Meeting East-Central Illinois Water Needs to 2050:
Potential Impacts on the Mahomet Aquifer and Surface Reservoirs

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Abstract

In this study we examined the impact of current and future water demands on streams and aquifers in east-central Illinois through the use of computer-based models. A numerical groundwater flow model was used to examine the Mahomet Aquifer, the principal groundwater resource in the region. Analytical and deterministic models were used to examine the four large surface water supply reservoirs. Future water supplies and demands out to the year 2050 were evaluated under three scenarios: baseline growth, more resource intensive, and less resource intensive scenarios.

Based on a conceptual model of groundwater flow and recharge in the Mahomet Aquifer system, a numerical groundwater flow model was developed that is composed of three aquifers and three confining layers. Model-predicted drawdowns from predevelopment to 2005 conditions show a large cone of depression in the Champaign region and relatively small drawdowns in limited regions of the confined portion of the aquifer stretching from Clinton through Normal to Morton. In the Havana Lowlands region the model matched field observations that showed no significant drawdowns since the area became heavily irrigated. The predicted increases in drawdown for the three scenarios mimic the historical drawdown with the largest increases in the Champaign cone of depression. The computed mass balance of the model changed with the 262 million gallons per day (mgd) baseline increase in pumpage from 1930 to 2050 largely by inducing an additional 150 mgd of recharge and decreasing baseflow discharge by 99 mgd. A majority of the baseflow reduction, or 82.3 mgd, came from large streams in the unconfined areas at the western end of the aquifer. The remaining 16.7 mgd of baseflow loss came from smaller streams flowing over confined portions of the aquifer with losses in individual watersheds ranging from 7 percent for Salt Creek to 16 percent for the upper Sangamon River above Lake Decatur.

None of the current groundwater users in the Mahomet Aquifer could be considered "at risk" for a future water shortage under the three demand scenarios. The model budget indicates that the available 2050 water supply for the aquifer as a whole is 2.3 times greater than the projected baseline demand. However, hydraulic conditions vary tremendously across the aquifer, and therefore, the aquifer-wide budget does not guarantee that the demand from additional high-capacity wells not in the prescribed demand scenarios will have acceptable impacts to private wells or baseflow in small streams. In this study, the Mahomet Aquifer has been subdivided into areas based on the expected types of impact that the new high capacity wellfield might have.

Surface waters are typically highly replenishable sources, but their availability for water supply can be greatly restricted during periods of extended drought. Knowledge of water availability in streams and reservoirs during times of drought or other periods of low flow is provided in this study through a combination of historical records and both analytical and deterministic models. Statistical estimates of streamflows were developed using streamflow gaging stations and enhanced by the Illinois Streamflow Assessment Model that considers variability in hydrologic records, regional similarity in flow conditions, and external influences such as water withdrawals and wastewater effluents.

Hydrologic changes associated with potential changes in future climate were evaluated using a deterministic watershed simulation model of the Sangamon River basin. Water yields from community reservoirs were analyzed through the use of water budget models that include various hydrologic records for data input.

The surface water supply analysis for east-central Illinois focuses primarily on water yields of community reservoir supply systems: Bloomington, Danville, Decatur, and Springfield. A drought vulnerability classification for these reservoir yields is based on the estimated probability that these community supplies could experience water shortages during an extreme drought as represented by the historical drought of record. Water budget analysis indicates that one of the community systems (Springfield) is an inadequate system, with greater than a 50 percent probability that a shortage would occur during a drought of record condition; two other communities (Bloomington and Decatur) are at-risk systems, with greater than a 10 percent probability of shortage. If each community's water demand increases as projected by the critical trend (baseline) scenario, both the Bloomington and Decatur systems will be classified as inadequate by 2020 unless supplemental sources are developed by that time. Water budget analyses and the resulting system classifications include considerations for drought response and water conservation measures as outlined in each community's Drought Action Plan. Drought preparation through water conservation measures could reduce the probability of shortages, but not to the extent where the overall drought vulnerability classification for any of these communities would be changed. Development of supplemental sources is considered essential for reducing each community's vulnerability to an extreme drought.

Introduction

Water is an essential part of all life. The availability and sustainability of an adequate and dependable water supply is essential for our public, environmental, and economic health. This important 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 supply 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 aspects of water supply assessment for the east-central Illinois planning region, an area comprising 15 counties: Cass, Champaign, DeWitt, Ford, Iroquois, Logan, Macon, Mason, McLean, Menard, Piatt, Sangamon, Tazewell, Vermilion, and Woodford (Figure 1). The results of our scientific analyses are intended to highlight the opportunities and challenges ahead for meeting future water demand in east-central Illinois.

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. Under the guidance of the Mahomet Aquifer Consortium (MAC), a 12-member grassroots water supply planning group was formed for east-central

Illinois, called the East-Central Illinois Regional Water Supply Planning Committee (RWSPC). The ISWS, 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 RWSPC and updating and expanding regional water resource information.

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

- Descriptions of the sources of water available to east-central 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 RWSPC was assigned the responsibility of developing water demand scenarios to 2050; this was accomplished via contract with Wittman Hydro Planning Associates, Inc. (WHPA), in Bloomington, Indiana. The ISWS and ISGS were responsible for quantifying the available water supply. The purpose of this report is to describe the water resources of east-central Illinois and summarize the impacts on those resources from increased withdrawals to meet prescribed scenarios of water demand to the year 2050.

Study Area

The water supply planning area for east-central Illinois consists of the 15 counties that overlie the Mahomet Aquifer and the watershed for the Sangamon, Mackinaw, and Vermilion Rivers (Figure 1). These include the counties of Cass, Champaign, DeWitt, Ford, Iroquois, Logan, Macon, Mason, McLean, Menard, Piatt, Sangamon, Tazewell, Vermilion, and Woodford. Christian County and portions of Shelby and Montgomery Counties lie within the Sangamon River watershed, but for water supply planning purposes these counties are included in efforts for a third planning region, the Kaskaskia River watershed. The thin strip of sand and gravel aquifer mapped as the Mahomet Aquifer along the west side of the Illinois River in Figure 1 was not included in this study because it behaves independently from the Mahomet Aquifer, being hydraulically separated from the rest of the aquifer by the Illinois River. The intensive use of groundwater from this portion of the aquifer in the Peoria area has been examined by Marino and Schicht (1969) and Burch and Kelly (1993). This study also does not include any analysis for the many small localized aquifers that occur within the study area but are not part of the Mahomet Aquifer flow system. Cravens et al. (1989) performed an analysis of the Silurian dolomite aquifer which underlies northernmost Iroquois County and is heavily used for irrigation.
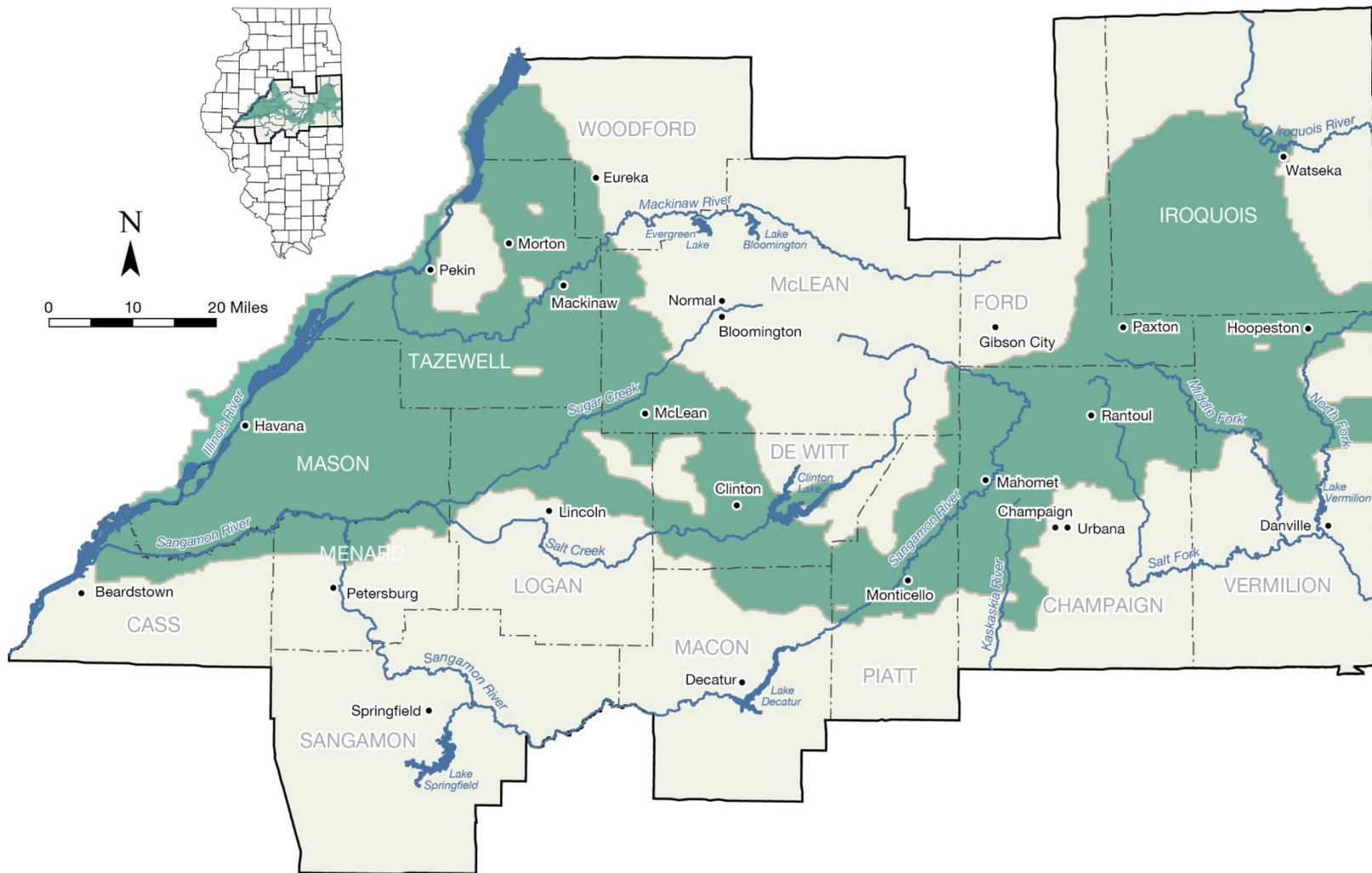
Figure 1. East-central Illinois regional water supply planning area

The assessment of water supply impacts focused on the Mahomet Aquifer that underlies portions of 14 counties in the 15-county study area and on the yields of the region's major surface water reservoirs supplying Bloomington, Danville, Decatur, and Springfield. A map of the planning region is shown in Figure 1.

Report Structure

The next section of this report, Section 2, provides a general discussion on water supply and demand and presents a brief presentation of the three scenarios describing future water demands to 2050, developed for the RWSPC, and how those scenarios were incorporated into analytic models to assess impacts.

The focus of Section 3 is groundwater availability. The section begins with a presentation of our present conceptual understanding of Mahomet Aquifer hydrology, starting with a description of the regional geology and hydrogeology of east-central Illinois, then providing insights on aquifer hydrology based on 50+ years of data collection and interpretation, moving from east to west across the aquifer in four segments: northeast area, Champaign area, west-central area, and the Havana Lowlands. This is followed by a description of the numerical groundwater flow model and model calibration. Results of the flow model analysis with an emphasis on the impacts of future water supply demands on the Mahomet Aquifer, based largely on currently active wells is then presented, finishing with a description of likely impacts based on prospective locations of potential new high capacity wellfields.

Section 4 focuses on surface water availability, emphasizing the analytical methods used to determine reservoir yields, uncertainties in data inputs, and the use of statistical methods to estimate the 90 percent confidence reservoir yield. For each of the four major surface water supplies (Bloomington, Danville, Decatur, and Springfield), a summary is presented that includes discussions of data inputs, comparisons of historical drought periods, possible characteristics of worse-case droughts, results of the yield analyses, and finally, the expected drawdowns during the droughts of record and worse-case droughts.

Section 5 presents a general summary of water resource availability and recommendations for further study.

Caveats

The primary focus of the water supply planning initiative is on 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;
- 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 expressed in this report.

How Much Water is Available in East-Central Illinois?

The amount of water the streams and aquifers of east-central Illinois can supply depends on where the demand is, how much users are willing to spend, and what societal and environmental consequences are acceptable. The amount of water available is not constant. Many water development projects act to increase water availability by capturing water that would otherwise be lost to flood flows or evaporation. Other projects and hydrologic processes act to decrease water availability such as reservoir siltation or aquifer desaturation. Future increases in water demand and water development projects will take place on a landscape where water is already heavily managed by drainage networks, dredged streams, reservoirs, water withdrawals, and wastewater discharges. Unlike other natural resources humans consume, such as petroleum, only a tiny amount of the mass of water used is converted to other compounds. Most of the water we consume is returned to the hydrologic cycle through wastewater discharge or evaporation.

In this study we examine the impact of current water demands and future water demands on the streams and aquifers in east-central Illinois through the use of computer-based models. Current water demands were estimated from annual surveys of large water users conducted by the Illinois Water Inventory Program (IWIP) at the Illinois State Water Survey. Future water demands were estimated by WHPA and are detailed in their report *Water Demand Scenarios for the East-Central Illinois Planning Region: 2005-2050* (WHPA, 2008). The modeling and analysis of groundwater and surface water in this study were conducted separately because of the fundamental difference in their hydrologic behavior and the analytical tools used to evaluate each. Surface water supplies are strongly influenced by the timing and magnitude of precipitation events and thus we chose to model them with transient simulations and statistical analyses of past streamflow records using the analytical Illinois Streamflow Assessment Model (ILSAM). Groundwater supplies exhibit more steady hydraulic behavior but vast variability in the spatial geometry of the aquifer materials, so we chose to model the Mahomet Aquifer with a deterministic numerical groundwater flow model, MODFLOW (McDonald and Harbaugh,

1988). Results of the ILSAM model were used to calibrate flow budgets in the MODFLOW model.

Where do scientists, and more importantly the public, draw the line as to what is or is not an acceptable impact? If impacts suggested by the models are considered by stakeholders (in this case, represented by the RWSPC) 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.

Acknowledgements

Water Supply and Demand in East-Central Illinois

To assess the available water supplies in the study area, the authors used different demand scenarios based on the different growth projections of current water use out to the year 2050. Up to five new industrial users were embedded in the demand scenarios, based upon known proposals for ethanol production facilities within the region (although ethanol production was used as an example, the idea was to assess water availability for potential new industrial uses within the region). An analysis of maximum water availability, regardless of impact, would involve creating new demand scenarios that would make too many assumptions to be meaningful. New wells and reservoirs would have to be sited where none currently exist. Discharge from new upstream users would have to be factored into the availability of water for downstream users. New technologies to capture flood waters or to treat and recycle wastewater could also increase the maximum water availability.

Conceptually, the supply and demand curves for groundwater and surface water systems behave differently (Figure 2 and Figure 3). Municipalities and power generators constructed reservoirs to store water during higher flows so there is sufficient water to sustain withdrawals during low flows. Because east-central Illinois receives an annual average of 38 inches of precipitation that is generally spread evenly throughout the year, reservoirs typically have adequate supply more than 95 percent of the time. If the surface water supply curve drops below the demand curve, demand must be reduced (Figure 2a) or alternate water sources must be found (Figure 2b). Alternate sources can include pumping of groundwater from emergency wellfields, such as at Decatur, or a side stream pumping station on another stream, such as at Springfield or Bloomington. The effectiveness of a supplemental groundwater source will depend on whether or not the aquifer being pumped is hydraulically connected to the stream that feeds the reservoir. For example, Decatur's Sangamon River emergency wellfield discharged groundwater pumped from the Mahomet Aquifer into the Sangamon River, which then flowed to Lake Decatur. The operation of this wellfield induced water out of an upstream reach of the Sangamon River (Roadcap and Wilson, 2001), and thus reduced the amount of supplemental water reaching the lake. This wellfield was subsequently mothballed for a wellfield much farther from the Sangamon River.

Groundwater supplies in the Mahomet Aquifer are more immune to seasonal and climatic fluctuations and have the potential to provide a more stable supply than a reservoir. A groundwater supply can increase along with increasing demand because lower water levels induce additional recharge by creating greater hydraulic gradients with streams and overlying geologic materials (Figure 3a). The removal of water from aquifer storage by pumpage can add or subtract from the available supply depending on if the saturated thickness of the aquifer decreases enough to significantly impact well capacities (Figure 3b). If the groundwater supply and demand curves become close or even cross, water will be removed from storage at an unsustainable rate (Figure 3c). This phenomenon is sometimes erroneously referred to as "mining" because most aquifers can be naturally refilled if the demand is removed. Groundwater supplies also can be supplemented with surface water or groundwater from a different aquifer (Figure 3d). For example, the original wellfield for the City of Normal in the shallow aquifer along Sugar Creek proved to be an inadequate supply. As a consequence, a new wellfield was constructed in the Mahomet Aquifer west of town.
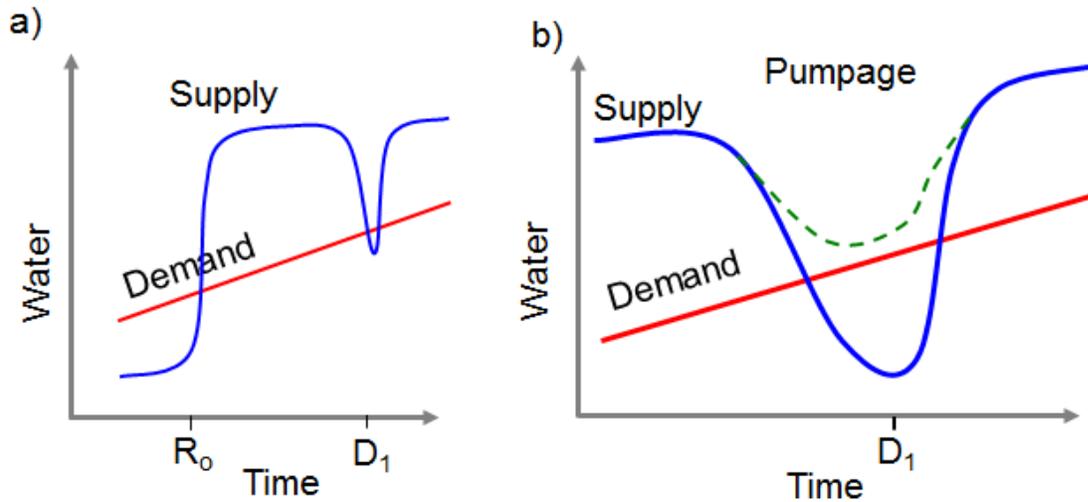
Figure 2. Conceptual supply and demand curves for surface water development: a) reservoir construction at time R_o and a drought at D_1,, b) supplemental supply (dashed line) during a drought at D_1

The two central questions in terms of sustainability for water supplies in east-central Illinois are:

1) Do we have enough water to meet projected demands?
2) Can we use the water in such a way as to minimize environmental and societal impacts?

In 2010, none of the larger groundwater supplies tapping the Mahomet Aquifer reported water supply shortages or unusual price pressures not related to treatment issues. In areas of intense use, such as at Normal, Decatur, or Champaign, the lowering of water levels has impacted some of the surrounding private wells. No environmental or other societal impacts have been reported. Many small groundwater supplies in the study area not located over the Mahomet Aquifer have experienced water supply problems. Some of these systems, such as at Roanoke, Farmer City, and Atlanta, have to rely on a larger number of wells tapping into less productive shallow aquifers, many of which have poor water quality. Other systems, such as at Tolono, St Joseph, and Philo, have abandoned their wells and started importing water from systems using the Mahomet Aquifer.

The sustainability of surface water supplies will always be clouded with the uncertainty of when the next drought will occur and how severe it will be. Communities have implemented steps to improve the sustainability of reservoirs such as raising dam elevations, dredging lake bottom sediments, or adding side-stream pumping stations on a different nearby stream. The operation of reservoirs is complicated by the actions of upstream users, water quality issues, and/or interactions with the major aquifers. In addition, some cities with reservoirs have, or are contemplating, the potential to build supplemental groundwater supplies. The construction of new reservoirs is also possible but the approval process comes with enormous economic and environmental hurdles.
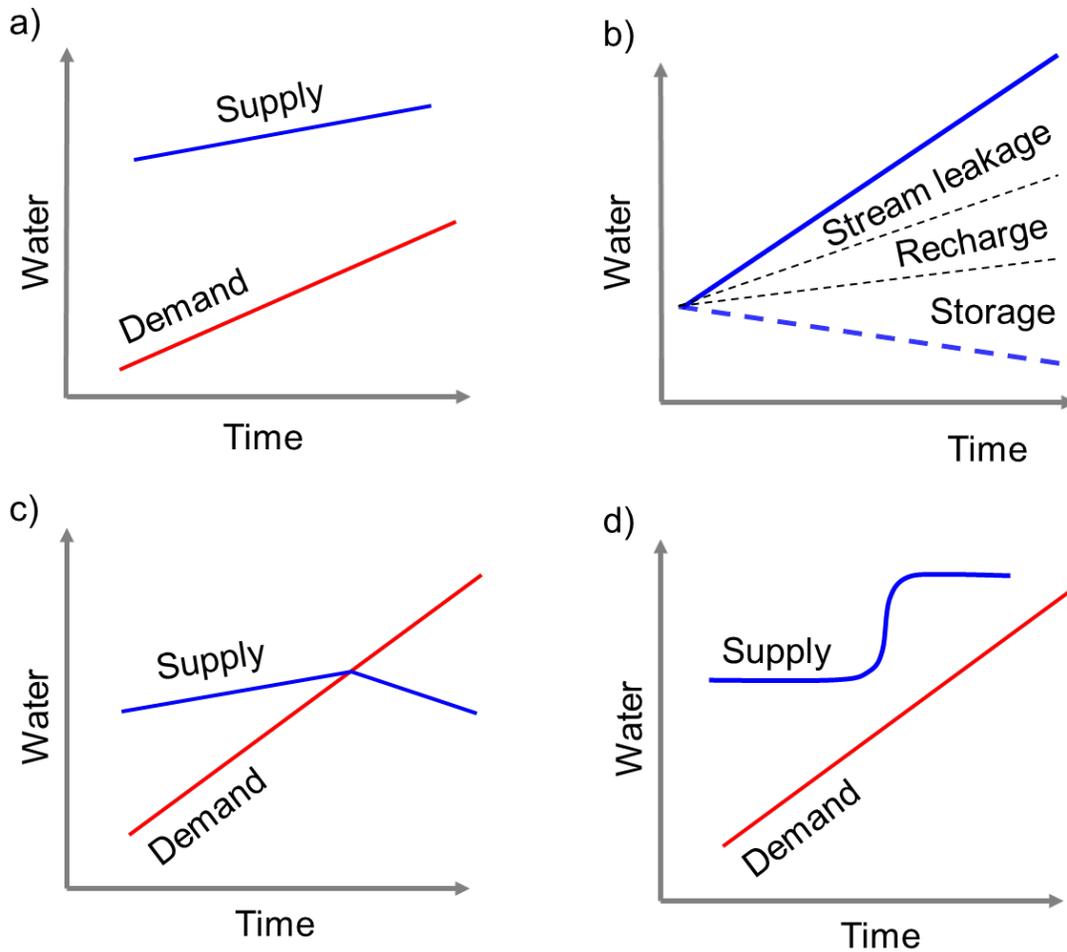
Figure 3. Conceptual supply and demand curves for groundwater development: a) sustainable withdrawals, b) sources of potential additional supply, c) unsustainable supply, and d) supplemented supply

Current and Future Water Use

A detailed analysis of current water use and future demands out to the year 2050 was performed by Wittman Hydro Planning Associates in conjunction with Southern Illinois University (WHPA, 2008). This analysis is based on water withdrawal information gathered through the IWIP operated by the Illinois State Water Survey. Through IWIP survey forms, operators of high capacity wells and surface water intakes annually report total yearly pumpage and maximum daily pumpage. Total water withdrawal for 2005 was estimated to be 339.2 million gallons per day (mgd) for public, industrial, and irrigation uses with an additional 1315 mgd continuously re-circulated through power plant cooling systems.

WHPA (2008) created three scenarios of future water demand out to the year 2050 based on different growth and economic assumptions (Table 1). The baseline (BL) scenario, which represents the future based upon historical trends, estimated demand to increase by 173 mgd (51 percent) from 339 mgd in 2005 to 512 mgd in 2050 (Table 1). At 3.8 mgd/yr, this rate of growth is below the historic trend of approximately 5 mgd/yr largely due to a decrease in the potential

number of new irrigation systems in the densely irrigated Havana Lowlands region. WHPA (2008) created less resource intensive (LRI) and more resource intensive (MRI) demand scenarios which show water demand increasing by 119 mgd (35 percent) and 232 mgd (68 percent), respectively. Table 2 shows the breakdown of the projected 2050 baseline water use by county and major use sector.

For the purpose of modeling the impacts of the three future demand scenarios on the Mahomet Aquifer, WHPA provided projected pumpage data for individual wells. Three major modifications were made to the dataset along with many small corrections. First, for the Illinois American Water Company (IAWC) wells in Champaign, pumping rates were changed from the same value for every well to a value proportional to the pumping capacity of each well. Second, because of the lack of specific, individual irrigation well use and location data for much of the study area, total irrigation pumpage in many counties was assigned disproportionately to the small number of known irrigation wells. This resulted in unrealistically large pumping rates that had to be reduced to expected levels, thus reducing the total irrigation pumpage slightly. Many unmapped irrigation systems are used to guarantee seed corn crops in areas with clay-rich soils so they generally do not pump large volumes of water. Mapping and quantifying the use from the irrigation systems in the central and eastern portions of the aquifer is a topic for future surveys and studies.

Third was the creation of a more realistic pumpage distribution for the irrigation wells in the Havana Lowlands using the map of the irrigation systems created by Farm and Home Publishers (1999) instead of the far fewer known irrigation wells based on the limited well records available in the ISWS Wells Database. Pumping rate assignments were based on water use estimates by the Imperial Valley Water Authority along with soil type (Natural Resources Conservation Service, 1995) and topographic information. A total of 1077 systems were digitized from the irrigation map. Small systems were grouped together, and the larger systems were divided so each system represented a quarter-mile pivot covering ~130 acres. The systems were then divided by soil type with 811 systems located on sandy soils, 226 systems on silty lake bed sediments found along some of the creeks, and 40 systems on the clay-rich soils in the upland areas. Because heavier soils retain more water, irrigation systems on silty lake bed sediments only pump half the amount of water systems on the sandy soils (Jeff Smith, RWSPC, personal communication). The systems on clay soils were assumed to run at a quarter of the rate of those on sandy soils.

The total irrigation pumpage estimated by the Imperial Valley Water Authority was then divided and proportionately assigned to individual wells. An average of the total pumpage for the six-year period from 2004 to 2009 was used to minimize yearly pumping fluctuations and to prevent the data from being skewed by one wet or dry growing season, such as the dry summer of 2005. The total annualized pumpage was 128 mgd with each well on sandy soil pumping 0.137 mgd. Average withdrawals over the four-month irrigation season are three times higher at 384 mgd, and a peak pumpage of 1 billion gallons per day occurred in July 2005. The future pumpage rates of irrigation wells were calculated out to 2050 with the same multipliers WHPA (2008) used for each of the three scenarios.

Table 1. Summary of Water Withdrawals in East-Central Illinois (from WHPA, 2008)

Scenario/Sector	2005 Normal (mgd)	2050 Modeled (mgd)	Change from 2005 (Normal) – 2050	
			(mgd)	(%)
Baseline Scenario (BL)				
Public supply	127.24	176.88	49.64	39.0
Self-supplied C&I*	63.70	137.51	73.81	115.9
Self-supplied domestic	8.86	12.01	3.15	35.6
Irrigation and agriculture	139.40	186.46	47.06	33.8
Subtotal (w/o power)	339.20	512.86	173.66	51.2
Power generation	1,315.35	1,275.54	-39.81	-3.0
TOTAL	1,654.55	1,788.40	133.85	8.1
Less Resource Intensive Scenario (LRI)				
Public supply	127.24	153.50	26.26	20.6
Self-supplied C&I	63.70	116.17	52.47	82.4
Self-supplied domestic	8.86	12.01	3.15	35.6
Irrigation and agriculture	139.40	177.21	37.81	27.1
Subtotal (w/o power)	339.20	458.89	119.69	35.3
Power generation	1,315.35	1,217.78	-97.57	-7.4
TOTAL	1,654.55	1,676.67	22.12	1.3
More Resource Intensive (MRI)				
Public supply	127.24	185.36	58.12	45.7
Self-supplied C&I	63.70	178.52	114.82	180.2
Self-supplied domestic	8.86	12.01	3.15	35.6
Irrigation and agriculture	139.40	195.77	56.37	40.4
Subtotal (w/o power)	339.20	571.66	232.46	68.5
Power generation	1,315.35	1,342.37	27.02	2.1
TOTAL	1,654.55	1,914.03	259.48	15.7

*C&I = Commercial and Industrial water sector; w/o = without

Note: All withdrawal values reported in million gallons per day (mgd)

Table 2. 2050 Withdrawals for Each County, by Demand Sector, for the Baseline Scenario (from WHPA, 2008)

County	Public water supply (mgd)	Domestic (mgd)	Power generation (mgd)	Commercial & industrial (mgd)	Irrigation & agriculture	Total (mgd)
Cass	2.32	0.44	--	3.16	15.84	21.76
Champaign	33.62	2.56	--	9.74	6.15	52.07
DeWitt	1.83	0.4	810.44	0.03	0.94	813.64
Ford	2.25	0.25	--	6.54	0.92	9.96
Iroquois	3.3	0.96	--	1.48	3.25	8.99
Logan	3.99	0.71	--	2.82	2.08	9.59
Macon	31.33	0.21	--	26.59	0.41	58.54
Mason	0.95	0.55	105.00	7.48	108.26	222.24
McLean	24.07	1.55	--	2.07	2.15	29.85
Menard	1.04	0.02	--	0.00	3.09	4.16
Piatt	1.42	0.46	--	1.56	0.48	3.94
Sangamon	31.74	1.54	331.46	7.93	1.64	374.31
Tazewell	25.39	0.12	25.88	62.05	39.14	152.59
Vermilion	10.52	0.66	2.76	6.04	0.72	20.71
Woodford	3.08	1.58	--	0.02	1.39	6.06
Total	176.88	12.01	1,275.54	137.51	186.46	1,788.40

All data reported in million gallons per day (mgd).

All sectors, except public water supply, are self-supplied.

A total of 1544 high-capacity wells with a combined pumpage of 208 mgd in 2005 were imported into the groundwater flow model (Figure 4). Wells in the 15-county area that are not completed in or above the Mahomet Aquifer, such as at Gibson City, Farmer City, and Riverton, are not included in the analysis. To run the historical simulations in the model, the 2005 rates were linearly extrapolated backward to 0 mgd in 1940 except at Champaign where 3.1 mgd was assigned to the start of the model to simulate pre-1940 pumpage from the Glasford Aquifer. The historical pumping rates at Normal and Champaign were assigned using the individual well completion dates as extrapolation points. Final pumpage data and trends, modified as explained above from the data provided by WHPA, were used for modeling the three future scenarios (Figure 5).

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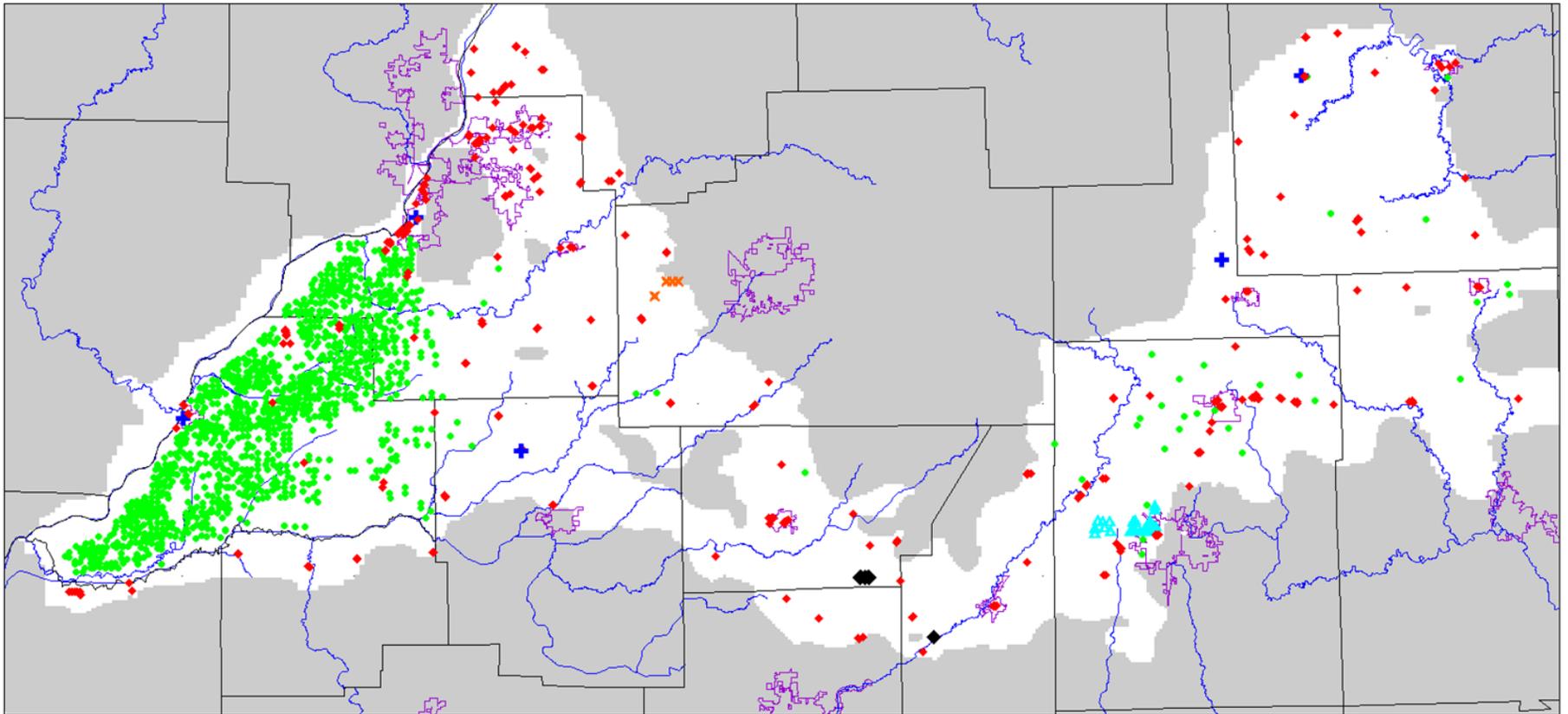
Figure 4. Distribution of high-capacity wells in the Mahomet Aquifer (green dots – irrigation wells; red diamonds – public and commercial wells; orange crosses – Normal wells; black diamonds – Decatur emergency wells; cyan triangles – IAWC Champaign wells; open cyan triangles – new IAWC Champaign wells; blue crosses – hypothetical new industrial plant wells)
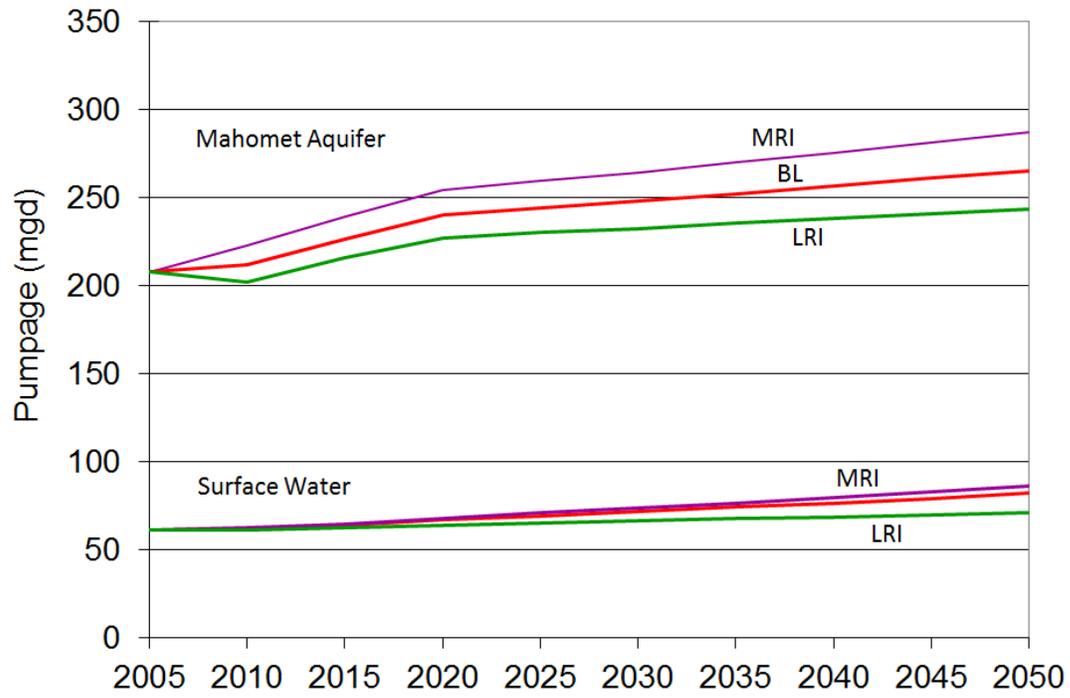
Figure 5. Simulated water demand projections out to 2050 for the Mahomet Aquifer and the surface water supplies of Springfield, Decatur, Bloomington, and Danville (modified from WHPA, 2008)

Groundwater Availability

Quantifying the availability of groundwater from the Mahomet Aquifer is an evolving and complex process. Because the aquifer is buried by thick glacial deposits from subsequent glaciations and has almost no surface expression except at the western end, much of the geology and hydrology have to be inferred from a limited number of widely spaced data points. Mapping information across such a large glacial aquifer, approximately 3940 square miles, is confounded by the fact that many controlling hydrologic features, such as an interconnection between two sands, may be less than a quarter square mile in size. Because any detailed analysis of the entire aquifer is a daunting and expensive task, our understanding of the aquifer has developed through a series of local and regional projects and aquifer-wide projects that tackle particular aspects of the aquifer, such as the isotopic composition of groundwater within the aquifer, but taken in combination provide a robust understanding of the aquifer system.

Our understanding of the aquifer is an iterative process that builds as new data are collected and interpreted, as is the assimilation of that information into conceptual, geological, and groundwater flow models which in turn guide further data collection efforts. The types of data used in this effort include:

1) Data and interpretations from previous studies
2) Geologic data from borings and well records
3) Geophysical data
4) Water level records from observation wells
5) Mass-measurements of water levels in private wells
6) Aquifer test data
7) Stream elevation and flow records
8) Flow statistics from surface water models
9) Geochemical and isotopic data
10) Model calibration results and discrepancies

Geology

Deposits of saturated sand or sand and gravel found within the Quaternary deposits in the 15-county planning region are aquifers that provide most of the water used in the region. Quaternary deposits directly overlie the bedrock and bury features of the bedrock surface. As a result of geological processes that have shaped the region, the hydrogeology of the 15-county planning region is very complex. Although the Mahomet Aquifer is the principal groundwater resource in the region, other sand and gravel aquifers are also present and comprise locally important sources of groundwater, particularly where the Mahomet Aquifer is absent. All of these aquifers generally lie concealed beneath the present-day landscape.

Bedrock Geology

The bedrock underlying the east-central Illinois water supply planning region (Figure 6) consists of several thousand feet of sandstone, limestone, dolomite, shale, and coal. Overall these sedimentary rocks dip to the south into the Illinois Basin. This regional dip is interrupted locally by the LaSalle Anticlinorium, a structural belt that trends north-south across the eastern part of the planning region.

The bedrock surface over much of the 15-county water supply planning region is composed of Pennsylvanian shales and relatively thin layers of sandstone, limestone, and coal (Willman et al., 1975). Because of the LaSalle Anticlinorium, older rocks (Silurian to Mississippian limestone, dolomite, and sandstone) form the bedrock surface in northern Champaign, southern Ford, and much of Iroquois Counties. Rocks at the bedrock surface along the southwest margin of the planning region are predominantly Mississippian limestones.

Two broad, deeply incised bedrock valleys, the Mahomet and the Mackinaw, are the prominent features of the bedrock surface in the water supply planning region (Figure 7). The bedrock surface in the region is generally concealed by the Quaternary deposits overlying it. However, bedrock is exposed at the land surface at some localities in the region, mostly in the southern half of Vermilion County, southern Menard County, and at isolated localities in Sangamon, Cass, and Logan Counties (Piskin and Bergstrom, 1975).

The Mahomet Bedrock Valley in Illinois extends from the state line in Iroquois and Vermilion Counties to its confluence with the Mackinaw Bedrock Valley in Tazewell County. It is part of a drainage system that existed before Illinois was glaciated, a time when bedrock formed most of the landscape. This ancient drainage system extended eastward from Illinois into Indiana and Ohio, where it is known as the Teays Bedrock Valley, and perhaps into West Virginia (Teller and Goldthwait, 1991). The bedrock surface was modified by the earliest continental glaciers that entered the state during the Ice Age (Killey, 2007), and by the large volumes of glacial meltwater that flowed from these very large ice sheets. The deepest parts of the Mahomet Bedrock Valley lie more than 500 feet below the present-day land surface (Kempton et al., 1991). The Mackinaw Bedrock Valley enters the planning region from the north in Tazewell County and trends to the southwest in Mason and Cass Counties where it exits the region. The Mackinaw is the course of the preglacial, ancestral Mississippi River. Similar to the Mahomet Bedrock Valley, the Mackinaw is filled with sediments left from continental glaciation and associated meltwater streams.
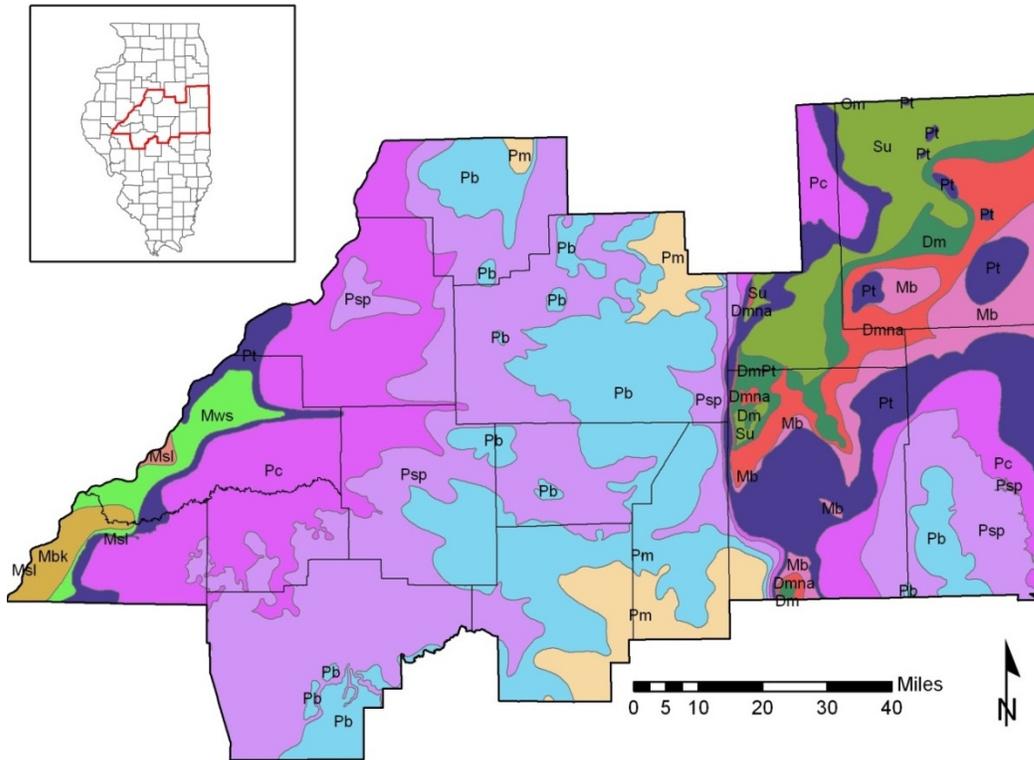
Legend

Pennsylvanian

- Pm Mattoon Fm
- Pb Bond Fm
- Psp Shelburn-Patoka Fms undivided
- Pc Carbondale Fm
- Pt Tradewater Fm

Mississippian

- Msl St. Louis Limestone
- Mws Warsaw Fm
- Mbk Meppen Limestone
  Fern Glen Fm
  Burlington-Keokuk Limestone

Mississippian

- Mb Borden Siltstone

Devonian

- Dmna New Albany Shale
- Dm Muscatatuck Group

Silurian

- Su Silurian System undivided

Ordovician

- Om Maquoketa Group

Figure 6. Bedrock geology of the east-central Illinois regional water supply planning area (modified from Kolata, 2005)
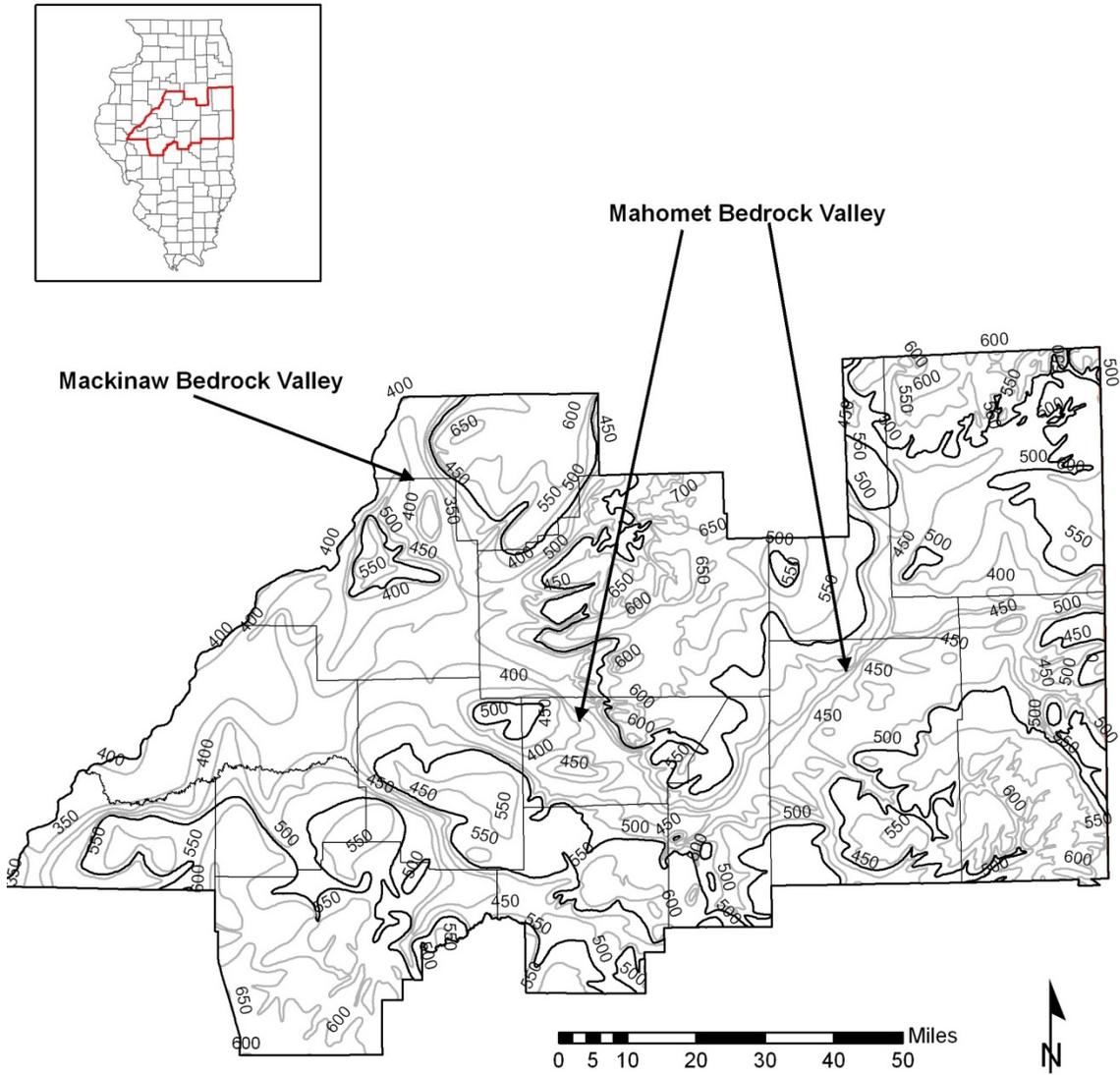
Figure 7. Topography of the bedrock surface within the east-central Illinois regional water supply planning area. The 500-foot contour line approximates the edge of the bedrock valleys (modified from Herzog et al., 1994).

The bedrock uplands in the water supply planning region are 200 to 300 feet higher than the bottom of the major bedrock valleys. Smaller bedrock valleys that are tributary to the major valleys dissect the uplands. The most prominent of these tributary valleys are shown in Figure 7. Understanding the topography of the bedrock surface of the major bedrock valleys is important because the topography constrains the areal extent and thickness of the aquifers located within the valleys.

Except for domestic supplies, bedrock aquifers are not significant sources of groundwater in the 15-county water supply planning region. Groundwater that is suitable for domestic use may be obtained from the fine-grained sandstones or small, widely spaced fractures in the limestone or coal layers of the shallow Pennsylvanian rocks found near the bedrock surface. On the bedrock uplands where glacial deposits are typically thin and do not contain extensive sand and gravel aquifers, bedrock aquifers are important sources of supply for domestic wells. Water supplies in parts of Iroquois County are obtained from the Silurian carbonate rocks. In general, the quality of groundwater in the bedrock decreases with depth. Groundwater in deep bedrock formations is too mineralized for most uses.

In the Mahomet Bedrock Valley, upward leakage of groundwater from the bedrock into the overlying Mahomet Aquifer may affect the quality of groundwater in the aquifer (Panno et al., 1994). A quantification of the potential leakage is described in the following sections.

Quaternary Geology

Continental glaciers flowed southward from Canada beginning about two million years ago, advancing into Illinois as great sheets of ice that were many hundreds of feet thick. Careful study of the vast deposits of sediment left by the continental glaciers has led to the understanding that there were at least three major episodes of continental glaciation, and that each episode included several advances and retreats of the ice sheets (Figure 8).

Deposits generally associated with continental glaciation are till, outwash, and lacustrine sediments. Till is unsorted, nonstratified sediment deposited directly from the advancing ice or left during its melting. Till may consist of widely variable amounts of clay, silt, sand, gravel, pebbles, cobbles, and boulders, although typically clay and silt predominate. Outwash consists largely of layers of sorted sand and gravel that were deposited by the huge volumes of meltwater that flowed from the ice front as proglacial streams and rivers. Lacustrine sediments include silt, clay, and very fine to fine sand that were deposited in proglacial lakes or in relatively quiet backwaters that filled during floods along main drainageways. Because outwash and lacustrine sediments are deposited in front of the ice margin, they are called proglacial sediments.

HUDSON EPISODE

Cahokia Fm; river sand, gravel, and silt

WISCONSIN EPISODE

Mason Group

Thickness of Peoria and Roxanna Silts; silt deposited as loess (5-ft contour interval)

Equality Fm; silt and clay deposited in lakes

Henry Fm; sand and gravel deposited in glacial rivers, outwash fans, beaches, and dunes

Wedron Group
(Tiskilwa, Lemont, and Wadsworth Fms) and Trafalgar Fm; diamicton deposited as till and ice-marginal sediment

End moraine

Till plain

ILLINOIS EPISODE

Teneriffe Silt; silt and clay deposited in lakes

Pearl Fm; sand and gravel deposited in glacial rivers and outwash fans, and Hagarstown Mbr; ice-contact sand and gravel deposited in ridges

Winnebago Fm; diamicton deposited as till and ice-marginal sediment

Till plain

Glasford Fm; diamicton deposited as till and ice-marginal sediment

End moraine

Till plain

PRE-ILLINOIS EPISODE

Wolf Creek Fm; predominantly diamicton deposited as till and ice-marginal sediment

Unglaciated

0   10   20   30   40 mi

ISGS 8.5x11 map series

Figure 8. Quaternary deposits of Illinois (the east-central Illinois regional water supply planning region is outlined in blue)

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Continental glaciation affects a region before the ice sheet itself arrives. The surface of the earth sinks under weight of the advancing ice sheet, which causes the earth's crust in front of the ice sheet to rise and create a forebulge (Clark et al., 1994). With the retreat of the ice sheet, the crust rebounds and the forebulge dissipates. The deformation of the crust and the weight of the overlying ice sheet alter the groundwater-flow regime in the bedrock and glacial deposits (Breemer et al., 2002).

Meltwater flows from the ice sheet in enormous volumes away from the ice front along existing drainageways. Continental glaciers transport large volumes of sediment that is carried away from the glacier by the meltwater and deposited in front of the glacier. These proglacial sediments then fill the meltwater channels. The advancing glacier overrides the proglacial sediment, modifying deposits by reworking or eroding them as the ice advances, and subsequently depositing till on top of them. The retreating glacier exposes the till to erosion. Meltwater flowing from the ice front reworks the till and redeposits the sediment along meltwater channels. Temporary lakes form if sediment or stagnant glacial ice block the flow of meltwater. The cycle begins again with the next advance of the ice sheet.

The earlier continental glaciers covered more of Illinois than did the later ones. Bedrock composed most of the preglacial landscape of Illinois. The initial episode of continental glaciation modified the topography of the existing landscape by glacial isostacy, erosion of the existing valleys in the bedrock surface, and deposition of proglacial and glacial sediment in them. Outwash, lake bottom and slack water sediments, and till from the earliest glaciation occupy the deeper parts of the bedrock valleys. These are overlain by the deposits left by the later glaciations. Repeated advances and retreats of continental glaciers modified the landscape in which they moved by erosion and by deposition of sediment directly from glacial ice, or along meltwater streams and in lakes in front of the ice margins. Continental glaciation ceased to affect Illinois directly about 12,000 years ago. The ice sheets and meltwater left more than 400 feet of glacial and proglacial deposits in some parts of the water supply planning region (Kempton et al., 1991).

Broad, arcuate ridges are features of the present-day landscape of the eastern two-thirds of the water supply planning region. These ridges, called terminal moraines, are formed by a thick accumulation of glacial and proglacial sediment. They mark the position of an ice margin when the flow of ice in the ice sheet equaled the rate at which the ice margin melted.

Glacial and other related deposits are identified, distinguished, and classified based on their physical characteristics (such as color, lithology, or mineralogy), stratigraphic position, and age. Buried weathered zones (paleosols), some containing organic rich horizons, serve as important marker beds. These zones indicate periods of warmth and weathering between major glaciations when buried glacial sediments formed the land surface. They are used to separate the glacial deposits into distinct stratigraphic units.

The glacial and related deposits that cover the water supply planning region are grouped into four major lithostratigraphic units (Figure 9). From oldest to youngest, these are the Banner Formation, the Glasford Formation, and the Wedron Group and the Mason Group. These units are locally separated by paleosols and organic horizons. Each of the major stratigraphic units includes sand and gravel deposits that form aquifers where saturated, and each of the units includes fine-grained sediments that form aquitards.

The Banner Formation is the deepest of the major stratigraphic units. It is thought to have been deposited more than 500,000 years ago during the pre-Illinois Episode (Soller et al., 1999). This formation rests directly on the bedrock surface in the bedrock valleys, is draped on the valley walls, and extends onto the bedrock uplands. The top of the Banner is marked by a discontinuous, buried weathered zone.
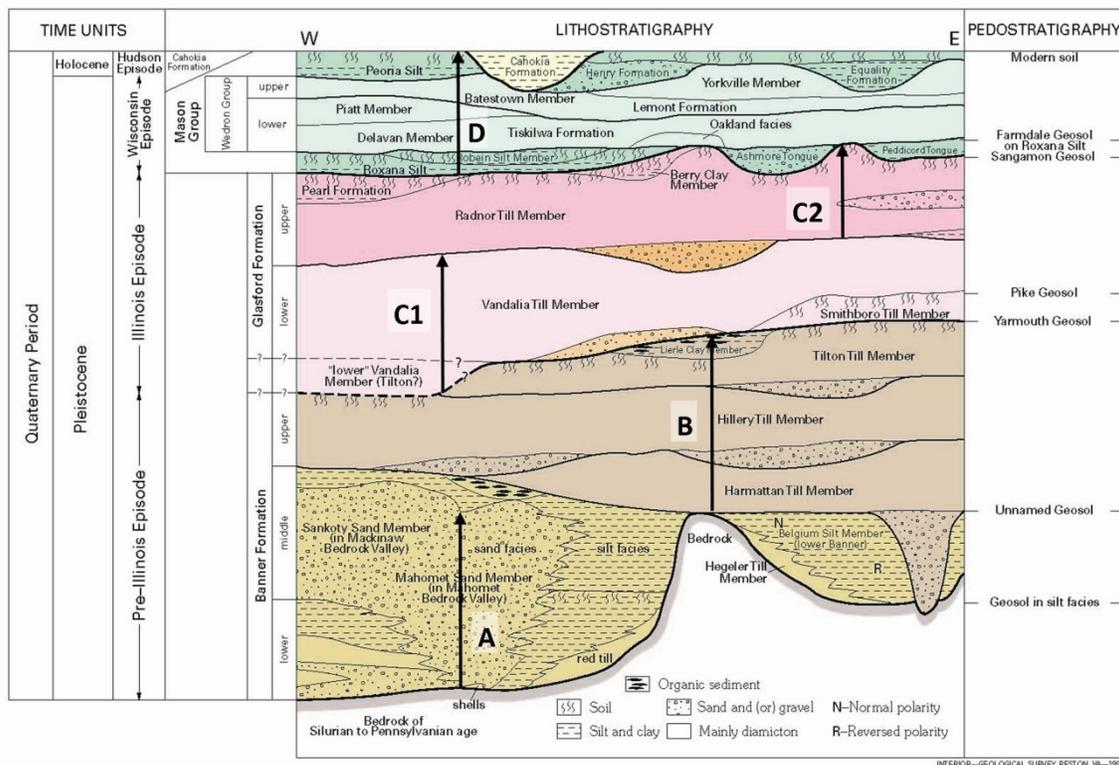
A — Mahomet aquifer
B — aquifers in the upper Banner Formation
C1 — aquifers in the lower Glasford Formation
C2 — aquifers in the upper Glasford Formation
D — shallow and surficial aquifers

Figure 9. Hydrogeologic framework of the Quaternary deposits in the east-central Illinois regional water supply planning area (from Soller et al., 1999)

The Banner Formation is divided into a lower, middle, and upper unit. Because the sediments of the lower Banner are locally present and in general not easily distinguished from the sediments of the middle Banner Formation, the lower and middle Banner are typically considered as one unit. Sand and gravel deposits in the Mahomet Bedrock Valley (the Mahomet Sand Member) and those in the Mackinaw Bedrock Valley (Sankoty Sand Member) are the predominant sediments in the two bedrock valleys. However, silt, clay, and very fine- to fine-grained sand deposited in temporary lakes are also present. These sediments typically occur in the tributary valleys and along the edges of the Mahomet and Mackinaw Bedrock Valleys, but they are also locally present along the main part of these bedrock valleys. The lower and middle Banner also includes relatively thin deposits of till. Three till members (Tilton, Hillery, and Harmattan) compose the upper Banner Formation. Deposits of sand and gravel occur at the base of the Harmattan and between the three till members. Although the sand and gravel deposits in the upper Banner Formation are quite variable in thickness and areal extent, they form locally significant sources of groundwater that supply rural domestic wells in the water supply planning region, especially at locations on the bedrock uplands.

The Glasford Formation was deposited during the Illinois Episode between about 180,000 and 125,000 years ago (Soller et al., 1999). The top of the Glasford is marked by distinctive, organic-rich zones (paleosols) that formed during the Sangamon Episode, the interglacial period following the Illinois Episode (Kempton et al., 1991). The Glasford Formation is composed primarily of till of the Radnor and the Vandalia Till Members. Deposits of sand and gravel that are found in the Glasford Formation typically occur between the Radnor and the Vandalia, and at the base of the Vandalia, although some deposits may be found within the till units. The sand and gravel deposits in the Glasford Formation typically are thin and limited in areal extent. These characteristics make it difficult to interpret the continuity and distribution of individual deposits. Where saturated, these deposits form locally important sources of groundwater in the water supply planning region for rural domestic supplies. If the deposits are sufficiently thick, they may provide supplies to small community. The Glasford Formation extends across the Mahomet and Mackinaw Bedrock Valleys and onto the bedrock uplands adjacent to these valleys.

The Wedron and Mason Groups are the shallowest major stratigraphic units in the water supply planning region. The sediments in these units were deposited during the Wisconsin Episode between 75,000 and 12,000 years ago (Soller et al., 1999). Although till predominates the sediments of the Wedron Group, the Wedron also includes very thin deposits of sand and gravel that are typically discontinuous and very limited in areal extent. The Mason Group consists predominantly of sand and gravel deposits, but also includes deposits of wind-blown silt (loess) and lake-bottom or slack-water sediments (Hansel and Johnson, 1996). The deposits of the Mason Group are found along the main drainageways in the water supply planning region, or as very shallow deposits. The Mason Group is thickest in the western part of the planning region, particularly in Mason County where sand and gravel of the Mason Group directly overlies older sand and gravel (Walker et al., 1965)

Hydrogeologic Framework of the Quaternary Deposits

Coarse-grained Quaternary deposits (sand, sand and gravel, or gravel), if saturated, form aquifers. These deposits readily transmit groundwater in part because of the high degree of interconnected pore spaces. Groundwater does not readily move through the fine-grained Quaternary deposits (silt, clay, or till) in part because the pore spaces are small and not well interconnected. Such deposits form confining layers. Informal aquifer names (Figure 9) can be assigned to the sand and gravel deposits based on their occurrence within the major lithostratigraphic units that are outlined in the previous section.

The shallowest unit in the water supply planning region consists mostly of the sand and gravel deposits (aquifers) found within the Mason Group, but the unit also includes the thin deposits of the Wedron Group (Figure 9). These sand and gravel deposits typically occur at or near the land surface, and predominantly along the valleys of major streams. Although they are in general thin, discontinuous, and limited in areal extent, they may be saturated and sufficiently thick locally to provide usable quantities of water for a domestic supply. They may also provide avenues along which groundwater can move into deeper, underlying sediments. The Mahomet Aquifer in the western part of the regional water supply planning area includes thick sand and gravel deposits that are part of the Mason Group.

The sand and gravel deposits (aquifers) found within the upper and lower Glasford Formations (Figure 9) are designated as the upper and lower Glasford Aquifers (Larson et al., 2003). The upper Glasford aquifers are composed of the sand and gravel deposits that generally occur in the Radnor Till Member. The lower Glasford Aquifers include the sand and gravel deposits found mainly between the Radnor and Vandalia Till Members, and near the base of the Vandalia Till Member. The Glasford Formation occurs above the Mahomet Bedrock Valley and the adjacent bedrock uplands. Consequently, the lower and upper Glasford Aquifers occur in a large area that includes the Mahomet Bedrock Valley and the bedrock uplands adjacent to it (Soller et at., 1999; Larson et al., 2003). The individual deposits of sand and gravel that compose the lower and upper Glasford Aquifers are typically thin, relatively discontinuous, and limited in areal extent. With the variability in depth, thickness, and areal extent of these deposits, it is likely that hydraulic connections occur locally between the two aquifers.

The sand and gravel deposits (aquifers) that occur in the upper Banner Formation are designated the upper Banner aquifers (Figure 9). These deposits, which are typically thin, discontinuous, and limited in areal extent, generally occur between the Tilton and Hillery Till Members and below the Hillery Till Member. Similar to the Glasford Formation, the upper Banner Formation occurs above the Mahomet Bedrock Valley and the adjacent bedrock uplands. Therefore, the upper Banner aquifers occur in an area that includes the Mahomet Bedrock Valley and the adjacent bedrock uplands (Soller et al., 1999; Larson et al., 2003). The groundwater in the upper Banner aquifers is of local significance in supplying water for rural domestic use.

The Mahomet Aquifer comprises the water supply planning region's major groundwater resource. The aquifer occupies the lower part of the Mahomet Bedrock Valley (Figure 9). In some reaches of the Mahomet Bedrock Valley, the Mahomet Aquifer directly overlies the bedrock surface. In other parts of the bedrock valley, the aquifer directly overlies till or other fine-grained sediments. Deposits of till, silt, and clay also occur locally within the aquifer. Where these fine-grained sediments are not present, the aquifer consists of a continuous interval of sand to sand and gravel. Drillers' logs in water-well records are the principal source of information used in determining the thickness and extent of the Mahomet Aquifer. Because most of the water wells that use the Mahomet Aquifer are constructed in boreholes that were not drilled through the entire thickness of the aquifer, the drillers' logs lack the information needed to determine the total thickness of the Mahomet Aquifer. The information used to assess the thickness of the Mahomet in general comes from the drilling of hydrogeologic test holes.

The Sankoty aquifer occupies the Mackinaw Bedrock Valley and coalesces with the Mahomet Aquifer in the confluence area of the Mackinaw and Mahomet Bedrock Valleys. Together these two aquifers form a single hydraulic unit, referred to herein as simply the Mahomet Aquifer.

Hydrology of the Mahomet Aquifer

The hydrology of the Mahomet Aquifer has been previously studied on both a regional basis and on a more detailed basis of individual segments. The ISWS files also contain a vast amount of information from individual wells and community water supplies. Visocky and Schicht (1969) discuss the geologic setting, aquifer properties, water use, water level fluctuations, and the results of an electric analog model. Wilson et al. (1998) created the first potentiometric surface map for the entire aquifer by combining data from regional studies with new data in McLean and Tazewell Counties. Burch (2008) constructed observation wells and measured water levels in the eastern half of the aquifer, including Piatt, Champaign, Ford, Vermilion, and Iroquois Counties.

The aquifer in the Havana lowland region of Mason and western Tazewell Counties has been studied by Walker et al. (1965), Clark (1994), Sanderson and Buck (1995), and Westcott et al. (2009). Burch and Kelly (1993) studied the Peoria, Pekin, and Morton area of northern Tazewell, western Woodford, and eastern Peoria Counties. The aquifer in eastern Tazewell County and western McLean Counties was examined through a series of studies by Kempton and Visocky (1992), Wilson et al. (1994), Herzog et al. (1995), and Wilson et al. (1998). Anliker and Sanderson (1995) conducted a mass measurement of water levels in Piatt and Dewitt Counties while Layne Geoscience (1999) and Roadcap and Wilson (2001) studied the impacts of the Decatur emergency wellfield. Groundwater in the Champaign area was been studied by Smith (1950), Foster and Buhle (1951), Sanderson and Zewde (1976), and Burch et al. (1999). Groundwater flow models were constructed for studies by Visocky and Schicht (1969), Clark (1994), Wilson et al. (1998), and Layne Geoscience (1999). Additional models were constructed by Marsh (1995) for Vermilion County and WHPA (2006) in the Champaign area.

Conceptual Model of Hydraulic Behavior

A conceptual model of flow in the Mahomet Aquifer system was developed from previous studies, analysis of new data, and the construction of the groundwater flow model (Figure 10). The Mahomet Aquifer exhibits a wide range of hydraulic behaviors due to the complex geometry of the glacial materials and the variable interconnection with the land surface and streams. These behaviors affect how the aquifer responds to variations in precipitation, streamflow, and pumpage from high capacity wells.

Although 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. In the Mahomet Aquifer system, the permeability of the sand aquifers is six orders of magnitude higher than the till units (Wilson et al. 1998). Hydrologic conditions for almost the entire Mahomet Aquifer and for the thicker portions of the Glasford Aquifer are suitable for the development of high capacity wells. Shallower or thinner sand layers can still be considered aquifers because they can provide useful quantities of water to small community systems, private wells, and springs. Although it is not used, the fractured carbonate rocks (limestone and dolostone) in the upper bedrock in portions of Champaign, Ford, and Iroquois Counties have the potential for the development of high capacity wells. The low-permeability glacial tills, the lacustrine silts, and bedrock shales form confining beds, or aquitards, which impede water movement to and from adjacent aquifers. At the surface, the glacial tills can be weathered and fractured enough to supply a sufficient quantity of water to a low capacity, large-diameter dug well. These types of wells were very common prior to the 1950s and are still being constructed in areas not underlain by the Mahomet or Glasford Aquifers.

The greatest uncertainty in our understanding of the regional groundwater hydrology lies with the complex nature of the glacial deposits that can cause unexpected hydraulic behaviors, such as interconnections between two seemingly separate aquifers. Water levels in the Mahomet and the Glasford Aquifers, for example, are often very close in elevation and exhibit similar hydraulic responses to the same events, even though drilling logs may show 50 feet of clay between the aquifers. The advances and retreats of the glaciers that covered east-central Illinois caused significant erosion, deposition, and reworking of existing sediments. The interglacial periods probably saw significant erosion and down cutting of streams. One extensive interglacial channel occurs in northwestern Champaign County (Stumpf and Dey, in press). Many of these complexities that cause the aquifer interconnections occur on a relatively small scale (< ¼ mile) and are simply too small to be intercepted by the widely spaced borings that are available to study. On an even smaller scale, fracturing of some of the till deposits may have occurred during the loading and unloading of the glacial ice, creating conduits for flow.
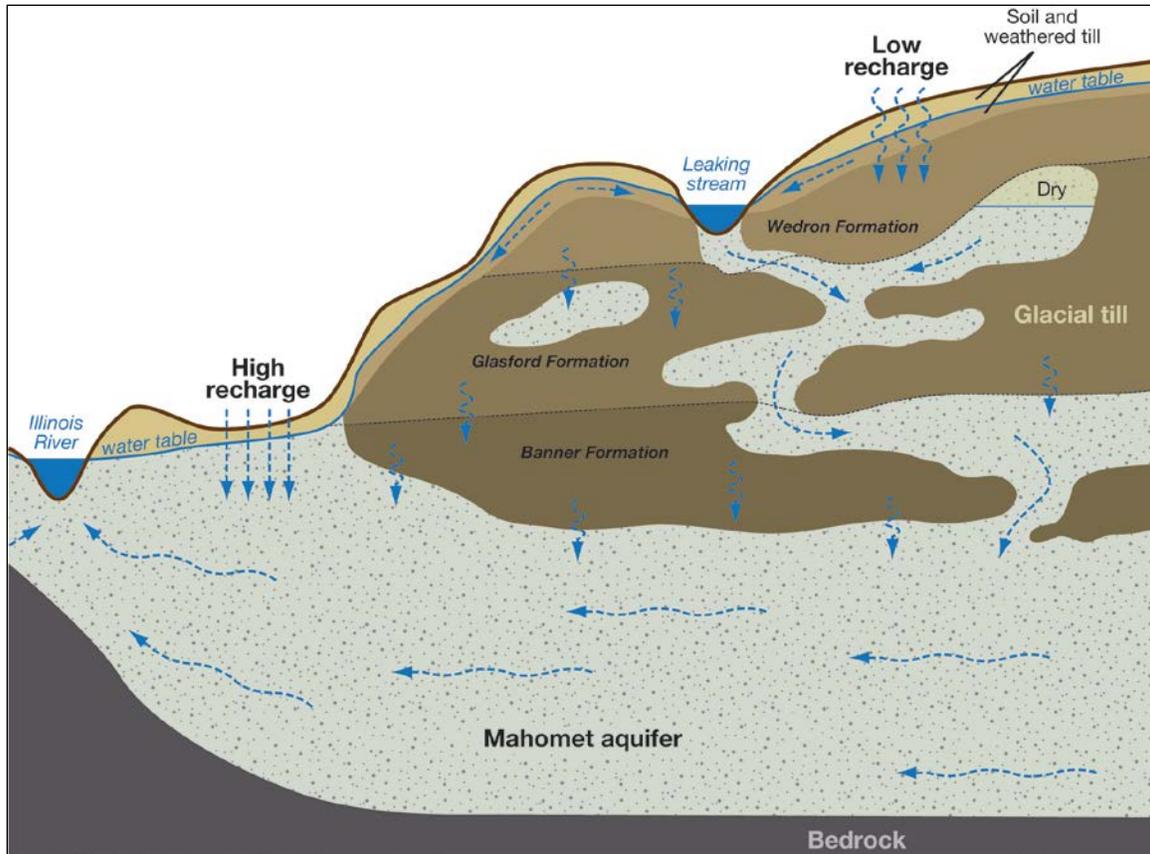
Figure 10. Conceptual model of flow in the Mahomet Aquifer (not to scale)

Adding to the uncertainty is the potential for buoyancy failures (e.g., sand boils or clastic volcanoes) from the excessive groundwater pressures that may have developed during the advance and retreat of the glacial ice. As a glacier advanced over an aquifer confined by glacial till, pore pressure builds up as a response to the weight of the ice. This pressurization spreads to areas in front of the ice, and if the pressure head in front of the ice becomes more than roughly twice the thickness of the glacial till confining the aquifer, the resulting buoyant forces can lift the till upwards, creating a rupture in the till to relieve the pressure in the aquifer. The hole then fills with heaving aquifer sands creating hydraulic connections to subsequently deposited sands. In a glaciotectonic ridge in Sweden, Fernlund (1988) describes a clastic volcano formed in this manner that is 50 feet high and 600 feet across. With the many glacial advances and retreats across east-central Illinois, the hydraulic conditions may have been suitable for many of these features to form.

The Mahomet Aquifer exhibits both unconfined and confined behavior. In the Havana Lowlands near the Illinois River, the Mahomet and Sankoty sands that compose the Mahomet Aquifer are at the surface, creating unconfined, or water table, conditions. In the low areas the water table intersects the stream surface elevations while in the uplands, on top of the dunes, the water table may be more than 40 feet below the land

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surface. During wet years the water table can rise above the land surface in the low areas and cause flooding. In the East Peoria/Morton area, unconfined conditions occur in the Mahomet Aquifer underneath the bluffs where the top of the sand is significantly higher than the level of the Illinois River; the sands drain more readily than overlying till units can recharge the aquifer, thus creating the unconfined condition. Unconfined conditions also occur in the overlying Glasford and Wedron sands where they outcrop in the modern alluvium along the larger streams. Unconfined conditions also can occur in the subsurface where a shallower sand drains into a deeper sand at a faster rate than it can be replenished by recharge through the overlying till (Figure 10). As the water table rises and falls, water will move in and out of storage in the pore spaces. A clean sand can have a porosity of over 20 percent; thus a cubic foot of aquifer material can store and release 0.2 ft^3 (1.5 gallons) of groundwater. A 1-foot drop in the water table over a square mile can release as much as 40 million gallons of water.

Most of the Mahomet Aquifer is under confined or artesian conditions because it is deeply buried and overlain by low-permeability glacial tills. The tills act as confining layers which pressurize the aquifer and cause the water in a well to rise to a level above the top of the sand, known as the potentiometric head. Some low-lying areas of Iroquois and Vermilion Counties are under flowing artesian conditions where the water level in a well will rise above land surface. The pore spaces in a confined aquifer are fully saturated so any change in potentiometric head does not significantly change the amount of water in storage. Because water is not being released from storage, a well pumping in the confined portion of the aquifer will have a much greater impact on water levels than the same well in the unconfined portion. Over much of the Mahomet system there are additional confined aquifers in the shallower deposits, each having a different potentiometric head.

The Mahomet Aquifer is replenished by recharge, a process by which precipitation or leakage from streams migrates downward through the subsurface to the water table. Recharge fluxes cannot be directly measured; rather they are calculated through flow net analysis and mass balance calculations in a groundwater flow model. Groundwater recharge occurs most readily where the aquifer is unconfined and at the land surface. Estimates of recharge in Mason County made by Clark (1994) average 10.88 inches per year (in/yr), out of a total average precipitation of 39 in/yr.

To recharge the confined portions of the Mahomet Aquifer, water must flow either downward through the confining beds or from distant areas where there is a direct connection to the surface or to other sources of water. A close-up of the land surface in the conceptual model shows the active flow system at the shallow water table and the fate of the precipitation (Figure 11). After the glaciers retreated, the exposed tills were weathered and fractured, greatly increasing the permeability of roughly the upper 20 feet. Wind-blown loess then blanketed the region, followed by the development of prairie soils with high water retention capacities. Unless the ground is frozen or already saturated, most of the water from a typical precipitation event will infiltrate into the soil and be stored in the form of increased soil moisture and a higher water table. Once in the soil, most of the water will be evaporated back to the atmosphere directly or through plant

transpiration. The rising water table creates more driving force for groundwater to flow to streams, resulting in increased baseflow in the stream without the aid of surface runoff.

To make the ground over much of east-central Illinois suitable for agriculture or urban development, vast networks of drains and ditches were installed to lower the water table. The discharge of groundwater from the flat-lying, low-permeability material is insufficient to maintain any baseflow in the streams during dry periods. Finally, groundwater from the soil zone can migrate diffusely downward through the glacial tills to underlying aquifers. Estimates of this downward flux are less than 1 in/yr based on previous modeling efforts (Wilson et al., 1998; Meyer et al., 2009). Finer scale geologic mapping and identification of aquifer interconnections act to reduce the estimated fluxes of water going through the tills by previous studies. The loess deposits may be obscuring areas where sands were originally deposited at the surface that could provide significantly higher recharge fluxes to the upper aquifers.

As discussed in the surface water availability section, the natural groundwater contribution to baseflow is highly variable in east-central Illinois. The greatest groundwater discharges occur where the Mahomet Aquifer intersects the major stream channels. This includes the Illinois River, downstream portions of the Sangamon River in Mason, Cass, and Menard Counties, Salt Creek in Menard and Logan Counties, Sugar Creek in Logan County, and the Mackinaw River in Tazewell County.
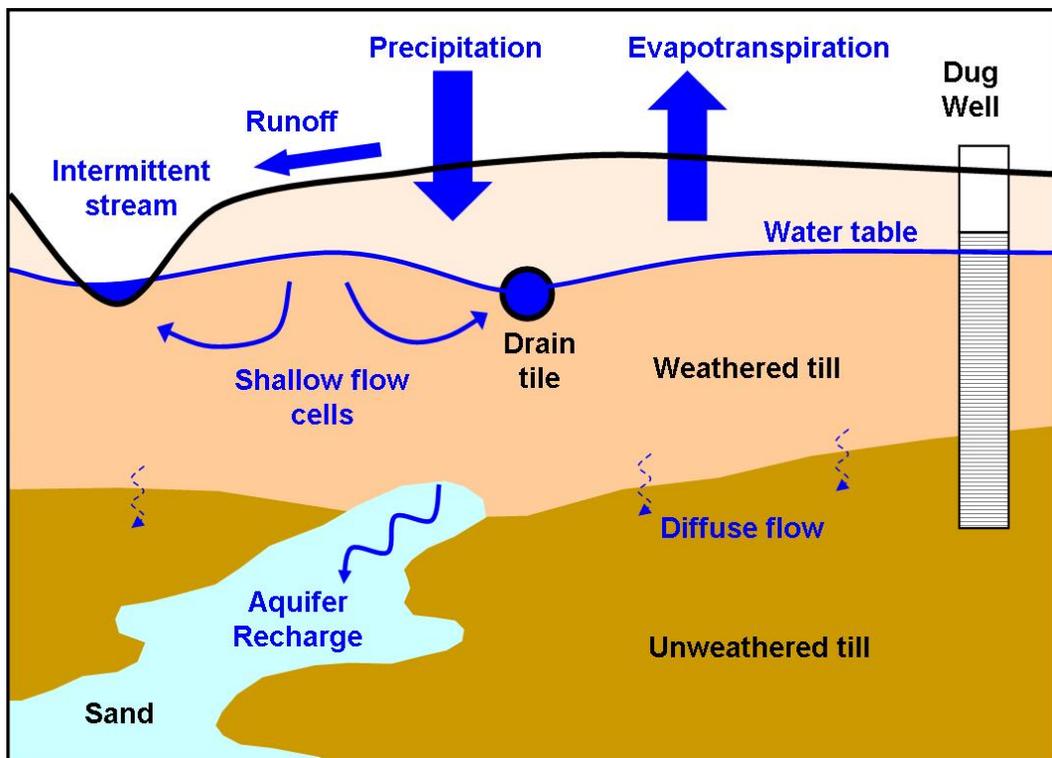
Figure 11. Conceptual model of groundwater flow at a land surface covered with till deposits

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Many streams in the region intersect shallower sand and gravel deposits in the Glasford and Wedron formations which can also add to the natural baseflow. Important recharge areas occur in the shallow sands along a leaky stream where there is a downward gradient and an interconnection to the deeper aquifers. Leaky stream segments have been found along the Sangamon River in Piatt County (Roadcap and Wilson, 2001) and along Sugar Creek in McLean County (Wilson et al., 1998). Streams with significant input from regional groundwater flow can be identified by the 7-day, 10-year low flow values ($Q_{7,10}$) where all of the streamflow is likely to be from regional groundwater flow which does not greatly diminish during dry periods.

For smaller streams, the shallow flow system (Figure 11) provides for the majority of the baseflow. The amount of baseflow will depend on precipitation, the height of the water table, and the density of ditched and drain tiles. On an annual basis, groundwater in glacial settings may provide baseflow at a rate of roughly the average between the Q_{50} (flow rate that is exceeded 50 percent of the time) and Q_{80} (flow rate that is exceeded 80 percent of the time) (Feinstein et al., 2005). During extended drought conditions, small streams receive very little groundwater and thus have no natural $Q_{7,10}$ low flow.

Observation Well Network

The ISWS collects data from an observation well "network" composed of over 180 wells at over 140 sites (Figure 12), largely composed of wells especially built for monitoring aquifer conditions (i.e., water levels and quality). Numerous sites contain "nested" observation wells to monitor the Mahomet Aquifer, overlying confined units, and the water table (solid circles, stars, and triangles).Water level observations generally are collected on a monthly or quarterly basis with selected wells containing digital data loggers polling water levels as often as hourly. Numerous local and state entities have funded cooperative ISWS/ISGS drilling and monitoring efforts. Two ISWS observation wells have 50+ year historical records (Snicarte and Petro North), having been started in the 1950s during or after the major drought of that era. The U.S. Geological Survey has outfitted two well sites (black diamonds) with telemetry equipment so data can be displayed in real time on their webpage.

In the west, the Imperial Valley Water Authority has outfitted 11 wells (blue asterisks) with data loggers for long-term water level monitoring. Also in this region are wells constructed for the Illinois Department of Agriculture (green crosses) for agrichemical sampling and ISWS wells (red circles) for local resource development monitoring. Just east of this area are observation well sites (orange triangles) maintained by the ISWS via funding from the Long-Range Water Plan Steering Committee, a coalition of local water authorities, counties, and communities, to assess the viability of the aquifer for a potential major development of 15 mgd to serve the City of Bloomington, the Town of Normal, and surrounding communities. The City of Decatur also maintains a set of observation wells (blue stars) around their emergency wellfields.

The eastern half of the aquifer contains a host of observation wells (red circles and magenta x's) drilled and maintained by ISWS/ISGS through state and private funds. Under the ISWS Aquifer Assessment program, 25 observation wells at 21 sites were constructed along the deepest part of the Mahomet Bedrock Valley where the aquifer should be at its thickest (Burch, 2008). Nested wells were installed at four of these sites. With funding from Illinois American Water Company and additional state funding, the ISGS installed 46 observation wells at 25 sites between 2007 and 2009; 19 of which are in the Mahomet Aquifer, 21 in the Glasford Aquifer, and six in the shallower aquifers. Nested wells were placed at 13 sites along with an additional three Glasford Aquifer wells placed next to existing Mahomet Aquifer wells. Together with other existing state and private observation wells, there are a total of 57 observation wells in the Mahomet Aquifer, 32 observation wells in the Glasford Aquifer, and six observation wells in the shallower sands in the eastern half of the aquifer.

Aquifer Test Data

Information on the hydraulic properties of the aquifer is available from aquifer tests and groundwater flow models. Over the past century the ISWS has analyzed a large number of aquifer tests at public and private facilities throughout the state and keeps the results in a database (Kohlhase, 1989). Some of the aquifer tests in the Mahomet Aquifer have been summarized for various portions of the valley by Walker et al. (1965), Herzog et al. (1995), Anliker (1999), and Visocky and Schicht (1969). Additional test data were available for the Decatur wellfield in DeWitt County (Layne Geoscience, 1999) and for the new wells near Champaign (WHPA, personal comm. and Malcolm Pirnie, 2006). Figure 13 shows the distribution and results of 24 aquifer tests that were analyzed using drawdown versus time data and had relatively high pumping rates and long test periods. The hydraulic conductivities (K) from these tests range from 210 feet per day (ft/d) at Petersburg to 440 ft/d at Champaign, Monticello, and northern Mason County. One notable exception was a test near Mapleton along the Illinois River where a K value of 2,000 ft/d was obtained from a well completed in a boulder field. Without the Mapleton test the mean K value is 320 ft/d and the geometric mean is 304 ft/d.

In the model of Mason and western Tazewell Counties, Clark (1994) contoured the hydraulic conductivities from 148 aquifer tests on file at the ISWS and used the resulting map as model input. Some adjustment of the hydraulic conductivities was necessary in small areas to calibrate the model. The hydraulic conductivity value of 275 ft/d used in the model of McLean and Tazewell Counties was arrived at during the calibration process, whereby an initial set of values was adjusted to minimize the amount of error between simulated and measured head values and flow budgets (Wilson et al., 1998). An initial hydraulic conductivity value of 335 ft/d for the Mahomet Aquifer layer was input into the model based on the similar results from the aquifer tests at Emden (310 ft/d) and Mackinaw (360 ft/d), conducted as part of that study and from tests at the Normal wellfield, which had a mean of 320 ft/d (Herzog et al., 1995). The variation in the results from the aquifer tests at Normal wells—#100 (390 ft/d), #102 (350 ft/d), and #103 (220 ft/d)—indicate that there is some variability within the aquifer, even over relatively short distances.
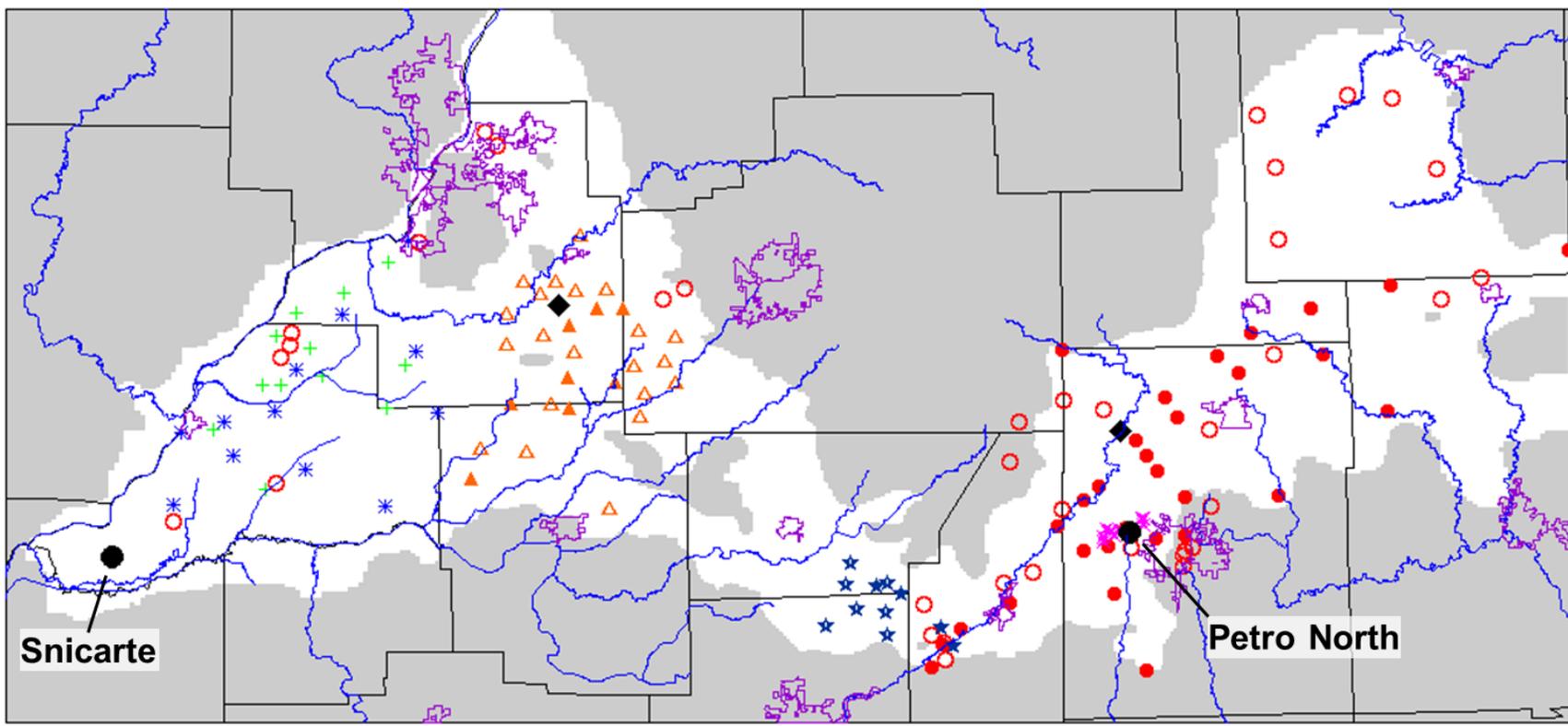
Figure 12. Location of observation wells in the Mahomet Aquifer (see text for explanation of map symbols)
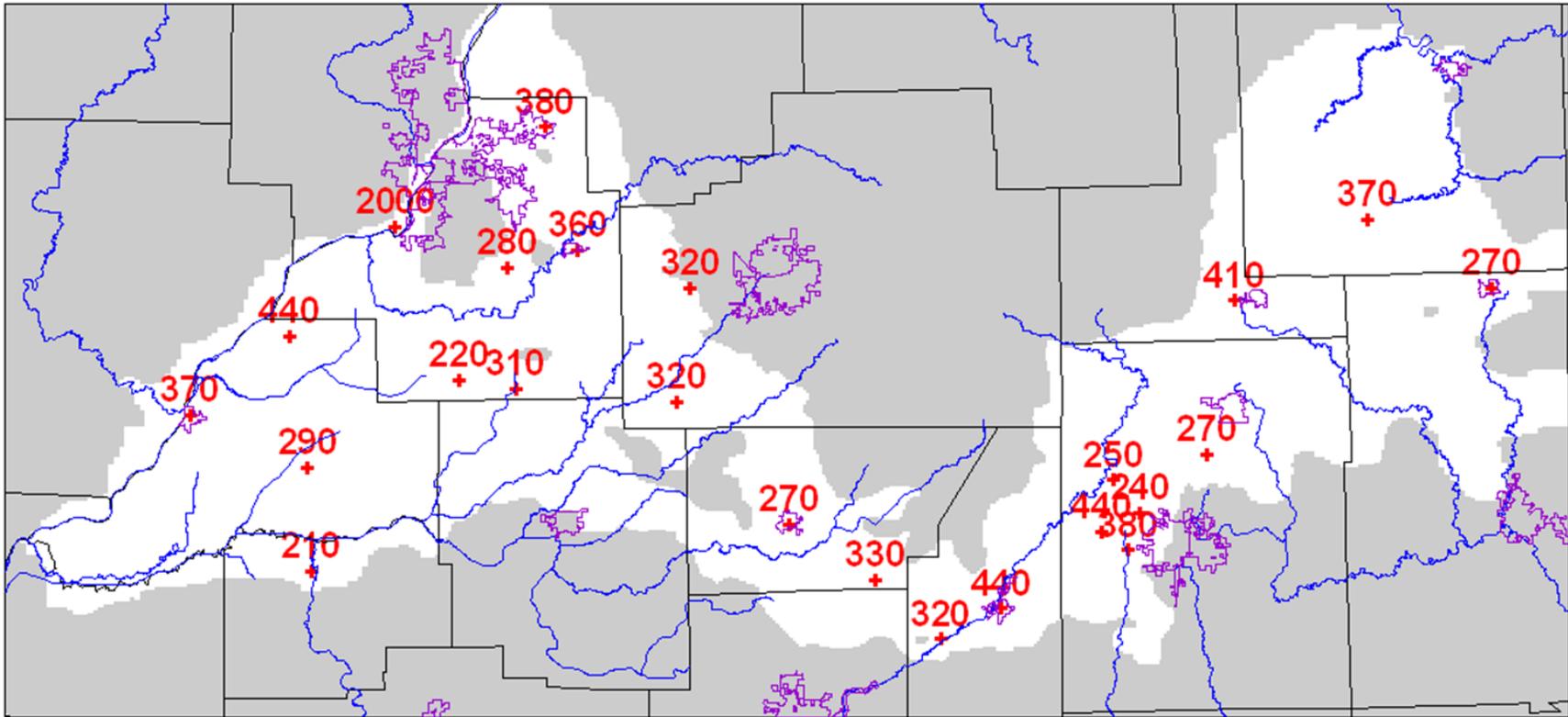
Figure 13. Mahomet Aquifer hydraulic conductivities estimated from aquifer test data (ft/d)

Groundwater Flow

Groundwater flow directions and areas of recharge and discharge for the Mahomet Aquifer can be determined from a contour map of water level elevations, or heads, in wells, known as a potentiometric surface map (Figure 14–Figure 18). On an aquifer-wide scale, the maps show that groundwater flow is divided into several sub-regional flow systems but there is an overall flow pattern from east to west. The eastern segment of the valley has two prominent features: a potentiometric high near Paxton in Ford County and a large cone of depression at Champaign. The western segment of the valley has a flow system that gets divided by several bedrock highs and has a gradient that steadily increases towards the Illinois River. The individual characteristics of each segment of the aquifer are discussed separately below.

Water levels for the potentiometric surface maps are obtained from measurements in observation wells, public and industrial wells, and private wells, and from the elevations of streams with strong groundwater connections. Because the extent of the aquifer is so large, conducting a synoptic mass measurement of water levels using large numbers of wells is not feasible. Instead, Wilson et al. (1998) stitched together a potentiometric surface map of the whole aquifer by combining several potentiometric surface maps created from different studies of portions of the aquifer. Figure 14 updates this potentiometric surface map with new data from the aquifer's eastern segment, including the counties of Piatt, Champaign, Ford, Iroquois, and Vermilion (Figure 15). The eastern segment had been previously mapped by Burch (2008) using observation well data. The potentiometric contours for the western half of the aquifer comes from synoptic measurements collected by Anliker and Sanderson (1995) in DeWitt, Piatt, and Macon Counties; Wilson et al. (1998) in McLean, eastern Tazewell, and Logan Counties; Sanderson and Buck (1995) in Mason and western Tazewell Counties; and Burch and Kelly (1993) for northern Tazewell and Woodford Counties.

To create a new potentiometric surface map for the eastern segment of the Mahomet Aquifer (Figure 15), water level measurements were collected from 141 wells. Measurements were collected in 2005 and supplemented with additional data as the new observation wells near Champaign were constructed between 2007 and 2009. Water level variations in the observation wells during the three-year period were generally less than 3 feet and were not great enough to significantly impact contouring. Because the Mahomet aquifer sands do not outcrop in the mapped area, no surface water elevations were used to create the map. The groundwater elevation data were contoured using the Kriging algorithm in the program SURFER®. Similarly, groundwater elevation data from an additional 78 wells were used to create a potentiometric surface map for the Glasford Aquifer in Champaign and eastern Piatt Counties (Figure 16). Because the Glasford sands are intermittently found throughout the mapped area and are not confined to the Mahomet Bedrock Valley, no aquifer outline is shown.
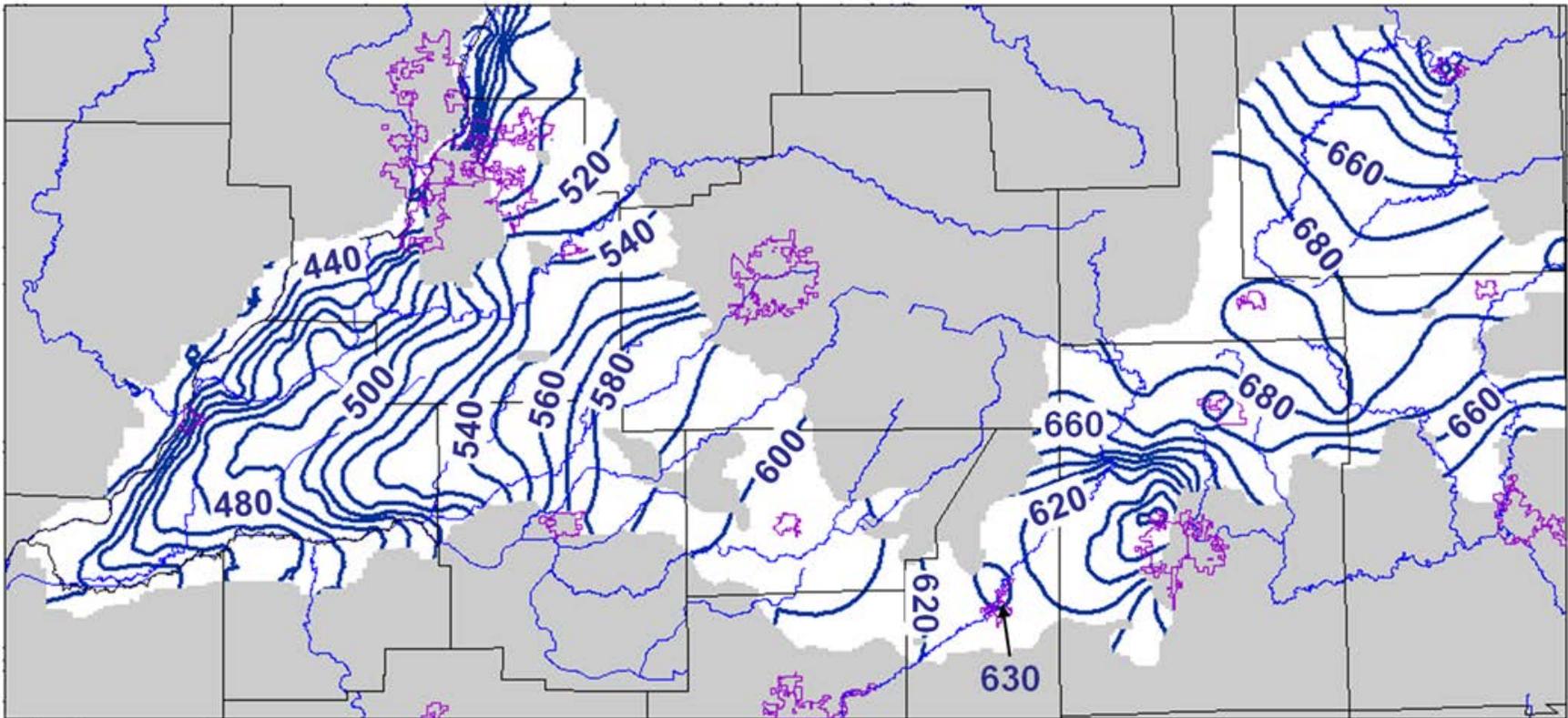
Figure 14. Composite potentiometric surface map of the Mahomet aquifer based on measurements from 1990 to 2009
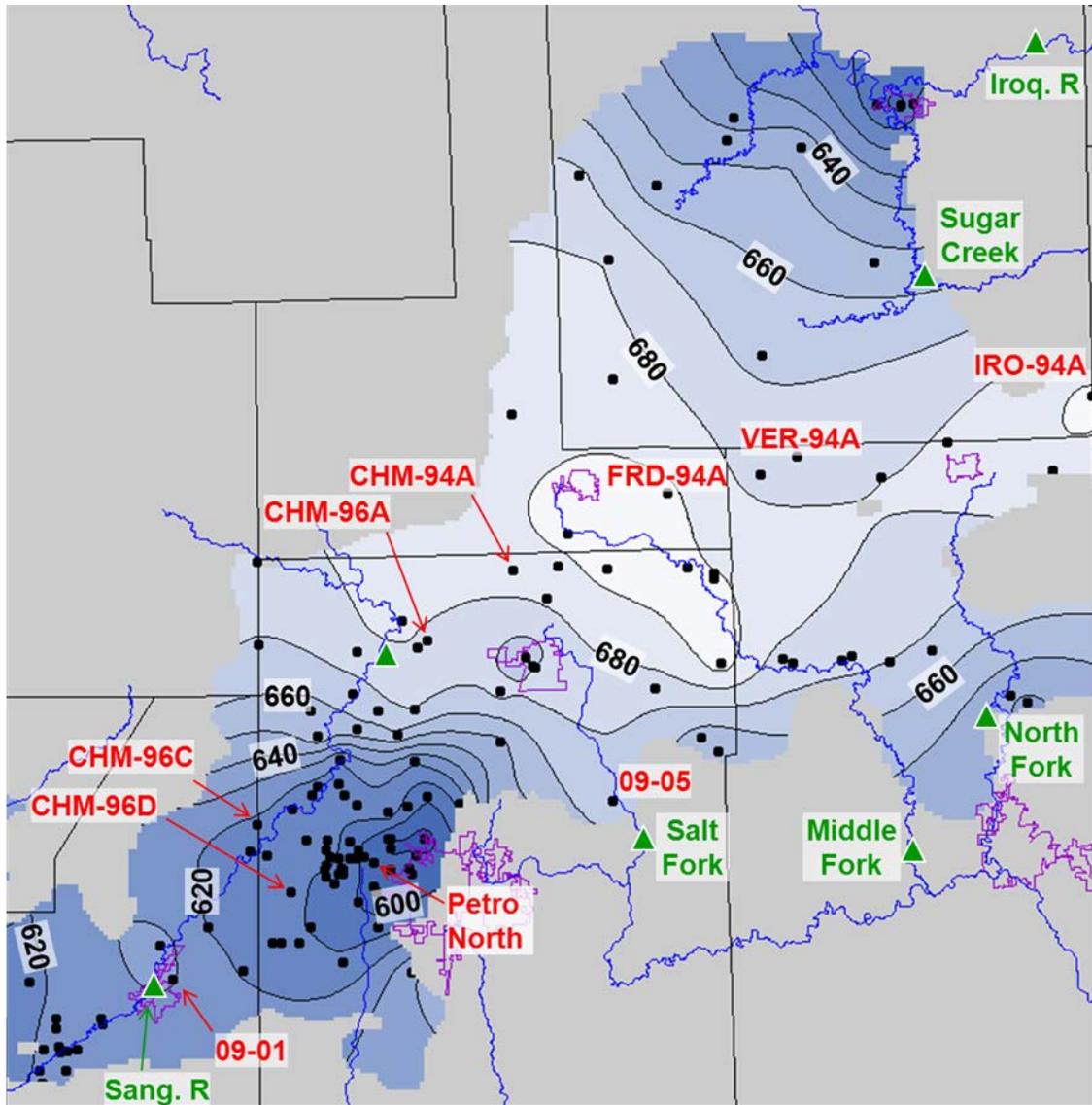
Figure 15. Potentiometric surface map of the eastern segment of the Mahomet Aquifer and location map for wells with plotted hydrographs (data points represented by black dots, USGS gauges represented by green triangles)

Different methods of contouring water levels have different bias issues. Hand contouring methods allow for good treatment of irregular aquifer boundaries, but the curvature of a line between two points is often very subjective. Kriging and other statistical algorithms are good for contouring large datasets of variable spacing and quality, such as from a large synoptic measurement dataset, but do not handle irregularly shaped aquifer boundaries very well, often suggesting water is flowing into or out of the aquifer boundaries. To get around these issues, water levels were contoured using the finite-difference solver from a groundwater flow model. Water levels from 2009 for all the observation wells across the entire aquifer were input as constant head nodes (Figure 17). Supplemental data from domestic wells, also shown on Figure 17, were used in Mason, DeWitt (USGS Groundwater Watch), northern Tazewell Counties, and along the
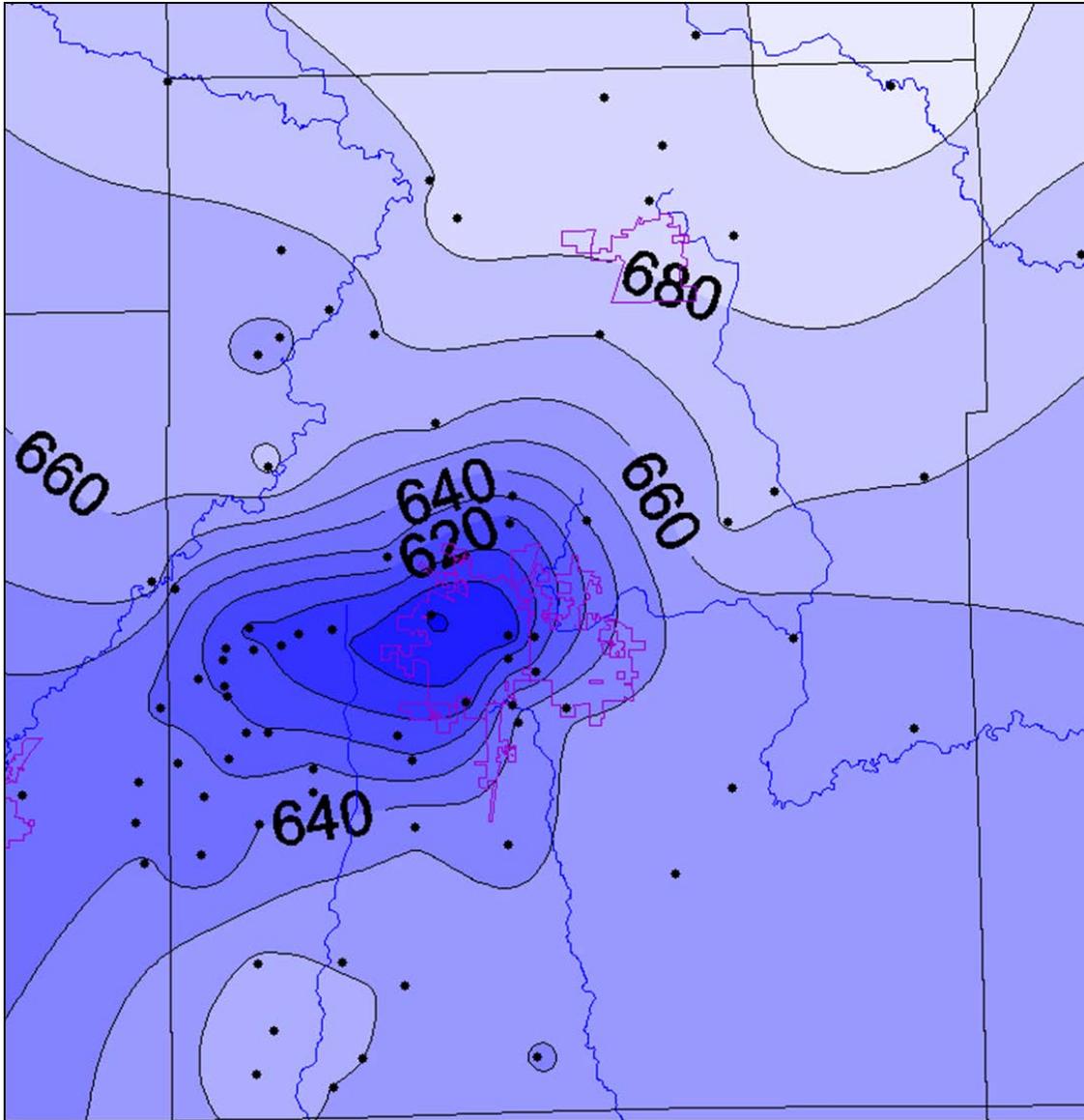
Figure 16. Potentiometric surface of the Glasford Aquifer in Champaign and eastern Piatt
Counties (data points represented by black dots)

Illinois-Indiana state line. Nodes for streams that are water table outcrops for the
Mahomet Aquifer were also assigned constant head values. A uniform hydraulic
conductivity was used for the entire aquifer, although the method is not sensitive to the
specific value. No recharge or other flux boundary conditions were used. The thickness
of the aquifer was used to capture the variation in transmissivity which can influence the
results in areas where there are no data points, such as near Danville and along the
Illinois River where the saturated thickness is rapidly changing. The resulting
potentiometric surface (Figure 18) represents a synoptic measurement for 2009 that can
be compared against future measurements.
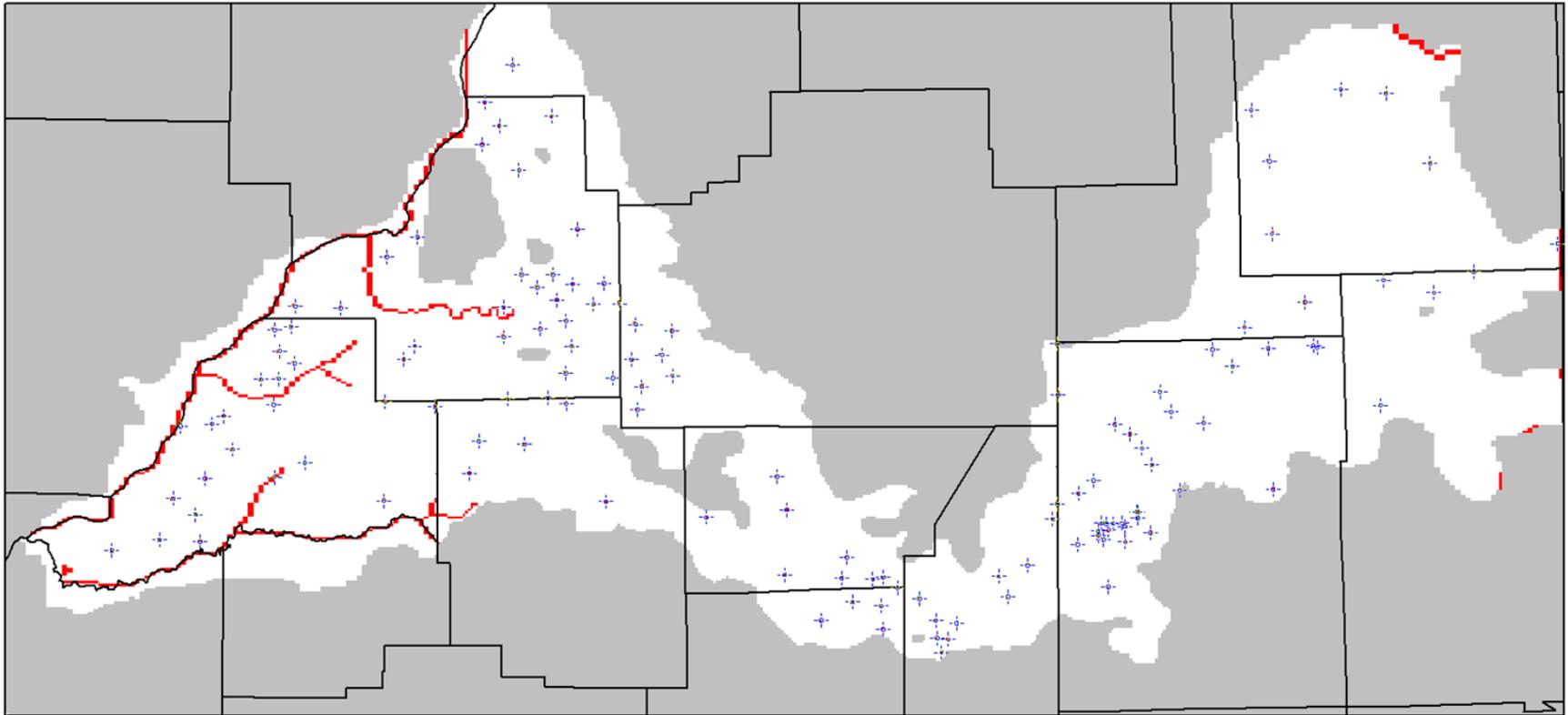
Figure 17. Location of data points used as constant head nodes for the finite-difference contouring (groundwater heads in wells are represented by blue crosses; river heads are represented by red squares)
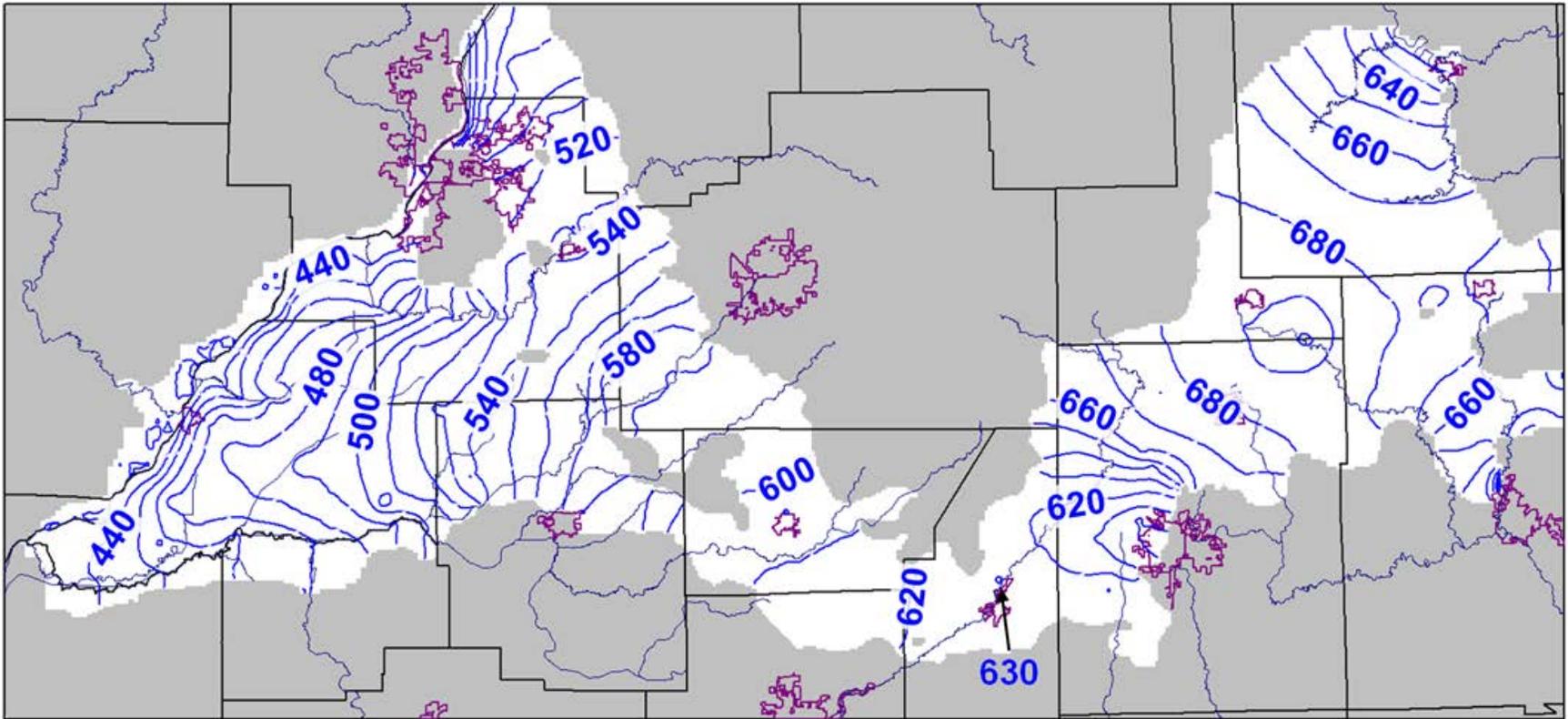
Figure 18. Potentiometric surface map of the Mahomet Aquifer for 2009 constructed using the finite difference contouring algorithm

Using the potentiometric surface maps for the Mahomet Aquifer and the sand thickness and geology data from the groundwater flow model, two derivative maps were created that can be used to plan future water supplies. The map of the height of the potentiometric surface above the top of the Mahomet sands (Figure 19) shows how much drawdown is available before conditions in the aquifer convert from confined to unconfined. The western end of the aquifer is unconfined so it shows up as being less than zero on the map. As observed by Burch (2008), available drawdowns of over 200 feet occur in Ford County. In the Champaign cone of the depression, the available drawdown has been reduced but is still between 50 feet and 100 feet for the Mahomet Aquifer. Conditions in the Glasford Aquifer in Champaign County are discussed separately in the following sections.

The saturated thickness map (Figure 20) shows the thickness of the Mahomet sands that are filled with water and can be used to locate new wellfields where the productivity is likely to be greatest. In the confined portions of the aquifer, the aquifer is fully saturated; in the unconfined portions, the elevation of the potentiometric surface controls the saturated thickness. Along the Illinois River the saturated thickness decreases substantially because of the sharp decline in the potentiometric surface and the rise in bedrock surface along the west side of the valley. Because the hydraulic conductivity in the aquifer varies only over a small range, it can double as a transmissivity map simply by multiplying the contours by 300 ft/d.

To understand how the behavior of the Mahomet Aquifer varies spatially, we constructed a contour map of the standard deviations in water levels from observation with at least six years of regular measurements (Figure 21). The greater the standard deviation is in a well, the greater the fluctuation in water level. Greater fluctuations can be caused by seasonal pumpage from nearby irrigation wells or from flooding along streams that have a strong interconnection to the aquifer. The greatest value of over 4 feet is at well CHM-95A near Rantoul in Champaign County which is close to an irrigation well. Greater standard deviations occur throughout Champaign County possibly due to seasonal pumpage by Illinois American and by the irrigators spread across the northern part of the county. In Piatt and McLean Counties, water levels in the Mahomet Aquifer are reacting to flooding on the Sangamon River and Sugar Creek, respectively, where there are stream-aquifer interconnections (Roadcap and Wilson, 2001; Wilson et al., 1998). Water level fluctuations also increase at primary aquifer discharge points along the Illinois and Mackinaw Rivers. Any large fluctuations due to seasonal irrigation pumpage in the Havana lowlands appear to be greatly dampened by the release of water from storage under unconfined conditions. The smoothness of the standard deviation data plot, such as in eastern Tazewell County, provides confidence that flow in the aquifer is regional in nature and that active recharge areas can be identified.
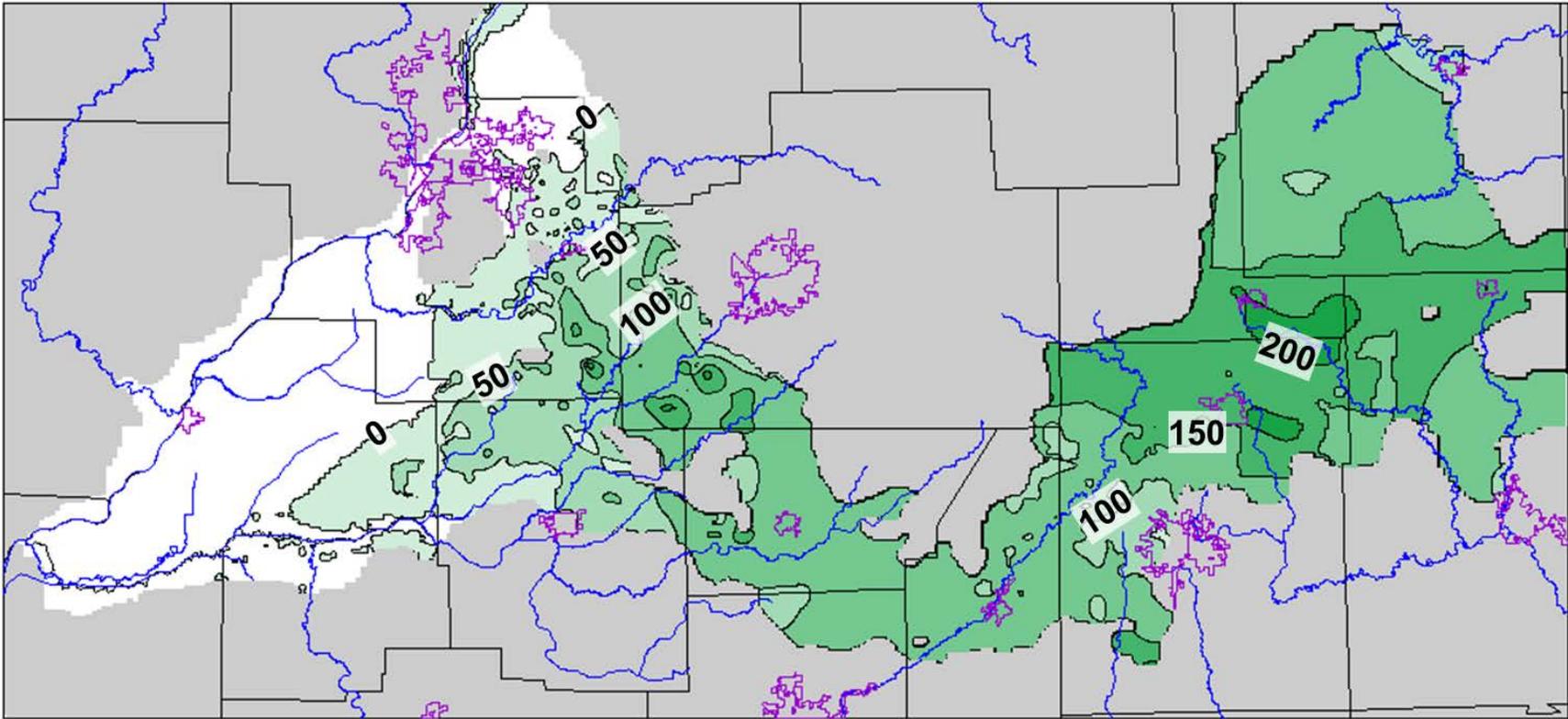
Figure 19. Height of the potentiometric surface of the Mahomet Aquifer above the top of the Mahomet sands. Unconfined areas are not shaded.
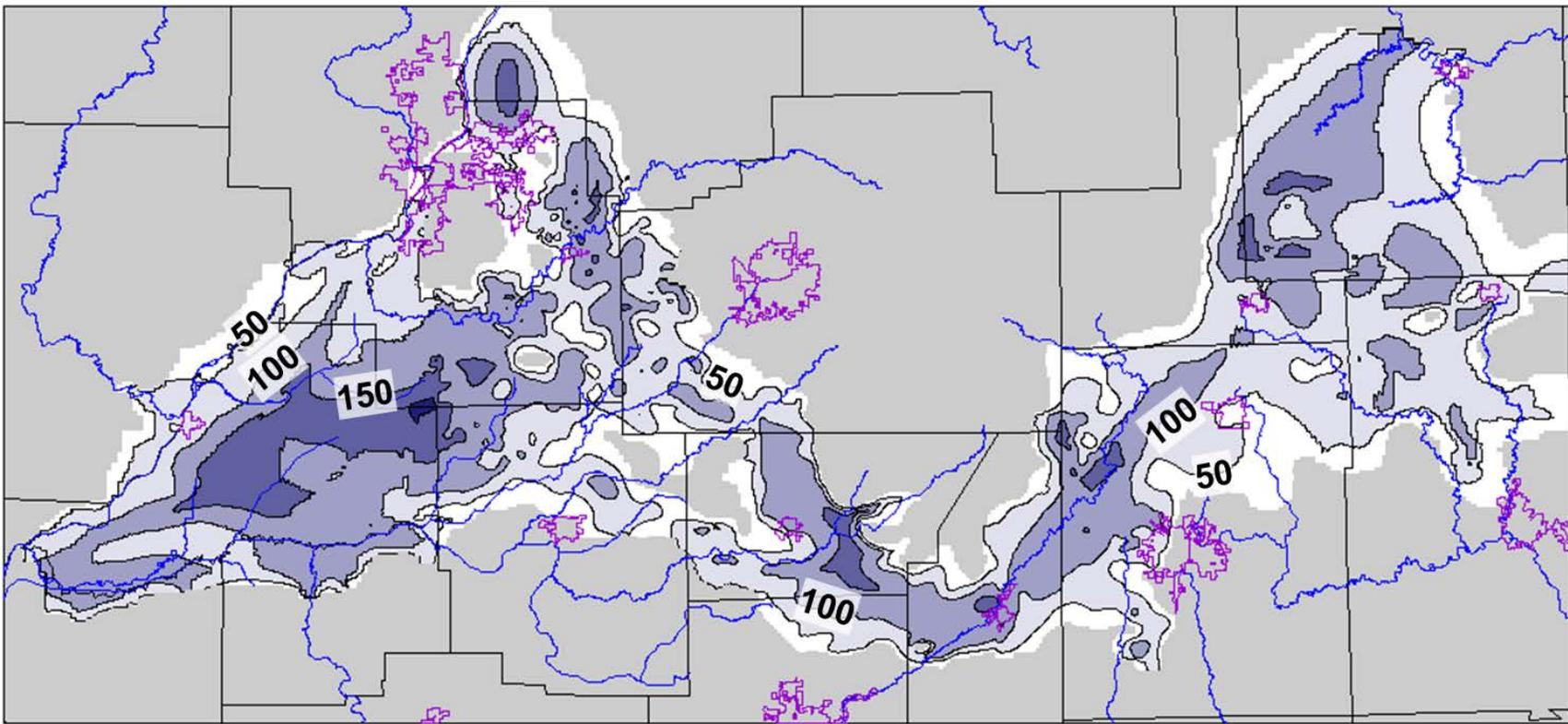
Figure 20. Saturated thickness of the Mahomet Aquifer
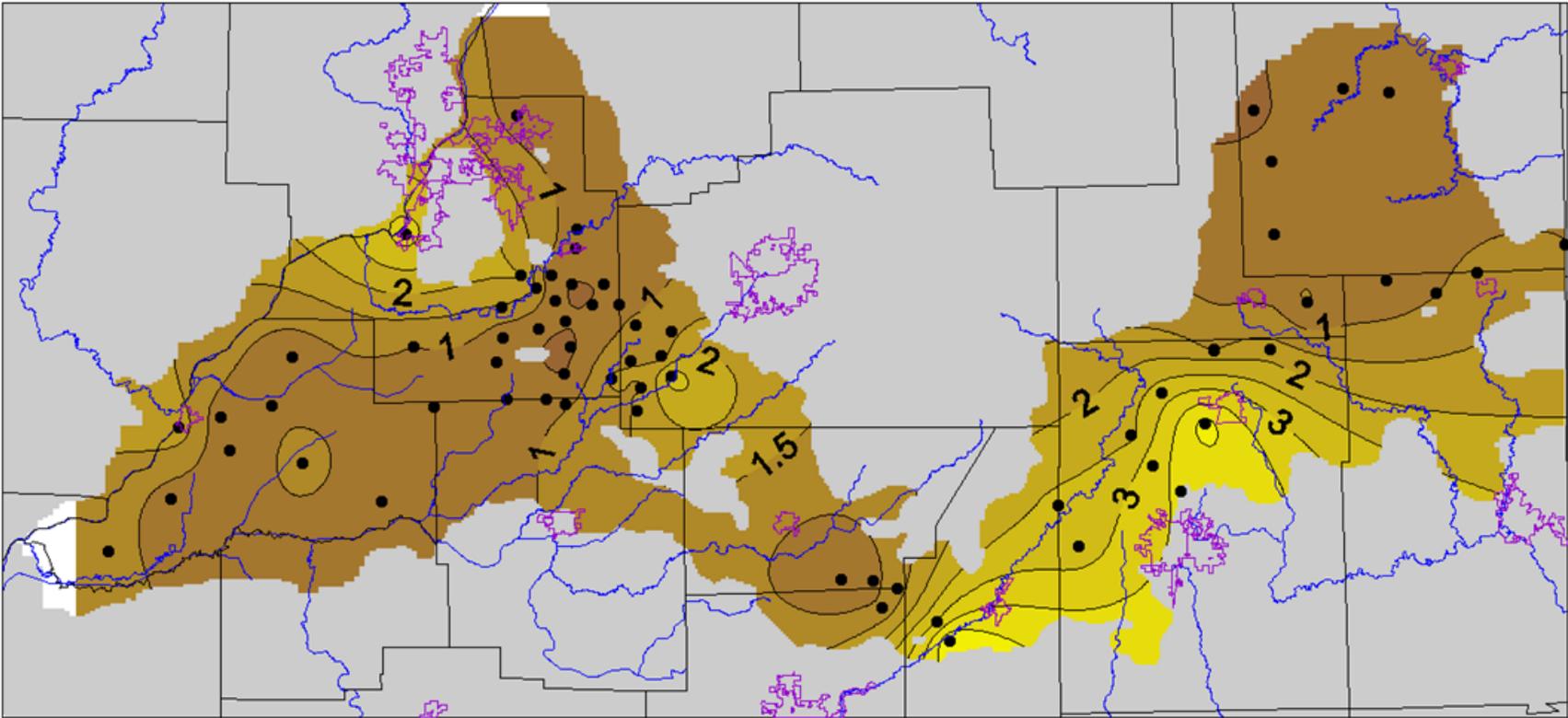
Figure 21. Standard deviation (ft) of water levels in wells (red dots) with long-term (>6 years) records

Northeastern Segment – Ford, Iroquois, Vermilion, Northeastern Champaign Counties. Highest groundwater elevations in the Mahomet aquifer, close to 700 feet above mean sea level (asl), are found in eastern Ford and northeastern Champaign Counties along Middle Fork of the Vermilion River downstream of Paxton (Figure 15). Groundwater flows radially away from this area in all directions except to the west and northwest where there is no aquifer. Adjacent to the river along this stretch are numerous sand and gravel pits up to 70 feet deep. The river has a sandy bottom and should be in good connection with the shallow aquifer. Low flow measurements collected in 2007 show a small increase in flow over this stretch, indicating that shallow groundwater flow and the release of water in storage in the unconfined sands and the pit lakes are probably sufficient to maintain baseflow. It is not known if the connection between the shallow sands and the Mahomet Aquifer underlies the river or is offset from the river. Even without a connection to upper aquifers or the Middle Fork, the area would likely be a potentiometric high simply because even a small amount of leakage coming through the overlying till could serve to maintain flow given the flatness of the regional gradient and the long distances to any discharge points. The area also coincides with two topographically high northwest-southeast trending moraines that form surface water divides between the Ohio and Mississippi River basins, so the hydraulic pressures in the aquifer would be greater than in the surrounding areas.

Groundwater flows north from the Paxton area towards the Iroquois River which cuts across central Iroquois County. The Mahomet aquifer sands may not be directly connected to the Iroquois River, so groundwater discharge may first travel through the Silurian dolomite which is connected to the river in places. Along the west side of this flow path, Panno et al. (1994) found high calcium, magnesium, and sulfate concentrations that they attributed to groundwater discharge from the Silurian dolomite which forms the west wall of the buried Mahomet Bedrock Valley. Due to the presence of a lake clay deposit, a thinning of the aquifer, and a drop in land surface elevation, flowing artesian conditions exist in central and south-central Iroquois County. Many domestic and municipal water supply wells in this area are naturally flowing and do not require pumps. Groundwater upflow to the surface (negative recharge) may exist, but any evidence for widespread diffuse groundwater discharge is masked by modern drainage tiles and ditches.

East of the Paxton groundwater high the potentiometric surface is shaped like a saddle. This saddle is formed where eastward flow from the Paxton high meets westward groundwater inflow from Indiana. The resulting flow is directed north toward the Iroquois River and south, possibly toward the North Fork Vermilion River near Danville. Although the data are limited, the shape of the potentiometric saddle suggests that inflow of groundwater from Indiana is not very significant.

Where the groundwater flowing towards Danville is discharged is not well understood. The North Fork of the Vermilion River drops below the head in the aquifer forming flowing artesian conditions in localized areas, such as at Potomac. The geometry of the sands within the Danville Bedrock Valley is complicated. Larson et al. (1997) shows that the Mahomet aquifer sands become connected with upper sands and surficial sands in the vicinity of Lake Vermilion. Although the exact location and amount of

groundwater discharge is unknown, it is probably occurring along the North Fork of the Vermilion River or within Lake Vermilion.

The different behaviors of the interconnection between the Mahomet and Glasford Aquifers are shown in hydrographs of four nested well pairs (separate boreholes) along a west-east transect along the northern boundaries of Champaign and Vermilion Counties. The two wells at Ludlow, CHM-94A&B, consistently differ in elevation by 1 to 2 feet but show very similar trends and downward spikes caused by nearby irrigation (Figure 22). The clay layer separating the two aquifers at this site is only 15 feet thick. At the two wells east of Paxton (FRD-94A&B), the water levels consistently differ by 3 feet and follow the same trends; however, the Glasford well does not respond to the irrigation pumpage that is affecting the Mahomet well (Figure 23). The clay separation between the aquifers at this site is 57 feet. Near Rankin the water levels in the two wells, VER-94A&B, do not show any significant head difference (Figure 24). Here the aquifers are separated by a 45-foot sequence of sands and clays that must have enough lateral variation to allow a hydraulic interconnection between the aquifers. In contrast, the two aquifers along the Illinois-Indiana state line, IRO-94A&B, are separated by a similar 49-foot sequence of sands and clays but have 15 feet of head difference (Figure 25). The interconnections between the Glasford and the Mahomet Aquifers appear to be highly variable and localized, making predictions of where they occur difficult.

Champaign Cone of Depression – Champaign and Piatt Counties. The groundwater flow patterns in Champaign and western Piatt Counties have been altered by the large cone of depression in the potentiometric surface formed by the major pumping center at Champaign. Prior to the late 1940s, the pumpage of groundwater in the Champaign-Urbana area was predominately from wells completed in the Glasford Aquifer in central portions of Champaign and Urbana. Smith (1950) estimated a total use in 1947 of 7.92 mgd: 4.11 mgd for municipal use, 1.66 mgd for industrial use, 0.96 mgd for use by the University of Illinois, and 0.27 mgd for private use. Due to large drawdowns in the Glasford Aquifer and the need for additional supply, new wells were drilled into the Mahomet Aquifer in 1947 by the Northern Illinois Water Company (now Illinois American Water Co., IAWC). In 1952, the Petro Chemical Company (now called Equistar) constructed four high-capacity wells along the Kaskaskia River to convey groundwater via the river to their plant downstream in Tuscola. To monitor the impacts of the industrial wells on Northern Illinois Water Company's wells, the ISWS Petro North and Petro South observation wells were constructed into the Mahomet Aquifer and long-term monitoring was initiated.

The hydrograph of the Petro North observation well shows the decline in water levels resulting from the steady increase in pumpage in the Champaign-Urbana area (Figure 26). The decline in water levels decreased from 12 feet per decade in 1956–1965 to 4 feet per decade in 2001 to 2010 under similar growth rates in pumpage, suggesting the cone is intercepting an additional source of water such as a stream or an unconfined aquifer. When constructed, the elevation of the water level at the Petro North well was in the range of 555 to 560 feet, but the historical pre-pumping level was more likely a little
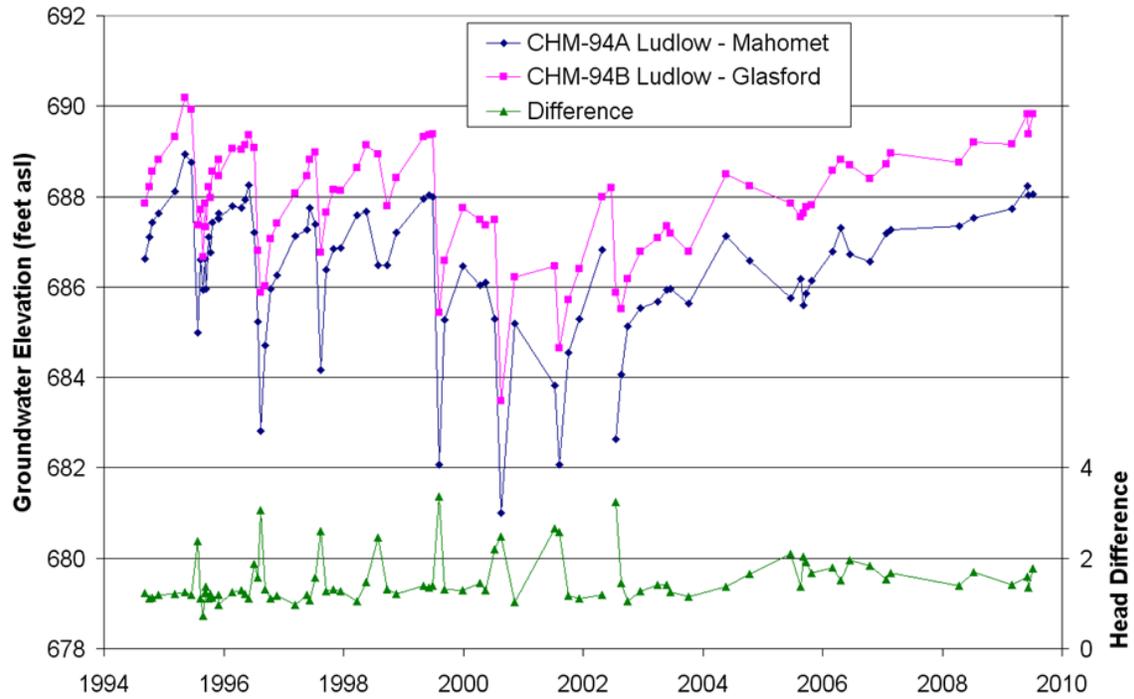
Figure 22. Hydrograph of nested wells CHM-94A&B near Ludlow
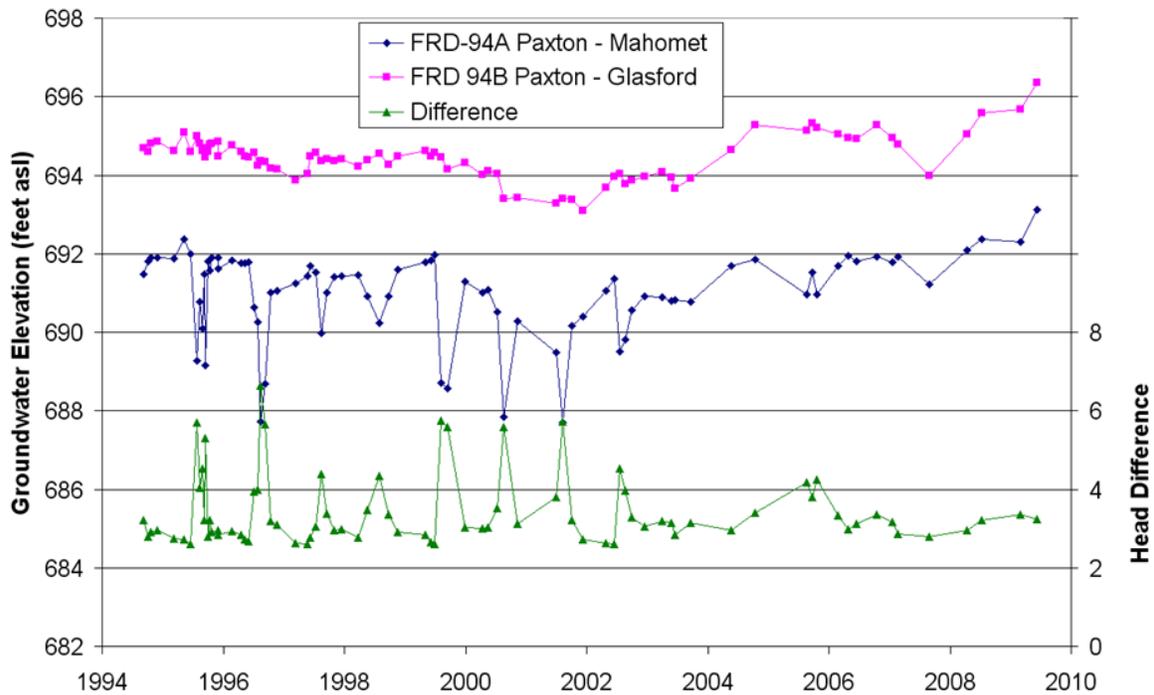
Figure 23. Hydrograph of nested wells FRD-94A&B east of Paxton

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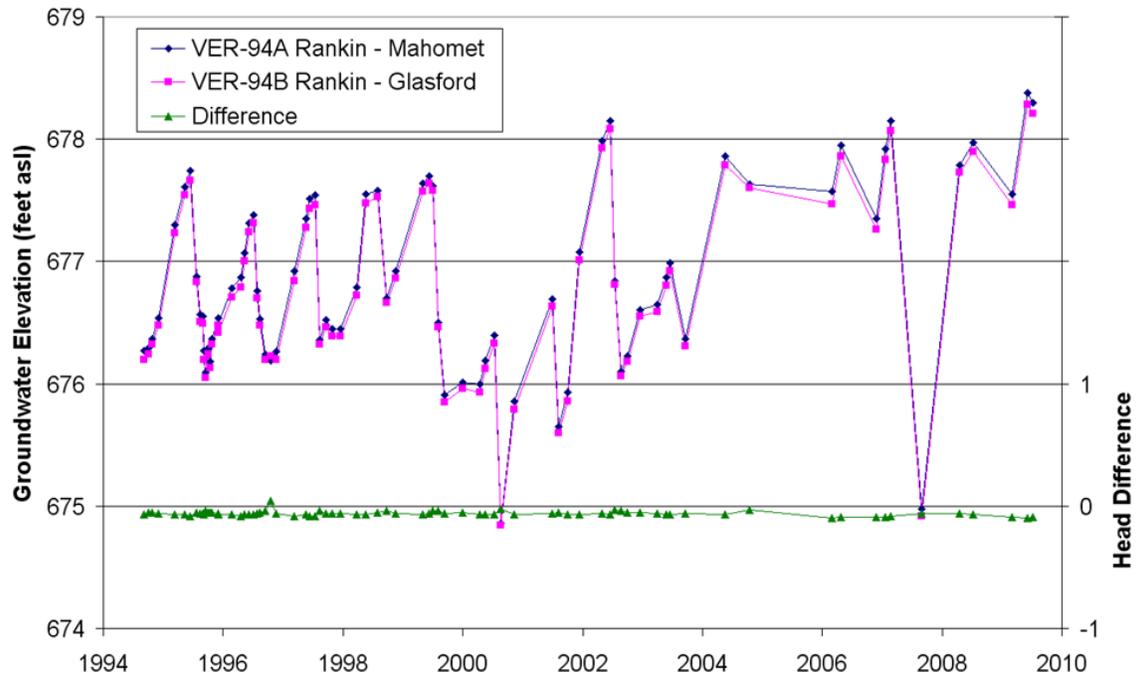
Figure 24. Hydrograph of nested wells VER-94A&B near Rankin
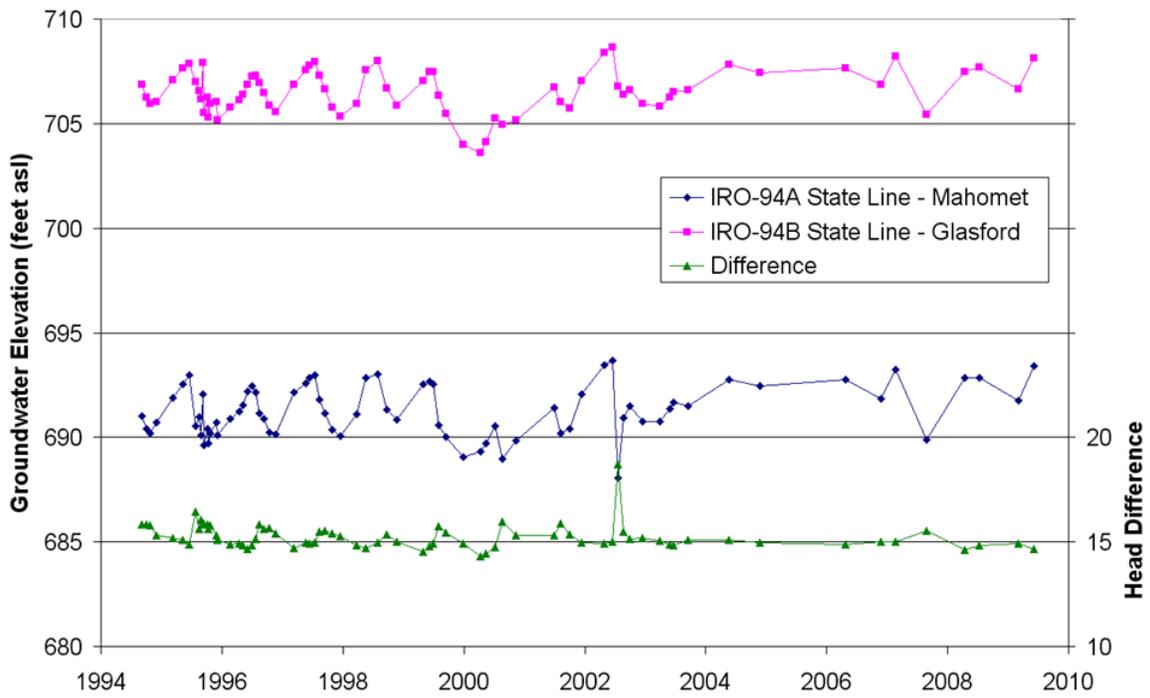
Figure 25. Hydrograph of nested wells IRO-94A&B along the Illinois-Indiana state line

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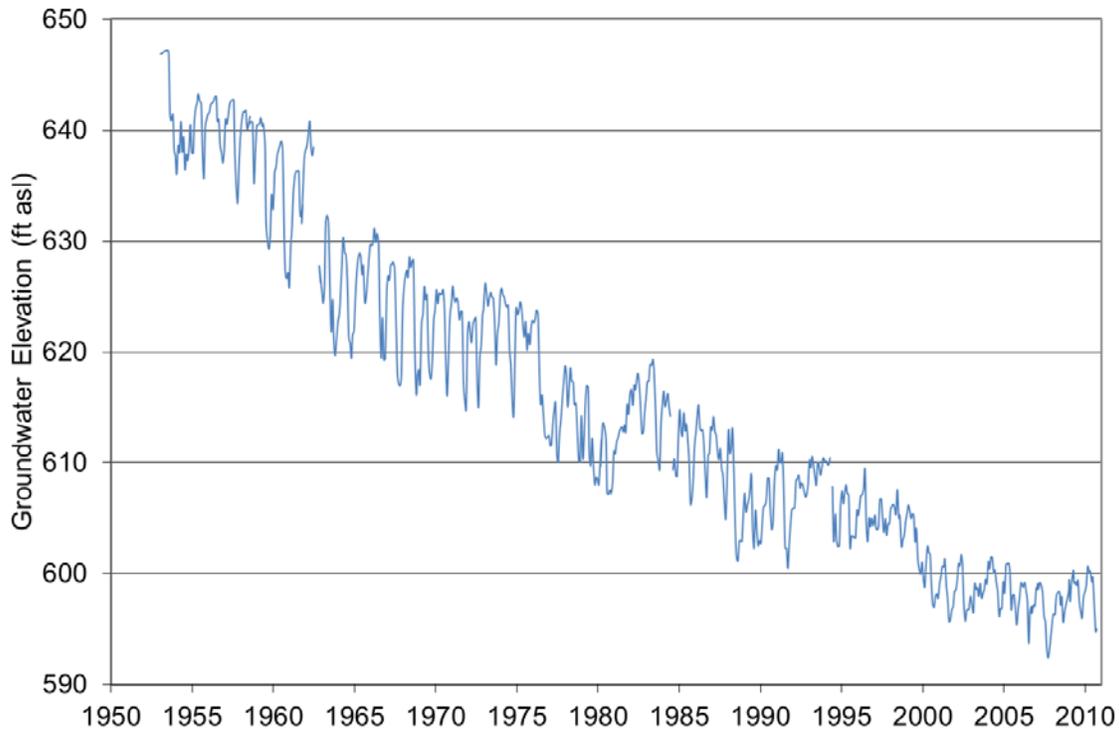
Figure 26. Hydrograph of the ISWS Petro North observation well, 1953–2010

higher in the range of 660 to 665 feet. Smith (1950) reports that the water level elevation in Champaign-Urbana was about 670 feet before pumping began in 1885. The overall slope of the decline corresponds to roughly 3 feet for every additional 1 mgd of pumpage. Because the observation well is only a mile away from several of the IAWC production wells, the hydrograph shows tremendous daily variations in water level as the production wells cycle on and off (Figure 27).

To determine the lateral extent of the cone of depression, the authors first constructed a historical potentiometric surface map based on data from pre-1948 well records, data compiled by Smith (1950) and Sanderson and Zewde (1976), and historic data from aquifer tests conducted by the ISWS (Figure 28a). Because these data were collected over a long period and are of variable quality, any nuances to the surface remain unknown. Subtracting the modern potentiometric surface (Figure 15) from the historic surface produces a map of the drawdown in the cone of depression (Figure 28b). The cone is deepest around the IAWC wells in northwest Champaign at close to 80 feet of drawdown. The proximity of the production wells to the valley wall magnifies the drawdown because water cannot radially flow into the wellfield from all directions. With the shift in pumpage in 2009 to the new IAWC west wellfield and closer to the center of the aquifer, water levels recovered by more than 2 feet around the existing wellfield, but fell by only 1 foot around the new wellfield. Thus, use of the new wellfield can support higher pumping rates with less drawdown in the aquifer than the old wellfield can.

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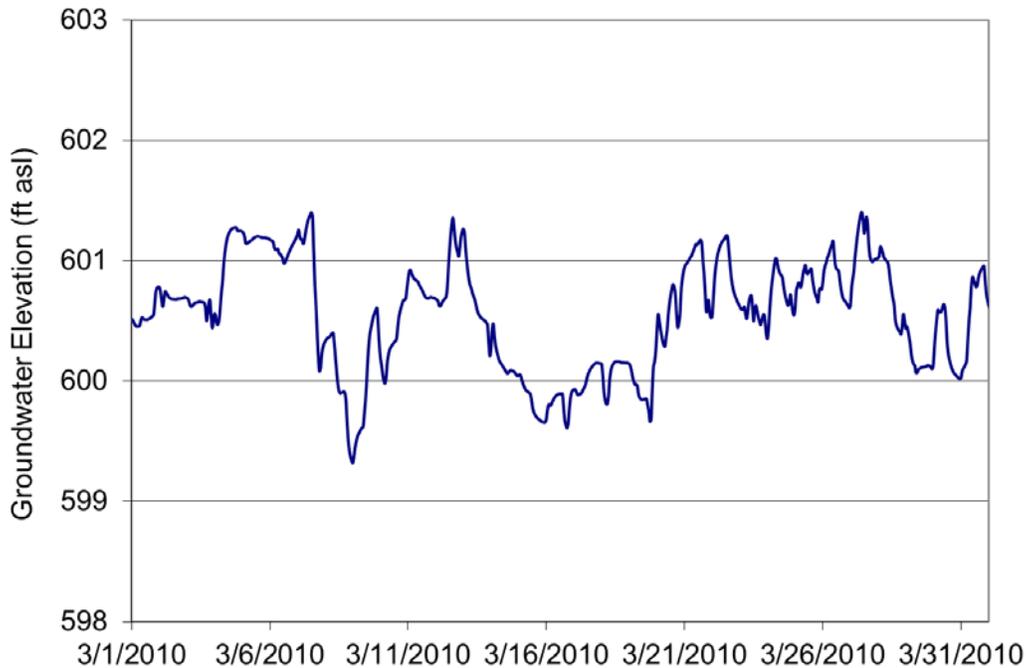
Figure 27. Hydrograph of the ISWS Petro North observation well, March 2010

The cone of depression (Figure 28b) has expanded to the southeast toward Monticello and north toward Rantoul and Fisher; however, it has a non-standard shape that indicates several significant changes in hydraulic behavior are occurring. A standard shaped cone has a logarithmic decrease in drawdown with linear distance away from a wellfield, resulting in mapped drawdown contours that become progressively spaced farther apart. In contrast, the Champaign cone has an abrupt steepening several miles north of the wellfield and a nearly linear slope to the southwest toward Monticello where it abruptly disappears even as the Mahomet Bedrock Valley narrows. A combination of four different processes could cause the non-standard behavior which has far-reaching implications for quantifying the available water supply:

1) Conversion to unconfined conditions
2) Interconnections with streams
3) Low-permeability flow barriers within the aquifer
4) Upflow from the bedrock.

Conversion to Unconfined Conditions. With a top elevation of between 500 feet and 520 feet, the Mahomet Aquifer remains fully saturated within the Champaign cone; however, the potentiometric surface maps of the overlying Glasford Aquifer and the hydrograph from Petro North both indicate unconfined conditions exist. The cone of depression in the Mahomet Aquifer is mimicked in the overlying Glasford Aquifer, indicating a strong connection that allows the Glasford Aquifer to act as an extension of the Mahomet Aquifer. Over most of Champaign County the potentiometric heads in the two aquifers are within 10 feet of one another except underneath the Champaign Moraine
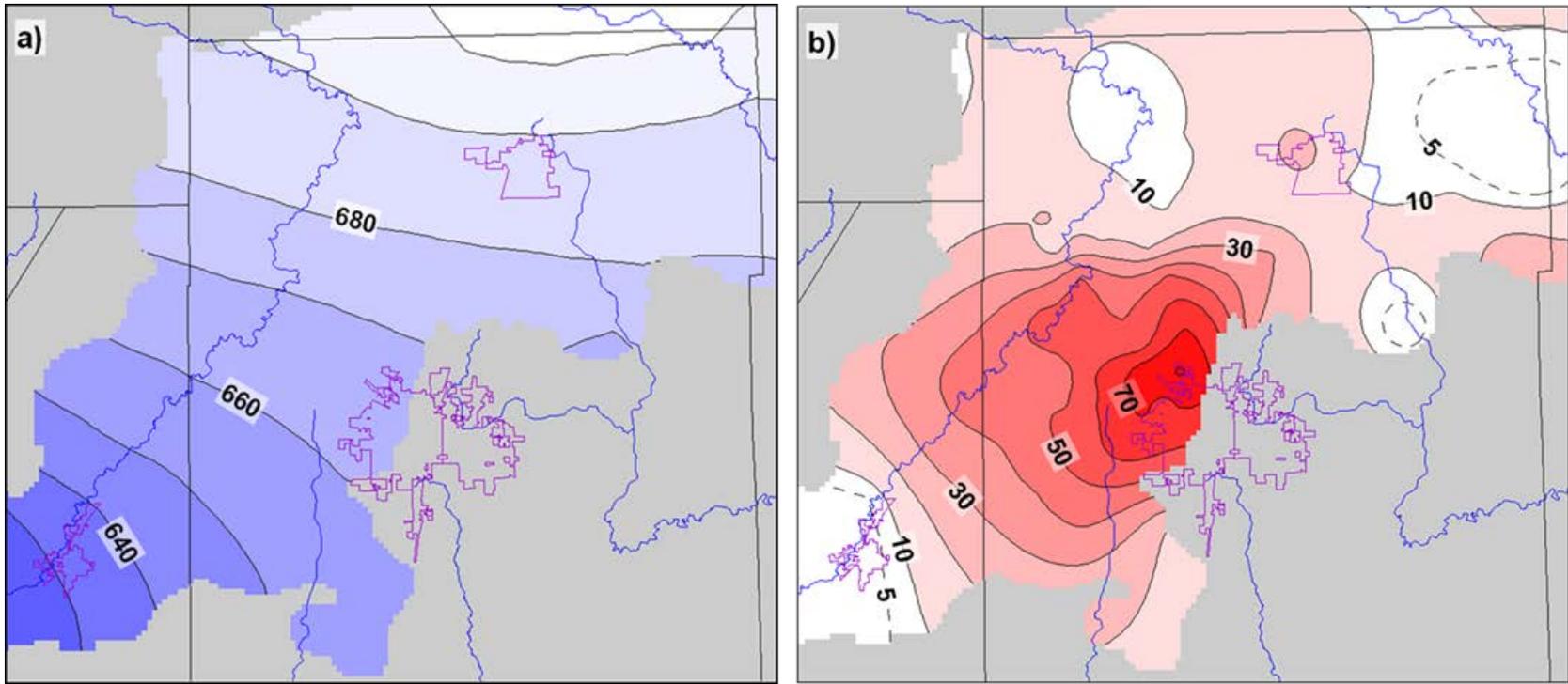
Figure 28. (a) Historic potentiometric surface map and (b) drawdown map of the cone or depression in feet

between the towns of Champaign and Mahomet where the Glasford sand is intermittent (Figure 29a).

A comparison of the measured Glasford potentiometric surface to the top of the Glasford sand (taken from a flow model layer discussed in a later section) shows a large unconfined area (the area within the 0-foot contour on Figure 29b) has developed around the production wells from northern Urbana to the west side of Champaign. Because the Glasford Aquifer acts as an extension of the Mahomet Aquifer, the Mahomet Aquifer will display unconfined behavior on a sub-regional scale around the unconfined zone. Under unconfined conditions, the aquifer is able to store and release water from the pore spaces as the water table moves up and down, thus the impacts on drawdown from a change in pumpage will be significantly smaller than the same pumpage change under confined conditions.

The location and behavior of the interconnections between the Mahomet and Glasford Aquifers appear to be quite variable. In three aquifer tests of the Mahomet Aquifer at IAWC #72 (WHPA, personal comm.), IAWC #57 (Panno et al., 2005), and The Andersons (Malcolm Pirnie, 2006), Glasford Aquifer observation wells did not respond to test pumping of the Mahomet Aquifer. On the other hand, hydrographs from other observation well nests show similar responses in both aquifers to changes in pumpage, such as the nested pair of wells at Seymour (Figure 30) even though the aquifers there are separated by 45 feet of clay. Interestingly, many of the low points on the Seymour hydrographs occur on Sunday nights when the sand filters in IAWC's new water treatment plant were commonly backwashed and greater pumpage was required.

A closer inspection of the slope of the water level decline on the Petro North hydrograph shows that in addition to the overall downward trend, the decline appears to occur in a step-wise fashion. The water level decline has five major steps that possibly correspond to droughts (Figure 31). The water level drops at the steps varied from 5 to 10 feet and occurred after the dry years of 1953, 1963, 1976, 1988, and 1999–2000. The 1999–2000 dry period differed from the other dry periods in that the Decatur emergency wellfield in DeWitt County was operated for 84 days at a rate of more than 10 mgd. Six miles to the west of Petro North, a water level drop of 5 feet was also observed at the Seymour observation well in 2000 (Burch, 2008). The total pumpage in the area, as approximated by the pumpage of IAWC for which good data exist, does not show any sharp increases in annual pumpage during the steps. Any additional drawdown caused by short-term increases in pumpage during a drought should be reversed when IAWC pumping rates return to normal and when any supplemental pumpage by irrigators, Equistar, or Decatur ceases. The reason for the steps is not known, but one possible explanation is that source beds in the upper Glasford or Wedron Formations are possibly becoming increasingly unsaturated and cannot supply as much water to help balance the drawdown. The steps in the early 1970s and mid 1980s also may have been extended by above normal precipitation.
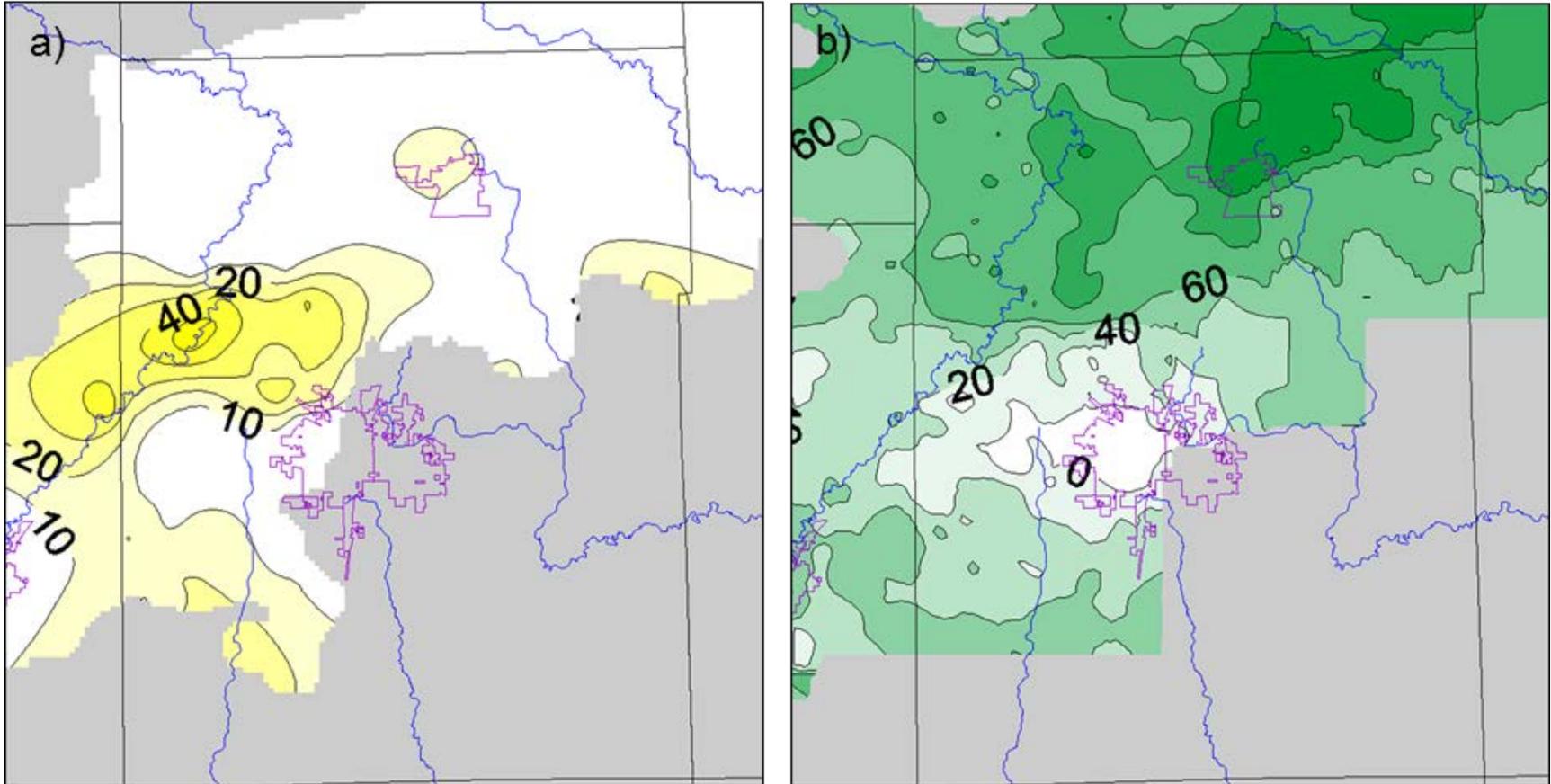
Figure 29. (a) Potentiometric head difference between the Glasford and Mahomet Aquifers and (b) the height of the Glasford potentiometric head above the top of the lower Glasford sand (feet)
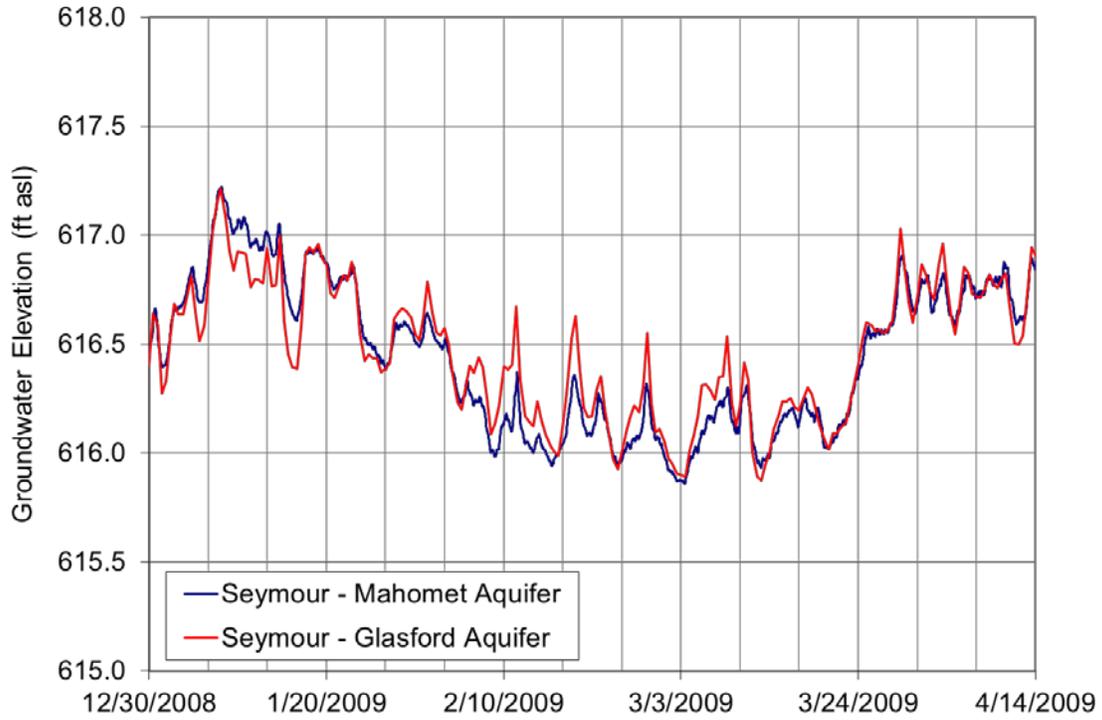
Figure 30. Hydrograph of the nested Seymour observation wells in the Mahomet Aquifer (CHM-95D) and Glasford Aquifer (CHAM-07-07). Vertical gridlines plotted on 7-day intervals on Mondays.
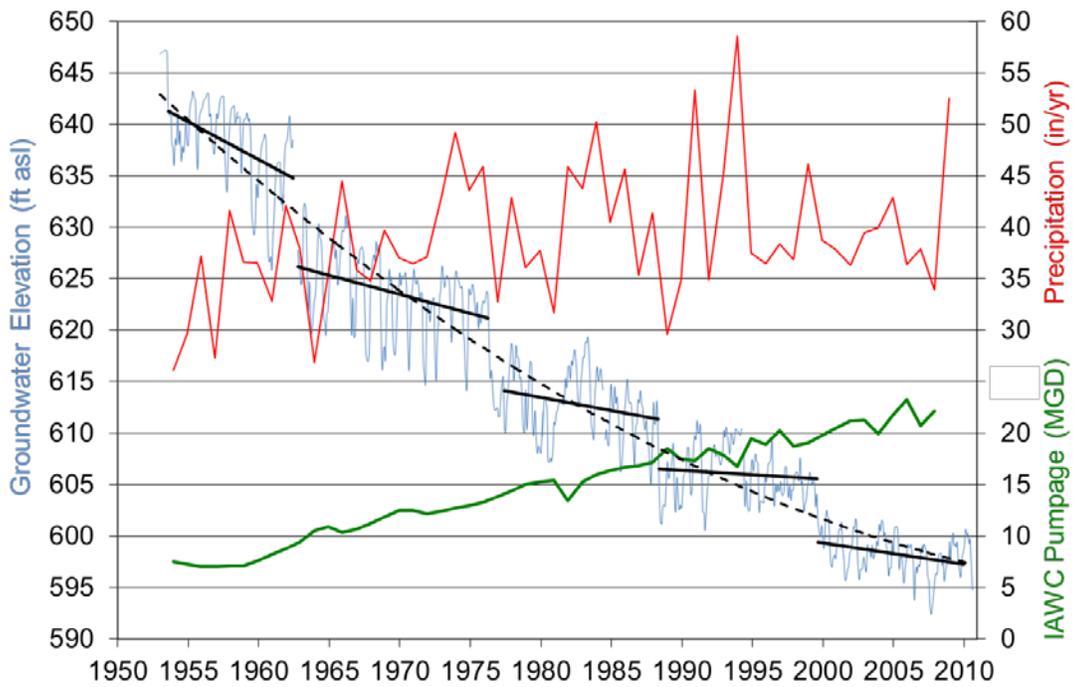
Figure 31. Hydrograph of the ISWS Petro North observation well (solid blue line), with a trend line for the entire record (dashed black line), trend lines for the individual time steps (solid black lines), pumping data (solid green line), and annual precipitation data (solid red line)

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An analysis of the hydroperiod for time periods for each downward step shows that the seasonal fluctuation in water levels is also decreasing over time from 7 feet to less than 4 feet (Figure 32). As the Glasford Aquifer has become progressively more unconfined, the increase in storage capacity has progressively dampened the change in drawdowns caused by changes in pumpage. In a fully-confined system this decrease in seasonal water level fluctuations would be contrary to an expected increase in seasonal fluctuations as seasonal pumpage differences grow with the growth in total pumpage. The hydroperiods shown in Figure 32 were normalized to the month of May to display the changes. Included in Figure 32 is the hydroperiod calculated from 1982–2010 data for the shallow water table measured at the WARM network well at nearby Bondville. Because pressure at the surface can be transmitted into the subsurface, the 3 feet of natural seasonal fluctuation in the water table may be having more of an impact on seasonal water level fluctuations at Petro North than changes in pumpage. In a glacial setting in Saskatchewan, van der Kamp and Maathuis (1991) showed that seasonal head fluctuations in confined aquifers are the result of mechanical loading and unloading of soil moisture at the surface.
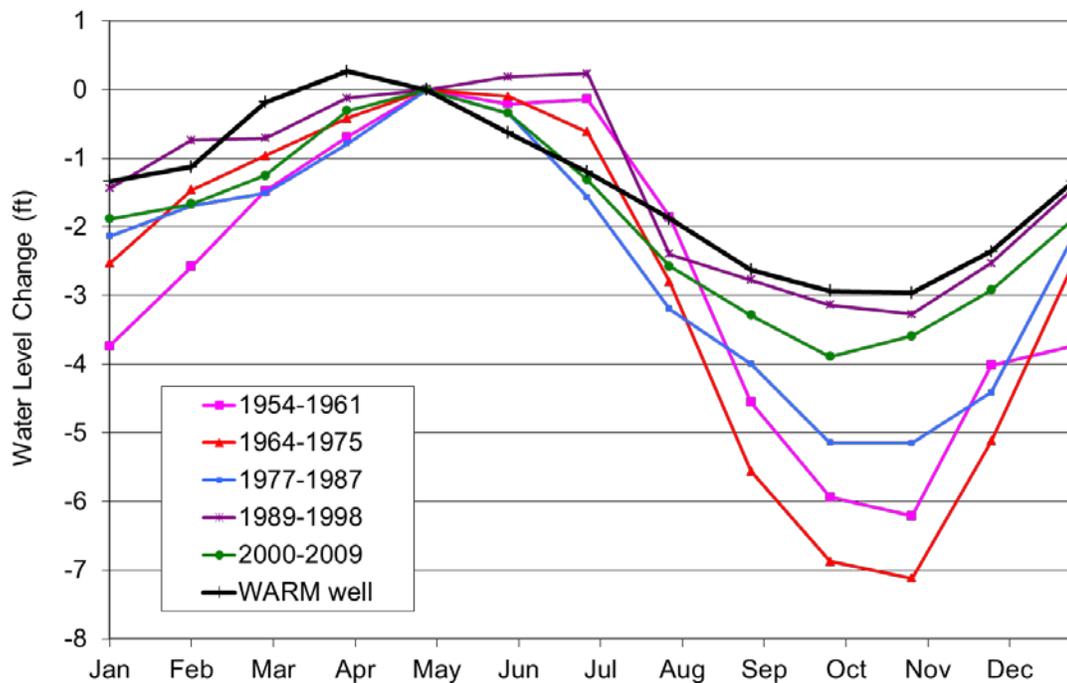
Figure 32. Hydroperiod variation for different time steps in the Petro North record and for the WARM network well at Bondville for the period 1982–2010

Interconnections with Streams. The spread of the Champaign cone of depression appears to stop where it intersects the three river segments that could be providing significant amounts of leakage: the Sangamon River at Monticello, the Sangamon River near Fisher, and the Salt Fork near Rantoul (Figure 28b). The relationship between the Mahomet Aquifer and the Sangamon River is complicated by scattered interconnections, significant alluvial sand deposits along the river, and no apparent impact on baseflow

since groundwater pumpage began. The Sangamon River in Piatt County also forms a divide between water flowing east to Champaign and west toward DeWitt County.

Hydrographs from wells along the Sangamon River in Piatt County show very different hydraulic responses to changes in river stage. At the Champaign-Piatt County line, observation well CHM-96C shows a seasonal correlation to the Sangamon River 4,000 feet away but no correlation to individual storm events (Figure 33). The elevation of the Sangamon River shown on Figure 33 is from the USGS gauge at Monticello, which is 7 miles downstream and roughly 26 feet lower than the river elevation near CHM-96C, making the true vertical head difference in Figure 33 closer to 52 feet. Approaching Monticello, the heads in the Mahomet Aquifer and the Sangamon River converge and the cone of depression abruptly ends. The hydrograph of observation well nest PIAT 09-01 on the north side of Monticello and 2,500 feet from the river shows the seasonal fluctuations and a strong response to individual storm events (Figure 34). The USGS gauge is 2 miles downstream so the Sangamon River stage near the wells is likely to be 5 feet higher. Sharp rises in groundwater levels in response to the storm events indicate that a substantial amount of river water is moving in and out of the aquifers. The Mahomet Aquifer at the PIAT 09-01 well nest was an average of 3.1 feet lower than the Glasford Aquifer, suggesting that the interconnection between the two aquifers is probably offset from the river. At the well nest the till layer separating the two aquifers is 41 feet thick.

Using the available head data from October 2009 to November 2010 for PIAT 09-01, the calculated head difference between the river and the Glasford Aquifer greatly increases during storm events from around 0 feet to as high as 4 feet (Figure 35). Because the exact location of the aquifer/stream connection is unknown, we did not correct the river elevations from the USGS gauge to account for the drop in topographic elevation from the well to the gauge. Without any correction the head in the river averages 1.5 feet higher than the head in the Glasford Aquifer, indicating that on a yearly basis there is a net inflow of surface water to the groundwater. For the period of record, 75 percent of the inflow occurred during storm events that lasted through June 2010. In July and August the gradient reversed and the aquifer may have discharged water back into river. By September the gradient reversed back to positive and the remaining 25 percent of the inflow occurred. During the month of September when streamflows are generally at their lowest, is when any impact on baseflow from leakage to the aquifer should be most apparent. However, a plot of the flow at the USGS gauge for September 30 of each year since the gauge was installed in 1908 does not show any observed impact to baseflow, remaining around 10 mgd since pumping from the Mahomet Aquifer began in 1948 (Figure 36). Plots constructed with other statistics, such as minimum daily flow or minimum monthly flow for each year, also do not show any observed impact to baseflow. Because of the interconnection, there must be areas in the upper aquifers that are unconfined, including the thick alluvial sand along the entire river. The release of water from storage in these sands likely maintains baseflow to the streams as well as preventing steep vertical gradients from forming at the interconnection.
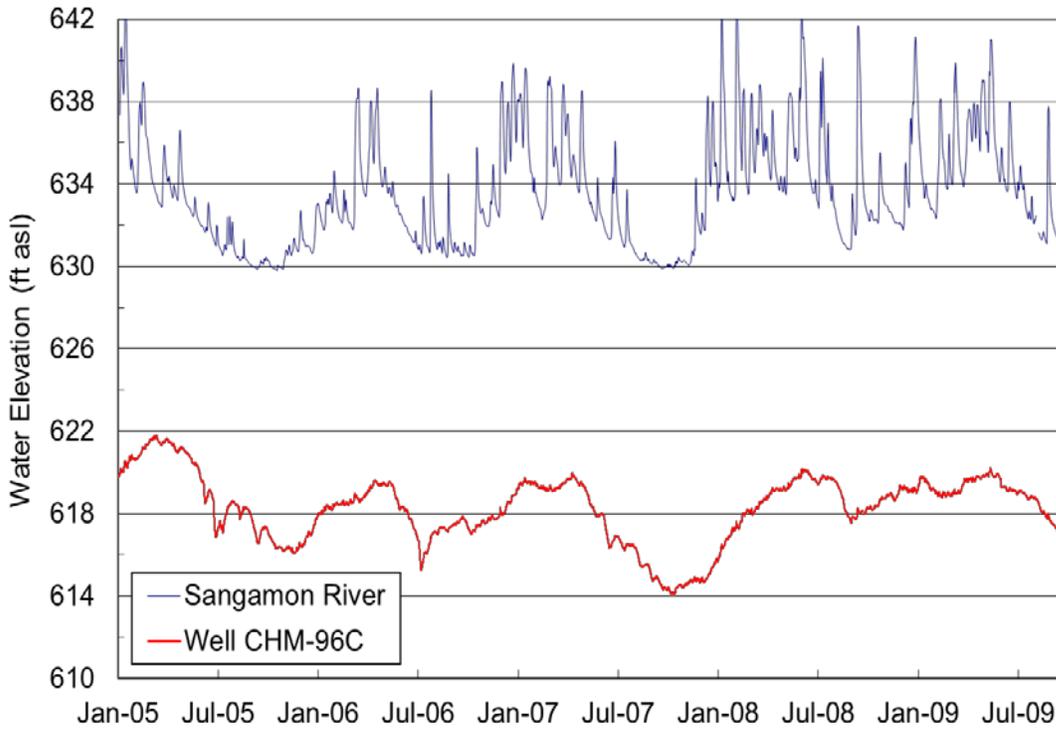
Figure 33. Hydrograph of observation well CHM-96C located near the Sangamon River along the Champaign-Piatt County line
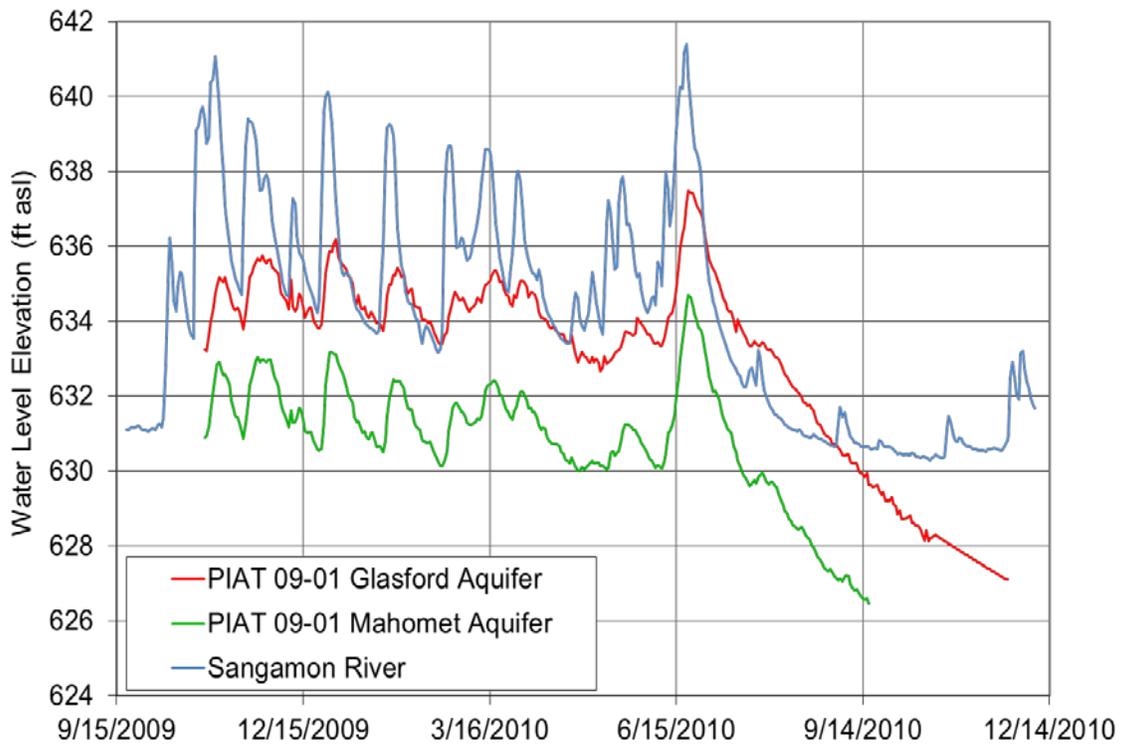
Figure 34. Hydrograph of observation well PIAT 09-01 located near the Sangamon River on the north side of Monticello

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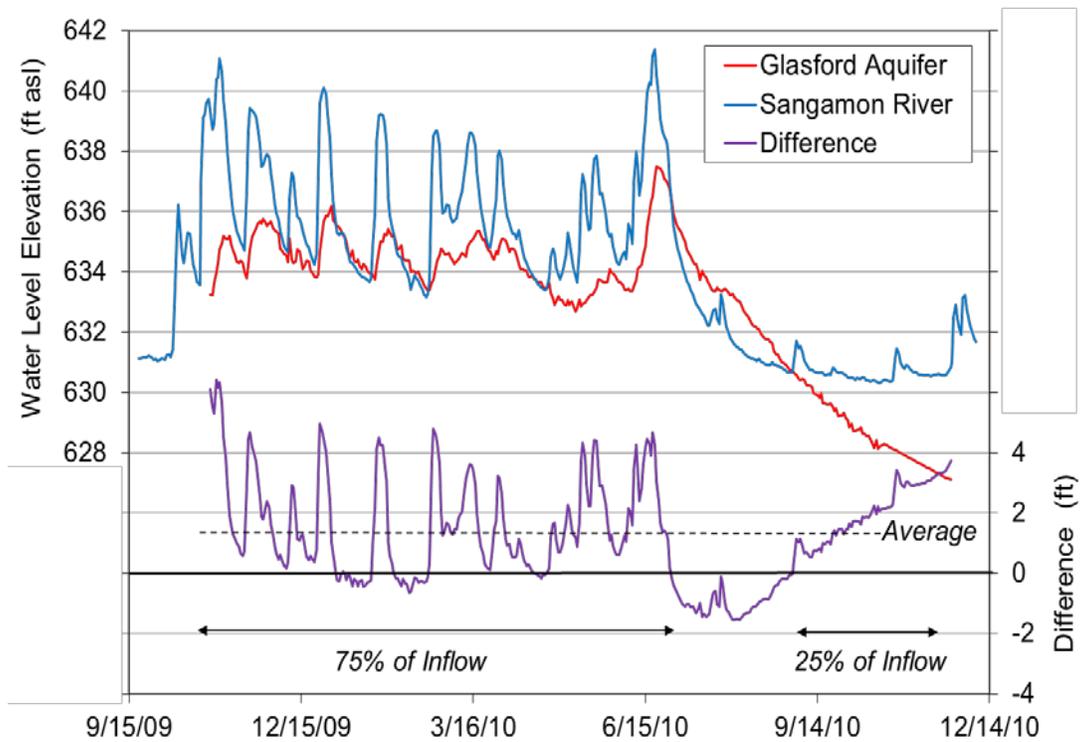
Figure 35. Gradient between observation well PIAT 09-01 and the Sangamon River
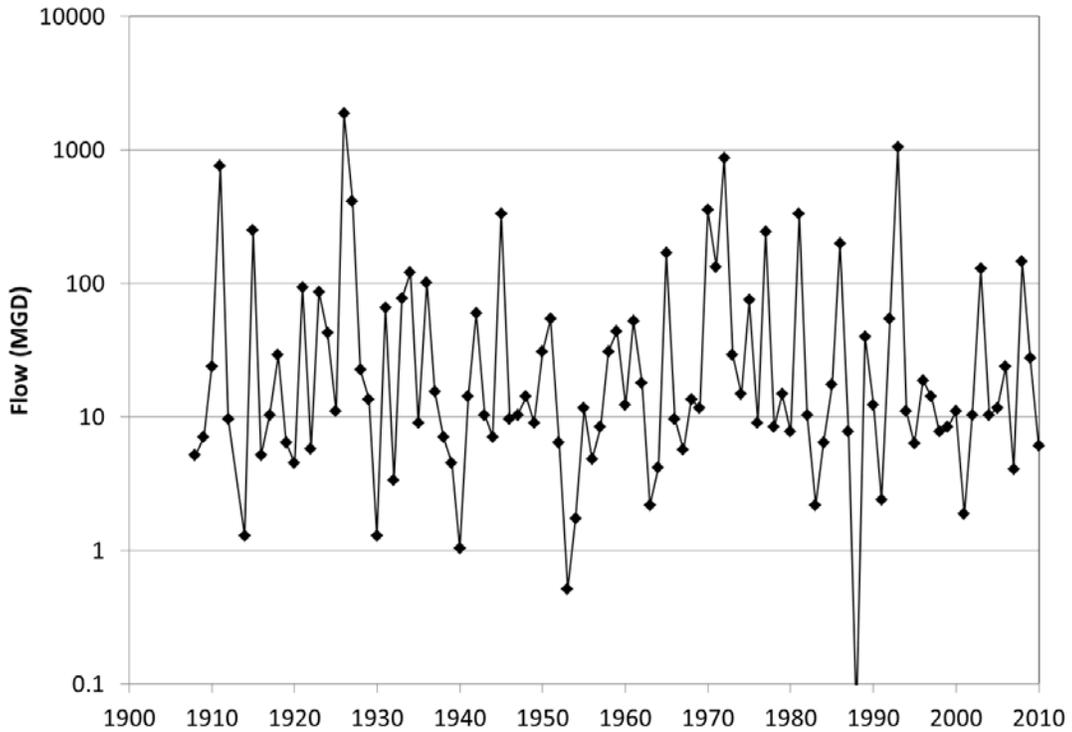
Figure 36. Flow in the Sangamon River on September 30 of each year from 1908 to 2010

Farther downstream of Monticello at Allerton Park, Roadcap and Wilson (2001) found a strong stream/aquifer interconnection by analyzing drawdowns caused by the use of the Decatur Emergency wellfield. Hydrographs for wells in the Allerton area strongly correlated to the daily change in river stage. Storm events on the river also created water level pulses in the Mahomet Aquifer that spread out over a large area because the aquifer is largely confined. Although the geometry of the sands connecting aquifer with the river is unknown, data indicate a connection exists. A rise of 4.09 feet in the river stage from a storm on June 11, 2003 formed a cone of impression in the aquifer that was more than 3.34 feet high near the river (Figure 37). Because the Decatur emergency wells are closer to the river than the production wells in Champaign, they have the potential to create more drawdown underneath the river and thus have a greater impact on baseflow. Mass balance calculations for Lake Decatur by the City of Decatur (Keith Alexander, personal comm.) and groundwater flow model results by Roadcap and Wilson (2001) suggest that the groundwater pumpage reduces baseflow in the Sangamon River which feeds the lake.
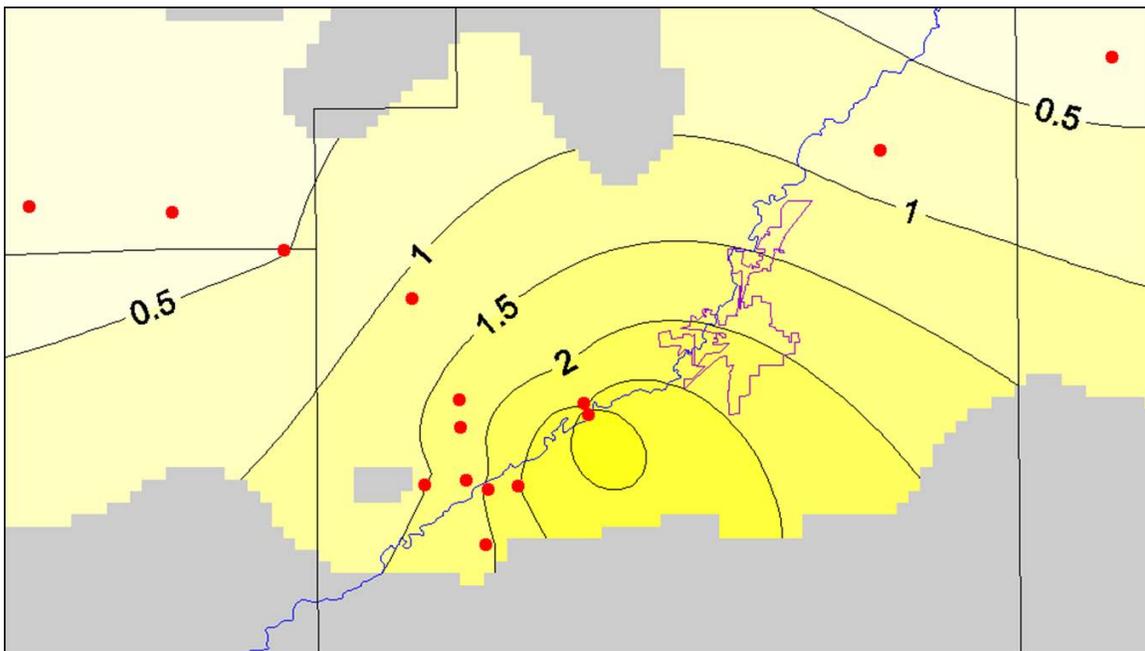
Figure 37. The cone of impression formed in the Mahomet aquifer from the storm event of June 11, 2003. The data were collected on June 5 and June 18, 2003.

The Champaign cone of depression also does not spread past the upper Sangamon River near Fisher or the Salt Fork of the Vermilion River near Rantoul. These two stream segments run over significant sand bodies located along the base of the Gifford Moraine. Storm water coming off the moraine and crossing over these sands could supply enough leakage to maintain the shallow water levels and offset any loss of water to the deeper aquifers. The hydrograph from observation well CHAM 09-05 along the Salt Fork between Rantoul and St Joseph shows a response to storm events (Figure 38). The stage record from the USGS gauge 3 miles downstream near St Joseph was adjusted upwards 4.43 feet to account for the gradient of the stream. The hydrographs for Glasford and

Mahomet wells are nearly identical, even though there is more than 30 feet of till separating the two aquifers. The Glasford hydrograph is not shown on Figure 38. The groundwater is 15 feet above the level of the creek, indicating that the connection is probably upstream near Rantoul. Downstream in St Joseph there are flowing wells along the creek.
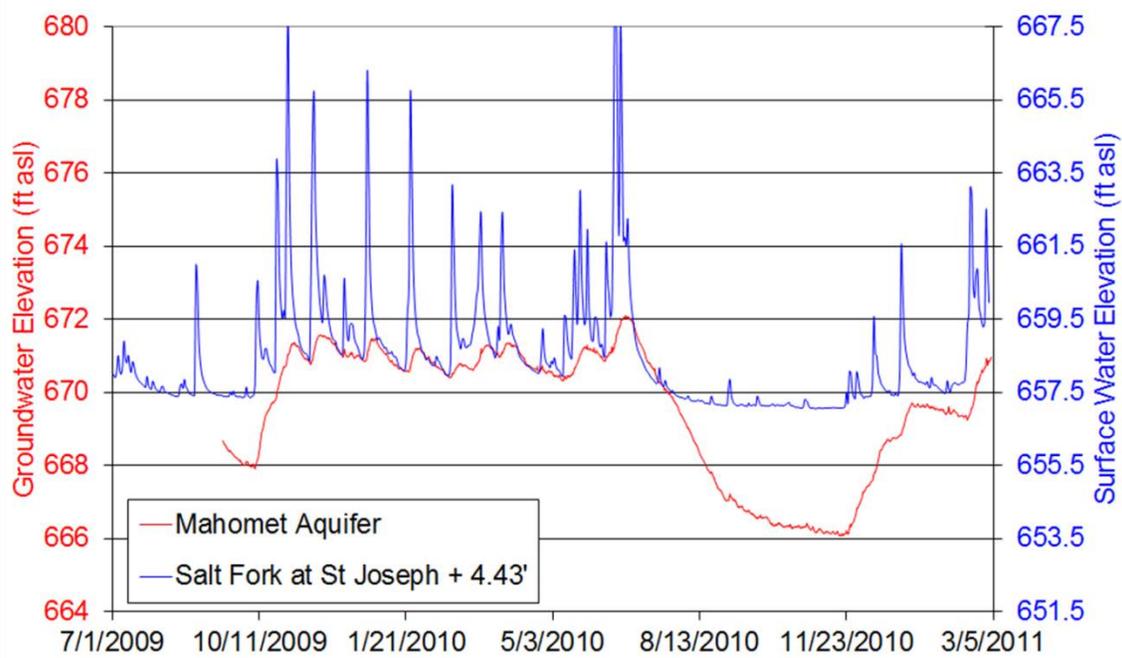
Figure 38. Hydrograph of observation well CHAM 09-05 located along the Salt Fork between Rantoul and St Joseph

From chemical and isotopic analyses of groundwater samples, Hackley et al. (2010) suggests the water in the Mahomet Aquifer throughout Champaign County is similar to present-day precipitation and that there is little to no Pleistocene water more than 11,000 years old in the aquifer system. Hackley et al. (2010) also suggests that the very low chloride concentrations found in Champaign County may be from the flushing of high volumes of freshwater (glacial meltwater) through stacked sands overlying the aquifer that are commonly found near a river. This chemical evidence agrees with the hydrologic evidence that the surficial sand deposits along rivers, such as the Sangamon or the Salt Fork, are large enough recharge areas to allow for the large volume of water necessary to flush the aquifer.

Low-Permeability Flow Barriers within the Aquifer. Halfway between Rantoul and Champaign the groundwater gradient steepens significantly with the potentiometric head dropping 40 feet over 3 miles (Figure 15). Because there was insufficient data to map the steepening in the historic potentiometric surface, it is also reflected in the drawdown map (Figure 28b). Burch (2008) attributes the steepening to a reduction in aquifer thickness and/or hydraulic conductivity. Flow in the aquifer generally moves south from observation well CHM-96B where the Mahomet sand is 182 feet thick to observation well CHM-95B where the Mahomet sand is only 27 feet thick. Therefore, the gradient

has to increase as the groundwater flow squeezes through this thin portion of the aquifer to reach Champaign. Between the two wells the bedrock elevation also climbs in elevation of 370 feet to 496 feet. A southwest to northeast trending bedrock high may run through the area, but it is not seen in any borings to the west of CHM-95B. It is not known how large the area of thin Mahomet sand is or if the sand pinches out completely.

Upflow from the bedrock. As mentioned in the discussion of the northeastern segment of the aquifer, geochemical studies by Panno et al. (1994) and Hackley et al. (2010) show that the carbonates exposed by the La Salle anticline in northwestern Champaign, Ford, and western Iroquois Counties are contributing water to the Mahomet Aquifer. The rate of mixing between the bedrock inflow, the recent recharge, and the existing reservoir of water in the aquifer is unknown. Therefore, different rates of bedrock inflow were tested in the model calibration process and are discussed in the modeling section. Also in northwestern Champaign County is the Manlove storage facility that stores natural gas under very high pressure (1650 pounds per square inch) in an anticlinal dome within the deeply buried Mt Simon Sandstone (Buschbach and Bond, 1974). The stored gas bubble displaces saline water that must migrate somewhere. If some of the displaced water migrates upward through the overlying units, possibly through fractures associated with the folding on the La Salle anticline, then it could displace water out of the carbonate aquifers at the bedrock surface and into the Mahomet Aquifer.

Additional Considerations. Another influence on the shape of the cone of depression may be the large number of wells constructed through the confining layers whose annular spaces (space between the well casing and the borehole) could act as conduits to transfer water between different aquifers. In some irrigation wells, for example, the annular spaces are backfilled with sand instead of bentonite clay to help maximize productivity. A homeowner in northern Champaign County reported that his shallow well goes dry when a nearby deep irrigation well is turned on. How much water possibly enters the Mahomet aquifer through poorly constructed wells is unknown, but could be an influence.

West-Central Segment – DeWitt, McLean, Logan, and Eastern Tazewell Counties. Groundwater flow in the west-central segment of the Mahomet Aquifer starts at the groundwater divide along the Sangamon River in Piatt County with a very shallow gradient that slowly increases through DeWitt, Mclean, Logan, and Tazewell Counties. Without any local observation wells it is difficult to determine the cause of the relatively flat, 1-foot per mile gradient in western DeWitt County and south-central McLean County. Contributing factors to this lack of a driving force could include the lack of regional inflow from the east, low amounts of vertical leakage into the aquifer, and/or interconnections with Salt Creek. Anliker and Sanderson (1995) measured water level differences between the Mahomet Aquifer and the overlying Glasford Aquifer of as much as 100 feet in northern De Witt County near Wapella, indicating a poor vertical hydraulic connection between the two aquifers. From geochemical analyses Panno et al. (1994) and Hackley et al. (2010) suggest saline water from the Pennsylvanian-age bedrock seeps into the aquifer from below and mixes with younger water leaking in from the Sangamon River. In western DeWitt County, heads in the Mahomet Aquifer and the water level in

Salt Creek become coincident, indicating that there may be a connection between the two. This connection could act to raise heads in the area and constrain the gradient through DeWitt County.

In 1989 the City of Decatur constructed an emergency wellfield capable of pumping up to 24 mgd along the southeastern border of DeWitt County. The pumped groundwater is discharged to Friends Creek which flows into the Sangamon River and feeds Lake Decatur, the city's primary source of water. An older emergency wellfield, located along the Sangamon River in Piatt County, is no longer active, but was pumped as recently as 2000. During the 1988 drought, the groundwater that was discharged directly into a dry Sangamon River from the old wellfield in Piatt County was all lost downstream due to infiltration. Water level data collected during the operation of the two wellfields in 1999–2000 showed that after 84 days of pumping the DeWitt wellfield at 6.5 mgd and the Piatt wellfield at 3.5 mgd, the resulting drawdowns were 31 feet and 16 feet, respectively (Roadcap and Wilson, 2001).

The 12-month yield of the DeWitt wellfield was estimated by Visocky (1990) to be 14 mgd based on aquifer tests and an available drawdown of 99 feet, a guideline based on the height of the potentiometric head over the top of the aquifer. The yields for shorter-term pumpage periods were as high as 30 mgd for one month. Using a groundwater flow model, Layne Geoscience (1999) estimated the continuous yield of the DeWitt wellfield to be only between 7.0 and 8.5 mgd. The main reason for the low yield estimate is the well interference caused by the close spacing of the eight wells which are in an area 1 mile long by a quarter-mile wide, and the information on the stream connections was discovered later. By factoring in the interconnection with the Sangamon River and possibly with Salt Creek and the available drawdown, the DeWitt should be able to yield close to 20 mgd. Pumping the wellfield at a high rate could cause problems for a significant number of private wells. As many as 17 private wells were impacted by past pumping events and had to be repaired by either lowering the pump or drilling a new well (Jack Guillou, personal comm.).

With the inclusion of the aquifer/stream interaction at Allerton Park, Roadcap and Wilson (2001) simulated the 1999–2000 pumpage with a modified version of the Layne Geoscience model and found that drawdowns at the Piatt wellfield were reduced by as much as 40 percent. Unfortunately for the City of Decatur, the new model results indicate that the Sangamon River would lose 5.1 mgd to the pumping wells, more than the $Q_{7,10}$ of 3.0 mgd estimated by Singh et al. (1988) for the USGS gauge at Monticello. However, the estimated leakage does not include drainage from unconfined sands along the river, which may provide a significant amount of water for the duration of the low flows. In January 2000, the flow in the river at Monticello dipped to 3.9 mgd, but the river did not go dry downstream by the Piatt wellfield. Because Lake Decatur is on the Sangamon River, any reduction in baseflow caused by pumping groundwater reduces the efficiency of the emergency wellfields to deliver water to the lake.

In central DeWitt County near Clinton the northwestwardly flow in the Mahomet Aquifer splits around a large bedrock high, and some flow is diverted to the

west through the Kenny Channel (see 600-foot contour on Figure 14). These two flow paths then rejoin in northern Logan and southern Tazewell Counties. In the Kenney Channel the overburden over the Mahomet sand becomes much thinner because the area was not covered during the Wisconsinan glaciation. Four streams, Salt Creek, Deer Creek, Kickapoo Creek, and Sugar Creek, cross over the buried channel, with stream elevations that generally coincide with the aquifer heads, suggesting significant aquifer/stream interactions that could constrain the heads.

Flow in the main Mahomet Channel continues northward from Clinton and crosses into southern McLean County before turning west. In Tazewell County, groundwater flow is further divided by several small bedrock highs before reaching the major bedrock high between Pekin and Morton that diverts some of the flow northward through the Mackinaw Bedrock Valley into the Illinois River at East Peoria. The principal flow path in the Mahomet Channel goes westward across southern Tazewell and northern Logan Counties toward the Havana Lowlands and discharge points along the Illinois, Mackinaw, and Sangamon River systems as shown in Figure 17.

A major change in the hydraulic gradient occurs in the area of the 580-foot contour in Tazewell, McLean, and Logan Counties (Figure 14 and Figure 18). As groundwater enters this area, the aquifer volume increases, and yet the gradient steepens, indicating an increase in the amount of recharge entering the aquifer or a decrease in transmissivity. Wilson et al. (1998) suggests this increase in gradient is located where direct hydraulic connections start to appear between the Mahomet Aquifer and the overlying Glasford Aquifers. These upper aquifers have similar potentiometric heads at the connections but higher heads away from them, indicating that groundwater in the upper aquifers is getting funneled through these connections down to the Mahomet Aquifer. In this area of the Mahomet Aquifer, the chloride concentration decreases by one order of magnitude and the concentration of modern carbon isotopes increases (Holm, 1995; Herzog et al., 1995), also suggesting a downward flux of water from the upper aquifers. In this same area, the upper reach of Sugar Creek may be losing a significant amount of water and is directly connected to the Glasford Aquifer. Statistical analyses also show that water level fluctuations along Sugar Creek in McLean County are greater than in the surrounding area (Figure 21). The influence of Sugar Creek can also be observed in different sets of measurements from the observation wells, such as during the seasonal rise in water levels that occurred in the winter of 2006-2007 (Figure 39).

Farther west in Tazewell and Logan counties, the connections with shallower aquifers become more numerous and the aquifers begin to coalesce (Wilson et al., 1998). At most of these locations there also are changes in water levels, chloride concentrations, and modern carbon isotope concentrations in the Mahomet Aquifer (Holm, 1995; Herzog et al., 1995) that indicate a vertical connection with downward leakage. The operation of the Town of Normal's wells in the Mahomet Aquifer, which is located at one of these upper aquifer connections, initially caused interference with a number of local shallow farm wells (Richards and Visocky, 1982). Chloride values in the Normal wells are also low, indicative of water coming from the upper sands.

The first natural groundwater discharge areas encountered by groundwater flow in the western segment of the Mahomet Aquifer are at the Mackinaw River downstream of Mackinaw and the lower reach of Sugar Creek and its tributaries northwest of Lincoln (Wilson et al., 1998). These two streams have down cut into the Mahomet Aquifer or into upper sands that are directly connected to the aquifer. Because the aquifer is still mostly confined in these areas (Figure 19), changes in stream levels are reflected by head changes in the aquifer (Figure 21 and Figure 39). The $Q_{7,10}$ flows calculated at the USGS gauges using the ILSAM model show that the low flow of the Mackinaw River increases from 1.2 mgd east of the aquifer at Congerville to 17.2 mgd over the aquifer at Green Valley. After subtracting 1.9 mgd of treated wastewater discharges, the net increase in low flow is 14.1 mgd. Because the increase in drainage area is small, almost all of this inflow is groundwater discharging from the Mahomet Aquifer and connected shallow aquifers. In northern Logan County the $Q_{7,10}$ flows calculated with the ILSAM model for Sugar Creek and Prairie Creek show gains of 3.1 mgd and 2.9 mgd, respectively.
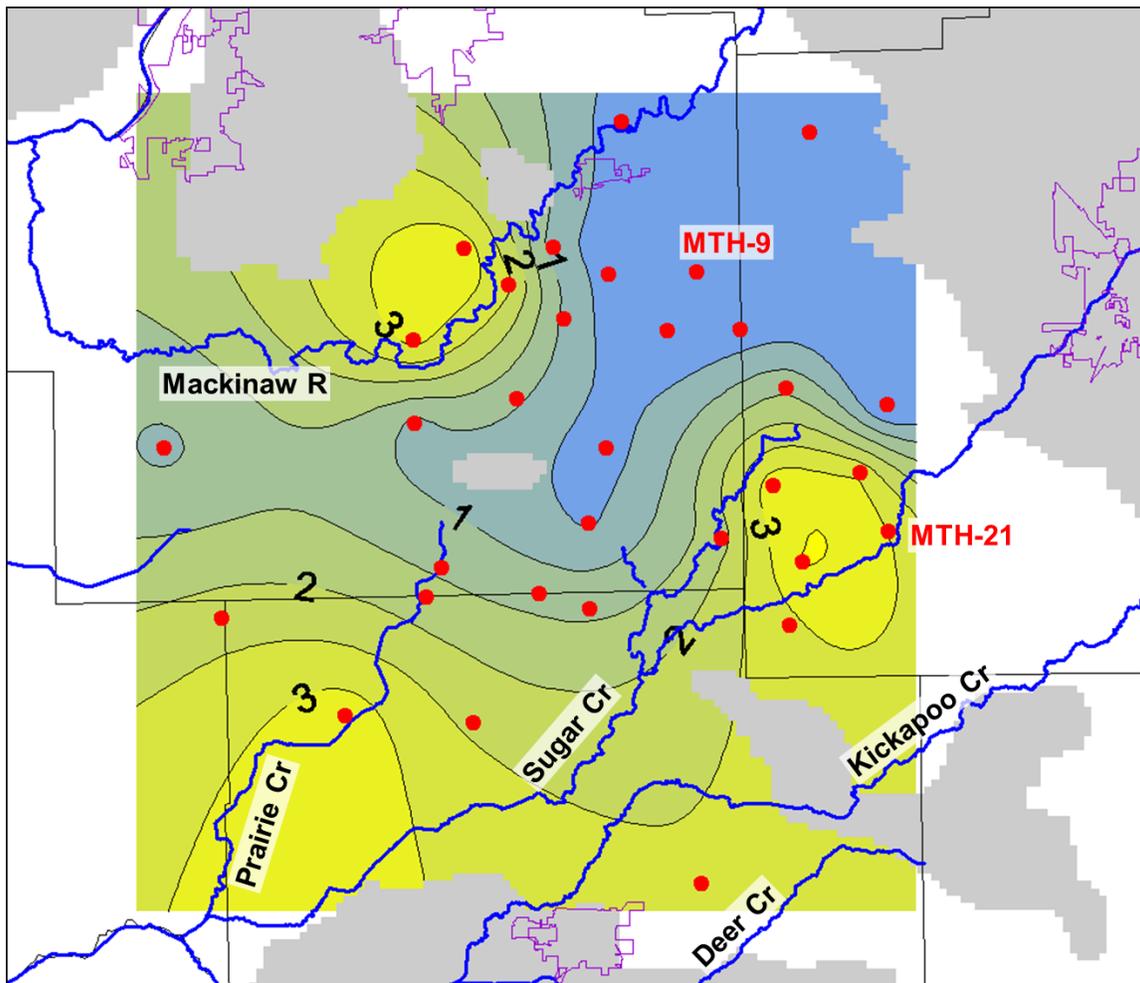
Figure 39. The rise in measured water levels (feet) from 11/1/2006 to 3/8/2007 in the network of observation wells in Mclean, southern Tazewell, and northern Logan Counties

Havana Lowlands – Mason and Western Tazewell Counties. In Mason and western Tazewell Counties, groundwater in the Mahomet Aquifer enters the Havana Lowlands. The area is known for producing specialty crops grown on the Lowlands sandy soils irrigated by over a thousand systems pumping upwards of one billion gallons of groundwater per day. The Havana Lowlands sit in a swath 5 to 13 miles wide along the Illinois River from Pekin to Beardstown and have a land-surface elevation that is significantly lower than over the rest of the aquifer. Figure 40 shows the Havana Lowlands shaded in yellow where there are clean sandy soils and in gold where there are heavier sandy soils. The area with clean sandy soils can be hilly and covered with sand dunes. The lack of streams and ditches indicates that there is no appreciable surface runoff and high infiltration rates. The heavier soils formed on very flat-lying lake beds; here the water table is close to the surface and drainage networks are needed in order to farm the land. The green area of Figure 40 is the modern Illinois River floodplain, and the cyan and blue areas are covered with till from the Illinoisan and Wisconsinan glaciations, respectively. The red and orange areas have special hydrologic feature discussed below.

The final discharge points for the Mahomet Aquifer are along the Illinois River, along the lower reaches of the Mackinaw River, Salt Creek, and the Sangamon River, and along Crane and Quiver Creeks which bisect the area (Figure 17). In southwestern Mason County a groundwater divide developed along the flowpath that separates flow toward the Illinois and Sangamon Rivers. The Snicarte observation well sits along this flow divide (Figure 14 and Figure 40). The water levels in the rivers affect the water levels in the aquifer. An extreme example of this occurred in 1993 when prolonged flooding and heavy precipitation caused the groundwater to rise above the land surface and form 171 lakes in low areas throughout the lowlands (Sanderson and Buck, 1995; Clark, 1994; Visocky, 1995). Hlinka et al. (1999) conducted a follow-up study of the largest of these lakes, the semi-permanent Sand Lake.

Water levels in the Havana Lowlands are also affected by pumpage. At the wellfield for the Jake Wolf Fish Hatchery northeast of Havana, 7.9 mgd of pumpage lowered the water level by 15 feet (Visocky and Sievers, 1992). Because of its widespread and seasonal nature, the effect of irrigation pumpage on the potentiometric surface is difficult to determine. Sanderson and Buck (1995) compared their potentiometric surface map from the fall of 1992 with a map from 1960 (Walker et al., 1965), which was made prior to the extensive use of irrigation. They found the water levels generally to be within ± 5 feet and concluded that irrigation pumpage had not lowered regional groundwater levels.

The 52-year record of water levels at the Snicarte observation well also shows a significant influence of the Illinois River 1.7 miles away and no discernible impact from irrigation (Figure 41). The Illinois River stage data on the hydrograph are from the U.S. Army Corps of Engineers gauge at Havana and plotted using only monthly data to make the trends more visible. Visocky (1995) conducted a multivariate statistical analysis of the Snicarte data and found a correlation coefficient of 0.599 to peak stage on the river and a better correlation of 0.741 to the total number of days the river is above flood stage. The correlation of the data to precipitation improved from 0.503 to 0.778 when the
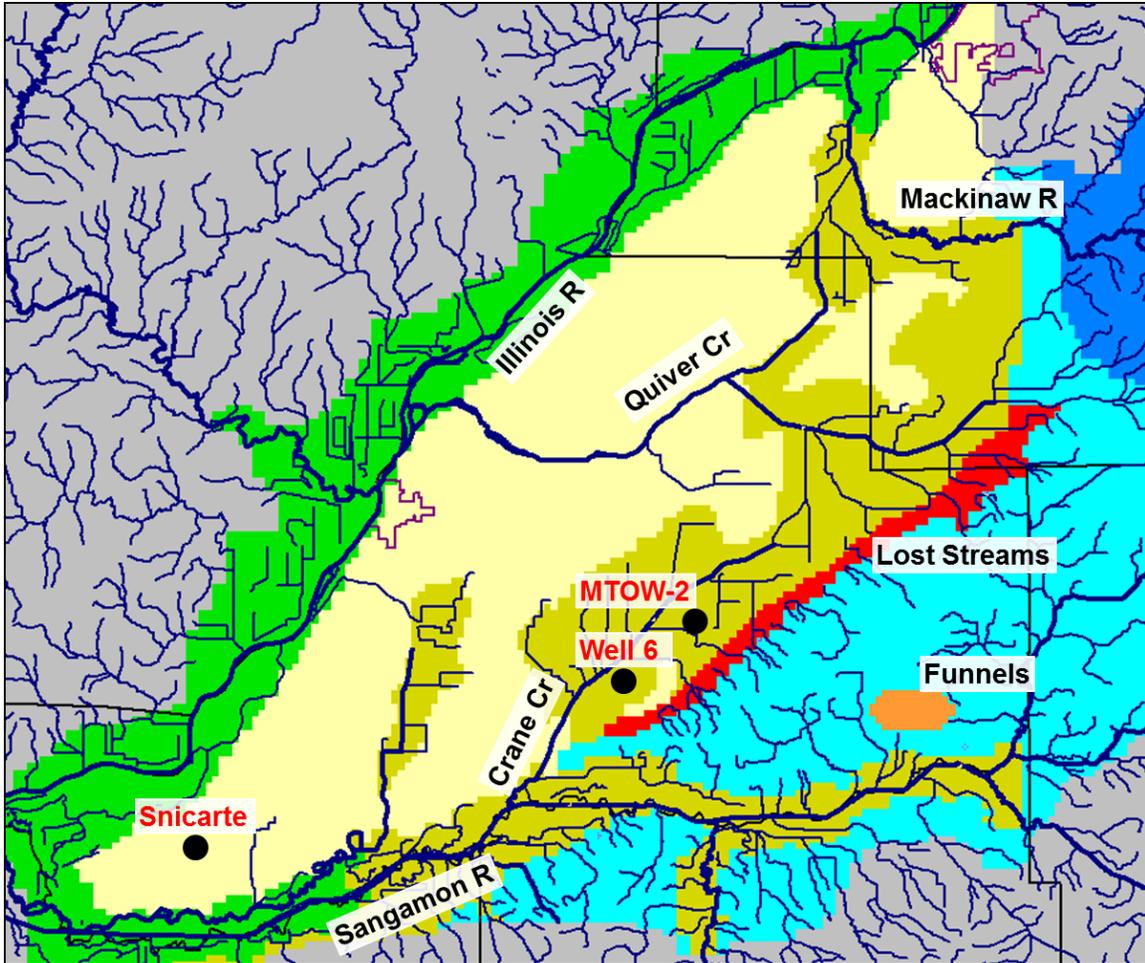
Figure 40. Generalized soil map of the Havana Lowland region (modified from Natural Resources Conservation Service, 1995)

duration of past precipitation data used in the calculation was increased from 3 to 24 months. The better correlations found to the long duration statistics by Visocky (1995) are likely due to the large storage capacity of the aquifer causing a lag in the response to external changes.

A remarkable feature of the Snicarte hydrograph is the lack of any downward trend since the initiation of large-scale irrigation. Water levels fluctuated in a narrow range between 446 feet and 451 feet, except during the 1993 flood and during dry periods in 1988, 2005, and 2007 when the water level fell below the bottom of the well. Assuming a porosity of 20 percent and no regional inflow, a typical single well irrigating 130 acres on a 160-acre plot for four months at the average rate of 0.41 mgd (11.3 inches per 160 acres for 4 months) will lower the saturated thickness under the plot a maximum of only 4.7 feet by removing water from storage. The Snicarte well sits in a sand dune where the depth to water table is over 35 feet so the pumping of irrigation wells is unlikely to induce any additional recharge from the surface. Although the surrounding rivers are lower in elevation, they act as a control on groundwater elevations and prevent
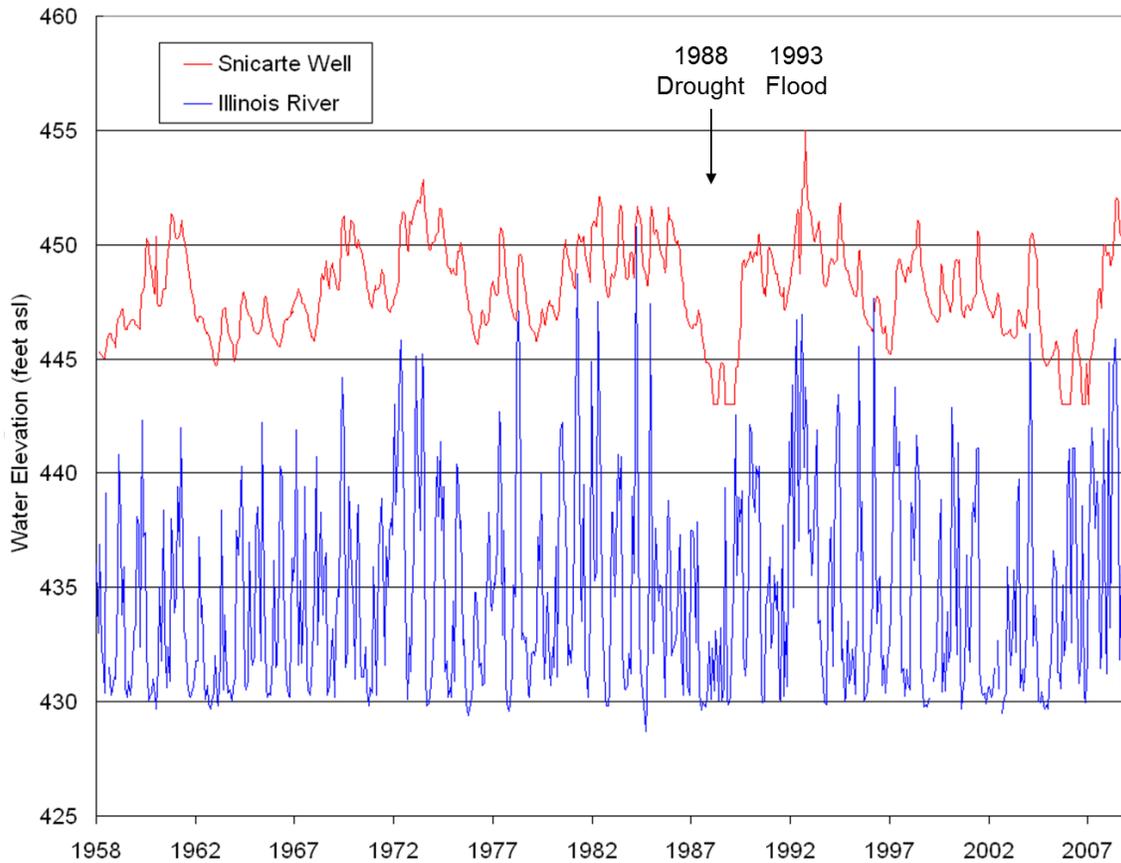
Figure 41. Hydrograph of the Snicarte observation well and the Illinois River at Havana.

any drawdown from reaching underneath them. With sustained rises in the level of the Illinois River of more than 8 feet every winter and spring, the resulting backwater effect raises groundwater levels and appears to overwhelm the impact from the irrigation. This backwater effect is transmitted throughout the Havana Lowlands by the Sangamon River, the Mackinaw River, and the tributary creeks and drainage ditches, often forcing the water table to rise above the land surface and causing flooding. Therefore, the interaction between the aquifer and streams prevents the accumulation of drawdown from one year to the next as long as the river continues to rise every winter/spring.

On the eastern edge of the Havana Lowlands, focused recharge areas occur where streams coming off the till upland intersect the surficial sands on the lowlands. Many definable streams and drainage ways are simply lost when they hit the sandy flat fields (red zone on Figure 40). A hydrograph from Well #6 at the Irrigation Test Site (Westcott et al., 2009) shows extremely large spikes in water levels after a storm event (Figure 42). Assuming an aquifer porosity of 20 percent, the 4-foot spike from the April 2004 storm is roughly equivalent to receiving 9.6 inches of infiltration. During these events the groundwater elevation stayed above that of Crane Creek, indicating that most of the flow is going through the groundwater system first. Well #6 is 150 feet from an irrigation well, and shows the cyclic drawdowns from the pumpage. There was 3.2 feet of drawdown
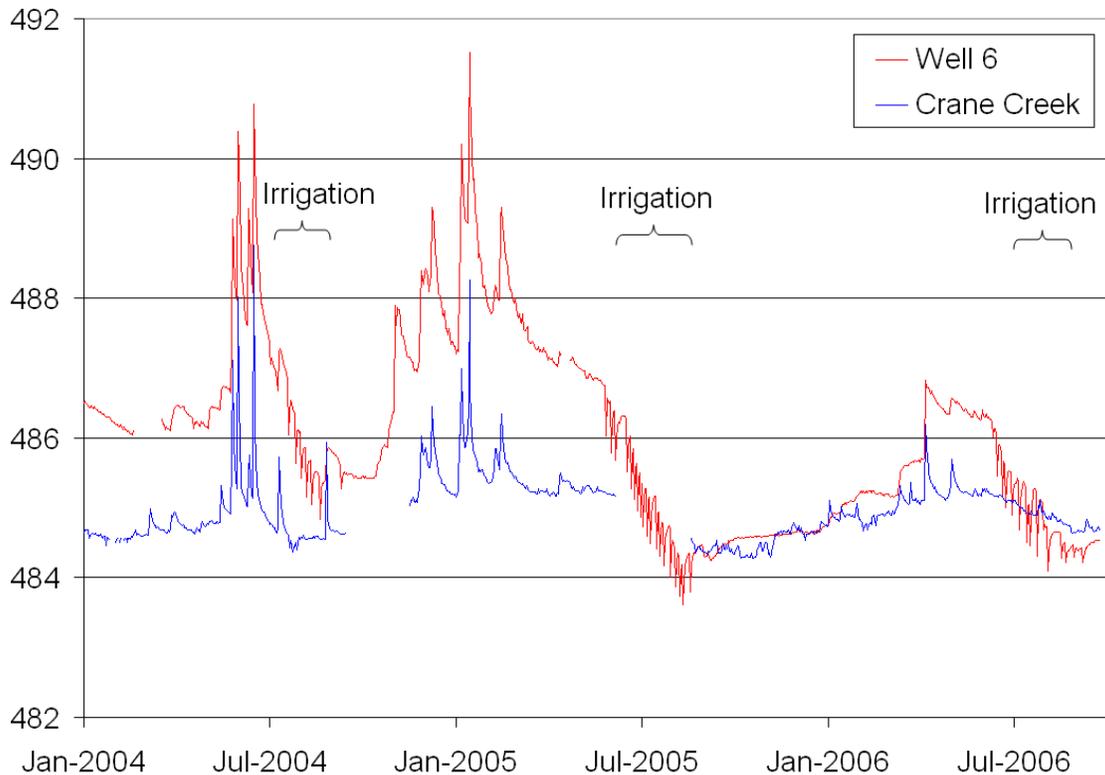
Figure 42. Hydrograph of observation well 6 at the Irrigation Test Site and Crane Creek adjacent to the site (from Westcott et al., 2009)

during the irrigation season of 2005; however, much of the decline would have occurred naturally due to the dry weather.

Perhaps the most unusual hydrologic features in the aquifer system occur in the upland area around Mason City (orange zone on Figure 40). North and east of town are many large closed depressions reaching depths up to 15 feet. Some of the depressions lie between sand dunes that overlie 50 feet to 100 feet of till. Lakes, such as Norton Lake and Ellsberry Lake, form in some of the depressions, although their elevation is still 40 feet above the head in the Mahomet Aquifer. Other depressions do not show any signs of accumulating any water, a fact confirmed by aerial surveys after the period of heavy precipitation in June 2010. Because there are no active sumps or drains in these dry depressions, the only plausible explanation is that water is being funneled down to the aquifer through unknown interconnections, such as erosional channels or clastic volcanoes. The presence of these "funnels" also helps explain the high groundwater elevations found in wells in Mason City. A large recharge flux is needed in this area to keep heads in the Mahomet Aquifer over 520 feet and maintain the steep groundwater gradient southward 3.5 miles to the Sangamon River, which is around 490 feet in elevation.

Recharge estimates for the Havana Lowlands have been made by Walker et al. (1965), Visocky and Sievers, (1992), and by Clark (1994). Using a flow net analysis,

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Walker et al. (1965) computed recharge values of 5.7 in/yr in the eastern part of Mason County where there is overlying till and 10.3 in/yr in the western part of the county where the aquifer is at the surface. These estimates were made prior to the start of extensive irrigation in the region. Using the five-spot method, Visocky and Sievers (1992) computed recharge rates between 6.1 and 10.6 in/yr at the Jake Wolf Fish Hatchery located in the Lowlands northeast of Havana. Clark (1994) used the PACE-GC watershed model developed by Durgunoglu et al. (1987) to estimate recharge values in the Havana Lowlands. These estimates show very large variations depending on annual precipitation patterns and have values ranging from 1.6 in during the drought year of 1956 to 23.8 in during the extremely wet year of 1993. For the period from 1950 to 1993, the yearly mean recharge was computed to be 10.88 in/yr.

An estimation of the annual recharge rate in the Havana Lowlands needs to include the effect of backwater flooding along the streams which raises water levels in the aquifer. Because there has been no long-term decline in water levels, the net recharge rate from precipitation and backwater flooding must have increased over time to match the increase in pumpage. Therefore, a groundwater flow model constructed with 1-year or longer time steps needs to include recharge rates that increase directly with the increase in total pumpage.

Quantifying the groundwater discharge to the Illinois River is very difficult because the volume of the discharge is very small compared to the overall flow in the river. Using a groundwater flow model, Clark (1994) estimated 134 mgd of groundwater discharged to the Illinois River and another 45 mgd was discharged to backwater lakes. Clark (1994) also estimated that 141 mgd was discharged to Crane and Quiver Creeks and the Mackinaw River and another 78 mgd was discharged to the Sangamon River and Salt Creek.

Similar to the Havana Lowlands, the potentiometric surface in East Peoria begins to drop rapidly three to four miles east of the Illinois River. Unlike in Mason County, the aquifer becomes unconfined underneath the modern bluffs where there is as much as 250 feet of clay covering the partially unsaturated Mahomet (Sankoty) sands (Burch and Kelly, 1993). By inhibiting the discharge of groundwater, the siltation of the bottom of Lake Peoria is likely contributing to higher groundwater levels and creation of new springs along the eastern Illinois River shoreline, such as at Spring Bay in Woodford County.

Conceptual Model Summary

Over more than 50 years, a tremendous amount of groundwater data have been collected throughout the Mahomet Aquifer area; these data are critical to the conceptualization of the aquifer's hydraulic behavior and are an important guide to the construction of a numerical groundwater flow model of the aquifer and overlying units. The most significant observations in addition to the basic flow directions include:

1) Effective recharge rates increase with total pumpage as a result of induced infiltration from the surface and hydraulically connected streams.

2) Changes in the surficial geology along a drainage way can create areas of focused recharge.
3) Leakage from interconnected streams can limit the spread of a cone of depression.
4) Leakage from streams preferentially occurs during high flows when the vertical gradients with the groundwater are the highest.
5) The behavior of hydraulic heads in nested observation wells can indicate aquifer interconnections in areas where there are no supporting geologic records.
6) Fluctuations in hydraulic heads and drawdowns in unconfined areas of the Mahomet Aquifer and interconnected portions of the Glasford Aquifer are dampened by the movement of water in and out of storage.
7) Droughts and possible dewatering of overlying sands can affect the heads in the aquifer, although more data are needed to understand and model this phenomenon.
8) Upflow from bedrock aquifers can contribute water to the Mahomet Aquifer.

Groundwater Flow Model

The purpose of constructing a numerical groundwater flow model of the Mahomet Aquifer is to bring the interpretive conceptual model and all of the hydrologic data together to form a quantitative tool that can be used to test hypotheses and make predictions. The hypothesis testing phase of the modeling process has been an ongoing effort since the first electric analog aquifer model was assembled at the ISWS in the 1960s (Visocky and Schicht, 1969). Model results, or more importantly a failure to get a good match between model results and field observations, have guided data collection efforts and have led to many revisions of the conceptual flow model. For example, the inability of an earlier version of the model to match the high heads at Mason City and the head spikes at well 6 led to making new field observations and data collection efforts that greatly improved the model and the understanding of flow in Mason County. For purposes of water supply planning, the flow model is used to quantify the impact of current demand on existing water resources and how the three different future demand scenarios would alter those impacts.

The Mahomet Aquifer model was constructed using the U.S. Geological Survey program MODFLOW (McDonald and Harbaugh, 1988), a widely accepted industry standard for modeling fresh water aquifers. The pre- and post-processing software programs, Groundwater VISTAS® and Visual MODFLOW®, were used to aid in the use of MODFLOW. The mathematics and finite-difference techniques for building groundwater flow models are well documented in many textbooks and papers. Essentially the aquifer is subdivided (or discretized) into gridded cells (rows, columns, and layers) with assigned sets of hydraulic properties and boundary conditions that the model uses to solve a three-dimensional groundwater flow equation matrix. The MODFLOW model used here subdivides the Mahomet Aquifer and overlying units into 362,609 active cells arranged in 275 rows and 603 columns with an equal spacing of 1320 feet (quarter-mile) and in seven layers with variable thickness distributions based on geology. The model

grid is too fine to show in map view. Because the model needs to be rectangular and the aquifer is irregularly shaped, only 38 percent of the cells representing the Mahomet sand and overlying units are active. The inactive cells are shaded gray on all the maps of model input or output.

The model is divided into seven active layers based on the simplified geologic model created by Wilson et al. (1998) and described further by Herzog et al. (2003). The geologic model consolidates the units into three sand aquifers: the Mahomet, the lower Glasford/Upper Banner, and the Upper Glasford, and three till layers: the Banner, the Glasford, and the Wedron. A seventh layer was added to the top of the model to represent the soil zone. An inactive eighth layer was added beneath the Mahomet Aquifer to visually represent the bedrock and other non-aquifer material between the sand and the bedrock. Figure 43 is a representative cross section of the model showing the model cells, conductivity zones, river conditions (lime green), soil and drain conditions (yellow), and wells (vertical blue lines). Figure 44 shows the overall layering of the model in a three-dimensional view.

The geologic model was expanded from the area of McLean, Tazewell, and Logan Counties described by Wilson et al. (1998) with data from several additional studies and the ISWS and ISGS well record databases. Differences in elevations between overlapping maps were rectified and smoothed so no artificial features resembling geologic faults are in the model. In areas where a geologic unit does not exist, the model layer was assigned a thickness of 1 foot and assigned hydraulic properties equal to the layer above or below. In the Havana Lowlands, the elevations for the upper model layers (for nonexistent geologic units that occur above the Mahomet Aquifer elsewhere) were assigned elevations approximately 20 feet below the water table so these model cells could stay saturated in order to help the numerical stability of the model.

In Mason and western Tazewell Counties, the model bedrock elevations were determined from Walker et al. (1965) and the till thicknesses from Clark (1994) and USGS surface topography maps. In the East Peoria-Morton area, bedrock elevations were determined from Horberg (1950) while the shallow units either have not been mapped or are unsaturated so they are not active in the model. The bedrock surface for south-central McLean, DeWitt, Macon, western Piatt, and southwestern Iroquois Counties was derived from Soller et al. (1999). Information on the Glasford and Wedron Formations in DeWitt, Macon, and western Piatt Counties came from maps prepared by Larson et al. (2003). Preliminary elevation data for the model layers representing eastern Piatt, Champaign, and southern Ford Counties were provided by the ISGS (Stumpf and Dey, in press). In Champaign County, the upper Banner sands lie directly on top of the Mahomet sand so the model represents the principal Glasford sand and an upper Glasford sand. Bedrock elevations for Iroquois and Vermilion Counties came from Kempton (1991) and the state-wide bedrock map by Herzog et al. (1994). Maps for the shallow units in Vermilion County by Kempton have not been incorporated into the model yet and there are no existing maps for Iroquois County, so shallow model layers are inactive in both of these counties. Land surface elevations for each cell were derived from a statewide digital elevation model and modified along the major streams to match stream stages.

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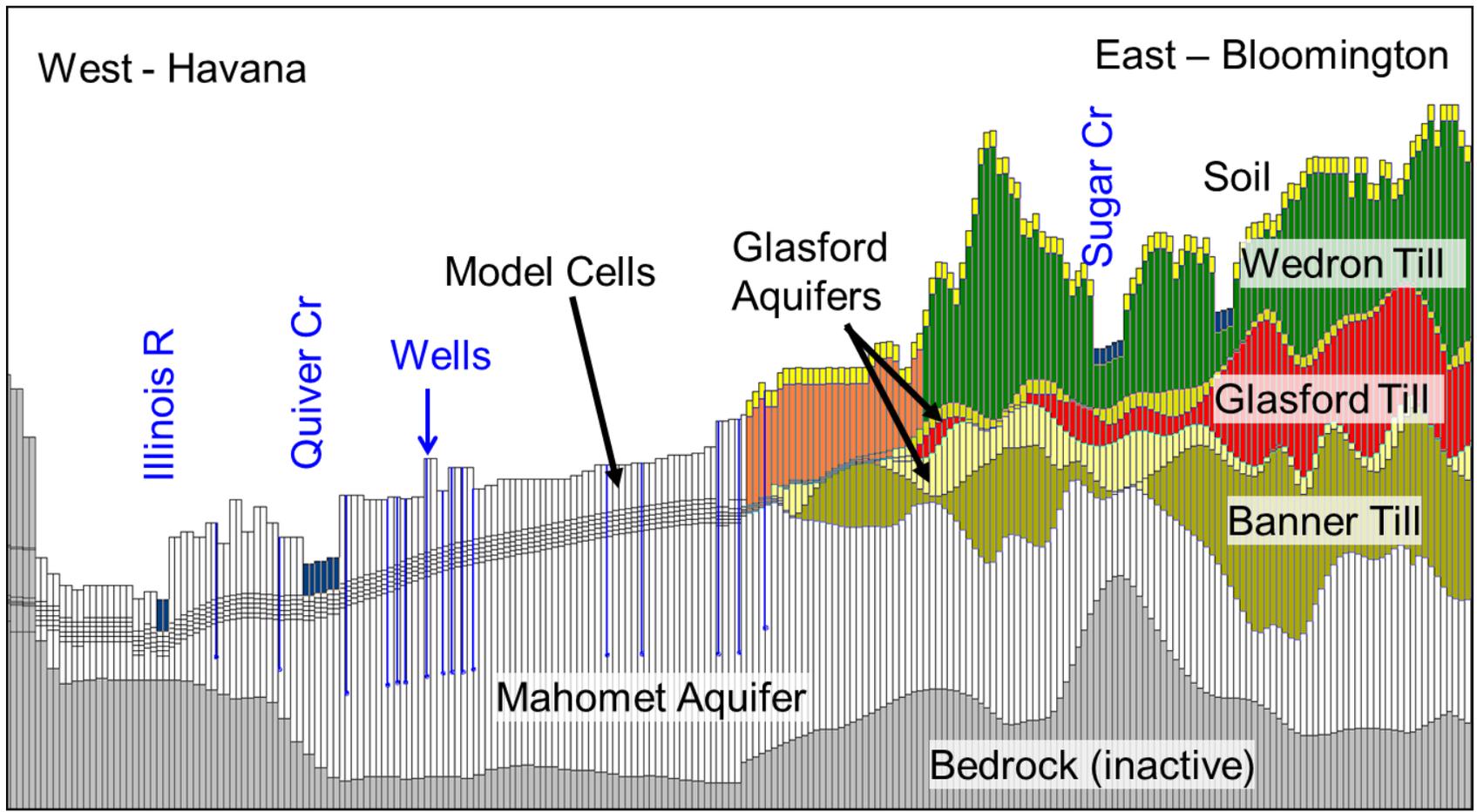
Figure 43. Representative cross section of the digital flow model from Havana to Bloomington
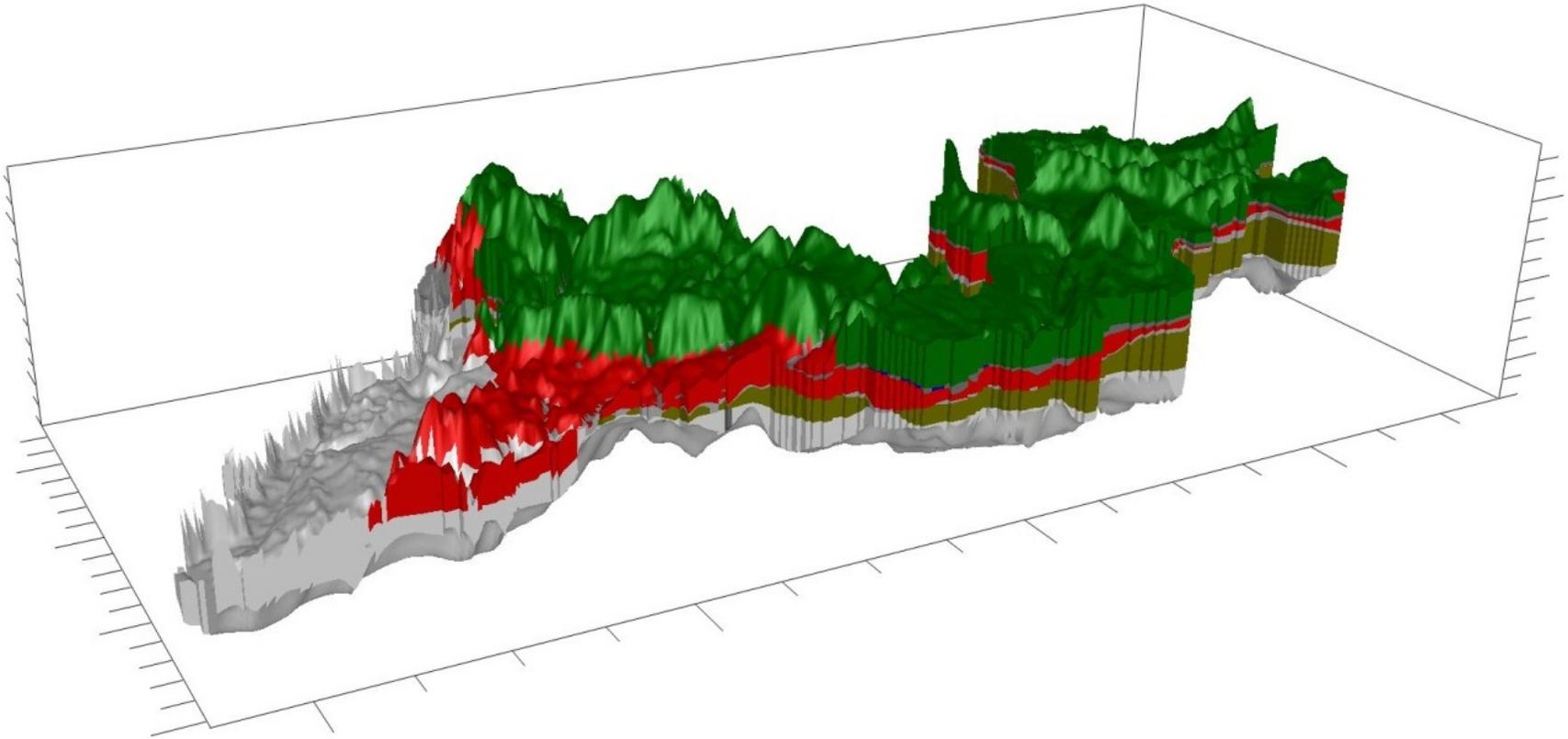
Figure 44. Three-dimensional view of the Mahomet aquifer digital model (vertical exaggeration: 250x)

For boundary conditions at the land surface, river cells were used to represent the major streams and lakes; drain cells were used to represent small tributaries and agricultural drain tile networks developed in clay-rich soils (Figure 45). The river cells were assigned elevations taken from USGS quadrangle maps, and the drain cells were assigned elevations equal to 3 feet below the land surface. Both the river and drain boundary conditions were assigned conductance values based on the hydraulic conductivity of the cell so that they were high enough as to not impede the inflow into the boundaries. Thus, river and drain conductance were not used as calibration parameters.

Inflow from the bedrock was simulated with constant-flux (per time step) boundary conditions in cells representing the Mahomet Aquifer that directly overlie the bedrock (Figure 46). The influx from the bedrock has not been quantified by any geochemical or hydrology studies so the influx value and distribution were calculated as part of the model calibration process. The total calibrated influx of 7.7 mgd helps maintain the west-to-east flow pattern in Iroquois County and the higher heads north of the steep flow gradient in Champaign County. Constant head boundaries were used along the Illinois-Indiana state line to allow flow to come across the border and to allow for discharge at Danville where the hydrology is poorly understood. Additional constant head cells were used in the Glasford Aquifers near Bloomington to account for flow coming in from unmodeled areas not over the Mahomet Aquifer (Wilson et al., 1998). Ideally the model should be extended to these areas in the future; however, the constant head contribution to the total flow in the model turned out to be a negligible 0.4 percent.

To better represent how the hydrologic processes occurring at the land surface impact the aquifer system (Figure 11), a 10-foot thick layer was added to the top of the model to represent the higher permeability soils that have developed in the lower permeability tills. The same approach was used for a model of the shallow aquifers in Kane County, Illinois (Meyer et al., 2009), which has a sequence of interbedded glacial outwash sands and tills similar to that of east-central Illinois. Because the water table in east-central Illinois is generally within 10 feet of the surface and not deep within the middle of the till, the vertical permeability of the till is too low to transmit all of the surface infiltration down to an aquifer. Therefore, by assigning a sufficiently large recharge rate to keep the soil zone saturated and exceed the downward flow rate of water across the till, the net recharge to the aquifer can be controlled by the vertical permeability of the till. Permeability is a measurable physical property of the material and fluid, whereas a recharge flux is spatially and temporally variable and is not an intrinsic property of either the material or the fluid. The excess recharge either flows laterally into the next model cell or is carried off by the river or drain boundaries within the cell and contributes to the calculated baseflow. In a sensitivity analysis, Meyer et al. (2009) found their model to be far more sensitive to the vertical permeability of the till than to the permeability of the sands or the recharge rates.
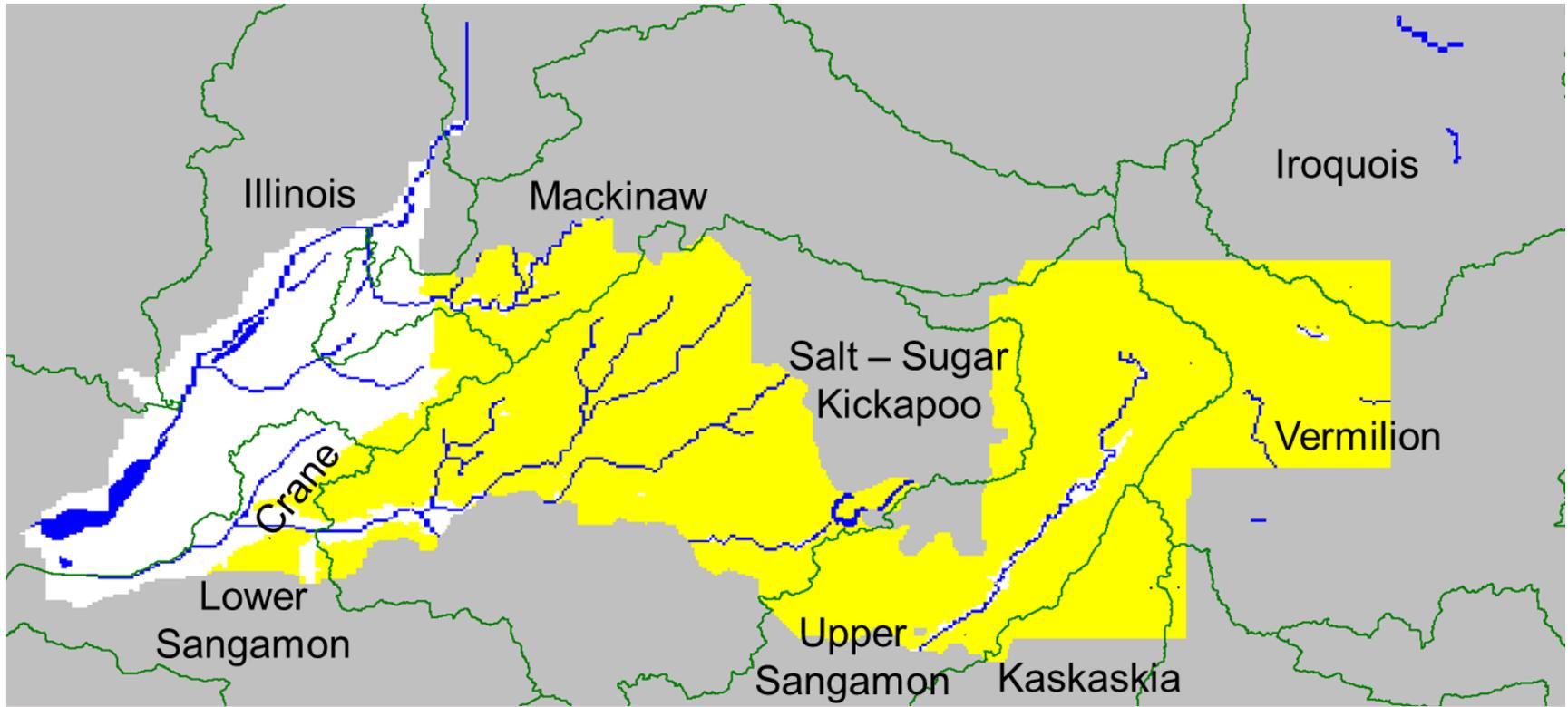
Figure 45. River cell (cyan) and drain cell (yellow) boundary conditions in layer 1 shown with the watershed outlines
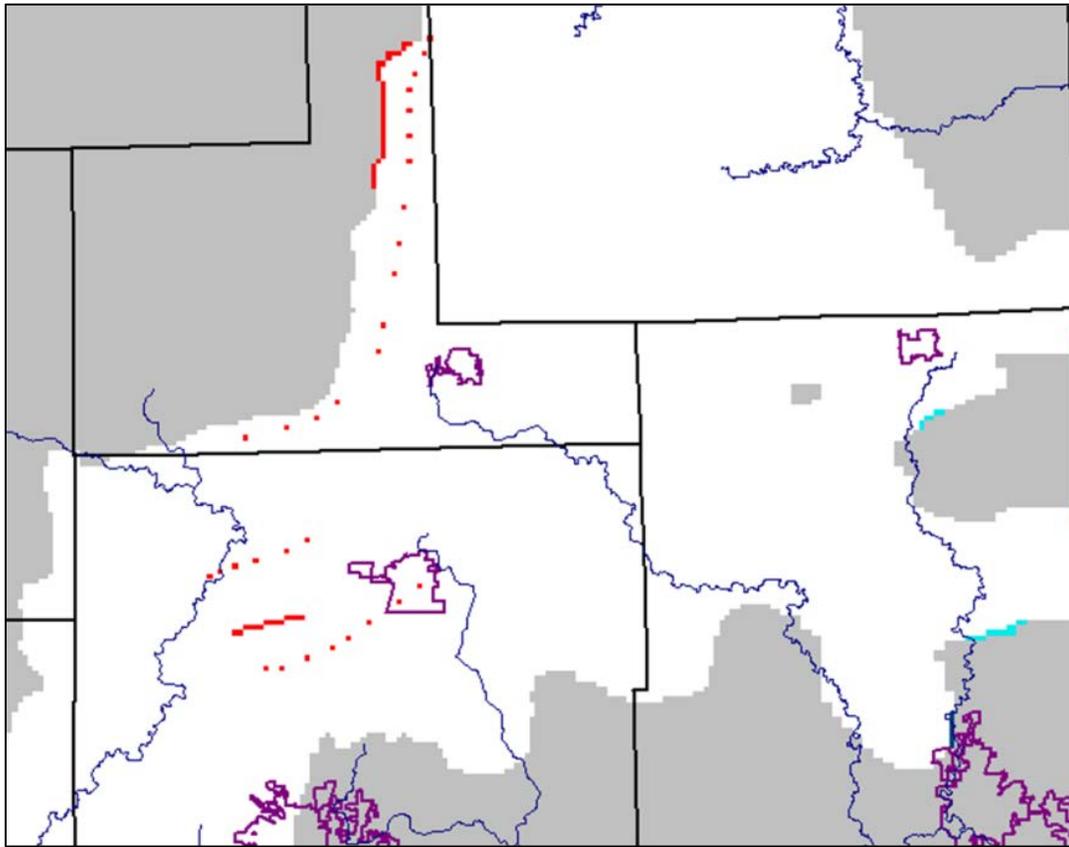
Figure 46. Constant flux (orange) and constant head (cyan) boundaries in model layer 7

The final values for hydraulic conductivity and recharge used in the model result from the calibration process and are presented in the calibration section below. Initial values for hydraulic conductivity and recharge came from the model by Wilson et al. (1998) and the estimates from the Havana Lowlands discussed earlier.

Model Calibration

Due to the transient effects of the increase in net recharge observed in the Havana Lowlands and the release of water from storage observed in the Champaign cone of depression, it was necessary to calibrate the model in transient mode. The initial time step for each model run was done using steady-state conditions to generate starting heads representing predevelopment conditions in 1930. The transient time steps then proceed in 10-year steps up to the year 2000. After 2000, a 5-year time step is used to the calibration year of 2005 and throughout the predictions out to the year 2050. To keep the model in sync with demand projections from WHPA (2008), the model calibration targets were assigned head measurements from 2005 and were supplemented with additional head measurements from the new observation wells constructed after 2005.

The model was calibrated by comparing predicted heads to observed heads in 133 observation wells distributed throughout the Mahomet Aquifer, 27 observation wells

in the Glasford Aquifer, and seven observation wells in the upper Glasford Aquifers. The mean residual error for the heads was 0.26 feet and the absolute residual mean error was 2.95 feet. The errors range from -10 to 8.6 feet. As shown in Figure 47, there were no large errors or systematic deviations from the 1:1 line. Because these errors are low compared to the 300-foot range in water levels and because of inherent errors associated with the observed heads, significant improvement to the head calibration is unlikely.
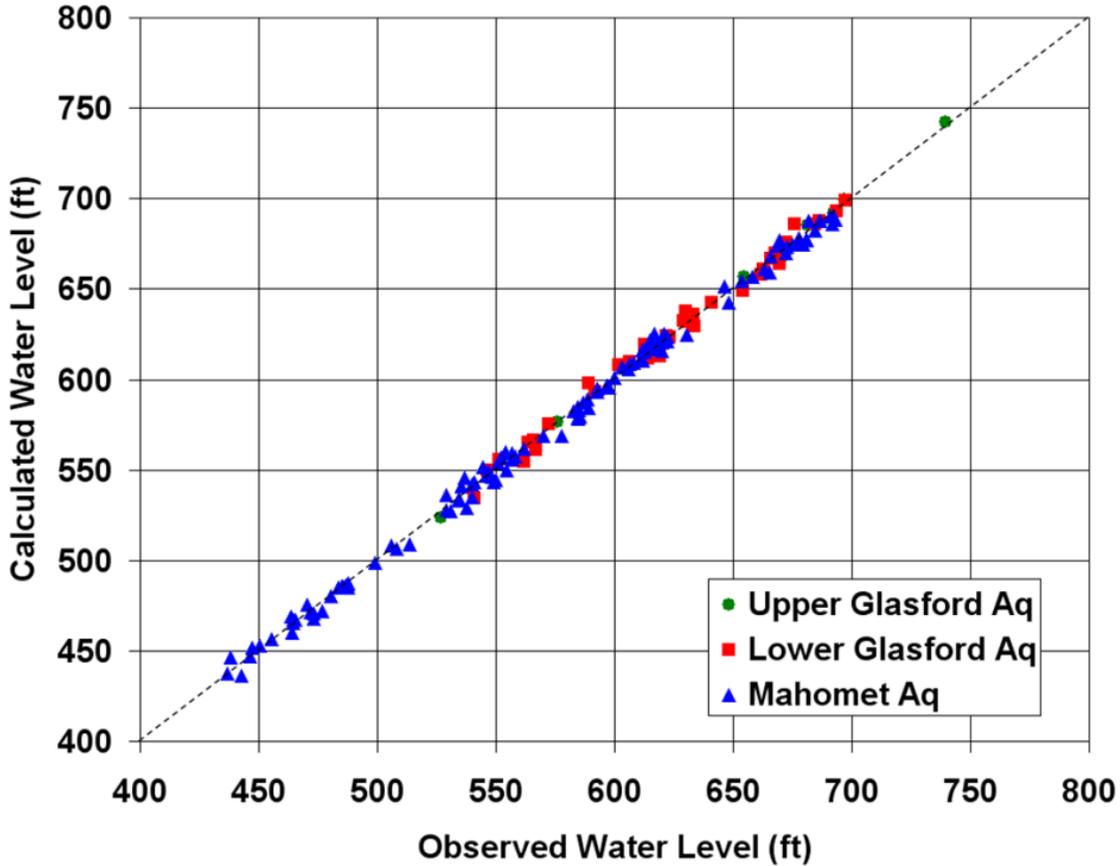
Figure 47. Calculated heads versus observed heads in the observation wells

The model fluxes were also calibrated by comparing the discharge of water in the model to the estimated baseflows for several watersheds that overlie the Mahomet Aquifer. As discussed earlier with the conceptual model, the target model discharges were assumed to be between the Q_{80} and Q_{50} flows in streams as defined by the Illinois Streamflow Assessment Model (ILSAM). The values from the ILSAM model were modified to account for the portions of each watershed that do not overly the Mahomet aquifer. The calculated 2005 flows fall within the baseflow targets for the upper Sangamon River and Salt Creek watersheds that cover most of the model area (Figure 48). The calculated fluxes for the Mackinaw River and Kaskaskia River watersheds are higher, but more uncertain due to the relatively small portion of the watersheds incorporated into the model (Figure 45).

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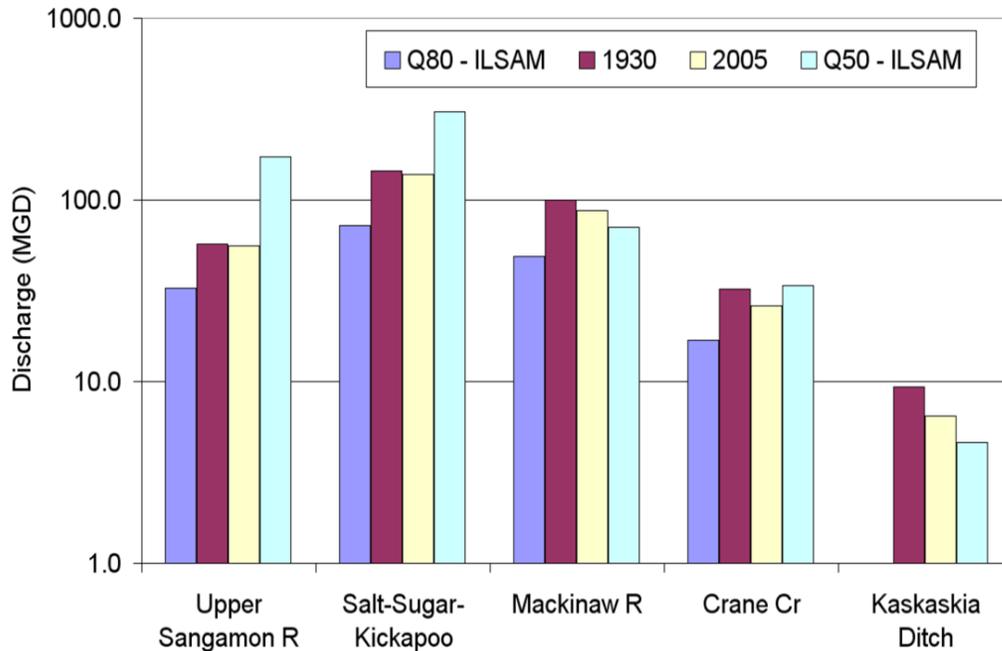
Figure 48. Calculated baseflows from the groundwater model and the ILSAM model

The calibrated hydraulic conductivities (K) for the principal hydrostratigraphic units in the model are listed in Table 3 and shown graphically in Figure 49 through Figure 54. The zonation of the hydraulic conductivities underwent small modifications in the calibration process based on new geologic or hydrologic evidence, such as new well logs or water level measurements. Because the different layers do not blanket the entire model, areas of a unit with zero thickness (1 foot in the model grid) were generally assigned the conductivity of the unit above except in the Havana Lowlands, where all the overlying units are absent. Three main areas where thicker zones exist with conductivity values that differ from the principal unit include the several small portions of the Mahomet sand in Champaign, DeWitt, McLean, and eastern Tazewell Counties; the Glasford till in eastern Mason and western Logan Counties; and the upper Glasford sands in Champaign County.

Table 3. Layer Scheme of the Mahomet Aquifer Groundwater Flow Model

Model Layer	Principal Hydrogeologic Layer	Hydraulic Conductivity K_x, K_z (ft/d)
1	Soil zone	0.01, 0.0015
2	Wedron Till	0.00036, 0.001
3	Upper Glasford sand	150, 20
4	Glasford Till	0.00036, 0.0001
5	Lower Glasford and Upper Banner sands	150, 35
6	Banner Till	0.00036, 0.00004
7	Mahomet–Sankoty Sands	275, 35

78
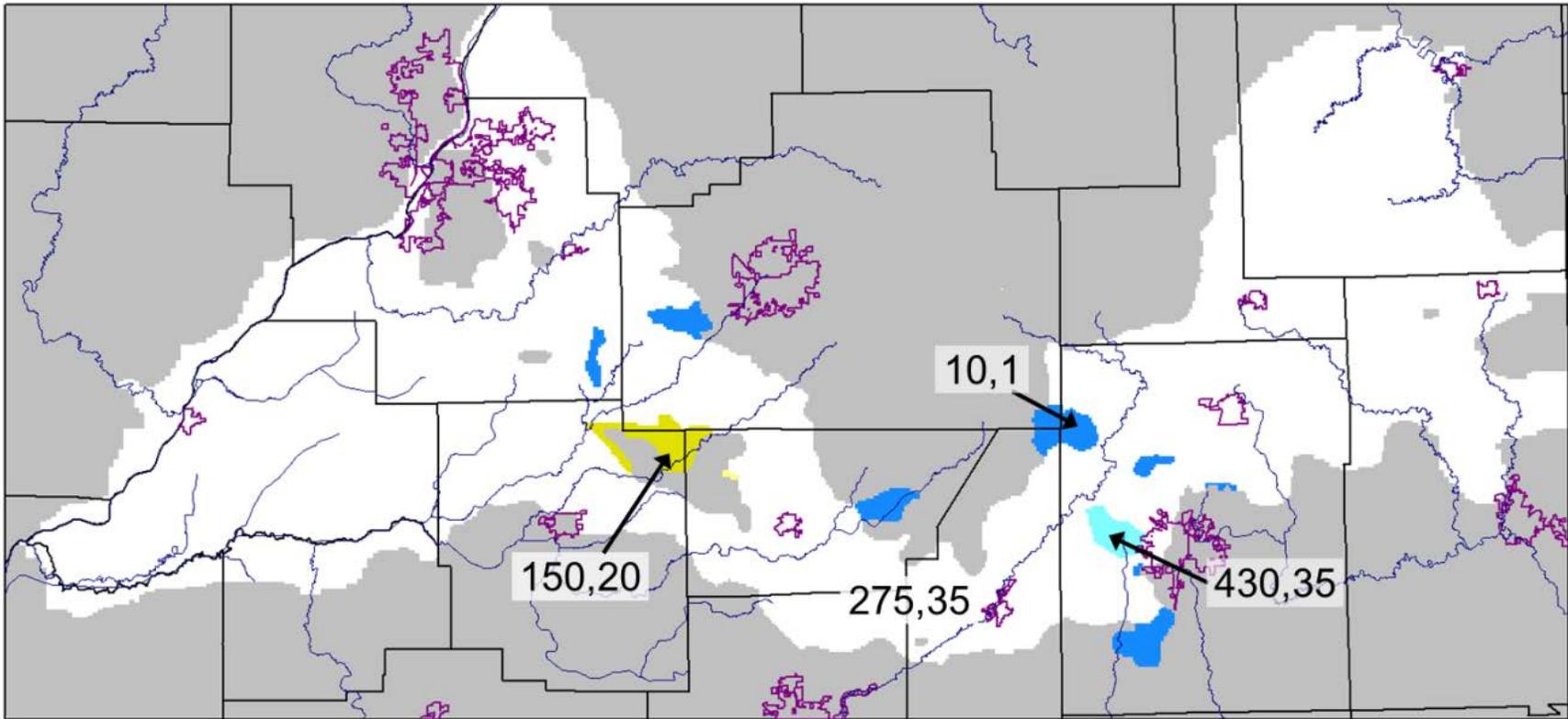
Figure 49. Hydraulic conductivities (Kx,Kz) of model layer 7 representing the Mahomet Sand (ft/d)
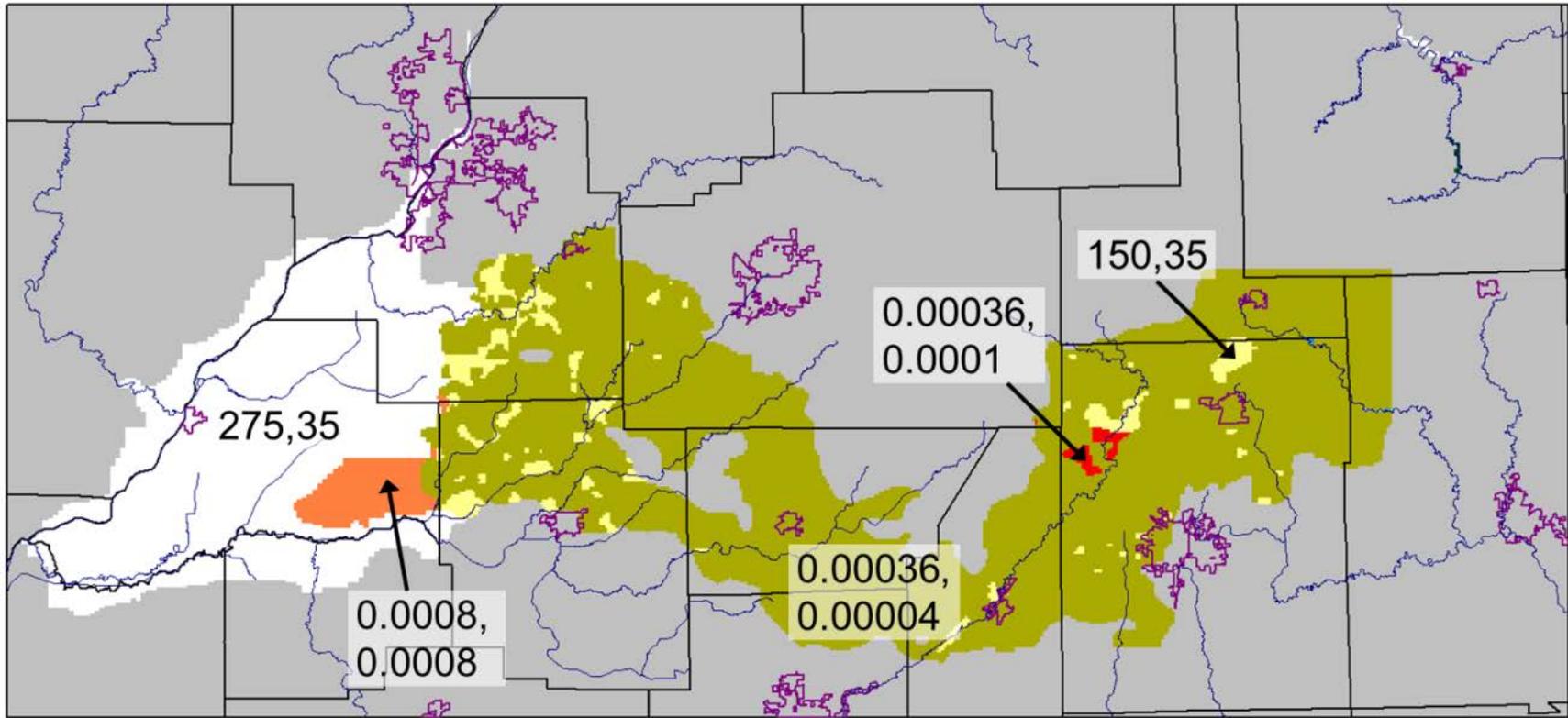
Figure 50. Hydraulic conductivities (Kx,Kz) of model layer 6 representing the Banner till (ft/d)
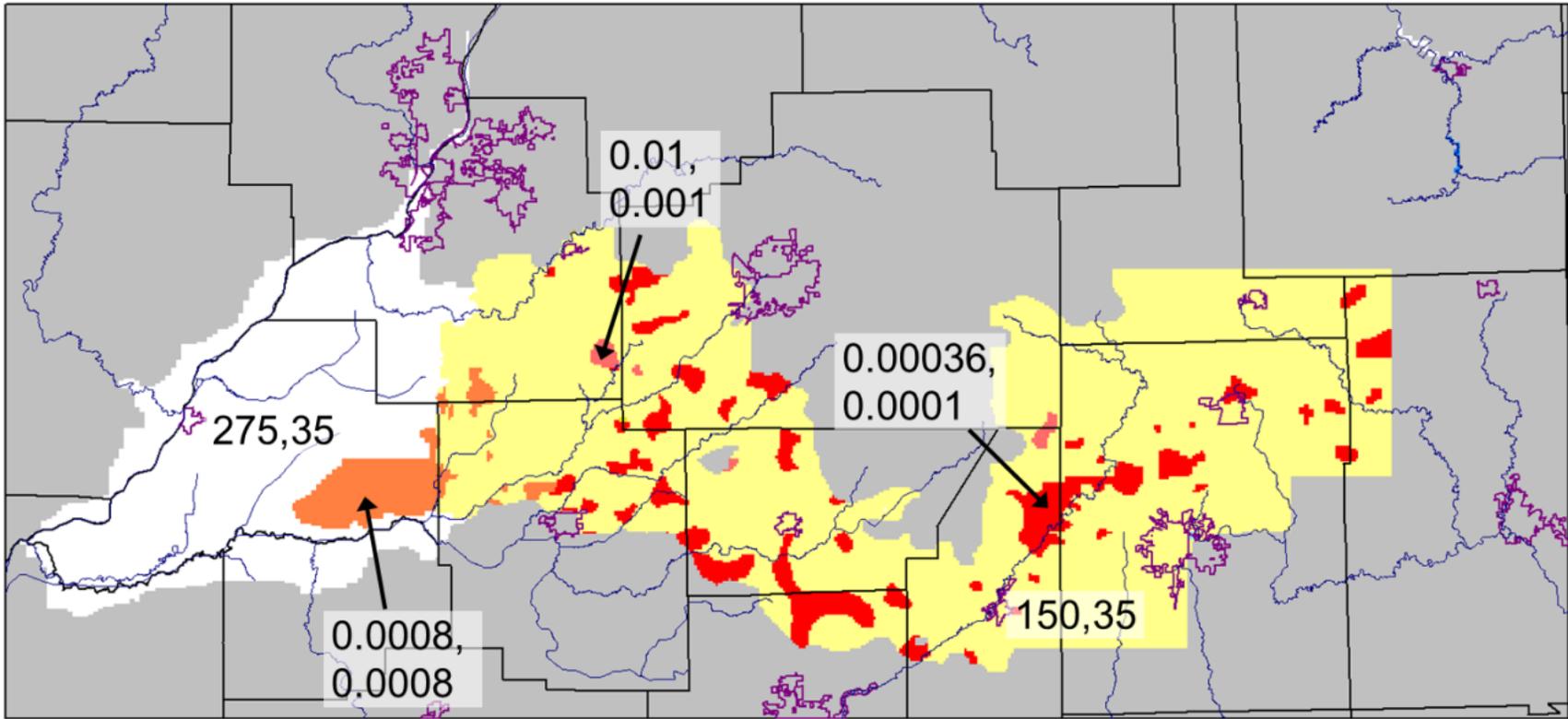
Figure 51. Hydraulic conductivities (Kx,Kz) of model layer 5 representing the upper Banner and lower Glasford sands (ft/d)
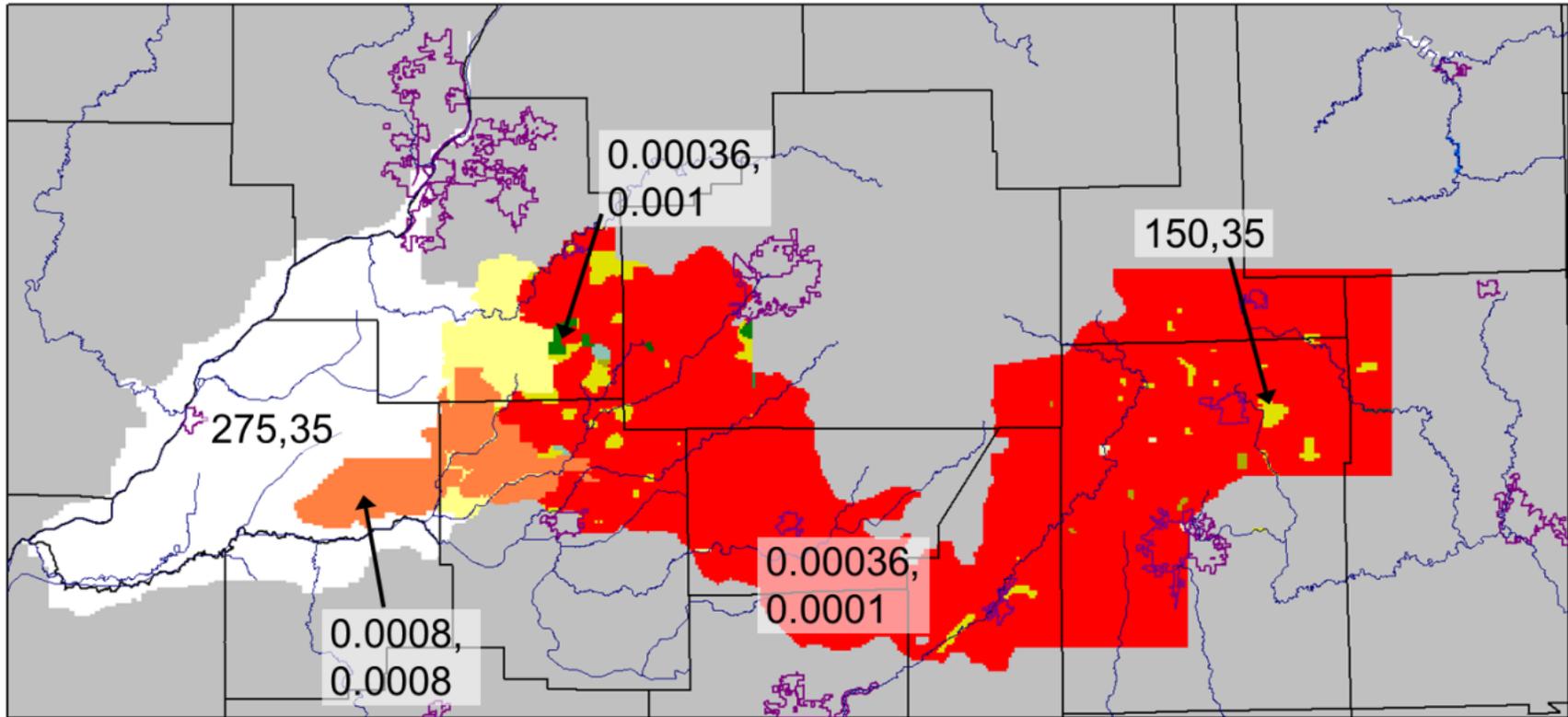
Figure 52. Hydraulic conductivities (Kx,Kz) of model layer 4 representing the Glasford till (ft/d)

0.00036,
0.001

150,35

0.1,0.1

1,1

275,35

0.0008,
0.0008

150,20
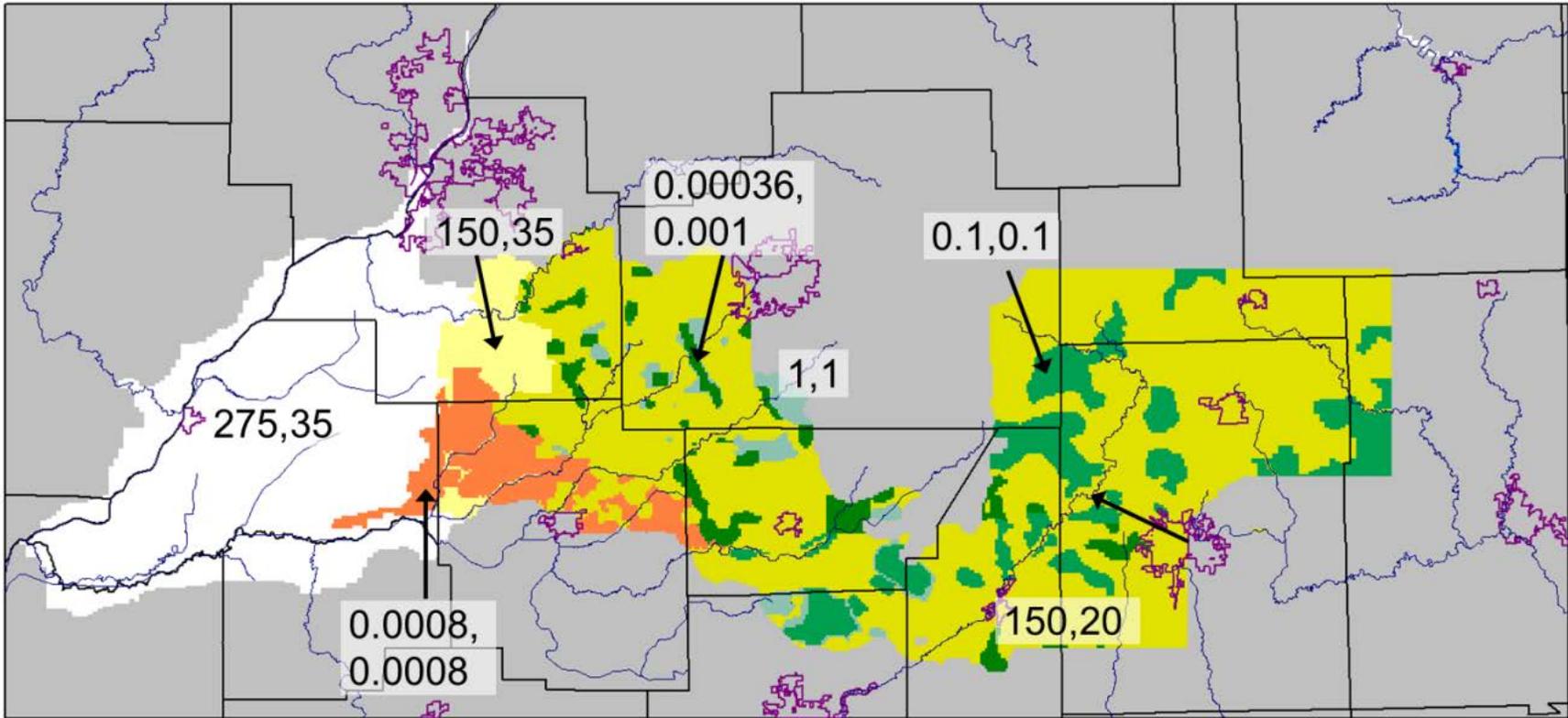
Figure 53. Hydraulic conductivities (Kx,Kz) of model layer 3 representing the upper Glasford sands (ft/d)

150,20

275,35

(0.00036, 0.001)
[0.01, 0.0015]

(0.0008, 0.0008)
[0.01,0.001]
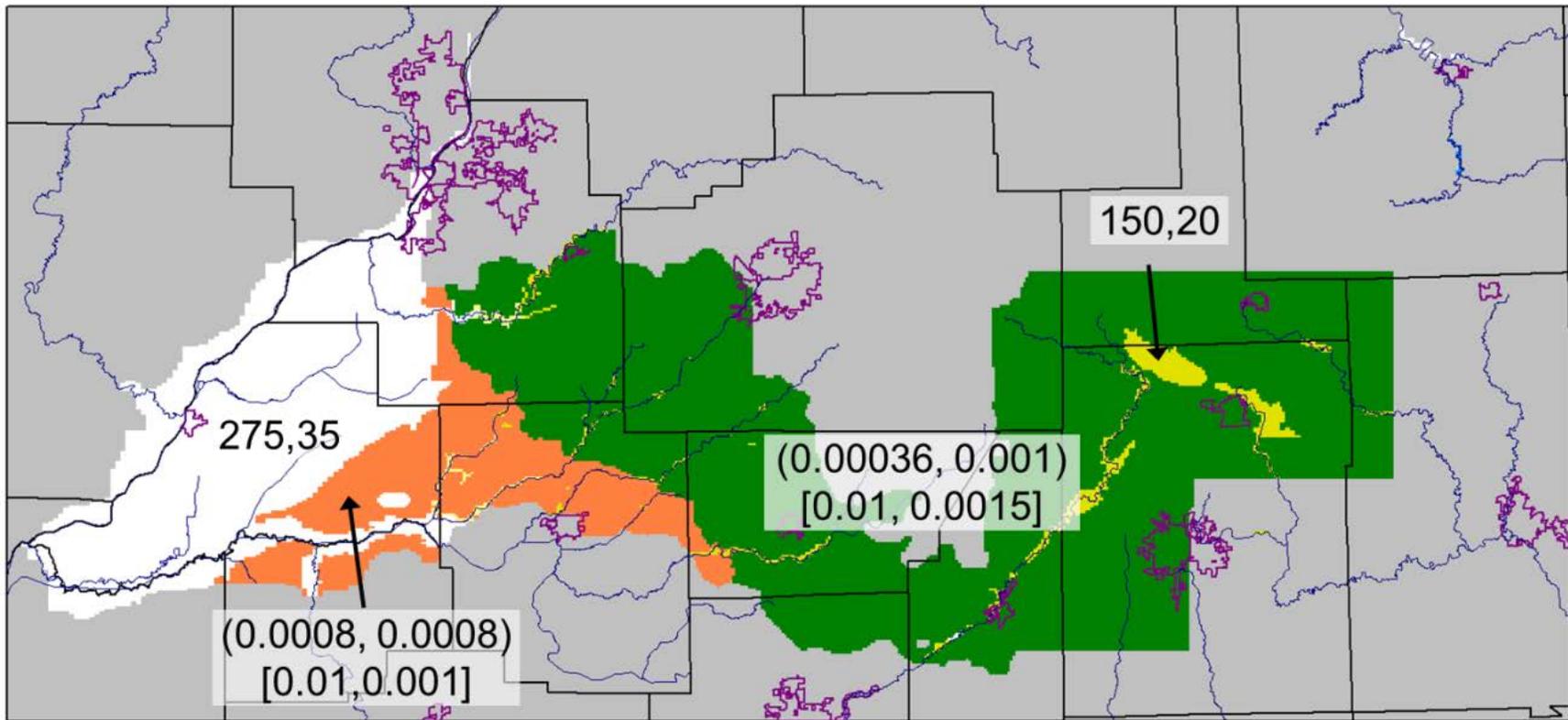
Figure 54. Hydraulic conductivities of model layers 1 [Kx,Kz] and 2 (Kx,Kz) representing the Wedron till and the soil zone (ft/d)

Hydraulic conductivity values were modified deterministically using the calibration results from Wilson et al. (1998) and Meyer et al. (2009) as guides. Changing the K_x value of 275 ft/d for the Mahomet sand from Wilson et al. (1998) did not improve model results and is negligibly different from the 304 ft/d geometric mean K_x of the aquifer tests. In addition to the lower K areas of the Mahomet Aquifer assigned by Wilson et al. (1998), low K areas were assigned to areas of Champaign County where the aquifer thins and there may be flow barriers. To most accurately represent the steepest portion of the Champaign cone of depression, a zone around the IAWC wellfield was assigned a higher K_x of 430 ft/d based on the aquifer tests. The K_x values for the upper sands were increased from the Wilson et al. (1998) values, but the model was not very sensitive to changing these values, as was the case for the Kane County model (Meyer et al. 2009).

The K_x of the buried tills were lowered slightly from the value of 0.0005 ft/d used by Wilson et al. (1998) to the value of 0.00036 ft/d used in the Kane County model. The K_z values were lowered below the values from both previous models. A lower value for the Banner till helped to keep heads from mounding up in the underlying Mahomet Aquifer in western Piatt, Macon, and eastern DeWitt Counties. The calibration process required higher K values for the Wedron till and the exposed Glasford till in Mason and Logan Counties. Higher K values were used in some of the absent areas of the sand layers because of uncertainty in the geology and to prevent mounding of the heads in areas where neither shallow sands exist. These tills are permeable enough to supply water to dug and bored domestic wells and may have higher K values due to weathering, fracturing, and/or large numbers of interbedded sand stringers. Calibrated values for the soil zone were also lower than those used in the Kane County model.

Recharge rates in the Havana Lowlands, as discussed earlier, need to change with pumpage to reflect the backwater effect from a rise in the Illinois River. Similarly, flooding along the Sangamon River and the Salt Fork in Champaign and Piatt Counties is also providing enough additional water to balance any drawdown in surficial sands prone to flooding or focused recharge. The calibration of the variable recharge rates in the model was conducted with transient simulations to match the long-term water level records and baseflow observations. These matches are shown with the model results discussed below. Attempts to use 2005 recharge rates in non-pumping simulations produced water levels that were above the land surface in the Havana Lowlands and more than 30 feet to 50 feet too high in Champaign. The calibrated rates for the dunal area of the Lowlands increased from 13 in/yr in 1930 to 20 in/yr in 2005 (Figure 55). Because irrigation growth is expected to decline in the future baseline demand scenario as all reasonably irrigable land becomes irrigated, the recharge increases to only 21 in/yr by 2050.

For the majority of the model surface, fixed recharge rates worked well in the model calibration. A value of 8.7 in/yr was used in the flat areas of the Havana Lowlands with heavier soils. For the strip of focused recharge along the east edge of the Lowlands, the calibrated value of 35 in/yr produced a good match to the relatively high baseflow values of the relatively small Crane Creek watershed (Figure 48). The Illinois River
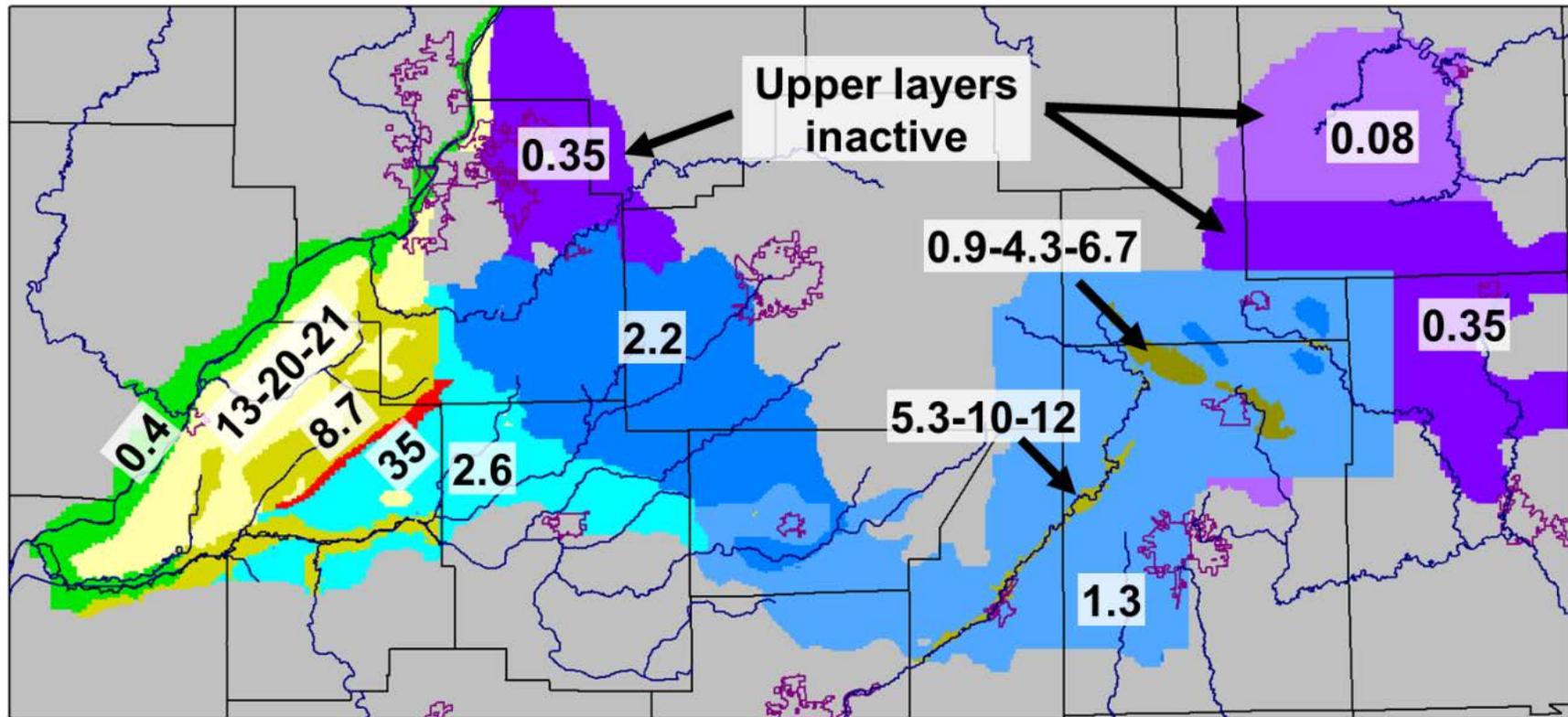
Figure 55. Recharge rates assigned to the flow model. Zones with three values indicate linearly varying values from 1930 –2005, 2005–2020, and 2020–2050 (in/yr).

floodplain was assigned a low value of 0.4 in/yr, although the model is not sensitive to the actual value because of the large number of river boundaries in this zone. A low value of 0.35 in/yr was assigned to northern Tazewell, Woodford, Vermilion, and southern Iroquois Counties where the upper layers of the model are inactive and the recharge is applied to the uppermost active layer (which happens to be the Mahomet Aquifer). The recharge value is almost zero in central Iroquois County where there is a blanket of low permeability lake deposits and flowing artesian conditions in many low-lying areas.

With the model set up to allow for excess recharge to the clay soils developed on the tills, the calibrated recharge rates of 1.3 in/yr to 2.6 in/yr have a greater impact on the baseflow calculations than the predicted heads in the aquifer. A more representative quantity of the effective amount of the recharge moving downward from the soil is the model calculated flux from layer 1 to layer 2 (Figure 56). The effective recharge rates in the till areas are substantially lower than the assigned values and vary widely depending of the vertical gradient and K_z across the till. The lowest effective recharge rates of less than 0.25 in/yr occur in areas where the upper Glasford Aquifer is absent, as seen by the similarities between Figure 56 and Figure 53. Lower effective recharge rates also occur along the thick moraines in Champaign County and along the moraines on the edge of the Wisconsinan glaciation in Tazewell and Logan Counties. In lower lying valleys the effective recharge rates were closer to assigned recharge rates. In the Kaskaskia River watershed the model calculated a baseflow decrease of 2.9 mgd (Figure 48), indicating that the lower aquifer heads have induced more recharge into the aquifer since the pumping in Champaign began. By letting the model calculate an effective recharge based on physical aquifer properties, head, and gradient, errors caused by injecting a recharge flux directly into a confining layer can be avoided. The sandy areas that do not have any drains receive the full amount of the assigned recharge rate. The blue areas indicate upflow to the rivers or where the model has upper Glasford sands pinching out, forcing the groundwater to upwell (Figure 56).

Projected Impacts of Current and Future Demands on the Mahomet Aquifer

The principal products of a groundwater flow model are predicted aquifer heads and flow budgets from different scenarios where conditions in the model are changed, such as pumpage, recharge, or river stages. For the purpose of water supply planning, model results for the five scenarios below are presented:

1) Predevelopment conditions (model verification)
2) 2005 conditions (model calibration)
3) 2050 conditions using the baseline (BL) demand scenario
4) 2050 conditions using the less resource intensive (LRI) demand scenario
5) 2050 conditions using the more resource intensive (MRI) demand scenario.

The potentiometric surfaces predicted by the model and the resulting drawdown maps made by subtracting these surfaces are shown in Figure 57 through Figure 63. The calculated 2005 map (Figure 57) closely matches the measured potentiometric surface maps (Figure 14 and Figure 18), as would be expected given the low calibration errors
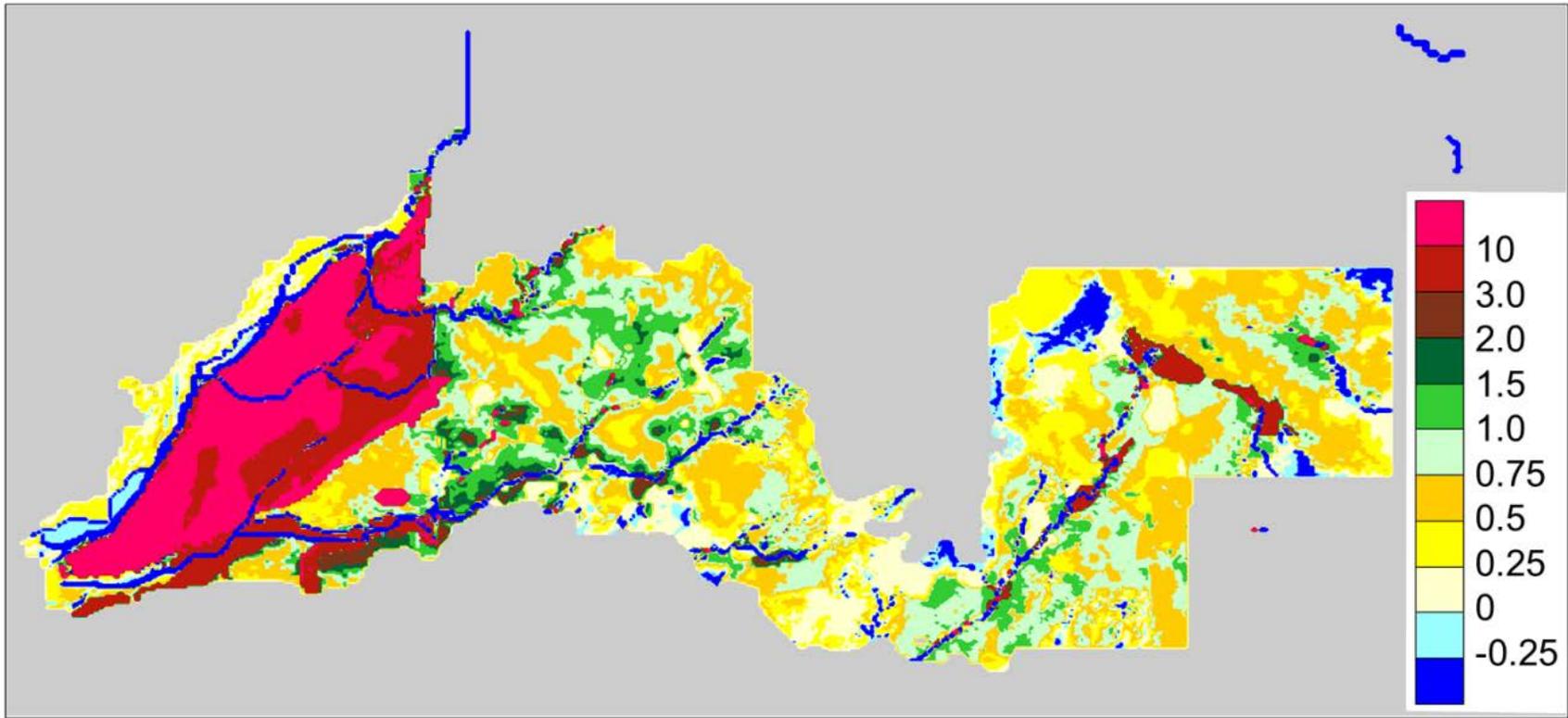
Figure 56. Calculated vertical fluxes from layer 1 to layer 2 displayed in units of in/yr

(Figure 47). The simulated predevelopment surface (Figure 58) shows what the potentiometric surface would look like without the pumping centers in Champaign, Normal, and Morton. Groundwater flow in Champaign County goes from the streams in the northern part of the county toward the Sangamon River in Piatt County.

The drawdown map from predevelopment conditions to 2005 conditions (Figure 59) shows the Champaign cone of depression and a relatively small amount of drawdown in the confined portion of the aquifer stretching from Clinton through Normal to Morton. The drawdown map matched field observations by showing no significant drawdown in the heavily irrigated Havana Lowlands. The predicted predevelopment heads generally match the estimated historical potentiometric surface for Champaign County (Figure 28a) that was based on the temporally scattered pre-1948 data from well logs. The predicted predevelopment heads are approximately 10 feet higher in the City of Champaign and along the upper reaches of the Sangamon River near Ford County, making the center of the modeled cone of depression 10 to 20 feet deeper than the estimated cone from the field measurements (Figure 28b). Differences in northwestern Champaign County suggest that the upper reaches of the Sangamon River may be providing more leakage to the groundwater system than was simulated in the model.

Running the model forward from 2005 to 2050 with the three future demand scenarios produced heads with additional drawdowns that mimic the historical drawdown (Figure 60 through Figure 63). In future scenarios, the variable recharge rates in the sandy areas were increased linearly to the rate shown on Figure 55 based on the pumpage for the baseline case. Thus, the ability of the wells in the MRI scenario to induce additional recharge will be limited so the drawdowns (Figure 63) will be slightly over predicted. Similarly, the drawdown in the LRI scenario (Figure 62) will be slightly under predicted. The only new areas to experience drawdown in the future simulations were around the wells in Ford County for the operating First Energy ethanol plant and around a hypothetical well for a proposed ethanol plant in Iroquois County (located on Figure 4). Hypothetical wells for the other three proposed ethanol plants in Pekin, Havana, and northern Logan County did not produce any mappable drawdowns over 5 feet.

The biggest predicted increases in drawdown were in the Champaign cone of depression and ranged from 8 feet for the LRI scenario to 31 feet for the MRI scenario at the Petro North observation well (Figure 64). Included on the hydrograph are the observed water level and the predicted heads from the 1930 to 2005 historical simulation. With the shift in pumpage by IAWC to the new wellfield west of Petro North, the center of the increased drawdowns are now directly over this long-term observation point. The Mahomet Aquifer remains under confined conditions with lowest head of 565 feet in the MRI scenario still 55 feet above the top of the Mahomet sand. On the northern side of the cone at Dewey the drawdown ranges from 0.5 feet to 5.8 feet, which is less drawdown than the well experiences during seasonal irrigation periods (Figure 65).
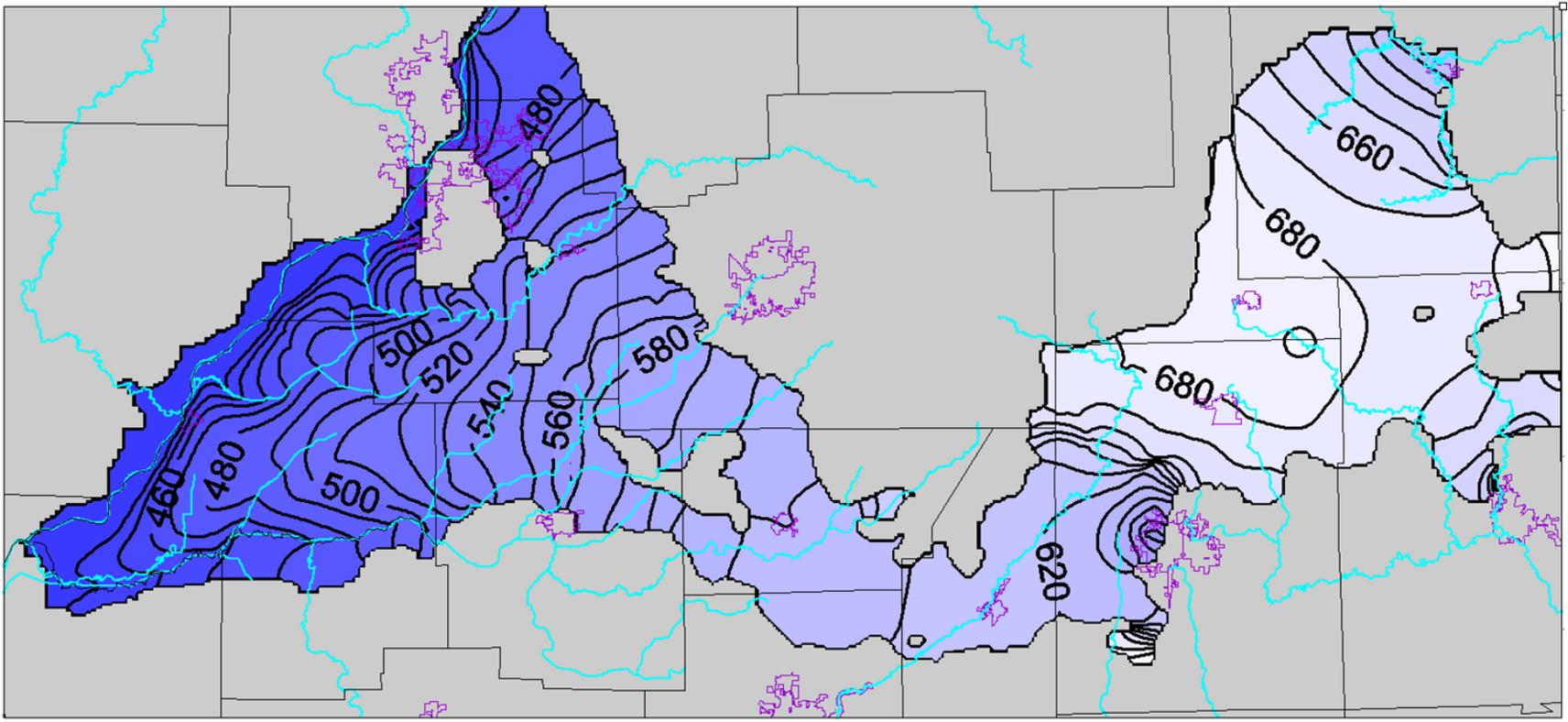
Figure 57. Predicted potentiometric surface for 2005 conditions
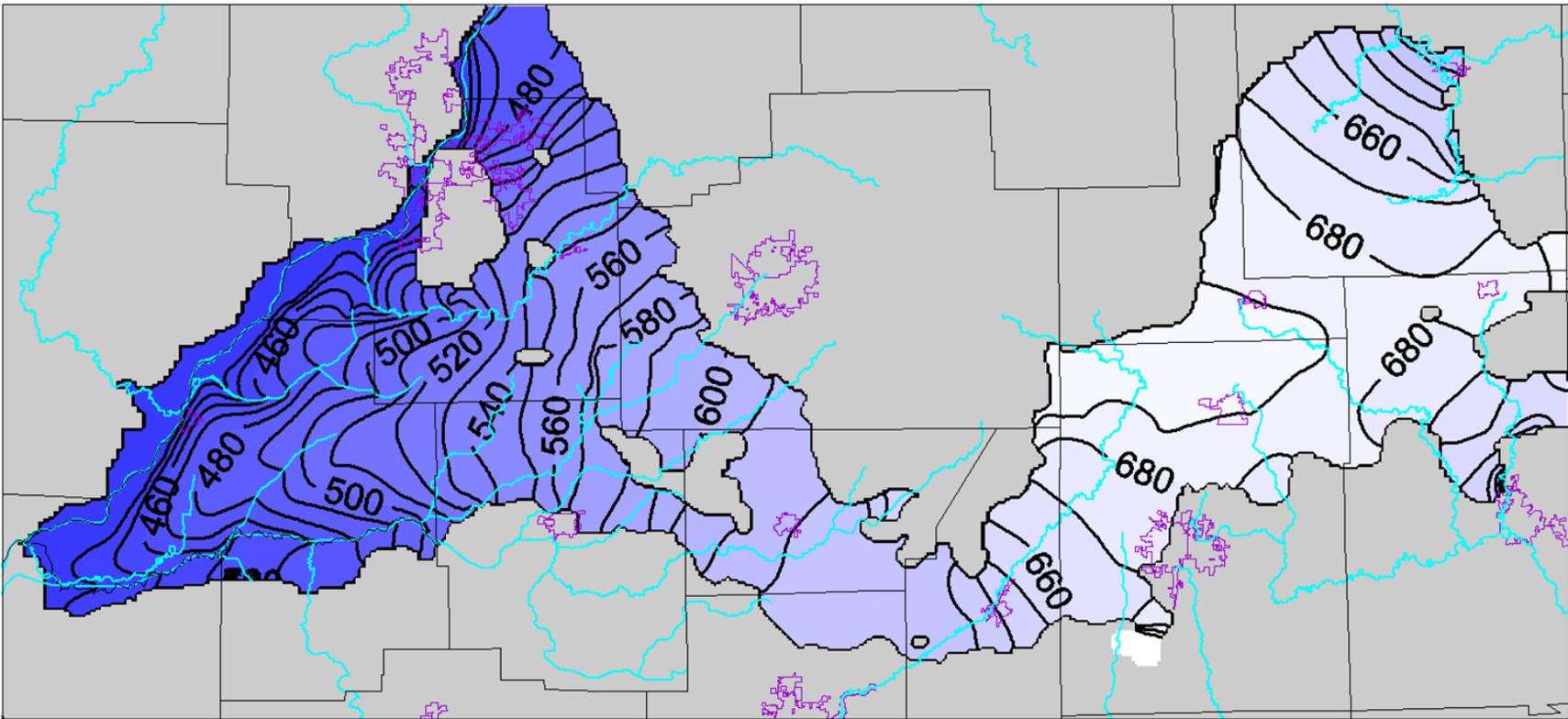
Figure 58. Predicted potentiometric surface for predevelopment conditions
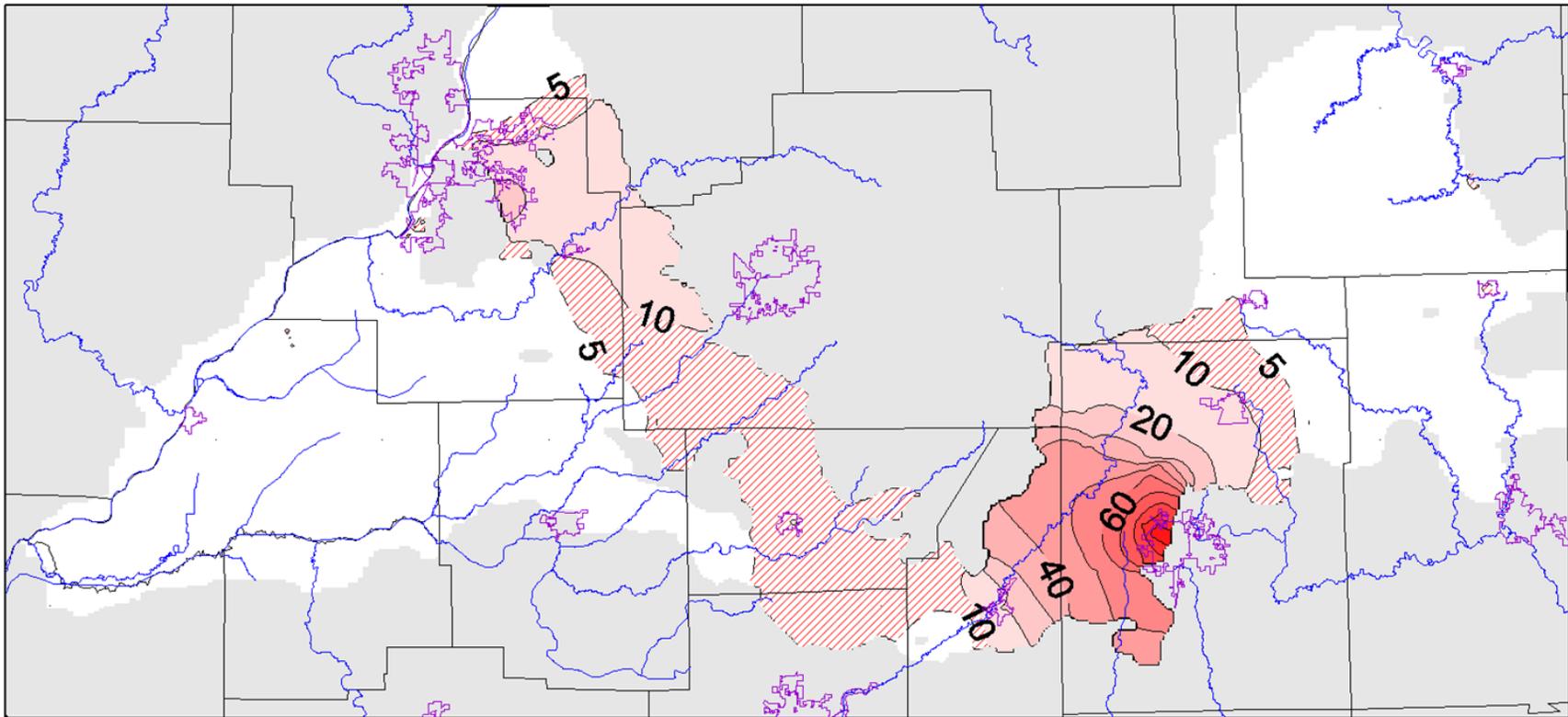
Figure 59. Predicted drawdown from predevelopment to 2005 conditions
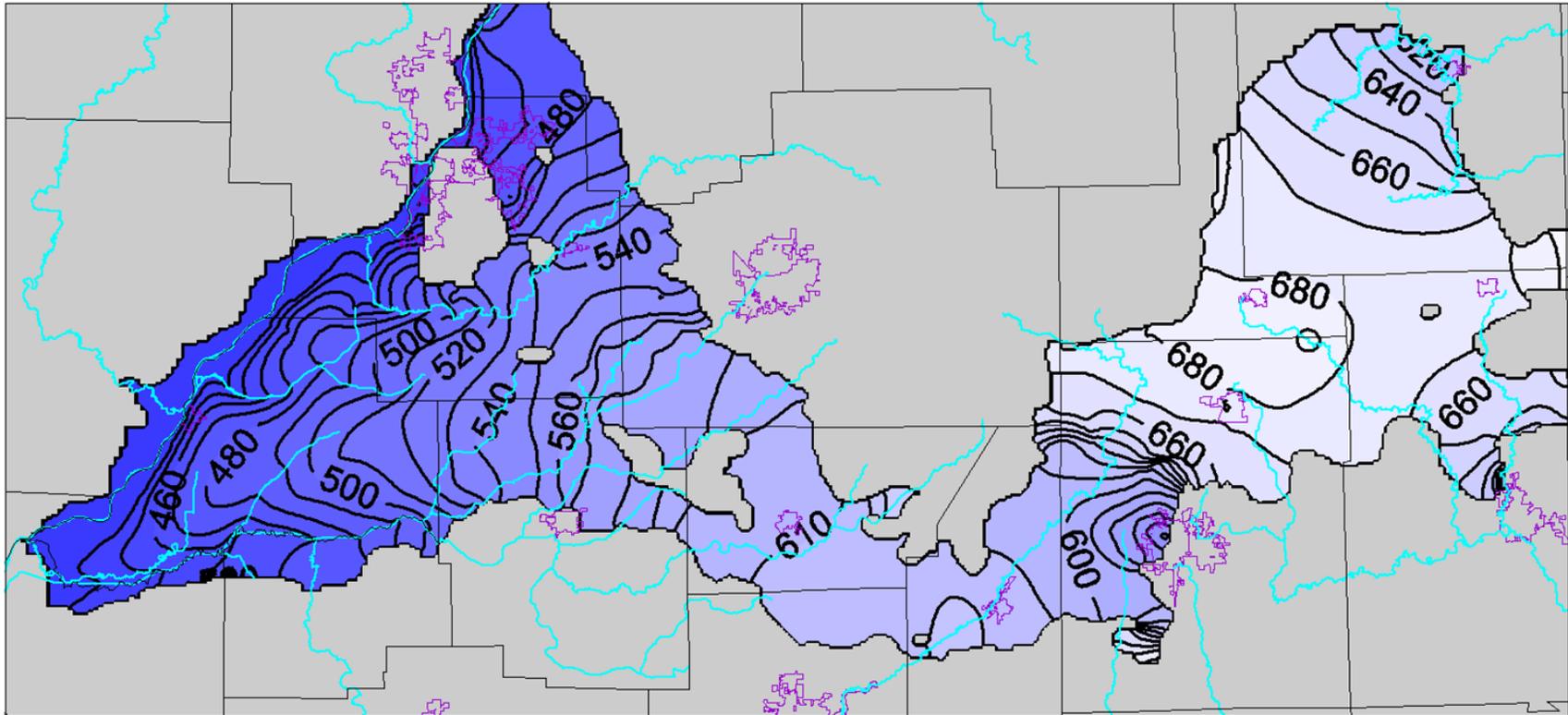
Figure 60. Predicted potentiometric surface for 2050 conditions with baseline demand projections
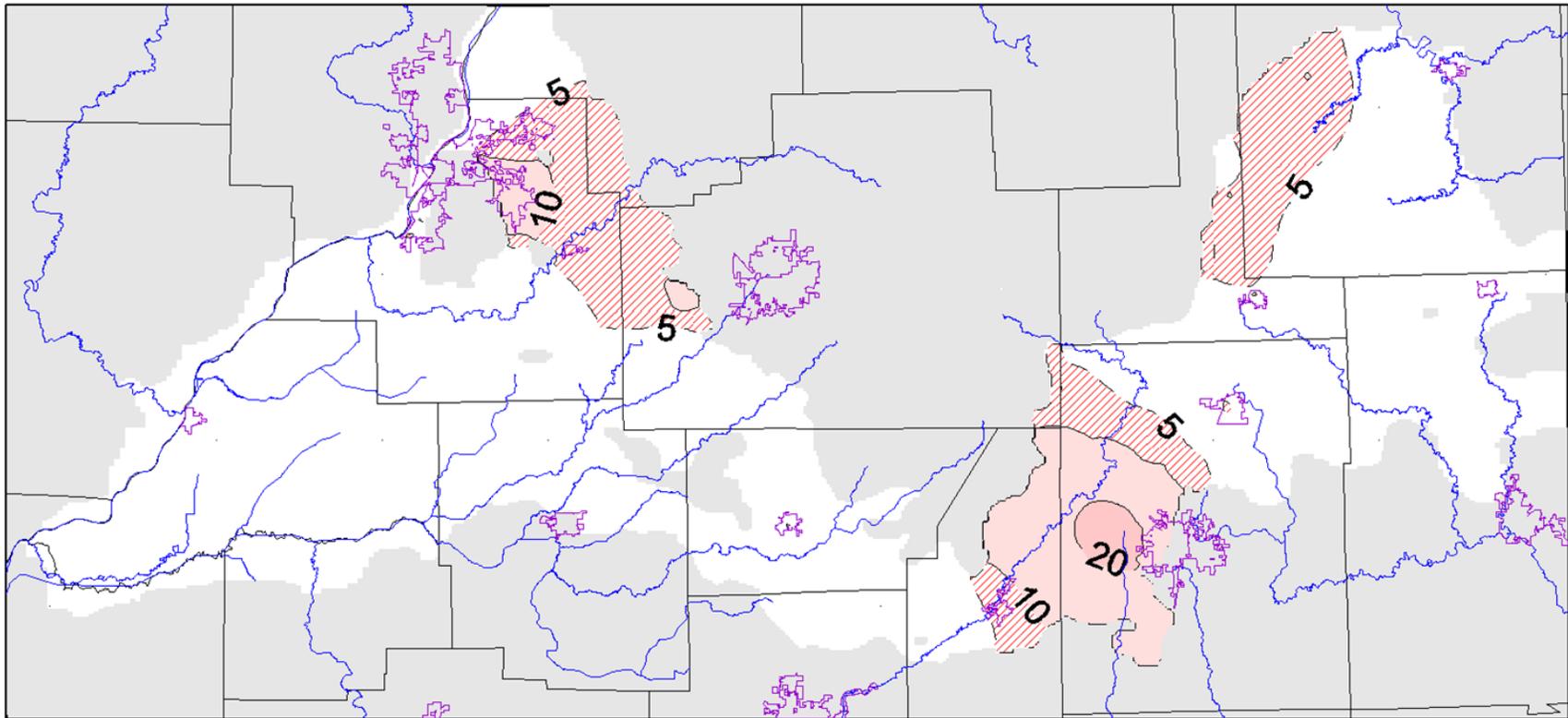
Figure 61. Predicted drawdown from 2005 to 2050 conditions using baseline demand projections
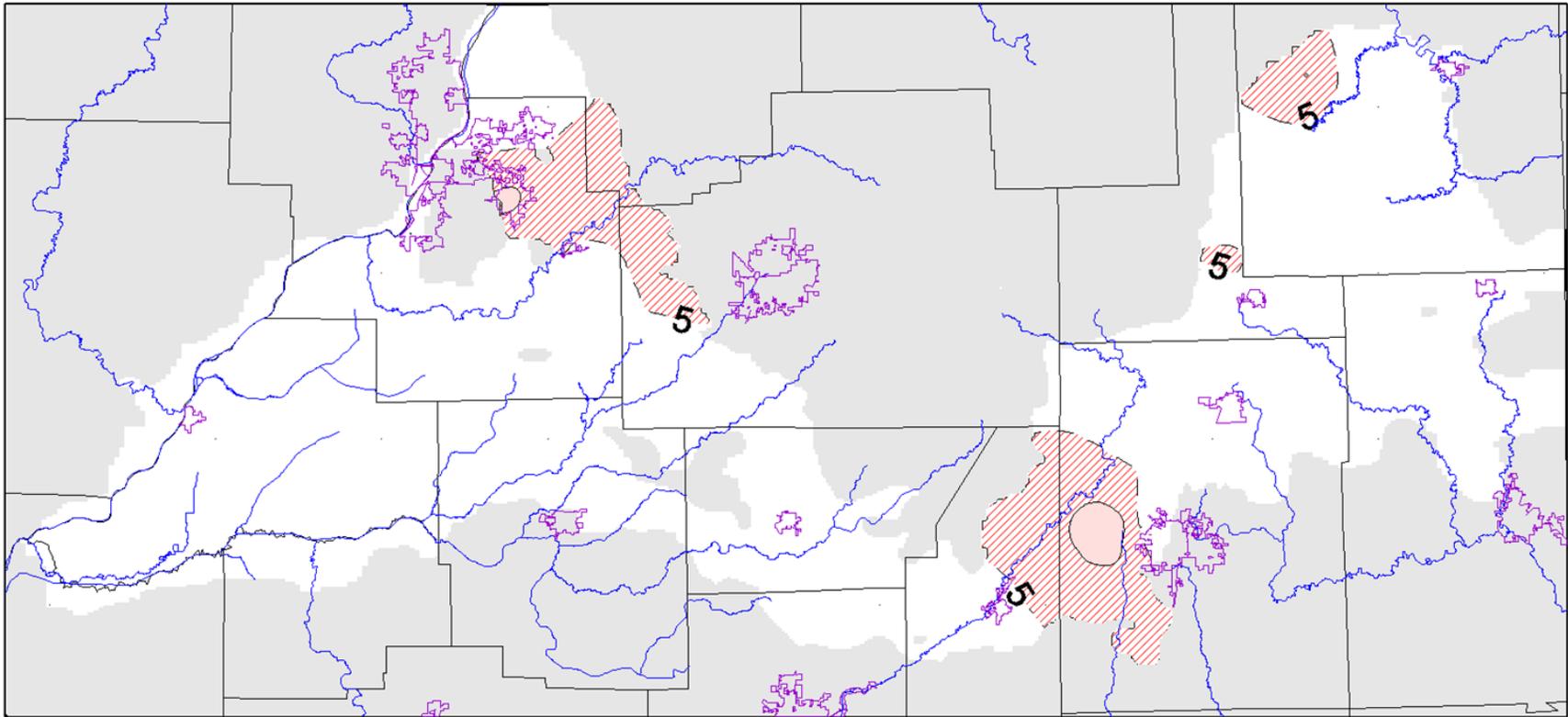
Figure 62. Predicted drawdown from 2005 to 2050 conditions using the less resource intensive demand projections
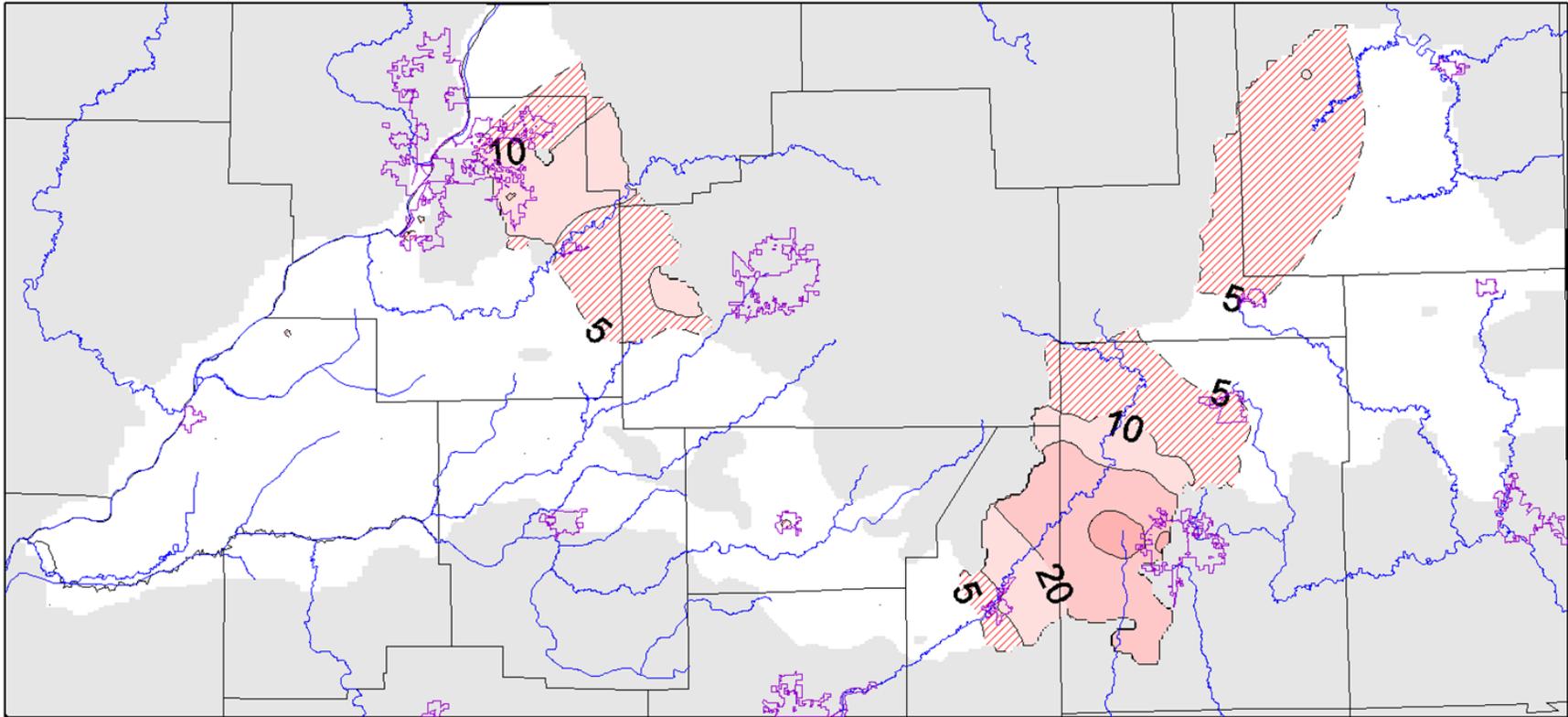
Figure 63. Predicted drawdown from 2005 to 2050 conditions using the more resource intensive demand projections
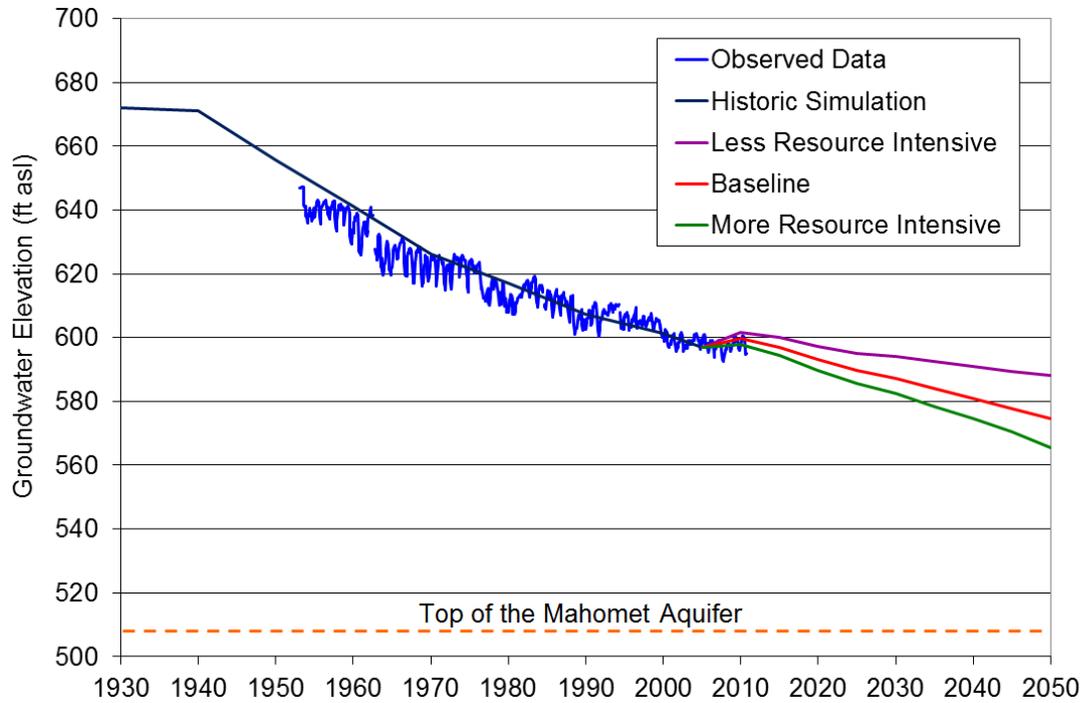
Figure 64. Predicted water levels at the Petro North observation well
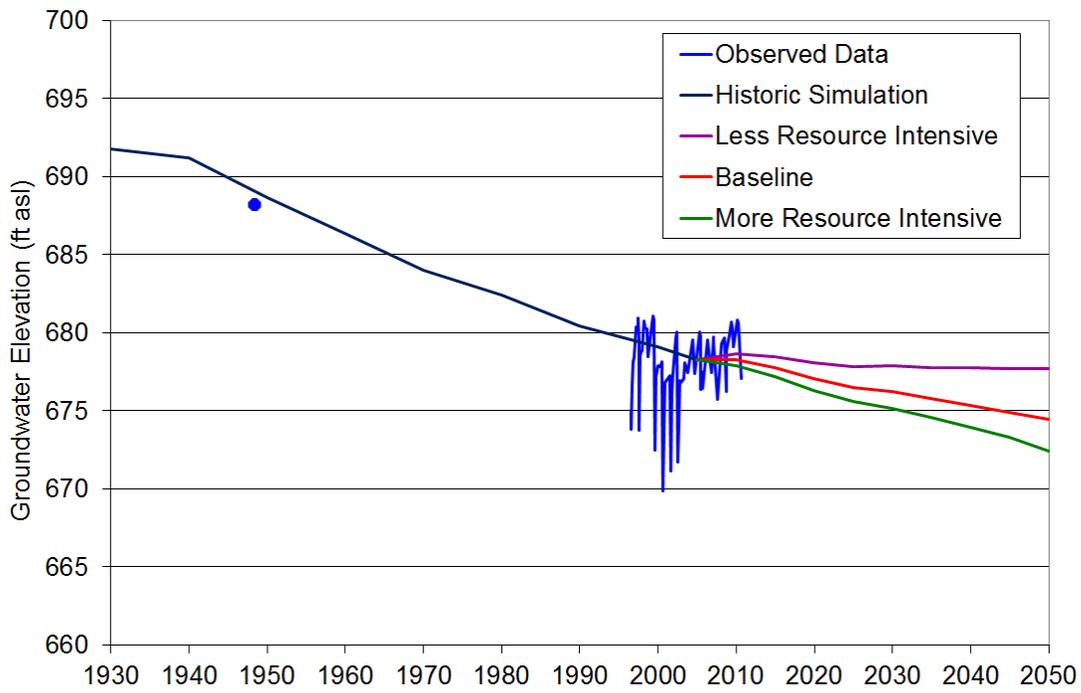
Figure 65. Predicted water levels at the Dewey (CHM-96A) observation well

Within the Champaign cone, drawdowns in the overlying Glasford Aquifer are predicted to increase by 14 feet to 26 feet at the Beckman observation well in northern Urbana near the shallow IAWC wellfield (Figure 66). The historical simulation approximates the heavy pumpage from this wellfield and the large resulting drawdowns that precipitated the construct of the production wells in the Mahomet Aquifer in the late 1940s. The modeled heads in the Glasford Aquifer produced a zone of partial saturation (Figure 67) that closely resembles the observed zone (Figure 29b). This zone is expected to expand by roughly a mile on all sides by 2050 with possible extensions farther to the west.

The flow budget for the Champaign region shows the increase in pumpage is being balanced by predominantly increasing recharge and decreasing discharge to streams (Table 4). Because of steeper gradients in the cone of depression, the total flow through the aquifer increased by almost 20 mgd between 1930 and 2005. The modeled baseflow discharge to the Sangamon River slowly dropped by 6.7 mgd during the historic simulation and then varies by less than 2 mgd out to 2050 (Figure 68). Analysis of the budgets for different river segments show that most of this modeled loss is occurring downstream of Monticello, a result consistent with the lack of observed baseflow depletion above the USGS gauge. The remaining 3.2 mgd of baseflow loss comes from the Salt Fork and the Middle Fork of the Vermilion River. Because the pumping rate is growing at a slower rate in later years, the amount of water released from storage decreases. Figure 69 shows sources of water contributing to the supply to meet the increased demand as conceptualized on Figure 3b. To balance the 38.6 mgd increase in the 2050 baseline demand, 25.8 mgd of new supply has entered the aquifer that was previously lost as flood waters or evaporation.
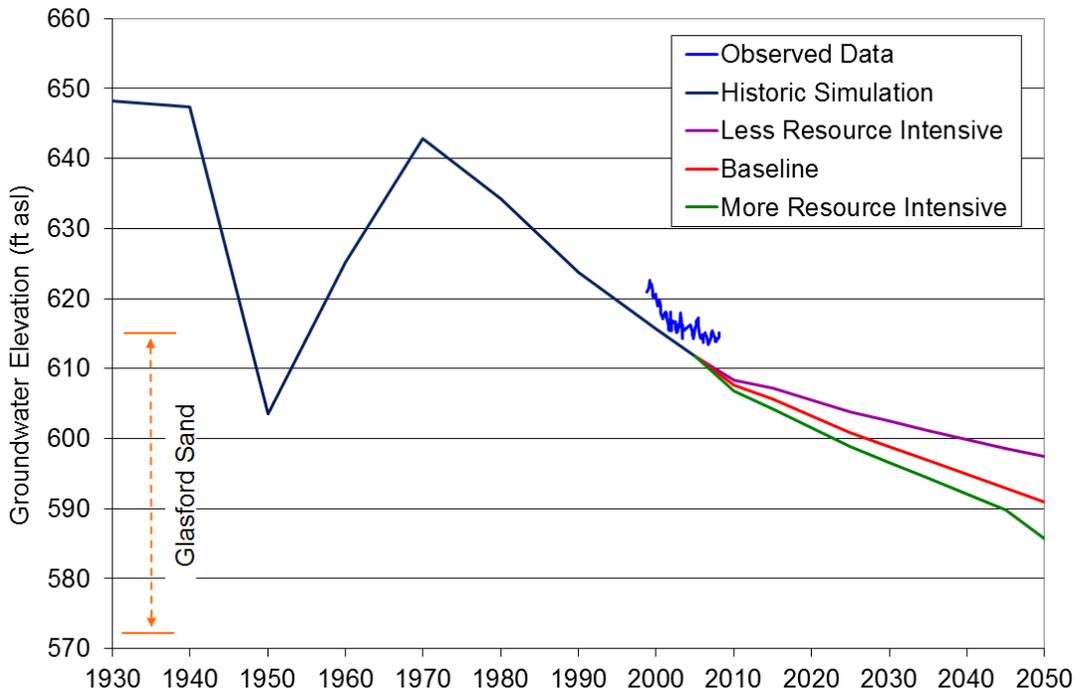
Figure 66. Predicted water levels at the U of I Beckman Institute observation well
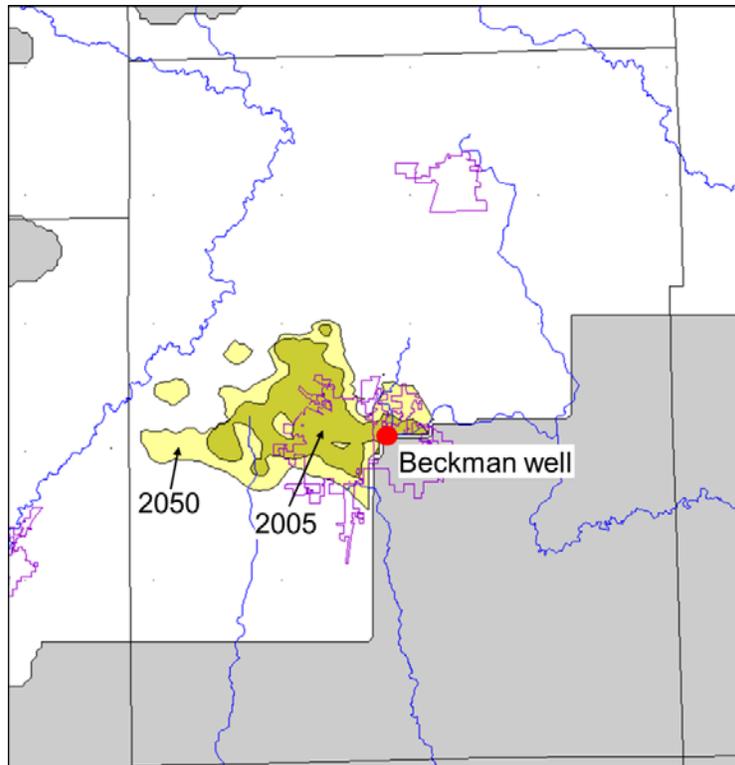
Figure 67. Projected growth of the zone of partial saturation in the Glasford Aquifer within the Champaign cone of depression under baseline conditions

Table 4. Flow Budgets for the Champaign Region for the Historic and the Baseline Simulations (mgd)

		1930	2005	2050
Inflows	Storage	0.0	3.2	1.7
	Bedrock	1.0	4.0	5.4
	Recharge	73.9	86.9	93.7
	Total	75.0	94.2	100.8
		1930	2005	2050
Outflows	Rivers	-66.5	-56.6	-54.1
	Wells	-3.1	-32.4	-41.7
	Lateral Flow	-5.4	-5.2	-5.0
	Total	-75.0	-94.2	-100.8

In McLean and eastern Tazewell Counties, the impact of increasing demand from the current wells out to the year 2050 is not very great. At observation well MTH-21 next to Sugar Creek (located on Figure 39), the modeled historical drawdown of 6.6 feet is within the observed fluctuation of 14 feet (Figure 70). The predicted heads at this well are expected to drop another 2.4 feet to 4.2 feet. Further north at observation well MTH-9, the modeled historic drawdown is 9.6 feet with another 4.2 feet to 7.2 feet of drawdown expected in the future (Figure 71).
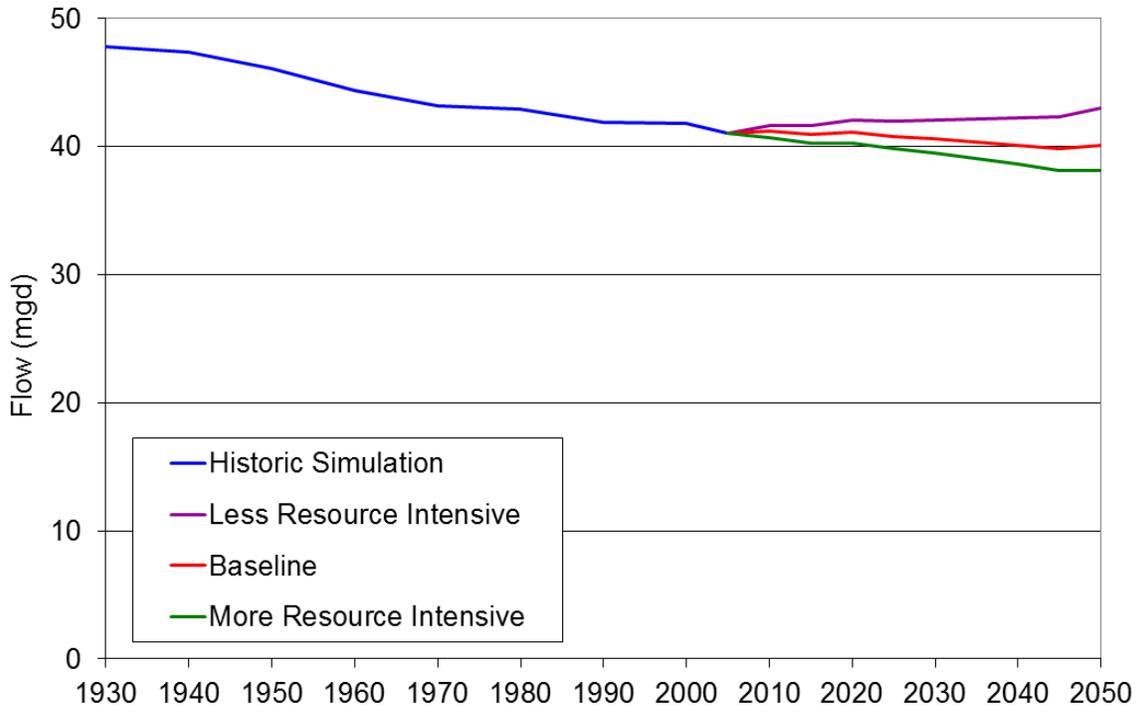
Figure 68. Predicted baseflow discharge to the upper Sangamon River
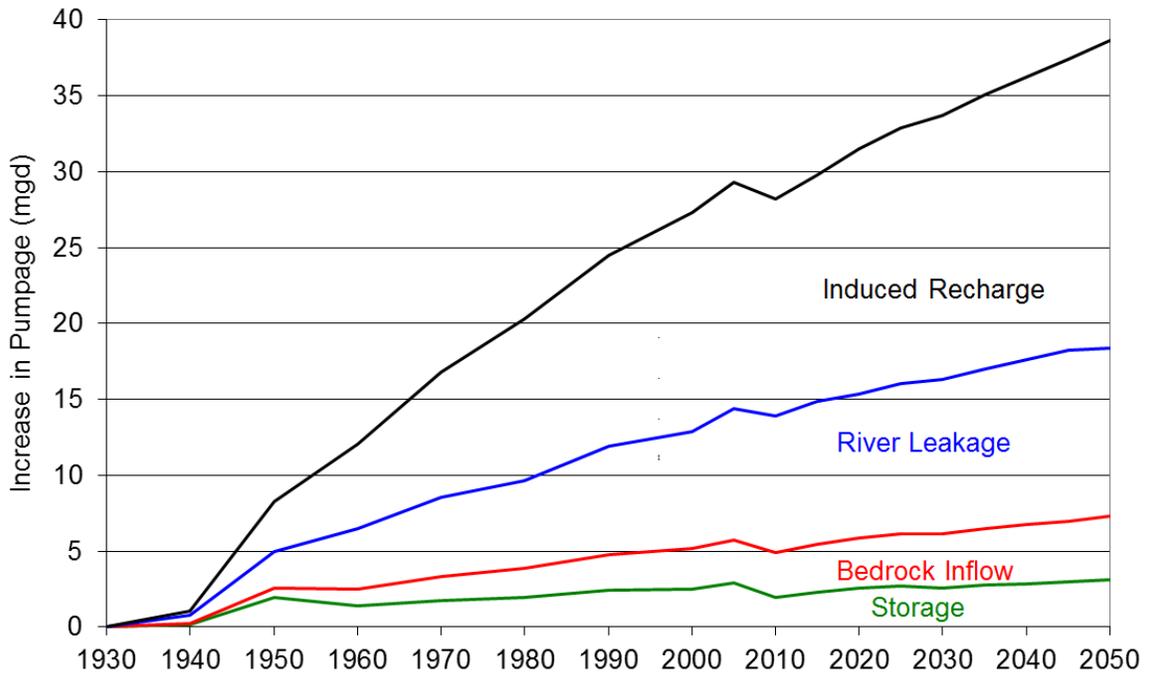
Figure 69. Sources of water balancing the increase in demand in the Champaign region
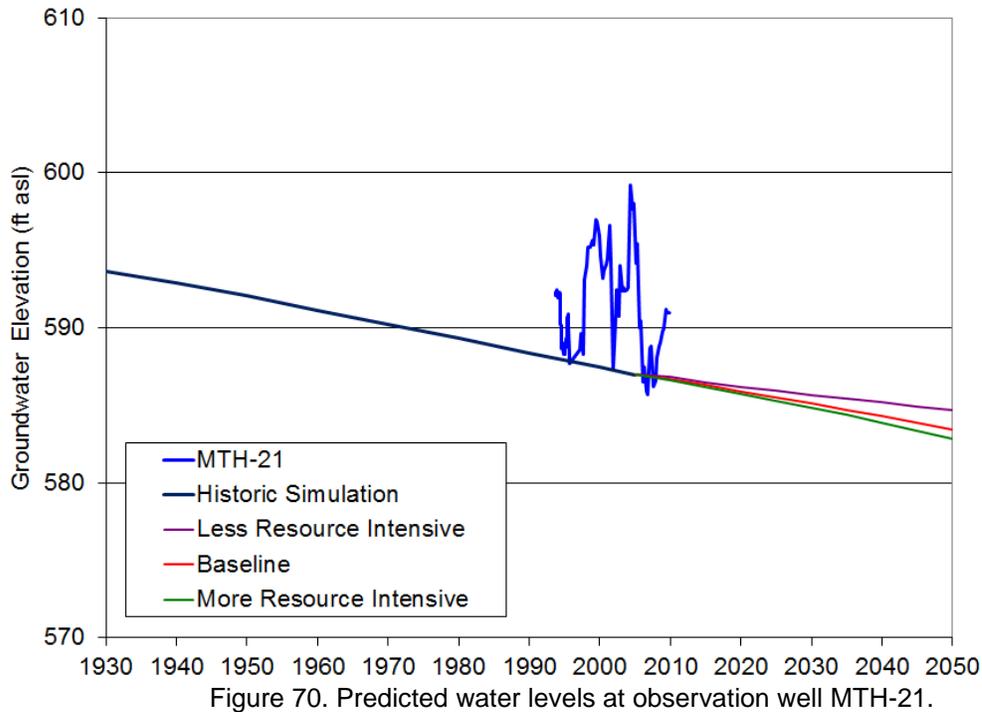
Figure 70. Predicted water levels at observation well MTH-21.

Model heads in the Havana Lowlands remain steady throughout the simulations as shown by the hydrographs of the Easton and Snicarte observation wells (Figure 72 and Figure 73). The natural fluctuations in heads are much greater than the decline in head caused by the growth in irrigation. Using a monthly time step in the model would show a greater seasonal impact, but the net long-term effect would not be any greater. The large volume of groundwater being removed from the aquifer lowers the modeled discharge to Crane Creek by up to 5.5 mgd, or 25 percent, for the baseline scenario (Figure 74). Because Crane Creek is a dredged drainage ditch, how it is maintained in the future will likely exert the most control on baseflow. If the ditch was filled in, much of the area would return to being an ephemeral groundwater lake. Taken together, the water level and baseflow results suggest that pumpage in the Havana Lowlands could be many times higher without a significant regional impact.

The total mass balance of the model is shown Table 5 for historic conditions (i.e., 1930), 2005 conditions, and 2050 conditions using the baseline demand scenario. Recharge is the dominant source of water into the model, increasing by 150.2 mgd over the 120-year simulation. Bedrock inflow is modeled to increase by 5.9 mgd. Water released from storage is initially zero because the first model time step for the historic simulation is steady-state. The rate of release of water from storage decreases slightly from 2005 to 2050 because the rate of change in pumpage per time step also decreases slightly. The largest groundwater outflow is the discharge to the major streams which decreases by 97.2 mgd (446.3 - 348.1 mgd) as 262.1 mgd (265.2 - 3.1 mgd) of water is diverted to the wells. Discharges to small tributaries and ditches through the drains remain relatively unaffected by changes in pumpage during the simulation. The total flow through the model increases by 162 mgd over the simulation.

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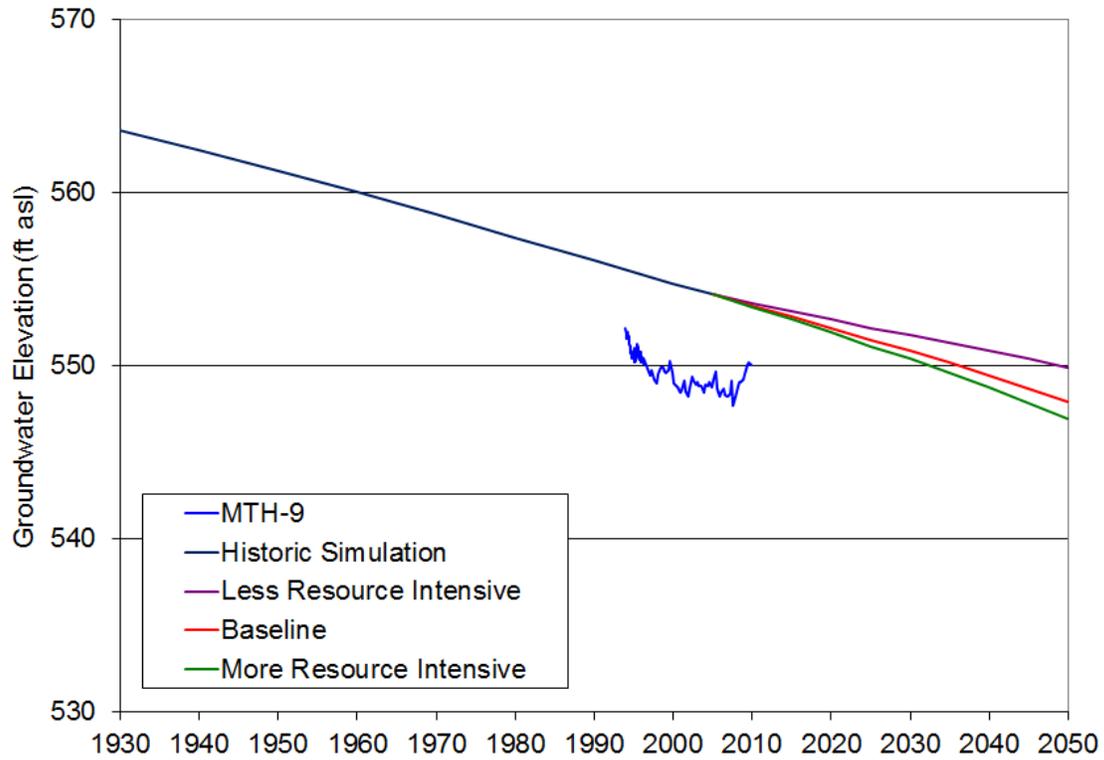
Figure 71. Predicted water levels at observation well MTH-9
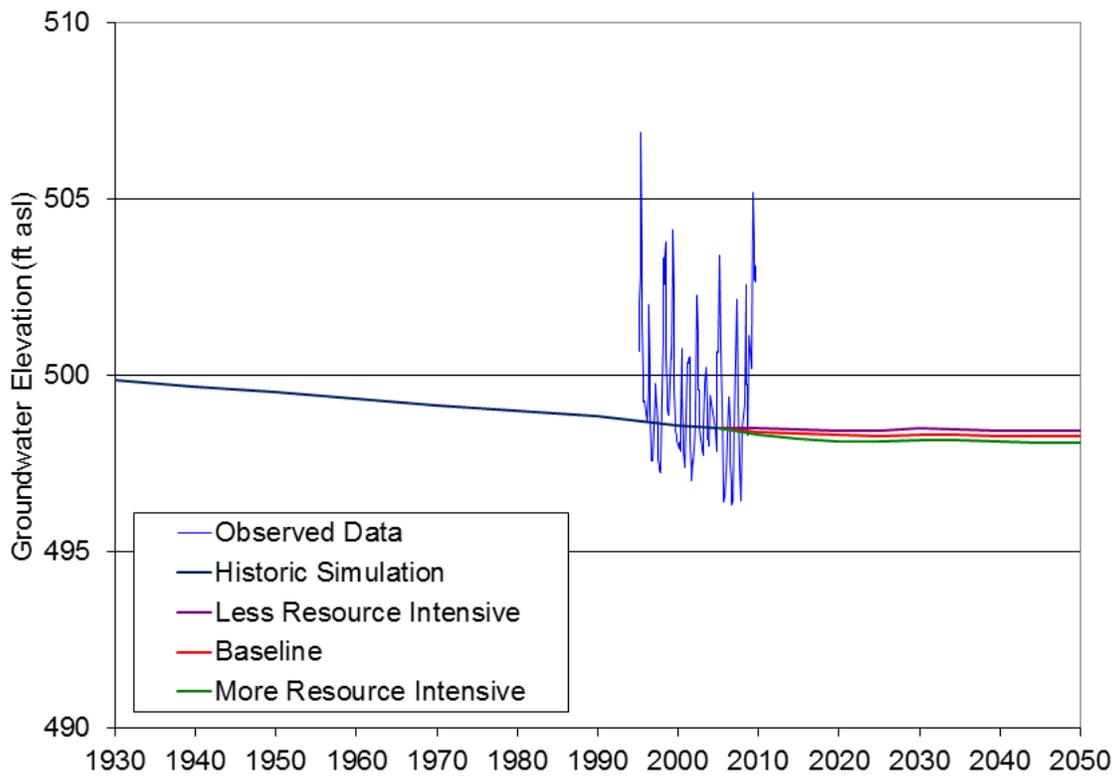
Figure 72. Predicted water levels at the MTOW-2 Easton observation well

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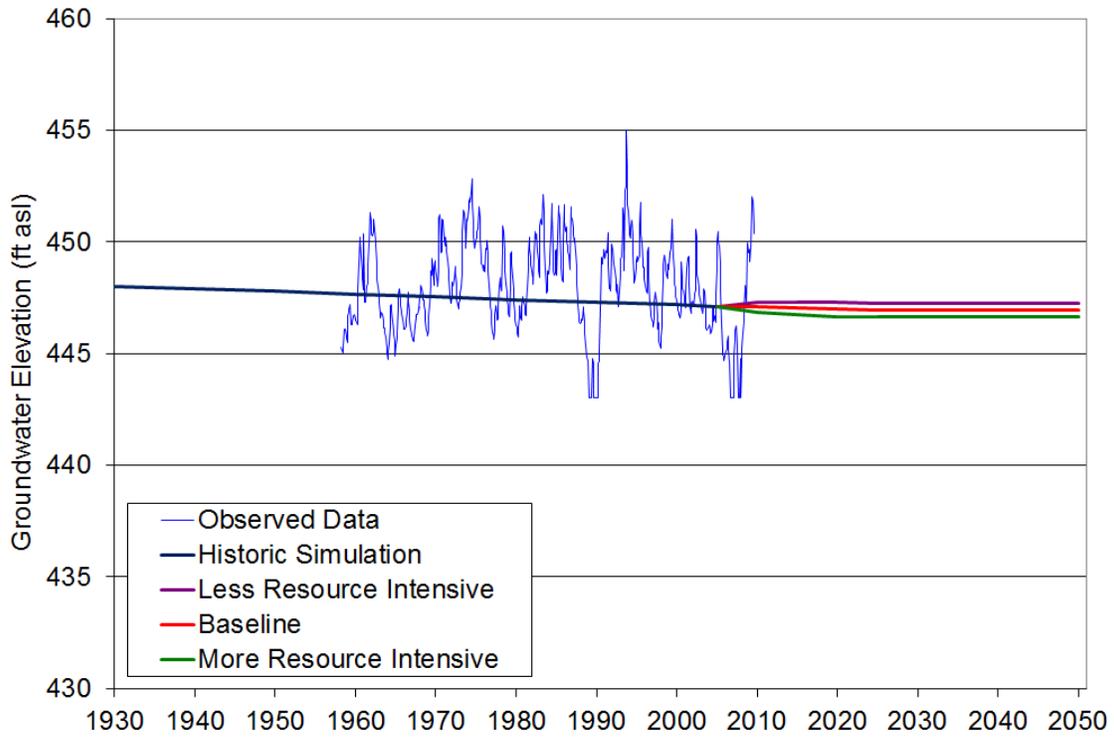
Figure 73. Predicted water levels at the Snicarte observation well
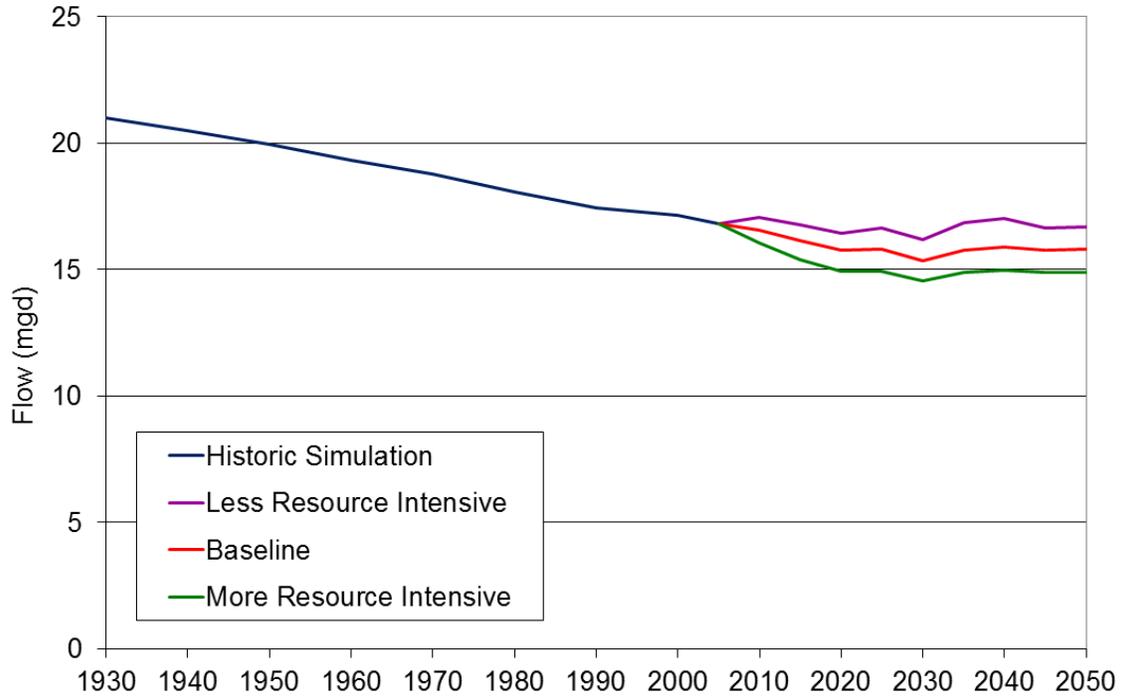
Figure 74. Predicted baseflow discharge to Crane Creek

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Table 5. Total Flow Budget in the Model for Baseline Conditions (mgd)

		1930	2005	2050
Inflows	Recharge	574.9	696.6	725.1
	Lateral Inflow	-0.9	0.0	0.5
	Bedrock	3.7	7.7	9.6
	Storage	0.0	4.7	4.4
	Total In	577.7	709.1	739.6
		1930	2005	2050
Outflows	River	446.3	376.2	349.1
	Drains	126.1	123.9	124.3
	Wells	3.1	207.7	265.2
	Total Out	575.5	707.8	738.6
	Budget Error	0.38%	0.18%	0.13%

The results of future demand scenarios extend the historical impacts to the Mahomet Aquifer by incrementally increasing drawdowns and reducing baseflow. None of the current groundwater users in the Mahomet Aquifer could be considered "at risk" for a future water shortage under the three demand scenarios. Other than small areas around Morton and Normal, the only area with significant drawdown greater than 10 feet occurs in the Champaign cone of depression. The greatest drawdown within the cone occurs around the new IAWC wellfield, although the total impact is somewhat ameliorated by placement of the new wellfield farther away from the aquifer's eastern boundary than the old wellfield. The zone of partial saturation in the Glasford Aquifer increases slightly by 2050, which could impact private wells; however, this zone is largely within the IAWC service area and several vulnerable wells near the new wellfield have already been replaced as a precaution. As water levels decline, pumps in some of the surrounding private wells may need to be lowered. The modeled head at the Petro North observation well remains well above the top of the Mahomet sand, indicating that deeper private wells are not likely to be impacted.

The modeled impacts to baseflow from 1930 to 2050 baseline conditions varied between the unconfined and confined portions of the Mahomet Aquifer. Of the 99 mgd reduction in discharge to rivers and drains, 82.3 mgd came from streams in the unconfined area, including the Illinois River, the Mackinaw River, the lower reaches of the Sangamon River, Crane Creek, and Quiver Creek. Modeled losses for Crane Creek and the Mackinaw River are 5.5 mgd (25 percent) and 11 mgd (17 percent), respectively. Flows from outside the model in the Illinois and lower Sangamon Rivers dwarf any baseflow loss due to groundwater pumpage. The watersheds on the confined portion of the aquifer account for the remaining 16.7 mgd in baseflow reduction. Losses in the Salt Creek, upper Sangamon River, and Vermilion River watersheds were 6.2 mgd (7 percent of 93.4 mgd), 7.6 mgd (16 percent of of 47.8 mgd), and 2.9 mgd (13 percent of 22.4 mgd), respectively. These baseflow losses represent long-term averages and do not

appear to critically impact the streams., However, short-term events, such as emergency pumpage by Decatur, could still cause critical impacts.

Looking at the aquifer as a whole, the model budget indicates that the available 2050 water supply is 2.7 times greater than the projected baseline demand (Figure 75). Assuming the baseflow draining into the small tributaries and ditches cannot be captured by wells, the available supply drops by 124 mgd but is still 2.3 times greater than demand.
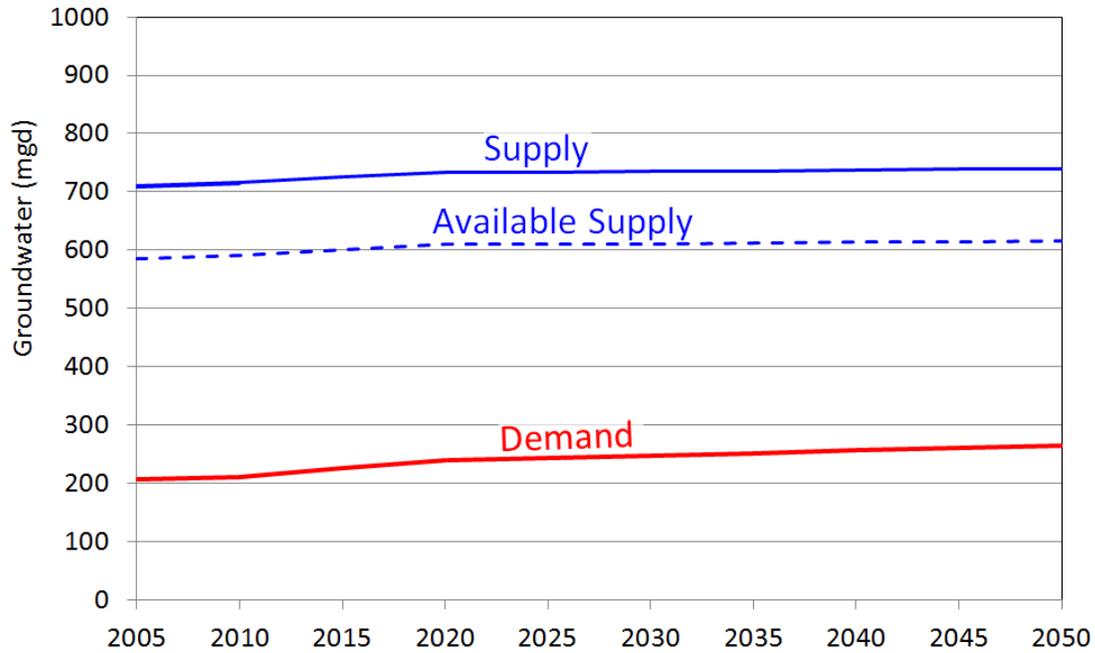
Figure 75. Groundwater supply and demand for the baseline scenario

Potential for Additional Groundwater Development

The quantification of available supply for the entire aquifer does not scale down to smaller sections of the aquifer where hydraulic conditions can vary tremendously. Future demands are not likely to be restricted only to the current pumping centers, but may involve the construction of new high capacity (> 20 mgd) wellfields. The prospective locations and expected types of impact for a new wellfield are shown in Figure 76. These conceptual zones are based on the observed impacts of pumpage in Champaign County, the Havana Lowlands, and Decatur's emergency wellfield as well as model results by Wilson et al. (1998) for a set of specifically proposed wellfields. Testing of hypothetical wellfields in these zones is a topic for future modeling efforts.

The five red zones on Figure 76 indicate areas where the development of a high capacity wellfield could cause large drawdowns and potentially impact large numbers of private domestic wells. Two of these zones are already occupied by the IAWC

Champaign wellfield and the Decatur emergency wellfield. The zone near Paxton in Ford County should be able to sustain high pumping rates because there is 150 feet to 200 feet of available head above the top of the aquifer. Based on model scenarios by Wilson et al. (1998) of a hypothetical 15 mgd wellfield at Mackinaw or Emden, it is likely that eastern Tazewell County and northern Logan County could each support a high capacity wellfield. Insufficient information is available in eastern Logan, southern McLean, Iroquois, and Vermilion Counties to be certain of what impact a new wellfield may have in these areas. Modeling work by Marsh (1995) suggests that 4 mgd of pumpage from a new wellfield in northern Vermilion County is possible without significant drawdown.

In areas where the head is close to the top of the Mahomet Aquifer, the drawdown from a new wellfield may cause conditions in the aquifer to change from confined to unconfined. The design and operation of such a wellfield would need to account for a loss in productivity due to decreasing saturated thickness. The potential also exists to affect surrounding domestic wells that are completed only in the upper part of the aquifer.

The orange zones on Figure 76 are around areas of known hydraulic connections between the aquifer and a stream. Induced leakage from the stream will help to reduce the drawdown from a high capacity wellfield and limit the impact to existing wells; however, the impact on baseflow will likely be much greater than a wellfield more distant from the stream. An example of reduced drawdown due to induced stream leakage is shown by Wilson et al. (1998) for a hypothetical wellfield along the Mackinaw River near Hopedale. More information is needed to determine the degree of interconnection between Salt Creek and the Mahomet Aquifer in DeWitt County. The potential for inducing water out of the North Fork of the Vermilion River also is unknown, although any groundwater development here would likely reduce baseflow into Danville's water supply on Lake Vermilion. The Middle Fork of the Vermilion River is a national recognized scenic river so the potential impact on low flows of any new groundwater development along it would need to be assessed.

In the unconfined portions of the Mahomet Aquifer, shaded green on Figure 76, determining the potential yield of the aquifer is very difficult because the observed impacts are so limited. As shown by the water level data and the results of the model, pumpage in the Havana Lowlands could be many times higher without a significant regional impact. As seen by the industrial pumpage near Pekin, large groundwater withdrawals next to a major river have very little impact on water levels in the aquifer. Therefore a new wellfield in the Havana Lowlands is not likely to create significant drawdowns unless it was pumped at an extreme rate, at which point it may be more economical to use surface water directly out of the rivers than to pay for the construction of a large number of production wells.

As shown conceptually in Figure 3d, a groundwater supply could be supplemented through conjunctive use of surface water, either directly or through the use of infiltration galleries. Four infiltration pits were constructed in Peoria in 1951 and 1956 to recharge the aquifer with Illinois River water. Total recharge from the pits reached 6.9
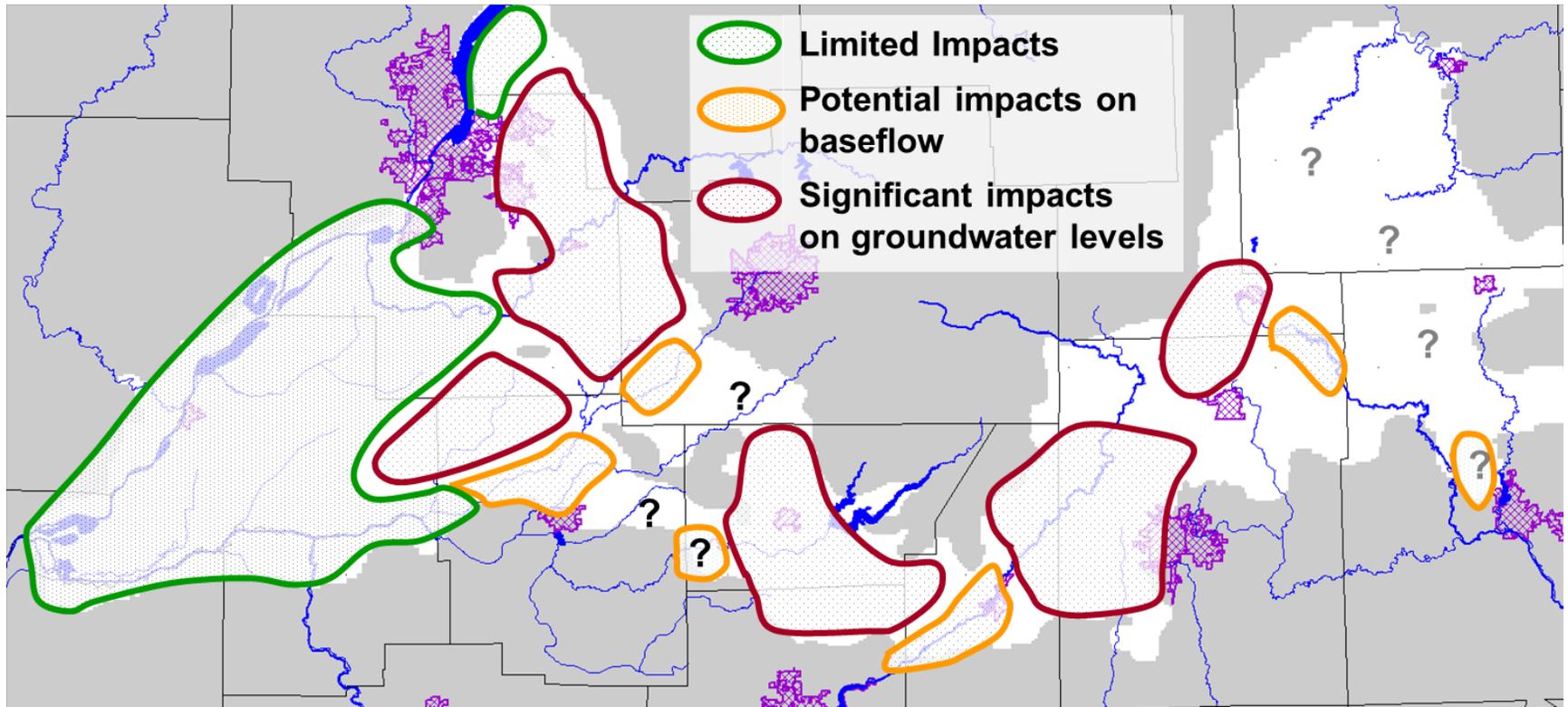
Figure 76. Prospective locations for a new high capacity wellfield and the type of expected impacts

mgd in 1961 (Marino and Schicht, 1969) although use of the pits later ceased due to dropping industrial demand and maintenance issues. Conditions for gravity-fed infiltration galleries exist over many parts of the aquifer because the head in the streams is higher than the head in the aquifer. For example, if one of the gravel pits along the Sangamon River in Champaign County was deepened and fed with 10 mgd of river water, a large cone of impression could be created in the Glasford and Mahomet Aquifers, which would offset some of the drawdown from pumping in Champaign (Figure 77). The river water would be diverted only during non-low flow periods (average flow at Monticello is 281 mgd) and could be passed through a second pit used as a setting basin before being infiltrated in the recharge pit.

Unlike surface water supplies, groundwater supplies developed from buried aquifers are relatively immune to droughts. The Mahomet Aquifer does appear to respond to droughts as suggested by the hydrograph of the Petro North observation well, although the mechanisms for the response have not been clearly established. Simulations of droughts would require short time steps with more water level data from the shallowest aquifers.

Potential climate change could impact recharge rates on a much longer term basis. Because the recharge rate to a buried sand aquifer is controlled by the low vertical permeability of the overlying glacial till and not the amount of precipitation, climate change is unlikely to have a major impact on heads in the Mahomet Aquifer. Simulations in the model of Kane County showed that aquifer heads have a low sensitivity to changing recharge rates to account for climate change (Meyer et al., 2009). The simulated change in recharge in the Kane model did, however, directly affect the amount of baseflow generated from small tributaries and drains. A more direct impact on the aquifer may result from climate change-induced water demand increases. WHPA (2008) estimated demands out to 2050 using five different climate change scenarios. In four of these cases, the increase in demand was close to or less than the increase in the MRI scenario. In the fifth and most extreme case (+6°F temperature, -3.5 inches precipitation), the demand increase is roughly double that of the MRI case, thus doubling the predicted drawdowns shown on Figure 63 for the MRI case. A subject for future investigation would be to assign pumping rates to individual wells for the different climate change scenarios and running the model.
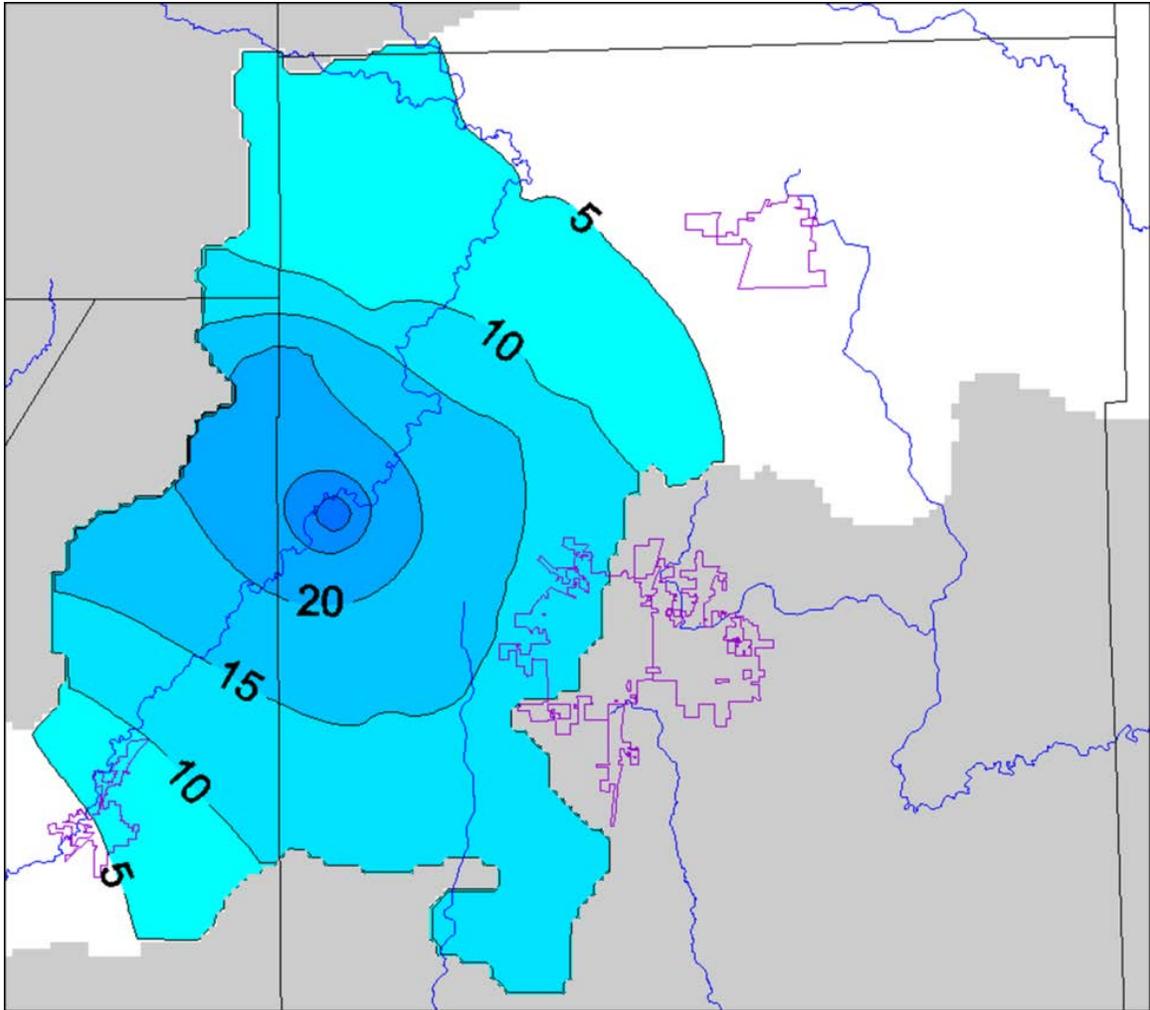
Figure 77. Cone of impression from a hypothetical infiltration lagoon along the Sangamon River

Surface Water Availability

Surface Water Supplies in East-Central Illinois

Surface water sources for water supply generally fall into two groups: 1) direct withdrawals from free-flowing rivers and streams, and 2) lakes and man-made reservoirs that store water. Although east-central Illinois rivers and streams normally carry abundant water, during severe to extreme droughts the flow in these streams can diminish to a very small fraction of their normal flow and many streams can dry up completely. In these circumstances, the use of surface water for a continuous supply requires that water be stored for use when the stream's flow is insufficient to support water demands. In some cases, a fairly small in-channel dam might provide sufficient storage when the streamflow is insufficient for short periods. But during severe droughts, flows in other streams may be insufficient for many consecutive months, in which case a large reservoir that impounds an entire stream valley may be required to provide sufficient surface water storage.

Under most circumstances, and if available, groundwater is a preferred choice for public water supply, primarily because of the needed additional water treatment for surface waters, but also because available surface water sources are often located farther from communities. If a community uses surface water as their predominant source, it is a reliable indicator that there is no local groundwater source that could produce water in sufficient quantity or quality. The largest cities in the east-central Illinois region that have water supply reservoirs (Springfield, Decatur, Bloomington, and Danville) by the early 1900s simply outgrew the capacity provided by local groundwater and/or low flows in the nearby river. Of the region's largest communities, only Champaign-Urbana, located above the Mahomet Aquifer, uses a groundwater supply. Not included is the Peoria water supply, located just outside the region, which obtains roughly half of its supply from shallow wells in the Illinois River floodplain.

Figure 1 shows the locations of major streams, rivers, and reservoirs in east-central Illinois. All of the largest lakes in central and eastern Illinois (not counting backwater lakes located alongside the Illinois River) are water supply reservoirs, providing water for either municipalities (Springfield, Decatur, Bloomington, and Danville) or for hydrothermal electricity generation (Clinton Lake and Lake Sangchris). Lake Springfield is the only reservoir that provides water for both municipal consumption and power generation. As will be discussed in the following chapter, water demand for the largest community reservoir systems has continued to grow over time, such that all of these lakes are considered to be fully utilized; i.e., they do not have surplus capacity that could be used to meet substantial growth in water demand, and in many cases are considered to provide an inadequate or marginal source of water supply during a severe drought such as the historical drought of record.

There are few rivers in the region that have sufficient natural flow during severe droughts to provide a larger continuous water supply, and those rivers tend to be located far from the major municipalities. These include the Sangamon River downstream of

Petersburg, Salt Creek downstream of Lincoln, and the Mackinaw River downstream of Hopedale. Low flows in many of these river reaches are supported by the hydraulic interconnection of the river channel with the Mahomet Aquifer. Additional river reaches have low flows that are now supported by large effluent discharges; among these are the Sangamon River downstream of the Decatur and Springfield wastewater treatment facilities, Sugar Creek downstream of Bloomington, and the Vermilion River downstream of Urbana and Danville.

There are three stream withdrawal sites in the region that are currently used for municipal water supply. These are located on: 1) the South Fork Sangamon River, which serves as a supplemental water supply source to replenish Lake Springfield; 2) the upper Mackinaw River, which serves as a supplemental water supply source to replenish Evergreen Lake; and 3) the Salt Fork Vermilion River, which provides water for the town of Oakwood in Vermilion County. Both the South Fork Sangamon River and Mackinaw River withdrawals are intermittent, and their locations do not have sufficient low flows to provide a continuous source of withdrawal.

Other selected regional streams, specifically Salt Creek in Logan County and lower portions of the Sangamon and Mackinaw Rivers, have sufficient low flows to provide for sizable withdrawals (>5 mgd) during drought. However, the lower portion of the Sangamon River is designated an Illinois public water (Figure 78), having a state-protected minimum low flow that restricts water withdrawals during very low flow conditions. Both the Salt Creek and lower Sangamon River are located a considerable distance from major municipalities and for this reason have never been developed for water supply. These rivers also flow through regions underlain by the Mahomet Aquifer and thus also have plentiful groundwater resources.

The low flow quantities that exist in streams during extreme drought conditions not only represent the maximum amount of water that could potentially be withdrawn from the stream, but also the water that is available to support instream flow needs in the stream. Examples of instream uses are the waters needed for aquatic habitat, assimilation of wastewaters, water-based recreation, and stream aesthetics. Efforts for maintaining flows in a river or stream for instream uses often focus on minimum flow quantities, but the water quality must also be of an adequate nature to support the various instream uses. A comprehensive evaluation of the biological, chemical, and socioeconomic factors that define the amount of water needed to satisfy a wide array of instream uses at given locations is not typically available. Instead, an arbitrary minimum flow value is typically selected to protect the low flows needed for instream uses.

The State of Illinois provides a protected minimum flow level only for the category of streams identified as "public waters" of Illinois. These public waters, shown in Figure 78, are primarily the larger navigable rivers within the state. Within the east-central Illinois region, only the lower portion of the Sangamon River downstream of Buckhart is identified as public water. IDNR has adopted the 7-day 10-year low flow value ($Q_{7,10}$) as the protected minimum flow for Illinois' public waters. This means that no new withdrawal from any of these rivers will be permitted if such withdrawal is

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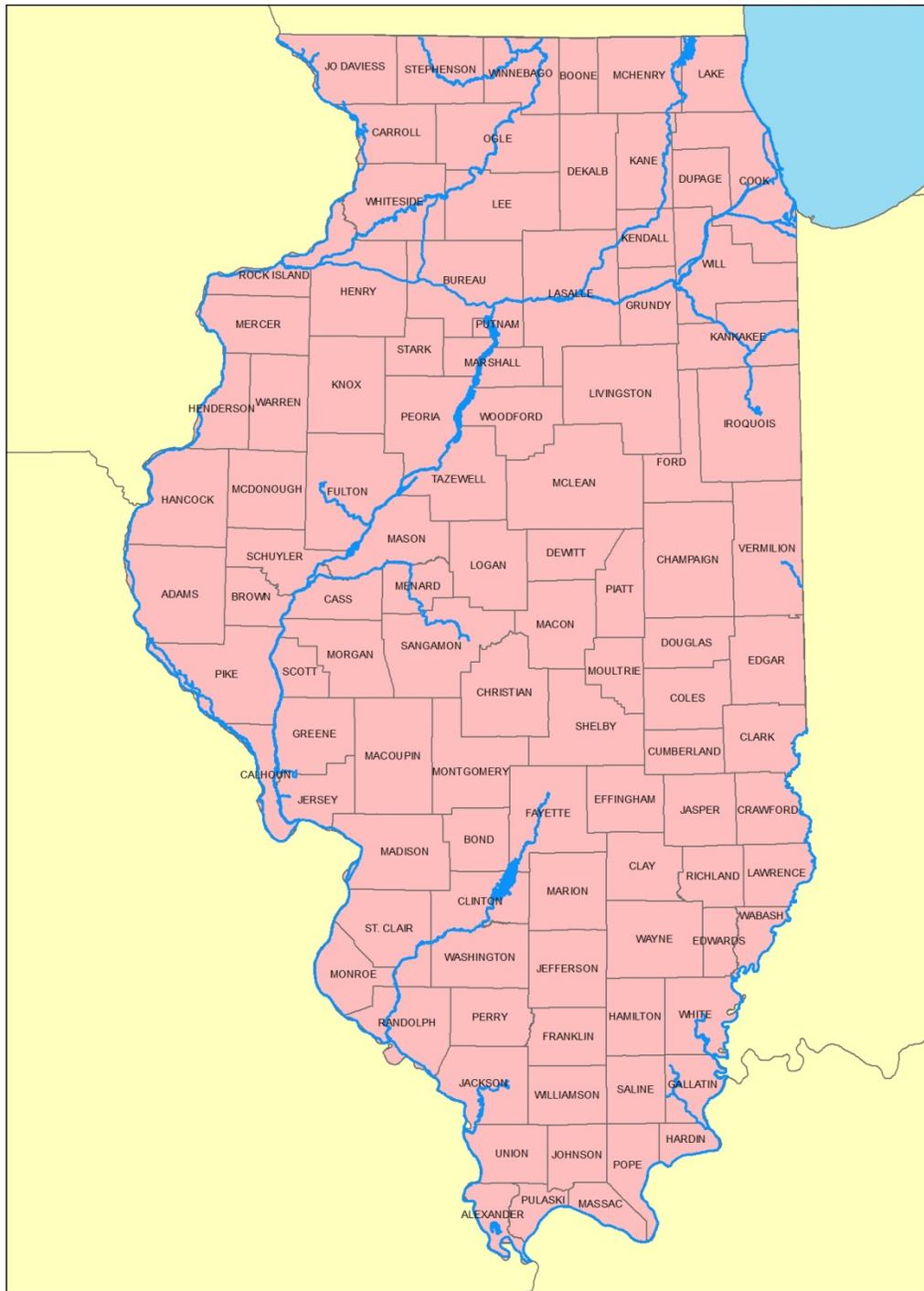
Figure 78. Public bodies of water in Illinois

calculated to cause the flow in that river to be reduced below the designated protected flow level.

Illinois Water Supply Droughts

Illinois is commonly described as being a water-rich state. While this is true 90 to 95 percent of the time, the state has experienced and will likely continue to experience infrequent, multi-year hydrologic drought episodes during which many surface water supply sources may face potential shortages. Over the period since hydrologic and climatic records have been obtained, the three most widespread and extreme hydrologic droughts in east-central Illinois occurred in the 1890s, 1930s, and 1950s. However, other drought periods, such as those in 1914–1915, 1939–1941, and 1988–1990, also were very severe in certain locales of the region. In evaluating surface water supply availability in Illinois, it is necessary to focus on expected drought impacts to both low streamflow amounts and reservoir supplies.

Although droughts are often discussed in meteorological terms, such as the amount of precipitation deficit over various time periods, it is the impacts that define the drought. A hydrologic drought is one that produces uncommonly low levels of streamflow, shallow groundwater, and/or reservoir storage. Oftentimes the term "water supply drought" is used instead of hydrologic drought, with the specific implication that the drought causes threats to or concerns regarding the availability of water for human water supply systems (as opposed to other hydrologic impacts, such as to low streamflows needed to support aquatic ecosystems). The occurrence of either a hydrologic or water supply drought requires a prolonged period of precipitation deficit, and is differentiated from shorter meteorological drought periods whose primary impacts are to agriculture.

In this report, the authors describe "extreme" water supply droughts as those that typically may occur on average only once in perhaps 30 or 40 years. The main defining characteristic of an extreme water supply drought in Illinois is that it lasts 18 months or longer, spans two summers, and lacks the normal wet period occurring in the intervening late winter and spring, which in almost all other years would allow water supply systems to recover. The most extreme water supply droughts tend to be the longest lasting droughts, not necessarily the most intense periods of precipitation deficit. The "drought of record" is defined as the most extreme of all the historical droughts, those being over the period in which there are hydrologic records available to evaluate a given water supply system. There is a further possibility that a future drought might be worse (such as longer in duration) than the historical drought of record. The most recent example of the potential for having a new drought of record comes from the 2007–2008 drought that affected Alabama, Georgia, and the Carolinas. Precipitation and streamflows measured in portions of these states were markedly lower than during their previous drought of record, with some records dating back to the late 1800s.

The susceptibility of a particular water supply system to drought impacts is not just a function of the lack of precipitation, but also is influenced by the type and size of

water supply sources in the system and the characteristics of the watersheds and/or aquifers that feed those resources. Because of differences in both local drought intensity and system characteristics, it is possible that the drought of record for one community may be different than the drought of record for a nearby community. For example, analysis of hydrologic records indicates that the drought of record for the Decatur water supply system occurred in 1930–1931; for Springfield it occurred in 1953–1955; and Bloomington in 1939–1941.

Although an extreme drought may be expected to occur "on average" once in 40 years, that does not mean that one will occur during every 40-year period. To the contrary, because of variations in climate, three extreme droughts could happen within a 50- to 60-year period and then not happen again for another 50 to 60 years. Many regions in Illinois have not experienced an extreme water supply drought since the 1950s. Of the major surface water supply systems in east-central Illinois, only the Bloomington system in the past 50 years–during the 1988–1990 drought–has felt the threat of shortages coming from an extreme drought. Analysis by the ISWS indicates that the 1988–1990 drought was only the third worst water supply drought at Bloomington in the past 80 years.

In contrast to the other sections of the report dealing mainly with groundwater, discussions on surface water availability do not typically address the issue of sustainability. There are issues of sustainability related to sedimentation of reservoirs and the potential interference of groundwater withdrawals on the flux of shallow groundwater to streams. But there is little concern with whether streams or reservoirs will fully recover following a drought. To the contrary, reservoir storage has the potential to be replenished very quickly at the end of a drought with just a few heavy rainfall events, after which the hydrologic system returns to the 90 to 95 percent of the time when surface water is plentiful enough–often too plentiful.

General Factors Affecting Surface Water Availability during Drought

The assessment of water supply availability–whether it is water available for community supplies or for maintaining water quality and aquatic habitat–is focused on the lowest streamflow conditions that occur during droughts. Even when analyzing yields of reservoirs, the focus of the analysis is on the amount of flow that can be provided to the reservoir by the stream that has been impounded.

Three primary factors have had a direct influence on flow availability during droughts: 1) climate variability and potential climate change, 2) return of treated wastewaters into streams, and 3) reservoirs and water withdrawn from the water supply reservoirs. It is expected that low flows are also influenced to a lesser degree by other factors such as land use changes and flow captures caused by shallow groundwater withdrawals; however, the magnitudes of these influences are usually not sufficiently large such that they can be directly observed or extracted from the hydrologic records. However, as discussed previously, there is the potential that future groundwater

withdrawals in the Sangamon River lowlands could expand to potentially cause a noticeable decrease in the river's low flow.

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, east-central Illinois 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 the 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, the "natural" hydrology is considered to be based on the evolved agricultural landscape.

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. Lateral flow of the shallow groundwater into streams (baseflow) occurs almost all the time in the region. But during dry conditions, baseflow is greatly reduced, even though during these times baseflow becomes the sole source of natural flow in the streams.

The natural groundwater contribution to low flows is highly variable in east-central Illinois. The greatest baseflow contribution occurs in locations where major stream channels intersect the top of the Mahomet Aquifer. This includes the downstream portions of the Sangamon River in Cass and Menard Counties, Salt Creek in Menard and Logan Counties, Sugar Creek in Logan County, and the Mackinaw River in Tazewell County. Other pockets of shallow sand and gravel deposits, scattered across portions of the region, can also add natural baseflow. However, for most locations in east-central Illinois, there is very little contribution of groundwater to streams during extended drought conditions, particularly in the southern portions of the region, resulting in very low streamflows.

Climate Variability

Climatic and hydrologic records from the past 100 years in Illinois show considerable long-term variability. Figure 79 shows the average precipitation and streamflow for the Sangamon River basin since 1900, as expressed as moving 10-year average values. The precipitation and streamflow values plotted in Figure 79 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. The streamflow values in Figure 79 are taken from the Sangamon River at Monticello (1915–2006), the longest gaging record in the region. 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 precipitation for the concurrent period. Figure 79 shows that the amount of precipitation and streamflow in the Sangamon River watershed have been increasing over much of the 20th century with the period since 1970 being consistently high. It is also clear that the 10-year average streamflow is very closely related to concurrent precipitation, with a correlation coefficient (r) of 0.901.

Available precipitation records in the vicinity of the upper Sangamon River watershed, used in Figure 79, date only to the late 1880s. However, earlier precipitation records from throughout Illinois indicate that the late 1870s and 1880s was a particularly wet period, as wet as any recent period. This is illustrated in Figure 80, which shows a comparison of 10-year average precipitation and streamflow for the upper Illinois River watershed.

There are very few regional precipitation records that predate 1870; however, the few that exist (Peoria, St. Louis, Ottawa) indicate that precipitation was often above-average from 1840 to 1870. The precipitation pattern for the entire Upper Mississippi River Watershed (Figure 81) further illustrates the conclusion that the mid-1800s were very wet, indicating that the recent 1970–2010 wet period in Illinois may not necessarily be unique when viewed from a long-term perspective. Because there is such a strong correlation between average precipitation and streamflow over the historical records, it is reasonable to assume that the mid- to late-1800s experienced reasonably high streamflow amounts. Therefore, increases in streamflow that are observed in east-central Illinois (and much of the Upper Midwest) during the 20th century may be viewed as part of long-term climatic and hydrologic variability instead of necessarily as an ongoing increasing trend.

Table 6 compares the average precipitation and streamflow for four separate periods of record at the Monticello gage: 1915–2008, 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 1948–2008, 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 28.4 inches per year, which is essentially an estimate of the average amount of water returned to the atmosphere through evapotranspiration (evaporation and plant transpiration). The average streamflow during the wettest period on record, 1970–1995, is 42 percent greater than the average streamflow during the driest period, 1930–1964. The average streamflow during the base period of 1948–2008 is close to that for the entire 91-year gaging record, 1915–2008.
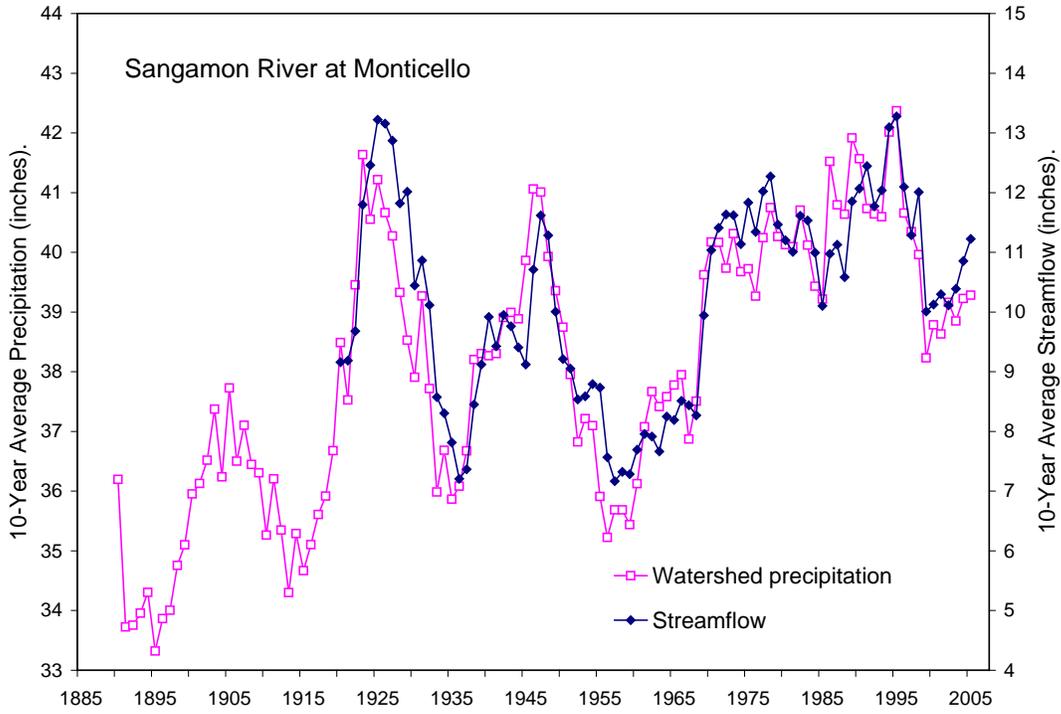
Figure 79. Comparison of 10-year running averages for annual precipitation and streamflow; Upper Sangamon River Watershed
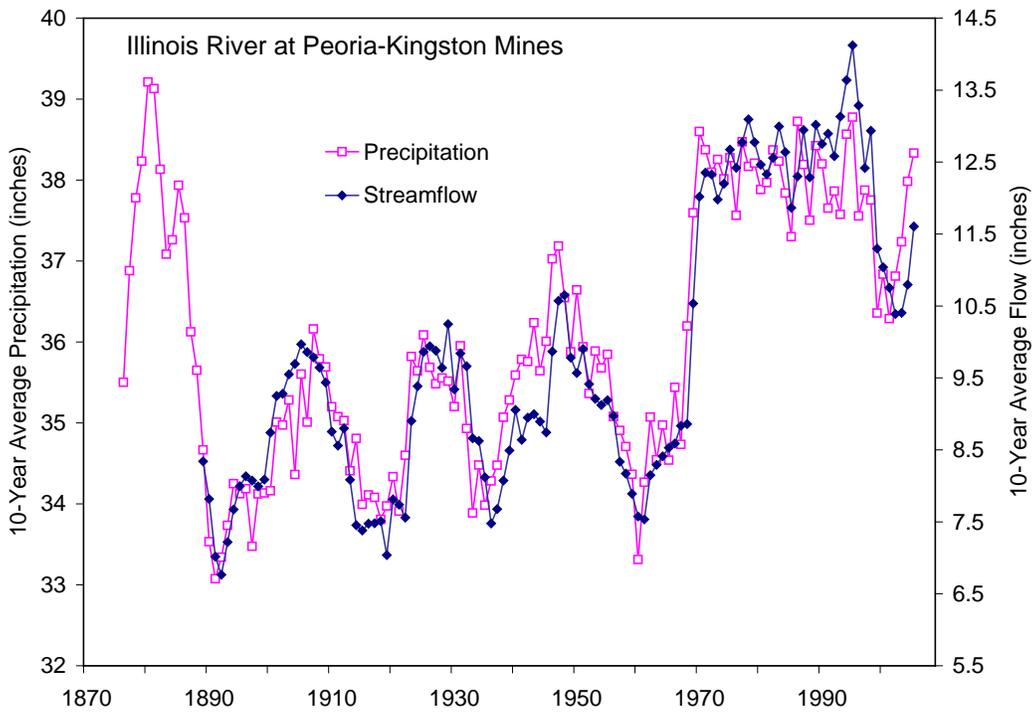
Figure 80. Comparison of 10-year running averages for annual precipitation and streamflow; Upper Illinois River Watershed
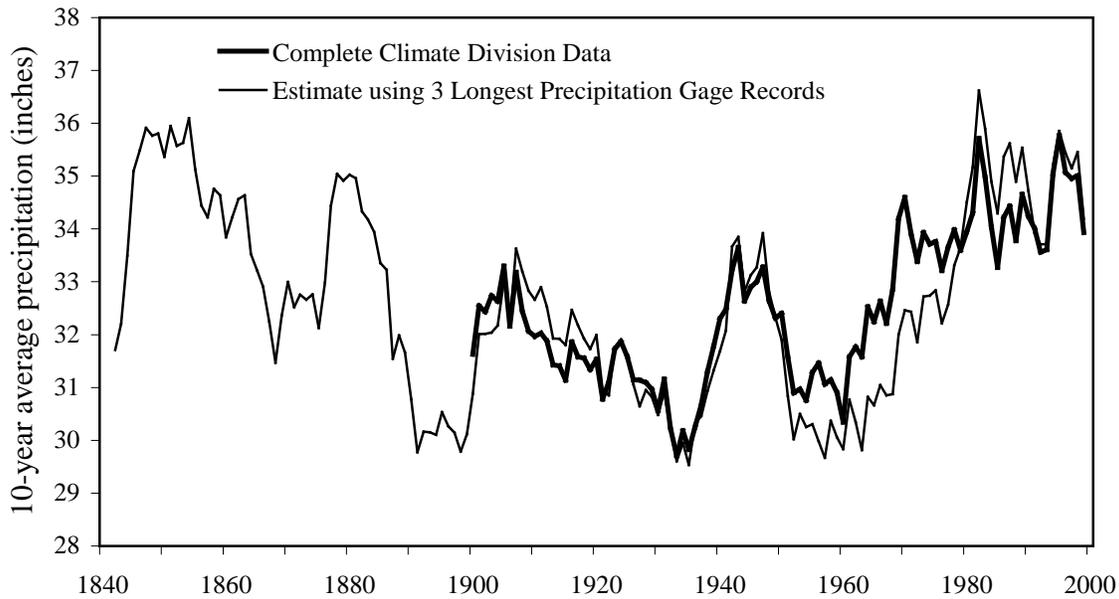
Figure 81. Estimated 10-Year Average Watershed Precipitation for the Upper Mississippi River Basin, 1840–2000 (from Knapp, 2005)

Table 6. Comparison of Average Precipitation and Average Streamflow for Four Selected Periods of Record, Upper Sangamon River Watershed

Years	Average Precipitation (inches/year)	Average Streamflow (inches/year)	Estimated Evapotranspiration (inches/year)
1915-2008	38.9	10.5	28.4
1930-1964	37.0	8.7	28.3
1970-1995	40.7	12.4	28.3
1948-2008	39.2	10.7	28.5

Reservoirs and Water Supply Withdrawals

The effect of a dam on the flow characteristics of its impounded stream can range from negligible to substantial depending on the physical dimensions of the dam, its reservoir, and outlet facilities. For most sizable reservoirs, the magnitudes of high and low flows released from the dam are less than inflow amounts, whereas medium flows from the dam tend to be at increased amounts. The tendencies of these flows can be changed, however, if there are either operational controls on the outflow or the reservoir serves a water supply function.

All major reservoirs in the east-central Illinois region were created for water supply. For those that supply water to community systems, the withdrawal of reservoir

water can cause a substantial reduction in the frequency of outflow from the reservoir, particularly affecting downstream low flows. Roughly 25 percent of the time, the flow of the Sangamon River into Lake Decatur is less than the coincident water supply withdrawal from the lake. During these periods, it can be expected that there will be little or no flow in the Sangamon River immediately downstream of the dam (Figure 82). The effect of water supply withdrawals on downstream flows can be even more pronounced as the comparative ratio between withdrawal amount and lake inflow increases. For Lake Springfield and Lake Bloomington, there is little or no flow downstream of the lakes nearly 50 percent of the time.

When reservoir water is used for cooling purposes, such as at the power plants on Clinton Lake and Lake Springfield, there is a consumption of water that is not directly obvious. Virtually all of the water withdrawn for once-through power plant circulation is returned to these lakes; however, it is returned at a higher temperature. The elevated water temperature causes a substantial increase in evaporation from the lakes above the ambient evaporation rate. For once-through cooling processes, it is estimated that 2 to 3 percent of the water being placed back into the lake is effectively evaporated. For Lake Springfield, the forced evaporation is estimated to have an average consumption rate of 2.3 mgd (CWLP, 2007). Although estimates for Clinton Lake are not available, based on its plant's generation capacity the forced evaporation is likely to have an average consumption rate in the range of 6 to 8 mgd.

Another factor affecting the flow frequency relationship downstream of Clinton Lake is the continuous low flow release from the lake, which maintains a 5 cubic feet per second (cfs) minimum downstream flow. A comparison of the pre-dam (1942–1977) and post-dam (1979–2007) flow records from the USGS gage on Salt Creek near Rowell (downstream of Clinton Lake) shows the composite effect of the reservoir, the water consumed for cooling, and minimum flow release on downstream flows (Figure 83). The resulting flow frequency curve has a backward "S" shape, which is indicative of modified flow and artificial low flow conditions. The minimum flow release from the dam maintains low flows in the stream that are higher than the pre-dam conditions. It is also noted that the pre-dam and post-dam flows do not provide a perfect before-and-after comparison because there has been an appreciably wetter climatic period since dam construction, which is why high flows have been greater in this latter period.

Effluent Discharges

Table 7 lists the amount of effluent being discharged by the largest wastewater treatment systems in the east-central Illinois region. The wastewater effluent discharges from each of the four largest communities in the region (Bloomington-Normal, Champaign-Urbana, Decatur, Springfield) have a considerable impact on low flow quantity in the streams to which they discharge. For example, during drought conditions, the low flows in the Sangamon River from Decatur to Riverton (roughly 24 mgd) almost entirely originate from the Decatur wastewater treatment plant. In a similar fashion, most of the low flows in the upper portions of the Kaskaskia River and Salt Fork Vermilion River originate from the two Urbana-Champaign treatment plants, and most of the low
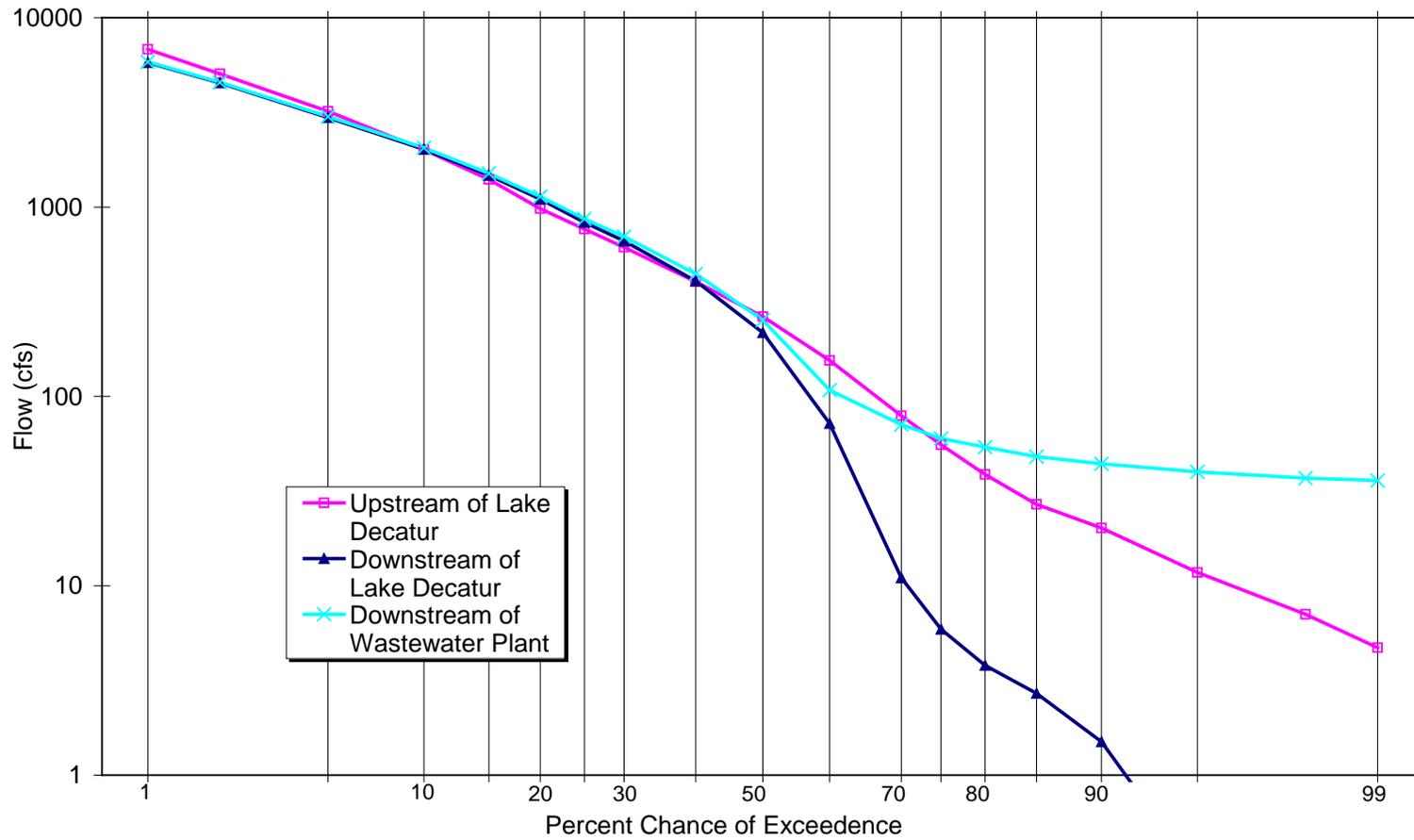
Figure 82. Flow frequency relationship for three locations on the Sangamon River near Decatur
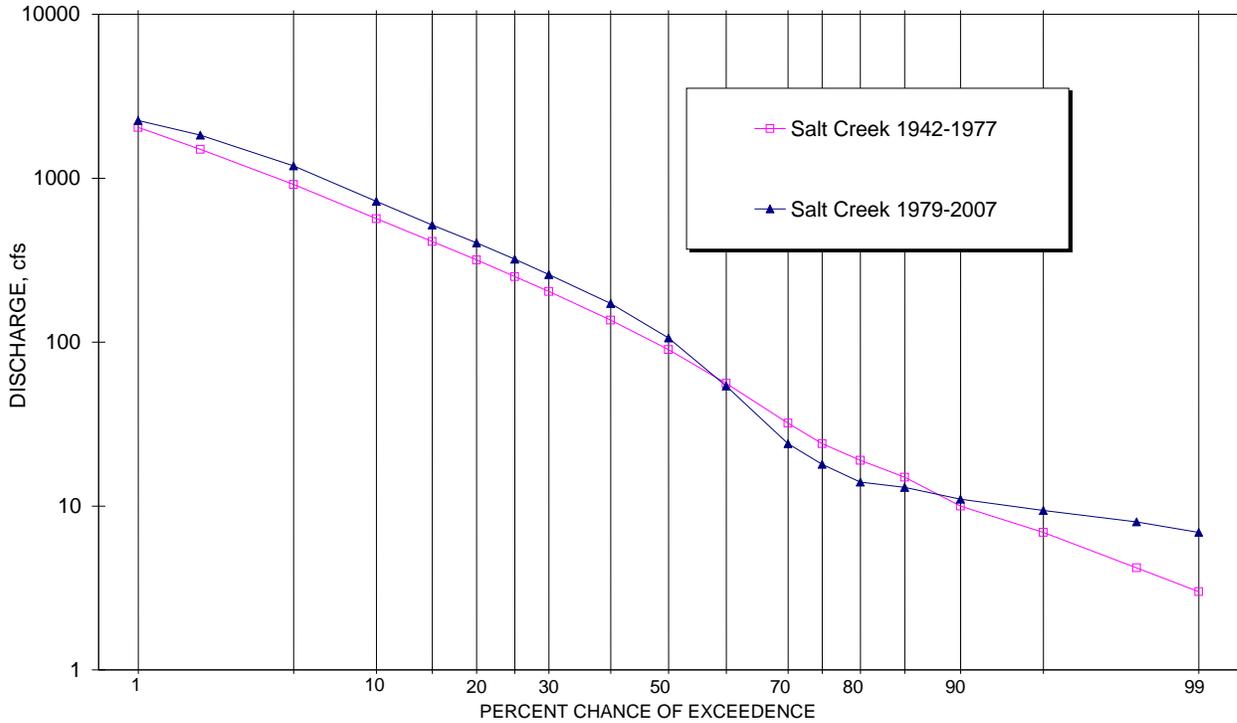
Figure 83. Flow frequency relationship for the USGS gage on Salt Creek near Rowell
(downstream of Clinton Lake)

Table 7. Largest Effluent Discharges in the East-Central Illinois Region

System	Average Discharge (mgd)	Low Flow Discharge (mgd)
Decatur	36	24
Springfield	29	16
Champaign-Urbana	21	14
Bloomington-Normal	17	9
Danville	8	5
Lincoln	4	2

flow in Sugar Creek in McLean County originates from the Bloomington-Normal treatment plant. The Sangamon River downstream of Springfield begins to pick up a considerable amount of natural baseflow; yet during the lowest flow conditions in a 10-year drought, the combined effluents from Decatur and Springfield still account for more than 60 percent of the flow in the river between Springfield and the confluence with Salt Creek in Menard County. Although there are associated water quality concerns with effluent-driven streams, not addressed in this study, in all cases the low flow quantity of the receiving stream is enhanced.

With projected water use increases for the larger communities in the region, it may also be expected that their effluent discharge amounts will also increase in the future. Thus, unless there are coincident climate changes that affect the natural low flow

contribution, it may be expected that affected streams will experience increasing low flow quantity with a higher percentage of low flow originating from treated effluents.

Wastewater effluents from smaller communities throughout the region are commonly discharged into creeks that otherwise would have no flow during drought conditions. In many of these cases, dry conditions cause the effluent to be gradually absorbed into the bed of the creek channel as the effluent flows downstream; thus the effect of the effluent on low flows during drought may be only local in nature.

Potential Reuse of Treated Effluents. A potential exists that water from these larger wastewater treatment plants may be reused, such as for industrial purposes, through a direct diversion from the treatment plant. A second form of reuse can occur if wastewater is released to a stream and withdrawn from that stream at a downstream location (in which case the water withdrawn may include a mixture of treated and naturally-occurring flows) or if the withdrawal takes place from shallow collector wells that induce flow from the stream. Regardless of method, the reuse may be expected to result in a net reduction of flow in the stream if a similar quantity of water is not also returned to the stream, and this flow reduction could be expected to impact the stream's aquatic ecology to some degree. If the stream in question is designated an Illinois public water, such as the lower Sangamon River, there would likely be a minimum protected flow restriction on a downstream withdrawal.

Analytical Approach to Determine Streamflow Availability

The Illinois Streamflow Frequency Assessment Model (ILSAM) is specialized computer software developed by the ISWS that computes the expected frequency of flow conditions for any stream within a selected region. ILSAM models use processed statistical data from USGS streamflow gages to identify regional relationships in flow amounts, from which algorithms are developed to estimate natural flow conditions for ungaged stream locations throughout the region. Additional algorithms are also developed to estimate the effects of effluent discharges, withdrawals, and reservoirs on streamflows. These models focus on how frequently flows occur, not on the sequence of flows or the dates of their occurrence. Thus the models can estimate the statistical properties of a 10-year low flow, but not the specific flows that may have occurred during the 1988 drought or other periods.

For east-central Illinois, ILSAM models have been developed for the Sangamon and Mackinaw River watersheds and provide flow characteristics for all streams in the watershed. Flow characteristics computed by the models are shown in Table 8 as provided for selected stream locations throughout the region. The streams shown in Table 8 are the only streams or rivers in the region having reaches that could feasibly support a sizeable, consistent water supply withdrawal during drought periods. The low flows in Sugar Creek and the Sangamon River have a high wastewater effluent contribution.

The ILSAM modeling approach is designed to estimate flow characteristics in the region's streams, but does not directly address water availability from reservoirs, the

primary surface water supply sources. ILSAM is also not capable of simulating changing streamflow conditions related to potential climate change. Two additional modeling approaches, 1) water budget modeling to determine reservoir yield and 2) water simulation modeling to characterize potential climate change impacts to water availability, are described in the next two report sections.

Table 8. Comparison of Low, Average, and High Flows at Selected Locations

Location	Low flow[1] (mgd)	Average flow (mgd)	High flow[2] (mgd)
Sangamon River at Monticello	1.5	281	1760
Sangamon River below Decatur	24	506	2700
Sangamon River at Riverton	32	1206	7050
Sangamon River at Petersburg	58	1500	9410
Sangamon River near Oakford	143	2330	12900
Salt Creek below Clinton Lake	3.2	148	968
Salt Creek near Lincoln	17	395	2370
Salt Creek near Greenview	59	833	4980
Mackinaw River near Congerville	1.2	343	2430
Mackinaw River at Mackinaw	2.2	379	2660
Mackinaw River near Green Valley	17	463	3000
Sugar Creek below Bloomington	9	35	180
Sugar Creek above Salt Creek	13	247	1530

Notes: (1) The listed value is the 7-day 10-year low flow
(2) The listed high flow value is the daily flow that has a 2 percent chance of exceedence.

Yields of Water Supply Reservoirs

The yield analyses conducted for surface water supply systems in east-central Illinois examine the hydrologic and climatic records from the past 95 or more years to identify and simulate water supply conditions that would be experienced if the worst droughts on record were to recur under present-day conditions. The analysis thus provides a juxtaposition of the historical drought periods with the existing water supply facilities and resources. This is accomplished by creating a water budget model of the existing system that simulates the expected gains in lake storage (stream inflows, precipitation, and diversions to the lake) and losses in lake storage (withdrawals and evaporation) during historical drought sequences and other selected drought scenarios. The present analyses also introduce the application of data uncertainty in determining reservoir yields and discuss how risk and uncertainty factor into the assessment of the drought vulnerability of each surface water supply system.

Water budget calculations are needed to evaluate water supply sources that depend on storage filled by streamflow. There are four basic types of systems included in this broad category. A typical water budget equation for storage in a surface water body is as follows:

$$AW(t) = CAP + P(t) - E(t) + QIN(t) + QDIV(t) - QOUT(t) + GW(t) \qquad (1)$$

where the available water for a specified period of time, AW(t), is computed as the sum of the available capacity of the reservoir (CAP) and the following additions and subtractions to the stored water over time, t:

P(t)	Precipitation over the surface water body
E(t)	Evaporation over the surface water body
QIN(t)	Water that flows into the surface water body from an upstream watershed
QDIV(t)	Water that is artificially diverted (pumped) into the body of water, such as stream water that is pumped into off-channel storage
QOUT(t)	Water that flows out of the surface water body
GW(t)	Net exchange of water between the surface water body and groundwater, either through seepage from the surface water body, release of bank storage into the surface water body, or other exchanges.

In application of the water budget equation, several terms are often considered to be zero or negligible. For example, for impounding reservoirs the water budget is typically computed only for the periods after the water level falls below the crest of the spillway or low channel dam, thus QOUT is considered to be zero.

Groundwater movement to and from the reservoir [GW(t)] is typically the most difficult part of the water budget calculation to assess. All reservoirs lose water through seepage, as the impounded water slowly moves through the dam and its foundation; seep water is often found at the base of earthen dams. Dam seepage is typically less during droughts and other periods of reservoir drawdown (Hudson and Hazen, 1964); the amount of seepage depends on underlying soil properties and the type of compaction and fill material used in dam construction. There will be an additional exchange of water between the reservoir and groundwater adjacent to the reservoir. As the reservoir fills with water, some of the surface water will seep into the groundwater, creating bank storage. When the reservoir water level falls, such as during a drought, bank storage often flows back to the reservoir, counteracting dam seepage losses, and in some situations, causing a net positive groundwater exchange into the reservoir. The gain or loss from bank storage will depend upon local hydrogeology, but data are rarely available to directly quantify the surface-groundwater interaction. Calculations from selected Illinois water supply reservoirs suggest situations where there is a net positive groundwater flow

into the reservoir during drought periods; but in general, reservoir yield calculations in Illinois have ordinarily assumed that GW(t) is negligible (McConkey-Broeren and Singh, 1989). However, the computation of GW(t) should always be included in water budget calculations whenever there is evidence of high seepage losses from a reservoir.

Equation 1 is reduced to the following for most Illinois reservoir water budget calculations:

$$AW(t) = CAP + P(t) - E(t) + QIN(t) + QDIV(t) \tag{2}$$

The QDIV term may also be eliminated if there are no alternative water sources that provide diverted flow to the reservoir, such as for the Danville water supply system. However, Decatur, Springfield, and Bloomington all employ supplemental sources of water that provide additional storage to their lakes.

Computation of Yield. The yield of the surface water body for the period, t, is equal to the available water, AW(t), divided by the duration of the drought *t,* or Δt:

$$Yield = AW(t)/ \Delta t$$

Thus, the yield is considered to be the steady amount of water withdrawn over the course of the drought without depleting the supply. For instance, if the available water for an impounding reservoir system was calculated to be 20,000 acre-feet during a 20-month drought, its yield would be 1000 acre-feet per month or 33 acre-feet per day, equivalent to 10.6 million gallons per day.

For an individual drought, the net yield (also called the safe or firm yield) is determined as the minimum value of $AW(t)/\Delta t$ considering all possible time periods. The value of Δt that produces the net yield for a surface water body is the duration of the critical drawdown period (critical duration). The critical duration is the period between when the reservoir first starts falling below full pool in the early stage of the drought and when the reservoir reaches its lowest level prior to recovery. To determine the relative adequacy of a supply, this net yield is compared to the quantity of water that needs to be withdrawn to meet demands during this same period. If estimated withdrawals needed during this period exceed the drought yield, the system's supply sources are considered inadequate for the drought for which they are planning.

Simulation of Historical Drought Sequences. The water budget equation is often applied to a specific time period, for example to a historical drought, where the hydrologic and climatic data used in the equation all represent a specific historical sequence. However, the water budget analyses can also be used to represent synthetic drought conditions that have no historical sequence, such as the 20-, 50-, or 100-year drought event. In these cases, termed non-sequential analysis, the streamflow, precipitation, and evaporation components of the equation are typically estimated using statistical analysis of hydrologic and climatic records. Traditional ISWS methods for estimating reservoir yield, originally developed by Stall (1964) and updated by Terstriep

et al. (1982), are based on the non-sequential analysis using regionalized estimates of streamflow frequency estimates. The non-sequential analysis lacked the ability to examine the day-to-day operation decisions that a community might face during a drought period.

The yield analysis presented in this study emphasizes the use of historical drought sequences. For systems with multiple water sources and/or a drought action plan for managing their sources, a sequential analysis can be used to simulate system operations during the drought. Each historical drought sequence may also have unique characteristics important for understanding and analyzing the potential effects of using alternative operation scenarios. Aside from the shift from non-sequential analysis to historical drought sequences, the basic data sources used in the water budget analysis are unchanged from previous yield estimates.

Another potential benefit to using historical drought sequences is improved communication with the public. It is considered more persuasive to discuss the possibility of a 1930s or 1950s drought happening again than it is to talk about a hypothetical 50- or 100-year drought. And, because the public doesn't often fully understand the concepts of recurrence intervals and climatic variability, it is difficult to describe why a "50-year drought" might not have occurred in the past 50 years. The introduction of risk and uncertainty in the analysis, described below, also favors the use of historical drought sequences.

Available Data and Evaluation of Data Uncertainties

The water budget analyses used in this study is different from previous traditional yield studies conducted by the ISWS in several ways, with the most important difference involving the quantification of uncertainties into yield estimates. The product of previous studies was a single yield value or "best estimate," based on the assumption that all data used in the analysis were exact and had no errors. However, all hydrologic and climatic data have measurement errors that are not typically accounted in the traditional analysis. To identify these errors, the ISWS examined the basic uncertainties inherent in the various data used for yield analysis, with results published in ISWS Contract Report 2007-08: *Uncertainties and Data Needs in Evaluating the Adequacy of Community Surface Water Supply Systems in Illinois* (Knapp, 2007).

All sources of data used in the water budget analysis have measurement or estimation uncertainties which can lead to either underestimation or overestimation of the yield. Instead of these errors "canceling each other out" as is sometimes assumed, they instead collectively add to the uncertainty of the yield estimate. It is not feasible to provide site-specific estimates of data errors for each reservoir analysis; instead approximate estimates of data uncertainty based either on literature reviews or collective comparisons from a larger number of reservoir samples must be used. The expected ranges in errors of reservoir capacity, inflow, evaporation, and precipitation estimates for the major east-central Illinois surface water supplies are described in the following section.

Reservoir Capacities. Reservoir capacity measurements can be provided by either: 1) a sedimentation survey that physically measures sediment and water depths along transects crossing the reservoir, or 2) a bathymetric survey that uses acoustic depth-sounding and global position system (GPS) instrumentation to measure water depth. With both methods, a sufficient number of transects are needed to accurately represent the topography of the lake bed. Both methods also require a considerable amount of post-processing after field measurements are taken, which require quality control and can provide an additional source of error. Sedimentation surveys typically have a greater number of manual depth measurements which improve the accuracy of depth information along each transect, but contain fewer transects across the reservoir, such that certain sectors of the reservoir (such as tributary arms) may not be directly measured. Bathymetric surveys are expected to provide depth information for a much greater area of the reservoir, but sufficient numbers of manual depth measurements (ground-truthing) must accompany the acoustic measurements to assure accuracy. The stability of the sounding instrument, as influenced by waves and tilting of the boat, is also a factor in the measurement accuracy.

The scientific literature suggests that detailed sedimentation and bathymetric surveys each produce reservoir capacity estimates with standard errors of estimate on the order of 10 percent. One example of comparative error is that provided by the bathymetric and sedimentation surveys that the ISWS performed on Otter Lake in Macoupin County (Lin et al., 1999). The capacity estimate of the lake from a 1997 bathymetric survey of the lake was 13,763 acre-feet. In comparison, a 1998 sedimentation survey produced a capacity estimate of 15,043 acre-feet, a difference between the two methods of 1,280 acre-feet or roughly 9 percent. In another example, the estimated capacities of Lake Decatur from the 2003 sedimentation survey and 2008 bathymetric surveys were 20,960 and 21,918 acre-feet, respectively; resulting in a difference of slightly less than 5 percent. There are no known systematic biases between capacity estimates produced by the two types of surveys.

The capacities for all major community reservoirs in east-central Illinois (for the Decatur, Springfield, Bloomington, and Danville systems) have been surveyed in the past 12 years, with all surveys considered to have a standard error of measurement of 10 percent. Lake Decatur and Lake Springfield have each had multiple surveys in the past 25 years, with results within 5 percent of the previous measurement with adjustments to account for expected sedimentation losses. Because of the corroborative results, the standard error of the reservoir capacity estimates for these two lakes is considered to be only 5 percent. Table 9 lists the most recent capacity measurements for the major community reservoirs as well as the 2010 capacity estimates based on available estimates of sedimentation rates. Both the 2003 and 2008 Lake Decatur measurements are listed because these values are considered to be equivalent.

Loss of Reservoir Capacity from Sedimentation. Over time, reservoirs lose capacity as sediment carried with inflow is deposited into the reservoir. The relative rate of sedimentation (percentage of reservoir capacity lost) is most directly related to the capacity of the reservoir compared to the size of its watershed, as well as other watershed

characteristics such as soil type, land slopes, etc. The progressive loss in capacity causes a reduction in the yields of water supply reservoirs. Although the drought vulnerability classifications presented in this report are primarily based on current reservoir capacity and yields, water supply planning efforts must also consider future yields based on projected reservoir capacities, particularly in cases where it may realistically take one or two decades to develop additional supplies.

Table 10 provides an estimate of the capacity loss rate for the region's five major water supply reservoirs and projected reservoir capacity for the next four decades. The sedimentation rates shown in Table 10 have been determined from sedimentation surveys for all major lakes except Evergreen Lake, for which the sedimentation rate was estimated by a regional regression equation developed by Singh and Durgunoglu (1990) and verified using the results of the 1999 bathymetric survey. Lake Decatur has an active dredging program that is able to remove roughly the same amount of sediment per year as is deposited; thus, its effective capacity loss per decade is considered negligible. There is increasing uncertainty over time associated with future projections of reservoir capacity; however, analysis by Knapp (2007) indicates that the standard error of capacity projections for Illinois reservoirs was less than 11 percent for cases where an accurate sedimentation survey of the reservoir had been conducted within the previous 35 years.

Table 9. Reservoir Capacity Measurements and 2010 Capacity Estimates (Acre-Feet)

Reservoir	Full pool elevation (feet)	Year of survey	Measured reservoir capacity	Source of survey	Estimated 2010 capacity
Lake Decatur	614.4	2008	21,918	H.L. Chastain	21,439
Lake Decatur	614.4	2003	20,960	ISWS	
Lake Springfield	560.0	2004	51,245	Springfield CWLP	50,280
Lake Bloomington	719.5	1999	6,768	Hanson Engineering	6,482
Evergreen Lake	720.0	1999	15,610	Hanson Engineering	15,369
Lake Vermilion	582.2	1998	7,971	ISWS	7,109

Table 10. Estimated Future Reservoir Capacity as a Result of Sediment Deposition

Reservoir	Approximate capacity loss per decade (%)	Estimated future capacity (acre-feet)			
		2020	2030	2040	2050
Lake Decatur*	5.5	21,439	21,439	21,439	21,439
Lake Springfield	2.0	48,960	47,660	46,380	45,100
Lake Bloomington	4.0	6,230	5,985	5,745	5,510
Evergreen Lake	1.4	15,150	14,935	14,720	14,510
Lake Vermilion	8.0	6,840	6,407	6,025	5,643

* Lake Decatur is considered to have no net sedimentation loss due to ongoing dredging.

Defining How Much of the Reservoir Capacity is Usable. It is normally assumed that, when reservoirs are drawn down at the end of a drought, part of the remaining pools of water within the reservoirs are considered unusable. This typically occurs because of problems with access, i.e., the remaining water is either at an elevation below the lowest water intake or is otherwise removed from the intake; however, it is also likely that sediment and other quality issues may make water from shallow pools undesirable for potable use. For purposes of uniformity, and unless otherwise stated, it is assumed that the lowest 10 percent of water in these lakes is unusable. Each community may have additional information on the physical and chemical restrictions, such as intake elevations, for determining a minimum usable pool or target elevation that is different from the 10 percent capacity used in the present analysis.

An additional and equally important question that communities should consider in determining the minimum pool level or usability is "How low can the reservoir get in a drought before a crisis situation is created in the community?" If the time of recovery at the end of the drought could be accurately forecasted, then this would be a relatively easy question because the community could be comfortable knowing that the reservoir level would not continue to fall. But in a real life situation, when the prospects for drought recovery are unknown, decisions must be made based on the potential that dry conditions could continue and the reservoir could fall even further below the desirable minimum. For this reason, communities may not want to face the situation in which the reservoir has fallen to 10 percent capacity with an uncertain recovery.

Reservoir Inflow. Knapp (2007) identifies three general types of uncertainty related to estimating low flows and drought flows for analyzing water supply availability: 1) accuracy of low flow records at streamgages, 2) ability to estimate flow characteristics of severe droughts at gaging sites when the available gaging record does not include a severe drought period, and 3) use of regional data (or data transferred from nearby gages) to estimate drought flow conditions at ungaged sites. In the case of simulating historical drought sequences with reservoir water budgets, the first and third types of uncertainties apply, as the water budget analysis uses either measured flows from a site upstream of the reservoir, or flow sequences transferred from a nearby gage.

Flow measurements at U.S. Geological Survey (USGS) gages typically have been scheduled at 6- to 8-week intervals, and the relationship between the river stage and the flow amount can vary or shift between measurements depending on flow conditions and character of the stream channel. For estimating flows occurring in the period between two field measurements, it often is assumed that there is a gradual change in the rating shift over time, but there is typically no information to determine when shift changes actually occur. The USGS considers a gaging station record to have a "good" rating if about 95 percent of the estimated daily discharges between measurements are within 10 percent of the true value, and most Illinois gages are judged by the USGS as having good ratings. For analyses that use gaging records from a site immediately upstream of the reservoir, this 10 percent value is adopted as the standard error of estimate for reservoir inflows

over the duration of the drought. Of the major community reservoirs, only Lake Bloomington has historical gaging records from sites immediately upstream of the lake.

For gaging locations located a farther distance upstream from the reservoir, a higher percentage of uncertainty should be used (Table 11). For example, the Sangamon River gage at Monticello is located 32 miles upstream of the Lake Decatur dam and measures flow from roughly 60 percent of the Lake Decatur watershed. In using this gage for the Decatur water budget analysis, a standard error of 15 percent is used for the flow estimates. It is noted that during the 1953–1954 drought, there were two USGS gages upstream of Lake Decatur located within 18 miles of each other, at Monticello and near Oakley. After flows were adjusted to account for differences in drainage areas between the two gaging sites, there was a 15 percent difference between the cumulative flow values at the two sites over the critical seven-month duration of the 1953–1954 drought, thus providing a clear example of the intrinsic uncertainty in the hydrologic data

Table 11. Standard Errors Used for Evaluating Uncertainties in Reservoir Inflow Data

Reservoir Inflow Data	Standard Error*
Lake Bloomington	10%
Lake Decatur	15%
Evergreen Lake	20%
Lake Springfield	30%
Lake Vermilion	35%

* Values are approximate standard errors based on guidelines from Knapp (2007)

The inflow estimates for Evergreen Lake and Lake Vermilion depend primarily on flow values that are estimated using either transferred data from regional gaging stations. For Lake Springfield the inflow estimates are provided by a watershed model that was calibrated using regional data. Errors from the regional estimates and watershed modeling were judged to have roughly the same overall error. Using guidelines from Knapp (2007) for the use of regional data, the standard error of cumulative inflow estimates for these three reservoirs during a severe 50-year drought may be expected to be in the range of 30 to 35 percent, with the estimated error for each reservoir being influenced by the duration of the drought and the size of the watershed. Inflows for the Evergreen Lake watershed are based on measured flows from the Lake Bloomington watershed, and in this case the estimate standard error was reduced to 20 percent because of the similarity and proximity of the two watersheds.

For both the Springfield and Bloomington systems, supplemental water is also obtained from pumping stations located on nearby streams. When sufficient flow exists on its respective stream, water from the South Fork Sangamon River is pumped into Lake Springfield and water from the Mackinaw River is pumped into Evergreen Lake. The available flow in the South Fork Sangamon River during a severe drought is estimated using historical flow data from the USGS gage located immediately downstream of the

pumping station. Because of the proximity of the gage, the data are estimated to have a 10 percent standard error of estimate. The available flow in the Mackinaw River during a severe drought is estimated using historical flow data from the USGS gage near Congerville, located roughly 20 miles downstream of the pumping station. This data must be adjusted based on differences in the watershed areas between the gage and the pumping station; these adjusted values are judged to have a standard error of estimate of 15 percent.

Evaporation and Precipitation over the Reservoir Surface. Evaporation from an open body of water is very difficult to measure directly. Thus, the amount of lake evaporation usually is represented using one of several estimation techniques. Pan evaporation measurements are frequently used by engineers to estimate lake evaporation because they are the only evaporation measurements available. However, pan evaporation measurements are highly variable and often do not provide an accurate estimate of lake evaporation even when adjusted using a pan evaporation reduction coefficient (Knapp, 2007). The evaporation estimates used in the current study for historical droughts are based on the equations and monthly values presented by Roberts and Stall (1967). The accuracies of empirical equations of the type similar to that used by Roberts and Stall were investigated by Winter et al. (1995). Equations that use regional climate stations for data inputs and do not require water temperature from the lake (the types of estimates expected for most applications) typically produced monthly evaporation estimates that have standard errors of 20 to 25 percent when compared to detailed computations of monthly evaporation. A comparison of the cumulative evaporation estimates over the course of a season or year, based on the data provided in Winter et al. (1995), result in a standard error of roughly 14 percent. This 14 percent standard error value was adopted for all lake evaporation estimates in the present study.

As discussed in Knapp (2007), precipitation measurements are considered to have low standard error compared to other data inputs, and also tend to be biased toward undercatchment of precipitation. For these reasons, the present study method does not address data uncertainties in precipitation when estimating yield uncertainty.

Use of Uncertainty and Confidence Limits in Estimating Drought Yields

The traditional method of estimating yield calculates average drought recurrence intervals and the probability that a system may experience a shortage in any given year. With a traditional yield estimate for a 100-year drought, for example, there is a 1 percent chance that a drought may begin in any given year that would ultimately cause the system to experience a water shortage in that year or subsequent years within the same multi-year drought period. Similarly, with a traditional 50-year drought yield, there is a 2 percent chance that a drought may begin causing the system to experience water shortages. Unfortunately, most people incorrectly assume that if a community's water demand is less than the 50- or 100-year drought yield, then that system is "safe" from experiencing shortages during such severe droughts. In reality, by producing what is considered to be the "best" estimate of a 50- or 100-year drought, traditional methods produce an estimate that has roughly a 50/50 chance of being underestimated and overestimated. Thus, if a community's water demand is exactly equal to the traditional

100-year drought yield, there may be only a 50 percent chance that the system could safely provide the community's demand during a severe 100-year drought, as further explained in the next paragraph. For water supply planning, it is expected that most communities would want more than a 50 percent certainty that they would survive a severe drought without experiencing shortages.

The potential 50 percent chance of experiencing a water shortage associated with traditional yield estimates is caused by typical data uncertainties which are unavoidable given data measurement methods. For most hydrologic and climate data sources there is roughly an equal chance that accepted data values are either underestimated or overestimated. When using water budget analyses, any underestimation or overestimation of data input is incorporated into the resulting yield estimate. Thus, there is roughly a 50 percent chance that the traditional best estimate of yield may be too high, such that during a severe drought the system may not be able to provide the stated yield. An alternative approach, which the ISWS has now adopted for its yield studies, is to explicitly identify and quantify the uncertainties in data and methods and use these uncertainties to provide confidence limits for yield values. The biggest concern in using uncertain data is that we may overestimate yield, resulting in less water being available than expected for use in a severe drought. For this reason, a 90 percent confidence yield estimate is also computed, such that there is 90 percent confidence that the "true" yield (an unknown amount) is greater than or equal to the computed 90 percent yield. This means that there is 90 percent confidence that there will be sufficient water during a severe drought and only a 10 percent chance that the "true" reservoir yield is less than the calculated amount. This also means, however, that the computed 90 percent confidence yield is a lower value than the traditional mid-estimate (50 percent) yield.

The selected 90 percent confidence value is a commonly used confidence limit. Similar estimates for other confidence levels, such as 70 percent, 80 percent or 95 percent, could also be prepared using reservoir water budget modeling if desired. Communities should determine what level of confidence is appropriate for their system based on costs, the potential adverse consequences of having a water shortage, and to what degree emergency supplies not considered in the yield analysis would be available in the case of shortages.

Monte Carlo Simulation of Data Uncertainties. The analysis of yield uncertainty presented in this study addresses only the three largest sources of uncertainty in data inputs to the water budget analysis, those being uncertainties in: 1) reservoir capacity, 2) reservoir inflow, and 3) lake evaporation. Other uncertainties, such as those in precipitation and in other variables typically ignored in the water budget analysis, such as groundwater movement to and from the reservoir, are not evaluated.

The most complete and reliable way of analyzing the composite uncertainty in yield associated with data input errors is achieved through conducting a Monte Carlo simulation analysis. In such an analysis, multiple (several hundred or more) water budget simulations are performed in which the major data inputs are allowed to vary individually

and randomly in every given simulation. If 300 simulations are performed, the result is 300 different estimates of the yield. The distribution of these yield estimates is then analyzed to determine the median (50 percent) estimate as well as the lowest 10th percentile of the 300 yield estimates, which then becomes the 90 percent confidence yield amount.

In randomly varying the data inputs in the analysis, all data errors are assumed to follow a normal probability distribution. Thus, in conducting up to a thousand random variations, an individual set of data may typically be expected to vary with maximum or minimum values as much as three standard deviations away from the measured amount. In varying reservoir inflow and evaporation, a collective error is applied to the entire duration of the drought simulation, as opposed to varying individual daily amounts.

As an example, Monte Carlo simulation analysis was used to estimate the drought-of-record yield uncertainty for Evergreen Lake, which is one of the two supply lakes for the Bloomington water system. Three hundred simulations were performed and the major data inputs were allowed to vary away from their measured amounts using a random normal distribution generator. The standard errors used for the reservoir capacity, reservoir inflow, and evaporation were estimated to be 10, 20, and 14 percent, respectively. Climatic and hydrologic conditions from the 1939–1941 drought of record were used as inputs into the water budget analysis for the lake, as taken from USGS flow records from Money Creek and estimated lake evaporation from Roberts and Stall (1967).

Figure 84 shows the distribution of the yield estimates from 300 simulations of the Evergreen Lake water budget. The estimated yields range from a minimum of 5.4 mgd to a maximum of 9.6 mgd, with a mean and median value (or best estimate) of 7.4 mgd. The standard deviation of the simulated yield amounts was 0.76 mgd. The 90 percent confidence yield (lower 10th percentile) from the analysis occurs at 6.4 mgd. It is assumed that the shape of the distribution shown in Figure 84 would approach a normal curve if the number of simulations were to increase; on the other hand, it is also possible that the yield estimates may not perfectly fit a normal distribution.

Approximate Method for Estimating the 90 Percent Confidence Yield. In the study by Knapp and Hecht (2010), resources were not available to develop Monte Carlo water budget simulations for all community surface water supplies in Illinois; thus a simpler computational approach for determining the 90 percent confidence yield for each system was sought. An approximate method was proposed in which each of the major data inputs to the water budget analysis was adjusted to reflect the potential that these data might overestimate the true yield. The adjustments involve a water budget analysis in which both the reservoir capacity and reservoir inflow are considered to be reduced and the evaporation is considered to increase. The true values of each of the data inputs are assumed to follow a normal distribution function, and the value associated with the 10th percentile of that distribution, occurring at 1.28 standard deviations from the mean, are computed. For example, if the standard error of a reservoir capacity measurement is estimated to be 5 percent, that reservoir's capacity would be reduced by 6.4 percent (5

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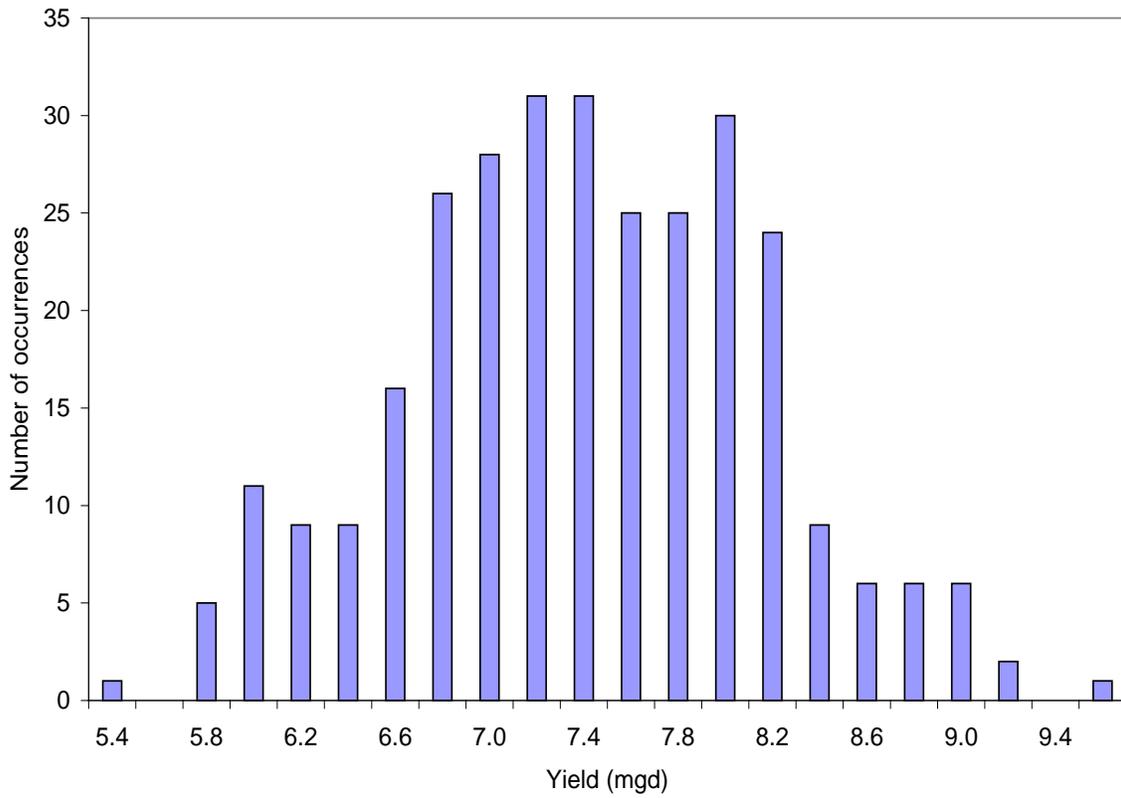
Figure 84. Distribution of yield estimates using a Monte Carlo simulation in which major data inputs to the water budget analysis are allowed to vary randomly to simulate the impact of data uncertainties

percent x 1.28 standard deviations) to compute the lowest 10th percentile value in the error distribution function. To repeat, all inputs into the water budget analysis are adjusted to produce the lower yield amount that has only a 10 percent chance of overestimation; i.e., reservoir capacity and inflow estimates are reduced and evaporation estimates are increased.

Three test cases were conducted to compare yield estimates from the approximate method with a Monte Carlo simulation of yield. Two of these case studies deal with east-central Illinois water supplies, namely the Decatur water supply system and the Evergreen Lake example shown earlier. The third analysis was the yield computation for the Wayne City off-channel storage system, located in southeastern Illinois. Table 12 compares the 90 percent confidence yields for the case studies estimated using both the approximate method and the Monte Carlo simulation analysis. From these results, the approximate method appears to provide a reasonably good estimate of the uncertainty in yield amounts.

Table 12. Comparison of 90% Confidence Yield Estimate (Drought of Record) using the Monte Carlo and Approximate Methods

Water supply system	50% yield estimate	90% confidence yield	
		Monte Carlo simulation	Approximate method
Decatur system	40.2	34.7	34.4
Evergreen Lake	7.4	6.4	6.4
Wayne City system	0.21	0.19	0.18

Categories of Drought Vulnerability

A separate study of water supply yield for all community surface water supplies in Illinois (Knapp and Hecht; 2010, in preparation) defines four categories of community drought vulnerability based on the uncertainty analysis of yield estimates:

Inadequate System – There is greater than a 50 percent probability that the current system would not be able to provide the community's current rate of water demand through a severe drought similar to the drought of record.

At-Risk System – There is greater than a 10 percent probability that the current system would not be able to provide the community's current rate of water demand through a severe drought similar to the drought of record.

Marginal System – Although there is greater than a 90 percent probability that the current system would have sufficient water during a drought similar to the drought of record, the pending threat of potential shortages during the drought might still force the community to take extraordinary measures (enacting severe water use restrictions or development of alternative supply sources) to avoid shortages.

Adequate System – There is greater than a 90 percent probability that the community will not experience any water shortages or threat thereof during a severe drought similar to the drought of record.

Based on these categories, more than 25 percent of the community systems that obtain water directly from Illinois surface water sources are considered to be at risk or inadequate. The surface water systems that are most vulnerable are those that depend on man-made reservoirs for their supply, with over half of these systems considered to be at risk or inadequate. For many growing communities that use reservoirs, water demand has increased without an accompanying expansion in the source of water supply. Because there have been few severe droughts in Illinois since the 1950s, the public may not perceive the potential threat that severe droughts pose to their supply system. For some small systems, a community may also be considered to be at risk simply because insufficient data are available to define the capacity of its supply well enough to provide a confident yield estimate.

The potential for water shortage is the primary measure considered in determining drought vulnerability. However, what constitutes a water shortage or an adequate supply is not typically well-defined. In identifying water shortages following the 1952–1955 drought, Hudson and Roberts (1955) judged that a community had suffered a shortage if there was less than a six-month supply of water remaining in their reservoir at the end of the drought. We believe that their experience indicates that there can be substantial socio-economic stresses to a community well before it runs out of water. The definition of a marginal system presented above alludes to the potential problems and difficult decisions that a community may have to face as its water supply is running low.

In a previous evaluation, McConkey-Broeren and Singh (1989) judged system adequacy based on an elevated level of water use that might be expected to occur during hot and dry weather. Thus in that study, systems were considered inadequate if they were incapable of supplying unabated water demands that were typically 20 percent above normal water use. Although experience has shown that water demands do rise considerably during the early stages of a drought, the assumptions used in the 1989 evaluation neglect the likelihood that the community will undertake conservation measures to reduce their use in later stages of a drought. A description of the variable water demand during various stages of a drought is provided in the following section. But even when there is a noticeable drop in water use in later stages in the drought, it may not make up the difference caused by heavy use during an initial summer period, such that total water use over the entire course of a drought may still be expected to be greater than the typical average annual water use. The present analysis assumes that voluntary and mandatory conservation measures will be employed by communities, such that the total water use over the course of an extreme drought may only be 5 to 10 percent greater than the community's average annual water use.

It is noted that when their reservoir levels are approaching dangerously low water levels, communities and their citizens will almost certainly employ extraordinary water demand reduction measures, beyond those typically addressed in drought response plans, to prevent the depletion of their water supply. Even if such measures are successful in carrying the water supply through the drought, it is suggested that in such cases the reservoir system may not have satisfactorily performed its function in providing a sustained water supply for the community, particularly if in the process there were noticeable adverse economic impacts to the community and its industries.

Water Demand during an Extreme Drought

All historical water supply droughts in Illinois have started during the summer, the season of highest water use. Community water use during a typical summer may often be 25 to 30 percent higher than the base water use throughout the rest of the year; during hot and dry summer conditions (that have the potential to develop into droughts), communities typically experience very high levels of water use. At the start of the 2005 drought (June 2005), the water use for Bloomington was over 17 mgd, roughly 56 percent above its base water use and over 20 percent higher than the demand for a typical summer month. In July 1999 (the first month of its 1999–2000 drought), Springfield's

potable water demand exceeded 32 mgd, over 65 percent higher than the base use and 20 percent higher than that for a typical summer month. Even in Decatur, where the rise in summer water use is tempered by industrial use (which has little seasonal variation), the months of June through August of 2005 had an average use of 45 mgd, or roughly 4 mgd greater than that of a typical summer. Nearly all of the higher usage in summer is related to outdoor water uses.

If the onset of droughts could be accurately forecasted, then a community would hypothetically be able to call for water use restrictions at the beginning of a drought. But in reality, there is little or no difference between the first months of a drought and many other dry periods that might occur once every several years. In order to reduce water use at the start of droughts, restrictions would likely need to be placed on outdoor water use for all summers. The drought response plans for Bloomington, Springfield, and Decatur each identify various stages of drought based on abnormally low water levels in their reservoirs. Such low reservoir levels do not occur until many months into the drought, typically during the fall or winter season when outdoor water use restrictions have little or no direct impact. Although Illinois community drought response plans almost exclusively address restrictions on outdoor water uses, their implementation usually also leads to coincident voluntary reductions in indoor water use via public awareness, such that the base water use in October through April may be reduced by as much as 5 percent. During the 2007–2008 worst drought on record in northern Georgia, water use during the entire first summer season in 2007 was extraordinarily high. Once restrictions were imposed, base level water use in the cool season months was reduced over the latter portion of the drought by more than 10 percent; however, to achieve this level of reduction, Governor Perdue of Georgia directed the state's Environmental Protection Division to modify water production permits for all community water supplies in northern Georgia (http://www.gaepd.org/Documents/news.html). Even then, this directive was not issued until October 2007, at which time some of the major water supply reservoirs in northern Georgia, such as Lake Lanier, were already approaching record-low water levels.

Yield Estimates for the Decatur, Springfield, Bloomington, and Danville Systems

Decatur – At Risk System

Decatur and its largest industry, Archer Daniels Midland Company (ADM), each have water treatment plants that withdraw water from Lake Decatur, the primary water supply source for both users. Because they share the same resource, the water supply yield for Decatur and ADM must be estimated jointly. The yield computations described in this study do not include the relatively small amounts of water that ADM obtains separately from its own wells. The combined average annual water use for Decatur and ADM in recent years (2007–2008) has been approximately 36 mgd, noticeably less than the 39 mgd average that was reported in 2001 to 2005. Water demand projections by Wittman Hydro (WHPA, 2008) suggest that the average water use rate will grow substantially over the next four decades primarily from the commercial and industrial sector. WHPA's baseline Scenario projections suggest that by 2030 the water demand will increase to 44 mgd. This is somewhat lower than the city's projection

of 48 mgd by the same time period (Will Sudduth, HLC, personal communication, 2007). For 2050, the WHPA Baseline projection is 52 mgd; their Less Resource Intensive projection is 45 mgd; and their More Resource Intensive projection is over 60 mgd.

The primary input for the Lake Decatur water budget analysis is the inflow from the Sangamon River watershed. A supplemental source of inflow to the lake is that provided from the DeWitt well field, operated by the City of Decatur, in which water is pumped from the Mahomet Aquifer and discharged into Friends Creek, which then flows into the Sangamon River and Lake Decatur. An additional supply source to the city during drought is pumpage from a City-owned former gravel pit, located in the Sangamon River valley downstream of Lake Decatur. The times during a drought at which the above supplemental resources are accessed during drought are defined by the city's Low Lake Level/Drought Action Plan (April 24, 2007 Revision). A possible third supply, Lake Tokorozawa, was used as an emergency source during the 1988 drought and the city's drought action plan includes its possible use when Lake Decatur falls below a level of 610 feet. However, the lake is privately owned and there is no standing agreement assuring that it would be available during a drought condition. Although there is the possibility that a negotiation with the owners could be arranged during an emergency, the lake is not considered in the present yield analysis as a dependable source. The city is also currently investigating options for additional sources of supply, including a collector well system in the Sangamon River valley near the Lake Decatur dam, but there has been no announced decision on which supplemental supply(ies) will be developed.

Summary of Data Inputs. As stated earlier, the capacity of Lake Decatur (at an elevation of 614.4 feet) has been estimated to be 20,960 acre-feet using a 2004 ISWS sedimentation survey and 21,918 acre-feet from a 2008 bathymetric survey of the lake conducted by H.L. Chastain and Associates (HLC). For the purposes of yield estimation, the ISWS and HLC estimates were considered equivalent values and were averaged to produce a capacity estimate of 21,439 acre-feet. A 6.4 percent reduction in this capacity (5 percent standard error) was used in estimating the 90 percent confidence yield. For the yield analysis, 90 percent of the lake's capacity is considered usable; the minimum elevation of the usable pool is roughly 604.5 feet.

Until the past few years, lake dredging by the city was reportedly removing sediment at a rate roughly equal to the long-term sediment deposition rate of 118 acre-feet per year estimated by ISWS surveys, thus maintaining the capacity of the lake. Since 2009, the rate of dredging has been increased and within the next few years is expected that it will result in a net increase in the lake capacity of roughly 3,000 acre-feet.

As stated earlier, estimates of inflow are provided from the USGS stream gage on the Sangamon River at Monticello, which has a continuous record of daily flows from 1914 to the present. In estimating Lake Decatur inflows, daily flows from this gage are adjusted by a drainage area ratio to reflect the increase in drainage area between the Monticello gage (550 sq mi) and Lake Decatur (925 sq mi). Over the course of a 7- to 9-

month drought, the total estimated inflow into Lake Decatur is expected to have a 15 percent standard error of estimate.

Supplemental Sources. Use of the DeWitt well field in 2005 and 2007 showed that well interference with nearby groundwater users became a problem after pumping at a rate of 9 mgd for 60 to 70 days. Studies conducted for the City of Decatur have indicated that the field should be able to yield 6.2–8.0 mgd on a continuous basis (Black & Veatch, 2007). The present yield analysis assumes that the well field will be pumped at a rate of 9 mgd for 65 days and pumping will then be reduced to 7 mgd for the remainder of the drought. During the 2011 drought, the city adopted an alternative scheme in which the wells were pumped at 13 mgd and turned off when needed to avoid well interference. Although the calculated system yield may change slightly with different pumping schemes, the overall yield difference is not expected to be much as long as the field can maintain an average rate of 6.2–8.0 mgd during the remainder of the drought after pumping is initiated. Initial pumping of the field will begin when the reservoir level reaches an elevation of 612.7 feet, which can occur 4 to 6 weeks after the time when the lake first starts to fall below full pool (614.4 feet). The 612.7 trigger level is slightly lower than the 613.0 trigger as outlined in the Drought Action Plan, but more similar to the response timing as evidenced in 2007. It is also assumed that 30 percent of the water pumped from the wells will be lost in transmission to Lake Decatur, either through evaporation or seepage losses from the channels of Friends Creek and the Sangamon River.

Pumping from the city-owned former gravel pit is assumed to begin when the level in Lake Decatur falls to 613.2 feet–again, slightly lower than 613.5 feet noted in the Drought Action Plan–but the timing difference has negligible influence on the estimate of total yield. It is assumed that a total of 300 million gallons can be pumped from the former gravel pit (4 mgd over a 75-day period), which is 10 percent less than the amount that was pumped from the pit in 2005, which was not considered a severe drought.

Comparison of Historical Drought Periods. Using the water budget analysis, preliminary yields were determined for the current system using seven historic drought sequences. For Decatur, the worst drought sequences, ranked in order from most severe (lowest yield) to moderate, occurred in 1930-31, 1914-15, 1953-54, 1963-64, 1988-89, 1940-41, and 1999-2000. The durations of these drought periods, from the simulated onset of lake drawdown to the time of the lowest pool level (if the droughts were to recur under present day water use conditions), are as follows:

Worst Drought:	July 15, 1930–April 20, 1931 (280 days)
Second worst:	June 12, 1914–January 31, 1915 (234 days)
Third worst:	July 30, 1953–March 12, 1954 (226 days)
Fourth:	June 16, 1963–January 19, 1964 (218 days)
Fifth:	June 12, 1988–November 11, 1988 (153 days)
Sixth:	July 4, 1940–December 30, 1940 (180 days)
Seventh:	July 24, 1999–February 10, 2000 (202 days)

For these historical droughts, lake drawdown was usually preceded by at least three months of dry weather. It is noted that the most severe droughts listed here have not necessarily been the most intense droughts, but instead tend to be the longest in duration. For example, the 1988 drought was probably the most intense of the drought periods, but was not comparatively long in duration and started to recover by November of that year; as a result, it is identified as only the fifth worst on record relative to its impact on yield. The worst four droughts listed above all have durations in excess of seven months, with the 1930 drought of record lasting nine months. Three of the listed droughts (1914, 1963, and 1988) started very early, causing lake drawdown to commence by the middle of June.

In the simulated water budgets for all seven historical drought sequences, Lake Decatur recovers back to full pool during either the following winter or spring seasons. For most of the historical droughts the date of full recovery is in March or April. But the latest recovery time is that associated with the 1930-31 drought of record, in which the simulated lake level does not return to full pool until early June 1931.

Possible Characteristics of a Worse-Case Drought. As discussed earlier, other regions of the United States have experienced new droughts of record in recent years. Although water supply planning is usually based on the severity and frequency of historical drought periods, droughts that are more severe can happen in the future and their possibility should not be ignored. As one example, it is possible that the spring season following a drought year could be exceptionally dry, causing Lake Decatur to not recover to full pool. Thus, the lake would enter the next summer season below capacity, creating a multi-year drought. Projected future increases in the city's water demand are expected to enhance the probability that the lake might not recover to full pool in the spring during a severe drought. A more likely scenario, however, is that a single-season drought will occur that is simply longer in duration than the 1930-31 drought of record. For example, if the drawdown period associated with the 1930-31 drought had started in mid-June instead of mid-July (similar to the onsets of the 1914, 1963, and 1988 droughts), then the duration of the critical drawdown period would have been extended from 9 months (July to April) to 10 months (June to April). In adding an extra month to the duration over which the available capacity must supply water, the safe yield of the system may be expected to be reduced by over 10 percent.

Results of Yield Analyses. Table 13 provides the safe yield of the Decatur water supply system as computed for the three worst historical droughts plus a simulated 10-month worse-case drought period. Yields are computed for two levels of confidence: 1) the 50 percent confidence yield (or best estimate), and 2) the 90 percent confidence yield. In addition to the standard computation assuming that 10 percent of the lake volume (unusable volume) remains at the point of lowest drawdown, the yield is also computed for a condition in which the system has a least a 30-day remaining supply at its lowest drawdown. The yield of the supply system for the 1930-1931 drought of record is computed to be sufficient (greater than the expected drought demand) at the 50 percent confidence level, but not at the 90 percent confidence level. For this reason, the system is considered at-risk for potential shortages during such a drought. It is also noted that the

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50 percent yield for the worse-case (10-month) drought scenario is less than the city's current average water use rate.

The yield estimates listed in Table 13 are based on an assumption that 30 percent of the water pumped from the DeWitt field is lost in transmission after it is discharged to Friends Creek. If instead the transmission loss was assumed to be 50 percent, the yield estimates for the 1930-1931 drought of record would be reduced by approximately 1.3 mgd for the 50 percent yield and 1.0 mgd for the 90 percent yield.

The yield of the city's system was also computed under the assumption that Lake Tokorozawa is not available as a dependable emergency supply. If the lake were to be added as a supplemental source, the amount of water that could be obtained from Lake Tokorozawa is estimated to be 2000 acre-feet (650 MG), essentially increasing the system's yield by roughly 2 mgd. However, this value is uncertain because: 1) the lake receives groundwater inflow, and 2) there has never been a situation in which the lake has been drawn down to an extent where withdrawal limitations have been tested. The addition of Lake Tokorozawa would not change the classification of the system as being at risk, but would reduce the probability that the system would experience shortages during a drought of record condition.

If ongoing dredging is able to increase the lake's volume by roughly 3000 acre-feet (to a capacity of 24,440 acre-feet), then the yield of the system can be expected to increase by roughly 3 mgd. If Decatur can continue a dredging program in the future to maintain the capacity of their reservoir, as has been done over the past decade, there would be no reduction in yield over time. If, however, the maintenance dredging were to cease, the system could expect to see a 5 to 6 percent reduction in yield per decade.

Table 13. Computed 2010 Yield of the Decatur Water Supply System, in mgd

Minimum water level = 10% of lake volume remaining

	50% yield	90% yield
1930 – 1931	38.1	32.8
1914 – 1915	39.0	33.4
1953 – 1954	43.5	36.4
Worse-case (10-month) drought	32.9	27.1

Minimum water level = 30-day supply of water remaining

	50% yield	90% yield
1930 – 1931	36.4	31.6
1914 – 1915	37.0	31.8
1953 – 1954	40.8	34.4
Worse-case (10-month) drought	31.8	26.5

Expected Lake Drawdown during the Drought of Record and Worse Case Drought Scenarios. Figure 85 and Figure 86 show simulated sequences of lake drawdown for Lake Decatur under two scenarios, respectively: 1) the 1930-1931 drought of record recurs along with the current water supply system and level of water use, and 2) a 10-month worse-case drought (starting like the 1988 drought and ending like the 1930-1931 drought) occurs with the current water supply system and level of water use. An average water demand rate of 35 mgd was used for this simulation; however, the demand rate was allowed to vary in a manner similar to what might be expected during a true drought situation–with a demand rate of 45 mgd during the initial weeks of the drought (prior to implementation of voluntary restrictions) eventually being reduced to 32 mgd with conservation measures from the community and its industries. The timing of water use restrictions and use of supplemental supply sources are defined by the City's Low Lake Level/Drought Action Plan, discussed earlier. The simulated sequences suggest that the reservoir would remain at very low pool levels for many months during the winter and spring prior to eventual recovery. It is recommended that additional water supply planning and response should examine the potential impact of such an extended drawdown period on the community and its industries.
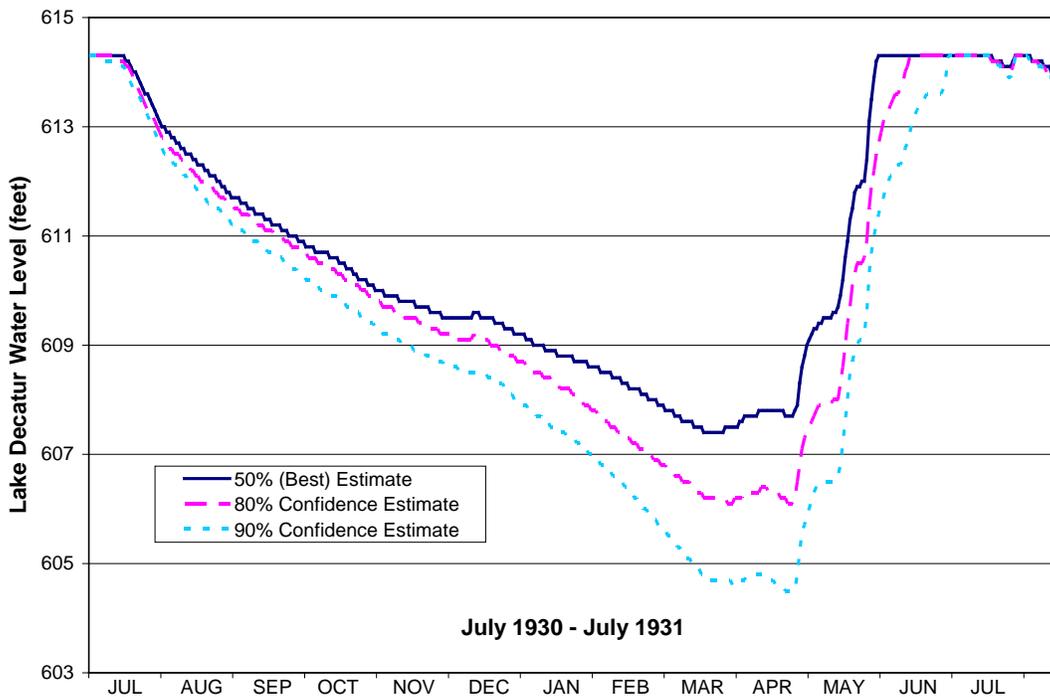
Figure 85. The sequence of simulated Lake Decatur drawdown for the current system assuming the conditions of the 1930–1931 drought of record were to recur
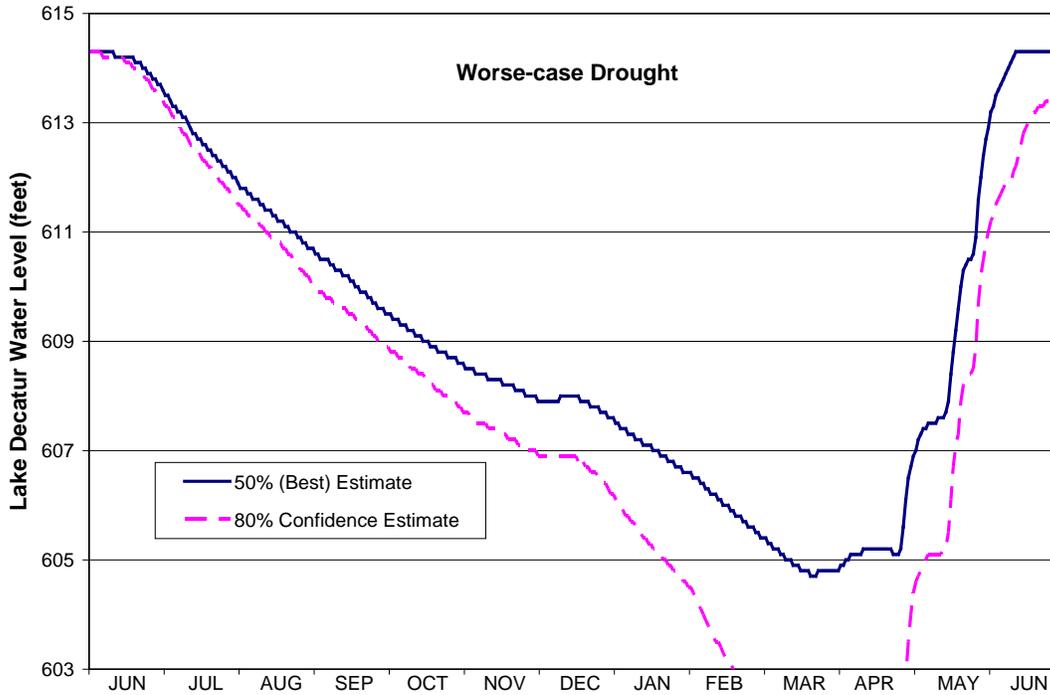
Figure 86. The sequence of simulated Lake Decatur drawdown for the current system assuming a 10-month worse case drought were to occur

Springfield – Inadequate System

In addition to providing potable water to residents of Springfield and nearby communities and to commercial and industrial users, Lake Springfield also provides water needed to operate the city's coal-fired electricity generating plants located alongside the lake. According to estimates provided by City Water, Light and Power (CWLP), the power plants consume an average 9.2 mgd of water for ash sluicing and cooling. Most of this water (6.9 mgd) is used to sluice coal ash from the power plants to settling basins located immediately north of Spaulding Dam. Although water from the settling basins has in certain situations been recycled back into Lake Springfield, this practice cannot be maintained for extended periods because it results in high levels of boron in the lake. For this reason, recycling of ash sluice water is not considered as a supplemental supply option in this analysis. Approximately 2.3 mgd of water is also consumed in the power plant cooling process, primarily through a net increase in evaporation from the lake. Despite changes in cooling technology between the new Dallman 4 plant and the recently retired Lakeside unit, the overall consumption rate for cooling water is not substantially different according to estimates provided by CWLP. The expected 2010 average annual water demand for the Lake Springfield system is nearly 32 mgd–22.6 mgd for the potable supply and 9.2 for power plant use. Estimates of total water demand by CWLP include some additional elements, not described here, which do not substantially affect the overall assessment of system adequacy. In addition, water demand during drought conditions is expected to be higher than this average use

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rate, even when considering the implementation of voluntary and mandatory conservation measures at progressive stages during a drought.

Springfield's water use has been slowly but steadily increasing in recent decades, with a growth rate of roughly 4 percent (1 mgd) per decade. Future water demand projections by CWLP are consistent with the current growth rate. Water demand projections by Wittman Hydro (WHPA, 2008) have a similar rate of increase for the Less Resource Intensive scenario, but adopt a higher growth rate of roughly 2 mgd per decade for their Critical Trends scenario. The total increase in water use using WHPA Critical Trends scenario is nearly 8 mgd.

The yield of the Springfield water supply system was analyzed in 1998 by the ISWS (Knapp, 1998). In that analysis, the traditional 50 percent confidence (best estimate) yields of the lake were computed for 10-, 25-, 50-, and 100-year droughts. Results from this previous analysis continue to provide the base yield estimates used by the city with minor adjustments for factors including the loss of capacity by sedimentation. The water budget model developed for the 1998 study used a sequential yield analysis from which yields for individual historical drought periods can also be identified. The water budget model was also adjusted for the present study to account for data and model uncertainties and compute the 90 percent confidence yield.

There have been no major changes to Springfield's water supply system since the 1998 yield study. Lake Springfield is the primary source of water, with its two major tributaries and source of inflow being Sugar Creek and Lick Creek. Streamflow from the South Fork Sangamon River is also pumped into the lake whenever the lake falls below normal pool and sufficient flow exists in the river. [Note: The pumping station for this supplemental supply is located on Horse Creek; a gate on the South Fork Sangamon River is raised to cause the flow in the South Fork to back up into Horse Creek from where it is pumped.] An additional emergency source of supply, which remains a temporary option while the city is pursuing alternatives for additional sources of water, is to create an inflatable dam on the Sangamon River that can back up water into the South Fork from where it can then be pumped into the lake. However, this option requires that a minimum instream flow level be maintained in the Sangamon River, and the flow in the Sangamon River during drought would already be limited upstream by Lake Decatur. If the 1953–1954 drought of record were to reoccur with the current system and drought response plan, it is estimated that this emergency supply would not be implemented early enough to provide a consequential amount of additional water to the lake.

Summary of Data Inputs. The 2010 capacity of Lake Springfield (at an elevation of 560 feet) is estimated to be 50,280 acre-feet, using capacity measurements and sedimentation rates substantiated from multiple sedimentation surveys, most recently the 2004 survey by CWLP (Brill and Skelly, 2007). The measured capacity of the reservoir from that survey, 51,246 acre-feet, closely matches the projected capacity based on the previous surveys (Singh and Durgunoglu, 1990) with adjustments to account for sediment dredging. Because of the agreement between successive measurements, the standard error of estimate for these surveys is judged to be only 5 percent. However, for verification it is recommended that in the future the city may also want to conduct a

bathymetric survey producing a measurement that is not based on the exact same transects as previous surveys.

For most reservoir yield analyses, the upper 90 percent of the reservoir's storage is considered usable for water supply. For Lake Springfield, this would represent the storage above a minimum usable elevation of roughly 538 to 539 feet. However, because Lake Springfield also serves as a cooling water supply, the elevation of the power plant intakes and the thermodynamics of the lake must be considered (in addition to water quality) in determining the usable capacity of the lake. CWLP has estimated that the minimum usable pool elevation for operating the Dallman 1-3 power plants is 548 feet. The usable capacity above the 548-foot elevation is estimated to be roughly 34,500 acre-feet, or approximately 70 percent of the total capacity of the lake.

Two historical streamflow records are available to assess the drought inflow into Lake Springfield and the availability of flow to be pumped from the South Fork Sangamon River. The USGS gage on the South Fork Sangamon River near Rochester, located at the site of the diversion gate, has a continuous flow record from 1949 to the present and provides a direct measure on the flow available to be pumped from the river to the lake. The standard error of measured flows for this gage is considered to be 10 percent over the course of a drought period. A second gage on Sugar Creek near Auburn, operated by the Illinois Department of Natural Resources, Office of Water Resources (OWR) from 1951 to 1978, provides a flow record for roughly 19 percent of the watershed that drains into Lake Springfield. Because this gage had a record of only 27 years and represented only a fraction of flows entering the lake, it was decided during the previous yield study (Knapp, 1998) that simulated daily flows from a watershed model, calibrated with regional streamflow data, would provide a more complete estimate of drought sequences of inflow into Lake Springfield for the purpose of analyzing the operation and yield of Springfield's water supply system. The simulated flows developed in this previous modeling effort were also used for the present analysis. Information on the development of the watershed model was provided in Knapp (1998). With the watershed model and daily climatic (precipitation and temperature) data, this previous study simulated a 105-year (1891–1995) flow record for Lake Springfield and South Fork Sangamon River watersheds. The standard error of simulating cumulative inflows into Lake Springfield during a severe drought using this modeling approach is approximated to be 30 percent.

Comparison of Historical Drought Periods. Using the water budget analysis, a 105-year sequence of reservoir operation for the Springfield system was used to determine yields for the current system using seven historic drought sequences. For Springfield, the three worst drought sequences, ranked in order from most severe, occurred in 1894–1895, 1953–1954, and 1930–1931. No other droughts in the 1891–1995 period were considered sufficiently severe to threaten the availability of the Springfield water supply. In this respect, observations and responses during the more recent 1988–1989 and 1999–2000 droughts do not provide a strong basis for evaluating and comparing the most severe droughts that Springfield has experienced. The durations of the three worst drought periods, from the simulated onset of lake drawdown to the time of

the lowest pool level (if the droughts were to recur under present day water use conditions), are as follows:

Worst Drought:	June 1894–December 1895 (19 months)
Second worst:	July 1953–December 1954 (18 months)
Third worst:	July 1930–October 1931 (15 months)

As is noted below in the yield analysis, the yields of the 1894–1895 and 1953–1954 droughts are very similar, such that in evaluating certain cases with alternative supply sources the 1953–1954 drought is instead identified as the worst drought. For example, it is estimated that 1953–1954 would be the worst drought for Lake Springfield if the South Fork Sangamon River were removed as a supplemental supply and the lake was the only supply source (Knapp, 1998). Because there are no measured hydrologic records from the 1894–1895 drought such that the yield analysis for that drought relies only on flow values simulated from climatic observations, the 1953–1954 drought is considered in this study to be the "drought of record."

Possible Characteristics of a Worse Case Drought. The water budget analysis and climatic records identify that the 1894–1895 drought actually started in 1893. If the 1893–1895 climatic conditions were to recur with the current system, the Lake Springfield water level would only briefly return to full pool in late spring of the second year (1894) before the lake drawdown resumed in early summer. If either the simulated inflows used in the water budget analysis were slightly lower or water demands slightly higher, the computed lake levels would not return to full pool and the simulated 19-month period of critical drawdown (1894–1895) drought would instead have become a 31–month (1893-1895) drought condition. Thus, it is quite plausible that a worse-case drought scenario would involve a critical drawdown period of 31 months or longer.

Results of Yield Analyses. Table 14 provides the safe yield of the Springfield water supply system as computed for the three worst historical droughts. In addition, a 100-year drought yield is estimated using a frequency analysis of the historical drought yields. Yields are computed for two levels of confidence: 1) the 50 percent confidence yield (or best estimate), and 2) the 90 percent confidence yield. The 50 percent confidence yield for the two worst historical droughts as well the 100-year drought of record is less than the city's current water demand, thus the Springfield system is designated as inadequate.

The impact of sedimentation on the yields of the Springfield system was also analyzed by Knapp (1998). The results of that study indicate that capacity losses will lead to a reduction in the system's yield by approximately 0.4 mgd per decade; thus, by 2050 the system yield is expected to be reduced by 1.6 mgd. The impact of sedimentation on yield is diminished somewhat because the yield computations are based on a usable pool elevation of 549 feet, and much of the expected sediment deposition is expected to occur below this minimum pool level.

Expected Lake Drawdown during the Drought of Record and Worse Case Drought Scenarios. Figure 87 and Figure 88 show simulated sequences of lake drawdown for Lake Springfield under two scenarios, respectively:

1) the 1953–1954 drought of record recurs with the current water supply system and level of water use;
2) the 1893–1895 drought recurs with the current water supply system and level of water use.

In addition to a constant 9.2 mgd demand rate for power plant consumption, these scenarios use an average potable water demand rate from 22 to 23 mgd. The potable demand rate was allowed to vary in a manner similar to what might be expected during a true drought situation–with a demand rate of 32 mgd during the initial warm-season months of the drought, eventually being reduced to a 18 mgd base use (cool season) in the latter stages of the drought following conservation efforts from the community and its industries. The timing of water use restrictions and use of supplemental supply sources are defined by the Drought Management Schedule of the city's Emergency Water Supply Plan.

Table 14. Computed 2010 Yield of the Springfield Water Supply System

Minimum water level = 548 feet

	50% yield	*90% yield*
1894 – 1895	27.5	23.1
1953 – 1954	27.8	25.7
1930 – 1931	33.0	31.1
100-year drought	26.4	23.3

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The simulated Lake Springfield levels indicate that during the later stages of these droughts the lake would fall below the 548-foot elevation needed to maintain operation of the city's power plants. In the best estimate (50 percent confidence) simulations for both the 1953–1954 and 1893–1895 droughts, the lake would be expected to remain below 548 feet for over three months. In the 90 percent confidence level simulations, the lake would remain below 548 feet for roughly six continuous months. During these times of lower lake levels, Springfield would presumably need to purchase most of its electricity from other suppliers. Water budget assessments of other power plant reservoirs in central and southern Illinois indicate that many such lakes will also likely experience low water levels and potential power plant shut-downs during these severe drought conditions. Thus, there may be a risk or uncertainty in being able to purchase a desirable amount of electricity on the open market at a time when the available supply is low.

When Lake Springfield's level falls below 548 feet, the lake has roughly a six-month potable supply remaining assuming: 1) a potable water use rate of approximately 20 mgd, and 2) the lowest 10 percent of the capacity is considered unusable for previously stated reasons. It is unlikely (less than a 10 percent probability) that the potable supply would be fully depleted under either the 1953–1954 or 1893–1895

drought scenarios. However, there is no guarantee that the next major drought could not be more severe or longer in duration than either of these two historical droughts. In the midst of such severe droughts, and lacking a reliable forecast of when the drought might end, the community would need to prepare for the possibility of continued (longer) drought. For this reason, even if the assessment of drought vulnerability were based solely on the potable supply, the Springfield system would be considered marginal.

To be considered fully adequate for the current level of both potable and cooling uses, it is estimated that the city would need to develop supplemental water sources that could develop an additional 9 to 10 mgd supply covering the entire duration of the drought. If supplemental supplies were only going to be accessed during the latter nine months of an 18-month drought, that being a response consistent with the Drought Management Schedule of the city's Emergency Water Supply Plan, then those sources would need to provide a rate of 18 to 20 mgd over that latter nine-month period. In addition to making up the present 9 to 10 mgd deficit, the city should also further expand its supply to include expected water use growth in the upcoming decades; otherwise the city would soon again be identified as a drought-vulnerable system.
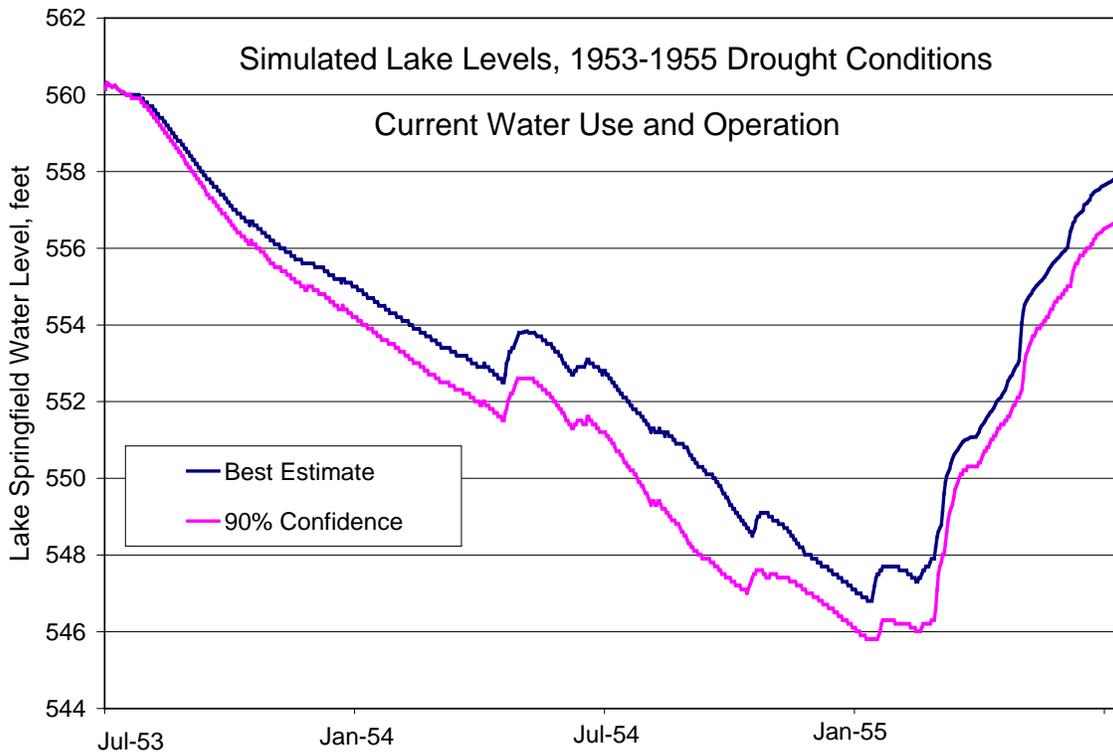
Figure 87. The sequence of simulated Lake Springfield drawdown for the current system assuming the conditions of the 1953–1954 drought of record were to recur
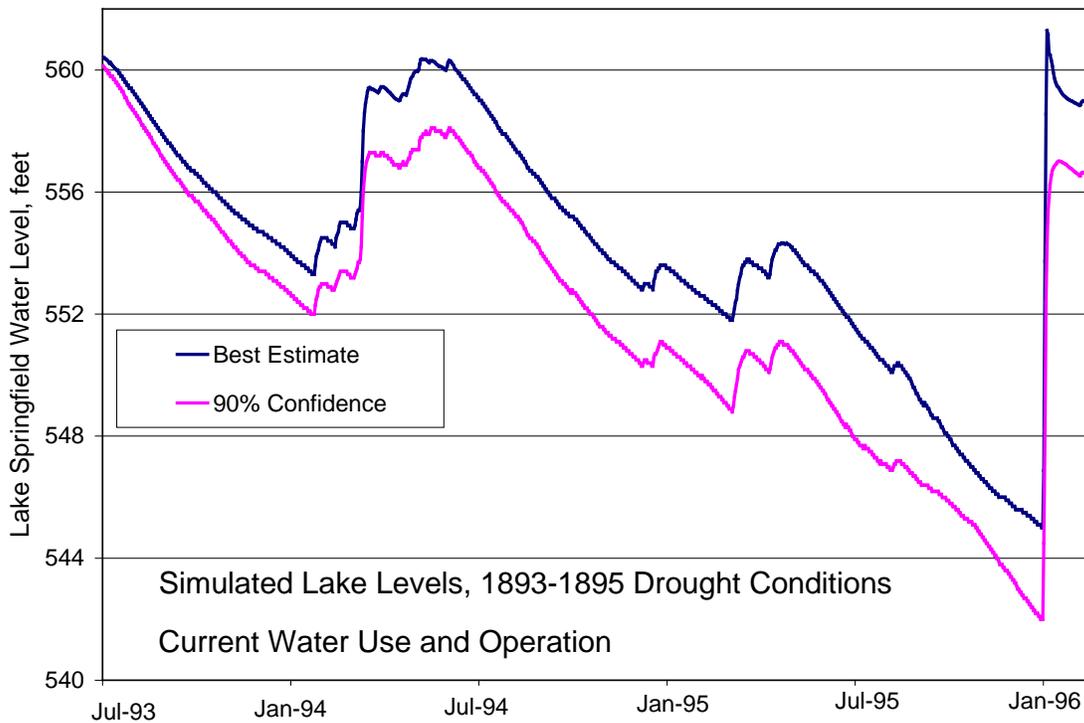
Figure 88. The sequence of simulated Lake Springfield drawdown for the current system assuming the conditions of the 1893–1895 drought of record were to recur

Bloomington – At Risk System

The City of Bloomington obtains its water supply primarily from two reservoirs in northern McLean County, Lake Bloomington and Evergreen Lake. The city's water treatment plant is located on Lake Bloomington, the primary supply source. Water from the larger Evergreen Lake is pumped to Lake Bloomington as needed. An intake on the Mackinaw River provides an emergency supply that can pump up to 14,000 gallons per minute (gpm) into Evergreen Lake during droughts, although there is a required instream flow level for the river that limits the availability of this source.

There have been two enhancements to the system's water availability since the last major drought occurred in 1988: 1) a pumping station on the Mackinaw River north of Evergreen Lake was installed to allow river water to be pumped into the lake during times when the river's flow exceeds an established minimum protected level, and 2) the spillway level for Evergreen Lake was raised 5 feet, creating an additional 4,000 acre-feet of storage at normal pool. Collectively, these additions increased the yield of the system by approximately 3 mgd. However, over the same 20 years the city's water demand has also increased by more than 2 mgd, such that the present drought vulnerability of the system is only slightly improved from what it was prior to the 1988 drought.

The reported average withdrawal from the lakes from 2003 to 2007 was approximately 12 mgd. Water demand projections by WHPA (2008) indicate that water

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use will increase by an additional 2.5 mgd over the next 20 years (2030) and 5 mgd by 2050 following the baseline (Critical Trends) scenario.

Summary of Data Inputs. The capacities of Lake Bloomington and Evergreen Lake were measured in 1999 using bathymetric surveys conducted for the city by Hanson Engineering. These capacity estimates were adjusted by the ISWS to reflect the expected amount of sedimentation loss from 1999 to 2010. The 2010 capacity of Lake Bloomington, at a full pool level of 719.5 feet, is projected by the ISWS to be 6,484 acre-feet. The 2010 capacity of Evergreen Lake, at a full pool level of 720.0 feet, is projected to be 15,369 acre-feet. The capacity estimates are expected to have a standard error of 10 percent. Yield estimates are based on the assumption that 90 percent of the storage in the two reservoirs is usable; thus the minimum lake levels for Lake Bloomington and Evergreen Lake were set at 699.0 and 692.3 feet, respectively. Differences in the minimum storage of a few hundred acre-feet may change the yield estimates by 0.1 to 0.3 mgd, but this would not be sufficient to affect the overall assessment of drought vulnerability.

A USGS streamflow gage was operated from 1933 to 1958 on Money Creek immediately upstream of Lake Bloomington. An additional USGS gage was operated from 1939 to 1958 on Hickory Creek, a smaller tributary to Lake Bloomington. The summation of flows from the Hickory Creek and Money Creek gages represents roughly 91 percent of the inflow to Lake Bloomington from 1939 to 1958, providing data over two major drought periods (1939–1941 and 1955–1957). After the lake's spillway was raised in 1958, both gages were discontinued because they were then affected by backwater from the lake. However, a replacement USGS gage on Money Creek (near Towanda) was installed farther upstream and operated from 1958 to 1982. This second gage represents 71 percent of the inflow to Lake Bloomington during this period, including the 1963 1964 drought period. During the specified drought sequences, observed flows from streamgages were adjusted using a drainage-area ratio to compute total inflow into the lake.

The observed flows at the Money Creek gages were also used to estimate the inflow from Sixmile Creek into Evergreen Lake, as adjusted using a drainage-area ratio to account for the difference in watershed size. For most applications where data from a nearby gage is adopted as a "surrogate gage" for estimating flows, the expected uncertainty for the cumulative flow amount would be roughly the same as the standard error in a regional regression equation (which in this case would be roughly 30 percent). However, because the Money Creek and Sixmile Creek watersheds have very similar watershed characteristics, a lower uncertainty estimate of 20 percent was assumed for the inflows into Evergreen Lake.

There are no streamflow data available for two other major drought sequences affecting the Bloomington system, 1930–1932 and 1988–1990. However, monthly records of lake level, water use, and precipitation are available for these drought periods as well as lake surveys from which monthly lake storage could be computed. The 1930–1932 data are recorded in Roberts (1948) and ISWS open-file reports. With water use and

lake level data, the water budget equation (Equation 2) can be used to back-calculate monthly inflow into Lake Bloomington. Using this approach, the cumulative inflow over the entire duration of these droughts can have nearly the same accuracy/uncertainty as observed streamflow records (10 percent) when an accurate elevation-storage relationship exists for the lake as measured from reservoir surveys.

Mackinaw River flow records from the USGS stream gage near Congerville (1945–present) were used to determine the amount of water that could be pumped from the Mackinaw River pumping station during drought years. The observed flows at Congerville were multiplied by a drainage area ratio (0.541) to estimate flows at the Mackinaw station. The pumping station allows for a maximum withdrawal rate of 20 mgd, limited by the minimum protected flow (100 cubic feet per second (cfs) from March through June and 20 cfs the remainder of the year). The analysis assumes that the pumping facility operates at 80 percent efficiency, in that pumps would likely be operated intermittently and might not always be turned on when sufficient flow is available.

Comparison of Historical Drought Periods. Using the water budget analysis, preliminary yields were determined for the current system using five historic drought sequences. For Decatur, the worst drought sequences since 1930 (ranked in order from most severe to moderate) occurred in 1939–1941, 1930–1932, 1988–1990, 1955–1957, and 1963–1964. The durations of these drought periods, from the simulated onset of lake drawdown to the time of the lowest pool level (if the droughts were to recur under present day water use conditions), are as follows. The critical drought durations listed above are as computed with Lake Bloomington and Evergreen Lake being used jointly following current operation practices.

Worst Drought:	July 21, 1939–March 31, 1941 (20 months)
Second worst:	June 1930–November 30, 1932 (30 months)
Third worst:	May 5, 1988–January 18, 1990 (20 months)
Fourth:	June 22, 1955–March 27, 1957 (21 months)
Fifth:	May 1, 1963–December 31, 1964 (20 months)

The 1930-1932 Drought. The construction of Lake Bloomington was completed in 1930, at the beginning of one of the worst droughts in central Illinois. According to an ISWS open-file report (Tippy, 1930), the lake had not completely filled following construction before water supply withdrawals commenced in August 1930. By the time lake levels were initially recorded in October 1930 there was no lake inflow (as estimated using changes in lake storage) and the lake level was already 3 feet below full pool and falling steadily. Although prior lake and inflow records are not available, a reconstruction of inflow during the late summer of 1930 using baseflow recession characteristics of Money Creek suggests that the lake was about 1 foot below full pool before withdrawals began in August 1930. A water budget analysis based on this reconstructed inflow and lake data from the remainder of the drought calculated a drought yield similar in magnitude to the 1939–1941 drought of record. More importantly, the critical drawdown duration during the 1930–1932 drought is estimated to be at least 30 months, substantially longer than the 20 to 21 months for the remaining major historical droughts examined in this study.

Possible Characteristics of a Worse Case Drought. The partial records from 1930 to 1932 identify the previous occurrence (and thus the future possibility) of a drought period lasting longer than the 20-month drought of record. A plausible worse-case drought scenario could include the possibility that such a long-duration drought may also share similar characteristics with some of the most intense droughts such as the 1988–1990 and 1939–1941 droughts. For example, what might have happened if the 1988–1990 drought had not recovered until 10 months later in 1990? A hypothetical 31-month "worse-case" drought scenario was fashioned having the identical hydrologic/climatic conditions as the first 20 months of the 1988 drought (using hydrologic data from May 1988 through December 1989) but with the duration of the 1930–1932 drought (finishing with data from the last 11 months from January to November 1932).

Results of Yield Analyses. Table 15 provides the combined safe yield for the Bloomington water supply system as computed for the four worst historical droughts. In addition, the yield is computed for the hypothetical 31-month "worse case" drought scenario. The system's yield is computed both with and without the supplemental supply provided from the Mackinaw Pumping Station and at two levels of confidence: 1) the 50 percent confidence yield (or best estimate) and 2) the 90 percent confidence yield. The computation and impact of the water that can be pumped from the Mackinaw pumping station is discussed in the following paragraph. Including the supplemental water from the Mackinaw pumping station, the 90 percent confidence yield for the 1939–1941 drought of record is less than the city's current water demand. As a result, the Bloomington system is designated as at-risk.

The yield of the worse-case drought is noticeably less than the yield of any of the historical droughts, suggesting that the system may be particularly vulnerable to a lengthy drought if, for example, future climate conditions were to shift toward that possibility. The reason the worse-case drought yield is low is because there would be little inflow into the reservoir during the additional 11 months of drought duration. In this respect, the vulnerability of the Bloomington system to a longer-duration drought may be heightened because both lakes are located in small watersheds, which are more likely to produce little inflow to the reservoirs during an extended drought condition. If such a worse-case drought scenario were indeed to occur, however unlikely, the storage in the reservoir would likely be depleted and the city would need to find water from other sources.

Table 16 compares the cumulative flow, expressed in inches of runoff, at both the Money Creek and Mackinaw River (near Congerville) gages for the four lowest 20-month periods on record. The Money Creek gaging records indicate that the 1939–1941 period had the lowest cumulative streamflows during any recorded drought period. There is no available flow record for the Mackinaw River during the 1939–1941 drought except for that measured at the USGS gage on the lower reach of the river near Green Valley in western Tazewell County. (The Green Valley flow record is not considered representative of flows at the Mackinaw River pumping station because the Green Valley flow record has uncharacteristically high baseflow levels resulting from the hydraulic connection of

the lower river with the unconfined portion of the Mahomet aquifer.) There are no flow records from which to assess the pumpage available from the Mackinaw River during either the 1930–1932 drought or worse-case drought scenario.

Also shown in Table 16 is the estimated yield that could be provided from the Mackinaw River pumping station under these different historical droughts. Because there is no flow record at the Congerville gage during the 1939–1941 drought from which to estimate daily flows on the Mackinaw River, the estimated yield is based on an assumption that the 20-month cumulative runoff at the pumping station was equivalent to that measured at the Money Creek gage, i.e., 0.8 inches of runoff.

Results of the water budget analysis indicate that if the capacities of the two reservoirs are reduced to reflect the expected capacity loss by 2050 due to sedimentation, the yield of the system would be reduced by approximately 1.1 mgd, or a loss of nearly 0.3 mgd per decade. The loss of yield per decade from sedimentation is relatively small compared to the anticipated growth in water demand over the next decade (+1.2 mgd) as estimated from WHPA. If the WHPA water demand projections hold true and no additional water sources are developed, within the upcoming decade the Bloomington system will be considered an inadequate system, with greater than a 50 percent chance of shortages if a drought similar to the 1939–1941 drought of record were to recur.

Table 15. Computed 2010 Yield of the Bloomington Water Supply System

Combined yield of Lake Bloomington and Evergreen Lake without Mackinaw pumping station

	50% yield	90% yield
1939-1941	12.1	10.1
1988-1990	13.2	10.7
1955-1957	13.9	12.6
Worse-case (31-month) drought	8.4	6.9

Total System Yield with Mackinaw Pumping Station

	50% yield	90% yield
1939-1941	12.7	10.6
1988-1990	14.6	11.8
1955-1957	15.9	14.2

Table 16. Comparison of Cumulative Flow (Inches of Runoff) for the Driest 20-Month Periods for Which Flow Records are Available, and Estimated Yield from the Mackinaw River Pumping Station

20-month period	Cumulative runoff (inches)		Estimated yield from the Mackinaw River pumping station, mgd
	Money Creek	Mackinaw River	
1939 – 1941	0.8	---	0.6
1955 – 1957	1.7	2.0	2.0
1963 – 1964	2.8	2.0	1.7
1988 – 1989	---	1.7	1.4

Expected Lake Drawdown during the Drought of Record and Worse Case Drought Scenarios. Figure 89 shows the simulated sequences of lake drawdown for Lake Bloomington and Evergreen Lake under a 50 percent confidence scenario in which the 1939–1941 drought of record recurs with the current water supply system and a constant water demand of 12.7 mgd. In this scenario, water is withdrawn from the two reservoirs in an alternate manner–first being withdrawn from Evergreen Lake during the summer months (when nitrate levels may be high) until that reservoir has been drawn down 5 to 6 feet, then being withdrawn from Lake Bloomington, etc. Based on the simulated conditions, the two lakes both reach near-minimum levels (with less than 2400 acre-feet of remaining joint storage) by March 1941 and remain near their minimum levels for nearly three months before replenishment begins in June 1941.

If the same 50 percent confidence scenario were simulated but instead using the community's current water demand (12 mgd), then the estimated joint storage of Lake Bloomington and Evergreen Lake during the March–June 1941 period would be reduced to 4400 acre-feet. This is roughly similar to the remaining storage that was in the lakes at the end of the 1988–1989 drought.
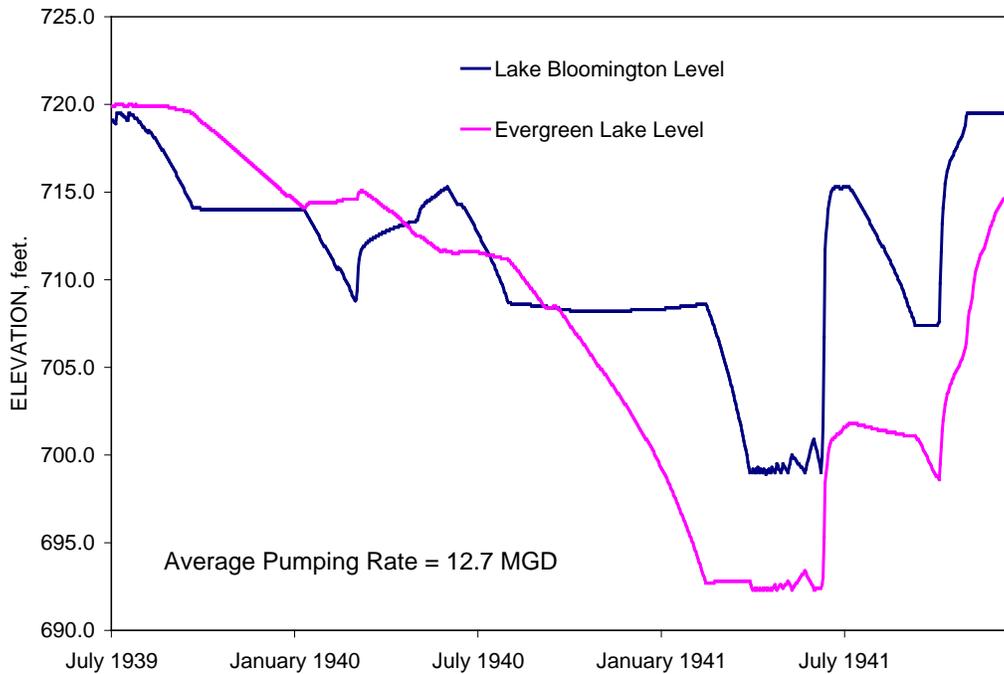
Figure 89. The sequence of simulated Lake Bloomington and Evergreen Lake drawdowns assuming the conditions of the 1939–1941 drought of record were to recur

Danville – Adequate System

The sole water supply source for the City of Danville water supply system (owned and operated by Aqua Illinois) is Lake Vermilion. Water is released from the lake to supply an intake located at a low-channel dam next to the water treatment plant approximately 2.4 miles downstream of the lake. The normal pool level of Lake Vermilion was raised 4 feet in 1991, more than doubling the amount of water stored in the lake. The present yield estimates for the system are based on adjustments to a yield analysis conducted by McConkey and Knapp (2001). In contrast to the drought-of-record analysis that has been conducted for the Decatur, Springfield, and Bloomington systems, the analysis presented here is for the 10-, 25-, 50-, and 100-year drought intervals as based on the previous study.

Danville's water demand has not changed substantially over the past 15 years, and is currently estimated as 8.4 mgd. The water demand is projected to increase to 9.0 mgd by the year 2050 (WHPA, 2008).

Summary of Data Inputs. A sedimentation survey of Lake Vermilion was conducted by the ISWS in 1998 (Bogner and Hessler, 1999), producing a measured capacity of 7971 acre-feet. Sedimentation in Lake Vermilion causes the lake to lose capacity by an average of 72 acre-feet per year (Bogner and Hessler, 1999), equivalent to about 1 percent of the lake volume per year.

There is a USGS streamflow gage located on the North Fork Vermilion River upstream of Lake Vermilion (near Bismarck); however, that gage's record was not directly used in the analysis because its period of record (1989–2009) does not include a significant drought period. If the gage continues to be operated in upcoming decades, its record could factor significantly into yield analyses and would be expected to reduce the uncertainty associated with the 90 percent yield estimate. The yield analysis by McConkey and Knapp (2001) instead estimates reservoir inflow using gaging data from several regional gages, with the greatest reliance on long-term records available from the USGS gage on the Vermilion River downstream of Danville.

Historical Droughts and Possible Characteristics of a Worse Case Drought. Although the analysis presented here does not identify yields for individual historical drought events, an evaluation of the flow records suggests that the 1930–1931 drought would likely be identified as the drought of record for the Danville system. Other significant historical droughts occurred in 1920–1921, 1940–1941, and 1963–1964. The drought hydrology of Lake Vermilion is roughly similar to that of Lake Decatur, both representing moderately-sized reservoirs within comparatively larger watersheds. The critical drought duration for Lake Vermilion is estimated to be nine months, such that the reservoir would be refilled during late spring following all historical droughts and no carryover storage is needed for a second year of drought. Like Decatur, a worse-case drought scenario could consider a longer, more severe drought during which Lake Vermilion does not completely fill in the spring.

Results of Yield Analyses. McConkey and Knapp (2001) estimated the yield of the lake from 1998 to 2040 based on projected changes in the lake's capacity, shown in Table 17. This analysis has been extrapolated to the year 2050 to produce the following mid-estimate (50 percent confidence) yields. These yield values were then adjusted to account for uncertainties in data used in the analysis. For the 90 percent confidence estimate, the reservoir capacity was reduced by 12.8 percent, the stream inflow was reduced by 32 percent, and the evaporation was increased by 18 percent, producing the following 90 percent confidence yields for the 50-year drought. The resulting 90 percent confidence yield estimates are also shown in Table 17.

From the yield estimates and projected growth in demand, it is estimated that the Danville system would be "At Risk" by about 2040 when based on a 50-year drought event, or by 2030 when based on a 100-year drought. It is worth noting that the uncertainty in estimating drought inflows into Lake Vermilion will likely be reduced in future years as the USGS streamflow gage near Bismarck accumulates a more extensive record. Thus, with better input data, it is possible that the 90 percent yield estimates would increase relative to the 50 percent yield estimates.

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**Table 17. Changes in Yield Estimates for the Danville Water Supply System
Based on Projected Losses in Reservoir Capacity**

Year	50% yield (mgd) at selected recurrence intervals	
	50-year	100-year
1998	15.0	13.4
2010	14.1	12.7
2020	13.4	12.2
2030	12.8	11.7
2040	12.3	11.3
2050	11.8	10.9
Year	90% yield (mgd) at selected recurrence intervals	
	50-year	100-year
1998	11.3	10.1
2010	10.5	9.5
2020	9.9	9.0
2030	9.4	8.6
2040	8.9	8.2
2050	8.5	7.8

Projecting Future Surface Water Availability in East-Central Illinois

Impacts of Future Water Use

To project the impact of future water use on surface water availability, it is necessary to develop certain assumptions or scenarios about not only how much water will be used, but also where that water will come from. Yield analyses for the three largest community systems in the region clearly indicate that their current sources of supply will be insufficient in the future when faced with a potential drought condition similar to the worst droughts of the 20th century. Thus, an analysis of future conditions cannot be based on a simple assumption that the current sources will continue to be used to provide all water for these communities.

Each of these communities (Bloomington, Decatur, and Springfield) have evaluated various options for expanding their current supply through developing additional water supply sources. Their options for new water sources fall into one of three general categories: 1) developing additional surface water storage, either through building off-channel storage or impounding a stream; 2) developing new well fields in regional groundwater resources; or 3) importing water from a source outside the immediate vicinity of their current sources. Conservation and water reuse are additional factors that potentially can influence the amount of water these communities will need in the future, but they are not expected to remove the overall need to develop additional

sources of water. Community decisions regarding alternative sources will ultimately be based on a number of factors, including but not limited to the reliability of the proposed resource, construction and maintenance costs, and environmental impacts. The current study does not attempt to evaluate the relative merits of the different alternatives that each community is considering, only to examine how certain alternatives could affect stream hydrology and surface water availability in the region.

Unless there are substantial developments in water reuse as community water use increases, so also will the amount of treated wastewater being discharged into the region's streams. The growth in effluent discharges is expected to gradually increase low flow quantity in the Sangamon River downstream of Decatur and Springfield and in Sugar Creek and Salt Creek downstream of the Bloomington-Normal Sanitary District facilities. However, there are a number of potential water use developments that could, on the other hand, decrease the low flow conditions in the Sangamon River between Decatur and Springfield, as outlined in the following three examples.

1. In recent years there was some consideration that effluent could be supplied by the Decatur Sanitary District to the proposed Taylorville Energy Center as a water supply. If carried through, the water to have been transmitted to Taylorville (an amount estimated to be 3 mgd) would have no longer been discharged into the Sangamon River, thus reducing the low flow in the river.

2. Pumping groundwater adjacent to the Sangamon River has also been considered by Decatur as an alternative for augmenting the city's water supply. If this supplemental source were to be developed, it is likely that much of the water taken would be induced from the river's flow, potentially causing additional reduction in the river's flow.

3. One proposed source of water supply for the City of Springfield is the water contained in several sand and gravel pits located adjacent to the river between Buckhart and Riverton. It is believed that there is a hydraulic connection between these gravel pits, the surrounding groundwater resource, and the river, such that the water level in the gravel pits can respond to the rise and fall of the river stage. With such a connection, it can be anticipated that potential water withdrawals from these sand and gravel pits will induce the flux of river water through groundwater into the pits. The extent of the hydraulic connection is not known and can only be determined by conducting pumping tests, ideally conducted during periods of low streamflow. However, prior to 1930 the City of Springfield obtained its water through a series of collector wells located in the Sangamon River floodplain, and at that time it was estimated that half of the water collected in the wells was induced from the river. If, for example, the gravel pits were capable of providing an 8 mgd (12 cfs) supply to the city during a major drought, then it is feasible that perhaps half of this amount or more could effectively be taken from the river.

For each of the above cases, detailed technical studies beyond the scope of this investigation would need to be conducted to determine the potential impacts of specific

water resource development on regional streams. In particular, the connection between river flows and the shallow aquifers adjacent to the rivers need to be better understood. Nevertheless, it can be inferred that potential projects of the type described could noticeably reduce the low flow characteristics of adjacent streams and affect availability for other uses including those for instream needs.

Impacts of Potential Climate Change

A hydrologic simulation model of the Sangamon River watershed was prepared to assess potential impacts of climate change on flows in the east-central Illinois Region. 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. The model development and calibration processes adopted for this study are similar to the Fox River modeling and analysis detailed in a separate report (Bekele and Knapp, 2009).

With the use of the watershed model, it is not only possible to simulate historical streamflow values, but also to simulate streamflows that could potentially result from a hypothetical combination of conditions. Specifically, it is possible to overlap climatic input from historic time periods or the hypothetical future with the land use and water use conditions that exist today (2005 data is used to represent today's water use conditions). Through this process, the model can address a variety of scenarios, 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?" Although the watershed model cannot produce an exact estimate of what streamflows would be under selected climate scenarios, flows produced by different scenarios can be compared to give an indication of relative changes.

Selected Climate Change Scenarios. The 1971–2000 climatic record and 2005 land use and water use for the Sangamon River watershed were taken as the baseline condition to which all other scenarios are compared. Eight hypothetical climate scenarios based on a combination of potential future changes in average precipitation and temperature were analyzed. The scenarios are as follows:

Scenario I. A 5-inch increase in annual precipitation above 1971–2000 recorded amounts.

Scenario II. A 5-inch decrease in annual precipitation above 1971–2000 recorded amounts.

Scenario III. A 3-degree (Fahrenheit) increase in average temperature above 1971–2000 recorded amounts.

Scenario IV. A 3-degree increase in average temperature combined with a 5-inch increase in average annual precipitation.

Scenario V. A 3-degree increase in average temperature combined with a 5-inch decrease in average annual precipitation

Scenario VI. A 6-degree increase in average temperature

Scenario VII. A 6-degree increase in average temperature combined with a 5-inch increase in average annual precipitation.

Scenario VIII. A 6-degree increase in average temperature combined with a 5-inch decrease in average annual precipitation

There is considerable variability in the projections by various global climate models, with each model considered to have equal credibility. In developing the selected scenarios described above, 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 range of the middle 90 percent of all climate model results.

The 6-degree Fahrenheit increase in some scenarios 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 show a smaller projected increase in Illinois' air temperature by 2050, the great majority of credible models show some level of increase. Climate scenarios with a 3-degree temperature increase can be viewed as either: 1) the maximum projected increase by 2025, or 2) a middle-of-the-road projection of the temperature increase that might be expected by 2050. For these scenarios, temperature increases are expected to occur uniformly over all 12 months. Warmer climatic conditions are expected to reduce water availability in the landscape, as more water will be returned to the atmosphere through evaporation and plant transpiration. Thus it is also expected that, if precipitation is unchanged, climatic warming will cause streamflow amounts to be reduced under most conditions. Roughly half of the climate models project an increase in precipitation by 2050, whereas the other half project a decrease. Scenarios that describe a 5-inch decrease and 5-inch increase in average annual precipitation amounts represent roughly the outer 5th and 95th percentile range of model results, and no change in precipitation represents more of a middle-of-the-road scenario. Potential increases and decreases in precipitation are not expected to be uniform. For scenarios with a 5-inch decrease in average precipitation, a decrease of 3.5 inches is expected to occur during the 5-month growing season, May through September. For scenarios with a 5-inch increase in average precipitation, half of the increase (2.5 inches) is expected to occur during the growing season.

Flow Simulation Results. Flow simulations from the watershed modeling are presented in two formats. Table 18 presents flow amounts (in cfs) for eight selected streamflow statistics using the model simulations from the baseline condition and the eight climate scenarios. As discussed earlier, these are not strict predictions, but can be compared to the baseline condition to identify relative differences. For each of the climate scenarios, simulated streamflow amounts were compared to the 1971–2000

baseline flow condition at each of four long-term stream gage locations: the Sangamon River at Monticello, Riverton, and Oakford; and Salt Creek near Greenview. Despite various calibration efforts, the watershed model was not able to reasonably simulate low flow conditions at a fifth site, the South Fork Sangamon River near Rochester, and for this reason these South Fork simulated flows are not reported.

In the second format, the first eight climate scenarios are arranged, as illustrated in Table 19, to show increasing temperature from left to right and precipitation increasing from top to bottom. The baseline condition using the 1971–2000 historical record (no climate change) is in the left column, second row. In general, the wettest flow conditions are associated with scenarios in the upper left of the table and the driest flow conditions are associated with scenarios in the lower right of the table. Selected flow simulation results, shown in Tables 20–22, are presented as percentage changes relative to the baseline condition (instead of simulated flow amounts in cfs). To further simplify the presentation, the values given in Tables 20–22 represent the composite change in flows for all four Sangamon River watershed gaging locations. Table 20 shows the percent changes in the mean annual flow; whereas Tables 21 and 22 show the percent changes in the average flow during the driest and wettest calendar years, respectively, during the 30-year simulation period.

An examination of Tables 18–21 provides the following observations regarding expected changes in streamflow amounts:

- The change in the mean annual flow (Table 20) associated with the climate scenarios ranges from -40 to +33 percent, which appears to be consistent regardless of location within the watershed. The change in mean flow is much more sensitive to potential changes in annual precipitation than to temperature increases.

- The cumulative flow during the driest year (Table 21) was more sensitive to changes in climate scenarios than was the flow during an average year (Table 20). Conversely, the cumulative flow during the wettest year (Table 22) is less sensitive than the flow during an average year. This suggests a general increasing sensitivity from wetter to drier conditions.

- In a related response, simulated low flows were more sensitive than high flows to the potential climate change scenarios (Table 18). Specifically, the percent change in low flows (90th percentile) was typically greater than the percent change in normal flows (50th percentile), which in turn was greater than the percent change in high flows (10th percentile). However, this apparently does not hold true for the three driest scenarios (scenarios II, V, and VIII), for which the percent change in low flows is less than the percent change in normal flows.

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Table 18. Statistics of Simulated Flow Amounts for Each Climate Scenario

Sangamon River at Monticello

Scenario	Min. daily flow	7-day 10-year low flow	90% low flow	50% Flow	Mean flow	10% high Flow	1% high flow	Max. daily flow
Baseline	0.0	1.4	14	218	459	1208	3133	6112
I	0.0	6.0	23	334	614	1515	3804	7361
II	0.0	0.4	7	116	331	910	2612	5603
III	0.0	0.3	12	191	420	1148	2676	6107
IV	0.0	3.4	20	318	567	1441	3325	7240
V	0.0	0.2	5	96	297	858	2177	5445
VI	0.0	0.4	9	170	387	1065	2472	5962
VII	0.0	1.5	19	300	531	1357	3026	7063
VIII	0.0	0.1	4	82	269	788	1967	5519

Sangamon River at Riverton

Scenario	Min. daily flow	7-day 10-year low flow	90% low flow	50% flow	Mean flow	10% high flow	1% high flow	Max. daily flow
Baseline	44	59	102	1192	2078	4932	13589	27032
I	45	63	153	1711	2778	6583	16268	36621
II	40	57	78	712	1526	3636	11335	26147
III	38	56	94	1092	1908	4621	11657	25148
IV	42	59	148	1603	2568	6095	14275	31059
V	40	55	75	611	1377	3444	10048	21213
VI	34	54	88	978	1745	4170	10932	25666
VII	35	56	133	1491	2386	5613	13391	29981
VIII	34	53	73	506	1252	3138	9228	20973

Sangamon River near Oakford

Scenario	Min. daily Flow	7-day 10-year low flow	90% low flow	50% Flow	Mean Flow	10% high flow	1% high flow	Max. daily flow
Baseline	149	184	366	2298	4039	9810	23724	41263
I	169	225	586	3338	5396	12809	28715	50568
II	143	168	251	1499	2954	7243	19744	35313
III	143	172	339	2132	3695	9121	20076	38619
IV	146	191	539	3119	4985	11867	25212	50142
V	136	165	236	1370	2674	6766	16444	29200
VI	136	167	299	1928	3399	8352	19373	39365
VII	142	192	484	2917	4646	11022	23783	49616
VIII	128	151	218	1245	2442	6173	14707	30455

Salt Creek near Greenview

Scenario	Min. daily flow	7-day 10-year low flow	90% low flow	50% flow	Mean flow	10% high flow	1% high flow	Max. daily flow
Baseline	93	109	174	847	1480	3608	8405	16353
I	103	122	296	1186	1963	4671	10026	20072
II	90	101	124	590	1093	2674	7003	15208
III	90	101	161	795	1364	3310	7811	15768
IV	92	110	243	1132	1822	4332	9507	19154
V	78	97	121	558	999	2469	6136	12993
VI	84	100	144	750	1267	3072	7273	15714
VII	90	107	224	1077	1714	4079	8958	19279
VIII	74	95	116	508	920	2293	5615	12897

Table 19. Climate Scenarios Arranged to Show Relative Changes in Temperature and Precipitation

Increasing Temperature →
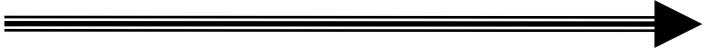
Decreasing precipitation ↓
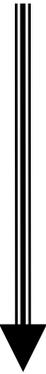
Scenario I	Scenario IV	Scenario VII
Baseline condition	Scenario III	Scenario VI
Scenario II	Scenario V	Scenario VIII

Table 20. Percent Change in the Mean Annual Flow Under Various Climate Scenarios

Increasing Temperature →

Decreasing precipitation ↓
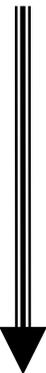
+33	+23	+15
0	-8	-16
-27	-34	-40

Table 21. Percent Change in Cumulative Flow During the Driest Year Under Various Climate Scenarios

Increasing Temperature →
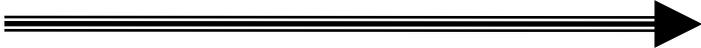
+54	+33	+15
0	-16	-28
-40	-47	-54
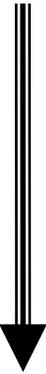
Decreasing precipitation ↓

Table 22. Percent Change in Cumulative Flow During the Wettest Year Under Various Climate Scenarios

Increasing Temperature →

+22	+16	+9
0	-6	-13
-19	-26	-33

Decreasing precipitation ↓
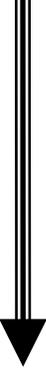
- The percentage changes in the 7-day, 10-year low flows ($Q_{7,10}$) and minimum daily flows, given in Table 18, display a wide range of variability depending on location. In general, the simulated flows in the Sangamon River at Riverton for the lowest flow conditions show the least sensitivity to climate change scenarios. Such results may be expected for this location because the lowest flow amounts in this reach of the Sangamon River during drought conditions come almost entirely from wastewater effluents, which were not adjusted under the climate change scenarios. The simulated $Q_{7,10}$ and minimum flows for Salt Creek near Greenview and the Sangamon River near Oakford generally show a maximum variability in the range of 15 to 20 percent from the baseline condition. The $Q_{7,10}$ and minimum flows in both of these locations are larger flow amounts that reflect a relatively high groundwater contribution. In these locations, it is noted that the sensitivity of these lowest flows during drought conditions is much less than the sensitivity to either the 90 percent low flow condition (Table 18) or to the cumulative flow during the driest year (Table 21). It is suggested that the minimum groundwater contributions to the streams during drought conditions may be more sustainable and less sensitive to climate change forces. Such a conclusion, however, should be verified using groundwater flow models. Finally, the simulated $Q_{7,10}$ for the Sangamon River at Monticello seems to be highly sensitive to the climate change scenarios. This result would seem to be more typical of conditions for most streams throughout the watershed that have little or no sustained groundwater contribution during drought conditions.

Impact of Climate Change Scenarios on the Current Reservoir Systems.
Results presented above relate to streamflow changes related to potential climate change. The changes in the minimum daily flow and 7-day, 10-year low flows, given in Table 18, would be most pertinent to impacts related to water supply systems that might withdraw directly from rivers in the region or to potential impacts on instream flow uses. However, the four major communities in the region obtain their water supply from reservoirs. The climate change modeling result that is most pertinent to these existing water supplies is the potential inflow reductions to these reservoirs during a severe drought year, and Table 21 (change in cumulative flow during the driest year) provides the most directly applicable results. The maximum change in the cumulative flow during the driest year is 54 percent (associated with scenario VIII), which simulates an average 5-inch reduction in annual precipitation and a 6-degree Fahrenheit increase in average temperature.

The yields of the Decatur and Bloomington systems were recomputed under the assumption that the inflows into the region's reservoirs and the flow in the Mackinaw River would all decrease by 54 percent during the drought of record. Other inflow sources in the Decatur water supply system, such as those provided by the former gravel pit and the DeWitt wellfield were not modified under this assumption. The modified yield computations indicated that the 50 percent confidence yield of the Decatur system during the 1930–1931 drought of record would be reduced by roughly 17 percent, from 38.1 to 31.6 mgd. Similarly, the 50 percent confidence yield of the Bloomington system during the 1939–1941 drought of record would be reduced by roughly 19 percent, from 12.7 to 10.3 mgd.

Thus, although the region's flows were estimated to be reduced by 54 percent, the yields of the community water supply systems under the hottest and driest climate change scenario would not be expected to decrease by more than 20 percent under the same condition. Although each community would need to seek additional water sources (or reduce water use by 20 percent) to account for the reduced yield associated with potential climate change, the amount of additional water needed is not substantially different from the quantities of water that each community is currently considering for development to meet their current water demands. For example, if Decatur were considering the construction of a 7,000-acre off-channel reservoir to augment its current supply, it would need to build a second similarly sized off-channel reservoir to accommodate the additional water needs associated with the scenario VIII condition (the hottest and driest climate change scenario) examined in this study.

It is important to recognize that the simulation results shown in Tables 20 to 22 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. Scenario VIII, discussed above, represents the hottest and driest of these scenarios. Many climate model results fall closer to the center portion of this range, with the "center box" in Tables 20 to 22 (scenario III) representing the presumed most likely of the presented scenarios. Under scenario III, the cumulative reduction of streamflow during the driest simulated year was simulated to be 16 percent. Using this scenario, the simulated yields of the Decatur and Bloomington systems during their respective droughts of record would be reduced by roughly 5 to 6 percent, from 38.1 to 36.1 mgd for Decatur and from 12.7 to 12.0 mgd for Bloomington.

Summary and Conclusions

In this study we examined the impact of current and future water demands on streams and aquifers in east-central Illinois through the use of computer-based models. Future water demands were estimated out to the year 2050 by Wittman Hydro Planning Associates (WHPA, 2008) under baseline growth, less resource intensive, and more resource intensive scenarios. Modeling and analysis of groundwater and surface water in this study were conducted separately because of the fundamental difference in their hydrologic behavior and the analytical tools used to evaluate each. Surface water supplies are strongly influenced by climatic variability and the timing and magnitude of precipitation events, thus we chose to model them using probabilistic approaches including the Illinois Streamflow Assessment Model (ILSAM). Groundwater supplies exhibit more steady hydraulic behavior but vast variability in the spatial geometry of the aquifer materials so we chose to model the Mahomet Aquifer with a deterministic numerical groundwater flow model, MODFLOW (USGS, 1988).

Summary of Groundwater Assessment

The collection and analysis of new groundwater data have been essential to the conceptualization and quantification of groundwater flow and recharge in the Mahomet Aquifer. Key elements of the new conceptual model involve recharge, stream leakage, and aquifer interconnections. Effective recharge rates to the groundwater system are spatially variable and have increased with total pumpage as a result of flooding along streams interconnected with the aquifer or induced infiltration from the surface. Leakage from interconnected streams has limited the impact of groundwater pumping and preferentially occurs during high flows when the vertical gradients between surface water and groundwater are the greatest. The behaviors of hydraulic heads in nested observation wells indicate that aquifer interconnections occur throughout the aquifer system even though many of the interconnections are not evident from the relatively sparse network of geologic boring records. Water released and gained from storage dampens the fluctuations in hydraulic heads and drawdowns in unconfined areas of the Mahomet Aquifer and portions interconnected to the Glasford Aquifer.

The numerical groundwater flow model of the system was developed from a geologic model composed of three aquifers and three confining layers. Head calibration of the model was achieved using water level measurements from 167 observation wells with a resulting mean residual error of 0.26 feet and an absolute residual mean error of 2.95 feet. Flux calibration was bracketed between the Q_{80} and Q_{50} streamflow values predicted by the ILSAM model. Model-predicted drawdowns from predevelopment conditions to 2005 conditions show a large cone of depression developed in the Champaign region and a relatively small amount of drawdown limited to the confined portion of the aquifer stretching from Clinton through Normal to Morton. In the Havana Lowlands region, the model matched field observations showing no significant long-term drawdowns since the area became heavily irrigated.

The groundwater flow model was used to simulate future water demands out to 2050 for three scenarios: a less resource intensive case, a baseline (current trends) case, and a more resource intensive case. The total 2005 water use of 208 mgd from the Mahomet Aquifer is projected to grow by 2050 to 244 mgd, 265 mgd, and 287 mgd in each scenario, respectively. The predicted increases in drawdown for the three scenarios mimic the historical drawdown with largest increases in the Champaign cone of depression, which ranged from 8 feet for the LRI scenario to 31 feet for the MRI scenario at the Petro North observation well. At this well, the Mahomet Aquifer remains under confined conditions with lowest head of 565 feet in the MRI scenario, leaving 55 feet of head above the top of the Mahomet sand. The only new areas to experience drawdown in the future simulations were around the wells for a new ethanol plant in Ford County and a proposed ethanol plant in Iroquois County. Simulated wells for the other three proposed ethanol plants in Pekin, Havana, and northern Logan County did not result in any drawdowns over 5 feet. The modeled heads in the Havana Lowlands remain almost steady throughout the simulations and are dwarfed by the natural water level fluctuations measured in the observation wells.

The computed mass balance of the model changed with the 262 mgd increase in pumpage from 1930 to 2050 largely by inducing an additional 150 mgd of recharge and decreasing baseflow discharge by 99 mgd. A majority of the baseflow reduction, 82.3 mgd, came from large streams in the unconfined areas at the western end of the aquifer. The remaining 16.7 mgd of baseflow loss came from smaller streams flowing over the confined portions of the aquifer with losses in individual watersheds ranging from 7 percent for Salt Creek to 16 percent for the upper Sangamon River above Lake Decatur.

None of the current groundwater users in the Mahomet Aquifer could be considered "at risk" for a future water shortage under the three demand scenarios. The model budget indicates that the available 2050 water supply for the aquifer as a whole is 2.3 times greater than the projected baseline demand. Hydraulic conditions vary tremendously across the aquifer; therefore, the aquifer-wide budget does not guarantee that the demand from additional high-capacity wells not included in the prescribed demand scenarios will not have unacceptable impacts to private wells or baseflow in small streams. In this study, the Mahomet Aquifer has been subdivided into areas based on the expected types of impact that new high capacity wellfields might have.

To better assess the available water resources of the Mahomet Aquifer, future additional work is needed to better understand the geology and hydrologic processes throughout the aquifer and in areas where data are limited. To fill in gaps in the observation well network, new wells are needed in many areas of the aquifer, particularly in Iroquois, Vermilion, DeWitt, Logan, south-central McLean, northern Tazewell, Woodford, and eastern Mason Counties. Additional observation wells in the shallow aquifer could be used throughout the study area. Equipping more observation wells with pressure transducers to digitally record water levels could also provide critical data. Additional water withdrawal data are needed to improve estimates of irrigation water use in the eastern portion of the aquifer as well as commercial and industrial withdrawals across the aquifer as a whole. More chemical and isotopic data are needed to better

understand the interactions of the Mahomet Aquifer with the land surface, overlying shallow aquifers, and underlying bedrock units. Additional research is needed to more accurately predict the impact of pumpage from the Mahomet Aquifer on private wells constructed in the shallower aquifers. To better quantify the impacts by groundwater pumpage on streamflow, new observation wells and streamflow measurements sites need to be developed where there may be significant groundwater/surface water interactions.

Summary of Surface Water Assessment

Because multi-decadal shifts in Illinois precipitation have been recorded in the past 150 years, both towards wetter and drier conditions at various times in the record, it is reasonable to assume that similar shifts will occur in the future independent of long-term potential climate change. Absent long-term climate change, it is expected that drought conditions similar to the historic droughts of the 1930s and 1950s will occur again, with the possibility that worse droughts might also occur on an infrequent basis. Given these expectations, it is both sensible and the recommendation of this study that water supply systems should plan for the recurrence of climatic conditions similar to those experienced in the early- to mid-1900s, with specific focus on the *drought of record*, that being the most severe of all the historical droughts for which there are hydrologic records available (to evaluate that water supply system). The report also considers the possible outcome (scenario) that long-term climate change may lead to warmer and drier conditions than those recorded in the past 150 years, although that particular scenario is not reflected in the climatic and hydrologic records of recent decades.

The ISWS categorizes the adequacy of community water supply systems based on their vulnerability to shortages during the drought of record. For an *inadequate* system, it is computed that there is greater than a 50 percent probability that the system will be unable to meet projected water use during the drought of record. For an *at-risk* system, the computed probability that the system will be unable to meet projected water use during the drought of record is between 10 and 50 percent. A *marginal* system is one in which there is less than a 10 percent chance that the system will fail to meet demands; however, the pending threat of potential shortages during the drought of record might still force the community to take extraordinary measures to avoid shortages.

Surface reservoirs are the primary water supply sources for four of the five largest communities in the region (Bloomington, Danville, Decatur, and Springfield). Analysis was performed to calculate the water supply yields of these four community water systems. The analysis examined the hydrologic and climatic records from the past 95 years for the purpose of identifying and simulating the water supply conditions that each system would experience if any of the worst droughts on record were to recur under present-day conditions. The analysis thus provides a juxtaposition of the historical drought periods with the existing water supply facilities and resources. This is accomplished by creating a water budget model of each community's system that estimates the expected inflows to, and losses and withdrawals from, their reservoir(s) during these drought periods.

The drought vulnerability classification based on the water budget analysis indicates that one of the community systems (Springfield) is an inadequate system and two others (Bloomington and Decatur) are at-risk systems. If each community's water demand increases as projected (WHPA, 2008), both the Bloomington and Decatur systems will be classified as inadequate by 2020 unless supplemental sources are developed by that time. The water budget analyses and the resulting system classifications include considerations for drought response and water conservation measures as outlined in each community's Drought Action Plan.

Water demand management, i.e., reducing water use through conservation and installing water-saving devices, is always recommended and has the potential to reduce the probability that there will be water shortages during droughts. However, the extent of demand reduction provided by such measures is not expected to dramatically change the vulnerability of the system.

All of the largest lakes in the east-central Illinois region (not counting backwater lakes located alongside the Illinois River) are water supply reservoirs, providing water for either municipalities (Springfield, Decatur, Bloomington, and Danville) or for electricity generation (Clinton Lake and Lake Sangchris). Lake Springfield is the only reservoir that provides water for both municipal consumption and electricity generation. Water demand for the largest reservoir systems in the region has continued to grow over time, such that all of these lakes are considered to be fully utilized; i.e., they do not have surplus capacity that could be used to meet substantial growth in water demand and in many cases are considered to provide an inadequate or marginal source of water supply during an extreme drought such as the historical drought of record.

There are few rivers in the region that have sufficient natural flow during severe droughts to provide a larger continuous water supply, and those rivers tend to be located far from major municipalities. These include the Sangamon River downstream of Petersburg, Salt Creek downstream of Lincoln, and the Mackinaw River downstream of Hopedale. Low flows in many of these river reaches are supported by the hydraulic interconnection of the river channel with the Mahomet Aquifer. Additional river reaches have low flows that are now supported by large effluent discharges; among these are the Sangamon River downstream of the Decatur and Springfield wastewater treatment facilities, Sugar Creek downstream of Bloomington, and the Vermilion River downstream of Urbana and Danville. The lower portions of the Sangamon and Vermilion Rivers are designated Illinois public waters, having a state-protected minimum low flow that restricts water withdrawals during very low flow conditions.

Climatic and hydrologic records from the past 100 years in east-central Illinois show considerable long-term variability. Average precipitation has been increasing over much of the 20th century with the period since 1970 being consistently high. However, earlier precipitation records from throughout Illinois indicate that the late 1870s through the 1880s was a particularly wet period, as wet as any recent period. Therefore, increases in streamflow that are observed in east-central Illinois (and much of the Upper Midwest)

during the 20th century may be viewed as part of long-term climatic and hydrologic variability instead of necessarily as an ongoing increasing trend.

Three separate modeling approaches were developed for analyzing existing and future water supply availability of the east-central Illinois region: 1) streamflow frequency assessment modeling, which looks at statistical characteristics that provide low flow estimates for the region's streams; 2) reservoir water budget modeling, used to estimate the yields of the major water supply reservoirs in the region; and 3) hydrologic simulation (watershed) models, which are primarily used in this study to analyze the potential impacts of climate change on streamflow availability.

The yield analysis presented in this study emphasizes the use of historical drought sequences. For systems with multiple water sources and/or a drought action plan for managing their sources, a sequential analysis can be used to simulate system operation during the drought. Each historical drought sequence may also have unique characteristics important for understanding and analyzing the potential effects of using alternative operation scenarios. Aside from the shift from non-sequential analysis to historical drought sequences, the basic data sources used in the water budget analysis are unchanged from previous yield estimates. Another potential benefit to using historical drought sequences is improved communication with the public. It is considered more persuasive to discuss the possibility of a 1930s or 1950s drought happening again than it is to talk about a hypothetical 50- or 100-year drought. And, because the public doesn't often fully understand the concepts of recurrence intervals and climatic variability, it is difficult to describe why a "50-year drought" might not have occurred in the past 50 years. The introduction of risk and uncertainty in the analysis, described below, also favors the use of historical drought sequences.

All sources of data used in the water budget analysis have measurement or estimation uncertainties which can lead to either underestimation or overestimation of the yield. Instead of these errors "canceling each other out" as is sometimes assumed, they instead collectively add to the uncertainty of the yield estimate. It is not feasible to provide site-specific estimates of data errors for each reservoir analysis; instead, approximate estimates of data uncertainty based either on literature reviews or collective comparisons from a larger number of reservoir samples must be used.

The biggest concern in using uncertain data is that we may overestimate yield, resulting in less water being available than expected for use in a severe drought. For this reason, a 90 percent confidence yield estimate is also computed, such that there is 90 percent confidence that the "true" yield (an unknown amount) is greater than or equal to the computed 90 percent yield. This means that there is 90 percent confidence that there will be sufficient water during a severe drought and only a 10 percent chance that the "true" reservoir yield is less than the calculated amount. This also means, however, that the computed 90 percent confidence yield is a lower value than the traditional mid-estimate (50 percent) yield.

Although experience has shown that water demands do rise considerably during the early stages of a drought, the assumptions used in the 1989 evaluation neglect the likelihood that the community will undertake conservation measures to reduce their use in later stages of a drought. But, even when there is a noticeable drop in water use in later stages in the drought, it may not make up the difference caused by heavy use during an initial summer period, such that total water use over the entire course of a drought may still be expected to be greater than the typical average annual water use. The present analysis assumes that voluntary and mandatory conservation measures will be employed by communities, such that the total water use over the course of an extreme drought may only be 5 to 10 percent greater than the community's average annual water use.

Yields were analyzed for the four community water supply systems in east-central Illinois that withdraw from surface water bodies: Bloomington, Danville, Decatur, and Springfield. Based on these yield results, Springfield has been classified as an *inadequate* system, as there is greater than a 50 percent probability that most of the city's electricity generating units would need to be shut down during a drought of record condition. The city's potable supply is also considered *marginal*, and with projected sedimentation losses in Lake Springfield, the potable supply will likely be reclassified as *at-risk* in the upcoming decade.

Both the Bloomington and Decatur systems are classified as at-risk, indicating that there is greater than a 10 percent probability that each would be unable to meet demands during a drought of record condition. With projected growth in demand, both systems will be considered inadequate (greater than 50 percent probability of shortage) by 2020. Danville is currently considered an adequate system, but with both projected growth in demand and sedimentation losses in Lake Vermilion, the supply is projected to become *at-risk* by 2040.

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