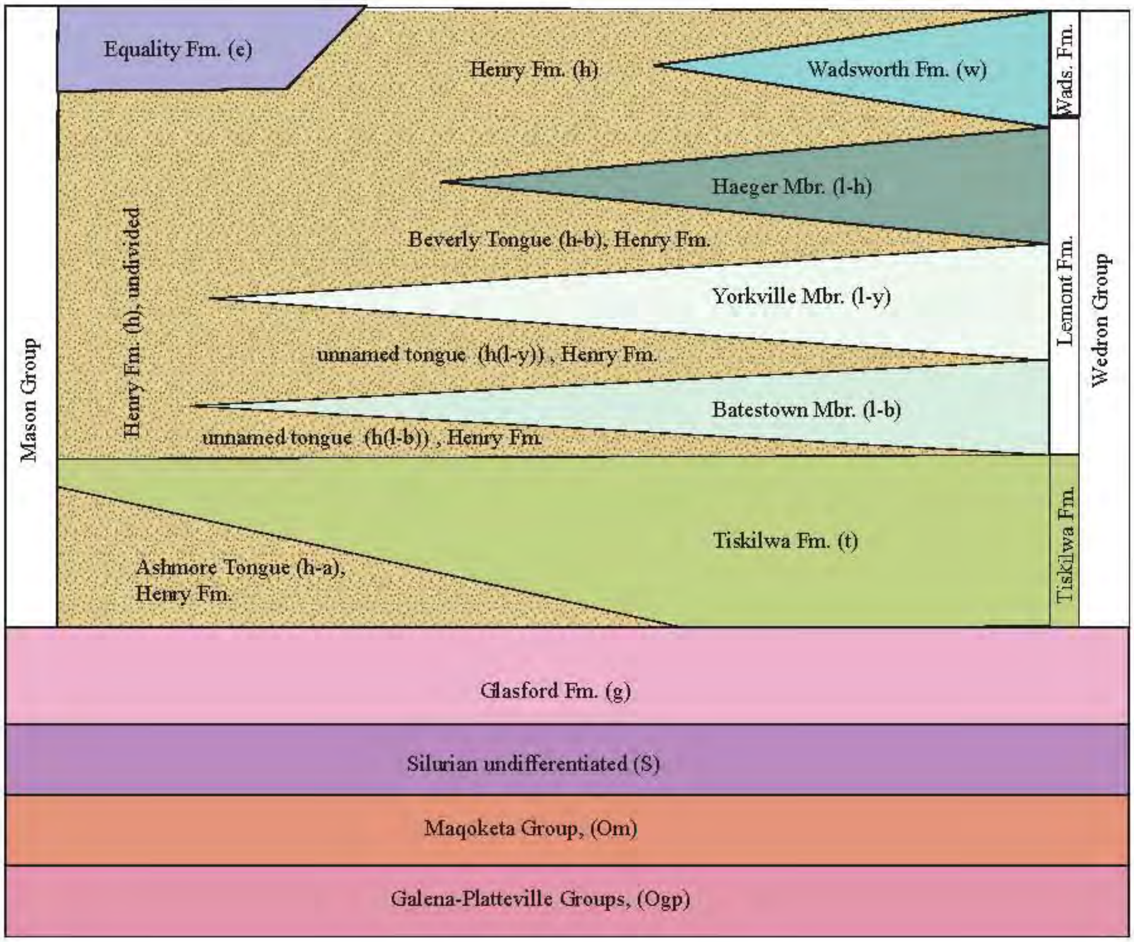

Figure B-3. Schematic cross section showing lithostratigraphic units of the Quaternary and shallow bedrock in northeastern Illinois [modified from Dey et al. (2007b)]

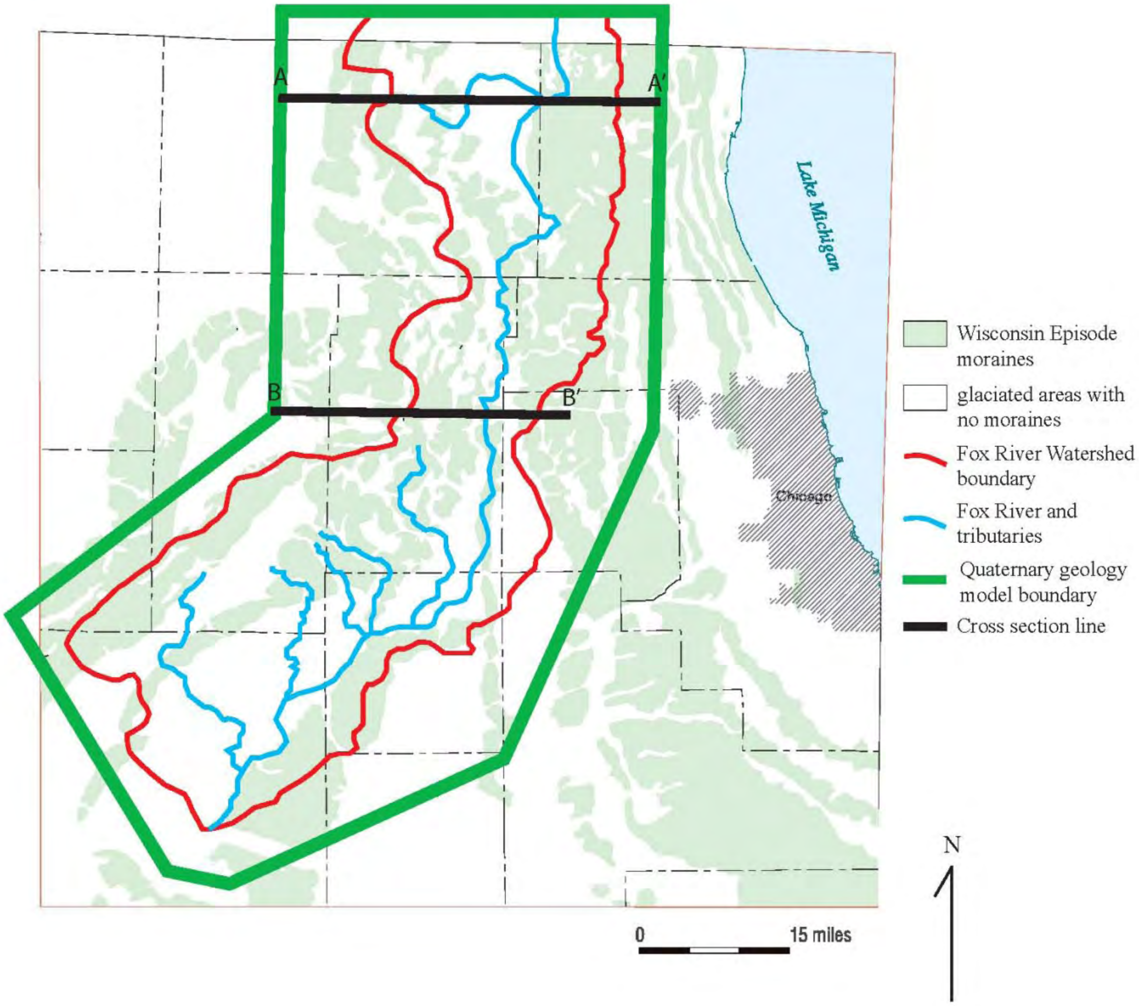

Figure B-4. Locations of cross sections shown in Figure B-5 and Figure B-6

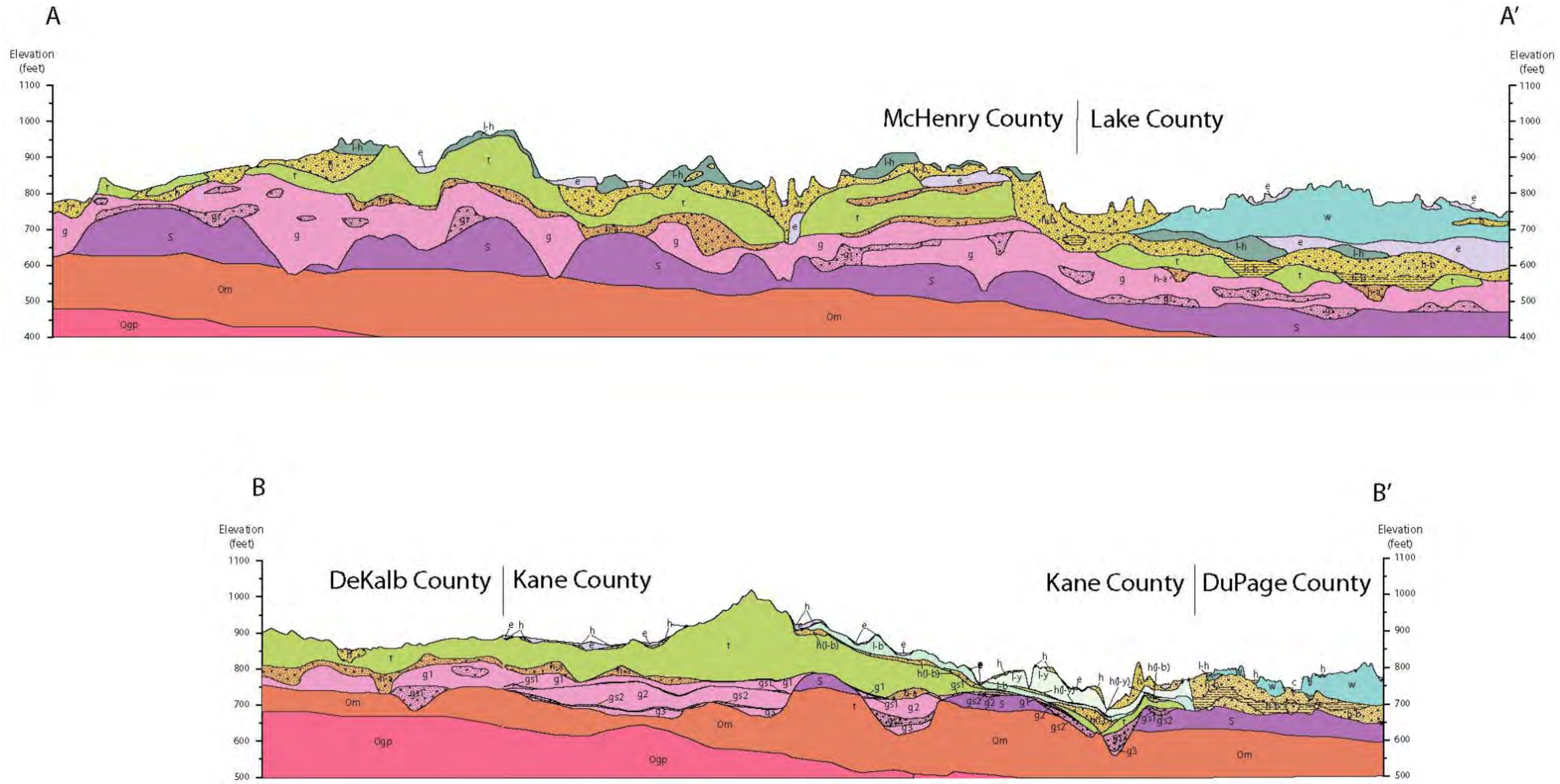

Figure B-5. Cross sections of the Quaternary materials and shallow bedrock in the study area using lithostratigraphic nomenclature shown in Figure B-3. A-A’ compiled and modified from Curry and Pavich (1996) and current mapping by the Central Great Lakes Geologic Mapping Coalition. B-B’ compiled and modified from Vaiden et al. (2004), Dey et al. (2007a), and Curry (2008). Lines of cross section are shown in Figure B-4.

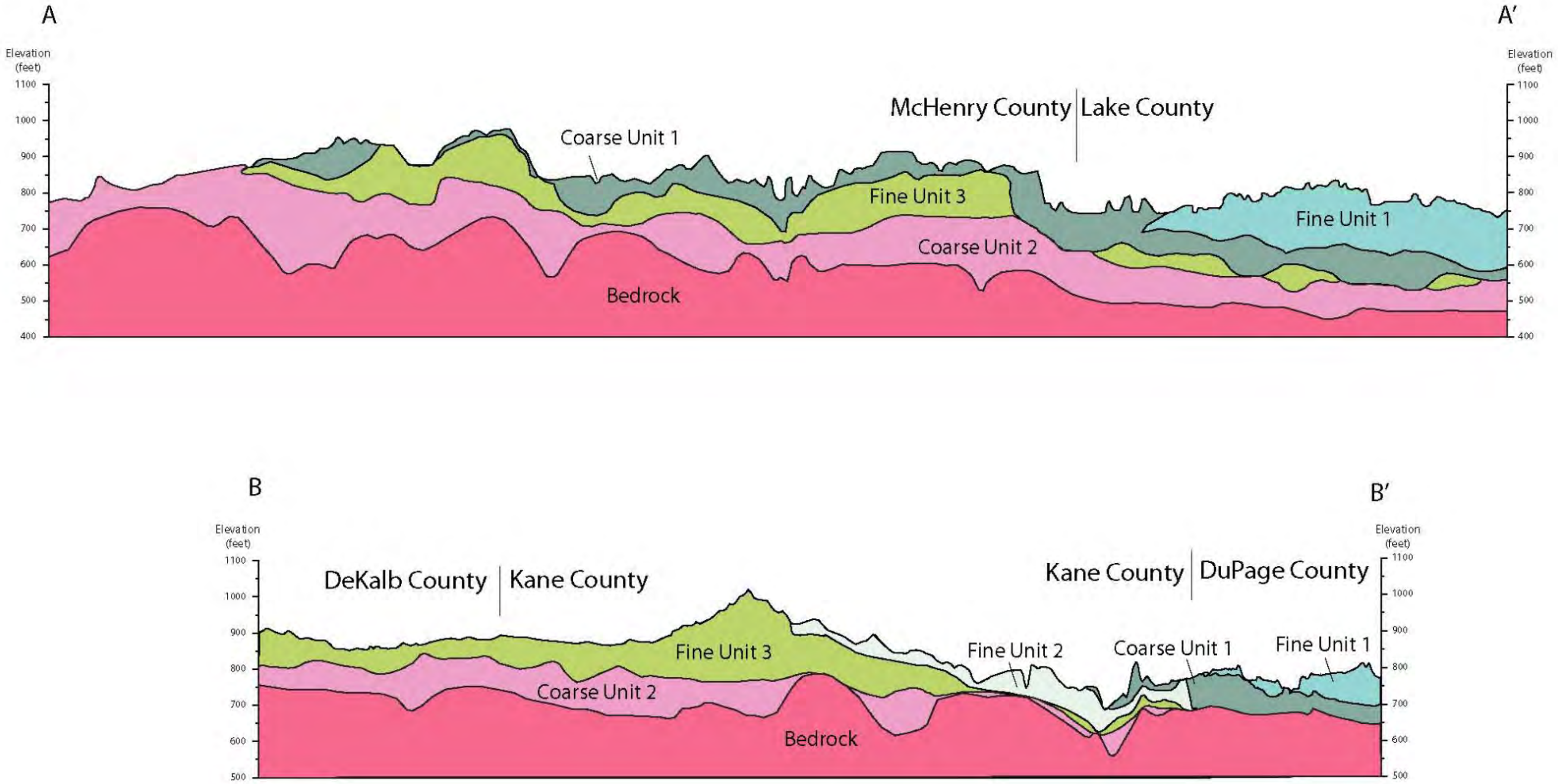

Figure B-6. Cross sections of the Quaternary materials and shallow bedrock in the study area using Quaternary hydrostratigraphic nomenclature discussed in Section B.3.1 through Section B.3.5.
Lines of cross section are shown in Figure B-4.

B.3.1. Coarse-Grained Unit 2

Coarse-Grained Unit 2 consists of the Glasford Formation and the Ashmore Tongue of the Henry Formation (Figure B-3). These sediments are widely distributed in the subsurface throughout the Fox River watershed geologic mapping domain and may reach a thickness of greater than 300 feet in bedrock valleys. The Glasford Formation consists largely of diamicton but also contains abundant stratified silt and clay with common lenses of sand and gravel. Where present, the Glasford Formation rests on bedrock (Figure B-5). Sand and gravel deposits associated with the Glasford are often used for water supply, and those gravels in contact with bedrock are likely in hydraulic communication with the Shallow Bedrock Aquifer. The Ashmore Tongue of the Henry Formation is an extensive sand and gravel deposit associated with the first advance of glaciers during the last Ice Age (Hansel and Johnson, 1996). Coarse-Grained Unit 2 is at its thickest along the western margin of the Fox River watershed geologic mapping domain; it is sporadically absent in the eastern part of the domain (Figure B-7).

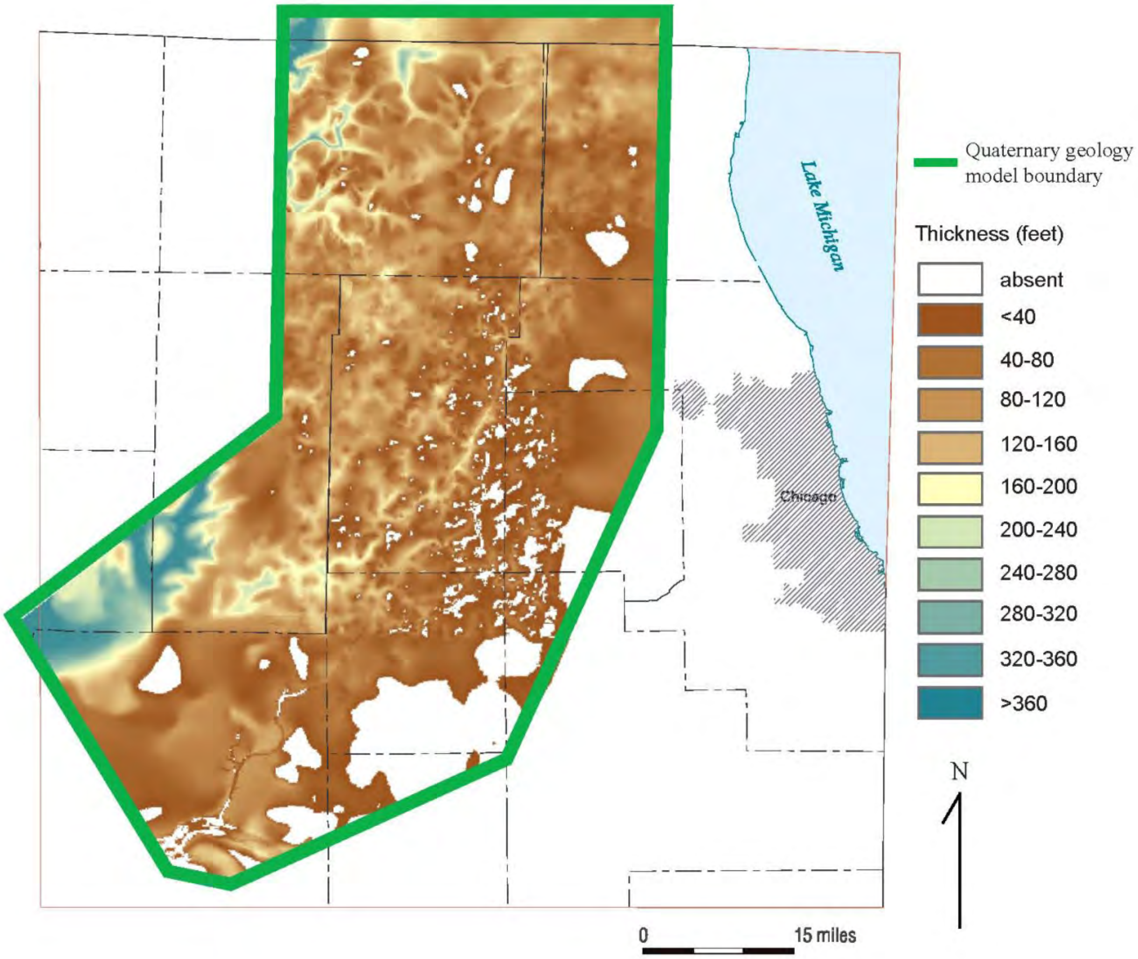

Figure B-7. Thickness of Coarse-Grained Unit 2

B.3.2. Fine-Grained Unit 3

Fine-Grained Unit 3 consists of the clay-rich, dense, widespread, and generally thick diamicton of the Tiskilwa Formation (Figure B-3). In moraines of McHenry, Kane, and DeKalb Counties, Fine-Grained Unit 3 may be nearly 300 feet thick, but it thins dramatically eastward to less than 30 feet near the eastern edge of the Fox River watershed geologic mapping domain (Figure B-8). Fine-Grained Unit 3 typically acts as a significant confining unit for underlying aquifers.

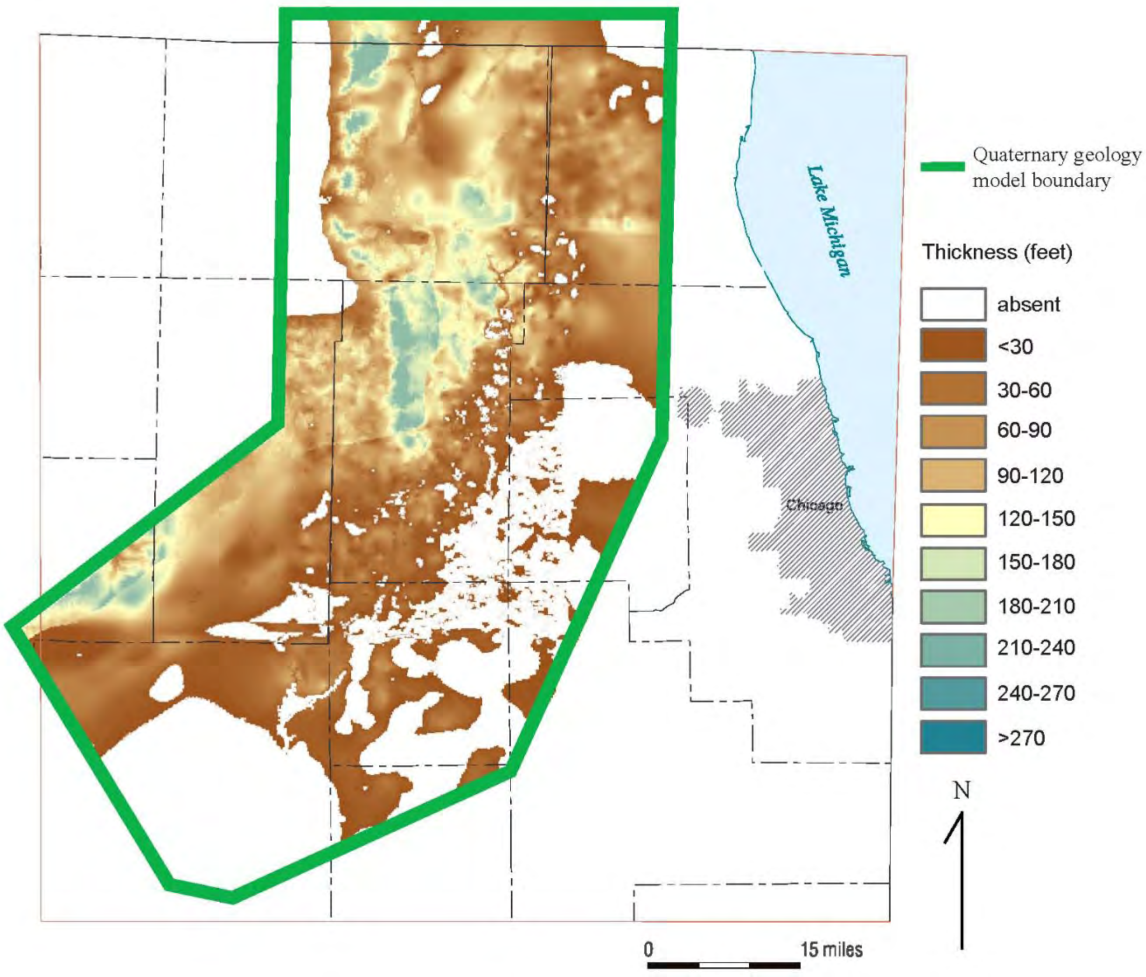

Figure B-8. Thickness of Fine-Grained Unit 3

B.3.3. Fine-Grained Unit 2

Diamicton of the Batestown and Yorkville Members of the Lemont Formation, and sand and gravel deposits underlying each of these (unnamed tongues of the Henry Formation) (Figure B-3), are grouped as *Fine-Grained Unit 2*. Within the Fox River watershed geologic mapping domain, the diamictons are quite similar in texture (very fine-grained) and distribution. The sand and gravel deposits underlying the Batestown and Yorkville Members are generally thin and discontinuous. Fine-Grained Unit 2 is generally less than 50 feet thick but can reach thicknesses of nearly 200 feet in moraines (Figure B-9). It is generally absent in northern McHenry and Lake Counties and eastern Cook, DuPage, and Will Counties.

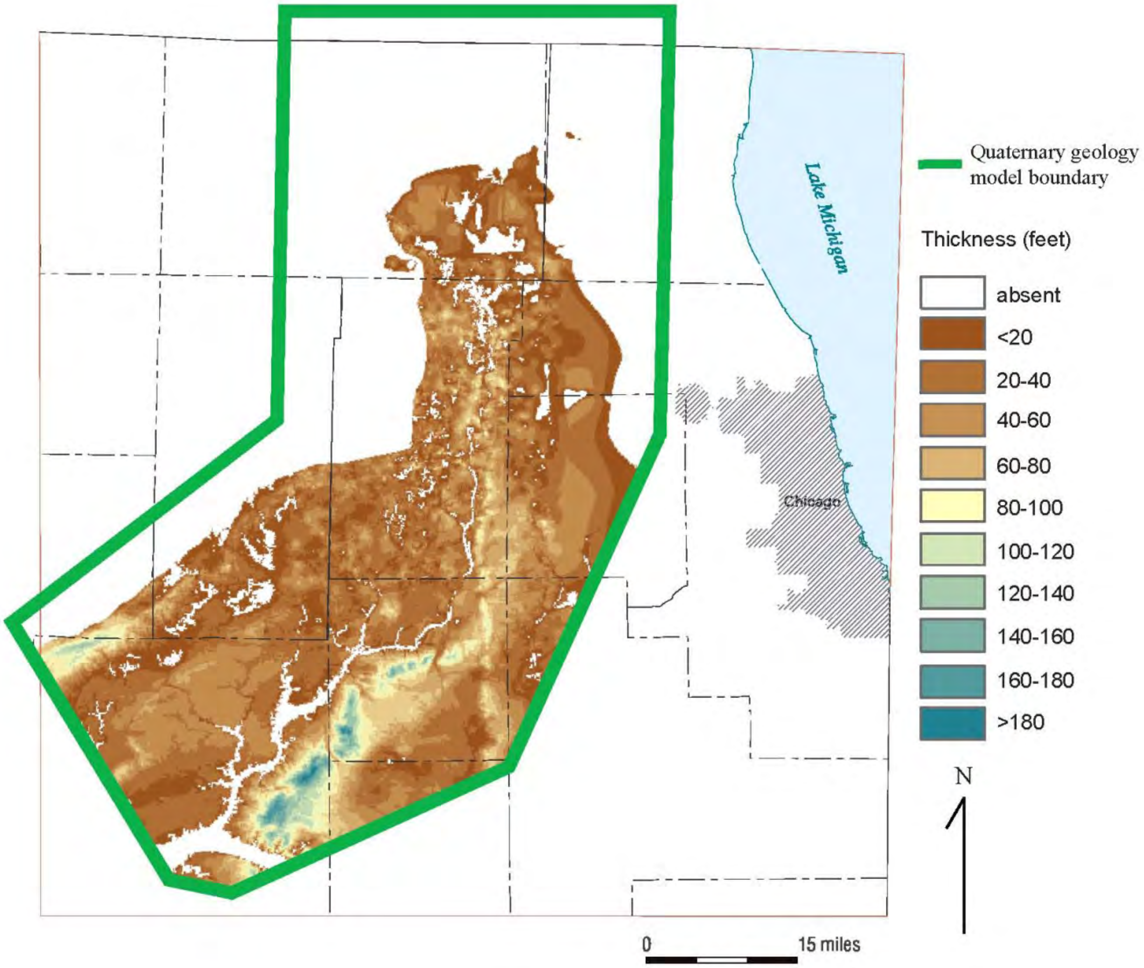

Figure B-9. Thickness of Fine-Grained Unit 2

B.3.4. Coarse-Grained Unit 1

The Haeger Member of the Lemont Formation and Beverly Tongue of the Henry Formation (Figure B-3) are grouped as *Coarse-Grained Unit 1*. The Haeger Member is a sandy diamicton with abundant beds of sand and gravel and thin beds of silt and clay. The Beverly Tongue is predominantly a coarse sand and gravel. In much of the Fox River watershed geologic mapping domain, particularly McHenry County, coarse-grained surficial deposits are also included in Coarse-Grained Unit 1. The unit is generally less than 100 feet thick, but it may be thicker in moraines and valley fills (Figure B-10). It is extensive in the Fox River watershed geologic mapping domain.

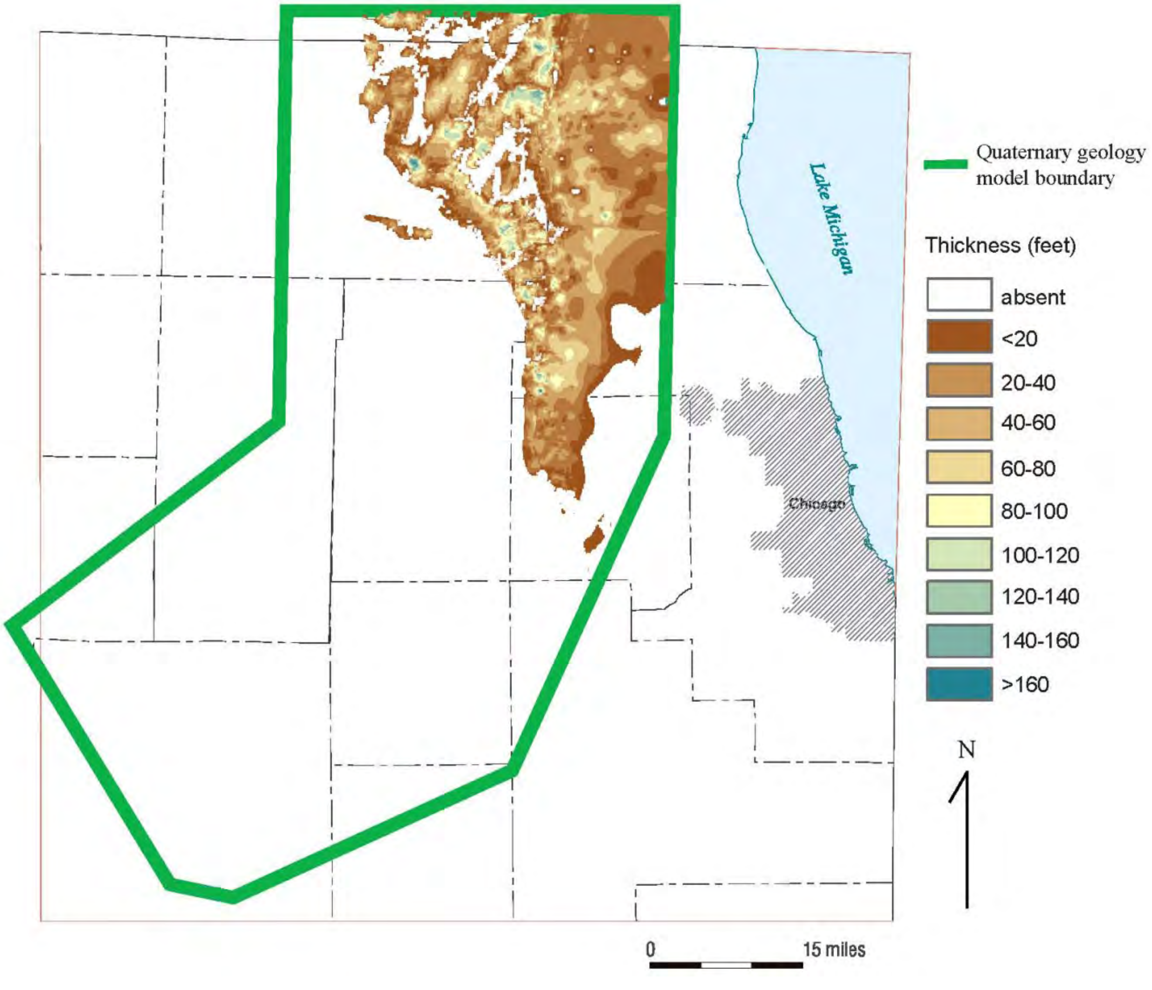

Figure B-10. Thickness of Coarse-Grained Unit 1

B.3.5. Fine-Grained Unit 1

Fine-grained Unit 1, the uppermost unit in the Fox River watershed geologic mapping domain, consists of fine-grained diamicton of the Wadsworth Formation (Figure B-3) and associated lacustrine and fluvial sediments. The unit is present throughout most of the northeastern part of the Fox River watershed geologic mapping domain and is commonly more than 100 feet thick in morainal deposits, most notably in western Lake County (Figure B-11). Where present, Fine-Grained Unit 1 is an extensive surficial aquitard.

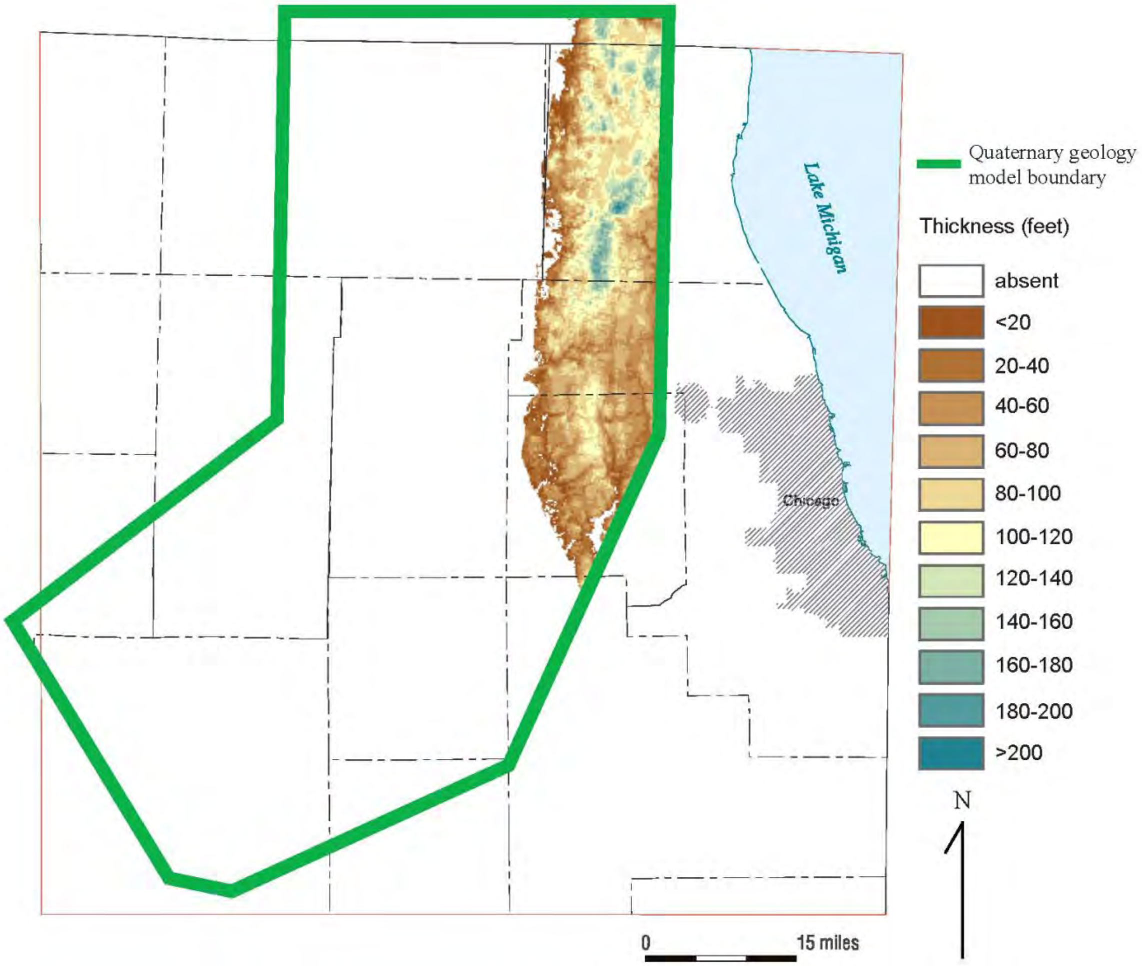

Figure B-11. Thickness of Fine-Grained Unit 1

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