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The Water Cycle and Water Budgets in Illinois:

A Framework for Drought and Water-Supply Planning

Derek Winstanley, James A. Angel, Stanley A. Changnon, H. Vernon Knapp,
Kenneth E. Kunkel, Michael A. Palecki, Robert W. Scott, and H. Allen Wehrmann

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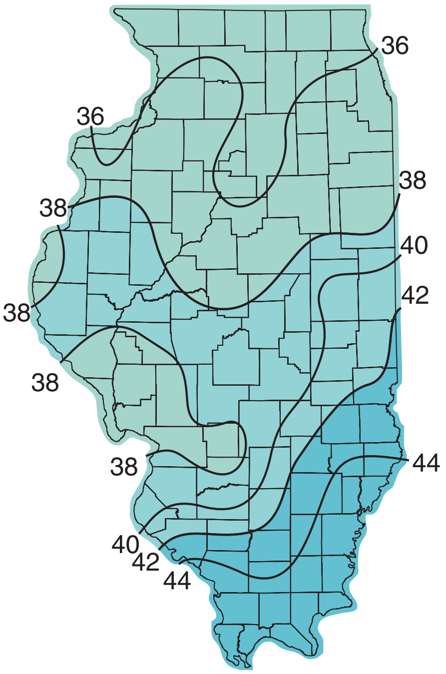

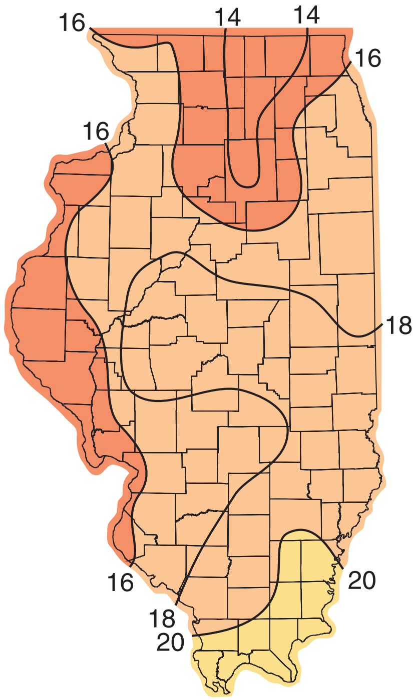

...FOR SEVERE DROUGHT?

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Illinois Department of Natural Resources
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June 2006

Front Cover: The left map shows mean annual precipitation in inches across Illinois during the period 1971-2000. The right map shows a calculation of the amount of annual precipitation that would be expected to occur during severe drought with a 200-year return period, based on the records at 74 stations.

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Executive Summary

Provision of adequate and reliable supplies of clean water at reasonable cost is a basic necessity for public health, the economy, recreation, and navigation. It is the goal of water-supply planning and management. As water withdrawals increase, so too does the need to protect watersheds, aquifers, and aquatic ecosystems for present and future generations. With sound planning and management, there is no reason why the residents of Illinois, a water-rich state, ever should face a water crisis. Without sound planning and management, however, current local problems and regional concerns could mushroom into conflicts and crises, and courts increasingly could be called upon to determine the reasonableness of withdrawals.

The less desirable alternative to sound planning and management is to adopt a "wait-and-see" and "contingency" strategy to find out whether or not existing water-supply facilities can cope with the next major drought and economic and population growth as they occur. Other states have discovered during recent worst-case droughts that contingency planning, as practiced by many community water-supply systems in Illinois, is not a wise substitute for drought-preparedness planning. In Illinois, about 35 of 90 existing surface water-supply facilities (streams, reservoirs, pumps, pipelines, treatment facilities, etc.) likely would experience severe impacts during a 50-year drought, and worse droughts would have more serious impacts on an even greater number of public and private surface- and groundwater systems. On the basis of their shallow depth, proximity to other shallow community wells, and proximity to identified streams, 208 wells representing 82 communities are deemed potentially vulnerable to drought conditions. Drought impacts can be reduced by incorporating information on water availability and demand into evaluations of system capacity and then developing appropriate drought-tolerant capacities.

A role of the Illinois State Water Survey (ISWS) is to provide useful scientific data for water-supply planning and management, consistent with the following framework:

Water-Supply Planning and Management

Goal: To Ensure Adequate and Reliable Supplies of Clean Water at Reasonable Cost

Main Components of Water-Supply Planning

- Determine the capacity of existing water-supply facilities.
- Determine current water withdrawals, uses, and impacts.
- Determine potential yields and water quality from surface waters and aquifers under variable climatic conditions.
- Construct future water-demand scenarios.
- Identify and evaluate drought, climate change, and other risks and uncertainties.
- Present and compare water-supply-and-demand scenarios (with uncertainties and risks).
- Evaluate the needs for increasing water supply and treatment and/or decreasing demand.
- Identify and evaluate the risks and costs (including negative impacts) of options for increasing water withdrawals, and/or decreasing water demand.

Main Components of Water-Supply Management

- Define acceptable levels of confidence (risk) and costs in providing adequate supplies of clean water over a specified time period.
- Select and implement water-supply/water-treatment/water-distribution and/or water-conservation/water-reuse projects.
- Evaluate the need for changes to existing policies, regulations, and management strategies.

Many factors can influence future water availability, two of the most important factors being climate variability and change. Climate variability in the form of the periodic occurrence of below normal precipitation, sometimes in conjunction with high temperature, is the major cause of drought and water shortages. This report analyzes historical climate records to quantify magnitudes and durations of previous droughts that have occurred throughout the state. These historical data then can be used to characterize future droughts, based on the assumption that what has occurred in the past can occur again in the future. Climate change over periods of decades and centuries, as evidenced by changed amounts and frequencies of precipitation and temperature, also can influence water availability. Thus, this report also analyzes 150 years of climate records in Illinois for evidence of climate change, and uses the output from climate models to project possible future climate conditions in the region.

Analysis of past and present conditions and problems, and possible future water-supply-and-demand scenarios has led the ISWS and the Illinois State Water Plan Task Force to identify high-priority watersheds and aquifers for study and planning. The priority aquifers are i) the deep bedrock aquifer system of northeastern Illinois, ii) the sand-and-gravel and shallow bedrock aquifer system of northeastern Illinois, iii) the Mahomet aquifer system of east-central Illinois, and iv) the American Bottoms of southwestern Illinois (MetroEast area). The priority watersheds, from a water-supply perspective, are i) the Fox River watershed, ii) the Kaskaskia River watershed, iii) the Sangamon River watershed, iv) the Kankakee River watershed, and v) the Kishwaukee River watershed. It is on the water-yield potential of these watersheds and aquifers that much of the sustainable economic development in these areas rests.

It is impossible in one report to analyze the possible impacts of climate variability and change on each water-supply system in the state. Thus, the approach adopted was to provide some examples of the impact of historical and possible future climate variations and change on surface- and groundwater resources. These analyses were based on the sound scientific understanding of the water cycle and water budgets in Illinois. There are many reports and much data on the water cycle and water budgets in Illinois, and these are summarized in Appendix A, which serves as a technical foundation for this report. Analysis of 150 years of Lake Michigan-Huron lake-level data under varying climate conditions, together with worst-case drought scenarios for the lake level, are presented in Appendix B. Data on community groundwater supplies are provided in Appendix C.

It is intended that the data and information presented will be useful to water-supply planners and managers in understanding the variability in the availability of water in Illinois, and will stimulate them to apply these and other data in analyses of the adequacy of their own water-supply facilities. Below is a list of some questions that water supply managers may raise in providing a preliminary review of the potential vulnerability of their facilities to drought-related shortages. Some values needed for certain calculations are found on maps and tables in the report, and other values that pertain to local conditions and records must be obtained locally.

Considerations in Evaluating Local and Regional Water Supplies

1. Changes in Water Use (Past and Projected)

- What has been the community's growth in average water use over the last 10-15 years?

- What is the community's projected growth in water demand in the near future? Is the community attempting to attract new industries or commercial enterprises that will increase its water use?

Reevaluation of system adequacy should be high priority for communities with a water use growth of more than 25 percent, particularly if the rate of growth is likely to continue into the near future.

- What is the community's water use during hot, dry periods?

For many communities, water use during a drought period is significantly higher than the average annual rate (Chapter 2). An evaluation of system adequacy should be designed around expected use over the course of a drought.

2. Changes to the Water Supply System

- What is the current system capacity?
  Raw water ________________
  Treated water ______________

- How does this compare to the average daily water demand? Peak demand? Can the system meet peak demands routinely without additional infrastructure (e.g., the need for back-up or redundancy)?

- What is the community's water source capacity (be it river, lake, reservoir, or aquifer)?

- What changes or improvements to the water supply system have been made in the last 15 years?

- Is the community planning for any changes or improvements to the water supply system in the near future or in the upcoming decades? Do these plans involve incremental improvements in the current supply, or are substantial modifications being planned?

3. Uncertainties and Potential Decreases in the Capacity of the Current System

- If the community has a groundwater supply, have well capacities decreased with time (or have drawdowns increased to provide the same amount of water)? How do groundwater levels react to pumping stress in dry periods? Are the wells close together and do they interfere with one another? Are they close to a surface-water body and do they depend on that surface water for recharge? Is a record kept of pumping and nonpumping water levels in the wells? Is a water level trend apparent and, if so, how does it compare to trends in withdrawals?

- Could the community's future water source capacity be impacted adversely by additional withdrawals from other parts of the aquifer or watershed?

- If the community withdraws water from a reservoir, has the capacity of that reservoir been measured in the last 20 years? Has the rate of capacity loss from sedimentation been measured?

4. Problems Experienced in Past Drought Periods

- Has the community experienced concerns with inadequate water supply during drought since 1970? Ever?

Supplemental sources and capacities added to the system since the last drought of major concern (addressed in item 2), minus potential losses due to reduction in pumping capacity or reservoir sedimentation (addressed in item 3) should have overcome not only the short-

comings in the system as experienced in this past drought, but also offset coincident increases in water use (addressed in item 1).

The worst water-supply droughts in Illinois occurred in the 1930s and 1950s. Although selected communities have been impacted by more recent and less-severe droughts, such as droughts in the mid-1960s, 1976-1977, 1988-1989, 1999-2000, and 2005, none of these recent droughts had the same type of widespread impact as the droughts of the early and mid 20th Century. Such severe droughts will occur again in the future. Many communities that have not experienced water-supply concerns in decades may still be at risk of having water shortages during a severe drought.

If analysis indicates expected water shortages or a high risk of shortages, or that future withdrawals may affect the yield of watersheds and aquifers adversely, then there is an opportunity to adopt preventative management strategies. The costs of water shortages and withdrawal impacts have two major components: damages caused by water shortages and withdrawals, and measures to avoid damages. Management decisions typically are based on assessments of benefits, risks, safety margins, and affordable costs. Making decisions only on what is affordable today for a certain degree of protection can, of course, lead to much higher future damage costs resulting from infrequent but severe events. A focus of this report is on showing the scientific data and uncertainties that managers would benefit from incorporating in risk analysis.

It is evident from activities in other states that efforts to improve water-supply planning and management that include the public and constituent groups are expensive and time consuming, but necessary. Such plans include consideration of surface water and groundwater (watersheds and aquifers), local and regional conditions, water quality, floods and stormwater, droughts, and water conservation. Many states have enacted legislation and provided the resources necessary to establish state and regional planning and management frameworks and procedures. Increasingly, Illinois recognizes the importance of state and regional water-supply planning and drought-preparedness planning. In 2005, the Drought Response Task Force and the State Water Plan Task Force agreed to revise the state drought-response plan to incorporate drought-preparedness planning. In January 2006, Governor Blagojevich issued Executive Order 2006-01 requiring the state to begin to formulate water-supply plans and to begin to implement these plans in Priority Water Quantity Planning Areas. These are important first steps in a long-term commitment to improve water-supply planning and management in Illinois.

Table of Contents

List of Tables

List of Figures

Appendices

Acknowledgments

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- Define acceptable levels of confidence (risk) and costs in providing adequate supplies of clean water over a specified time period.
- Select and implement water-supply/water-treatment/water-distribution and/or water-conservation/water-reuse projects.
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Introduction

Provision of adequate and reliable supplies of clean water at reasonable cost is a basic necessity for public health, the economy, recreation, and navigation. It is the goal of water-supply planning and management. As water withdrawals increase, so too does the need to protect ecosystems, watersheds, and aquifers for present and future generations. With sound planning and management, there is no reason why the residents of Illinois, a water-rich state, ever should face a water crisis. Without sound planning and management, however, current local problems and regional concerns could mushroom into crises.

In addition to maintaining the operations of existing water-supply facilities, water-supply planners and managers must look to the future to identify and evaluate factors that can influence both the supply of and demand for clean water at reasonable cost. Water-supply planners can identify these factors and analyze them to provide options for consideration and decision making by water-supply managers.

Successful water-supply planning and management in Illinois requires understanding the amount of water stored and available for use in different hydrologic (water) reservoirs, how water moves through the environment, and how these reservoirs and flows vary over time. That information also is crucial to understand related issues of water quality.

It would be relatively simple for planners to identify cost estimates of water-supply options to meet increased demand, if future water availability and demand could be predicted within narrow confidence limits. Unfortunately, there are large uncertainties in projecting future climatic conditions and the future availability of water in lakes, reservoirs, streams, and aquifers, in projecting water demand and water quality, and in determining water needs for ecosystem preservation. This makes water-supply planning a difficult task that requires scientists and engineers to articulate levels of technical understanding by defining and quantifying uncertainties, which then need to be translated into benefits, costs, and risks. This translation requires analysis by economists, especially to evaluate the costs of withdrawing, treating, and distributing water, and of providing adequate safety margins during droughts and other emergencies. Final decisions by water-supply managers are made with consideration of uncertainties and risks in a formal or informal risk-assessment and risk-management framework.

The role of the Illinois State Water Survey (ISWS) in water-supply planning is to provide scientific data and evaluations that will be informative and useful for water-supply planning and management by quantifying the past and future variability in the availability of water in Illinois. The ISWS does not manage water resources, nor determine policy or regulations.

Uncertainties in projecting future water availability and demand are associated with geographical patterns of economic and population growth, aquifer and watershed properties, variable climatic conditions, land-cover changes, sedimentation rates, withdrawals and diversions, regulations, and other factors. Many of the human-made changes will depend upon economic and population growth in Illinois, the nation, and the rest of the world. These economic and demographic drivers will increase water demand. They also will contribute to changes in water availability and the chemical composition of the atmosphere (and possibly climate) and water supplies. As Illinois' climate is part of the global climate system, it is reasonable to assume that future climate conditions and water budgets in Illinois will, to some extent, be modified by natural and human-made climate changes on both regional and global scales.

Ideally, water-supply planning and management would be served best by an accurate capability to predict future water budgets for each watershed and aquifer. However, such capability is hampered by the limited predictability of human activities and future climate conditions, inadequate understanding of hydrologic processes, limitations of mathematical models (Winstanley and Changnon, 2004), and inadequate characterization of watersheds and aquifers. Land-cover changes that also can affect climate, evaporation, and runoff rates are equally difficult to predict. High sedimentation rates reduce storage capacity in lakes and reservoirs, but the loss of water storage capacity often is not known. New water withdrawals and diversions can have negative impacts on existing withdrawals and diversions, other water uses, and the integrity of aquifers and surface waters, but these impacts often are not known in advance. And regulations can change and can affect how much water can be withdrawn from aquifers and surface waters.

Planners, perhaps, would prefer an approach that provides "best estimates" of water availability and demand, one that establishes probabilities of the occurrence of future conditions. Where appropriate in this report, uncertainties are quantified in terms of the probability of occurrence of future events. However, best estimates can be biased and often are too simplistic; in many cases, science cannot at this time provide meaningful probabilities of future water availability and demand. For the most part, the future can be bounded only by the reasonableness of conceptual models and key assumptions. The approach adopted was to develop scenarios, each scenario being dependent on one or more conceptual models and reasonable assumptions about key factors that will influence water availability and demand. This approach states that "if *x* happens, then *y* will be the result". It does not place a probability on the occurrence of *x* or *y.* It puts onus on water-supply planners and managers to understand and evaluate uncertainties and risks based on conceptual models, assumptions, and associated data, rather than simply relying on best estimates.

Lake Michigan, the single largest source of water in Illinois, supplies Chicago and many suburbs. On average, over 2 billion gallons of water are withdrawn from Lake Michigan each day in northeastern Illinois, but the amount of water Illinois is allowed to divert is limited by a U.S. Supreme Court decree. This diversion of lake water is the only major diversion of Great Lakes waters and long has been a contentious issue for Illinois, other lake states, and Canada. Major legal controversies over the amount of water diverted at Chicago have occurred when the lake fell to low levels. However, by virtue of its nature, Lake Michigan as a major source of water has been drought resistant.

If the past teaches lessons applicable to the future, then one can interpret previous events and attempt to project what may happen in the future, as it pertains to the Chicago diversion and fluctuating climate conditions, and to an ever-changing society. One lesson clearly illustrated is that these pressures have shifted greatly since 1895, and viewpoints will continue to shift.

A second lesson concerns the rapid growth of the Chicago metropolitan area and ensuing water demand. The future of Chicago could take several directions. The city's position as the interior metropolis of the continental United States appears secure; hence, growth is predictable. The only questions seem to be the rate of future growth and the source of the needed water. Studies of the highly sensitive groundwater situation in northeastern Illinois and the effect of the shift of many suburbs to use of lake water found that the water demands of suburbs still relying on remaining groundwater supplies in Wisconsin and parts of northeastern Illinois would exceed the sustainable yield of major aquifers in the next 15 or 20 years (Visocky, 1982). Thus, continued use of the groundwater resource is expected to cause further drawdown of groundwater supplies, which also can affect lake level.

A third factor with great influence on the future is the possible change in climate over the Great Lakes basin and environs. Some climate models that incorporate increased concentrations of greenhouse gases in the atmosphere indicate a warmer and drier climate could occur on the basin (Kunkel et al., 1998). This could lead to reduced water levels, problems for lake shipping, altered water resources, urban, environmental, and water-management problems, and changes in policy. For example, a permanent lowering of the lake level would cause major problems for Chicago's lakeshore facilities, including water intakes, harbors, and outfalls. The cost of restructuring these facilities over 50 years would exceed $600 million in 1993 dollars (Changnon, 1993). Drier conditions beyond the basin would lead to deficient water supplies, decreased agricultural production, and searches for additional sources of water. Other climate models indicate higher precipitation in the future, and higher precipitation could increase lake levels and stormwater runoff, which are important variables in Lake Michigan water diversion.

Whatever the climate conditions, lake level, and water demand, Illinois recognizes that it must plan for the future knowing that the current limit on water diversion will continue.

As has been stated, economics plays a key role in determining the supply of clean water at reasonable cost. For example, large quantities of water in the deep Mount Simon aquifer underly much of Illinois, but much of this groundwater is of poor quality. Large quantities of water could be pumped from this deep aquifer, but would have to undergo expensive water treatment to make it potable. Similarly, large amounts of water could be withdrawn from the Mississippi and Ohio Rivers, but again costs of treatment and distribution would be high. And there is much potential for building new reservoirs in Illinois, but again financial and environmental costs are high. Construction, treatment, and distribution costs typically are passed on to consumers as higher prices, which is why the authors adopted the goal of providing adequate and reliable supplies of clean water at reasonable cost.

One of the most important factors to be considered in water-supply planning and management is the occurrence of drought, which can decrease water availability and increase water demand. The American Meteorological Society (2004) "...recommends that appropriate institutions at the local, state, regional, federal, and international levels initiate or increase drought planning, drought preparedness, drought warning, and drought mitigation efforts. Efforts must be made to increase knowledge and information about climate variability, drought impacts, mitigation technologies, societal response such as conservation, and preparedness strategies."

The current drought contingency plan for Illinois (Illinois State Water Plan Task Force, 1983) focuses on drought response after drought occurs, beginning with identification of drought onset. The present report contains data on the probabilities of occurrence of drought conditions throughout Illinois based on historical climate records, information on the sensitivity of surface-water and groundwater supplies to droughts, and case studies of drought impacts on several existing water supplies. An important goal of this report is to provide a basis and encouragement for water-supply planners and managers to evaluate the adequacy of their facilities to meet demand during droughts of varying intensity and to develop appropriate supply capacity before the next major drought. Scientists cannot predict with confidence when droughts will occur, but are certain that they will occur in the future. In the western United States, many states already have experienced worst-case droughts in recent years, and northern Illinois experienced a significant drought in 2005.

If analyses indicate expected water shortages during future droughts, or potential adverse impacts of future withdrawals on the sustainable yields of watersheds and aquifers, then there is an opportunity to adopt preventative management strategies. These responses will depend largely on individual risk assessments: determination of the severity of the risk for which to plan, the safety margin desired, and affordability. This is similar to dealing with hurricanes in Florida: it is well known that hurricanes of varying severity occur from time to time. Decision makers decide the severity and frequency of hurricanes for which to prepare, for example, by adopting appropriate building codes and levee heights. In the case of drought, water-supply facilities can be tailored to meet pre-determined reductions in water availability and higher water demand.

On the flip side of the climate coin are floods caused by excess precipitation, which also can have adverse impacts on water quality, damage water facilities, reduce water availability, and generate additional costs.

Severe impacts of droughts and floods, and the recognition that demand for additional water supplies is increasing, have focused attention in some states on the inadequacy of many existing water-supply plans and management schemes. As a result, many states have recognized the importance of improved water-supply planning and management and are engaged in intensive efforts to develop state and regional water-supply plans.

The alternative to being prepared is to adopt a wait-and-see strategy to find out whether or not water-supply facilities can cope with major droughts and economic and population growth when they occur. Illinois has adopted a proactive approach. In 2005, the Drought Response Task Force and the State Water Plan Task Force agreed to revise the state drought-response plan to incorporate drought-preparedness planning. In January 2006, Governor Blagojevich issued an Executive Order requiring the state to begin to formulate water-supply plans and to begin to implement these plans in Priority Water Quantity Planning Areas. These are important first steps in a long-term commitment to improve water-supply planning and management in Illinois. Currently, water supplies generally are managed in a quite fragmentary manner by individual entities. It is intended that the new planning and management program will lead to increased coordination among all major users, and to consideration of the cummulative impacts of withdrawals, and to protection of aquifers and watersheds

This report updates some data and information in earlier reports (e.g., Changnon, 1987) and also provides information on worst-case droughts and possible future climatic conditions. Scenarios of water availability and demand are presented primarily at the state level, with case studies at the local level and for selected watersheds and aquifers. Assumptions underlying the scenarios are identified. As stated above, a particular challenge is to translate scientific uncertainties, biases, and assumptions into meaningful data and information for consideration in risk-based water-supply planning and management.

Chapter 1 provides analyses of drought severity, drought return periods, and drought impacts based on the historical record. Information on the impacts of floods on water supplies also is included.

Based on analyses of water budgets, at-risk water supplies, and future climate and water demand scenarios, Chapter 2 provides information on possible future water-supply conditions and issues in Illinois.

Analysis of past, present, and possible future water-supply-and-demand scenarios led the ISWS to identify priority watersheds and aquifers. These priority watersheds and aquifers are discussed in Chapter 3. It is on the water-yield potential of these watersheds and aquifers that much of the sustainable economic development in these areas rests.

Guidance for evaluating local and regional water supplies is provided in Chapter 4, which is followed by a set of conclusions.

There are many reports and much data on the water cycle and water budgets in Illinois, and these are summarized in Appendix A, which serves as a technical foundation for this report. Appendix A contains a general description of the hydrosphere and some scientific laws and methodologies relevant to its study that serve as a firm scientific foundation for describing and quantifying the water cycle and water budgets in Illinois. As Illinois lies within the Upper Mississippi and Ohio River basins, and its climate is influenced by climate conditions in other parts of the world, information also is presented on water budgets on a regional scale and on the nature of interrelationships among regional climatic conditions. Analysis of 150 years of Lake Michigan-Huron lake-level data under varying climatic conditions, together with a worst-case drought scenario for the lake level, are presented in Appendix B. Data on community groundwater supplies are provided in Appendix C.

Chapter 1

Droughts, Floods and Water Supplies

Drought is a complex physical, biological, and social phenomenon of widespread significance. Despite all the problems drought has caused, it has been difficult to define. There is no universally accepted definition because: 1) a drought, unlike a flood, is not a distinct event; and 2) a drought often is the result of many complex factors acting on and interacting within the environment and society. Another complication is that drought often has neither a distinct start nor end. It is usually recognizable only after a period of time and, because a drought may be interrupted by short spells of one or more wet months, its termination also can be hard to recognize.

Drought can be measured by departures of precipitation (for example, 3-12 months) from a long-term average or "normal" over an extended time, using drought indices such as the Palmer Drought Severity Index (http://www.drought.noaa.gov/palmer.html), or by specific impacts: low soil moisture, low streamflow, or low groundwater levels. Typically, a particular precipitation threshold or drought index is chosen in relation to a particular impact. For example, agricultural drought is most sensitive to precipitation deficits during the growing season, while groundwater may respond to a 12-month or longer precipitation deficit.

The first parts of the hydrologic cycle affected by a precipitation deficit are near-surface soil moisture and streamflow. Changes in soil moisture can be quite rapid during the growing season when demand on soil moisture is high due to plant growth. Changnon (1987) assessed and mapped the drought susceptibility of Illinois soils. Dry periods in Illinois typically have a near normal number of days with rain, but rains are more spotty and less intense than usual. As a result, streamflow also drops due to a lack of heavy rainfall events. Any rain that does fall first is absorbed by the dry soil, reducing runoff. Smaller streams usually respond more quickly to drought than rivers due to their smaller drainage area and smaller storage. Severe drought conditions greatly reduce flow in rivers and streams, and some streams dry up. Figure 1 shows the low-flow rates of selected streams, in Illinois which range from less than 1 to greater than 2000 cubic feet per second or cfs (http://www.sws.uiuc.edu/docs/wsfaq/addl/q5lowflows.gif, accessed November 20, 2005). Low flow is defined as the lowest 7-day flow that occurs, on average, once every 10 years.

Long-term precipitation and streamflow records show considerable interdecadal variability. Knapp (2004) thus concluded that the period of record analyzed can have a significant influence on the perception of trends from hydrologic and climatological records. Knapp reported that the most important factor related to the magnitude of low flows is the precipitation deficit accumulated over a comparatively long period preceding the low-flow event. For the 7-day low flow, the precipitation deficit accumulated over the previous 24 months has the highest correlation ($r = 0.772$); for the 18-month low flow, precipitation deficit accumulated over the previous 5 years has the highest correlation ($r = 0.743$). Thus, periods of below normal precipitation can have long-reaching, persistent effects on streamflows.

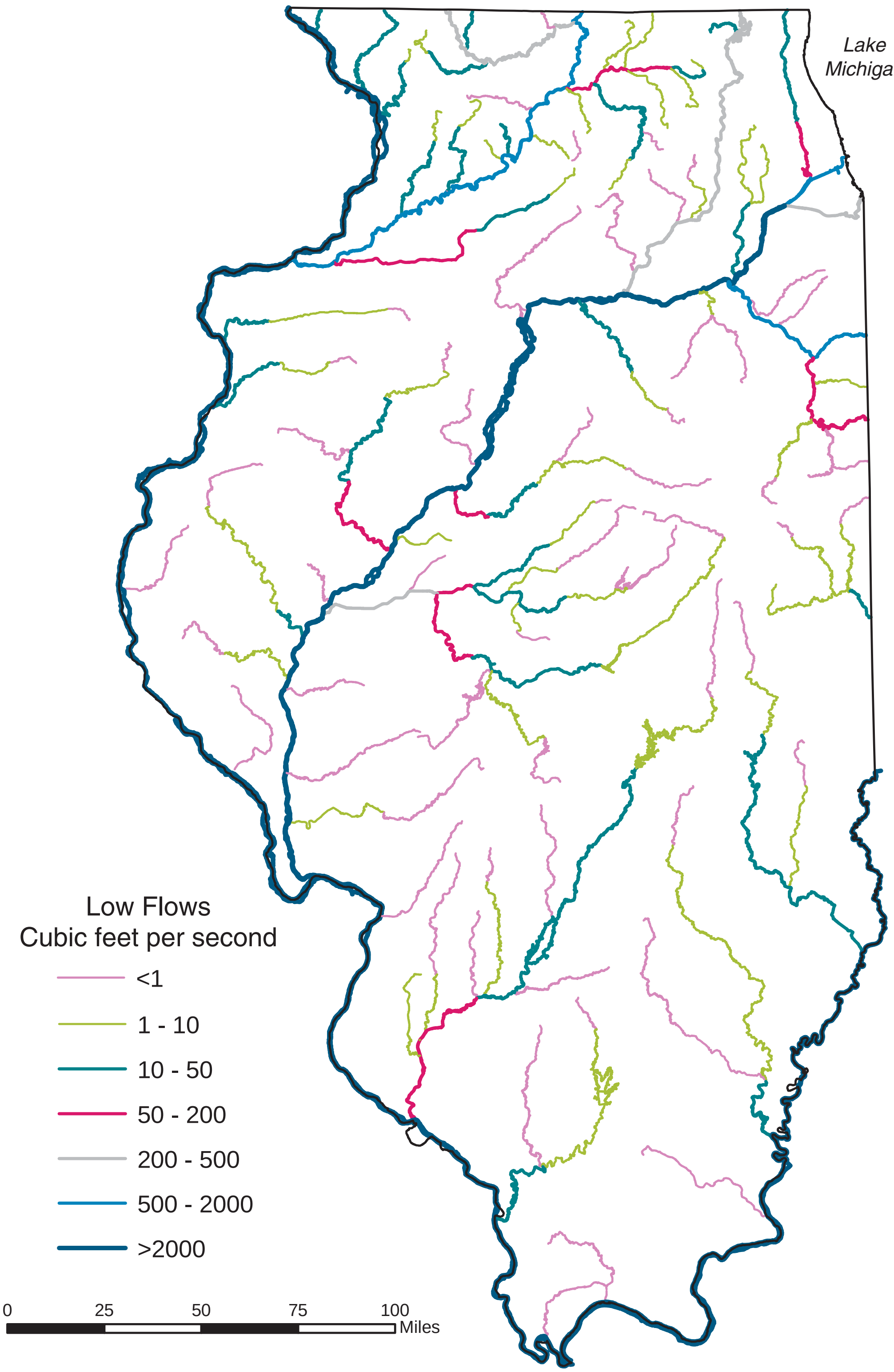


Figure 1. Low-Flow Rates for Streams in Illinois that Range from Less than 1 to Greater than 2000 Cubic Feet per Second (http://www.sws.uiuc.edu/docs/wsfaq/addl/q5lowflows.gif, Accessed November 20, 2005).

Northern Illinois is less susceptible to short-term precipitation deficits than southern Illinois, because in northern Illinois a higher percentage of streamflow comes from groundwater discharge into streams. Southern Illinois has fewer large aquifers, and the percentage of groundwater discharge to streams is much smaller due to characteristics of the soils and topography, making it more vulnerable to precipitation deficits.

Rivers and streams feed most lakes and reservoirs used for public water supplies, and several months of low streamflow, especially during normally high streamflow periods in spring, can lead to water-supply problems. Smaller reservoirs often more quickly reflect drought conditions than large reservoirs due to smaller water storage and reliance on smaller streams.

Groundwater levels often are slower than streamflow to respond to precipitation deficits, only after soil moisture and streamflows are down. Groundwater levels also recover more slowly from drought and do so only after precipitation exceeds evapotranspiration and soil moisture demands. In many places, shallow aquifers act as reservoirs from which groundwater can percolate slowly downward to recharge deep aquifers. As a result, deep aquifers are buffered from short-term droughts and only show effects during extended periods of more severe drought.

The timing of drought also is important. For example, short, intense droughts during the growing season typically have a significant impact on agriculture. On the other hand, droughts that start in fall and end in spring may have minimal impact on agriculture, because demands for water are lower.

The primary cause of drought is below normal precipitation, sometimes associated with high temperatures. Periodic droughts in Illinois are well documented in historical climate records for the past 100 years. Precipitation statewide averaged only 76 percent of normal during the1988 drought. However, climate records indicate that more severe droughts have occurred (Table 1). In fact, 1988 was only the 8th most severe one-year drought in the last century. The most severe one-year drought statewide occurred in 1901: precipitation averaged 67 percent of normal (26.3 inches or in.). Multi-year severe droughts occurred in the 1930s and 1950s, when high temperatures compounded the adverse impacts of low precipitation.

Analysis of precipitation records since 1837 indicates all of the eight driest 5-year precipitation deficits in the Upper Mississippi River Basin (UMRB) occurred between 1887 and 1967 (Knapp, 2004). Although popular conception is that agricultural drainage has reduced low flows in streams in the Midwest, Knapp concluded that since 1879 there is no evidence of a reduction in low flows in the UMRB above Keokuk, Iowa.

All the above data are averages for large areas, but climate anomalies also vary geographically. In any particular region, drought conditions can be more or less severe than the statewide average. For example, annual precipitation in southern Illinois in 1988 averaged 85-95 percent of normal compared to 60-85 percent of normal in central and northern Illinois. During a drought period, some 75 percent of the state often experiences drought conditions (Changnon, 1987).

Table 1. Ten Driest Years in Illinois since 1895

Year	*Amount (in.)*	*Percent of Normal*
1901	26.3	67
1930	27.9	71
1963	27.9	71
1953	28.1	72
1914	28.6	73
1976	28.9	74
1940	29.3	75
1988	29.6	76
1936	30.3	77
1956	30.7	78

Note: Percentages are based on a 1971-2000 statewide normal of 39.23 inches (in.)

Droughts also occur on different time scales. The greatest precipitation anomalies generally occur on short time scales. For example, no precipitation fell in Urbana in November 1904, and monthly totals of less than 0.1 in. were reported in five other months since 1888. For April-September, the lowest precipitation since 1888 in Urbana was 40 percent of normal (9.9 in. in 1913). The lowest annual precipitation in Urbana was 45 percent of normal (18.3 in. in 1894). The lowest precipitation over a 2-year period was 52 percent of normal (21.2 in. annually in 1893-1894); and for a 5-year period, 63 percent of normal (25.6 in. annually in 1891-1895). For both surface- and groundwater, climate anomalies can have lingering and cumulative effects for years.

During drought periods, especially in warmer months, the demand for water increases due to, for example, irrigation of crops and watering of golf courses and lawns. In investigating the impacts of drought on water supplies, this increased demand also must be taken into account. High temperatures increase evapotranspiration rates, which tend to reduce the amount of surface water, soil moisture, and groundwater. When considering the impacts of future precipitation anomalies on water supplies, it is important also to consider the impacts of possible high temperatures.

Traditionally, the historical climate record is considered a guide to the future: what has occurred in the past could recur in the future. The following analyses are based on statistical analysis of the 1895-2001 Illinois instrumental climate record and on analyses of the pre-instrumental climate record derived from paleoclimatic records.

Palmer Drought Severity Index for Illinois

The Palmer Drought Severity Index (PDSI), a widely used index of drought severity, is based on temperature, precipitation, and soil characteristics. The time series of monthly PDSI values averaged for the entire state is shown (Figure 2). An index of -4 or less represents extreme drought, -3 to -3.9, severe drought, and -2 to -2.9, moderate drought. Values between -2 and +2 are considered near normal. Larger positive values indicate anomalously wet conditions. There is considerable variability in the PDSI for Illinois at different time scales, a few months to a few years.

As measured by the PDSI, the most extreme drought statewide occurred in 1934, reaching peak intensity in July (PDSI of -6.9). This was part of a multiyear period of dry and hot conditions, with extreme drought also in 1931 (PDSI of -6.5) and in 1936 (PDSI of -5.1). Crop yields, essential for the agriculturally-based economy of that era, were cut drastically.

The moderately severe drought in 1988 can be contrasted with the 1930s droughts. A PDSI of -4.2 in September 1988 indicated a drought of lesser intensity than those in the 1930s. However, timing of the 1988 drought caused serious impacts. April-June 1988 was the driest spring on record. Continuing dryness in July and August resulted in a sharp reductions in crop yields and very low flows in streams and rivers. Many municipalities faced water shortages, and low water levels disrupted barge traffic on the Illinois and Mississippi Rivers.

Another drought of note in Illinois during the early 1950s reached its peak in March 1954 (PDSI of -6.1). What is most notable about that drought is its duration; the PDSI remained negative, indicating drought conditions, from April 1952 through March 1957, the longest such period in Illinois' recorded history.

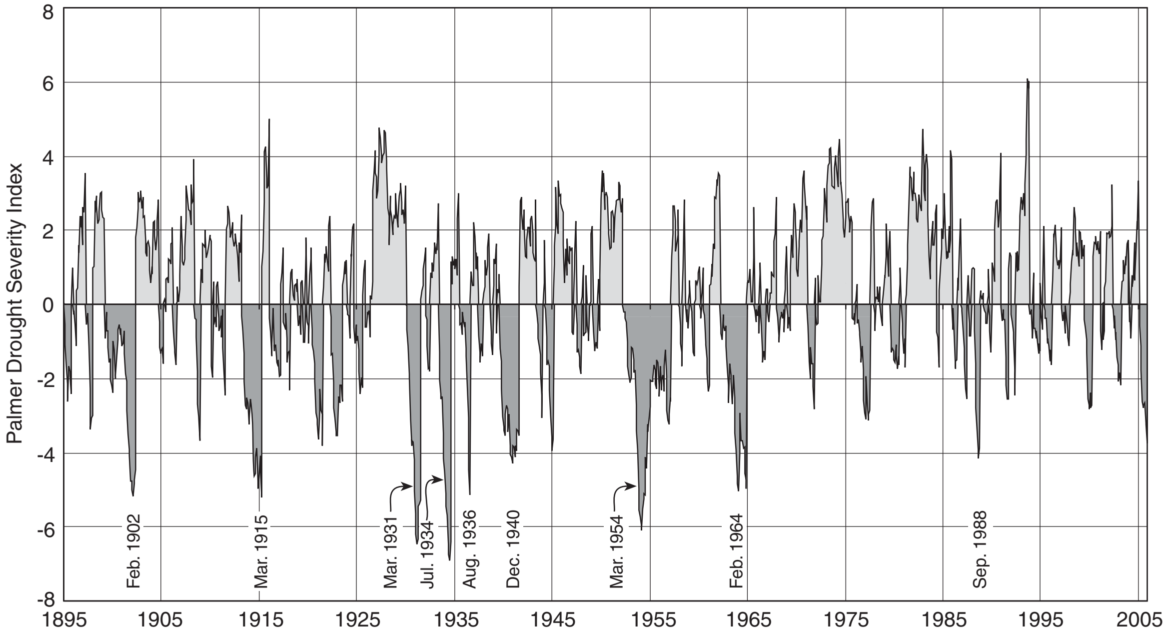


Figure 2. Monthly Statewide Palmer Drought Severity Index for Illinois since 1895.

Other notable droughts occurred in 1901-1902, 1914-1915, 1940-1941, and 1963-1964. While the statewide PDSI dropped below -4 during eight periods before 1965, it only dropped below -4 once between 1965 and 2005, in 1988.

Worst-Case Drought Scenario for Illinois Based on Paleoclimatic Records

Paleoclimatology is the study of climate prior to the widespread availability of records of temperature, precipitation, and other instrumental data. Scientists especially are interested in the last few thousand years because this best-dated and best-sampled part of the past climatic record can help establish the range of natural climatic variability since the last ice age. Proxy records of climate have been preserved in tree rings, ice cores from glaciers and ice caps, and layers of lake and ocean sediments. These records have a greater degree of uncertainty than the instrumental record because they are influenced by various environmental factors and also are subject to different interpretations. For example, tree-ring growth can be influenced by temperature and precipitation, as well as by floods, fire, disease, and pests.

The development of a worst-case drought scenario based on paleoclimatic records is dependent upon definition. The time scale is a key consideration, because external forcing of the climate system varies on multiple time scales. Changes in solar forcing due to astronomical factors varying on time scales of thousands of years are a prominent example. Should those factors be considered in these scenarios? If so, then evidence of drier conditions around 7000 years ago should be incorporated. However, to the extent that different astronomical conditions may have been partly responsible for the drier conditions, such scenarios may have no practical application for present time scales for planning purposes of 100 years or less. Another consideration is the length of a drought: a worst-case, short drought (for example, 6-12 months) will have a larger precipitation departure than a longer drought (for example, 2-3 years).

The worst-case drought scenario described here was based on several decisions. First, the primary foundation was the evidence for the actual occurrence of past droughts; speculative methods were not used. Second, past dry periods during different astronomical forcing were not considered, thus restricting the analysis to the past 2000 years. Third, the purpose of these scenarios was to assess water-supply impacts, so multiyear droughts were the focus.

After considering several sources of paleoclimatic data, the record developed by Cook et al. (1999) was chosen. They constructed a gridded field of summer (June-August) PDSI values based on all available tree-ring data. The grid spacing was 2° X 3° latitude/longitude, and reconstructions were calibrated and verified against the instrumental PDSI for the period since 1895, calculated from actual temperature and precipitation records since 1895. For Illinois, Cook et al. were able to reconstruct the summer PDSI back to 1469 in north-central Illinois [Grid Point (GP) 110] and back to 1000 A.D. in south-central Illinois (GP111) between Springfield and St. Louis near Mt. Olive.

Examination of GP110 revealed no extraordinary droughts in the pre-instrumental record, but GP111 contained an interesting drought feature between 1565 and 1574 (Figure 3) corresponding to the core of the mid-to-late 16th Century “megadrought” over North America, as described

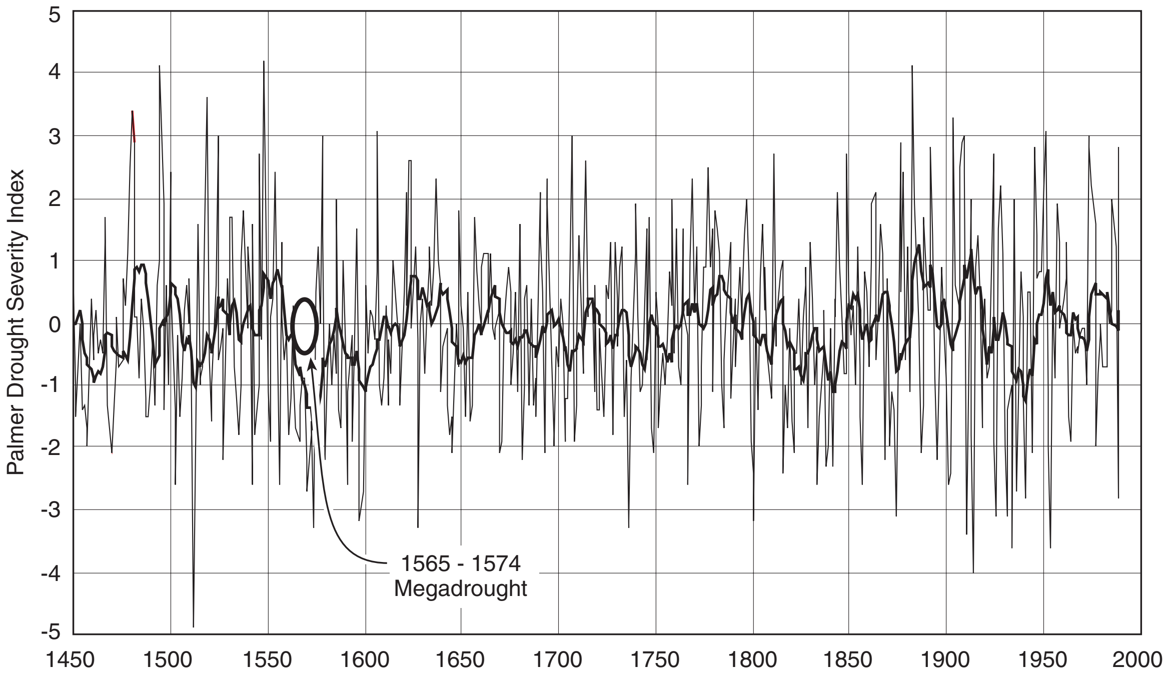


Figure 3. Palmer Drought Severity Index for June-August (thin line) and 10-year Moving Average (thick line) for South-Central Illinois Reconstructed from Tree-Ring Analysis (from Stahle et al., 2000).

in Stahle et al. (2000). This drought is the only time in the tree-ring time series that the PDSI remained below zero for ten consecutive years. This was not the case in the 1930s and 1950s droughts, when wet years were interspersed among dry years. Therefore, tree-ring evidence suggests that an unrelenting 10-year summer drought period is physically plausible in south-central Illinois.

The next step was to reconstruct corresponding deficits in the annual precipitation associated with this 10-year drought. This was complicated by two factors. First, a summer PDSI value reflects precipitation in about the previous 6 months, not the entire year. Second, the tree-ring PDSI was very good at detecting abnormal dryness but not abnormal wetness. In other words, below average precipitation was a limiting factor in tree growth, average to above average precipitation was not. Therefore, the relationship between PDSI and annual precipitation was linear until the PDSI was positive, then the variance increased.

After trying several approaches, 10-year moving-average annual precipitation departures for the instrumental period were calculated to correspond with the 1565-1574 megadrought. A 10-year period also would eliminate some year-to-year noise in the relationship between PDSI and precipitation.

The largest 10-year precipitation deficit in the instrumental period (1895-2001) was 3.1 in. per year for a total deficit of 31 in. The longest negative 10-year average PDSI for the 20th Century in the PDSI time series was -1.2. The 10-year tree-ring PDSI for 1565-1574 was -1.8, 50 percent more severe than during the worst 20th Century period. Using the linear relationship found between precipitation and PDSI for droughts provides a 10-year mean annual precipitation deficit of 4.6 in., or a total deficit of 46 in. In other words, the 10-year annual precipitation for 1565-1574 was an estimated 88 percent of normal. Such a reduction would have made annual precipitation in central Illinois during that period similar to Oklahoma today.

In summary, the tree-ring PDSI indicated a 10-year, unrelenting drought that was probably more severe than anything in the modern record for south-central Illinois. Although there is no evidence for such a severe drought in northern Illinois, it is reasonable to assume that such a drought could occur statewide. Thus, the worst-case drought scenario based on tree-ring data is a 10-year period with annual precipitation 88 percent of normal statewide. As there is considerable uncertainty in translating PDSI values into precipitation values, the 10-year worst-case drought scenario should be at least 85 percent of normal (see next section).

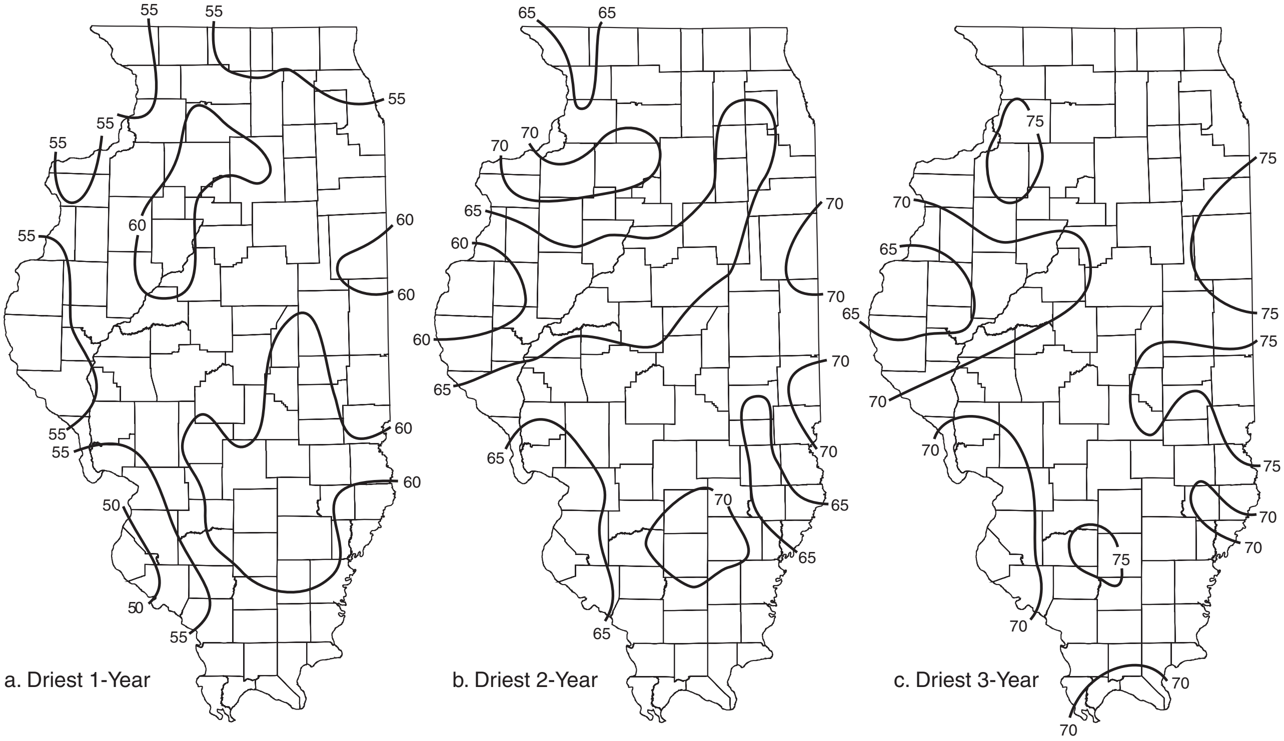
Worst-Case Drought Scenario for Illinois Based on Observational Data

Another approach to determining the worst-case drought in Illinois was to examine the driest sequences in historical climate records. Digital climate records became sufficiently dense from the 1890s onward to enable a spatial analysis for Illinois. The analysis used 79 Illinois Cooperative Network stations with reasonably complete long-term records (less than 10 percent missing data). For each station, the driest 1-, 2-, 3-, 5-, and 10-year periods were computed, expressed as percentage of their respective 1971-2000 normal. These point values then were plotted and contoured (Figure 4). This contrasts sharply with the results of Table 1, which is constrained by state-wide precipitation departures (i.e., the average departure of all stations in a particular year). It is impossible to get the statewide average in any particular year (e.g., 1901, or 1930) as uniformly dry as the statewide figures shown in Figure 4, which are based on the driest years on record at each station.

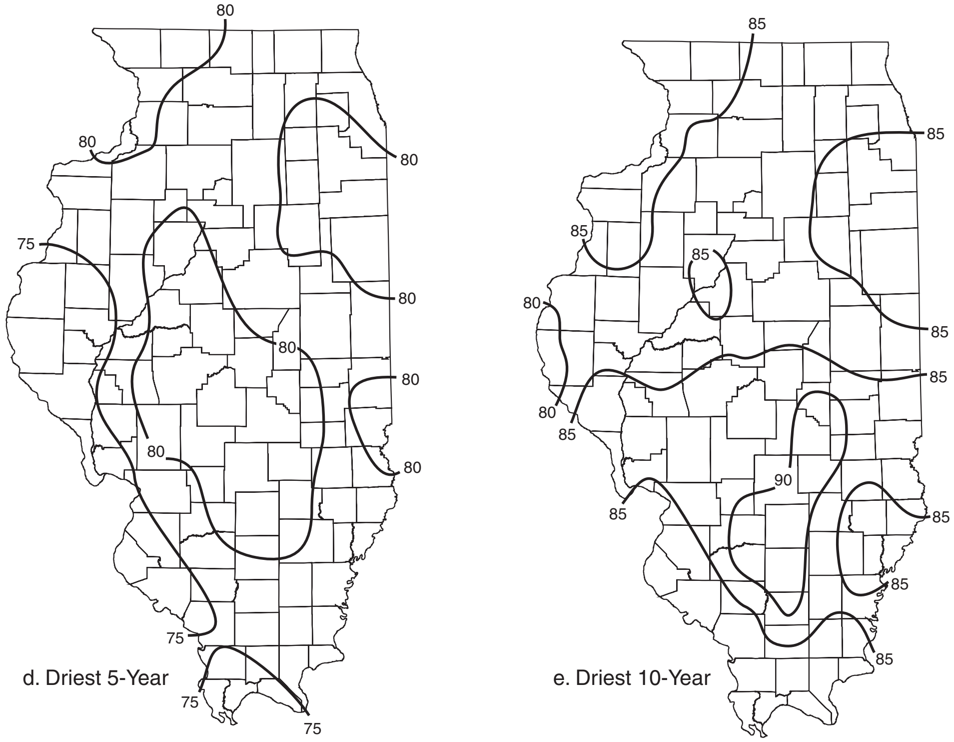
Figure 4a shows that the worst one-year precipitation drought results in significant dryness, averaging 50-60 percent of normal in most areas. On a statewide basis, the precipitation average is 56 percent of normal. The most severe departures are along Illinois' western and northern borders. Slightly less severe conditions prevail in portions of the Illinois River basin and in south-central Illinois.

The worst 2-year precipitation drought (Figure 4b) results in a statewide average precipitation of 66 percent of normal. Slightly less severe conditions occur to the east of Moline and in south-central Illinois, although in a lesser degree than the one year map. A band of more severe conditions extends from just north of Quincy eastward. This band also occurs in the 3-year precipitation drought map (Figure 4c). Slightly less severe conditions prevail along the eastern borders of the state. Overall, the statewide average precipitation is 72 percent of normal for the driest 3-year period.

The statewide average precipitation for a 5-year drought is 77 percent of normal (Figure 4d). Large areas of slightly less severe conditions prevail in central Illinois, northeastern Illinois from Chicago southward, and in northwestern Illinois. More severe conditions occur along the western border of the state.



a. Driest 1-Year b. Driest 2-Year c. Driest 3-Year



d. Driest 5-Year e. Driest 10-Year

Figure 4. Precipitation Departures for Sites across Illinois Experiencing their Driest a) 1 Year, b) 2 Years, c) 3 Years, d) 5 Years, and e) 10 Years, Expressed as Percent of Normal 1971-2000 Precipitation.

Statewide average precipitation for a 10-year drought is 85 percent of normal (Figure 4e). There is an area of slightly less severe conditions in south-central Illinois and slightly more severe conditions in far western Illinois.

Droughts of less than a year in duration were not considered in the analysis because their impact on surface- and groundwater supplies is not as widespread. However, water supplies susceptible to shorter droughts are particularly vulnerable because there is typically little time to respond to water-supply shortages. Summer droughts are most problematic because they can be quite severe (for June-August, the statewide average precipitation is 29 percent of normal in the worst-case drought scenario) and occur when water demand is typically highest. In fact, during summer drought, water consumption for irrigation and residential watering can double that used in a normal summer. In some cases of extremely high water use, the ability to deliver water may be limited not by the actual water-supply source (e.g., the aquifer or lake), but rather by capacity to treat and distribute water. It also should be noted that because water demand is highest in summer, the effects of a long-term drought may be felt most acutely in summer. A good example is the 1988-1989 drought: most impacts were noticed first in the summer of 1988 (Lamb, 1992).

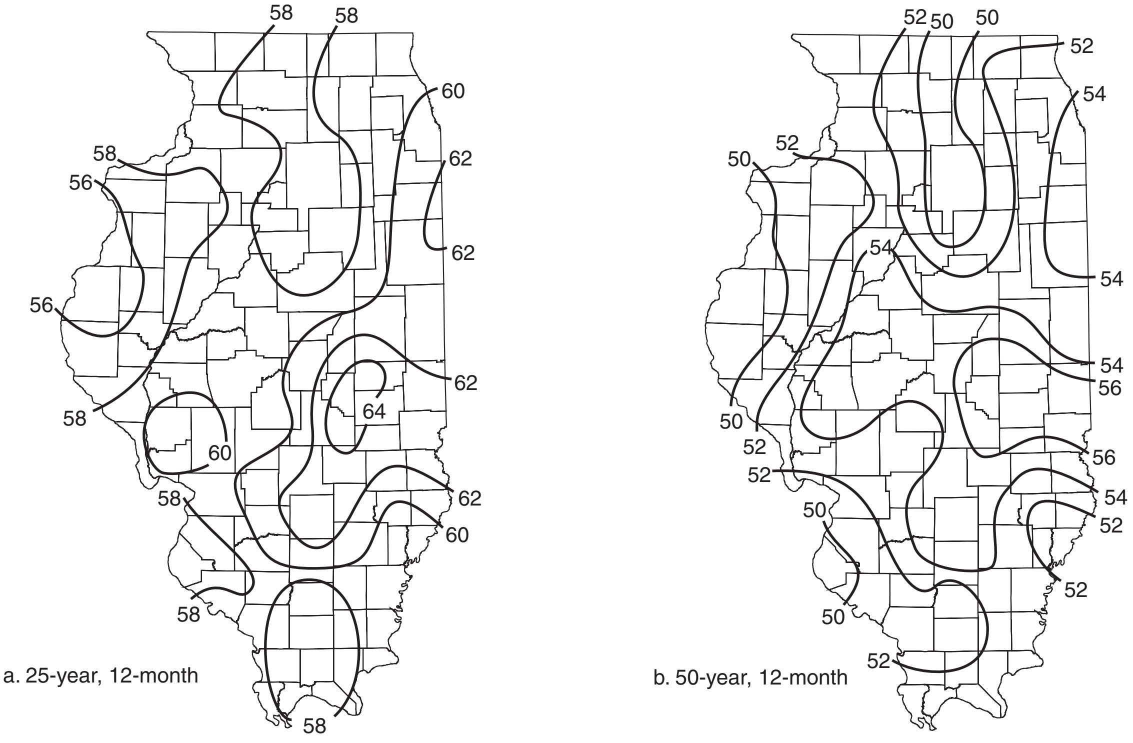
Two patterns emerged from this analysis. First, the departure from normal decreases as drought duration increases, suggesting that the climate system can sustain much below normal precipitation only for short durations. Even though departures at longer durations are relatively less extreme, the accumulated precipitation deficits are larger and thus can have profound negative effects on water supplies. Second, while average annual precipitation shows a strong north to south gradient, no such gradient exists for the worst droughts at each site when expressed as a percent of normal. No other spatial pattern stands out other than the tendency for droughts in parts of western Illinois to be slightly more intense than elsewhere in the state. This pattern also is evident in the regional analyses provided by Winstanley et. al (2006, Figure 1-A).

Drought Return Periods

Other planning tools that water-supply planners and managers find useful are maps of the percent of normal precipitation expected during droughts at selected return periods (frequencies) and durations. The advantage of a return period or frequency analysis is that it assigns a level of risk to the precipitation shortfall. This allows users to choose a level of protection from drought in their planning and management.

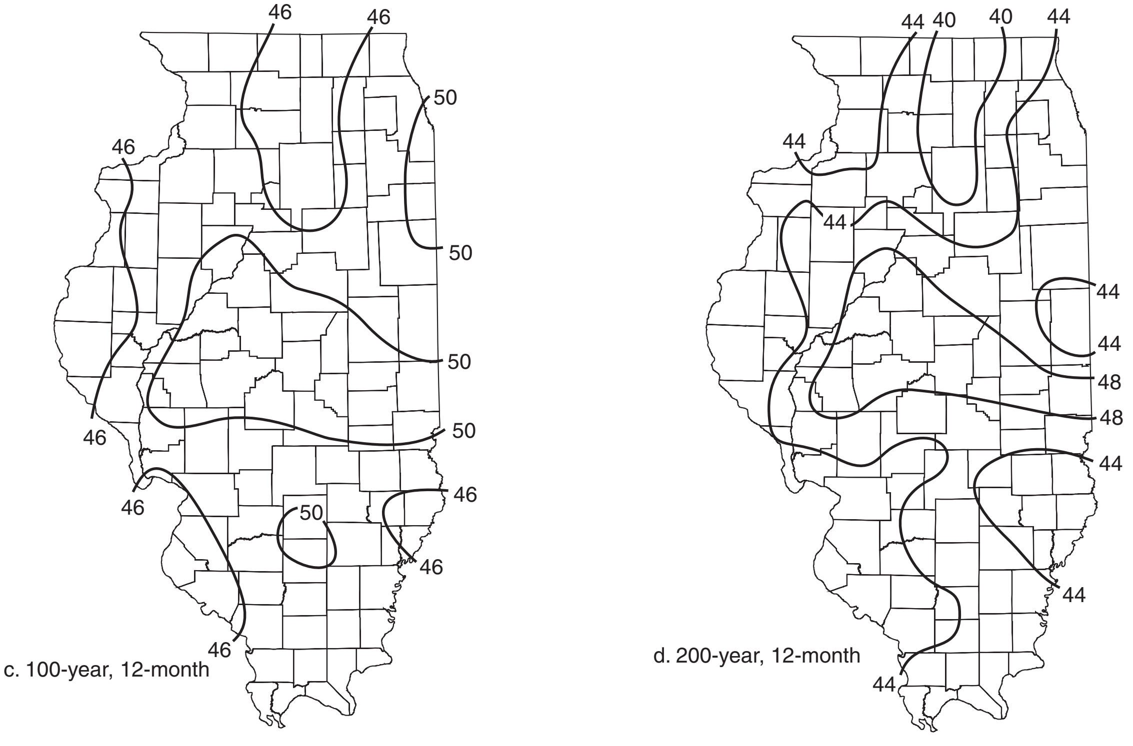
Return-period maps were developed from 74 long-term, reliable stations in Illinois. For each station, the driest 12-, 18-, 24-, 36-, 48-, and 60-month periods were identified for each decade. A fixed time interval helps ensure that the time series includes only independent events. The resulting drought time series for each site then was fitted to a three-parameter Generalized Extreme Value distribution using public-domain L-moments software (Hosking,1996). By fitting a distribution through scattered data points, the expected precipitation amounts at specific return periods can be estimated. The maps stop at the 200-year return period.

Figures 5-10 present the results of this analysis. The contours are in percent of normal based on the 1971-2000 average precipitation for the duration in question. Differences across the



a. 25-year, 12-month

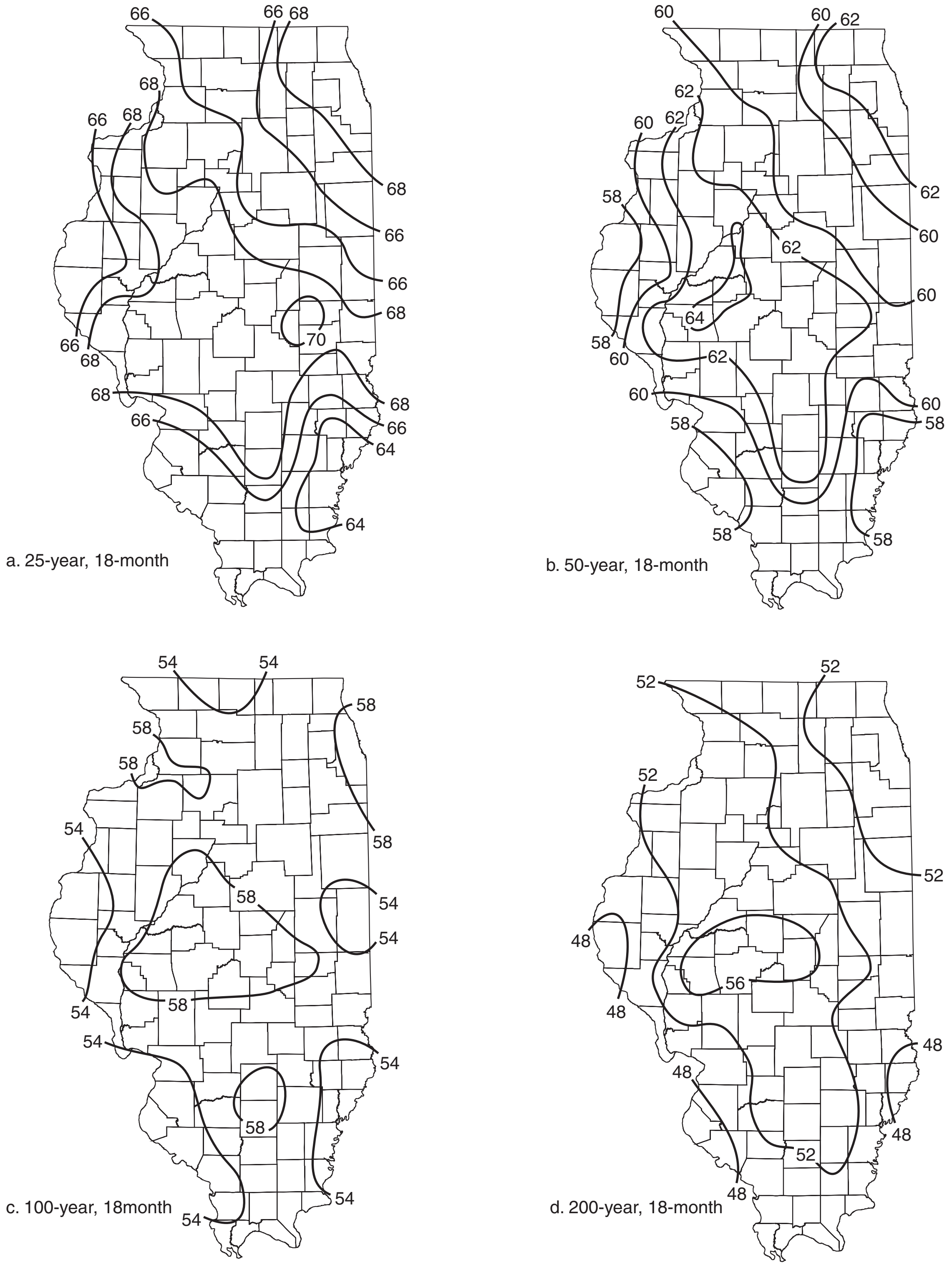
b. 50-year, 12-month



c. 100-year, 12-month

d. 200-year, 12-month

Figure 5. The 12-Month Drought at Return Periods of a) 25 Years, b) 50 Years, c) 100 Years, and d) 200 Years, Expressed as Percent of Normal 1971-2000 Precipitation.



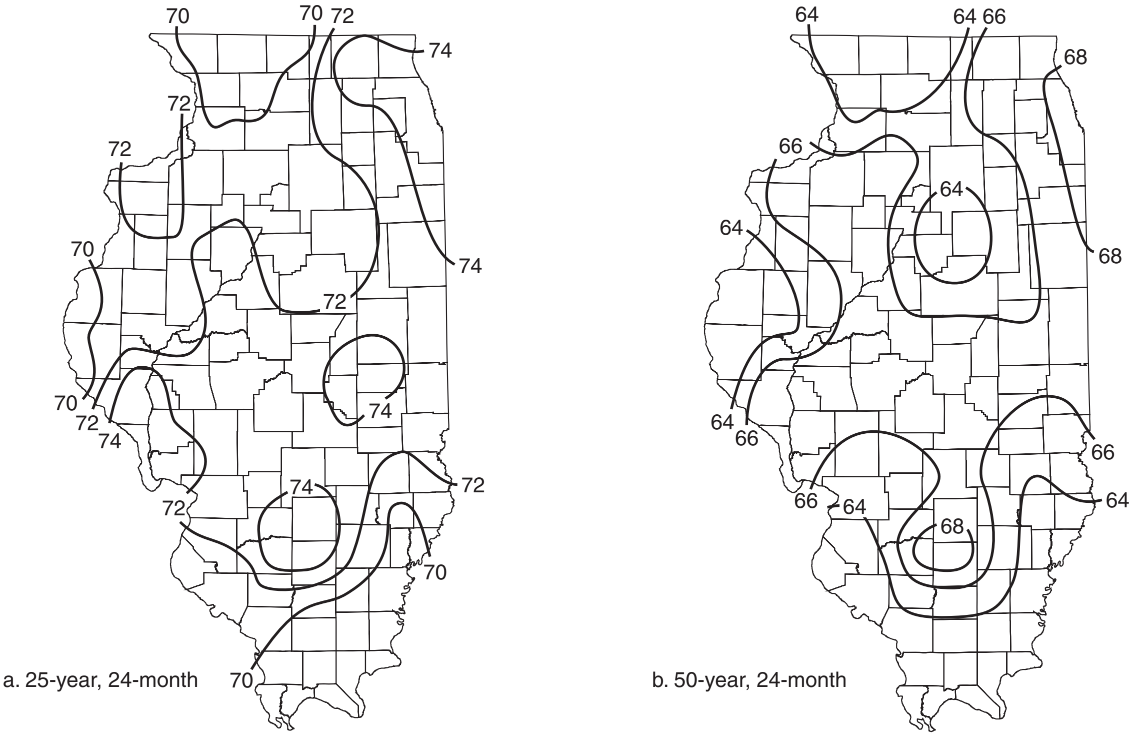
a. 25-year, 18-month

b. 50-year, 18-month

c. 100-year, 18month

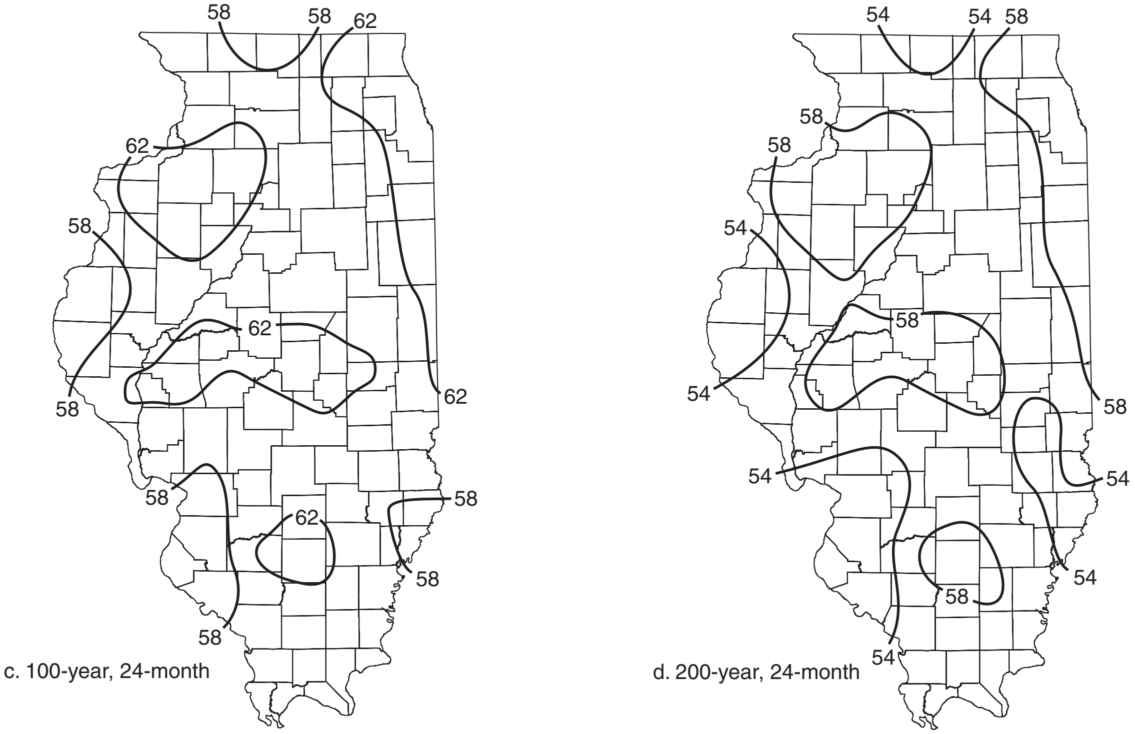
d. 200-year, 18-month

Figure 6. The 18-Month Drought at Return Periods of a) 25 Years, b) 50 Years, c) 100 Years, and d) 200 Years, Expressed as Percent of Normal 1971-2000 Precipitation.



a. 25-year, 24-month

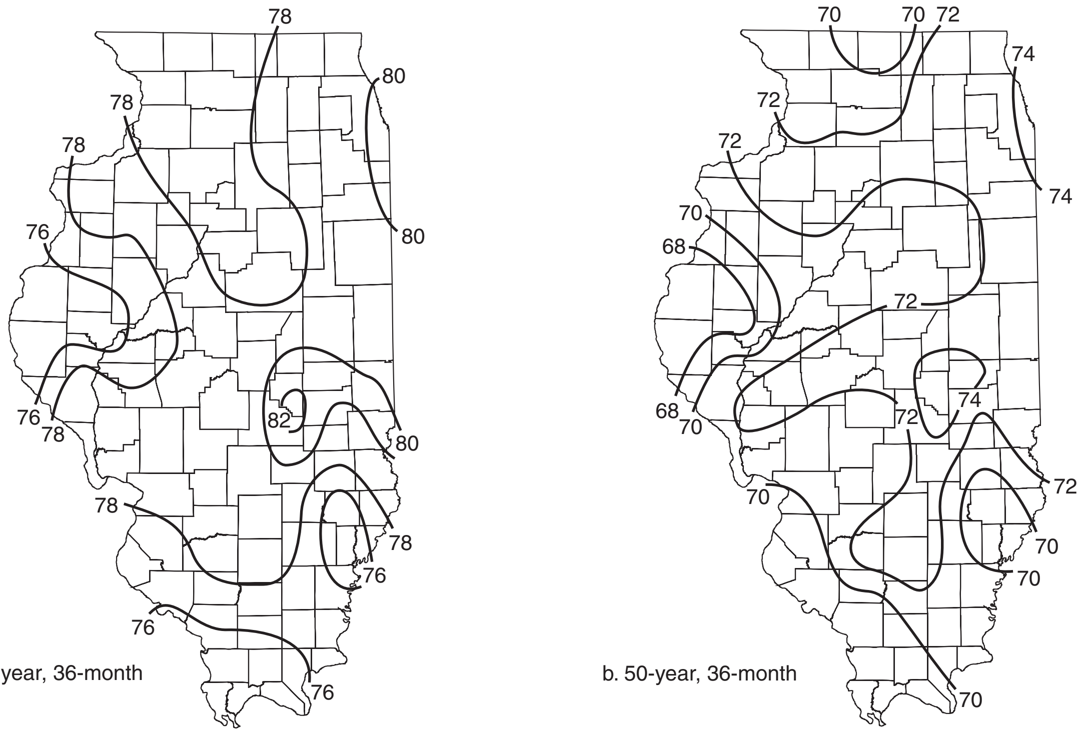
b. 50-year, 24-month



c. 100-year, 24-month

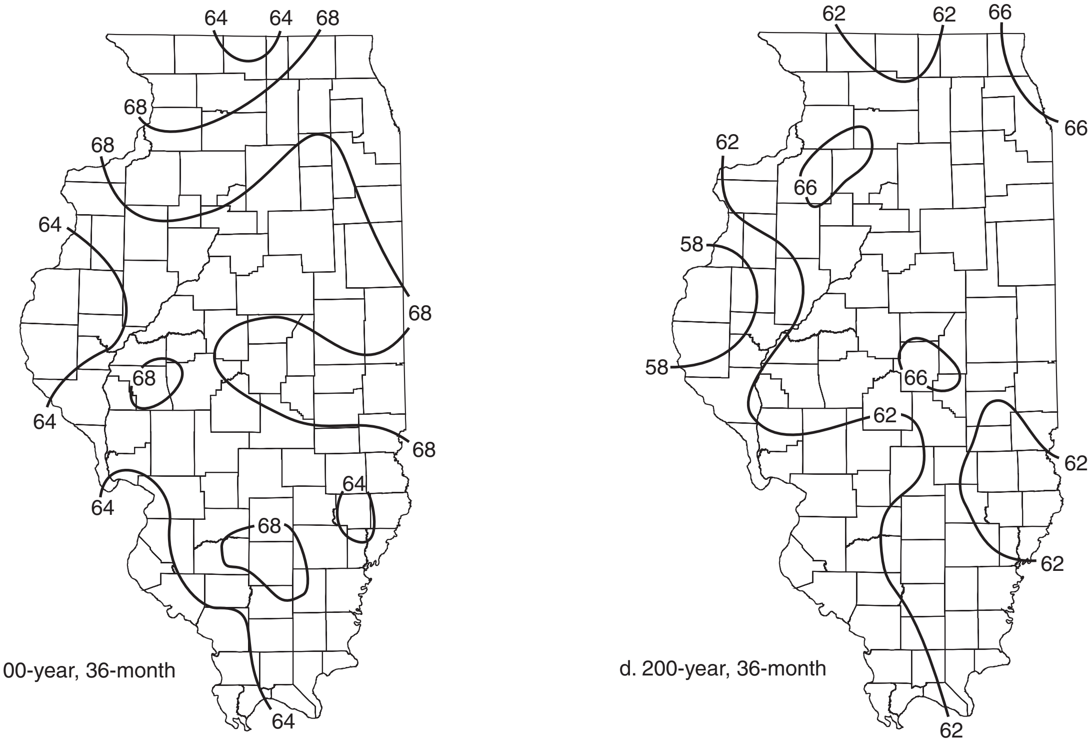
d. 200-year, 24-month

Figure 7. The 24-Month Drought at Return Periods of a) 25 Years, b) 50 years, c) 100 years, and d) 200 Years, Expressed as Percent of Normal 1971-2000 Precipitation.



a. 25-year, 36-month

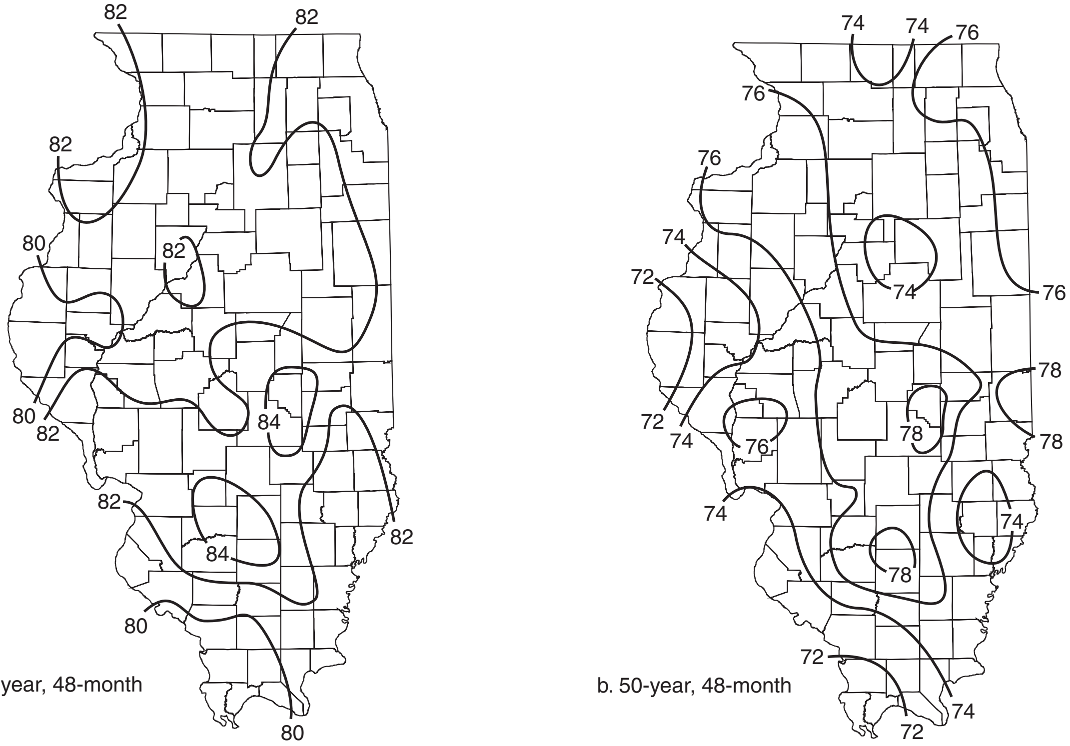
b. 50-year, 36-month



c. 100-year, 36-month

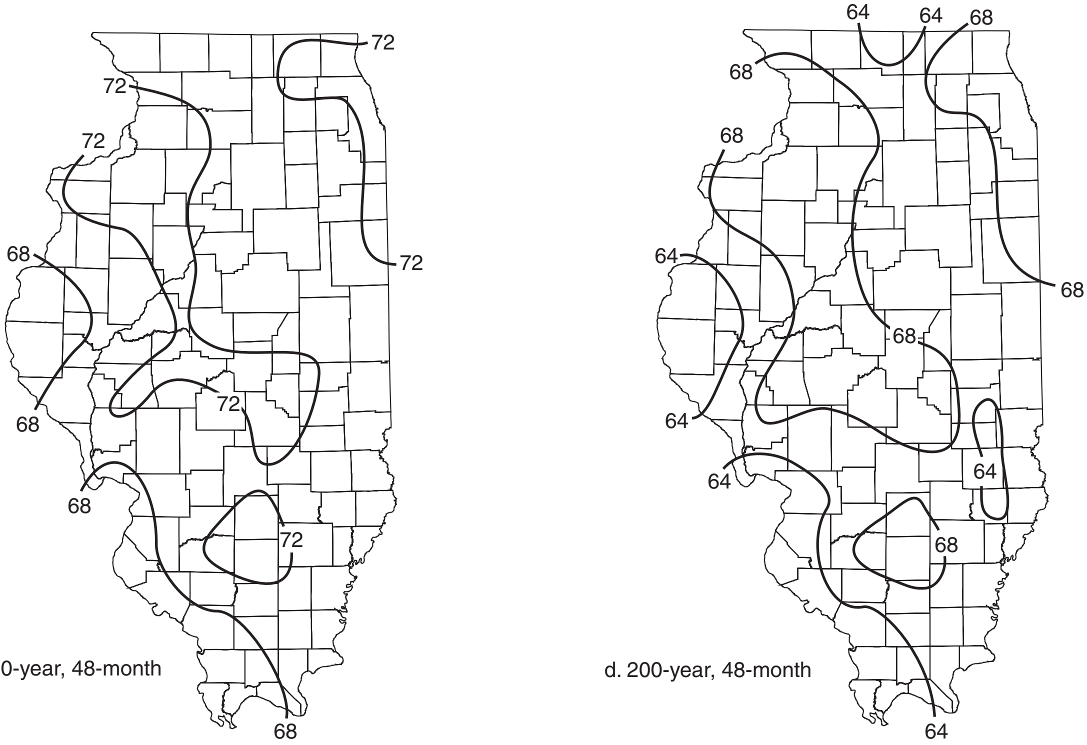
d. 200-year, 36-month

Figure 8. The 36-Month Drought at Return Periods of a) 25 Years, b) 50 Years, c) 100 Years, and d) 200 Years, Expressed as Percent of Normal 1971-2000 Precipitation.



a. 25-year, 48-month

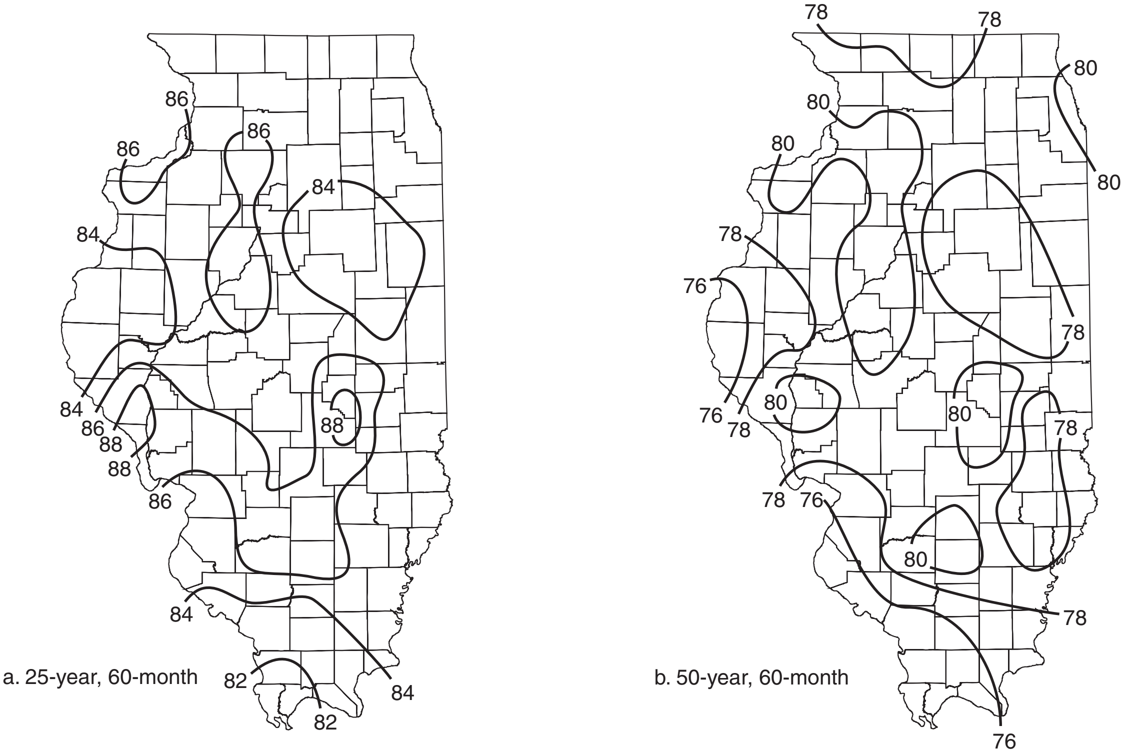
b. 50-year, 48-month



c. 100-year, 48-month

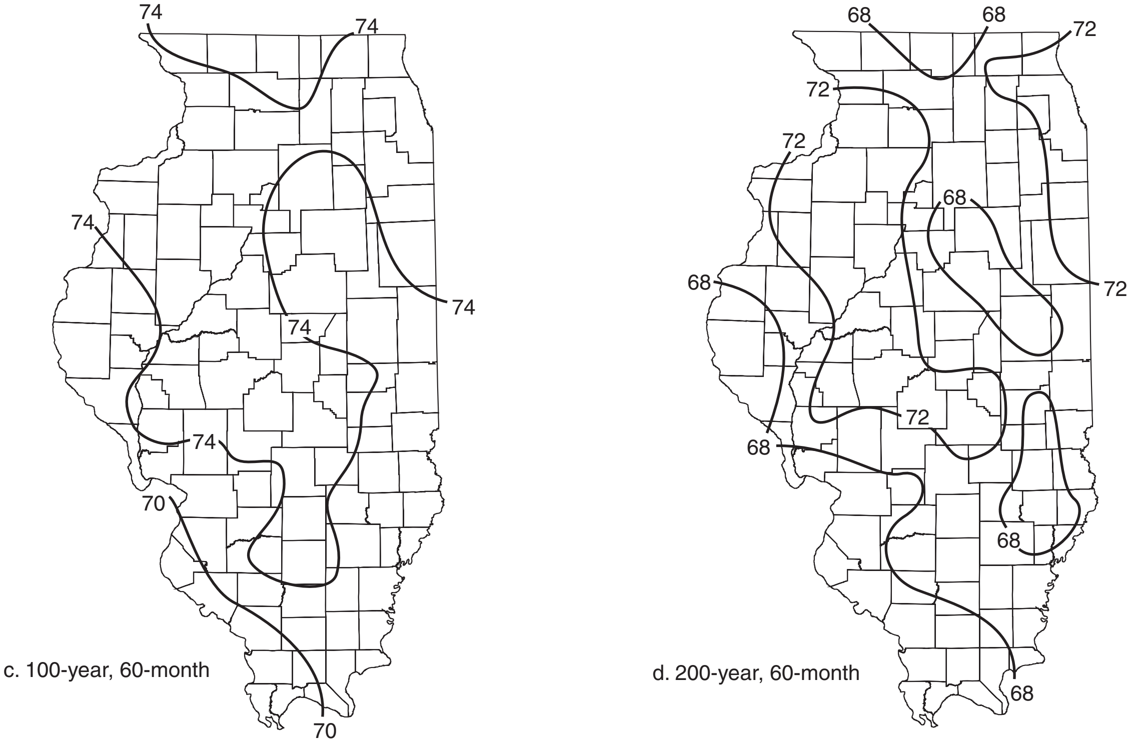
d. 200-year, 48-month

Figure 9. The 48-Month Drought at Return Periods of a) 25 Years, b) 50 Years, c) 100 Years, and d) 200 Years, Expressed as Percent of Normal 1971-2000 Precipitation.



a. 25-year, 60-month

b. 50-year, 60-month



c. 100-year, 60-month

d. 200-year, 60-month

Figure 10. The 60-Month Drought at Return Periods of a) 25 Years, b) 50 Years, c) 100 Years, and d) 200 Years, Expressed as Percent of Normal 1971-2000 Precipitation.

state in this series of maps typically are small. For example, the 100-year, 12-month statewide values (less than 46 to over 50 percent of normal) suggest that the risk of drought is quite evenly distributed across the state. Table 2 summarizes the expected average precipitation for all sites in the state (expressed as percent of normal) for selected drought durations and return periods. Precipitation shortages are most severe for shorter-duration droughts. However, slightly less severe precipitation shortages at the longer time scales prove to be more taxing for the water resources of the state, because the accumulated shortfalls are larger.

Figure 11 shows one way of identifying drought return periods at a specific location, Urbana in east-central Illinois. Based on the 1888-2003 precipitation record, the statistical probability of varying precipitation deficiencies (departures from 1971-2000 normal precipitation) are shown for the warm season (April-September). After a 50-year drought, percentage deficiencies start to level off; the difference between a 50-year and 1,000-year drought is about 18 percent. Figures 5-10 reflect this pattern as the percentages do not change much from one return period to the next. Figure 11 also suggests that the selection of a reasonable worst-case drought for Urbana would be about 30 percent of normal for the April-September time frame. This kind of analysis can be conducted for any length of drought for any specific location having a long climate record. Such analysis provides a basis for evaluating potential impacts of differing intensities and probabilities of precipitation drought on hydrology and water availability.

Figure 12 shows that monthly average soil saturation in Illinois in summer can fall below 30 percent during drought periods, but can exceed 60 percent in wet years (Findell and Eltahir,1997). They reported a linear correlation between initial soil saturation and subsequent rainfall, reaching a peak of $r^2>0.4$ in mid-June. This suggested the possibility of a feedback mechanism maintaining the wet (or dry) conditions established in the beginning of each summer, or a flag indicative of some large-scale process that affects both soil moisture and precipitation.

Table 2. Expected Average Precipitation for All Sites, Expressed as Percent of Normal (1971-2000), for Selected Drought Durations and Return Periods

Drought Duration	*25-year return period*	*50-year return period*	*100-year return period*	*200-year return period*
12 months	59.1	52.5	47.8	44.0
18 months	66.8	60.1	55.2	51.3
24 months	71.9	64.8	59.7	55.5
36 months	77.8	71.1	66.2	62.2
48 months	81.8	75.0	70.1	66.1
60 months	85.3	78.3	73.2	69.0

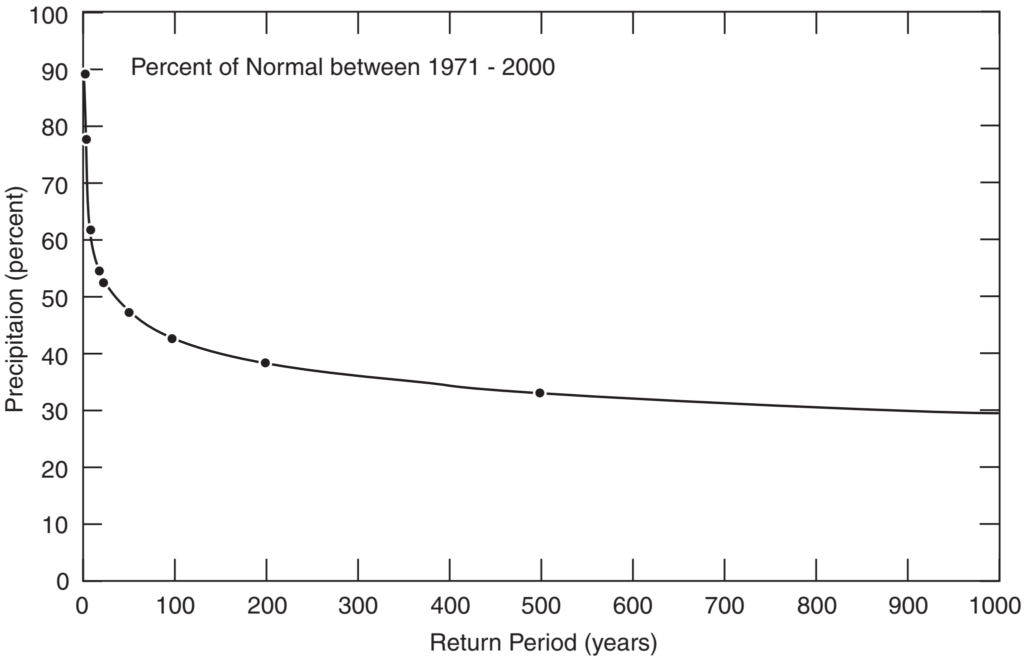


Figure 11. Frequency Distribution of Warm-Season (April-September) Drought in Urbana, Illinois, Using the 1888-2003 Record.

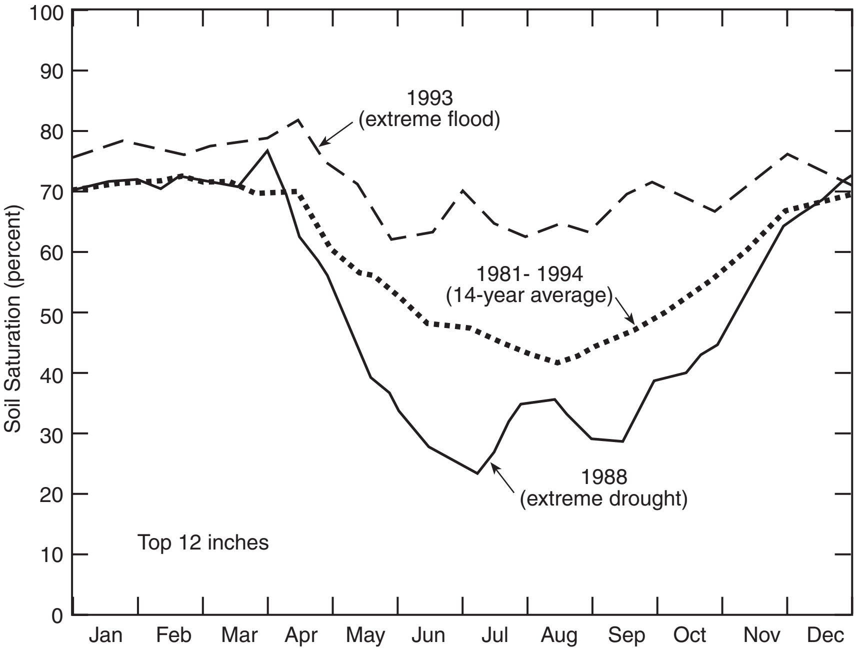


Figure 12. Annual Average Soil-Saturation Cycles in Illinois for the Top 12 in. for 1981-1994 (Thick Dotted Line); 1988 Extreme Drought (Solid Line); and 1993 Extreme Flood (Dashed Line) (from Findell and Eltahir, 1997).

Evaluating Drought Impacts on Water Supplies

Precipitation deficiencies have varying impacts on water supply depending on the timing, duration, severity, and geographical location of the droughts, and on the nature of the water supply. Surface water and groundwater are the two sources of water-supply. Surface-water sources include lakes, streams, rivers, and reservoirs, and their water levels respond quickly to climate anomalies. For these supplies, relationships between precipitation anomalies and stream discharge can be established readily at those sites for which long-term records exist. For sites without such records, those relationships can be estimated by applying models that use precipitation and discharge records from other sites in the same region.

Groundwater occurs in aquifers at varying depths below the surface and in varying geological formations and parent materials. In general, shallow sand-and-gravel aquifers are the most susceptible to droughts, but recharge rapidly. Deeper aquifers generally recharge more slowly, up to thousands of years, and are less susceptible to short-term droughts.

Drought Sensitivity of Surface Waters

The impact of drought on a surface water-supply system depends greatly on the source of the supply, as well as drought intensity and duration. Systems that obtain water by direct withdrawal from a stream or from a low-channel dam are susceptible to any short, intense drought that causes low flow (such as a severe period of precipitation deficit lasting at least three months). Reservoirs with ample storage (relative to both the average inflow and water use) are designed to supply water during multiyear droughts, and therefore may not have severe impacts from short, intense droughts. Reservoirs with less storage rely on inflows to replenish the reservoir during the wet season each year and may be susceptible to either sustained or shorter intense droughts. Table 3 gives examples of drought durations most critical for selected surface-water-supply facilities in Illinois.

Table 3. Critical Drought Duration for Selected Surface-Water Supplies (from Knapp et al., 1994)

Critical duration (months)	*Public water-supply systems*
0-2	Breese, Flora, Elgin, and Aurora (direct withdrawals from streams or low-channel dams)
7-9	Decatur and Danville
18	Springfield, Bloomington, and Macomb Taylorville, Marion, Matoon, and Paris
30	Canton
54	Pana, White Hall, and Carlinville

The impact of drought on these surface-water supplies usually is preceded by a relatively long period of below normal precipitation. Initial stages of a hydrologic drought typically have hot and dry weather, promoting increased water use, which then amplifies the impacts of the dry conditions. When the adequacy of a water-supply system is threatened, water-use restrictions and conservation measures may reduce further impacts of drought.

Hudson and Roberts (1955) suggested that a reservoir suffers water shortages when less than six months of capacity remains. Recent, less severe droughts have shown this to be an appropriate concept. Even if a water-supply system does not go dry, a reservoir in short supply has considerable socioeconomic impacts and stresses, and there is uncertainty that this supply will be sufficient. The 6-month shortage criterion may be too long for reservoir supplies with short critical durations of less than 18 months.

Table 4 lists the number of public water supplies that experienced shortages during selected droughts. The 1930-1931 and 1953-1955 droughts, two of the worst historical droughts in Illinois, each affected most of Illinois. In contrast, the 1980-1981 and 1988-1989 droughts were more regional and generally of shorter duration, as was the 2005 drought. The 1988-1989 drought was an intense period of precipitation deficit that lasted for only nine months in most regions of Illinois. Major differences between a moderate and severe streamflow drought usually are related to the duration and geographic coverage of the drought.

Are public water supplies that depend on surface water better equipped to handle drought conditions today than in the past? McConkey Broeren and Singh (1989a) estimated that 25 surface-water facilities would be inadequate during a 50-year drought without considerable water conservation. Ten other systems listed by McConkey Broeren and Singh likely would have less than a six-month supply at the end of the drought, so they too would be considered to suffer from drought impacts. Thus, it is possible that 35 of approximately 90 existing systems, approximately 40 percent, would experience severe impacts during a year drought. While this is an improvement over the percentages of systems with shortages during the 1930-1931 and 1953-1955

Table 4. Surface-Water Public Water-Supply Facilities with Drought Shortages.

Drought year	*Number of facilities (impacted/susceptible)*	*Source of data*
1930-1931	40/58	Gerber (1932)
1953-1955	53/98	Hudson and Roberts (1955)
1980-1981	12/90	Changnon et al. (1982)
1988-1989	8/91	IEPA public water-supply memoranda

Note: The number of facilities susceptible to impacts includes all surface-water systems except those that withdraw water from Lake Michigan or border rivers.

droughts (Table 4), it is not a particularly significant improvement and serious inadequacies in planning for major droughts. Some of these susceptible systems have upgraded their capabilities since 1989, and/or changed their source of water supply, but others have become more susceptible to drought because of increased water use and decreased reservoir capacity.

With each drought, lessons are learned, and some steps are taken to reduce the impact of future droughts. Severe droughts are very infrequent, but water-supply systems also can develop problems associated with aging facilities, reservoir sedimentation, a lack of capacity analysis, and increased water use. A number of facilities still are not adequately prepared for a once-in-50-year drought, and this report identifies the possibility of once-in-a 100-year, once-in-a 200-year, and worst-case droughts, whose impacts on a larger number of public and private facilities likely would be much more severe.

Case Study: Springfield Water Supply

The City of Springfield obtains its water from Lake Springfield, which impounds Sugar Creek southeast of Springfield, and the South Fork (Horse Creek) pumping station, which withdraws water from the South Fork of the Sangamon River, when sufficient flow is available, and discharges that water into Lake Springfield. The lake not only provides a public water supply for Springfield and satellite communities, but also provides water for operating and cooling the City's coal-fired power plants. There are three primary consumptive uses of water from the water-supply system:

- Public water supply
- Sluicing coal ash from power plants
- Net forced evaporation from the lake when power plants discharge heated water into the lake

In 2002, average use for public water supply was 21.7 million gallons per day (mgd). Water uses for ash sluicing and forced evaporation were about 8 mgd and 2.4 mgd, respectively. During hot, dry summers, such as typically occur during the initial stages of a water-supply drought, public water-supply use exceeds 30 mgd. Even with water conservation measures in later stages of the drought, overall public water-supply use during a drought lasting 18 months can exceed the normal average use of 21.7 mgd by 5-10 percent.

Roughly 20 percent of the lake storage resides beneath primary intakes used for public water supply and power-plant operation (elevation of 547 feet above mean sea level). Although temporary intakes can be used for public supply when the lake level falls below this elevation, the power plant would have to cease operating.

An ISWS study (Knapp, 1998) estimated the yield of the Springfield system during drought conditions of varying frequency and severity (Table 5). Two values of yield are presented. The first assumes that the lake level does not fall below an elevation of 547 feet, below which the power plant cannot operate. The second assumes a practical minimum lake level of 540 feet using temporary intakes.

Table 5. Estimated Yield of Springfield System during Drought Conditions of Varying Frequency and Severity

	Water-supply yield (mgd)	
Drought frequency	*Minimum level (547 feet)*	*Minimum level (540 feet)*
10 year	68.4	83.2
25 year	47.8	58.2
50 year	30.5	37.1
100 year	27.2	33.1
200 year (estimated)	26.1	32.0

Drought yields presented in Table 5 indicate a considerable difference in water-supply yields between 10-year and 50-year droughts, the main difference being the amount of inflow into the reservoir during the drought and the amount of water that can be pumped from the South Fork. Little inflow into the reservoir occurs during a 50-year drought and more infrequent 100- and 200-year droughts, so there is little change in system yield at increased levels of drought severity. Reservoir storage provides more than 90 percent of the system yield for 100- and 200-year droughts, and this fixed quantity is relatively insensitive to drought severity. Yields of reservoirs that have considerable inflow during drought conditions can be expected to be more sensitive to worst-case drought conditions, however.

If ash-sluice water is available for continual recycling into the lake, the average consumptive water use for Springfield is about 24 mgd, but could exceed 26 mgd over the course of a drought when water use is typically higher. Under this situation, it is estimated that Springfield water supply could provide water during a 100-year drought without water levels falling below the 547-foot elevation, although the water level would approximate that elevation by the end of the critical 18-month duration of the drought. Ash-sluice water has high concentrations of boron and reportedly has produced elevated boron levels in Lake Springfield, so water no longer is recycled to the lake. Without this recycled water, the average consumptive water use for Springfield exceeds 32 mgd and may exceed 34 mgd during drought conditions. Without the availability of recycled ash-sluice water, the level in Lake Springfield likely will fall below a 547-foot elevation approximately 13 months into a 100-year drought, shutting down the power plant (probably in mid-summer) for the remainder of the drought. More importantly, it is estimated that remaining storage in Lake Springfield almost entirely would be spent during the remaining 5 months of the 100-year drought, and fall to a level of 540 feet. In the midst of such a drought, there is no certainty that recovery would occur at the end of the projected critical 18-month duration. Average public water-supply use for Springfield continues to increase steadily (roughly 4-percent growth over the past 10 years), and the total volume of water in Lake Springfield gradually is being reduced through sedimentation. Without measures augmenting water supply or reducing water use, it is likely that the Springfield system will, by the next decade, have an inadequate supply even for a 50-year drought. At present, it already is expected that the power plant will need to shut down during a 40 to 50-year drought.

Case Study: Ashland Water Supply

The village of Ashland, with a 2000 census population of 1361, is located 20 miles northwest of Springfield. For the past few decades, Ashland's annual water use primarily has been in the range of 100,000-110,000 gallons per day, although in recent years the reported water use has risen to 120,000 gallons per day. Prior to 1964, the village obtained its water supply from three sand-and-gravel wells; however, total yield from the wells had been inadequate during drought periods in the mid-1950s and early -1960s, during which time water had to be hauled from Springfield. The well water also suffered from poor quality, with high iron content and appreciable hardness. In 1964 the city discontinued use of the wells and began using a new impounding reservoir, located 2 miles south of Ashland, which had a reported capacity of 26 million gallons, but later was estimated to be around 18 million gallons. In 1977 a larger side-channel reservoir was added with a reported original capacity of 52 million gallons.

Ashland's water supply now is obtained from three surface-water intakes. Water from 1) Little Indian Creek, with a drainage area of approximately 14 square miles, is pumped to 2) the side-channel reservoir (the "new reservoir"), and from there to 3) the "old reservoir," which provides the raw water for the treatment plant. Little Indian Creek does not have flow for extended periods in drought years, and during drought periods the village must rely on the water stored in the reservoirs. In the summer of 2005, the water level in the reservoirs was approximately 4 feet below full pool, and this meant a significant reduction in water storage. There were voluntary restrictions on water use and discussion of possibly reactivating the old wells to help fill the two reservoirs.

Analysis of the hydrologic data from Knapp (1982) suggests that Ashland should have at least an 18 month supply of water in its reservoirs to provide a reliable supply through a severe and protracted drought, such as the drought of the 1950s. The storage capacities of the two reservoirs apparently never have been measured and there is no direct information regarding either the accuracy of the original capacity estimates or siltation rates. Thus, the true capacity of the two reservoirs could be noticeably less than the estimated combined capacity of nearly 70 million gallons (which represents an 18- to 20-month supply). Measurement of the capacities of the two reservoirs could remove much of the uncertainty associated with the adequacy of Ashland's water supply.

Many of the water supply concerns facing Ashland are similar to those facing Springfield, but community size may limit the resources and solutions available. Small communities such as Ashland often do not have the technical expertise to identify potential vulnerabilities in their water supply and may not have the financial resources to freely hire technical consultants. Although every community is responsible for developing plans to maintain an adequate water supply, tools and information from state and/or regional entities, including the type of information provided here, are important to help small communities adequately plan. As it turns out, Ashland may be looking to get away from the use of the reservoirs. Their plan, potentially to be implemented in about 5 years, is to hook onto the yet-to-be-established Cass County Rural Water District, with the source of water being well water from along the Sangamon River.

Sensitivity of Groundwater Supplies to Drought

The rate of groundwater recharge is one of the key variables influencing the amount of water that can be withdrawn from an aquifer over the long term. Groundwater recharge is arguably one of the least understood and quantified components of the hydrologic cycle. It cannot be measured directly, is highly variable in space and time, and must be inferred from measurements and determinations of related geologic and hydrologic properties.

> "The major sources of recharge to aquifers in Illinois are direct precipitation on intake areas and downward percolation of stream runoff (induced infiltration)….Recharge from direct precipitation and by induced infiltration of surface water involves the vertical movement of water under the influence of vertical head differentials. Thus, recharge is vertical leakage of water through deposits. The quantity of vertical leakage varies from place to place and it is controlled by the vertical permeability and thickness of the deposits through which leakage occurs, the head differential between sources of water and the aquifer, and the area through which leakage occurs" (Walton, 1965).

An analysis of the impact of the 1988-1989 drought on water resources was presented by Lamb (1992). A similar report on the drought of 1980-1981 was presented by Changnon et al. (1982). Both reports contain analyses of drought impacts on shallow groundwater conditions based on groundwater-level data from an ISWS-maintained shallow groundwater-level observation well network. This network consists of shallow water-table wells located in areas remote from pumping; the observation wells are shallow (mean depth = 28.5 feet) and, by design, were not completed in the state's major aquifers. While data from this network are useful for examining impacts of weather and climate on the water table, and thus are useful for extrapolating to impacts on shallow wells, the impacts of drought on recharge to the state's aquifers is less well-documented or understood.

> "... water stored in thick deposits of glacial drift is available to deeply buried aquifers so that drought periods have little influence on water levels in these aquifers. Ground-water storage in deposits above aquifers and in aquifers permits pumping for short periods of time at rates greater than recharge. However, many aquifers are greatly limited in areal extent and thickness, and pumping at rates much above recharge rates for extended periods results in rapid depletion of aquifers" (Walton, 1965).

Groundwater is withdrawn from three aquifer "types" in Illinois. Generally, these are categorized as sand-and-gravel aquifers within the unconsolidated geologic materials overlying the bedrock, shallow bedrock aquifers lying within 500 feet of land surface, and deep bedrock aquifers lying at depths greater than 500 feet of land surface. Principal aquifers were defined in Illinois as aquifers with potential yields greater than 100,000 gallons per day per square mile (gpd/mi^2) and occupying an area greater than 50 square miles (O'Hearn and Schock, 1984).

Figures 13–15 present the locations of community wells overlain on maps of the principal sand- and-gravel, shallow bedrock, and deep bedrock aquifers, respectively. Two observations are

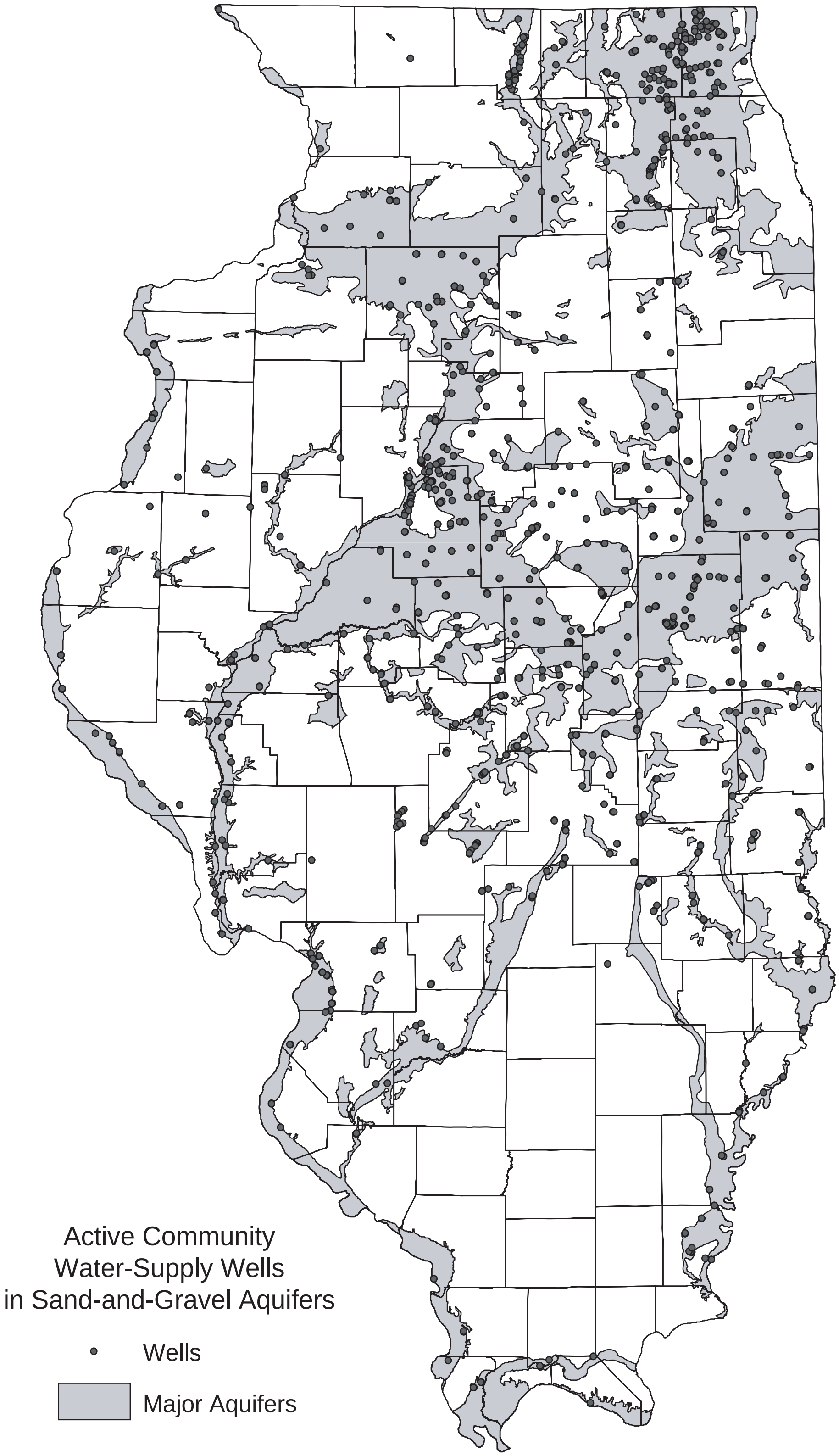


Figure 13. Location of Community Sand-and-Gravel Wells and Illinois' Principal Sand-and-Gravel Aquifers.

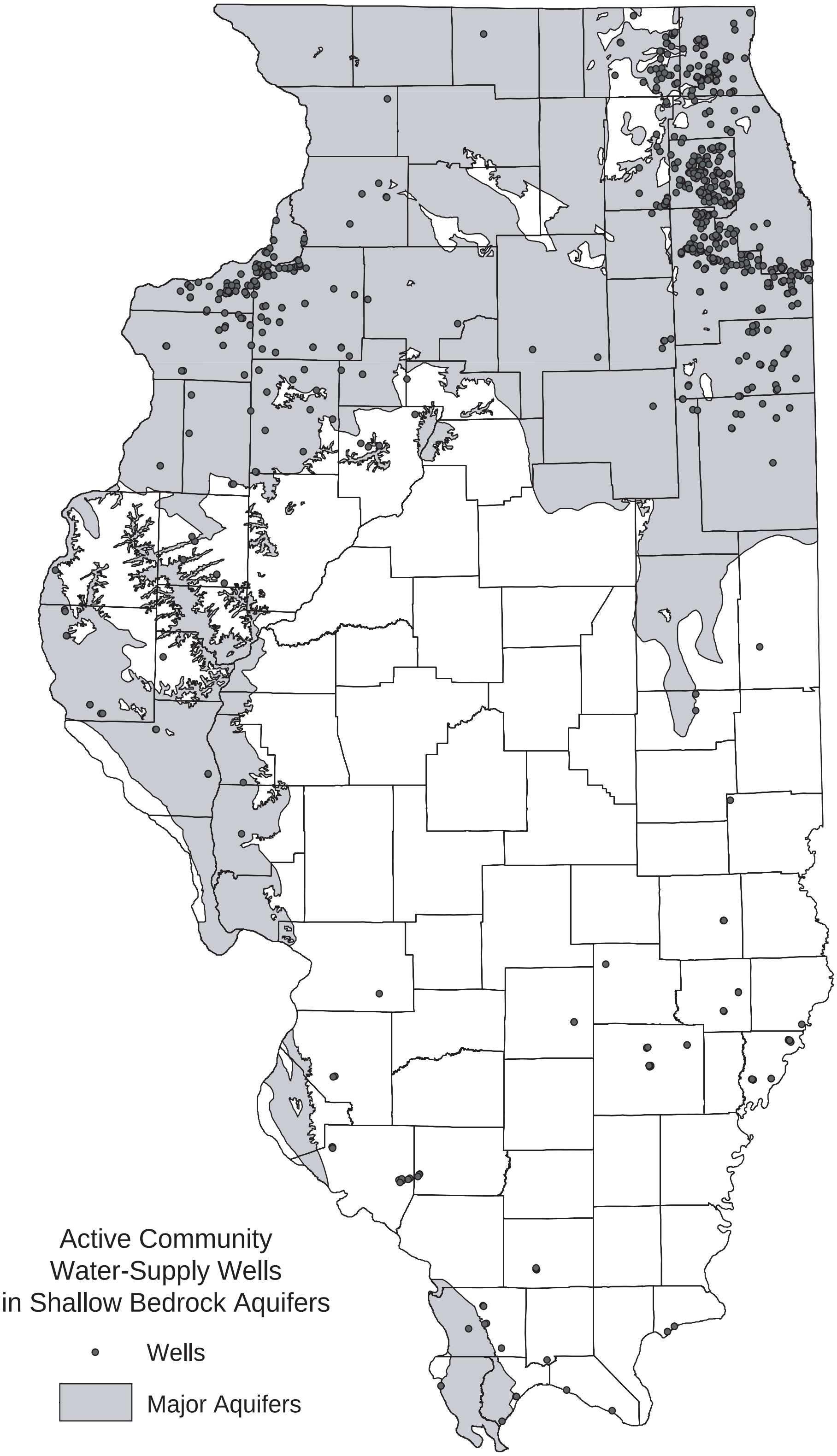


Figure 14. Location of Community Shallow Bedrock Wells and Illinois' Principal Shallow Bedrock Aquifers

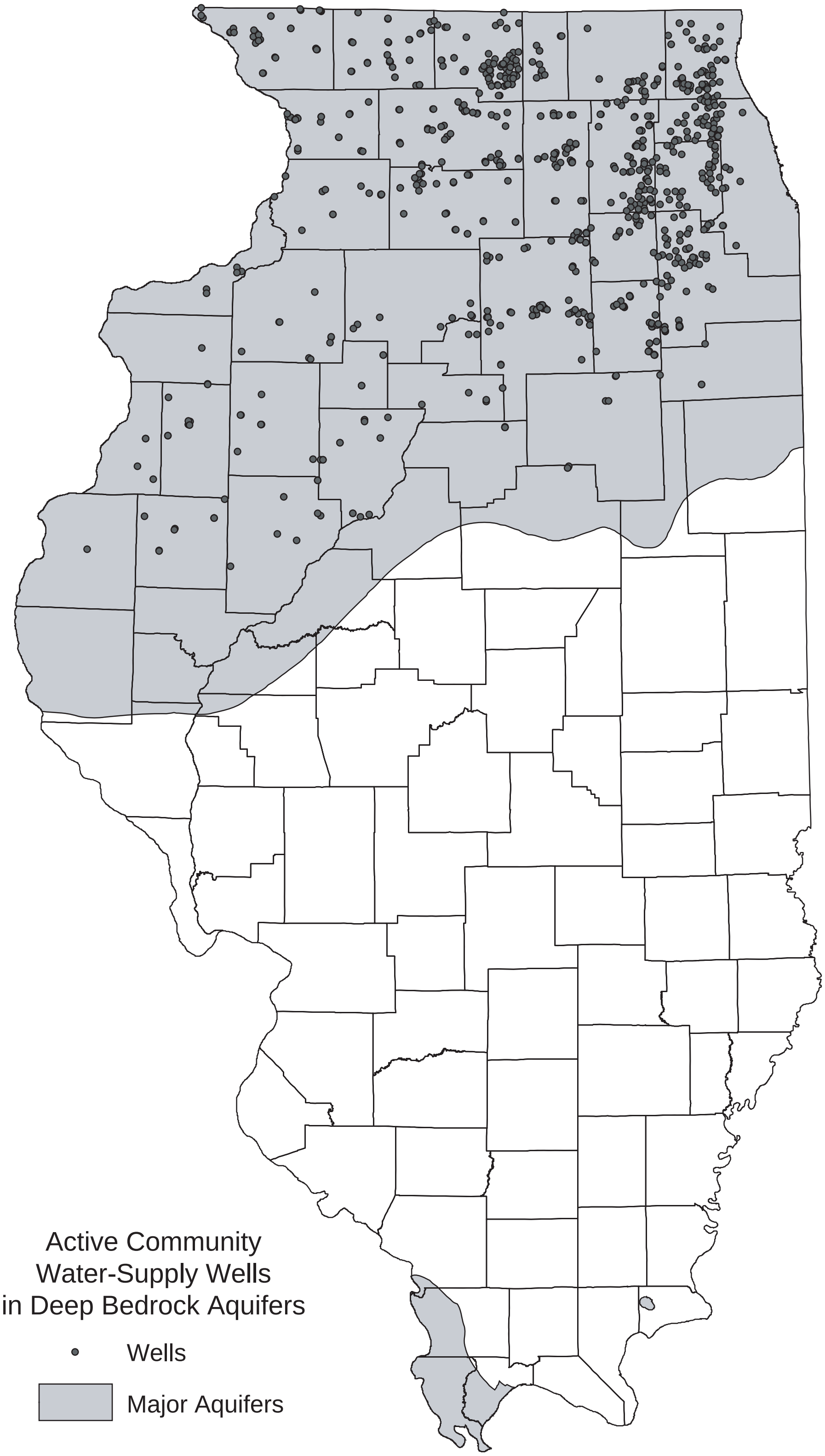


Figure 15. Location of Community Deep Bedrock Wells and Illinois' Principal Deep Bedrock Aquifers.

apparent from viewing these maps: a) numerous community sand-and-gravel wells are not completed in the state's principal sand-and-gravel aquifers and b) groundwater availability is heavily weighted toward the state's major river valleys and the northern third of Illinois which is underlain by one or more principal aquifers. Geologic and hydrologic data clearly show the tremendous spatial variability in the character, thickness, and hydraulic conductivity within the glacial deposits overlying these aquifers. This variability, in turn, causes great variability in recharge to underlying aquifers.

Shallow, surficial aquifers (sand-and-gravel and bedrock) do not have water stored in overlying deposits from which they can draw during times of drought. Therefore, water levels in such aquifers are more sensitive to climatic conditions and will decline in response to dry weather. Available drawdown in wells (the difference between the non-pumping water level and the allowable pumping level, such as the top of the well screen) will be reduced correspondingly. The situation can be exacerbated further by the effects of well interference; water demand often increases during drought, causing wells to be operated at higher pumping rates and/or for longer periods.

Alluvial valley aquifers often are in hydraulic communication with the streams occupying the valleys in which the aquifer is situated. In the humid Midwest, groundwater discharge to streams is often a large component of stream flow (Grannemann et al., 2000) and may be all of the flow in perennial streams during low flow periods, especially during drought. However, as described by Walton above, wells completed in these aquifers can induce infiltration of surface water through stream beds. If stream flow is affected significantly by drought, well yields can also be affected adversely. Conversely, pumping wells that induce recharge from nearby streams will reduce stream flow - an effect that may be unacceptable if ecological streamflow thresholds are crossed.

Perhaps the best way to assess drought sensitivity is through the use of groundwater flow models where the effects of reduced or no recharge can be examined. However, there are hundreds of Illinois community wells that would require modeling. Due to the intensive data requirements and time needed to develop groundwater flow models, it is simply not practical for the ISWS to develop detailed flow models for each of these supplies. However, community supplies can be prioritized in terms of drought sensitivity and population served. Groundwater flow models have been developed for many communities as part of groundwater recharge area delineations for Illinois EPA's Source Water Assessment and Protection (SWAP) program. With time and resources, such models could be adapted to examine the groundwater resource and facility capability to respond to drought.

Identifying At-Risk Community Groundwater Supplies

A practical methodology to identify community wells potentially at-risk due to drought was devised. Digital databases were used to provide input to a geographical information system for display of selected well parameters that may suggest a community supply is drought-sensitive. A summary of the approach is presented below.

Well Depth. Community well data were segregated on the basis of well depth. Shallow wells are most likely to be affected by a lack of recharge resulting in lowered groundwater levels. Shallow wells also tend to have less available drawdown within which they can operate. Lower non-pumping water levels due to drought will further reduce available drawdown. Communities with wells less than 100 feet deep were deemed potentially sensitive, with wells less than 50 feet deep being most sensitive. Of approximately 3,000 active community wells in Illinois, about 192 are less than 50 feet deep and 574 are between 50 and 100 feet deep.

Proximity to Surface Waters. Shallow community wells were identified further on the basis of proximity to streams using a buffer of 1000 feet to highlight wells that receive potential recharge through streambed infiltration. These wells potentially could be affected by low streamflow during a drought or, conversely, could severely impact low streamflows during drought. Therefore, shallow community wells (wells <100' deep) in proximity to streams could be given higher priority. Eighty-two (82) community wells less than 50 feet deep were found to be within 1000 feet of an identified stream and another 179 community wells between 50 and 100 feet deep were found to be within 1000 feet of an identified stream (total: 261 wells).

Well Density. Community wells were examined on the basis of well density, that is, the number of wells within a defined area. Typically, communities that use areally-limited aquifers will have several low-capacity wells in a very confined area; for example, Lewiston has approximately 6 - 8 wells within a 10-acre area. During drought, water demand typically increases, causing wells to operate for longer periods and at higher rates, increasing the effects of mutual interference. For this analysis, shallow community wells within 1,000 feet of one another and within 1,000 feet of an identified stream were identified. Fifty-nine (59) community wells less than 50 feet deep and 149 community wells between 50 and 100 feet deep were found, as shown in Figure 16 and listed in Appendix C.

Population Served. Potentially drought-sensitive communities that serve larger populations than other potentially drought-sensitive communities also could be prioritized on the basis of risk to human health. For this reason, the population served is included with those communities listed in Appendix C. Very few of the listed communities serve populations greater than 10,000 and most of those may not, in fact, be drought-sensitive for reasons discussed below.

Uncertainties. In some cases, community wells that are identified through the above process may not be drought-sensitive because the alluvial deposit in which those wells are completed is adjacent to a major river system (e.g., the Mississippi, Illinois, and Wabash River bottoms) or the aquifer is extensive and thick enough such that, even though shallow, is quite drought-resistant (e.g., western portions of the Mahomet Aquifer). Conversely, many drought-sensitive wells may not be identified by this methodology. Well depths of 100 feet and proximities of 1000 feet to other wells or streams were selected as methodological examples. Such an analysis ignores deeper wells that may have been completed in drought-sensitive aquifers and wells at greater distances from other wells that still could be affected by mutual interference. Nor does this analysis attempt to identify supplies that may be vulnerable due to facility deficiencies. Water demand often increases during drought and facility capability to meet increased demand is often

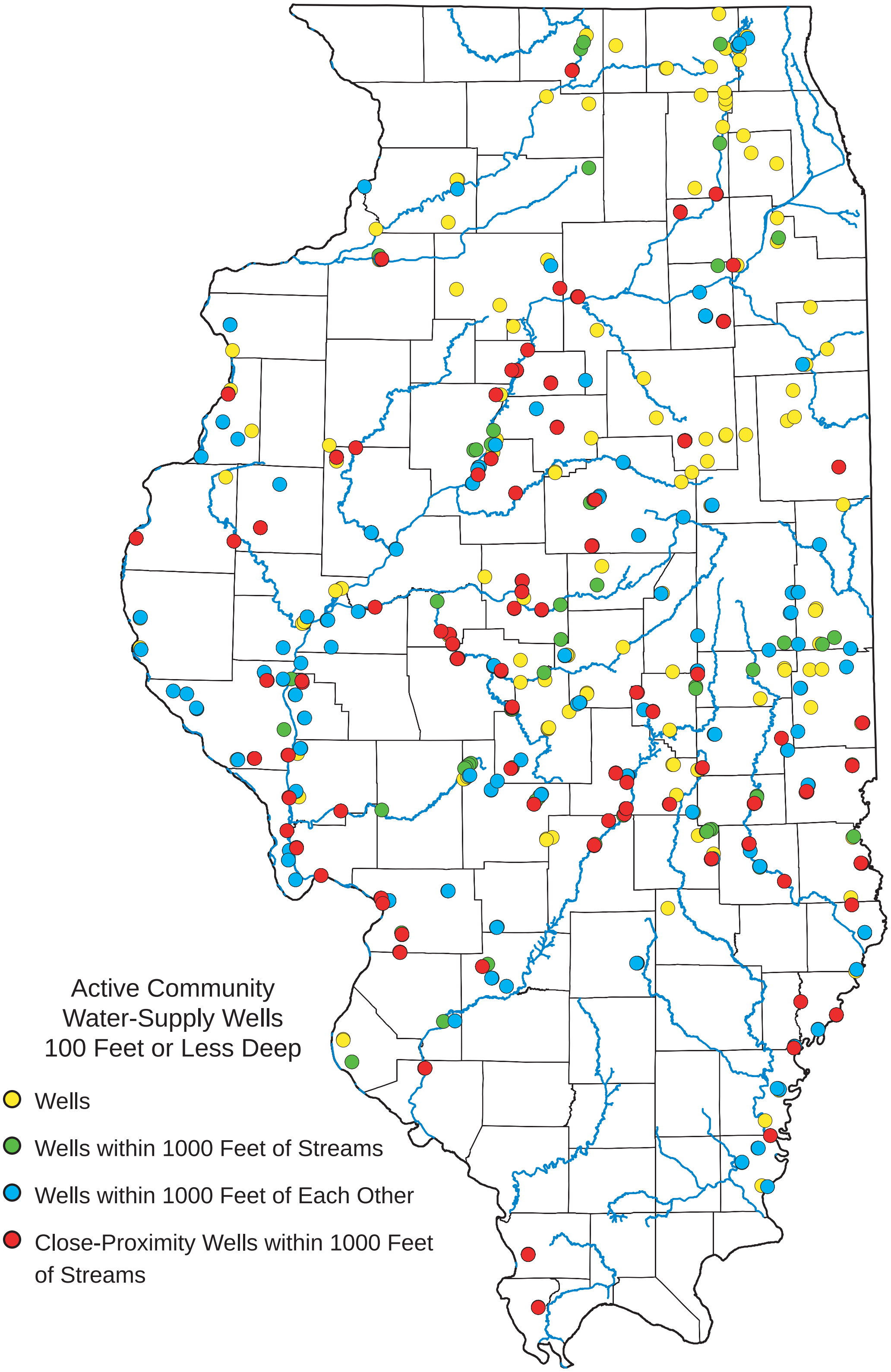


Figure 16. Community Water-Supply Wells Less than 100 Feet Deep, Within 1000 Feet of Another Community Well, and Within 1000 Feet of a Recognized Stream.

a critical component of drought preparedness. Aquifer and well capabilities aside, a community also needs capacity to meet the maximum daily demands that occur during hot, dry weather often associated with droughts.

Summary. From a list of over 3000 community wells serving over 1,100 community systems, this methodology pared the list to 208 wells, representing 82 communities (Appendix C). These community wells are deemed potentially vulnerable to drought conditions on the basis of their shallow depth, proximity to other shallow community wells, and proximity to identified streams. Examination of the map with respect to Illinois' major sand and gravel aquifers shows that most of the potentially drought-sensitive community wells are located in southern east-central Illinois, south of the Mahomet Aquifer and along minor river valleys, such as the upper reaches of the Kaskaskia, Embarras, and Little Wabash Rivers. Follow-up analyses need to be conducted with the intent of developing alternative water supplies for drought-sensitive communities. Alternatives include locating additional wells in the same aquifer or different aquifer; developing alternate water sources (e.g., surface water); deepening wells and/or lowering pumps; reducing or curtailing pumpage from other non-essential wells, such as irrigation and golf course wells; repairing system leaks; increasing storage; and instituting water conservation measures.

Groundwater flow models can be developed for those community wells determined to be most drought sensitive. In some cases, advantage can be taken of groundwater flow models already developed for many community recharge area delineations as part of regulatory SWAP program.

Identifying At-Risk Private Groundwater Supplies

Several hundred thousand people in Illinois depend on private wells for their water. Therefore, the sensitivity of private, domestic groundwater supplies to drought also is important. Using the private well database maintained by the ISWS, a summary of private well statistics for each county was conducted to assess potential private well drought sensitivity. A county-by-county summary of the total number of wells, those less than 50 feet deep, greater than 50 feet but less than 100 feet, and greater than 100 feet was conducted. An examination of the prevalence of bored or dug domestic wells also was conducted by examining the total number of domestic wells, the total number of drilled domestic wells, and the total number of bored or dug domestic wells. Two county statistics, the total number of wells in the database and the relative prevalence of bored or dug wells, are shown in Figures 17 and 18.

It is readily apparent that, based on the number of records in the ISWS private well database, the greatest number of wells in Illinois occurs in northeastern Illinois in Lake, McHenry, Cook, DuPage, Kane, and Will Counties (Figure 17). Many fewer wells exist in southeast Illinois (i.e., Edwards, Wabash, Hamilton, Gallatin, Williamson, Saline, Hardin, Pope, Johnson, and Alexander Counties) and in a number of western Illinois counties (Pike, Calhoun, Jersey, Scott, Brown, and Schuyler). County populations aside, the number of wells clearly is influenced by the presence or absence of major aquifer systems (shown in Figures 13-15). Northeastern Illinois is blessed with multiple aquifer systems, one lying over another; whereas,

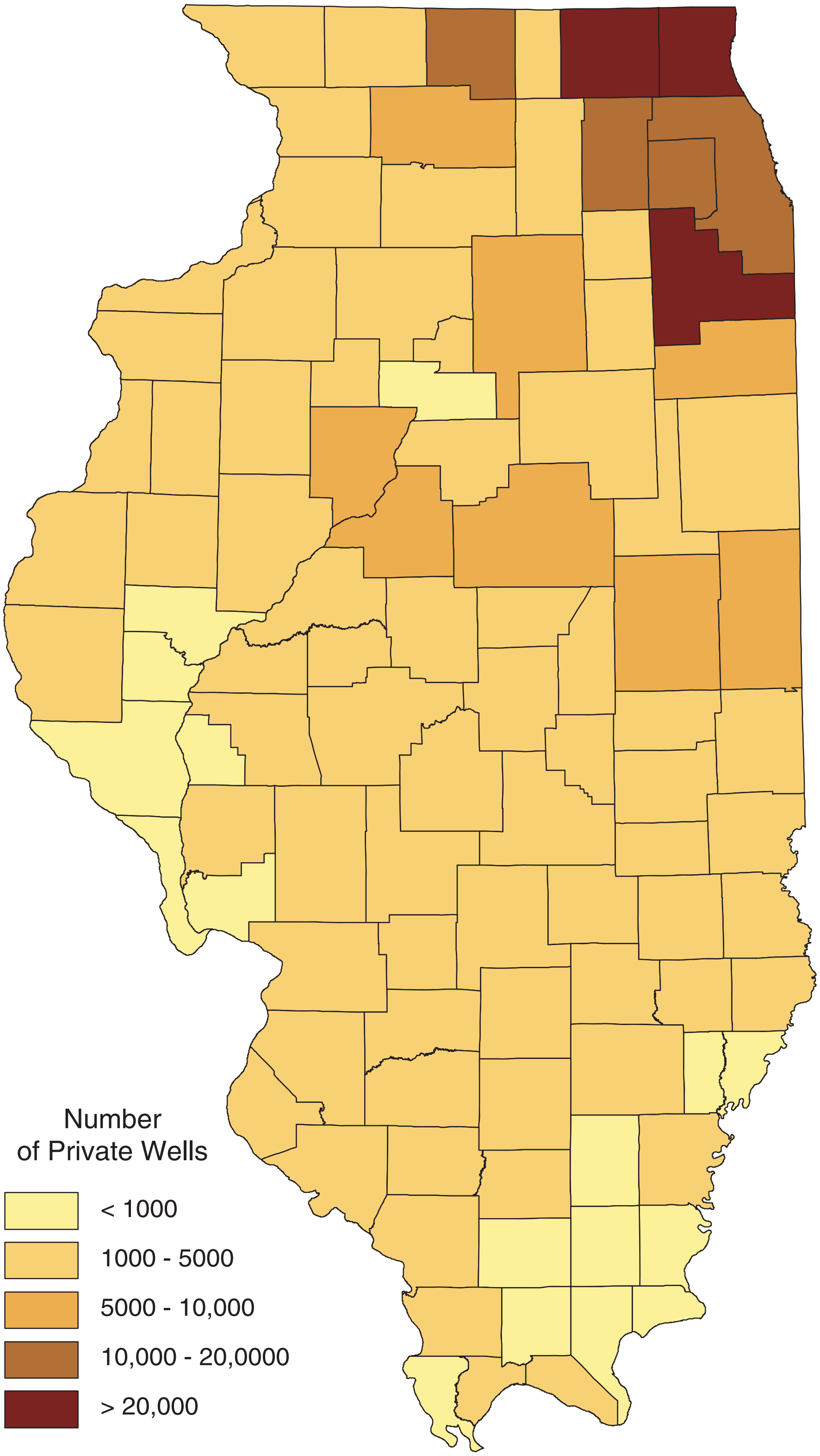


Figure 17. The Number of Wells in the ISWS Private Well Database, by County.

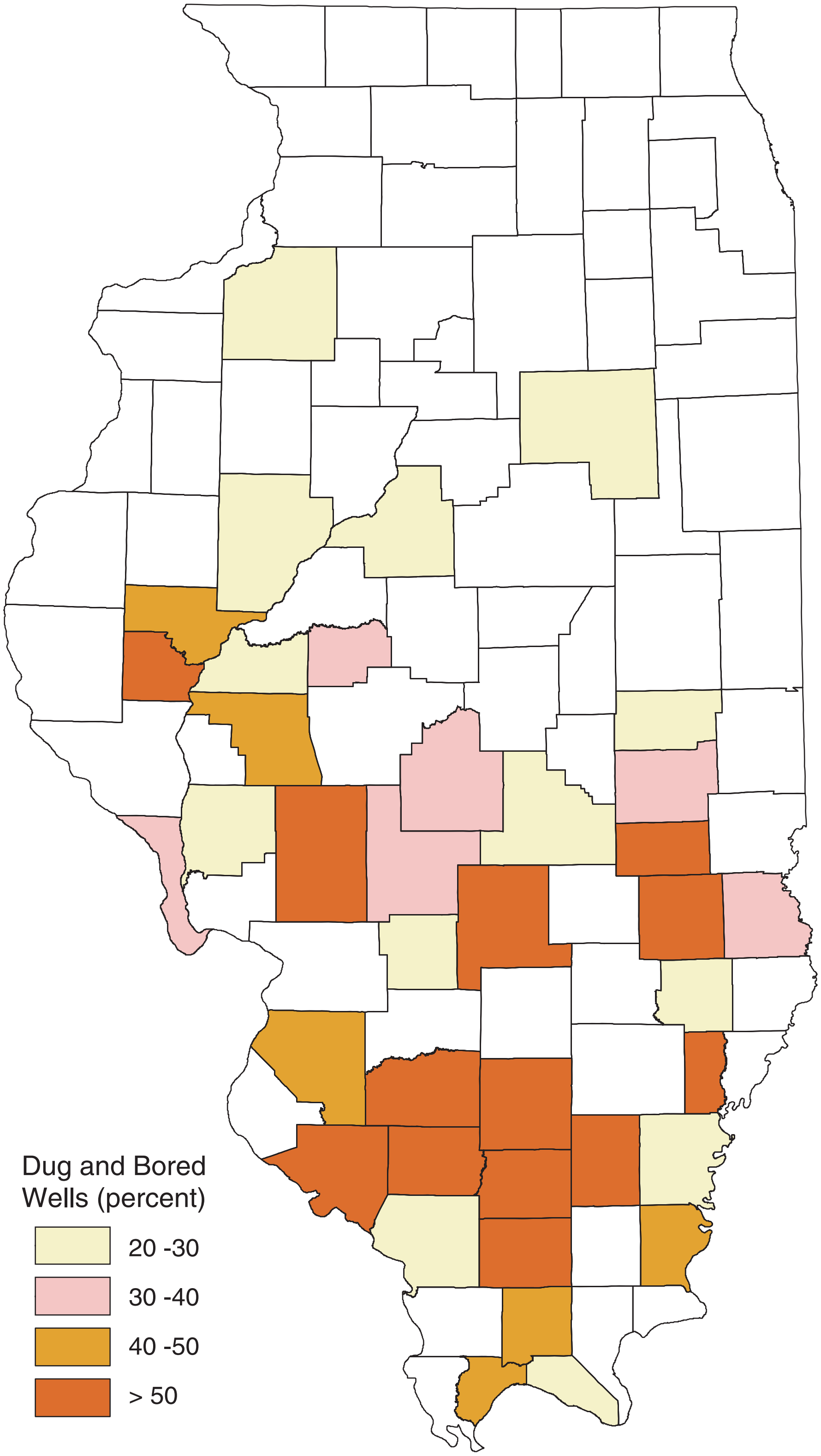


Figure 18. The Predominance of Dug and Bored Wells in Illinois, as a Percentage of the Total Number of Wells in the ISWS Private Well Database, by County.

southern Illinois generally is groundwater poor, relying on alluvial aquifers within the major river valleys (Wabash, Illinois, Mississippi, and Kaskaskia).

Bored and dug wells are the principal well type in areas where no local aquifer exists. Water demands are met by the water in storage within the well bore (a typical 36-inch diameter well contains 53 gallons of water per foot of water depth). These wells rely on seepage from thin stringers of silts, sands, and gravels to replenish the water within the large bore during low-demand periods (e.g., nighttime). As such, these wells are susceptible to dry conditions and, depending upon depth and water use demands, many go dry during normal summers. Bored and dug wells, therefore, are extremely sensitive to drought. Examination of the ISWS private well database reveals the predominance of these well types across much of southern Illinois (Figure 18). In many cases, over 50 percent of the wells in these counties are bored or dug wells. As with community water supplies, private wells also are drought-sensitive in the groundwater-poor region of southern Illinois.

Increased Water Use during the Warm Season and Drought Periods

Although water use remains relatively constant over cooler months between November and April, most public water-supply facilities experience a notable increase in water use during the warmer months. Monthly water-use data from 25 public water supplies in central and southern Illinois show that average May-October water use is 11 percent greater than during the cool season, and July-August water use is roughly 15 percent greater. Increased water use during the 6-month warm season varies 4-27 percent among different public systems. In general, increased summer water use is less for smaller communities. It is expected that most of this increase comes as the result of outdoor use of water, for example, for lawn watering, irrigation of golf courses, and car washing. Water use for commercial and industrial purposes usually does not change substantially during summer; therefore, communities that provide higher rates of water use for these purposes will see less of a relative increase in water use during summers.

During particularly hot, dry summers, especially those during drought conditions, the average water use is even greater. Average monthly water use during the June 1999-October 1999 period, one of the driest 6 months in the past 10 years, was 17 percent above the cool season rate. Overall 12-month water use during that mild drought (June 1999-May 2000) was about 8 percent higher than average annual water use. An analysis of annual water-use data for the more severe 1988-1989 drought shows that the average increase in annual water use in 1988 was 10 percent higher than in typical years, and some systems experienced annual water-use increases that exceeded 20 percent in 1988. These increases occurred in many communities despite voluntary or mandatory restrictions on outdoor water use. For this reason, the ISWS has evaluated the adequacy of surface water-supply facilities during drought using water-use rates as much as 20 percent higher than the average rate (McConkey Broeren and Singh, 1989a,b).

If water supply facilities do not meet peak demands, whether these peaks are caused by drought or other factors, then water shortages occur.

Floods and Water Supplies

Above average precipitation and water in Illinois streams generally benefit water supplies, but a large excess over a short period can create problems for water supplies. Floods on Illinois rivers and streams can have serious, very damaging impacts, particularly for surface water, including losses in water volume, physical damage to water-supply systems, and diminished water quality, as well as damage to shore-line recreational facilities, businesses, residences, public and private roads, and bridges. Those impacts reduce available water supplies and increase costs in Illinois.

Most damaging floods from heavy precipitation result in high runoff rates. These conditions enhance soil erosion, and runoff captures various surface pollutants, such as agricultural fertilizers and pesticides that can pollute streams and reservoirs. The volume of water from flooding often overwhelms water-treatment facilities built along rivers. Similarly, flooding can lead to the loss of sewage-treatment facilities typically built along rivers and streams. As a result, untreated wastes are released into rivers that serve as water supplies at downstream locations. The widespread spring floods of 1982 led to closure of 16 community sewage-treatment plants and numerous plant bypasses after release of raw sewage into streams and rivers. This created major water-supply problems for water-treatment plants located along the downstream river (Changnon et al., 1983). The 1993 floods damaged chemical facilities alongside the Mississippi River and three downstream water-treatment plants (Changnon, 1996). Soil erosion from the record 1993 rains and flooding exceeded more than 20 tons per acre over 13 percent of Illinois' croplands. The sediment load in the Mississippi River in mid-1993 was equivalent to 70 percent of the river's annual average sediment load (Changnon, 1996).

Additional eroded soil carried in flooded rivers is deposited in downstream lakes and reservoirs, which leads to major decreases in available water storage. In some instances, major floods and rapidly moving floodwaters have damaged locks and dams on state reservoirs, as well as water-treatment plants. For example, the 1993 floods destroyed 3 community water-treatment facilities, badly damaged 9 others, and made 11 others inoperable for weeks after the flood (ISWS, 1994). Thirty-four communities also had prolonged boil orders for their water supplies as a result.

Floodwaters replenish groundwater aquifers in bottomlands and floodplains, but several aquifers became polluted from infiltration of polluted floodwaters in 1993. In addition, polluted floodwaters typically caused extensive contamination of wells, resulting in contamination of aquifer systems by pesticides, herbicides, and other hazardous chemicals (Changnon, 1996).

The floods of 1996 resulted from record intense rainfalls in the Midwest. Soil erosion was extensive, 12-15 tons per acre, and damages to sewage-treatment plants led to closures and loss of drinking water to more than 8,000 persons. Some treatment plants were out of commission for 8 weeks, and repair costs exceeded $2 million.

Clearly, water-supply planners and managers need to consider periodic excesses of precipitation that create floods as well as periodic shortages that create droughts. This report focuses on droughts.

Chapter 2

Water Budgets in Illinois: Looking to the Future

A water budget quantifies systematically the flows and reservoirs of water in the hydrosphere over a period of time (see Appendix A). A water budget can be created at any geographical scale and over any period of time. For water-supply planning and management, water budgets for aquifers and watersheds are most meaningful. As all components of the water cycle are connected, estimating future water budgets allows water-supply planners and managers to evaluate the impacts of system changes on water availability, and the impacts on the water-supply system of increased withdrawals.

Water budgets in Illinois are variable from year-to-year, decade-to-decade, and over centuries and millenia. Variations and changes in climate, geology, soils, vegetation, and hydrology have produced different inputs, storages, and flows of water. Similarly, it can be expected that water budgets will change as land cover and climate change, and as water withdrawals and diversions occur. In water-supply planning, it is important to project those variations and changes to water budgets as a basis for evaluating water availability and demand, the capacity of existing systems to meet projected demand, and options for new water-supply projects.

Water availability is very much dependent upon climate conditions, especially precipitation and temperature. Scientists cannot predict with confidence climate conditions decades ahead, but plausible climate scenarios can be constructed based on assumptions that climate conditions observed in the past could recur, and that climate projections made by global climate models have some validity. For central North America, the Intergovernmental Panel on Climate Change (IPCC) of the United Nations (IPCC, 2001) reports that models generally are biased warm. In that report, five global models show temperature biases of approximately -2.0 to +5.0°F in winter and approximately +1.0 to +6°F in summer in simulating 1961-1990 temperature. Precipitation biases are approximately +/-20 percent and -10 to +40 percent respectively. These biases in simulating recent climate conditions must be taken into account when the same models are used to project future climate conditions. In a recent study using somewhat newer model versions (Kunkel and Liang, 2005), the late 20th century biases appear to be reduced somewhat. For winter, four models show cool temperature biases up to -4°F while four other models show warm biases up to +2° F. For summer, four models show cool biases up to -1.6°F, while four others show warm biases up to +2°F. Precipitation biases are -20 to +50 percent and -25 to +17 percent for winter and summer, respectively. These biases, other model limitations, and uncertain emissions scenarios result in uncertain future scenarios of climate change (Winstanley and Changnon, 2004).

The IPCC reports that, based on global model simulations of increasing temperature for a wide range of scenarios, global average water-vapor concentration and precipitation also are projected to increase during the 21st Century (IPCC, 2001, p. 596-602). For central North America, simulated temperature change between 2071 and 2100 ranges from approximately +3 to +12°F in winter and approximately +4 to +13°F in summer. Simulated precipitation change ranges from approximately -5 to +25 percent in winter and approximately -40 to +30 percent in summer. The global climate models do not simulate well the observed 20th Century cooling in the Midwest and southern United States, a period over which carbon dioxide (CO_2)-equivalent greenhouse-gas concentrations have increased by 50 percent. From the more recent study of Kunkel and Liang (2005), the Climate System Model of the National Center of Atmospheric Research, a global climate model, shows no warming in Illinois with a 50 percent increase in atmospheric CO_2 concentration from current levels, in better agreement with observed trends in the Midwest. That model shows a warming of 2°F in Illinois with a doubling of CO_2 in the year 2100. The National Assessment Synthesis Team (2000) used two primary climate scenarios based on a mid-range emissions scenario that assumes no major changes in policies to limit greenhouse gas emissions. The primary climate models used in the assessment (Canadian model and Hadley model) project that U.S. temperature will rise 3 to 15°F over the next 100 years. Precipitation in the Midwest is expected to continue its upward trend: 10 to 30 percent increases are projected across the region. Increases in the proportion of heavy and extreme precipitation are stated to be very likely. However, increased evaporation is projected to lead to a soil-moisture deficit, reduced lake and river levels, and more droughtlike conditions.

For the Great Lakes region, Kling et al. (2003) predict that temperature in the region will increase 5-12°F in winter and 5-20°F in summer by 2100. Although average precipitation levels are unlikely to change, they reported that precipitation is likely to increase in winter by 10-25 percent and decrease in summer by 5-20 percent, and the region may grow drier with declines in water levels of inland lakes and the Great Lakes, and reduced groundwater recharge. Nevertheless, they also anticipate increased flooding.

Seneviratne et al. (2004) highlighted the importance of land-surface processes in climate integrations, suggesting that the risk of enhanced summer dryness in the Midwest in the future may be less acute than reported by earlier modeling studies that used very simple representations of those land-surface processes. Two factors reportedly explain much of the reported reduced risk of summer dryness: the soil is not fully saturated in spring and can absorb extra precipitation during this season; and evapotranspiration increases are relatively moderate. The climate model used in that study incorporated a more sophisticated representation of land-surface processes, but the simulations entail other simplifications that may produce questionable results.

A diagnostic analysis of climate model data examined precipitation, surface-air temperature, and related atmospheric features for Illinois and the central United States (Kunkel and Liang, 2003). Data were obtained for 21 global general circulation models (GCMs) participating in the Atmospheric Model Intercomparison Project (AMIP) and 9 models participating in the Coupled-Model Intercomparison Project (CMIP). Values of simulated average annual temperature range (48.0-57.5°F for AMIP models and 48.3-54.1°F for CMIP models) were compared to an observed value of 51.4°F. All AMIP models and all but one CMIP model were drier than actual fall observations.

Milly (2005) reported that the upward trend in precipitation in the Mississippi River basin over the past half century is unlikely to be sustained into the future. An eventual return to normal conditions would decrease flows through the basin. The future direction of precipitation trends in the basin associated with anthropogenic climate change was reported to be unknown.

Given the highly variable nature of Illinois climate and the uncertainties of predicting the future, the present study investigated the effects of plausible changes in precipitation and temperature on evapotranspiration, streamflow, and groundwater recharge in Illinois to the year 2040, a reasonable time span for water-supply planning. Based on 150 years of climate conditions in Illinois, climate trends, and the results of climate scenarios generated by different global climate models, 10-year average annual precipitation in Illinois could change by +/- 20 percent and 10-year average annual temperature possibly could increase by up to 7°F, or decrease by 1°F. Beyond 2040, there is a possibility of greater climate change, but there is also greater uncertainty about possible future climate conditions.

Almost all global climate model simulations project an increase in average annual temperature for Illinois as concentrations of greenhouse gases in the atmosphere increase. However, as noted above, concentrations of greenhouse gases, expressed as CO_2 equivalents, already have increased about 50 percent since pre-industrial times, but the average annual temperature in Illinois has not increased since the 1930s. A negative correlation, or lack of correlation, between the concentration of greenhouse gases and average annual temperature in Illinois suggests that current models may not simulate all processes important to changes at the regional scale, or may not simulate them accurately, although internal variations of the climate system could possible explain the differences. Nevertheless, the overall differences between model simulations and observations increases the uncertainty of the future climate projections made by the global climate models. As a basis for evaluating the possible impact of higher temperatures on evapotranspiration and runoff, climate warming scenarios of 3°F and 7°F were used in this report. These scenarios are not necessarily representative of any specific GCM, but rather represent the possible range of conditions that could occur in 2040, based on many different GCM simulations.

Appendix A (Figure A-13) shows the results of the ISWS soil-moisture budget model to estimate the sensitivity of runoff and evapotranspiration to changes in temperature and precipitation. Runoff is very sensitive to precipitation changes. A decrease in precipitation by 20 percent causes a decrease in runoff of 49-55 percent. An increase in precipitation by 20 percent causes an increase in runoff of more than 60 percent. Runoff is less sensitive to temperature change. For example, for a precipitation increase of 20 percent, runoff varies from an increase of 60 percent for a temperature increase of 7°F to 68 percent for no change in temperature. Although it is counterintuitive for runoff to increase with an increase in temperature, the slight increase shown by the model appears to be due to two factors. One, crops develops faster under warmer conditions, thus extracting soil moisture for a shorter period. Two, high temperatures put crops under stress more frequently, which in turn causes stomates to close. It is not clear whether this reflects reality or is simply an artifact of model construction. Changes for evapotranspiration are considerably smaller: a 6-8 percent decrease for a 20 percent decrease in precipitation, and a 1-4 percent increase for a 20 percent increase in precipitation.

All the above climate scenarios illustrate the sensitivity of Illinois' water balance to a plausible range of climate changes; they are not climate predictions. Clearly, such a large range of uncertainty about possible climate conditions less than four decades ahead imposes equally large uncertainty about future water budgets in Illinois, and on future water availability. To reduce this uncertainty, the ISWS is implementing regional climate modeling and model intercomparison programs.

Watershed Studies

Watershed modeling applications for the Fox River and Iroquois River watersheds have been used to evaluate the response in simulated streamflow to historical climate conditions and the following climate scenarios (Knapp et al., 2004):

Wet2050. All historical precipitation values were increased by 5 percent; all historical temperature values were increased by 2°F.

Wet2100. All historical precipitation values were increased by 11 percent; all historical temperature values were increased by 4°F.

Dry2050. All historical precipitation values were decreased by 3 percent; all historical temperature values were increased by 6°F.

Dry2100. All historical precipitation values were decreased by 10 percent; all historical temperature values were increased by 14°F.

Unlike the scenarios represented in Figure A-13, specific GCMs were used to develop those four scenarios. Although these GCMs produce quite different outcomes for the future climate, they do not represent the entire range of GCM outcomes. The Wet2050 and Wet2100 scenarios are associated with simulations from the Hadley GCM (U.K. Meteorologic Office's Hadley Center Climate Model version 2) for years 2050 and 2100, respectively. The Dry2050 and Dry2100 scenarios are associated with simulations from the Japan GCM (Japan Center for Climate System Research Model), also for years 2050 and 2100. The two watershed applications use different hydrologic simulation models, because the true hydrologic response to variations in climate is unknown, and using different models can present a range of credible simulated hydrologic responses. More work will be required to identify and separate the varying responses related to different model algorithms versus the varying responses related to the physical characteristics of individual watersheds being modeled. The parameters used in the simulations are shown (Tables 6 and 7).

Dry scenarios result in a considerable reduction in simulated flows for both modeling applications, although the specific amount of reduction varies considerably between the two applications. Wet scenarios cause relatively small change in simulated streamflow amounts. Changes in most flow parameters for the wet scenario are less than 10 percent for the Fox River watershed and less than 15 percent for the Iroquois River watershed. In particular, results indicate that increases in precipitation values may not necessarily translate into increased flooding conditions, if also accompanied by warmer temperatures.

The authors concluded that there will be substantial impacts on streamflows and likely a water-supply crisis in Illinois if a dry scenario occurs in the future; but there will be broader

Table 6. Comparison of Parameters for Simulated Water Budget and Streamflow, Fox River Watershed

Parameters	*Present*	*Wet2050*	*Wet2100*	*Dry2050*	*Dry2100*
Average annual precipitation (inches)	33.0	34.5	36.6	32.0	29.7
Average annual evapotranspiration (inches)	24.7	26.0	27.5	26.6	28.0
Average annual flow (inches)	8.3	8.5	9.1	5.4	1.7
Average flow (cfs)	531	547	582	343	107
Maximum daily flow (cfs)	6825	6307	6551	4498	3051
Minimum daily flow (cfs)	10	9	10	0	0
7-day, 10-year low flow (cfs)	71	89	92	11	0
3-month, 25-year low flow (cfs)	61	57	61	7	0
18-month, 25-year low flow (cfs)	303	260	284	126	16

impacts for agriculture, land use, and ecosystems that will change expectations related to water-supply management substantially. In contrast, if the wet scenarios occur in the future, streamflow amounts may be modified only slightly, and water-supply management more likely may be driven by other societal changes, such as those associated with population growth. Thus, overall impacts for future water supply will become clearer as ability to identify climate change and climate variability improves.

A 5-year period with average annual precipitation close to 20 percent higher than the 1971-2000 normal does not exist in the historical climate record. However, considering the very high level of Lake Michigan-Huron around the mid -19th Century and some climate projections from climate models, a climate scenario with a 20 percent increase in precipitation is reasonable.

Aquifer Studies

Water-supply planning and management require a firm understanding of water use and water availability. Wehrmann et al. (2004) compared Year 2000 groundwater withdrawals against estimated aquifer potential yields (http://.sws.uiuc.edu/pubdoc/CR/ISWSCR2004-11.pdf). The comparison is presented as a ratio of groundwater use (withdrawals) to groundwater yield (i.e., potential aquifer yield) on a township basis (Figures 19-21). Geographical Information System (GIS) technology was used to determine township use-to-yield ratios for three aquifer types: sand-and-gravel, shallow bedrock, and deep bedrock.

Table 7 . Comparison of Parameters for the Simulated Water Budget and Streamflow, Iroquois River Watershed

Parameters	*Present*	*Wet2050*	*Wet2100*	*Dry2050*	*Dry2100*
Average annual precipitation (inches)	39.0	41.0	43.3	37.8	35.1
Average annual evapotranspiration (inches)	24.7	25.6	26.8	26.5	28.2
Average annual flow (inches)	14.3	15.4	16.5	11.3	6.9
Average flow (cfs)	2200	2375	2531	1734	1059
Maximum daily flow (cfs)	27569	28452	29758	25345	21639
Minimum daily flow (cfs)	0	0	0	0	0
7-day 10-year low flow (cfs)	2.6	4.6	3.9	0	0
3-month 25-year low flow (cfs)	24	24	26	15	6
18-month 25-year low flow (cfs)	1081	1175	1234	819	412

A high use-to-yield ratio (e.g., >0.9) suggests an area with existing or imminent groundwater availability problems. However, in cases where the area of influence of a well or well field extends beyond township boundaries in which pumpage occurs, potential aquifer yields may appear to be reached or exceeded, even though the withdrawal does not exceed total potential aquifer yield. Therefore, delineation of high groundwater use-to-yield areas by this method should be considered simply as a means for calling attention to areas to prioritize on a statewide basis for water-supply planning and management.

Comparing groundwater withdrawals and potential aquifer yields in a GIS format is a useful technique for identifying areas in which stresses may occur (or are occurring). However, such an analysis cannot replace local investigations, particularly those that incorporate detailed information in groundwater flow models that assess local conditions accurately. For example, the analysis may highlight large, relatively isolated withdrawals within an extensive aquifer, such as those in the Mahomet Aquifer near Champaign in east-central Illinois. Effects of such pumpage will be spread across a larger area than the townships in which wells are located, smoothing the use-to-yield ratio over a larger area. In at least one other area near East St. Louis, withdrawal in one township intentionally exceeds potential yield for purposes of dewatering to protect below-grade highway roadbeds. However, areas where the aquifer may be confined to a narrow valley, where multiple pumping wells are located within a small area, or where withdrawals do indeed exceed the estimated recharge rate can be identified (e.g., Fox River valley, Peoria, Lewiston, and Normal). Certainly, areas with multiple townships exhibiting high use-to-yield ratios clustered together (e.g., the deep bedrock of northeastern Illinois) should signify locations warranting additional research, data collection, and water resource planning.

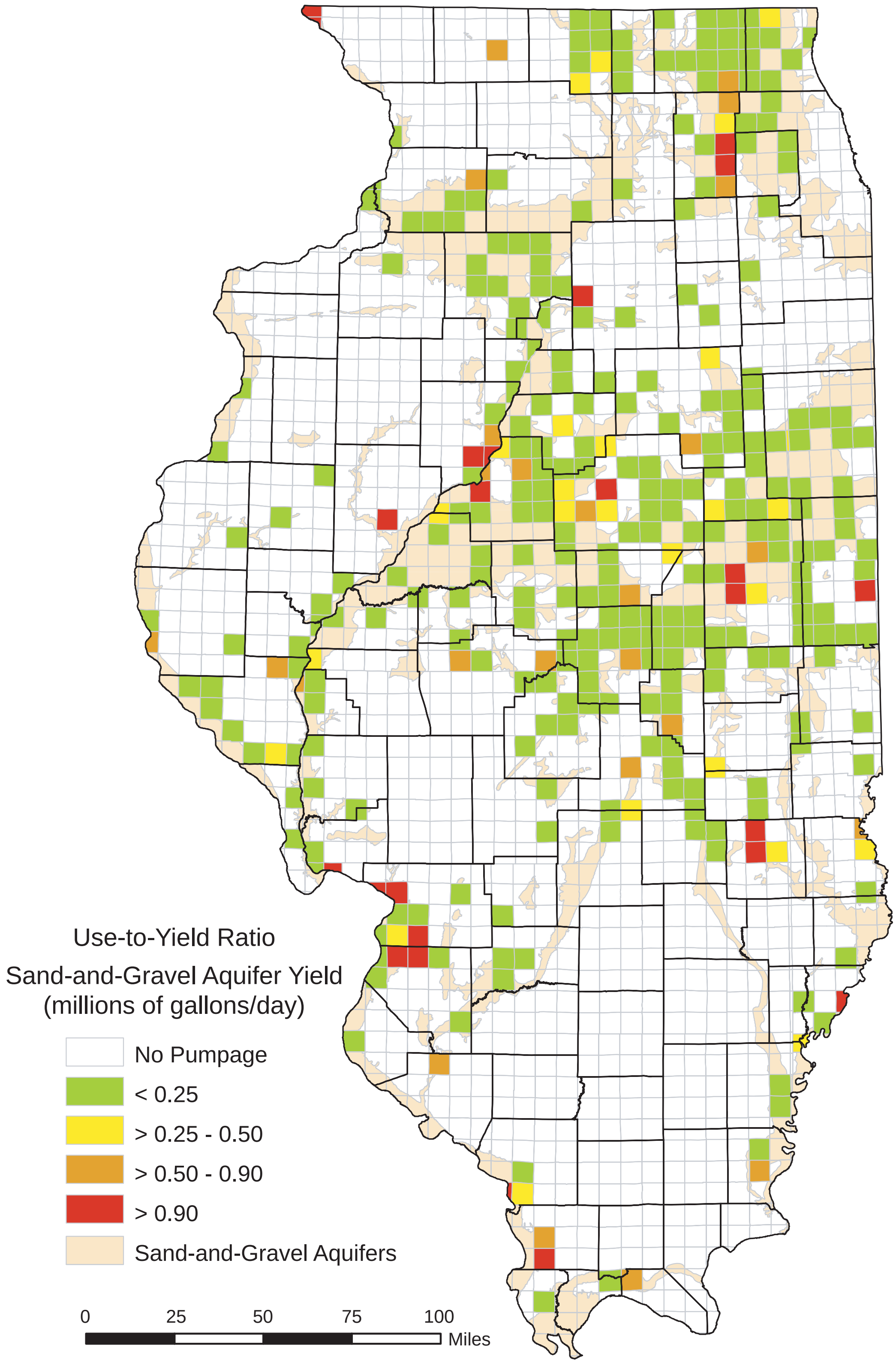


Figure 19. Ratio of Groundwater Use (Withdrawals) to Groundwater Yield (Potential Aquifer Yield) for Sand-and-Gravel Aquifers on a Township Basis.

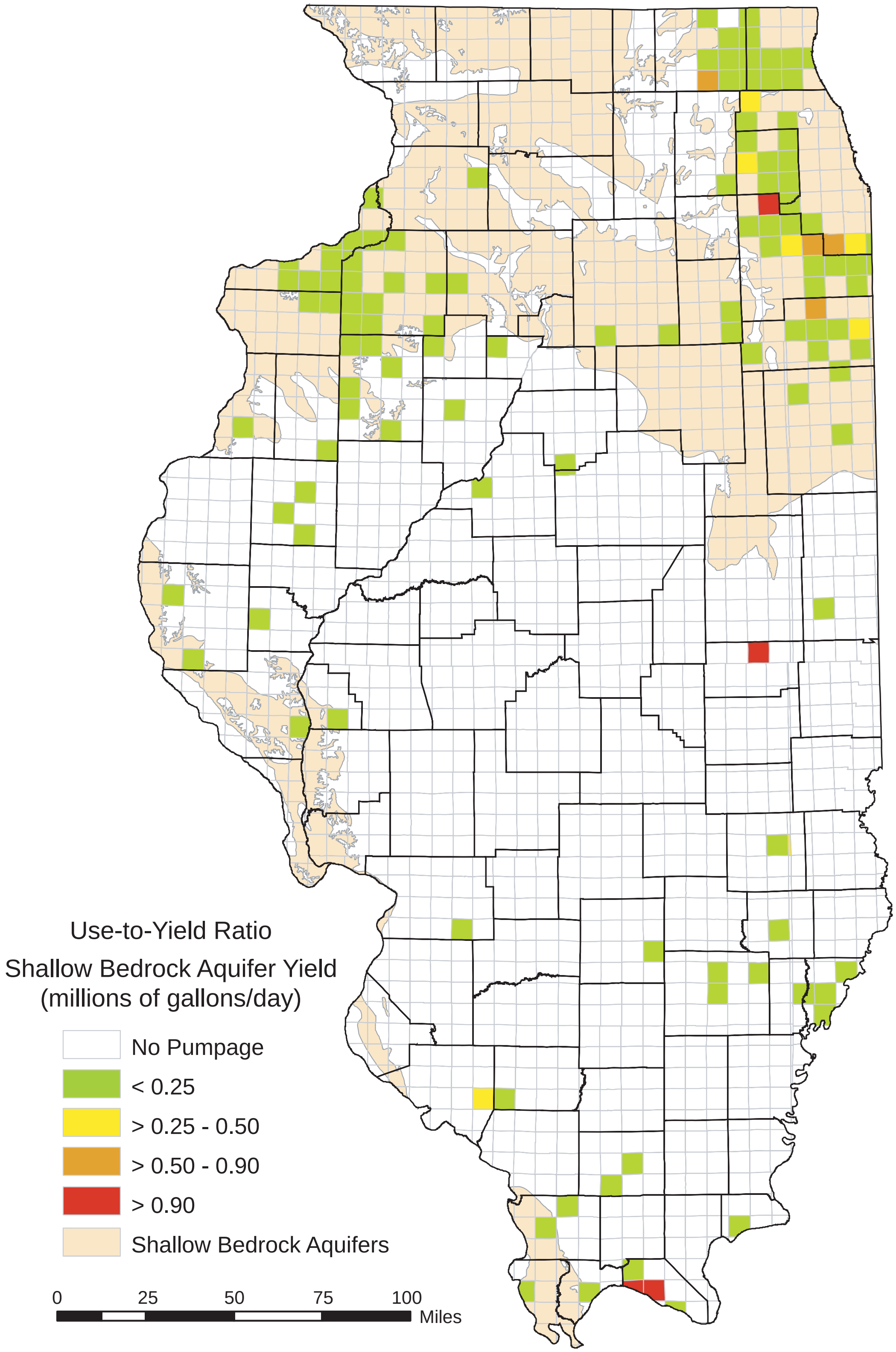


Figure 20. Ratio of Groundwater Use (Withdrawals) to Groundwater Yield (Potential Aquifer Yield) for Shallow Bedrock Aquifers on a Township Basis.

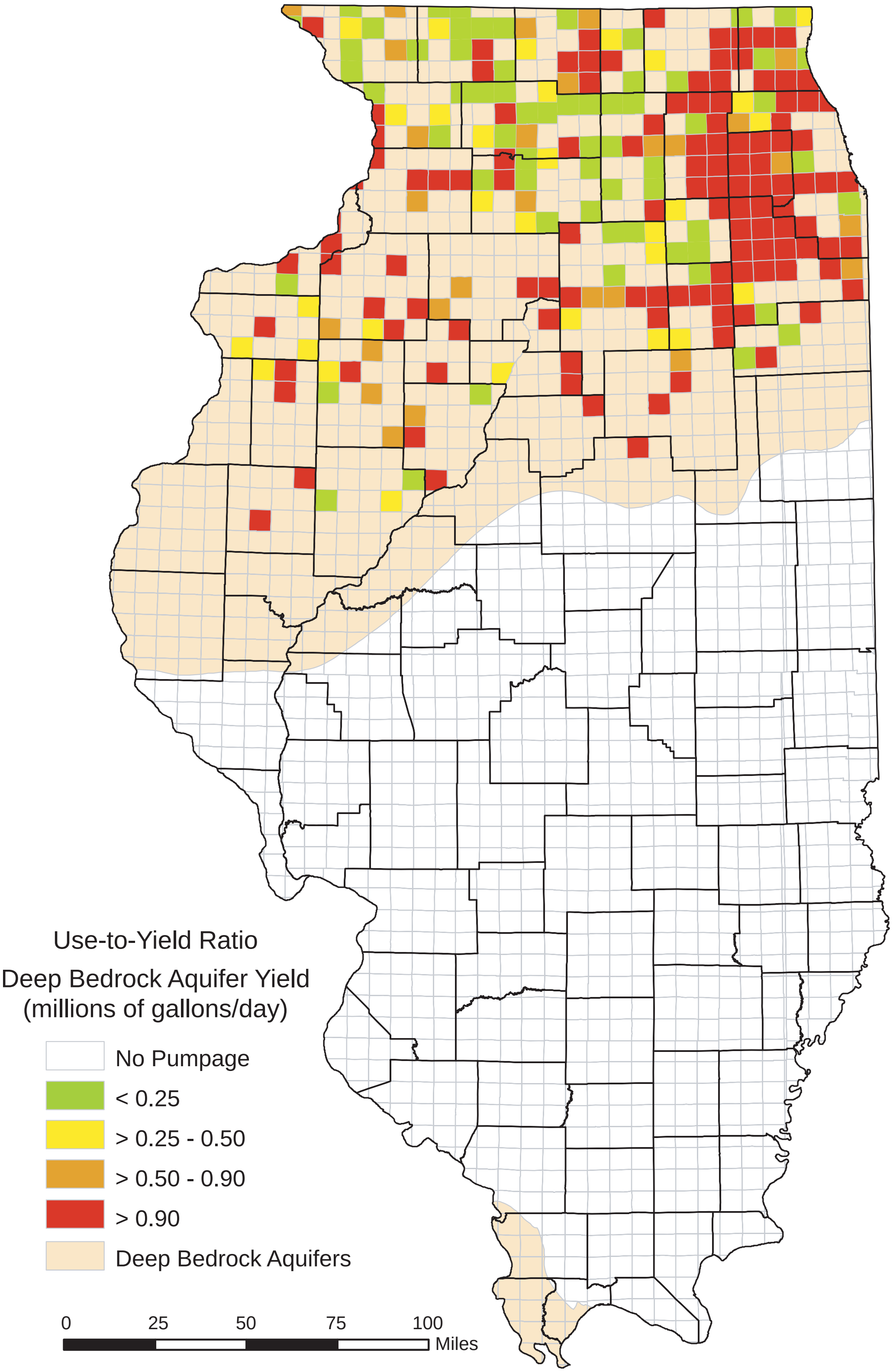


Figure 21. Ratio of Groundwater Use (Withdrawals) to Groundwater Yield (Potential Aquifer Yield) for Deep Bedrock Aquifer on a Township Basis.

Groundwater resources are underused in large portions of Illinois, but competition among users is increasing. Only a small number of townships in the sand-and-gravel and shallow bedrock aquifers appear to be approaching or exceeding yield capabilities. However, in northern Illinois many townships served by the deep bedrock aquifers appear to approaching or exceeding yield capacities. Further analyse are warranted to project future demands for comparison with aquifer potential yields. Additional analyses also could examine the combination of aquifer yields to meet demand in areas with multiple aquifers overlying one another; however, consideration must be given to the effects of shallow aquifer development on recharge (and hence yields) to underlying aquifers. Again, areas with multiple townships exhibiting high use-to-yield ratios clustered together (e.g., the deep bedrock of northeastern Illinois) warrant additional research.

Water-Demand Scenarios

The accuracy of projected future water demand is subject to the uncertainties of estimating explanatory factors such as population, economic development, per-capita water use, technology, and conservation, and to uncertainties of historical water-use data. Little information currently is available to assist small systems in assessing future water needs and infrastructure investments (Dziegielewski et al., 2004).

Water usage by the population served by public water supplies in Illinois is projected to increase by 528 mgd (31.5 percent) from 2000 to 2025 (Dziegielewski et al., 2004). Dziegielewski et al. provide assumptions used in the preparation of the state model. Twenty-six counties are projected to have an increase in water demand greater than 0.5 mgd. Approximately 54 percent of the projected increased demand is due to projected population growth and 46 percent to a projected increase in per-capita water demand. Approximately 71 percent of total statewide public supply withdrawals and 82 percent of projected growth in water demand in 2025 is projected to take place in Cook, DuPage, Kane, Lake, and Will Counties. Water demand in these counties is projected to increase by an average of about 30 percent. Demand can be reduced through demand management, such as conservation.

Average summer air temperature was found to be a significant variable in Illinois with an elasticity of +1.2336. This elasticity indicates that a one percent increase in summer temperature would result in approximately 1.2336 percent increase in per-capita water use.

The estimated value of per-capita income elasticity for the Midwest was reported to be 0.2445. This value indicate that a one percent increase in per-capita income would result in approximately a 0.2445 percent increase in per-capita water use.

Providing a meaningful comparison of system capacity with demand, even at the county level, was hampered by the lack of a uniform method for reporting infrastructure capacity, or even water-system production. Evaluations of water-supply-and-demand scenarios and infrastructure capacities are dependent upon further data collection and analysis, preferably at the township level and from priority aquifers and watersheds.

Chapter 3

Priority Watersheds and Aquifers

To provide a focus for further scientific studies and for water-supply planning and management purposes, ISWS scientists used data and information on water supply and demand to prioritize the state's watersheds and aquifers from a water-supply perspective. Figure 22 identifies the priority watersheds and aquifers in Illinois, which are described in this chapter.

Priority Aquifers

A Plan for Scientific Assessment of Water Supplies in Illinois (ISWS, 2001) provides a preliminary list of 14 major aquifers suitable for characterization and modeling. The plan states that priority will be placed on those aquifers for which further study and management attention are most critical, based on an assessment of groundwater use to aquifer potential yield. Such a use-to-yield study has been completed and coupled with general historical knowledge about the aquifers, and the potential for future demands on those aquifers. Four aquifer systems were identified for further study: deep bedrock aquifer system of northeastern Illinois, sand-and-gravel and shallow bedrock aquifer system of northeastern Illinois, Mahomet Aquifer of east-central Illinois, and American Bottoms of southwestern Illinois (MetroEast area).

Locations of the state's priority aquifers are shown (Figure 22). Of principal interest for each prioritized aquifer system is evaluation of the potential impacts of future water withdrawals on, for example, groundwater levels, surface flows, groundwater quality, and recharge, and the effects of drought and possible climate change on aquifer-yield estimates.

Deep Bedrock Aquifers of Northeastern Illinois

In the 1960s and 1970s, up to 180 mgd were withdrawn from the deep bedrock aquifers, but significant declines in deep aquifer artesian heads and deteriorations in water quality occurred. Withdrawals decreased to about 70 mgd in the 1990s, but in recent years have increased again. Use of this resource continues to exceed the estimated yield in many townships in northeastern Illinois.

Modern groundwater modeling techniques were used to assess a variety of questions related to deep aquifer usage. Of particular concern are the consequences of long-term withdrawals at current or higher rates on water levels (heads) and quality (e.g., total dissolved solids, and radium) in the deep aquifers. Recent discussions regarding water withdrawn as a result of leakage through lakebed deposits and groundwater captured prior to natural discharge to the lake suggest that an assessment of diversion amounts also is a topic of concern for Great Lakes states and Canadian Provinces.

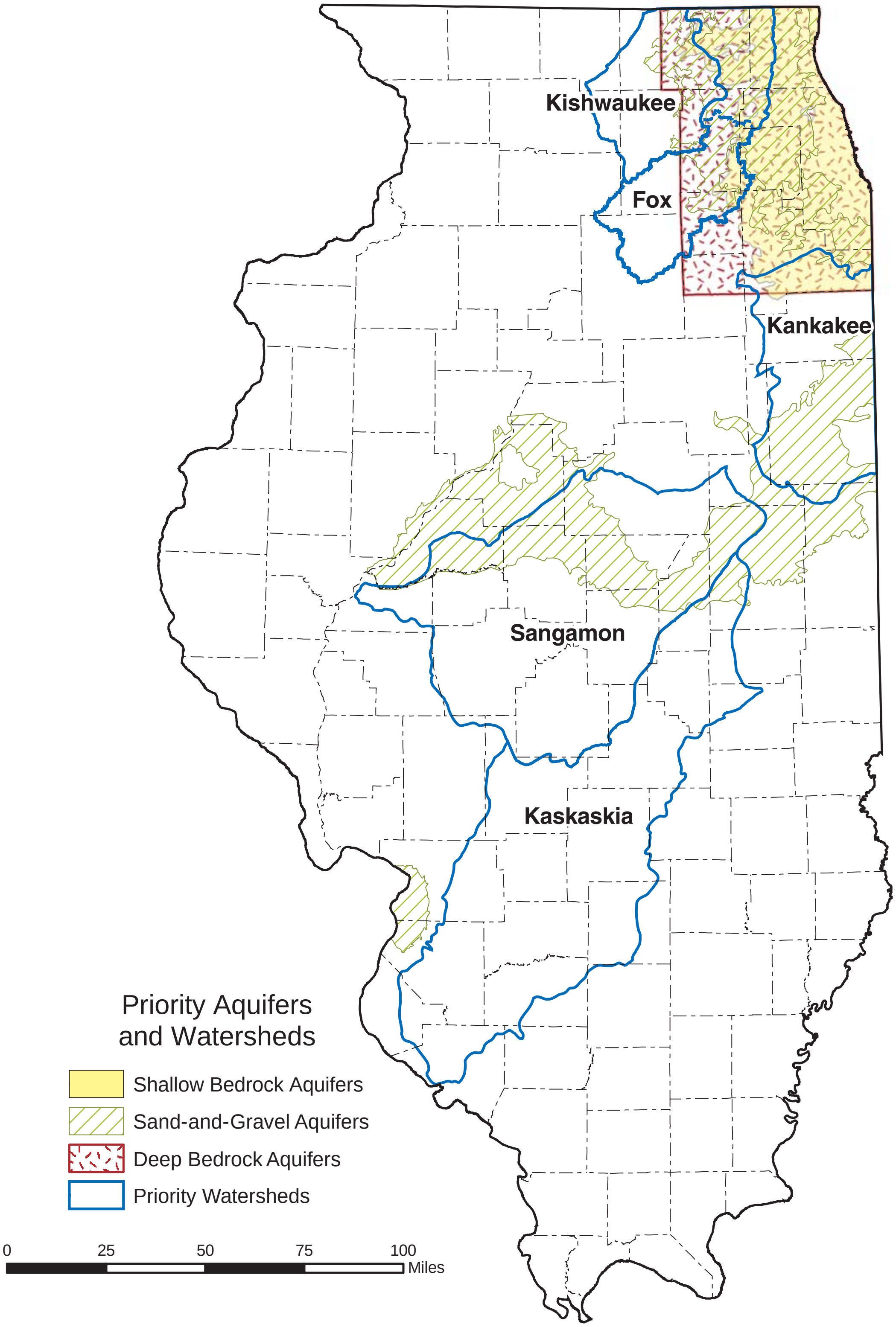


Figure 22. Priority Watersheds and Aquifers for Water Supply in Illinois (from Wehrmann and Knapp, 2006).

Shallow Aquifers of Northeastern Illinois

With continued rapid growth of population, commerce, and industry in northeastern Illinois, the need for additional water also continues to grow. The Northeastern Illinois Planning Commission (NIPC) *Strategic Plan for Water Resource Management* (NIPC, 2002) has been quoted widely for its depiction of 11 townships that will face water shortages by 2020 if steps are not taken to accommodate increasing demands. Limitations on expanding the area served by Lake Michigan water and pumpage from the regional deep bedrock aquifer system will force the need for increased withdrawals from the shallow bedrock and sand-and-gravel aquifers of the area, and from rivers.

A greater understanding of the availability of shallow groundwater resources throughout this region is necessary so that managers can make better water-use and growth decisions, and the public can better understand development impacts on surface water (e.g., Fox River) and wetlands. Current groundwater withdrawals in two townships along the Fox River are nearing or exceeding the potential yield (use-to-yield ratio, or UTY > 0.9) of sand-and-gravel aquifers in that area and UTY in several other townships exceeds 0.5. An examination of the shallow bedrock aquifers, often considered to have a hydraulic connection to overlying sand-and-gravel aquifers, shows an additional township in northeastern Illinois with a UTY > 0.9, based on current withdrawals and use-to-yield estimates for the shallow bedrock. Given the need to meet additional water demands and the limits on expanding the Lake Michigan service area and the limited yield of the deep bedrock aquifers, additional water withdrawals from shallow aquifers will be necessary and more townships can be expected to approach or exceed shallow-aquifer yields in the future.

Mahomet Aquifer of East-Central Illinois

Withdrawals in the Champaign-Urbana area may be approaching aquifer yield, as noted in the original UTY analysis paper (Wehrmann et al., 2004). Current population and projected population growth in east-central Illinois do not approach current or projected levels for northeastern Illinois, and the Mahomet Aquifer is, as a whole, estimated to be capable of yielding 5-6 times more water than the deep aquifers of northeastern Illinois. However, large withdrawals may have major impacts locally.

Numerous cities in east-central Illinois that currently use surface water have examined or are examining the use of Mahomet aquifer groundwater as an alternative to surface reservoirs. These communities include Springfield, Decatur, Bloomington, and Danville and represent a potential for more than doubling current demand on the aquifer. Additional new needs for water supplies abound (e.g., large dairy near Bellflower, a hog-processing plant in Rantoul, the possibility of a clean-coal technology power plant in Tuscola, and ethanol plants). Recent ISWS research has shown a hydraulic connection between the Mahomet Aquifer and the Sangamon River in the Allerton Park area. Additional similar connections also are thought to exist farther up the headwaters of the valley. So, while the yield of the Mahomet Aquifer appears to be adequate to sustain considerable growth, there is a potential for local conflicts depending upon placement of new wells and well fields in relation to existing wells and surface connections. Many large

Mahomet Aquifer water users have been very active in advocating science before regulation. This aquifer would appear to serve as an excellent pilot case for using science to help water-supply planning and management, and the Mahomet Aquifer Consortium is promoting this approach.

American Bottoms Aquifer of Southwestern Illinois

The sand-and-gravel aquifer of the American Bottoms provides a unique contrast to the aquifers of central and northeastern Illinois. Withdrawals by industry and the public in the 1950s and 1960s far exceeded current withdrawals. As industries closed and public supplies shifted to use of the Mississippi River, groundwater use fell and groundwater levels rose rapidly. Infrastructure built when groundwater usage was high became inundated; sewer breakages and flooded basements in portions of the area became common. As a consequence, the Illinois Department of Transportation (IDOT) currently pumps more than 20 mgd to keep groundwater levels below several stretches of below-grade highway in a large area in southwestern Illinois along the Mississippi River. Both IDOT and their consultants have contacted the ISWS Center for Groundwater Science regarding changes to pumping needs and patterns as a result of construction of a new bridge over the Mississippi River. There are numerous technical challenges before this project could get started, but a working aquifer model being developed by the ISWS could answer questions regarding aquifer yield, well field design, and impacts on the resource for these and any other development in the area that requires large quantities of groundwater.

Priority Watersheds

Several major watersheds in Illinois were identified, for which available water supply is already limited, substantial population growth in the near future will test available water sources, or where planning is necessary to avoid overuse and local conflicts about water-supply sources. These watersheds shown in Figure 22 are listed in order of priority regarding the potential benefit and relative urgency of water-supply planning: the Fox River watershed, the Kaskaskia River watershed, the Sangamon River watershed, the Kishwaukee River watershed, and the Kankakee River watershed. In addition to potential planning needs on a watershed or regional scale, there also is a need to evaluate the adequacy of individual surface-water public systems throughout southern and central Illinois that likely will be susceptible to water-supply shortages during a major drought.

Fox River Watershed

As the Chicago metropolitan area expands to the west, the Fox River watershed is experiencing significant growth of population and water use. The 1995 surface- and groundwater withdrawals for public water supply within the Fox River watershed were about 73 mgd, and this is expected to increase by more than 50 percent over the next 20 years. Currently, the amount of water withdrawn from the Fox River for public water supply is about 22 mgd.

The current emphasis for developing additional water supply is on shallow groundwater resources. A significant concern in developing shallow groundwater is potential effects on water levels in nearby streams and wetlands. Deep sandstone aquifers have been overused in this region, and increased use of this resource may not be sustainable.

Potential use of the Fox River for additional water supply is limited by the need to maintain low flows in the river for aquatic habitat, recreation, wastewater assimilation, and other in-stream needs. Low-flow concerns affect the Fox River only during very dry years, collectively less than 10 percent of the time. At all other times, however, the Fox River potentially could provide an abundant source of water, if alternate supplies were available during low-flow periods, possibly from groundwater resources, storage of surface water, or interbasin transfers of water. Conjunctive use of Fox River water supplemented with groundwater would create significant challenges related to water treatment and distribution. For example, there is concern about the effect of treated wastewaters on water quality of the Fox River and the importance of the river in assimilating this wastewater. During low flows, treated wastewaters can account for 30-40 percent of the flow in the river. With continued growth in population and water use, this percentage can be expected to rise. The potential impact of increased wastewater levels on the river's in-stream uses and its use for water supply must be evaluated.

Kaskaskia River Watershed

The Kaskaskia River is the most managed river in Illinois for water-supply use. As recently as four years ago, the water supply from the river and its two large federal reservoirs, Carlyle Lake and Lake Shelbyville, virtually was untapped. However, with recent allocations administered by Illinois Department of Natural Resources' Office of Water Resources for use with electricity generation and regional water supplies, the available water supply from the federal Carlyle Lake and Lake Shelbyville, roughly 50 mgd, is fully allocated.

Water for moderate growth at existing public water supplies on the Kaskaskia River has been considered in the allocation of water from the federal reservoirs, but any additional development of the Kaskaskia River for water supply would reduce the water-supply yields of these reservoirs. Future water-supply growth in the watershed essentially must come from 1) sources outside the watershed, 2) purchase by the State of Illinois of additional water-supply storage from the two federal reservoirs, or 3) development of new water-supply reservoirs on tributaries to the Kaskaskia River. Reallocation of federal reservoir storage likely would require an extensive study and public review on the regulation policy for the lakes and associated environmental impacts.

Various proposals using substantial quantities of water for power generation within the basin have looked at interbasin transfers of water from the St. Louis area, including either using groundwater from the American Bottoms near East St. Louis or withdrawing water from the Mississippi River, both potentially requiring that this water be piped over a distance of up to 50 miles. Although long-distance transfers of water such as this can be developed independently, they also create the potential for developing a regional water supply system that can provide water to intermediate locations.

Groundwater resources in the region are limited, and current groundwater use in the Kaskaskia River watershed (downstream of Lake Shelbyville) is less than 2 mgd. There is the potential for limited development of shallow groundwater aquifers in the floodplain of the Kaskaskia River. The effect of such groundwater withdrawals on low flows and allocated waters in the Kaskaskia River would need to be evaluated, however.

Sangamon River Watershed

Three of the largest cities in central Illinois (Springfield, Bloomington, and Decatur) are located in or border the Sangamon River watershed. All three cities rely on reservoirs for their primary water supply, and none of those supplies may be adequate to meet water-use demands during a severe drought. The Mahomet Aquifer, which crosses the watershed, provides an abundant water-supply resource for the region, but there are concerns that water use from this aquifer must be managed effectively to avoid local water shortages and/or conflicts in water use. Decatur already has developed a well field in the Mahomet Aquifer to supplement its reservoir supply, and Bloomington and Springfield both have investigated the potential use of the aquifer. The Mahomet Aquifer also supplies water for Champaign, numerous smaller cities, and irrigation in the Imperial Valley-Havana Lowlands.

From a regional perspective, a combination of surface and groundwater sources provides an opportunity to investigate the joint use of multiple regional water supplies. In addition, there also may be hydrologic connections bet1ween the surface and groundwater resources; for example, the Mahomet Aquifer intersects the Sangamon River near Cisco, upstream of Lake Decatur. Hydrologic connections between surface and groundwater require the impacts of groundwater withdrawals on rivers and streams to be evaluated, and vice versa.

Kishwaukee River Watershed

Expansion of the Chicago metropolitan area, which already has created water-supply planning concerns in the Fox River watershed, also is beginning to extend into eastern portions of the Kishwaukee River watershed in Kane and McHenry Counties. Like the Fox River watershed, this area has abundant shallow groundwater supplies that likely will be used for water-supply development. The primary concern in developing shallow groundwater is the connection between aquifers and nearby streams and wetlands, and potential impacts of groundwater pumping on reducing water levels in these bodies.

As communities in the watershed expand and their water use increases, there will be more effluent discharge into local streams from wastewater treatment plants. This will increase low flows in the Kishwaukee River and tributaries, but also create water-quality concerns as effluent discharges account for an increasingly larger percentage of the low flow. During this process, it is essential to preserve the quality and potential use of the Kishwaukee River as a water-supply source in addition to supporting its aquatic habitat, recreation, wastewater assimilation, and other in-stream uses. Because many water-planning issues are the same as those currently being faced in the Fox River watershed, investigations and lessons learned from the Fox River watershed likely will be instrumental in the initial stages of analysis and planning for the Kishwaukee River watershed.

Kankakee River Watershed

Although the Kankakee River watershed has not yet experienced substantial increases in water use, such increases likely will occur over the next two decades. Population forecasts by

NIPC indicate that the population of Will County, half of which is located in the northern portion of the Kankakee River watershed, will more than double by the year 2030, with an increase in population of more than 600,000 people. As the Chicago metropolitan area moves closer to the Kankakee River, the river increasingly will be viewed as a potential water supply for the region. Joliet already has identified the Kankakee River as a possible source of water to replace its current use of deep groundwater. That groundwater has high levels of radium, which, in turn, is related to the deep cone of depression in the deep aquifer caused by groundwater mining.

The portion of the river from Kankakee to Wilmington has significant value for fishing and other recreational activities, aesthetics, and aquatic habitat. Already there are occasional fish kills and environmental concerns along the river during low flows in extremely dry years, and associated scrutiny of the existing influence of hydroelectric power generation at Kankakee and water withdrawn for thermoelectric generation at Braidwood (even though both facilities cease operation during low flows). Potential additional withdrawals will exacerbate these concerns. An additional concern that became apparent during the 1988 drought is groundwater use for irrigation in eastern Kankakee County (and Indiana) and its possible hydraulic connection to low flows in the Kankakee River.

The projected time frame for expected growth in the Kankakee River watershed is short. Thus, planning activities conducted soon in cooperation with officials in Indiana could deflect potential water-use problems and conflicts before they become acute.

Chapter 4

Evaluating Local and Regional Water Supplies

It is intended that the data presented in this report will be useful to water-supply planners and managers in understanding the variability in the availability of water in Illinois, and will stimulate them to apply these and other data in analyses of the adequacy of their own water-supply facilities. Although site-specific data are needed to evaluate fully the adequacy of any given water supply facility, several factors may be considered by water supply managers in providing a preliminary review of the potential vulnerability of their facilities to drought-related shortages.

In general, a much higher proportion of surface-water systems and shallow aquifers are susceptible to problems during severe drought periods than deeper aquifers. Water-supply systems that depend on reservoirs also are generally more likely to be susceptible to shortages during drought, primarily because of the uncertainties in: 1) calculating the capacity of the reservoir in cases where there has not been a recent bathymetric or sedimentation survey, and 2) estimating inflow to the reservoir during a drought period, since reservoir systems are more likely to be located in smaller watersheds which typically do not have long-term streamgaging records. In contrast, direct withdrawals without storage are more likely to be on larger streams and rivers that have long-term streamgaging records.

Because surface-water supplies outside the Lake Michigan Service Area are susceptible to drought impacts, the regions in Illinois that are supplied predominantly from surface-water sources (southern and central Illinois) are more likely to have water-supply problems during major droughts than areas supplied with deep groundwater (northern Illinois). Aside from this strong tendency and those noted in the preceding paragraph, there are no identifiable regional factors that cause water supplies in any one region of Illinois to be more naturally susceptible to drought impacts than other regions. Combinations of local factors such as well depth, pumping capacity, the size of a reservoir, the hydrogeologic characteristics of a watershed or groundwater contribution area, and the amount of water demand have considerable influences on the potential adequacy of each individual system. The presence or absence of drought preparedness and drought response planning also is a critical factor influencing a system's potential vulnerability. Communities that over time have experienced growth in population and water use without corresponding increases in the size or number of their water supply sources also are more likely to be susceptible to future droughts, as are communities that have had only incremental increases in water supply capacity or other "stop-gap" measures implemented in response to past droughts.

Long-term streamgaging records indicate that, for most of Illinois, the most severe hydrologic droughts occurred prior to 1960. These hydrologic records agree well with the drought climatologies discussed in Chapter 1. Records also indicate that the most severe droughts of the 1930s and 1950s had much longer durations than drought periods since then. Water systems that have experienced even mild or moderate drought concerns since the 1960s should reexamine their possible vulnerability to shortages during severe droughts such as those droughts of the 1930s and 1950s.

A community's self-assessment of current and near-future water use related to population growth and commercial development, and an awareness of available material regarding state drought plans, water supply regulations, and water conservation measures, are important first steps towards developing an evaluation of system vulnerability. Historical records of water use and the water-supply system behavior in previous drought periods also can be useful in evaluating the present supply, particularly when juxtaposed with measures of historical drought severity as provided by regional climatological and hydrological data. A lack of recent, detailed data regarding the capacity of the system is, in itself, an indicator of uncertainty and potential vulnerability in the system's adequacy.

Considerations in Evaluating Local and Regional Water Supplies:

1. Changes in Water Use (Past and Projected)

- What has been the community's growth in average water use over the last 10-15 years?
- What is the community's projected growth in water demand in the near future? Is the community attempting to attract new industries or commercial enterprises that will increase its water use?

Reevaluation of system adequacy should be high priority for communities with a water use growth of more than 25 percent, particularly if the rate of growth is likely to continue into the near future.

- What is the community's water use during hot, dry periods?

For many communities, water use during a drought period is significantly higher than the average annual rate (Chapter 2). An evaluation of system adequacy should be designed around expected use over the course of a drought.

2. Changes to the Water Supply System

- What is the current system capacity?
  Raw water ________________
  Treated water ______________
- How does this compare to the average daily water demand? Peak demand? Can the system meet peak demands routinely without additional infrastructure (e.g., the need for back-up or redundancy)?
- What is the community's water source capacity (be it river, lake, reservoir, or aquifer)?

- What changes or improvements to the water-supply system have been made in the last 15 years?

- Is the community planning for any changes or improvements to the water-supply system in the near future or in the upcoming decades? Do these plans involve incremental improvements in the current supply, or are substantial modifications being planned?

3. Uncertainties and Potential Decreases in the Capacity of the Current System

- If the community has a groundwater supply, have well capacities decreased with time (or have drawdowns increased to provide the same amount of water)? How do groundwater levels react to pumping stress in dry periods? Are the wells close together and do they interfere with one another? Are they close to a surface-water body and do they depend on that surface water for recharge? Is a record kept of pumping and nonpumping water levels in the wells? Is a water level trend apparent and, if so, how does it compare to trends in withdrawals?

- Could the community's future water source capacity be impacted adversely by additional withdrawals from other parts of the aquifer or watershed?

- If the community withdraws water from a reservoir, has the capacity of that reservoir been measured in the last 20 years? Has the rate of capacity loss from sedimentation been measured?

4. Problems Experienced in Past Drought Periods

- Has the community experienced concerns with inadequate water supply during drought since 1970? Ever?

Supplemental sources and capacities added to the system since the last drought of major concern (addressed in item 2), minus potential losses due to reduction in pumping capacity or reservoir sedimentation (addressed in item 3) should have overcome not only the shortcomings in the system as experienced in this past drought, but also offset coincident increases in water use (addressed in item 1).

The worst water-supply droughts in Illinois occurred in the 1930s and 1950s. Although selected communities have been impacted by more recent and less-severe droughts, such as droughts in the mid-1960s, 1976-1977, 1988-1989, 1999-2000, and 2005 none of these recent droughts had the same type of widespread impact as the droughts of the early and mid 20th Century. Such severe droughts will occur again in the future. Many communities that have not experienced water-supply concerns in decades may still be at risk of having water shortages during a severe drought.

If analysis indicates expected water shortages or a high risk of shortages, or that future withdrawals may affect the yield of watersheds and aquifers adversely, then there is an opportunity to adopt preventative management strategies. The costs of water shortages and withdrawal impacts have two major components: damages caused by water shortages and withdrawals, and measures to avoid damages. Management decisions typically are based on assessments of benefits, risks, safety margins, and affordable costs. Making decisions only on what is affordable today for a certain degree of protection can, of course, lead to much higher future damage costs resulting from infrequent but severe events. A focus of this report is on showing the type of scientific data and uncertainties that managers would benefit from incorporating in risk analysis.

An analogy can be drawn to 2005's Hurricane Katrina. A decision was made decades ago to protect New Orleans from Category 3 hurricanes but, implicitly, not from Category 4 and 5 hurricanes. The cost of protecting the city from Category 4 and 5 hurricanes would be much greater, but probably less than the damage caused by Katrina. Although Category 4 and 5 hurricanes occur only infrequently, we know that they do occur and will be catastrophic. Like hurricanes, the cost of protection from droughts must be weighed against the risk of occurrence and magnitude of droughts, and damages caused by them.

Conclusions

Beyond meeting current water demand and complying with regulations, water-supply planners and managers also should address certain basic questions:

- For what changes in water supply and future water demand should preparations be made?
- For what level of emergencies (e.g., droughts) should preparations be made?
- What safety level in water supply or, put another way, what level of risk is acceptable in providing adequate supplies of water? In general, the less risk, the greater the cost, and vice versa.

This report presents data and evaluations on topics of relevance for water-supply planning and management in Illinois. The concepts of the water cycle and water budgets provide a framework for documenting and evaluating changes in water availability under variable, possibly changing environmental conditions. Historical climate data and output from climate models illustrate ranges of possible future climatic conditions. The concept of use-to-yield ratios provides a framework for documenting and evaluating water withdrawals in the context of available water supplies. And water-demand projections provide insights about additional quantities of water that may be required in the future, and/or highlight the need to reduce water demand.

Analysis of climate and hydrologic records extending back more than 100 years provides insights about the dynamics of the water cycle and variations in water budgets in Illinois. A key feature of these records is the periodic occurrence of drought, which creates some of the most serious emergencies facing water-supply planners and managers. On the assumption that the past provides a guide to the future, analysis of historical records provides probabilities of future drought occurrences, duration, and intensity in Illinois. It is intended that water-supply planners and managers will find these data, together with case studies, informative and useful and will ask themselves whether their own water-supply systems are capable of dealing with inevitable future droughts. Selecting a level of drought preparedness is subjective and influenced strongly by assessments of risks and costs. Being prepared for a low probability, worst-case drought affords the most protection, but also may be the most costly strategy. However, worst-case droughts cause the greatest damages, so the cost of not buying protection for infrequent severe droughts should be included in risk assessment and risk management.

The worst-case drought scenario described in Chapter 1 is a 10-year period with precipitation 15 percent below normal for a statewide average, and a standard deviation (SD) of 5 percent. The statewide average for the worst-case (1 in 200 years) 5-year drought would have precipitation 69 percent of normal (SD of 5 percent). The worst-case 3-year drought would have statewide average precipitation 62 percent of normal, (SD of 4 percent). The worst-case 2-year drought would have statewide average precipitation 55 percent of normal, (SD of 5 percent). The worst-case one-year drought would have statewide average precipitation 44 percent of normal (SD of 5 percent).

The use of drought return periods, applied to individual locations, illustrates the increasing severity of droughts as the return period increases. For example, a 12-month drought with a 25 year return period is characterized by precipitation 59 percent of normal. With a 50-year return period, precipitation decreases to 52 percent of normal. For a 100-year return period, precipitation decreases further to 48 percent of normal, and for a 200-year return period, precipitation averages 44 percent of normal. Similarly, the severity of longer-term droughts (up to 10-year duration) increases as the return period increases. Water-supply planners and managers can use these data to select drought intensity and duration for which they choose to prepare and, by default, for which they choose not to prepare. The costs of droughts have two major components: damages caused by droughts, and protection to avoid damages. Information on both components should be factored into drought preparedness plans.

When the authors started to prepare this report in 2004, it was 15 years since the last significant drought in Illinois in 1988-1989. As this report was being prepared, drought once again gripped northern and western Illinois in 2005. A considerable number of surface- and groundwater facilities still are not adequate to meet demands during a 50-year drought, and this report identified the possibility of 100-year, 200-year, and worst-case droughts, which likely would have greater impacts on even more public and private facilities. Recent events in the West and other countries show that low-probability, worst-case droughts do occur and have dramatic impacts. Illinois has an opportunity to improve its drought preparedness.

Periodic droughts must be considered in the context of other factors that increase water demand more systematically, e.g., population growth and economic development. Over 80 percent of increases in withdrawals from public water supplies to 2025 are projected to occur in five counties: Cook, DuPage, Kane, Lake, and Will Counties. In these counties, public water demand is projected to increase by about 31 percent (456 mgd). Water use also is projected to increase by more than 4 mgd in McHenry, Sangamon, Madison, St.Clair, Winnebago, and Champaign Counties.

Historical climate and hydrologic records and output from climate models have been used to create possible scenarios of future water availability in Illinois. Future precipitation and water availability in Illinois could increase or decrease, depending on assumptions made and models used. Particularly because the magnitude and timing of human influence on Illinois' climate and hydrology remain uncertain, probabilities for these scenarios cannot be set. It is suggested that water-supply planners and managers evaluate the sensitivity of their water-supply systems to a range of climate-change scenarios, especially low-precipitation, high-temperature scenarios.

As a prelude to determining how much water can be withdrawn over time to meet increasing demand, it is important to establish the capacity of existing water-supply facilities (streams, reservoirs, aquifers, pumps, etc.). To provide some insight into the capacity of aquifers to sustain more withdrawals, use-to-yield data have been provided by township. Whereas the majority of groundwater in Illinois is underused, some townships are withdrawing groundwater at rates that exceed or approach exceeding safe yields for the aquifers. Whether aquifers can yield more water in and around these townships should be examined carefully.

Combining projections of water demand to 2025 with aquifer use-to-yield data has allowed identification of priority townships and aquifers recommended for detailed water-supply planning and careful management. Using the same demand projections and information about surface-water availability, priority watersheds also have been identified.

This report is intended to help water-supply planners and managers understand the variability in the availability of water in Illinois. Then they can apply these and other data to analyze the adequacy of their own water-supply systems as a basis for developing appropriate system capacity. Also, much remains to be done to develop water-supply plans jointly by constituents in communities, townships, and counties that withdraw water from each aquifer and watershed.

Experience in other states shows that bringing together many diverse stakeholders to develop regional and state water-supply plans is costly and time-consuming, but results in greater confidence that all residents and users will have safe and adequate supplies of clean water in the future. Such plans include joint consideration of surface- and groundwater (watersheds and aquifers), consideration of local and regional conditions, water quality, climate change, floods and stormwater, droughts, water conservation, water reuse, and new water supply, treatment, and distribution systems.

Increasingly, Illinois also recognizes the importance of state and regional water-supply planning and drought-preparedness planning (Illinois Interagency Coordinating Committee on Groundwater, 2003; Subcommittee on Integrated Water Planning and Management, 2002; Illinois Department of Natural Resources, 2005). In 2005, the Drought Response Task Force and the State Water Plan Task Force agreed to revise the state drought-response plan to incorporate drought-preparedness planning. In January 2006, Governor Blagojevich issued an Executive Order requiring Illinois to formulate water-supply plans and to begin to implement these plans in Priority Water Quantity Planning Areas. These are important first steps in a long-term commitment to improve water-supply planning and management in Illinois.

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Appendix A.
The Water Cycle and Water Budgets in Illinois

Appendix A

The Water Cycle and Water Budgets in Illinois

This appendix documents the scientific understanding of the water cycle and water budgets in Illinois. It documents the interrelatedness of all components of the water cycle and establishes the need for comprehensive, integrated planning of water supplies.

The Hydrosphere

The hydrosphere includes all gaseous, liquid, and solid water stored in and moving through the atmosphere, geosphere, and biosphere. Water is stored in and moves through the hydrosphere's reservoirs: atmosphere, oceans, lakes, rivers, glaciers, aquifers, soil, vegetation, wetlands, and impoundment reservoirs. Oceans contain more than 96 percent of the water on Earth, and the remaining 4 percent is found in freshwater. Glaciers hold 69 percent of freshwater; lakes and rivers, 1 percent; and groundwater 30 percent (Dingman, 1994). Water is an integral component of the atmosphere, geosphere, and biosphere and follows the complex path of the hydrologic (water) cycle (Figure A-1).

The water cycle moves water through the atmosphere, on and under the surface of the earth, and through vegetation. Water moves downward as precipitation, into the soil and through the unsaturated zone as infiltration, and through the saturated zone to shallow and deep aquifers as recharge; laterally on the surface as surface runoff to lakes, wetlands, streams, and rivers, and underground as groundwater flow; upward as evapotranspiration from lakes, wetlands, streams and rivers, plants, soil, and groundwater, and as groundwater discharge, to surface waters; and laterally aloft as atmospheric moisture that includes clouds and precipitation.

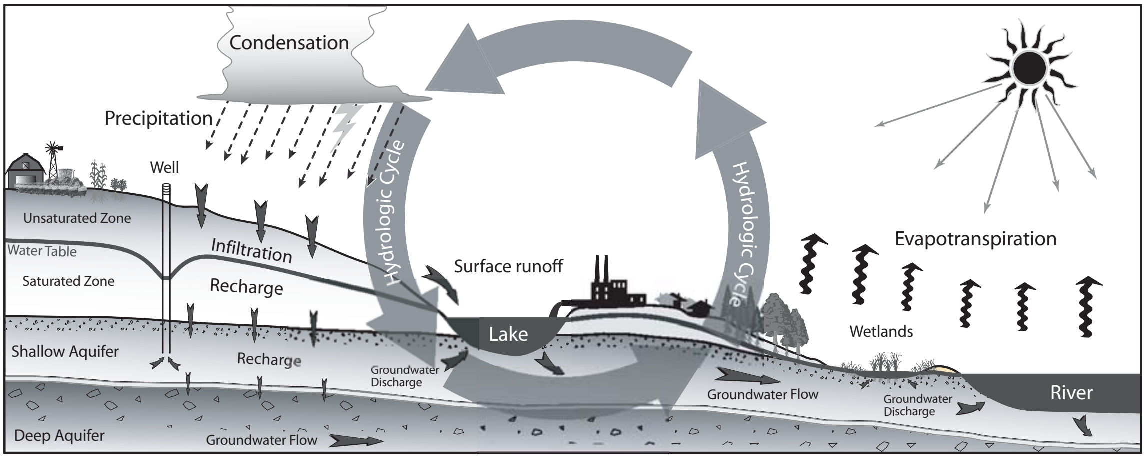


Figure A-1. The Water Cycle (http://www.sws.uiuc.edu/docs/watercycle/, Accessed November 20, 2005).

Reservoirs are interconnected and the output from one reservoir can become the input to another. Water movements within and among reservoirs are called fluxes. Fluxes among reservoirs occur through precipitation, condensation, interception, evaporation, transpiration, infiltration, percolation, groundwater flow, spring or seepage flow, advective flow, overland flow, channel flow, withdrawals, and diversions. Globally, the land surface receives 60 percent more water through precipitation than is transpired and evaporated from it. The remainder produces surface runoff and groundwater recharge. To continue the cycle, groundwater discharges into surface waters.

Residence times of water in continental reservoirs are highly variable: a few days or weeks in river channels; months to years in lakes, reservoirs, and wetlands; hours to years in soil moisture; and days to tens of millennia in groundwater.

All parts of the water cycle are interconnected, laying the scientific foundation for comprehensive regional water-supply planning. All major components of the water cycle, their variability over time and space, and their interactions must be quantified to provide a scientific basis for evaluating future water budgets and water availability. It is wise to study and manage groundwater and surface water together, not separately, because they are parts of one system.

Water is an important medium for transporting and transforming dissolved and particulate materials, and the water cycle is an important factor in water-quality issues. Discharge of manmade pollutants into surface waters and aquifers and natural pollutants, such as arsenic, radium, and dissolved solids, can affect water quality and the need for and cost of water treatment. Hypoxia in the Gulf of Mexico is reported to be an example of a problem that occurs when large quantities of nutrients from nutrient-rich areas are transported by the Mississippi River to the Gulf of Mexico, resulting in overenriched coastal waters and subsequent decline in water quality (Goolsby et al., 1999). Biological activity and physical, chemical, and photochemical processes have strong influences on the fluxes and fates of water-borne chemicals.

A water budget quantifies systematically the flows and reservoirs of water in the hydrosphere, based on the principle of the conservation of mass. That principle assumes that water is neither created nor destroyed in the system, an assumption that facilitates mass balance studies that track all physical phases of water, thereby accounting for water storage, transport, and transformation. Water budgets can be created at any geographical scale and over any period of time. For water-supply planning and management, water budgets for aquifers and watersheds are most meaningful. As all components of the water cycle are connected, estimating future water budgets allows water-supply planners and managers to evaluate the impacts of system changes on water availability, and the impacts on the system of increased withdrawals. A 40 to 50-year time horizon is suitable for water-supply planning.

The Water Cycle and Water Budgets in Illinois: Past and Present

Scientists at the ISWS have conducted many studies related to the water cycle and water budgets in Illinois. Long-term monitoring conducted by the agency's Water and Atmospheric Resources Monitoring (WARM) Program provides a wealth of unique data used by scientists around the world in studying the water cycle and water budgets (http://www.sws.uiuc.edu/warm/). Other major data sources are extensive climate records archived by the National Oceanic and Atmospheric Administration's (NOAA's) National Climatic Data Center (http://www.ncdc.noaa.gov/oa/ncdc.html) and extensive water quantity and quality records archived by the U.S. Geological Survey (http://water.usgs.gov/). Much data and information on the dimensions of water availability in Illinois appear on the ISWS Website (http://www.sws.uiuc.edu/docs/wsfaq/) and in the *Climate Atlas of Illinois* (Changnon et al., 2004).

Information and data on the water budget in Illinois for recent decades, especially the most recent climatological normal period of 1971-2000, were used to establish reference conditions. Even longer records of precipitation, temperature, streamflow, and groundwater levels help establish an understanding of the variability of the water cycle and water budgets in Illinois. These historical records, together with assumptions about future conditions embodied in mathematical models, provide a platform for presenting future climate and hydrologic scenarios, and evaluating their potential effects on the water budget and water availability in Illinois.

Figure A-2 shows the 1971-2000 water budget for Illinois. On average, an estimated 2000 billion gallons of water per day (bgd) pass overhead in the atmosphere, 104 bgd fall as precipitation, 73 bgd return to the atmosphere through evapotranspiration, 31 bgd flow out of the state in

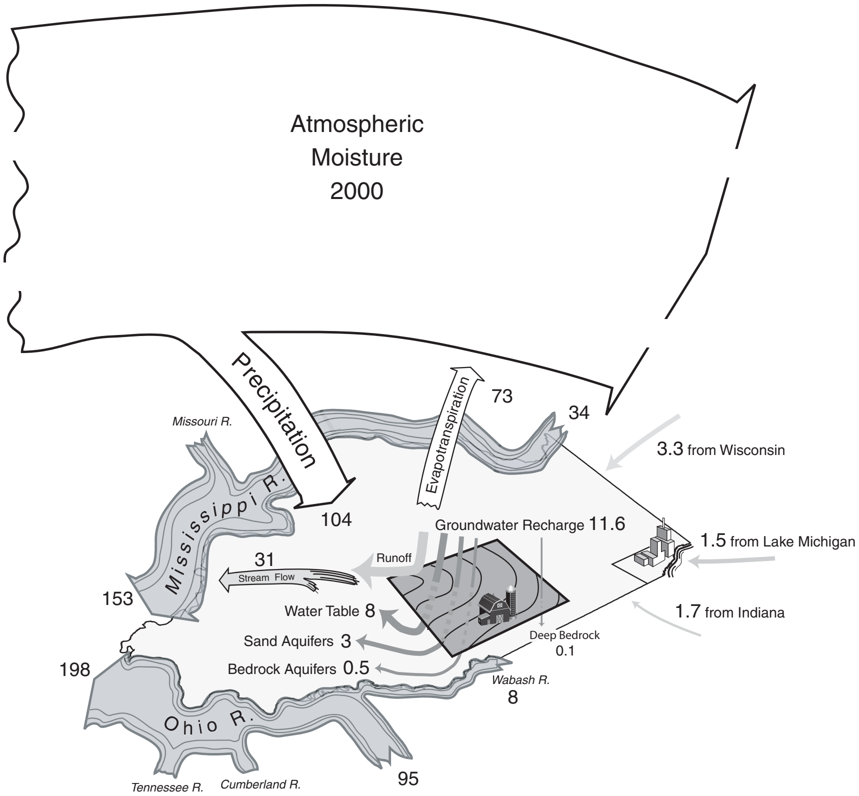


Figure A- 2. Water Budget (bgd) for Illinois, 1971-2000 (http://www.sws.uiuc.edu/docs/watercycle/, Accessed November 20, 2005).

rivers and streams, and groundwater recharge uses 11.6 bgd, of which 11.5 bgd are returned as groundwater discharge to surface streams. Additional surface water flows into Illinois from rivers in Indiana and Wisconsin, and water enters Illinois through the diversion from Lake Michigan at Chicago. Much of the water in the Mississippi, Ohio, and Wabash Rivers originates upstream of Illinois. Uncertainties are minimal (<5 percent) for the Lake Michigan diversion and state-wide precipitation, quite small (~5-10 percent) for surface water fluxes, but larger for water storage and fluxes in the atmosphere (>10 percent) and for evapotranspiration and water storage in the soil and aquifers (>20 percent).

Figure A-3 shows the effects of hypothetical fluctuations in precipitation over a 4-year period on runoff, soil moisture, streamflow, and groundwater levels. In general, it takes about a month before shallow groundwater levels start to reflect precipitation or the lack thereof (Changnon, 1987).

The amount, intensity, seasonal variability, and physical phase of precipitation all affect the water budget in Illinois. The distribution of average annual precipitation in Illinois for the period 1971-2000 is shown (Figure A-4a). Average annual precipitation is 36 in. in the northeast and 48 in. in the south. Statewide average precipitation is about 39 in. The highest annual statewide precipitation, 54 in., occurred in 1837 (based on data from a small number of stations), and

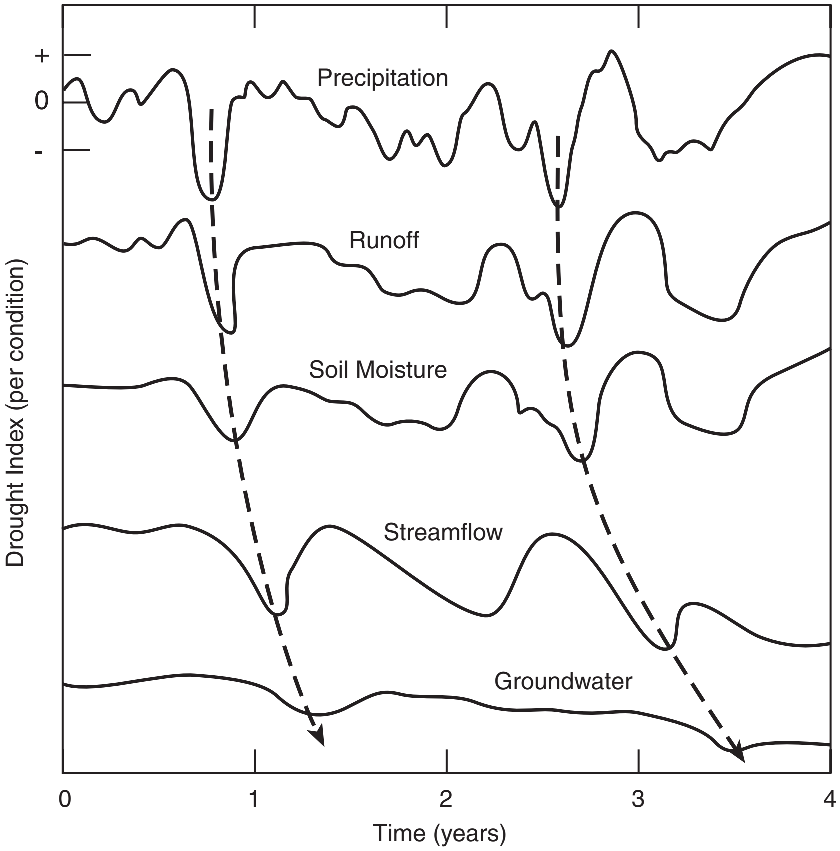


Figure A-3. Schematic Showing Precipitation Deficiencies during a Hypothetical 4-Year Period are Translated Through Other Physical Components of the Water Cycle (from Changnon, 1987) the lowest value, 26 in., occurred in 1901 (http://www.sws.uiuc.edu/docs/wsfaq/addl/q1wettestdriest95-02.gif; accessed November 12, 2005).

Temperature also affects the water budget through influences on the physical phase of water, evapotranspiration, and the moisture content of the atmosphere. In general, the lower the temperature, the lower the moisture content of the atmosphere and the greater the probability for ice and snow; evapotranspiration also is less. The opposite is generally true for warmer climatic conditions. Figure A-4b shows that average annual temperature in Illinois increases from about 48°F in the north to 58°F in the south. The warmest year on record in Illinois (statewide average temperature using data from a small number of stations) was 1846 (57°F), and the coldest 1919 (47°F). These geographical and temporal variations in temperature influence both water demand and water availability.

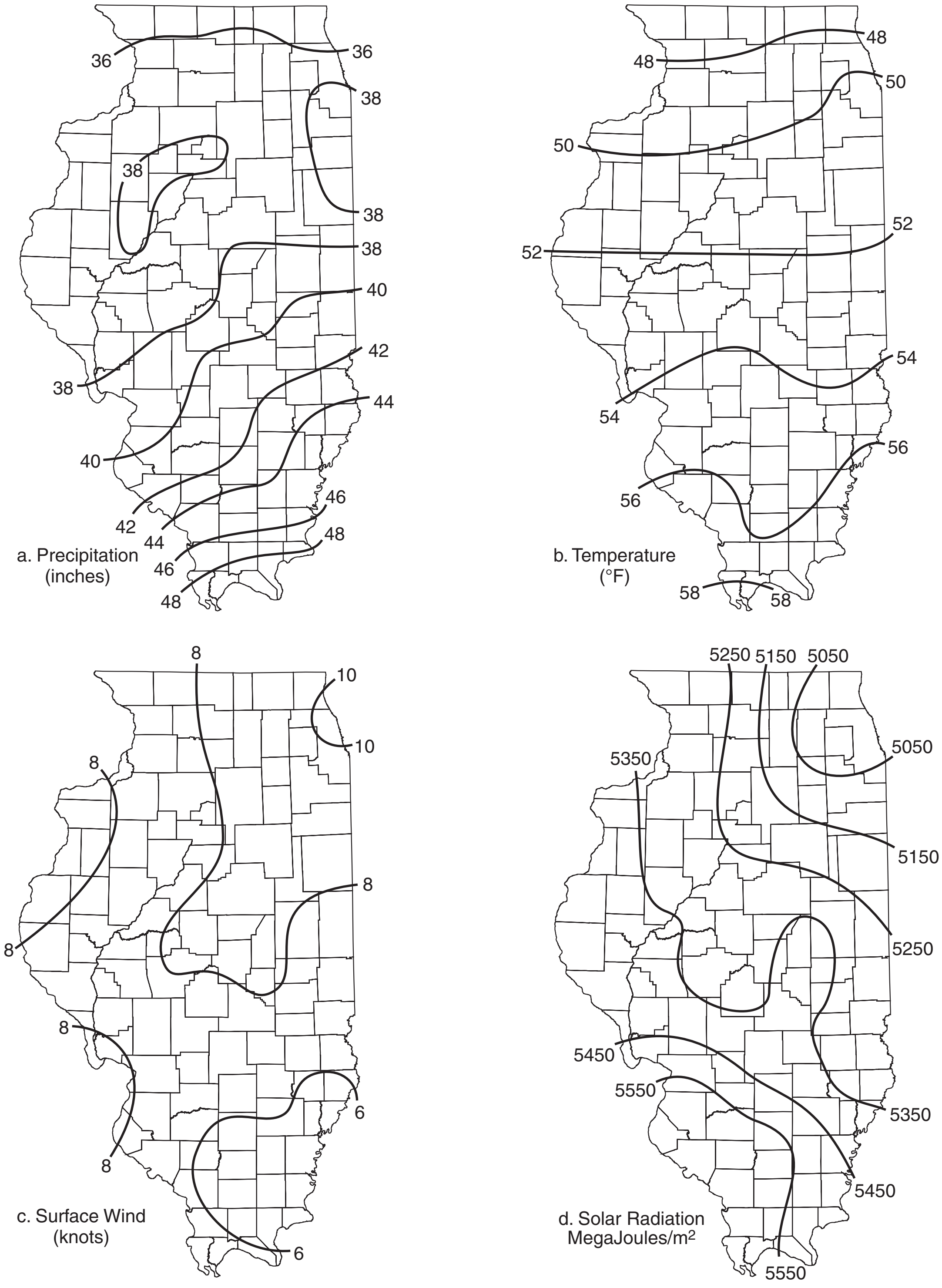
Higher wind speed generally increases the evapotranspiration rate. The highest average annual wind speed occurs in northern and central Illinois (Figure A-4c).

Higher solar radiation also increases evapotranspiration, and average annual solar radiation is highest in southern Illinois (Figure A-4d). Modern estimates of potential evapotranspiration for the period 1992-2004 (Figure A-5) are about 5-30 percent higher than an earlier estimate by Jones (1966). These modern estimates were calculated with the Van Bavel procedure, which uses a more complete set of climate variables that affect potential evapotranspiration (temperature, humidity, solar radiation, barometric pressure, and wind speed) and, thus, the estimates are believed to be more accurate. Average monthly values of air temperature and potential evapotranspiration in Illinois for the period 1992-2004 are shown (Figure A-6). The highest values occur in July, the lowest in January. An approximately linear relationship between 13-year monthly average air temperature and potential evapotranspiration for the period 1992-2004 is shown (Figure A-7). Although the relationship is approximately linear, deviations reflect the influence of other climatic variables, particularly solar radiation, whose annual cycle variation precedes that of temperature. Potential evapotranspiration increases approximately 1 inch for each 10°F increase in temperature.

Although direct observations of evapotranspiration are not available, Yeh et al. (1998) estimated regional evaporation over Illinois from 1983 to 1994 using two different approaches: soil water balance and atmospheric water balance. Climatologies of the monthly evaporation estimates from the two methods agree reasonably well and within a 10 percent error; however, substantial differences exist between the two estimates of evaporation for individual months.

The net effect of the above variables, together with variations in vegetation, soil, and geology, determined the fluxes and reservoirs of water in Illinois from 1983 to 1993 (Figure A-8). Eltahir and Yeh (1999) showed maximum average monthly rainfall of 4.43 in. in November. It should be noted that average monthly November rainfall for Illinois for 1983-1994 was 3.41 in. (personal communication, Jim Angel, ISWS, September 14, 2005).

Eltahir and Yeh (1999) described and analyzed the observed characteristics of the variability in the regional water cycle in Illinois for the period 1970-1996. They described the



a. Precipitation (inches)

b. Temperature (°F)

c. Surface Wind (knots)

d. Solar Radiation MegaJoules/m²

Figure A-4. Distribution of a) Average Annual Precipitation, b) Average Annual Temperature, c) Average Annual Surface Wind Speed, and d) Average Annual Solar Radiation in Illinois, 1971-2000.

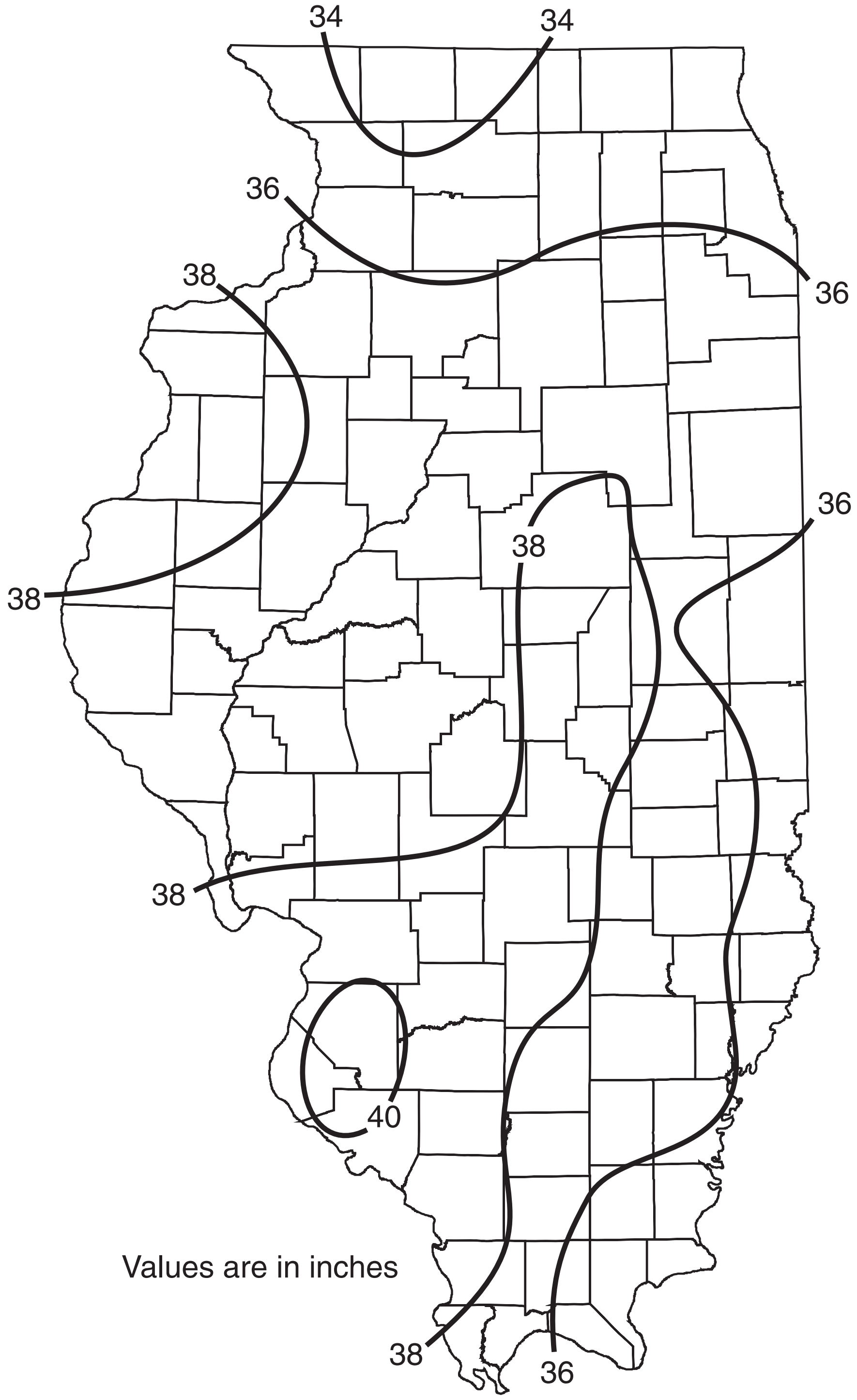


Figure A-5. Distribution of Average Annual Potential Evapotranspiration in Illinois, 1992-2004.

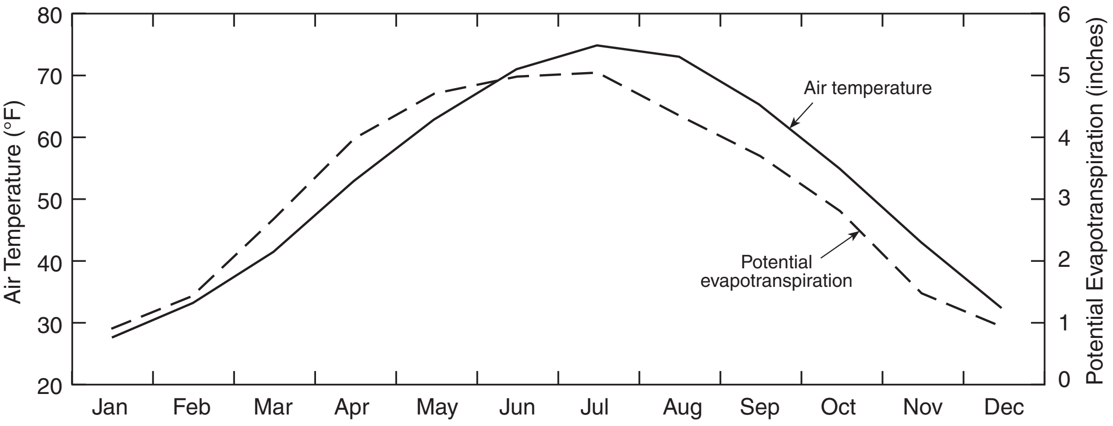


Figure A-6. Statewide Average Monthly Air Temperature and Potential Evaporation in Illinois, 1992-2004.

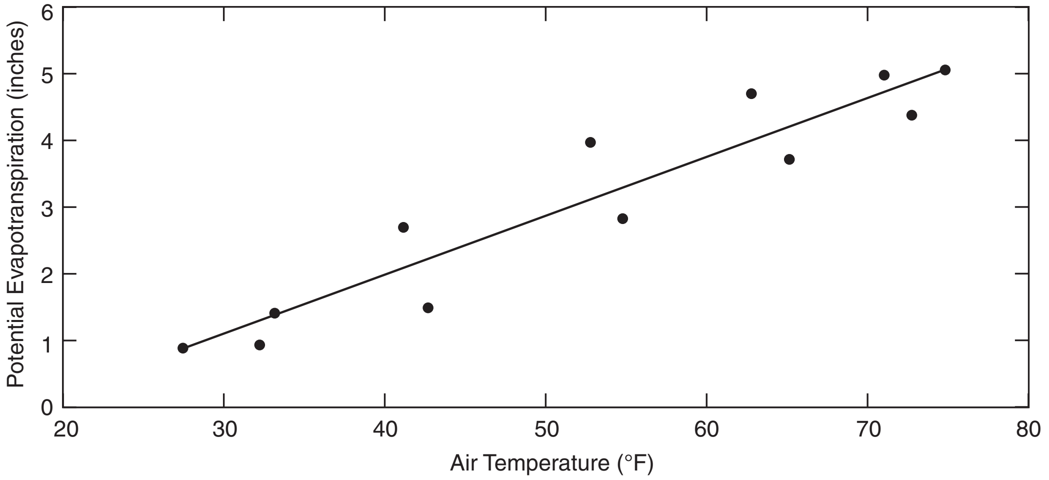


Figure A-7. Relationship between 13-Year Monthly Average Air Temperature and Potential Evapotranspiration in Illinois, 1992-2004.

decadal, interannual, and seasonal climatology of precipitation, evaporation, soil moisture content, groundwater storage, and river flow. Figures A-8 and A-9 show the seasonal variability in incoming solar radiation, atmospheric moisture convergence, precipitation, evaporation, soil moisture, groundwater level, river flow, and as well as changes in subsurface water storage. Precipitation occurs throughout the year, although spring is relatively wet. The seasonal cycle of incoming solar radiation is the main driving force for the observed seasonality in evaporation, soil moisture (water fraction by volume of soil), groundwater level and river flow. In summer, high evaporation exceeds precipitation, atmospheric moisture diverges away from Illinois, and subsurface water storage acts as a moisture source to the atmosphere. Upward water flux from the shallow aquifer by capillary diffusion outweighs gravity drainage, replenishes the root zone soil moisture, and results in a steep decline of the water table (Yeh and Eltahir, 2004).

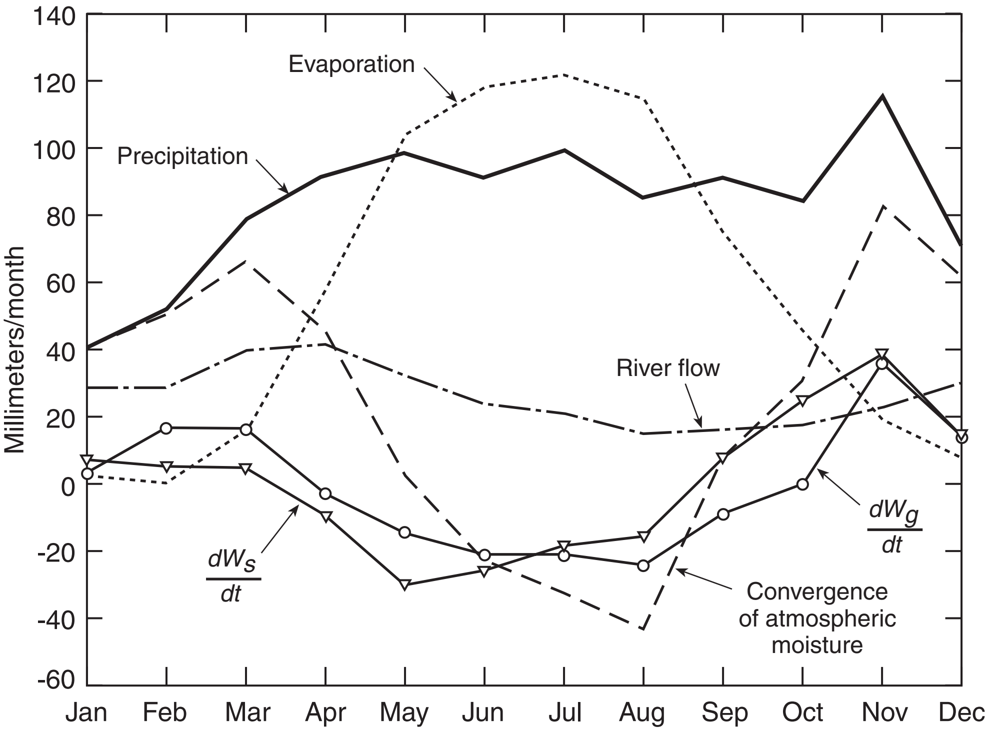


Figure A-8. Seasonal Cycle of Hydrological Components in Illinois, 1983-1994: Precipitation; Evaporation; River Flow; Convergence of Atmospheric Moisture; dW_s/dt Change in Unsaturated (Soil) Storage; and dW_g/dt Change in Saturated (Aquifer) Storage (from Eltahir and Yeh, 1999).

Precipitation exceeds evaporation the rest of the year, and a significant amount of moisture converges toward the region, which helps to replenish subsurface water storage. The seasonal cycle for groundwater levels lags behind that for soil moisture by about one month, and the seasonal cycle of river flow follows closely that for groundwater levels. Snowmelt in spring has a relatively minor impact on river flow, which peaks then in association with higher precipitation and groundwater levels. Eltahir and Yeh (2004) found that discharge to streams from groundwater aquifers is an efficient dissipation mechanism for wet anomalies in aquifer level, but the nonlinear dependence of the groundwater discharge on aquifer level may explain why droughts leave a significantly more persistent signature on groundwater hydrology than floods. Table A-1 shows the average monthly soil and atmospheric water balance in Illinois, 1983-1994.

Quantifying the moisture content of soils in Illinois is made difficult because of differences in soil types at the WARM sites and their individual abilities to hold water. Figure A-10 shows the average 1983-2003 moisture content for the 0-79 in. layer. Values of water equivalent by volume are computed regularly within 11 layers: 0-4 in.; every 8 in. thereafter down to 75 in.; and 75-79 in. There are 19 readings per year at each site, with mid-month readings in March - September, thus biasing the values to the growing season. Using up to 399 neutron probe readings at each site, layer averages of soil moisture were generated for the entire period of record at each site. Soil moisture was highest in southeastern Illinois (>29.9 in.) and lowest in northeastern

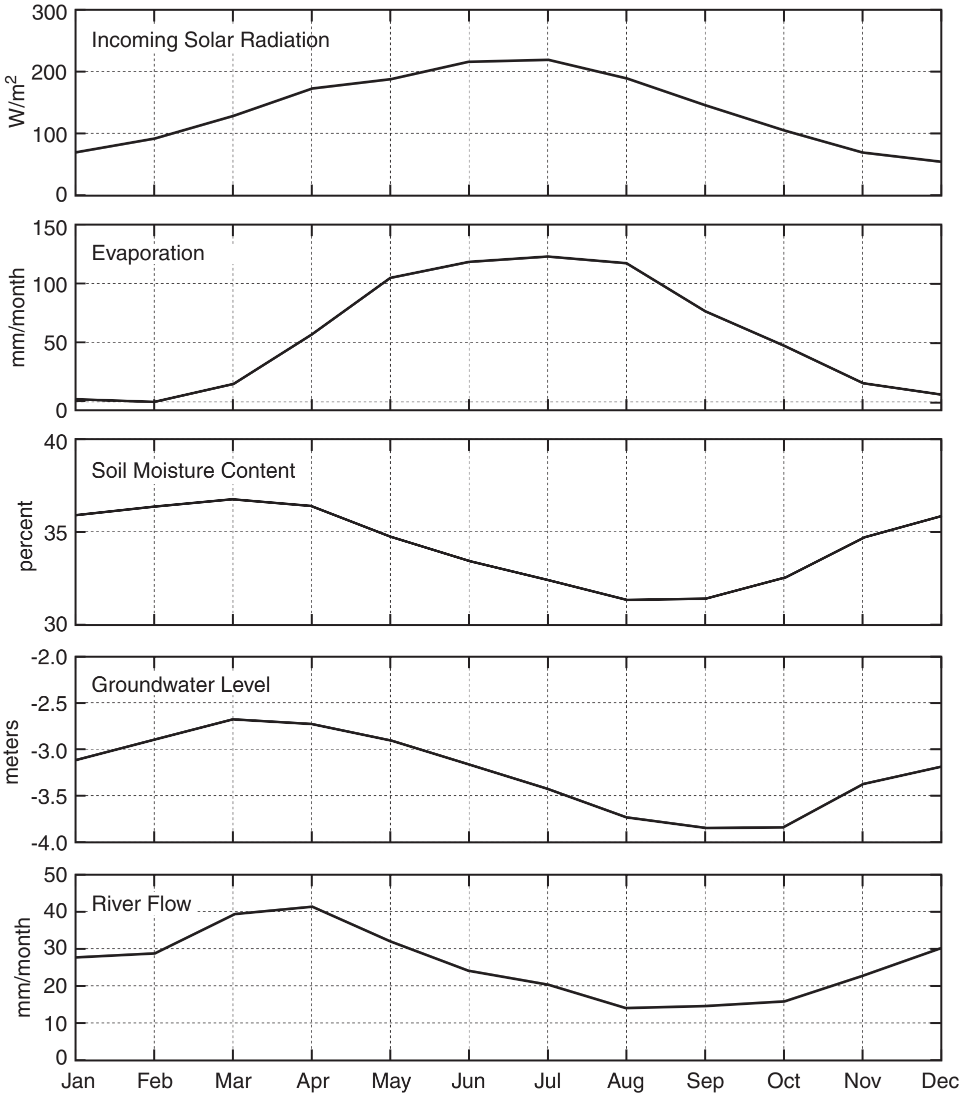


Figure A-9. Seasonal Cycle of Incoming Solar Radiation, Evaporation, Soil-Moisture Content, Groundwater Level, and Riverflow in Illinois, 1983-1994 (from Eltahir and Yeh, 1999).

Illinois (<25.2 in.), both equivalent to about 9 months of precipitation. Figure A-11 shows average annual 1983-2003 soil moisture content for the 0-79 in. layer.

Soil moisture at the WARM sites is measured under short grass, which is not a representative land cover for most of Illinois. The ISWS is conducting experiments to determine if there are any differences in soil moisture below short grass, corn, and soybeans, and in temperature and humidity above short grass, corn, and soybeans.

At interannual and decadal time scales, the major factor shaping natural variability in the regional water cycle is variability of atmospheric circulation and precipitation. In investigating the impact of land-atmosphere interactions on the temporal variability of soil moisture at a regional scale, Kochendorfer and Ramirez (2005) showed that soil-moisture-dependent precipitation-

Table A- 1. Average Monthly Soil Water Balance Components and Atmospheric Water Balance Components in Illinois From 1983 to 1994.

	P, mm	E_{soil}, mm	R, mm	s, %	H, m	$nD(ds/dt)$, mm	$Sy(dH/dt)$, mm	$E_{atmo.}$, mm	C, mm
Jan.	39.2	1.5	27.7	35.9	−3.10	7.2	2.9	0.4	41.4
Feb.	50.2	−2.5	28.7	36.3	−2.89	7.5	16.5	−0.4	50.2
March	77.1	12.3	39.5	36.7	−2.69	8.9	16.4	12.6	66.6
April	90.0	59.0	41.2	36.4	−2.73	−6.9	−3.3	51.7	45.8
May	94.8	108.7	32.3	34.8	−2.91	−31.9	−14.3	96.9	2.8
June	89.3	112.0	24.6	33.5	−3.17	−26.2	−21.0	122.5	−22.4
July	97.3	117.5	20.9	32.5	−3.43	−20.6	−20.5	126.9	−32.0
Aug.	83.5	114.6	14.8	31.4	−3.73	−21.9	−23.9	120.4	−42.2
Sept.	89.0	80.5	15.2	31.5	−3.83	1.8	−8.6	74.1	7.9
Oct.	83.0	42.5	16.6	32.6	−3.83	23.8	0.1	50.6	31.1
Nov.	112.5	9.9	22.7	34.8	−3.38	43.5	36.4	21.0	82.9
Dec.	69.0	3.8	30.0	35.8	−3.19	19.8	15.3	5.5	62.1
Average	82.1	55.0	26.2	34.4	−3.24	0.42	−0.33	56.9	24.5
Total	974.8	659.8	314.1	...	...	4.98	−4.01	682.2	293.7

P, precipitation; E_{soil}, evaporation estimated from soil water balance; R, river flow; s, soil moisture content; H, groundwater level; $nD(ds/dt)$, change in unsaturated (soil) storage; $S_y(dH/dt)$, change in saturated (aquifer) storage; $E_{atmo.}$, evaporation estimated from atmospheric water balance; and C, convergence of atmospheric moisture (from Eltahir and Yeh, 1999).

efficiency feedbacks can be significant contributors to the variability of soil moisture. Yeh and Eltahir (2004) reported a significant, nonlinear relationship between average water-table depth and corresponding streamflow at a monthly time scale in Illinois. These authors concluded that because of long memory, groundwater would create significant persistence of anomalies and feedback to impact future climate. Precipitation recycling, on the other hand, does not contribute to atmospheric moisture flux sufficiently to have significant impact on soil-moisture variability.

Another key element in the description of the water balance is geographical scale. Nieman and Eltahir (2004) developed a framework that integrates simple but physically-based descriptions of water-balance processes from a local instantaneous scale to an annual, basinwide scale. Potential evapotranspiration is assumed to be constant in space and time because of data limitations. Using average soil saturation between 0 and 4 in., they suggested that spatial correlation of soil saturation is not significant at a regional scale. Precipitation rate and soil saturation

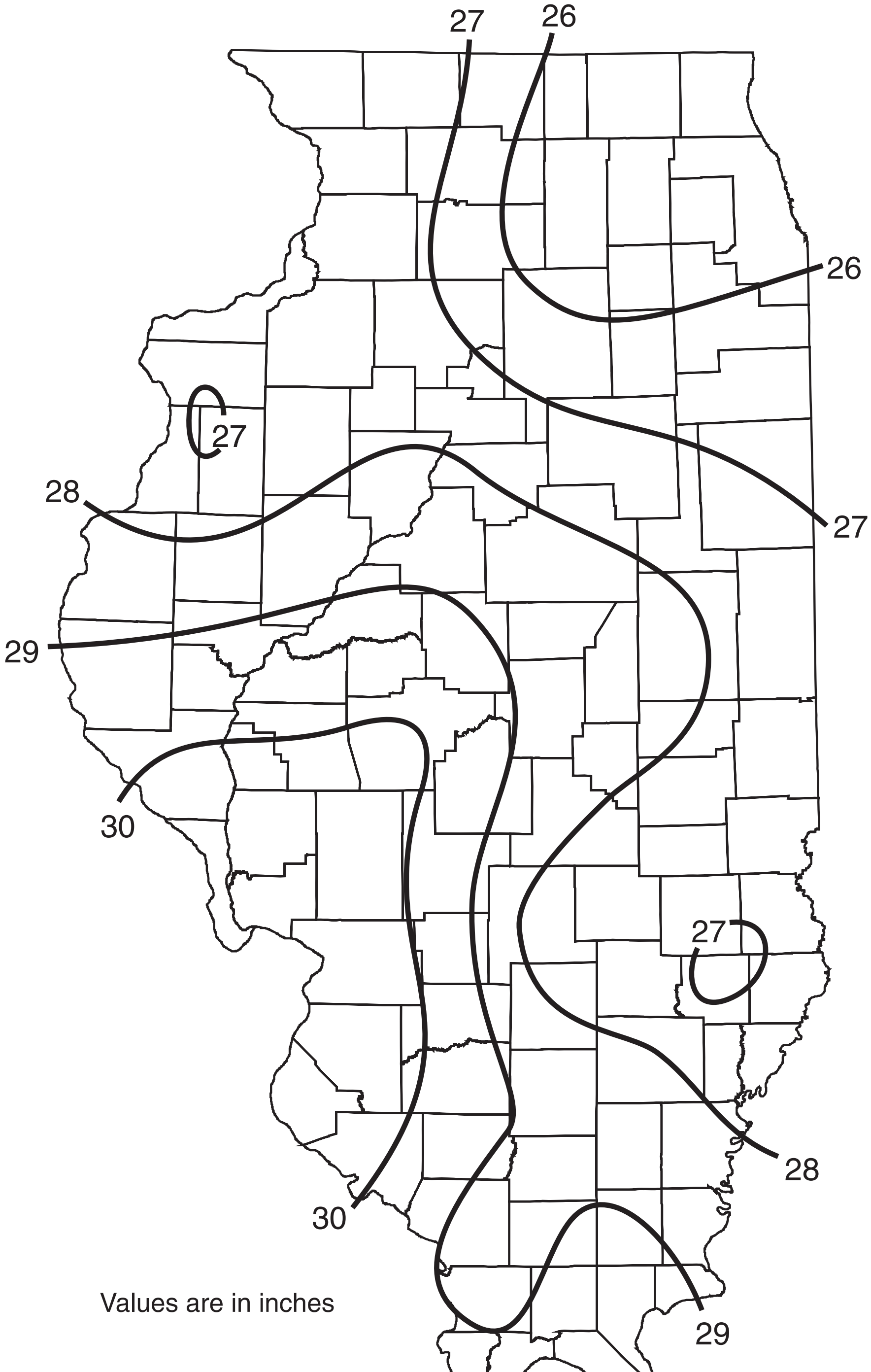


Figure A-10. Average Soil-Moisture for the 0-79 in. Layer Across Illinois, 1983-2003.

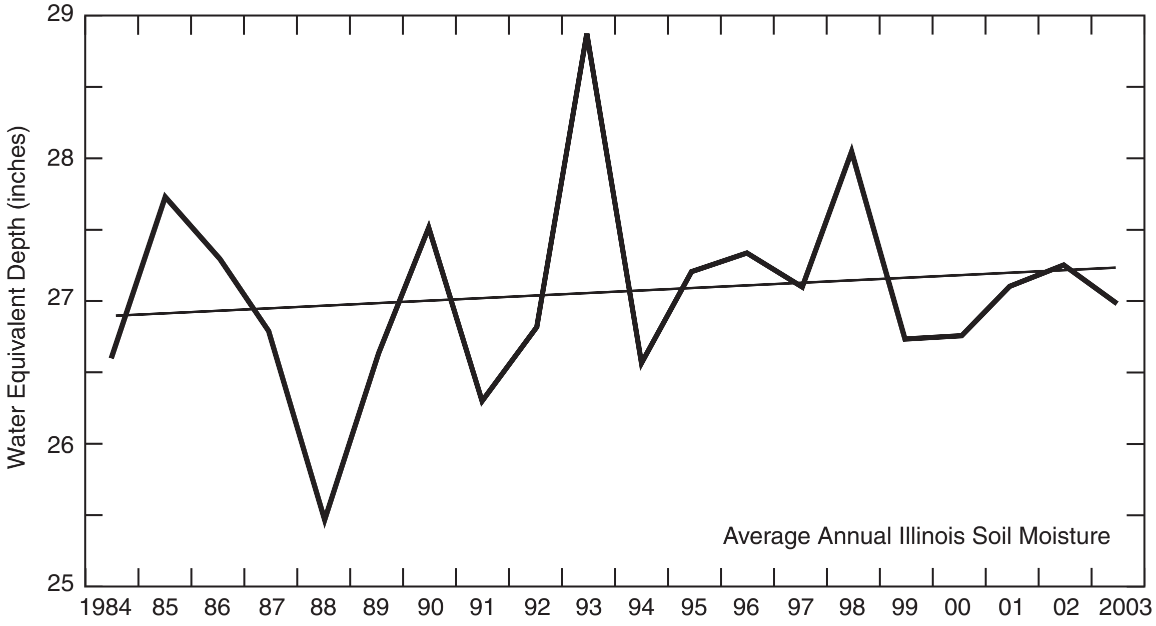


Figure A-11. Average Annual Soil Moisture for the 0-79 in. Layer Across Illinois, 1983-2003.

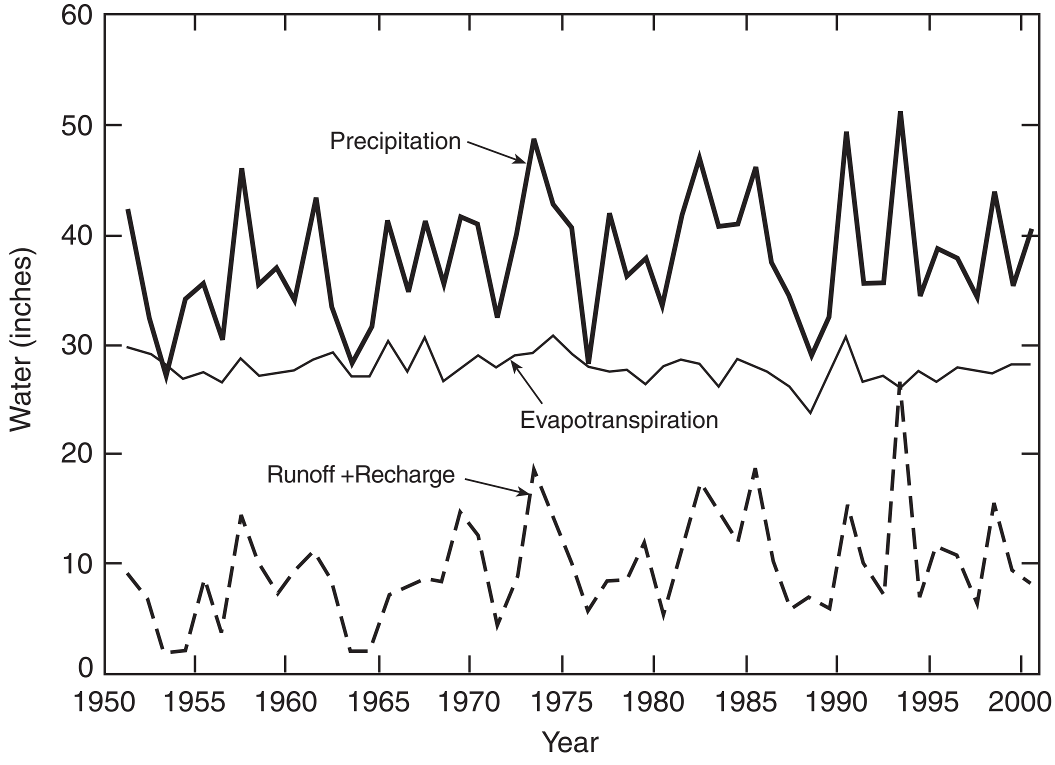
are treated as random variables in space and time within the Illinois River basin. But precipitation was found to be a better predictor of runoff than soil saturation. The modeled relationship between space-time average runoff and precipitation for the Illinois River basin is nearly linear in the range for which observations are available. Modeling also showed that soil saturation has more variability in space during wetter periods than dry periods.

Changnon (2003) used an existing watershed model developed and calibrated on a well-instrumented small, rural basin in central Illinois to estimate the distribution of additional water from three levels of increased summer rainfall simulated to occur during actual sequences of recent dry and wet years. Results showed that about half of the added water percolated into groundwater storage, which would have major benefits because most urban and rural water-supply systems in central Illinois depend on groundwater sources. In dry years, 10-15 percent of the additional water went to transpiration, reflecting water use by crops and potential yield increases. In wet years, 35-40 percent of the added water became runoff, compared to 13-22 percent in dry years. The simulated rain increase, consisting of a 25 percent increase on moderate to heavy rain days, exhibited the greatest effects on the basin's hydrologic components.

A physically consistent soil-moisture-budget model, based on the Crop Environment Resource Synthesis (CERES)-Maize corn growth and development model was used to simulate annual evapotranspiration and runoff, using observed precipitation values averaged for the entire state for the period 1951-2000. That model updates water-budget components daily. Corn is assumed to be the surface cover. Daily precipitation and temperature provide weather inputs to the model. For each day, the model calculates evapotranspiration based on weather conditions, growth stage of corn, and amount of soil moisture. If precipitation falls, the model calculates the runoff, based on soil moisture, precipitation, and surface slope. Remaining precipitation recharges soil moisture. If soil-moisture levels are above field capacity, some soil water infiltrates the water table; in this simple model, this water is assumed to add to runoff. The model is run for each crop reporting district in the state, and averaging these data provides a statewide value.

Figure A-12 shows the modeled annual values of evapotranspiration and runoff plus recharge, as well as observed precipitation values, averaged for the entire state for the period 1951-2000. Annual precipitation exhibits the typical large interannual variability. By contrast, modeled evapotranspiration exhibits little interannual variability, typically in the range of 25-30 in. Runoff and recharge exhibits very high interannual variability, ranging from less than 3 in. in some years to more than 20 in. in 1993. The 50-year averages are 37.9 in. for precipitation, 28.0 in. for evapotranspiration, and 9.7 in. for runoff and recharge. These values are slightly less than the values shown in Figure A-2 for the period 1971-2000.

Change in runoff and evapotranspiration for various prescribed changes in precipitation and temperature, as derived from the above soil water-balance model are shown (Figure A-13). It can be seen that runoff is very sensitive to precipitation. A 20 percent decrease in precipitation results in more than a 50 percent decrease in runoff, and a 20 percent increase in precipitation



Note: Precipitation values are derived from observations while evapotranspiration and runoff values are derived from soil-water-balance model.

Figure A-12. Model Annual Values of Evapotranspiration and Runoff, as well as Observed Values of Precipitation, Averaged for the Entire State, 1951-2000.

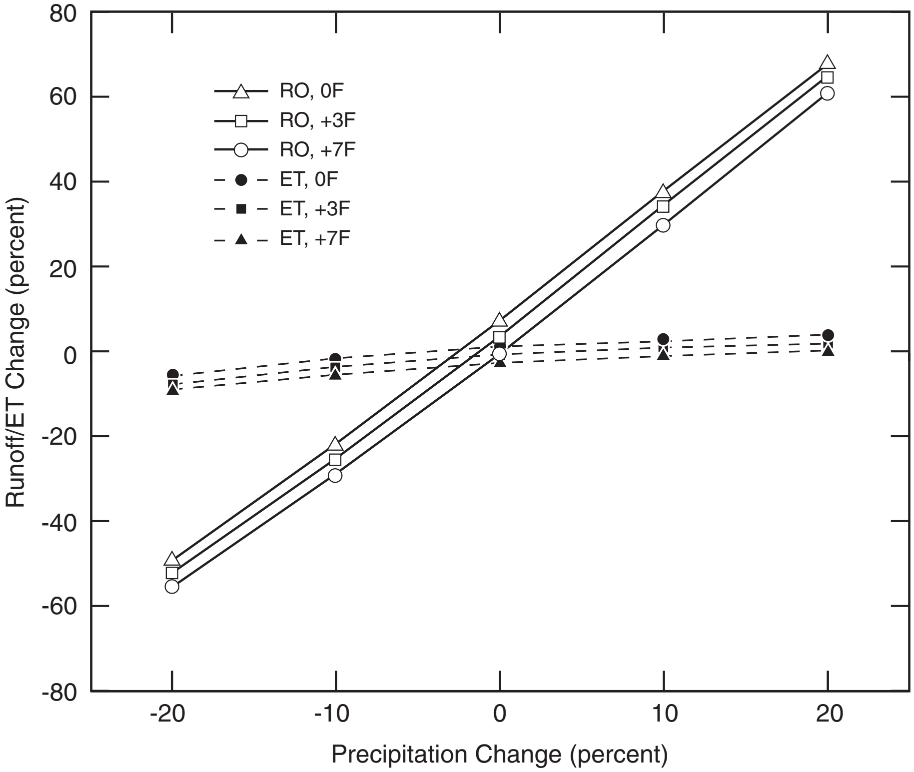


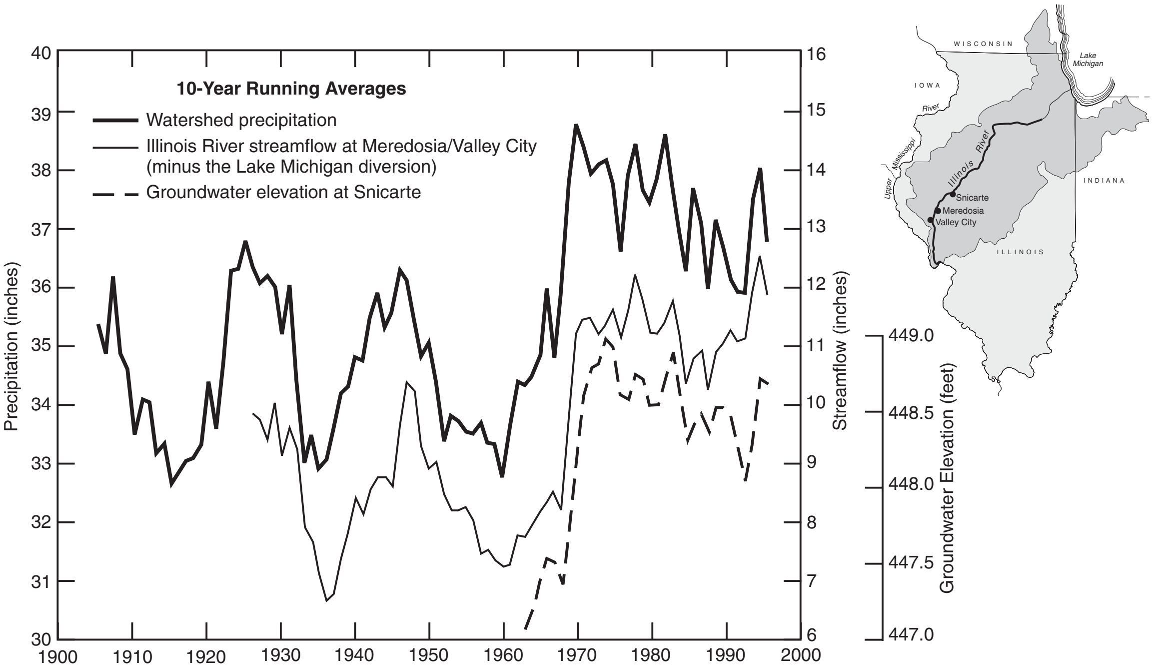
Figure A-13. Change in Runoff and Evapotranspiration for Various Prescribed Changes in Precipitation and Temperature Derived from a Soil-Water-Balance Model.

results in more than a 60 percent increase in runoff. Changes in evapotranspiration are less sensitive to precipitation, and neither runoff nor evapotranspiration is as sensitive to temperature as precipitation.

Long-term monitoring data can be used for model validation. In the Illinois River basin, there is a high positive correlation between variations in precipitation, runoff, and groundwater level (Figure A-14). From about 1960 to the early 1970s, precipitation increased by about 15 percent, runoff by about 50 percent, and shallow-groundwater levels by almost 2 feet.

As a further reality check on these calculations, the authors selected the only 5-year period in the last 150 years when average annual precipitation was close to 20 percent below normal. In 1952-1956, average annual precipitation across Illinois averaged 18 percent below normal. For that 5-year period, average annual temperature was 2.1°F above normal. Average annual runoff for Illinois over the 5-year period was 16 bgd, roughly 48 percent below normal (1971-2000). This runoff estimate is for all land area in Illinois but excludes inflows from Indiana and Wisconsin and water diverted from Lake Michigan. These data help to further validate model results shown in Figure A-13.

Average annual precipitation over the Illinois River basin in 1952-1956 was 15 percent below normal (1971-2000). For the Illinois River at Valley City, the 1952-1956 average flow was



Note: Streamflow quantity has been converted from cubic feet per second to reflect the number of inches of runoff over the entire Illinois River watershed.

Figure A-14. The 10-year Moving Averages of Illinois River Watershed Precipitation, Streamflow (Minus Lake Michigan Diversion), and Groundwater Elevation.

16,100 cubic feet per second (cfs), 39 percent below the 1971-2000 average of 26,100 cfs. When the amount of the Lake Michigan diversion (3200 cfs) is removed, the 1952-1956 Illinois River flow drops to 44 percent below normal. Given uncertainties associated with precipitation and streamflow measurements and changes in land cover since the 1950s, these results lend credibility to the statewide runoff and evapotranspiration curves with no temperature change as shown in Figure A-13.

The historical climate record does not contain a 5-year period with average annual precipitation close to 20 percent higher than the 1971-2000 normal. However, considering the very high level of Lake Michigan-Huron around the mid-19th Century, some projections from climate models show a 20 percent increase in precipitation, which seems reasonable.

The authors of this report concluded that the relationships between precipitation and evapotranspiration or runoff shown in Figure A-13 provide a reasonable basis for evaluating first-order impacts of changes in precipitation and temperature on streamflow in Illinois.

Other ISWS scientists have established hydrologic budgets for small watersheds in Illinois. Schicht and Walton (1961) prepared hydrologic and groundwater budgets using precipitation, streamflow, and groundwater-level data for Panther, Hadley, and Goose Creeks. Their computed annual evapotranspiration from hydrologic budgets was compared with annual potential evapotranspiration determined from meteorological data and to annual water loss determined from precipitation and streamflow records. Except for a dry year, annual evapotranspiration was calculated to be 77-87 percent of average annual potential evapotranspiration, close to the numbers computed from meteorological data. During a dry year, evapotranspiration in Panther Creek was reduced to 66 percent of potential evapotranspiration.

On a larger scale, Knapp (2004) analyzed longer climate and streamgage records for Illinois and the Upper Mississippi River Basin (UMRB), thus providing a context for possible future climate and hydrologic variability. Although most long-term streamflow records in Illinois started only in the 1940s, the longest records at 15 gages date from 1914-1915. However, even the longest available flow records in Illinois are not long enough to represent hydrologic conditions prior to most changes in land drainage such as would be necessary to identify and verify the effects of such changes. Except for the growth of urbanized areas, farmland covers most of Illinois, and changes to the general hydrology of agricultural areas since the early part of the 20th Century have been comparatively subtle and difficult to identify from existing records.

To understand the water cycle and water budgets in Illinois, specific attention must, of course, be focused on conditions within the state. Climate conditions in Illinois also are dependent on climate forcings in other parts of the nation and the world, however. Thus, it is important to understand linkages between these forcings and conditions in Illinois.

Oceanic conditions, especially sea-surface temperatures, have significant impacts on climate conditions over the continents. The El Niño/Southern Oscillation (ENSO) is a major mode of oscillation of the climate system in the Pacific Ocean and has impacts on the climate in many parts of the world, including the Midwest. In a modeling study of ENSO influence on the terrestrial energy profile, Chen and Kumar (2002) reported that propagation of the ENSO-related temperature anomaly from the land surface to deep soils occurs over several months. They also found that the variation of the anomaly of terrestrial heat storage in the shallow soil zone, consisting of heat stored in soil water and soil particles, is dominated by the variation of the soil-water storage, while that in the deep soil zone is determined by the variation of the soil temperature.

Tootle et al. (2005) demonstrated coupling between large-scale interannual and interdecadal oceanic-atmospheric variability and streamflow in the United States for the period 1951-2003. They showed that in addition to the ENSO signal the Pacific Decadal Oscillation, the Atlantic Multidecadal Oscillation, and the North Atlantic Oscillation influence streamflow variability. McCabe et al. (2004) concluded that much of the long-term predictability of drought frequency in the conterminous United States may reside in the multidecadal behavior of the North Atlantic Ocean. Kunkel et al. (2006) indeed demonstrated that the 2005 drought extending from Texas to the Great Lakes was associated with a weaker than normal southerly flow of moist air from the Gulf of Mexico/Atlantic Ocean moisture sources. This flow anomaly was associated with warm sea-surface temperatures in the North Atlantic Ocean and a weaker than normal Bermuda High over the North Atlantic Ocean.

These results demonstrate the importance of coupling terrestrial, oceanic, and atmospheric processes and also how this coupling enhances or dissipates the persistence of anomalies in the atmosphere forced externally by sea-surface temperatures thousands of miles away. Temperature propagation in deep soil layers may have important implications in the prediction of regional climate conditions.

In an investigation of the large-scale atmospheric moisture field over the Midwest in relation to summer precipitation, Zangvil et al. (2001; 2004) confirmed a widely held view that land-atmosphere interactions are involved in pronounced seasonal, regional climate anomalies, but apparently with considerable complexity that includes plant behavior, solar radiation forcing, and challenging time-scale interrelations. They concluded that a modeling capability must be able to treat and interrelate the daily-to-interannual time scales.

Most of Illinois lies within the Mississippi River basin. Major terms in the water balance of the entire Mississippi River basin for the period 1949-1997 are provided (Table A-2). During the latter half of the 20th Century precipitation in the Mississippi River basin increased 2.1 percent per decade, and runoff increased 5.5 percent per decade (Milly, 2005). One of the factors Milly identified for this increase in runoff was the filling of reservoirs in the early decades of this period. The decreasing rate of water storage helped free up runoff to support an increase in human-induced evapotranspiration. An estimated 6 percent of natural runoff is diverted to evapotranspiration as a direct result of human activity, especially irrigation. Milly concluded that much of the observed upward trend in precipitation was a manifestation of natural variability.

For the UMRB, Jha et al. (2004) used a regional climate model (RegCM2) to generate two 10-year simulated climates for the continental United States by downscaling a global climate model (HadCM2). One global-model run simulated current climatic conditions (1979-1988), and another simulated greenhouse gas concentrations to the 2040s, but sulfate-aerosol effects were not included. The simulated climates were used to drive a hydrologic Soil and Water Assessment Tool (SWAT) model over the UMRB. Uncertainties and biases were documented, and model

Table A-2. Major Terms in the Water Balance of the Mississippi River Basin, 1947-1997.

		mean flow (in./y)
A	precipitation	32.9
B	natural evapotranspiration	25.1
C	human-induced evapotranspiration	0.5
D	total evapotranspiration	25.6
E	natural runoff	7.8
F	runoff lost to fill surface reservoirs	<0.1
G	net removal of groundwater	<0.2
H	Mississippi River discharge	7.4

Note: Mean flows obey the following equations: A=B+E; B+C=D; E-C-F+G=H. Some of these equations are not exactly obeyed by the numbers in the table because of rounding (from: Milly, 2005).

performance was evaluated. The combined model system reproduced annual streamflow values well, but failed to capture seasonal variability. A 21 percent increase in future precipitation simulated by the regional climate model produced a 51 percent increase in surface runoff, an 18 percent increase in snowfall, and a 43 percent increase in groundwater recharge, resulting in a 50 percent increase in net annual water yield. The disproportionate change was attributed to more intense precipitation events and the nonlinear nature of water-budget components.

Climate variability also has influenced streamflow quantity significantly. Most long-term streamgages in Illinois were installed between 1935 and 1948, a period of below normal precipitation marked by frequent droughts. In contrast, precipitation since 1970 generally has been above normal, punctuated by only a few droughts. More than half of the long-term records collected from the 1940s to 2004 display increasing trends in average streamflow (Knapp and Markus, 2003).

Because the period of record can have a substantial influence on perceived climatic and streamflow trends, one of the first steps in analyzing streamflow trends in Illinois was to examine the longest climatic and hydrologic records available from the Midwest to gain greater knowledge about possible long-term variations and anticipated trends. Knapp (2004) reported that the records for the Mississippi River at two Iowa stations arguably provide the best examples of long-term flow records in the United States for studying long-term relationships between climate and streamflow. Flow records for the Keokuk and Clinton gages began in 1878 and 1873, respectively. Knapp (2004) also constructed a daily discharge record for the Illinois River at Peoria beginning in 1884 and concluded that the potential error of the constructed record prior to 1910 was about 10 percent when used in estimating most flow statistics. The author identified in the report limitations of the constructed record.

From an analysis of different long-term precipitation records in the UMRB, Knapp (2004) concluded that the average precipitation since 1980, the highest during the 20th Century, apparently is matched in magnitude by a 20-year period during the 1840s and 1850s (Figure A-15).

Knapp (2004) found that the correlation between precipitation and streamflow in the UMRB exceeds 0.97 when averaged over a 30-year time period or longer, but is less than 0.50 for a 1-year time period. The 10-year average selected represents a point when most of the relationship between precipitation and streamflow for most watersheds can be explained and has a correlation coefficient of about 0.95. For the graphs shown (Figure A-16), the 10-year moving average is presented at the mid-point of the 10 years.

Figure A-16a compares the 10-year moving average of watershed precipitation and streamflow for the Mississippi River at Keokuk. Figure A-16b compares the 10-year moving average of watershed precipitation and streamflow for the Illinois River at Peoria-Kingston Mines. Compared to the Mississippi River trends, in which the changes in precipitation and streamflow appear to be almost cyclical, changes for the Illinois River watershed are abrupt, indicating a step increase around 1970. Long-term precipitation records suggest that there may have been similar steep shifts in the past, such as the general reductions of precipitation (and streamflow) in the Upper Mississippi and Illinois River watersheds that occurred in the 1880s.

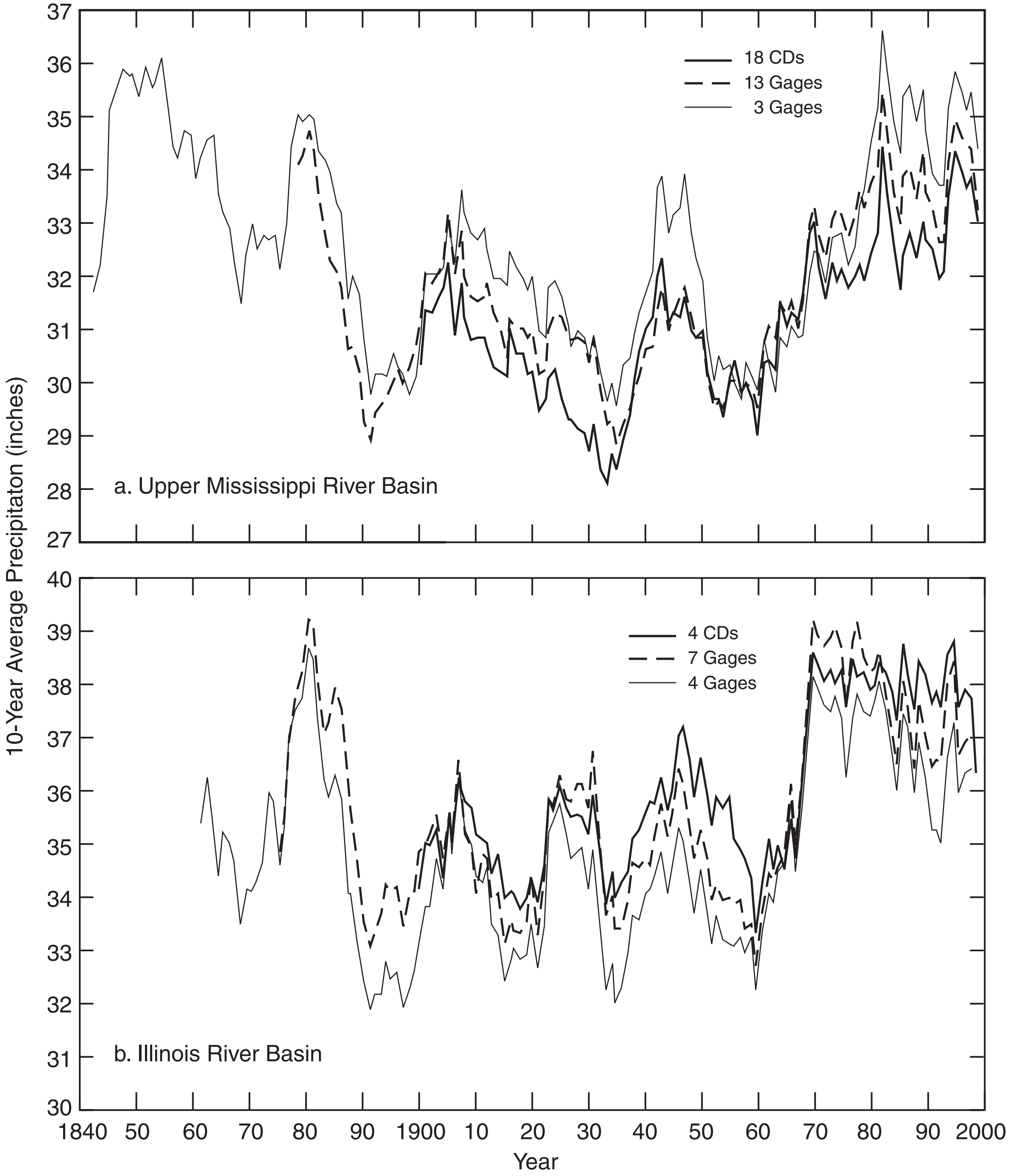


Figure A-15. Comparison of Three Estimates of Watershed Precipitation: a) the Upper Mississippi River Basin Upstream of Keokuk, Iowa, and b) the Illinois River Basin Upstream of Peoria, Illinois (from Knapp, 2004).

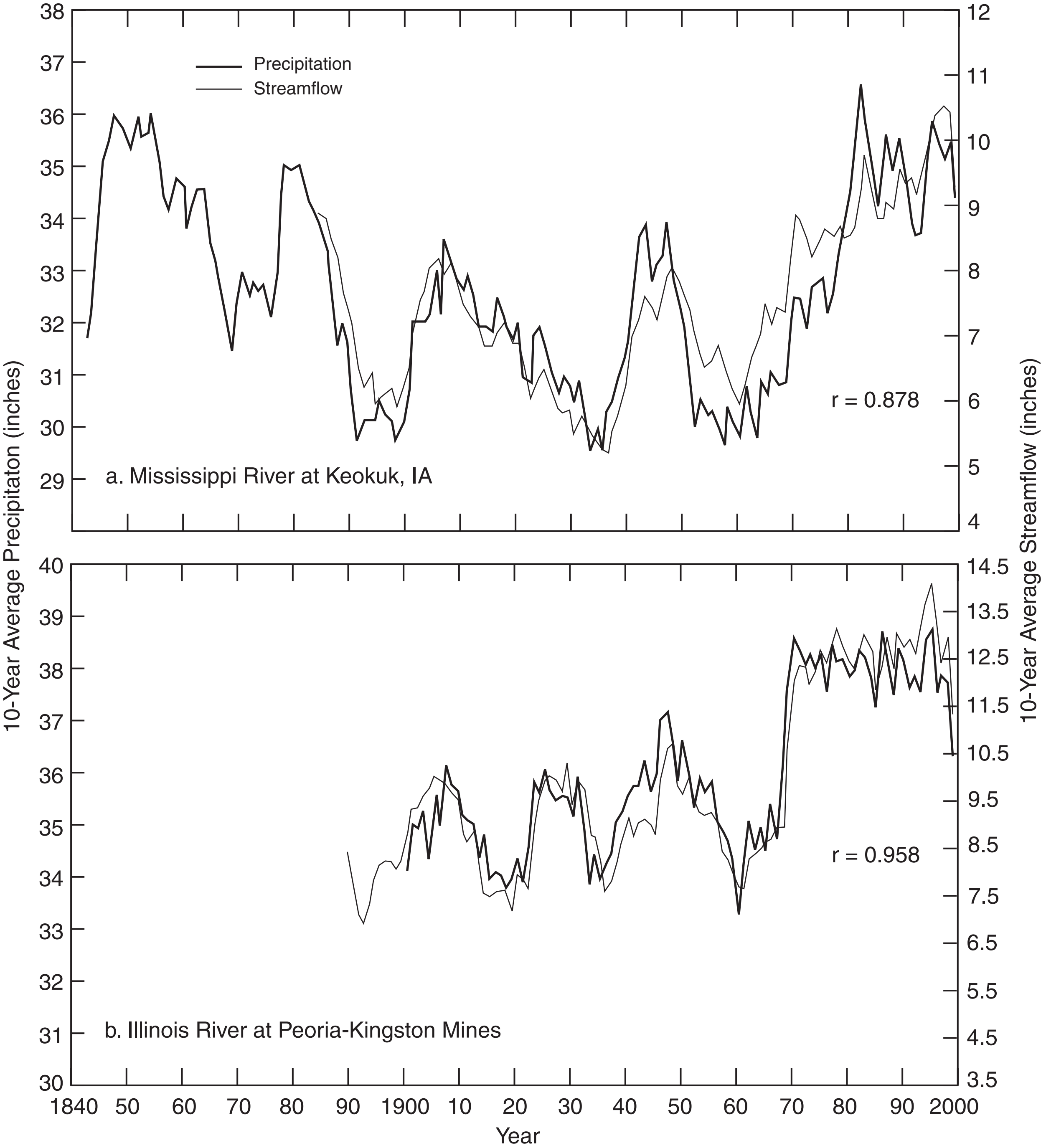


Figure A-16. Comparison of 10-Year Moving Averages of Watershed Precipitation and Streamflow for a) Mississippi River at Keokuk, Iowa, 1837-2002, Using 3 Precipitation Gages, and b) Illinois River at Peoria-Kingston Mines, 1870-2002, Using Data from 4 Climate Divisions (from Knapp, 2004).

Knapp (2004) found that the frequency and occurrence of low and high flows on the Mississippi and Illinois Rivers relate closely to longer interdecadal changes in average precipitation and flow. In general, the major hydrologic droughts and lowest flow events occurred in 1890-1970, when average precipitation and streamflow were well below the long-term average. Occurrences of major floods tend to be clustered in portions of the flow records before 1890 and after 1970, extended periods when average precipitation and streamflow were well above normal. Contributing effects of other factors on the frequency of major floods, such as changes in land use, were not analyzed, but they appear to be of secondary influence for these large rivers.

Knapp (2004) reported that it appears that navigation works (locks, dams, and pools) have caused a noticeable shift in the magnitude and seasonality of low flows on the Mississippi River since about 1940. Low flows on the Illinois River are dominated by the amount of flow from the Lake Michigan diversion, and it was reported that the influence of other factors, including climatic variability, cannot be determined. Low flows on the Illinois River have decreased since 1996, apparently as part of an effort to limit the long-term net diversion to the 3200 cfs amount decreed by the U.S. Supreme Court.

Berbery and Luo (2003) discussed the 1995-2002 water and surface-energy budgets over the Mississippi River basin and sub-basins using the Eta operational mesoscale model. In the eastern part of the basin, they found no well-defined interactions between the land surface and the atmosphere, suggesting that other effects, such as the advection of moisture, may be more relevant for precipitation. Compared with the dry western basin, vegetation in the more humid east may not show signs of transpiration stress, except in severe droughts.

Kochendorfer and Ramirez (2005) concluded that precipitation recycling within the region does not contribute to atmospheric moisture flux sufficiently to have a significant impact on soil-moisture variability. However, using a large-scale water-balance model and observations of relevant hydrologic and atmospheric variables, they reported that their study suggests that energy-budget feedbacks are a substantial source of the variability of soil moisture in the region.

Recognizing that terrestrial water storage is an essential part of the water cycle, Seneviratne et al. (2004) investigated monthly terrestrial water-storage variations from water-balance computation results for the whole Mississippi River basin and its sub-basins. Atmospheric water-vapor data (vapor-flux convergence and atmospheric water-vapor content) from reanalysis data and conventional runoff measurements were used. For Illinois, the water-balance estimates reportedly show excellent agreement with observations and well capture mean seasonal cycle and interannual variations, except the late spring drought of 1989. Yeh et al. (1998) came to similar conclusions. However, because of biases, Seneviratne et al. (2004) reported that estimating the evolution of terrestrial water storage over periods longer than 4-6 months is possible only with appropriate detrending.

Milly and Dunne (2001) reported on trends in evaporation and surface cooling in the Mississippi River basin above Vicksburg, Mississippi. They concluded that an upward trend in evaporation during recent decades is driven primarily by an increase in precipitation and secondarily by human water use. A cloud-related decrease in surface net radiation appears to have accompanied the precipitation increase, which they most readily explained as part of an unusually large internal fluctuation in the climate system. Resultant evaporative and radiative cooling of the land and lower atmosphere quantitatively explain downward trends in observed pan evaporation. They concluded that these cooling tendencies reconcile the observed regional atmospheric cooling with the anticipated regional "greenhouse warming". Walter et al. (2004) also reported increased evapotranspiration rates over the past 50 years for several large basins across the conterminous United States, including the Mississippi River basin. They concluded that this contributes to mounting evidence suggesting that the hydrologic cycle is accelerating. The fact that water-storage terms were not included in their estimates of evapotranspiration trends could impose a limitation on their study.

Conclusions

Successful water-supply planning depends on the availability and use of scientific data. This appendix demonstrates that a wealth of historical data on all components of the water cycle exists in Illinois. Analyzing and interpreting these data and incorporating them in mathematical models provide means to investigate possible variations and changes in future water availability, and to evaluate alternative strategies for providing adequate and safe supplies of clean water at reasonable cost. Characteristics of streamflow in any region will, over time, vary from earlier conditions because of the cumulative impact of human activities, climate variability, and other potential factors. Virtually all of Illinois has experienced considerable land-use changes since European settlement, including cultivation of land, drainage modification, removal of wetland areas, deforestation, and urbanization. It is recommended that future land-use scenarios be incorporated in calculations of future climate change and water budgets for Illinois.

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Appendix B.
Historical Lake Levels and Worst-Case Drought Scenarios for Lake Michigan-Huron

Appendix B

Historical Lake Levels and Worst-Case Drought Scenarios for Lake Michigan-Huron

The level of Lake Michigan-Huron varies rather slowly, but rises or falls substantially in response to extended multi-year wet or dry spells. Past fluctuations of lake level have caused sizeable impacts on shoreline communities. In some instances, such fluctuations have lasted for a decade or more. The slow response of the lake to changes in climate is a serious concern for resource management. On the positive side, a short severe drought will have a relatively small impact on lake level. However, once a low lake level has been established in response to an extended drought, it can take years after the drought has ended for the lake to return to higher levels.

Low lake levels make bulk transportation by freighters more costly due to load reductions, exceeding 5 percent in some cases in response to shallow drafts in navigation channels. Pleasure craft also have trouble navigating near coasts and in marinas, and accelerated dredging schedules are very expensive. There also are many environmental impacts in the nearshore zone, where established wetlands have dried, and new ones with thick weeds have replaced clean recreational beaches. Low water levels exposed nearshore portions of water intake pipes to freezing conditions in January 2004 in Sheboygan, Wisconsin, threatening the water supply for tens of thousands of people.

The potential for Great Lakes water to be directed to drought stricken non-basin locations through the diversion at Chicago, as was done in 1956-1957, was essentially eliminated by a 1967 U.S. Supreme Court decree establishing a strict limit to all diversions for use in northeastern Illinois (Changnon and Glantz, 1996). Ironically, lower lake levels assist Illinois in meeting diversion limits, as less water is used for lock operations or lost as runoff; since municipal runoff flows to the Illinois River rather than Lake Michigan, it is counted against the Illinois diversion limits.

The most severe and costly potential impacts of low lake levels would occur if levels fell lower than have been observed since the mid-1800s. Changnon (1993) found that a lowering of Lake Michigan to 4.3 feet below the long-term average (1 foot below the observed record) would damage Illinois shoreline installations, require extensive dredging in harbors, impact water intakes, and cause shoreline recreational facilities to be relocated, at a total cost of $500-700 million dollars (2006 dollars). Most importantly, a lowering of Lake Michigan to this level would require a complete rebuilding of municipal sewage and regional runoff systems, including major dredging and reconstruction of all diversion facilities. This cost would dwarf the direct shoreline and transportation effects, costing at least $25 billion and possibly up to $60 billion (2006 dollars). A further drop of Lake Michigan levels to 8.2 feet below normal could double these costs.

The following examination of historical lake levels documents the magnitude and duration of extreme levels, providing a context for management of this important resource.

Paleolake Levels

Low levels seen in the Michigan-Huron lake system in the past few years appear to be near the lowest levels recorded by the lakes over the last 4000 years. Research integrating geomorphologic, sedimentologic, and stratagraphic methods calibrated by radiocarbon dating indicate that only at periods centered approximately 600 and 1000 years ago did lake levels exist in the range of recent low levels (Thompson and Baedke, 1999). The reconstruction of lake level indicates a periodicity of about 150 years over the last 3000 years. Low levels in the mid-20th Century correspond to a low point in these cycles, if the pre-observation periodicity is continued into the observational record. That the early 2000s low stand of lake levels does not correspond to this cyclic pattern makes this event all the more unusual.

A recent study by Quinn and Sellinger (2006) points out a necessary further step when interpreting pre-modern levels of Lake Michigan-Huron. Large changes in hydraulic configuration across the St. Clair River and Detroit River, mostly due to dredging, have lowered the nominal level of Lake Michigan-Huron by at least 1.2 to 1.6 feet (International Joint Commission, 1987), and possibly more. Therefore, when using proxy climate data to reconstruct past lake stands, it is best to refer these reconstructed lake level variations to the current normal levels. From tree ring climate reconstructions, Quinn and Sellinger (2006) found that given the climate of the last 400 years, Lake Michigan-Huron levels would have reached lower levels than the extended-mid 20th Century low stand at least twice, but not by more than half a foot.

Long-Term Observed Lake-Level Variations

Changnon and Burroughs (2003) examined the low frequency variations of lake levels across all the Great Lakes using data from the U.S. Army Corps of Engineers for 1861-2001. Smoothing the Michigan-Huron annual lake-level data with 5-year, 15-year, and 25-year moving averages, the overall record indicated higher levels in the mid-19th Century, a lower stand in the mid-20th Century, and a return to higher overall lake levels in the late 20th Century (Figure B-1). It should be noted that a substantial portion of the apparent downward lake level changes are due to dredging at the St. Clair River outlet of Lake Huron, especially in the decades prior to 1900 and around 1960-62. These and other engineered changes may have had a cumulative lowering effect of up to 1.2 to 1.6 feet on the mean level of Michigan-Huron since 1860 (International Joint Commission, 1987), as noted earlier. The curve representing the 5-year averaging interval indicates briefer periods of extreme high and low lake levels, the three lowest being 1933-1937 (577.1 feet), 1962-1966 (577.4 feet), and 1923-27 (577.7 feet), compared to the long term average of 579.4 feet.

The range of U.S. Climate Division (Karl et al. 1986) precipitation variations within the Lake Michigan and Lake Superior basins during 1898-2002 are shown in Figure B-2. Using the 15-year percentages of the long-term average for the most anomalously wet and dry divisions in each basin, the time series indicate an increasing shift from the early period to the late over the Lake Michigan basin that is not found in the Lake Superior basin. The last two 15-year periods, 1973-1987 and 1973-2002, also had a wider range of values and higher maxima than any other periods (Figure B-2). Increased precipitation over the Lake Michigan basin during these periods

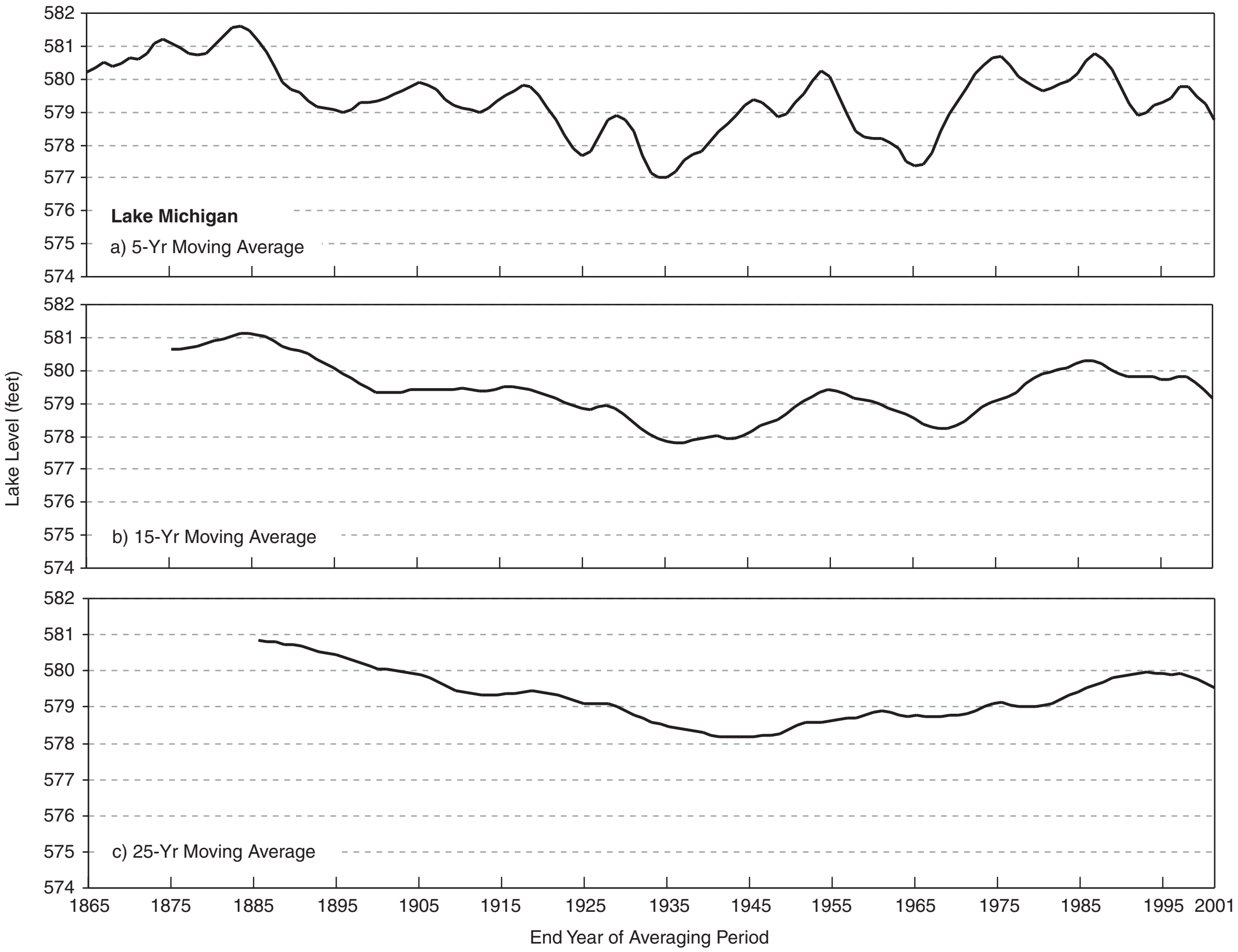

Figure B-1. The 5-, 15-, and 25-year Moving Averages of the Level of Lake Michigan, 1861-2001, with the Value Placed in the End Year of each Averaging Period, (from Changnon and Burroughs, 2003).

corresponds to a period of greater lake-level variation, as indicated by 15-year moving standard deviation values (Figure B-3).

Monthly Observed Lake Levels

Measurements at Harbor Beach, Michigan, on the western shore of Lake Huron provide the reference lake level for the Michigan-Huron lake system from 1860 to present. While lake levels may vary daily and even hourly along the shores of the lakes, monthly and annual average observations are quite similar across the lakes. Monthly data for Harbor Beach were extracted from the NOAA Center for Operational Oceanographic Products and Services (CO-OPS) Website at (http://www.co-ops.nos.noaa.gov/data_res.html). Because data for the 1970s were missing from the monthly data compilation, daily data for this period were extracted elsewhere from the same Web site and processed to complete the monthly time series.

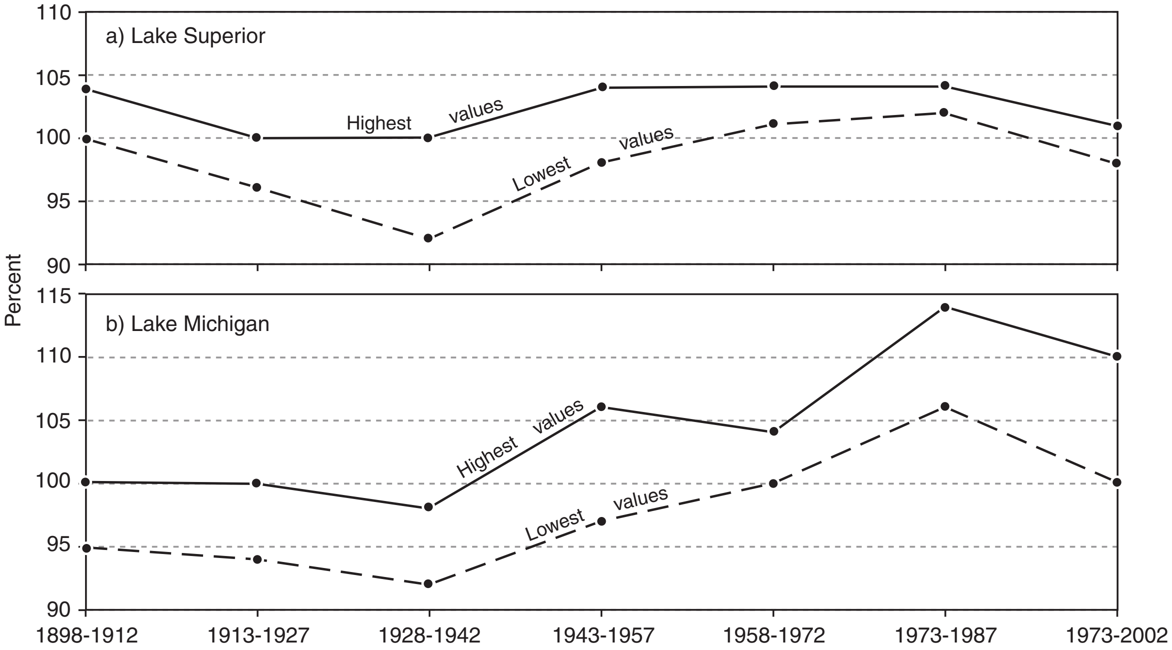

Figure B-2. The Range of Annual Precipitation Values Within Seven 15-Year Periods, from 1898-2002, Expressed as a Percent of the Long-term Average, for the U.S. Climate Divisions in the Lake Superior and Lake Michigan Basins, (from Changnon and Burroughs, 2003).

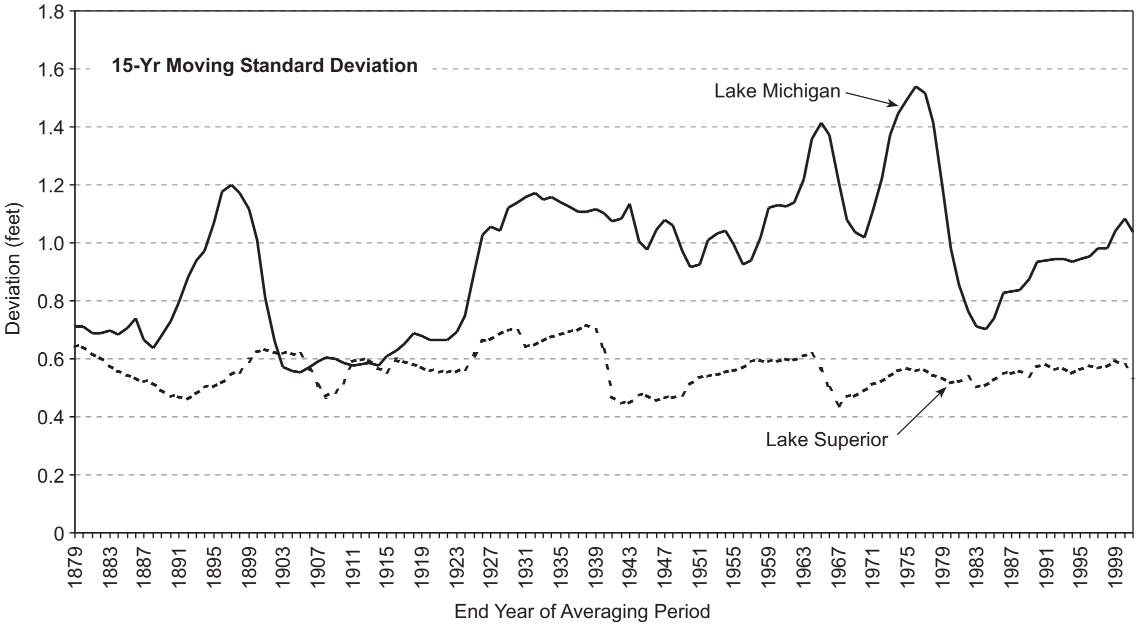

Figure B-3. The 15-Year Moving Average Standard Deviations of Lake Levels for Lake Michigan and Lake Superior, 1865-2001, with the Value Placed in the End Year of each Period, (from Changnon and Burroughs, 2003).

The 1860-2003 average seasonal cycle was calculated and removed from the lake level data, yielding a time series of monthly departures from the long-term average (Figure B-4). The single-month minimum departure of -3.3 feet occurred during July 1964. However, the minimum 5-year lake-level departure was found during the 1930s national drought. Overall, the period from 1860 to the 1890s was denoted by a steady high level, followed by low levels from the 1920s to the 1960s, and high levels from the 1970s until the late 1990s. Recent low levels in March 2003 ranked third after the 1930s and 1960s lake-level minima. The departure of -2.5 feet below the long-term average during this month reached the 4th percentile of the observed distribution. The empirical distribution of lake levels indicates that the departure from normal of the 100-year low lake level event varies from -2.7 feet in December to -3.0 feet in July/August.

Lake Levels and Local Precipitation and Temperature

Lake levels in the Michigan-Huron lake system are a function of lake inputs and outputs. Water flowing into the system from Lake Superior, stream runoff, groundwater inputs, and precipitation is balanced over long periods by water flowing out the St. Clair River and various diversions, and lost through evaporation into the atmosphere. However, the balance can be upset over intraannual to decadal periods by precipitation and temperature departures that affect lake level inputs and outputs. Monthly precipitation data for land areas of the Michigan-Huron basin were compiled for the period 1883-1999 by the Great Lakes Environmental Research Laboratory (GLERL), using the methods of Croley and Hunter (1994). Because similar GLERL compilation

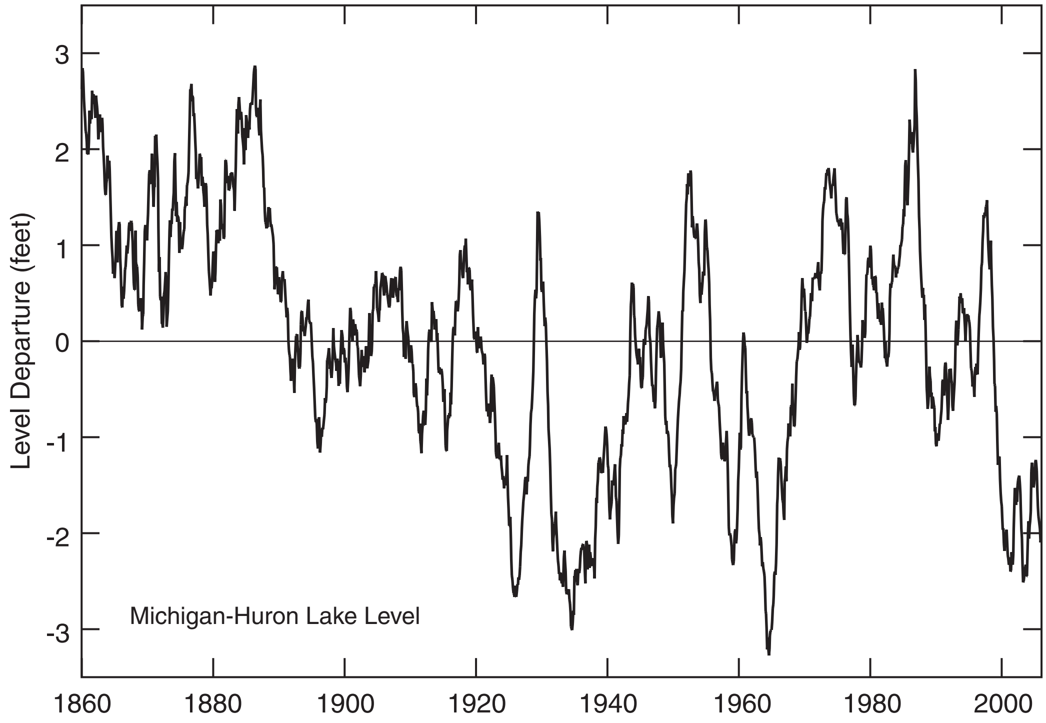

Figure B-4. Michigan-Huron Lake-level Departures from 1860-2003 Monthly Averages at Harbor Beach, MI (NOAA CO-OPS).

of temperature starts only in 1948, the average surface air temperature for the state of Michigan was gathered from the National Climatic Data Center Climate Divisional Data Set (Karl et al., 1986). This time series integrates 1895-2003 temperatures over most of the land area of the Michigan-Huron basin. Climate division precipitation for Michigan was substituted for basin precipitation during the period 2000-2003; both precipitation time series share the same average value within 1 percent.

The best correlation between monthly precipitation and lake-level departures over the period 1860-2003 is found at the accumulation time scale of about 5 years (Figure B-5). The precipitation values for a 60-month period were plotted against the monthly lake-level departure in the last month of the 60-month period. Although the correlation is only 0.43, this is highly significant. The precipitation record visually appears to track the majority of large lake-level departures, so digital smoothing probably would enhance this correlation. There also appears to be a very substantial step change in basin precipitation values in the late 1960s to a new and higher average level about 12 inches more per year after 1980 than the overall 1883-2003 average. Late 20th Century high lake levels correspond with this heavy precipitation period.

An interesting feature of late 20th Century record is that precipitation and lake-levels began to diverge. For the period January 1970 to December 2003, the correlation between the 60-month temperature departure and lake-level departure in the last month of each 60-month period is -0.64, explaining much more variance than precipitation. A strong negative correlation is

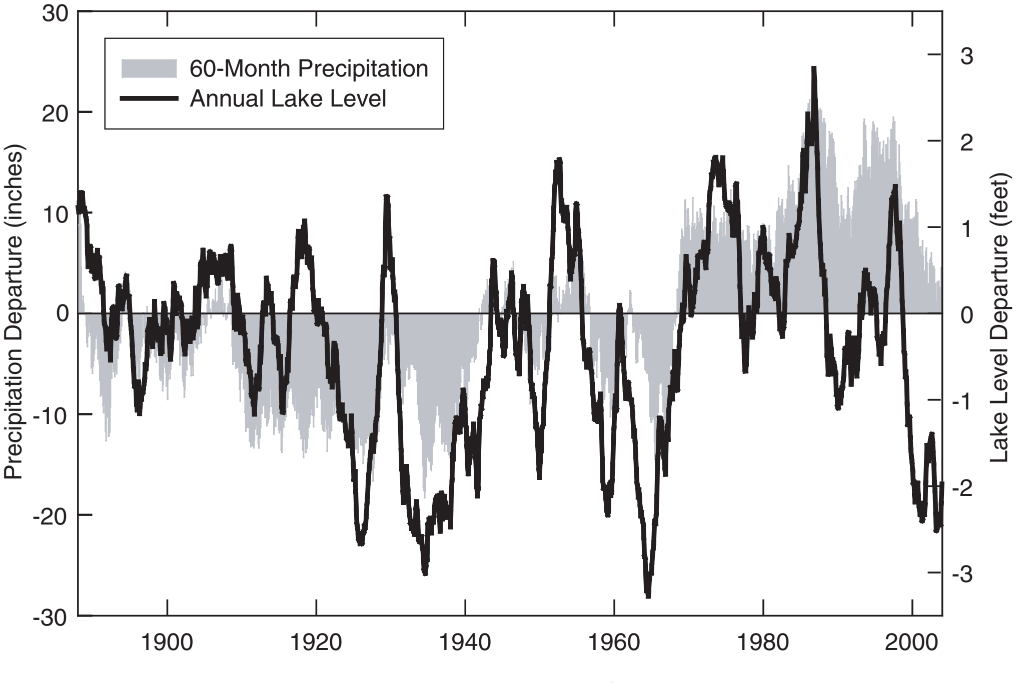

Figure B-5. Michigan-Huron Lake-level Departures from 1860-2003 Monthly Averages and Michigan-Huron Basin 60-Month Precipitation Running Mean Departures Derived from data by Croley and Hunter (1994). Precipitation Data are Available from 1883-2003, and 60-Month Departure Values are Placed in the End Month of each Period Against the Lake-level Departure that Month.

evident in the graph of the two time series (Figure B-6), although prior to 1970, temperature and lake level were not always locked into the same negative phase. Temperatures may have been important in enhancing lake level variations in cooperation with precipitation variations of opposite sign during the 1920s and 1930s especially.

The highest temperatures since 1895 correspond with recent low lake levels of 1999-2003, indicating that higher evaporation may be important in explaining low lake levels, which occurred despite above normal precipitation during the period. The evaporative component of the net basin supply calculated using the GLERL net basin supply model (Croley and Hunter, 1994) indicates much larger magnitudes of positive departure from the long-term average since the early 1970s (Figure B-7), due mostly to the direct effect of air temperatures on lake levels. The role of temperature in lowering the lake levels in this latest low stand appears to be unprecedented in the 150 years of observational history (Assel et al. 2004). These findings have implications for future lake levels, especially if anomalously warm episodes like the early 2000s become more common and correspond to periods with below normal precipitation.

Integrating all precipitation and temperature factors, the net basin supply is a modeled variable that should have a high correlation with lake levels. The annual net basin supply acquired from GLERL for the 1954-2002 period (Croley and Hunter, 1994; personal communication, Tim Hunter, GLERL, May 4, 2004) was accumulated for 5-year periods, and graphed with

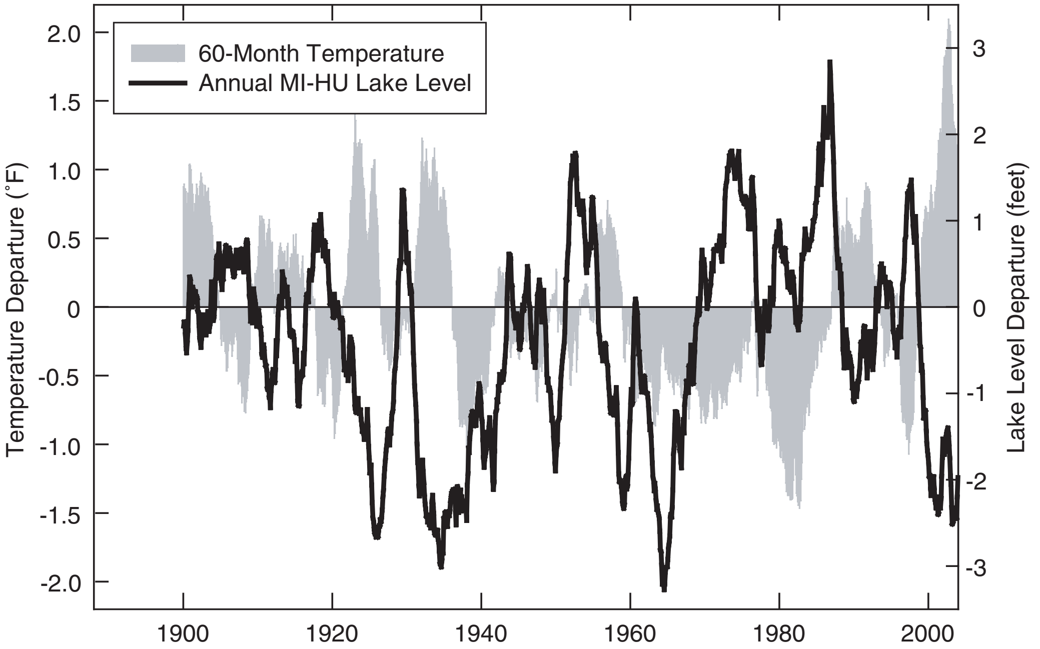

Figure B-6. Michigan-Huron Lake-level Departures from 1860-2003 Monthly Averages and Michigan Basin 60-Month Temperature Running Mean Departures Derived from Karl et al. (1986). Temperature Data are Available from 1895-2003, and 60-Month Departure Values are Placed in the End Month of the Period Against the Lake-level Departure that Month.

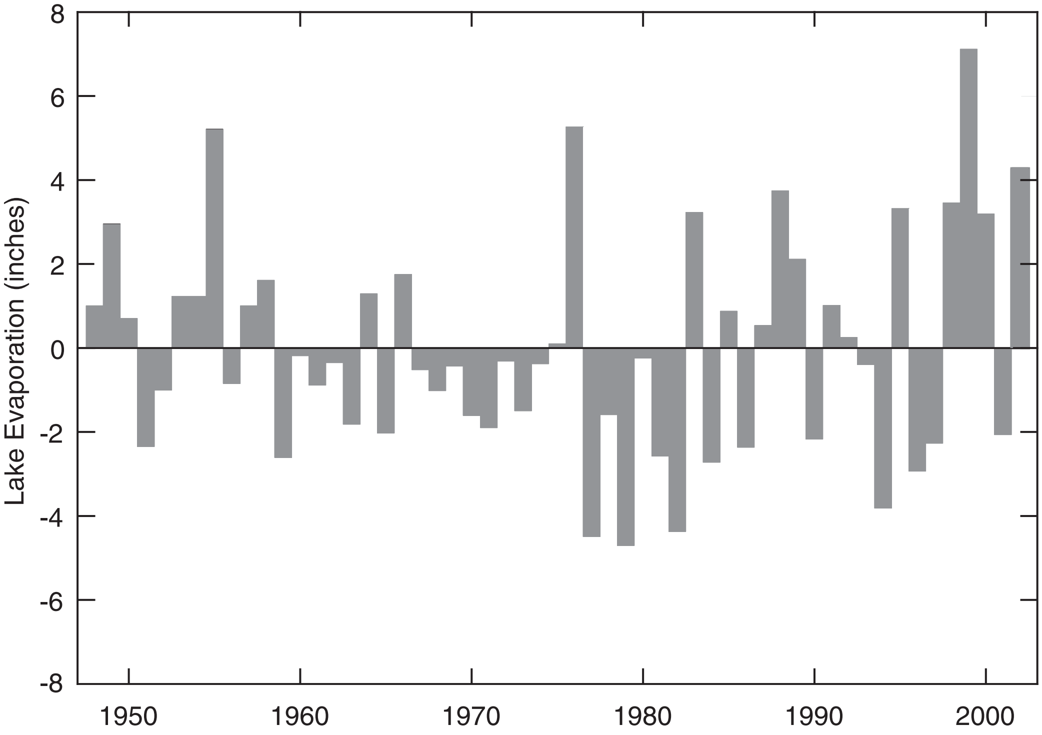

Figure B-7. Annual Evaporative Component for Lake Michigan-Huron in the GLERL Net- Basin-Supply Model (Croley and Hunter, 1994), 1948-2002.

the average level of Lake Michigan-Huron in the last year of each period (Figure B-8). A very strong positive relationship occurs over the period, with 65 percent of the variance in lake levels explained by the net basin supply. Other factors, such as climatically varying inputs from Lake Superior and human-induced changes in outputs would account for much of the unexplained variance in lake levels. Variations in net basin supply appear to correlate negatively over long time-averaging periods with North Atlantic sea-surface temperatures (Figure B-9). With a 5-year averaging period, the explained variance is 57 percent. It appears that the future climate state of the North Atlantic Ocean will be a very important determinant of future Michigan-Huron lake levels.

Conclusions

Historical records show that the level of Lake Michigan-Huron has varied up to 6 feet over the past century and a half in response to climatic fluctuations and human changes. The previous low stands in 1934 and 1964 reached more than 3.0 and 3.3 feet below normal, while the recent low stand reached 2.5 feet below normal in 2003. The 100-year return interval for low lake-level departures from normal is -3.0 feet in mid-summer. Reconstructions from tree rings of lake levels over the last 400 years indicate that the 100-year return interval calculated from observed lake levels is quite robust, having been exceeded only three times over the last 400 years. The key and unique feature of the recent low stand is that it occurred despite near to above

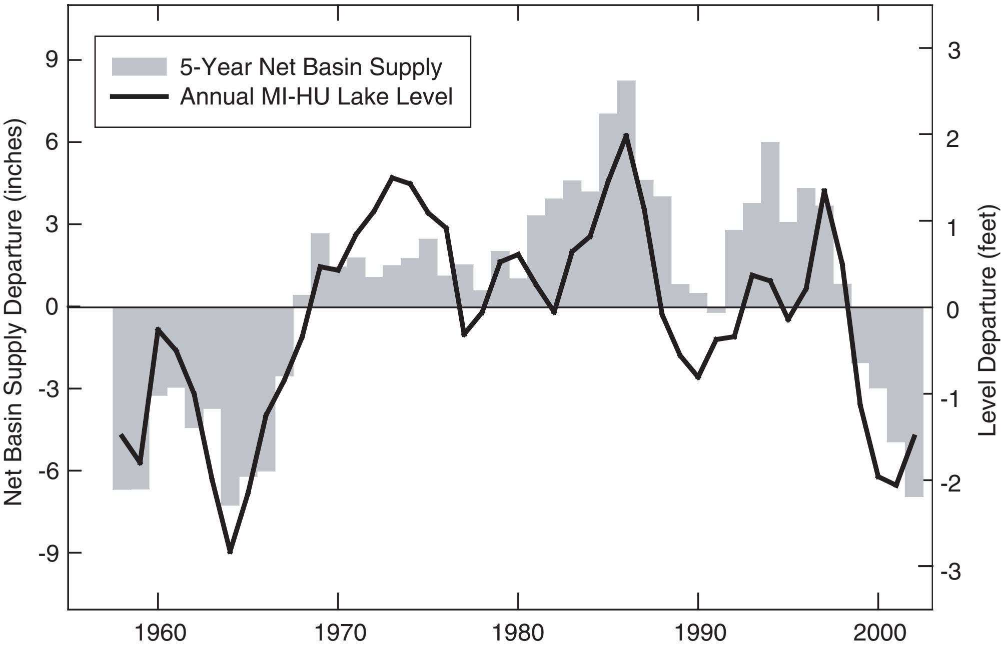

Figure B-8. The Relationship Between the Michigan-Huron Lake-level Annual Departures from 1860-2003 Averages and the 5-Year Average of the Net Basin Supply Calculated by GLERL (Croley and Hunter, 1994). Net Basin-supply Data are Available from 1954-2002, and the 5-Year Average is Placed in the End Year of the Period Against the Annual Lake-level Departure that Year.

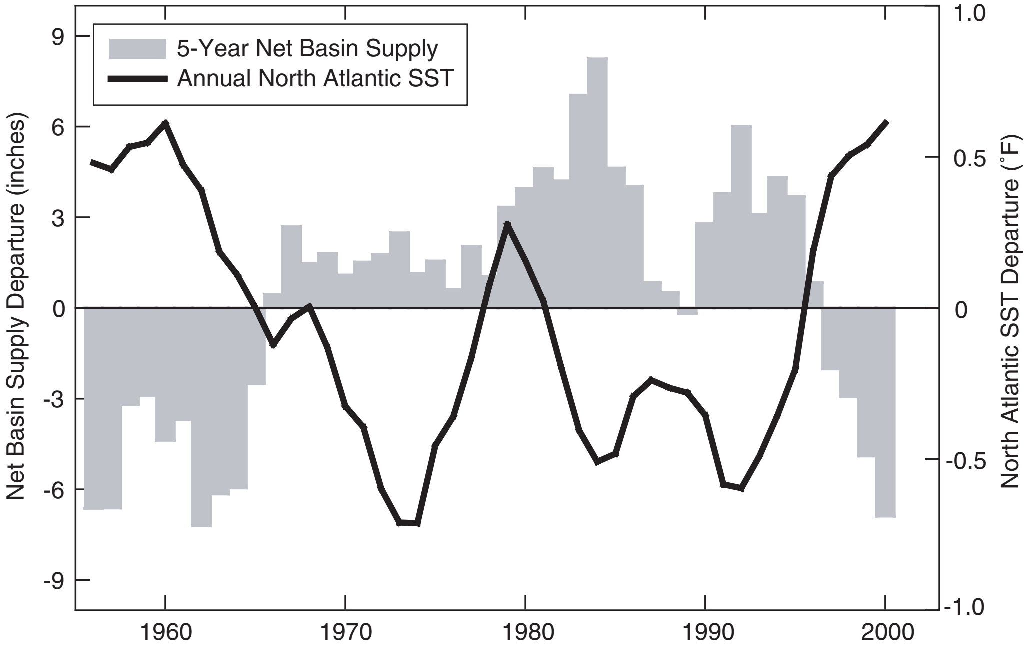

Figure B-9. A Comparison of the 5-Year Average Net Basin-Supply Departure (from Croley and Hunter, 1994) and the North Atlantic Sea-surface Temperature Average. Net Basin-supply Data and Sea-surface Temperature Data are Available from 1954-2002, and the 5-Year Average is Placed in the Center Year of the Period for Both Variables.

normal precipitation during the antecedent period. This indicates the predominance of temperature effects and evaporation in causing this low stand. If a similar high temperature evaporative forcing is combined with a low precipitation episode like in the 1930s, the Michigan-Huron system could well see new record lows beyond 3.3 feet below normal. This eventuality would have very significant impacts on drainage systems, water resources, freight transportation, and the recreation/tourism industry, as well as natural ecosystems.

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Appendix C.
At Risk Community Groundwater Supplies

Appendix C

Community Wells Less Than 100 feet Deep, Within 1000 feet of Another Community Well, and Within 1000 feet of a Recognized Stream

Community Name	County	Well No.	Depth (feet)	Population Served
Community wells < 50 feet deep				
DALZELL	BUREAU	4	19	717
DALZELL	BUREAU	5	18	717
EDINBURG	CHRISTIAN	9	43	1135
EDINBURG	CHRISTIAN	10	44	1135
EDINBURG	CHRISTIAN	11	44	1135
EDINBURG	CHRISTIAN	12	43	1135
EDINBURG	CHRISTIAN	13	40	1135
MORRISONVILLE	CHRISTIAN	4	39	1068
MORRISONVILLE	CHRISTIAN	5	41	1068
ASHMORE	COLES	1	42	806
ASHMORE	COLES	2	44	806
CLEAR WATER SERVICE CORP	COLES	6	36	5400
CLEAR WATER SERVICE CORP	COLES	7	32	5400
GREENUP	CUMBERLAND	5	40	1532
GREENUP	CUMBERLAND	8	40	1532
BONE GAP	EDWARDS	1	47	287
BEECHER CITY	EFFINGHAM	7	33	493
BEECHER CITY	EFFINGHAM	12	38	493
DIETERICH	EFFINGHAM	5	24	600
DIETERICH	EFFINGHAM	10	25	600
FAYETTE WATER COMPANY	FAYETTE	2	47	2000
FAYETTE WATER COMPANY	FAYETTE	3	44	2000
FAYETTE WATER COMPANY	FAYETTE	4	40	2000
LONDON MILLS	FULTON	2	25	447
LONDON MILLS	FULTON	3	28	447
MINOOKA	GRUNDY	7	42	4500
DALLAS RURAL WATER DISTRICT	HENDERSON	6	42	3000
PLANO	KENDALL	3	40	5633
PLANO	KENDALL	4	37	5633
PLANO	KENDALL	5	41	5633
FAIRBURY	LIVINGSTON	1	39	3968
FAIRBURY	LIVINGSTON	5	48	3968
FAIRBURY	LIVINGSTON	7	45	3968
BROADWELL	LOGAN	1	48	150
MOUNT PULASKI	LOGAN	4	34	1800
MOUNT PULASKI	LOGAN	5	32	1800
MOUNT PULASKI	LOGAN	6	39	1800
LA ROSE	MARSHALL	1	47	130
LA ROSE	MARSHALL	2	47	130
SPARLAND	MARSHALL	2	33	550
SPARLAND	MARSHALL	3	34	550
COLCHESTER	McDONOUGH	5	32	1750

Community Name	County	Well No.	Depth (feet)	Population Served
Community wells < 50 feet deep (continued)				
COLCHESTER	McDONOUGH	8	32	1750
COLCHESTER	McDONOUGH	9	34	1750
COLCHESTER	McDONOUGH	12	33	1750
WITT	MONTGOMERY	1	39	991
WITT	MONTGOMERY	2	39	991
WITT	MONTGOMERY	3	37	991
WITT	MONTGOMERY	4	39	991
GRIGGSVILLE	PIKE	1	33	1259
GRIGGSVILLE	PIKE	2	33	1259
GRIGGSVILLE	PIKE	4	34	1259
CURRAN-GARDNER PWD	SANGAMON	5	44	4800
DAWSON	SANGAMON	1	36	2220
DAWSON	SANGAMON	3	41	2220
COWDEN	SHELBY	4	32	650
TOWER HILL	SHELBY	4	48	609
TOWER HILL	SHELBY	5	48	609
LAKE WINDERMERE ESTATES SUBD	TAZEWELL	1	32	300

Community Name	County	Well No.	Depth (feet)	Population Served
Community wells from 50 to100 feet deep				
SOUTH WATER INC	ALEXANDER	1	64	1196
SOUTH WATER INC	ALEXANDER	2	64	1196
HARDIN	CALHOUN	3	79	1000
HARDIN	CALHOUN	4	77	1000
KAMPSVILLE	CALHOUN	2	52	400
KAMPSVILLE	CALHOUN	3	54	400
CHANDLERVILLE	CASS	3	65	704
CHANDLERVILLE	CASS	4	60	704
CASEY	CLARK	11	76	3831
CASEY	CLARK	12	82	3831
CASEY	CLARK	13	78	3831
MARSHALL	CLARK	3	70	4600
MARSHALL	CLARK	4	73	4600
AVISTON	CLINTON	1	74	1231
AVISTON	CLINTON	2	67	1231
ROBINSON PALESTINE WATER COMM	CRAWFORD	10	84	11317
ROBINSON PALESTINE WATER COMM	CRAWFORD	11	87	11317
ROBINSON PALESTINE WATER COMM	CRAWFORD	13	76	11317
ROBINSON PALESTINE WATER COMM	CRAWFORD	14	81	11317
ROBINSON PALESTINE WATER COMM	CRAWFORD	15	76	11317
ARTHUR	DOUGLAS	7	92	2283
ARTHUR	DOUGLAS	8	50	2283
ARTHUR	DOUGLAS	9	50	2283
VERMILION	EDGAR	1	55	300
VERMILION	EDGAR	2	55	300
BONE GAP	EDWARDS	2	92	287

Community Name	County	Well No.	Depth (feet)	Population Served
Community wells from 50 to100 feet deep (continued)				
AVON	FULTON	1	63	900
AVON	FULTON	2	85	900
AVON	FULTON	3	98	900
NEW HAVEN	GALLATIN	1	60	459
NEW HAVEN	GALLATIN	2	57	459
KANE	GREENE	1	57	500
KANE	GREENE	2	57	500
BOOKWALTER WOODS MHP	GRUNDY	2	100	380
BOOKWALTER WOODS MHP	GRUNDY	3	60	380
BOOKWALTER WOODS MHP	GRUNDY	4	60	380
MINOOKA	GRUNDY	6	50	4500
PLYMOUTH	HANCOCK	1	57	562
PLYMOUTH	HANCOCK	2	58	562
DALLAS RURAL WATER DISTRICT	HENDERSON	4	62	3000
DALLAS RURAL WATER DISTRICT	HENDERSON	5	57	3000
GENESEO	HENRY	25	57	6500
GENESEO	HENRY	26	60	6500
MILFORD	IROQUOIS	7	78	1369
MILFORD	IROQUOIS	8	80	1369
E J WATER CORPORATION	JASPER	1	54	10248
E J WATER CORPORATION	JASPER	2	52	10248
E J WATER CORPORATION	JASPER	3	57	10248
SAINT MARIE	JASPER	3	51	262
GRAFTON	JERSEY	101	80	850
GRAFTON	JERSEY	102	76	850
JERSEYVILLE	JERSEY	1	96	10000
JERSEYVILLE	JERSEY	2	99	10000
JERSEYVILLE	JERSEY	3	93	10000
MONTGOMERY	KANE	10	82	14500
MONTGOMERY	KANE	11	59	14500
GALESBURG	KNOX	100	90	33706
GALESBURG	KNOX	102	97	33706
LA SALLE	LA SALLE	4	58	9700
LA SALLE	LA SALLE	6	56	9700
LA SALLE	LA SALLE	9	63	9700
LA SALLE	LA SALLE	10	68	9700
LA SALLE	LA SALLE	11	64	9700
BIRDS-PINKSTAFF WATER DISTRICT	LAWRENCE	1	82	715
BIRDS-PINKSTAFF WATER DISTRICT	LAWRENCE	2	82	715
FAIRBURY	LIVINGSTON	3	57	3968
FAIRBURY	LIVINGSTON	4	52	3968
BROADWELL	LOGAN	2	53	150
BROADWELL	LOGAN	4	52	150
ILLINOIS AMERICAN WATER CO - LINCOLN	LOGAN	11	50	15200
ILLINOIS AMERICAN WATER CO - LINCOLN	LOGAN	12	50	15200
ILLINOIS AMERICAN WATER CO - LINCOLN	LOGAN	14	54	15200
ILLINOIS AMERICAN WATER CO - LINCOLN	LOGAN	16	52	15200
ILLINOIS AMERICAN WATER CO - LINCOLN	LOGAN	18	54	15200
COLLINSVILLE	MADISON	9	98	29500
COLLINSVILLE	MADISON	11	100	29500

Community Name	County	Well No.	Depth (feet)	Population Served
Community wells from 50 to100 feet deep (continued)				
EAST ALTON	MADISON	21	92	6695
EAST ALTON	MADISON	24	90	6695
EAST ALTON	MADISON	25	97	6695
EAST ALTON	MADISON	26	100	6695
EAST ALTON	MADISON	27	100	6695
EAST ALTON	MADISON	28	96	6695
MARYVILLE	MADISON	1	100	9000
MARYVILLE	MADISON	3	99	9000
WOOD RIVER	MADISON	1	79	12750
HENRY	MARSHALL	3	62	2540
HENRY	MARSHALL	4	74	2540
LACON	MARSHALL	2	50	1979
LACON	MARSHALL	3	50	1979
LACON	MARSHALL	4	60	1979
COLCHESTER	McDONOUGH	6	68	1750
HEYWORTH	McLEAN	1	62	2431
HEYWORTH	McLEAN	2	59	2431
HEYWORTH	McLEAN	3	50	2431
NORMAL	McLEAN	9	90	37509
NORMAL	McLEAN	10	57	37509
ATHENS	MENARD	3	53	4350
ATHENS	MENARD	4	57	4350
TALLULA	MENARD	3	52	900
TALLULA	MENARD	4	52	900
BETHANY	MOULTRIE	6	68	1320
BETHANY	MOULTRIE	7	63	1320
DALTON CITY	MOULTRIE	2	78	581
DALTON CITY	MOULTRIE	3	79	581
FAWN HILLS SUBD	PEORIA	1	95	175
FAWN HILLS SUBD	PEORIA	2	95	175
NEBO	PIKE	2	52	435
NEBO	PIKE	3	58	435
PEARL	PIKE	3	62	180
PEARL	PIKE	4	63	180
RED BUD	RANDOLPH	101	67	3100
RED BUD	RANDOLPH	102	65	3100
CURRAN-GARDNER PWD	SANGAMON	1	50	4800
CURRAN-GARDNER PWD	SANGAMON	4	55	4800
DAWSON	SANGAMON	2	54	2220
DAWSON	SANGAMON	5	54	2220
PLEASANT PLAINS	SANGAMON	2	60	1236
PLEASANT PLAINS	SANGAMON	3	61	1236
PLEASANT PLAINS	SANGAMON	4	61	1236
BLUFFS	SCOTT	3	59	748
BLUFFS	SCOTT	4	60	748
BLUFFS	SCOTT	6	70	748
COWDEN	SHELBY	2	54	650
COWDEN	SHELBY	3	53	650
HERRICK	SHELBY	1	78	524
HERRICK	SHELBY	2	80	524

Community Name	County	Well No.	Depth (feet)	Population Served
Community wells from 50 to100 feet deep (concluded)				
SHELBYVILLE	SHELBY	4	59	6681
SHELBYVILLE	SHELBY	5	61	6681
STEWARDSON	SHELBY	1	50	770
STEWARDSON	SHELBY	3	52	770
EAST PEORIA	TAZEWELL	25	63	22638
EAST PEORIA	TAZEWELL	28	66	22638
GROVELAND TOWNSHIP WATER DISTRICT	TAZEWELL	1	84	2430
GROVELAND TOWNSHIP WATER DISTRICT	TAZEWELL	2	85	2430
LAKE WINDERMERE ESTATES SUBD	TAZEWELL	3	55	300
ANNA-JONESBORO WATER COMM	UNION	2	81	99
ANNA-JONESBORO WATER COMM	UNION	3	80	99
ANNA-JONESBORO WATER COMM	UNION	4	83	99
ANNA-JONESBORO WATER COMM	UNION	6	82	99
MOUNT CARMEL	WABASH	1	67	8300
MOUNT CARMEL	WABASH	2	67	8300
MOUNT CARMEL	WABASH	3	70	8300
GRAYVILLE	WHITE	1	68	2194
GRAYVILLE	WHITE	3	73	2194
GRAYVILLE	WHITE	4	72	2194
NEARTOWN MHP	WINNEBAGO	1	50	85
RIVERVIEW MHP	WINNEBAGO	3	60	214
ROANOKE	WOODFORD	3	52	1994
ROANOKE	WOODFORD	5	51	1994

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