Potential Impacts of Climate Change on Water Availability

Introduction

Climate is a key factor in water supply planning (http://www.sws.uiuc.edu/wsp/climate/ClimateFactors.asp). Precipitation, in particular, greatly influences the amount of water flowing through the water cycle (http://www.sws.uiuc.edu/wsp/watercycle/) and, consequently, water availability. In general, the higher the precipitation, the more water is available. Low precipitation and droughts generally reduce water supply.

Temperature also influences water availability. The higher the temperature, the greater the amount of water that is lost from the Earth's surface and returned to the atmosphere through evaporation and transpiration, collectively known as evapotranspiration.

Historic climate and hydrological records are used as a solid basis for quantifying relationships between climate changes and the amount of water in rivers and aquifers. Projecting future climate and hydrological conditions, especially those modified by human influences such as an enhanced greenhouse effect, however, is highly uncertain.

Long-range water supply planning requires selecting a future time frame for conducting analyses. Two regional planning groups in northeastern and east-central Illinois selected 2050 as the time horizon for planning studies. Recognizing inherent uncertainties, the Illinois State Water Survey (ISWS) has chosen to construct future climate, water availability, and water demand scenarios rather than make firm predictions or forecasts.

Scenario analyses of the sensitivity of water availability and demand to climate change will provide estimates of how much more or less water will be available on the surface and in aquifers, and how much more or less water will be needed by consumers if climate changes by specified amounts.

Climate, water availability, and water demand scenarios are based on a set of specified reasonable assumptions about the future, including population and economic growth. Planners must understand these assumptions and plan for the future, recognizing great uncertainties. Strategic planning must be a process of risk assessment leading to risk management.

ISWS scenarios to 2050 are based on the assumption that climatic conditions experienced from 1971 to 2000 (the period for which 'normal' climate conditions are calculated) will continue into the future. These three scenarios include (1) a current trend scenario; (2) a higher-demand scenario; and (3) a lower-demand or conservation scenario.

In addition, Wittman Hydro Planning Associates, Inc. and Professor Ben Dziegielewski at Southern Illinois University will provide sensitivity analyses on the current-trend water demand scenario to 2050. The following climate scenarios will be used in the water availability and water demand studies:

- An increase in temperature from 1971-2000 normal conditions ranging from 0^oF to $+6^oF$
- A change in annual precipitation from 1971-2000 normal ranging from -5 inches to +5 inches

Combinations of these climate scenarios will be used to produce scenarios of Lake Michigan water level and possible impacts on surface water and groundwater quantities. Water demand studies for northeastern and east-central Illinois will be completed in the spring of 2008 and draft water availability studies will be available in October 2008.

This report addresses the importance of climate in water-supply planning, the nature of climate variability and change, and uncertainties in assessing possible future climatic conditions. It also explains why water supply planners must consider a range of possible future climatic conditions.

Before addressing complex human factors, we start with historical records that provide evidence of primarily natural forces on climate and hydrology. We reasonably assume that whatever climate and hydrological conditions have occurred in the past can recur in the future. This approach gives us one way of identifying potential future climate changes and their affects. We then move on to examine output from computerized mathematical global climate models that include human influences on climate.

Definitions of Climate, Climate Variability, and Climate Change

Climate

Climate is the aggregate of weather conditions that represents the varying aspects of the atmosphere-hydrosphere-land surface climate system over the earth. Climate varies over time in any one geographical area and also varies from one geographical area to another.

Typically, climate is characterized in terms of averages of climate elements over periods of a month or more. Beginning with the view of local climate as little more than the annual course of long-term averages of surface temperature and precipitation, the concept of climate has broadened and evolved in recent decades in response to increased understanding of the underlying processes that determine climate and its variability.

Climate variability and change can be understood in the context that the atmosphere and oceans are fluids that interact with each other and are influenced by conditions on the earth’s surface. Oceans and the atmosphere transport heat and moisture over the globe in such a way that climate conditions in one area are linked to climate conditions in other, often distant, areas. These distant climate connections are called teleconnections.

Important mechanisms linking world climates are ocean currents and jet streams in the atmosphere that transport heat and moisture from one part of the earth to another. Climate models are able to simulate the global climate system and cast light on these teleconnections.

In Illinois, climate is determined not only by its location in the middle of a large continent, but also by conditions in and over, for example, the Atlantic and Pacific Oceans. Most precipitation in Illinois comes from moisture that is transported northward from the Gulf of Mexico. Precipitation and temperature in Illinois also are influenced, for example, by El Niño and La Niña conditions in the equatorial Pacific Ocean and the North Atlantic Oscillation. Illinois climate variations and change are due to conditions in these regions as well as conditions over North America.

For more information about climatic conditions in Illinois, visit the Illinois State Climatologist Office web site, http://www.sws.uiuc.edu/atmos/statecli/index.htm

Climate Variability and Change

Climate varies on time scales ranging from months to millennia. For water supply studies, climate variations from months to centuries are most relevant.

The seasonal cycle is the most regular of all climate variations. Seasonal changes in precipitation and temperature greatly influence variations in streamflow, lake, reservoir, and groundwater levels, and groundwater recharge.

Monthly deviations from long-term average precipitation and temperature can either cancel each other out during the course of a year or accumulate and lead to deviations from the long-term annual average. Deviations from the annual average can either cancel each other out during a decade or lead to a deviation from the long-term decadal average, and so on.

By convention, ‘normal’ climatic conditions are those expressed during the most recent 30-year period (i.e., 1971-2000). In 2011, the climatic normal period will change to 1981-2010.

Climate normals can be set for average monthly, annual, or decadal values. As climatic conditions vary from year to year, climate normals also can include the range and frequency of climatic conditions that can be experienced. In addition, climate normals can include statistics of how frequently heatwaves, cold spells, droughts, floods, hurricanes, and tornadoes occur. It is these climate extremes that often have the greatest impacts.

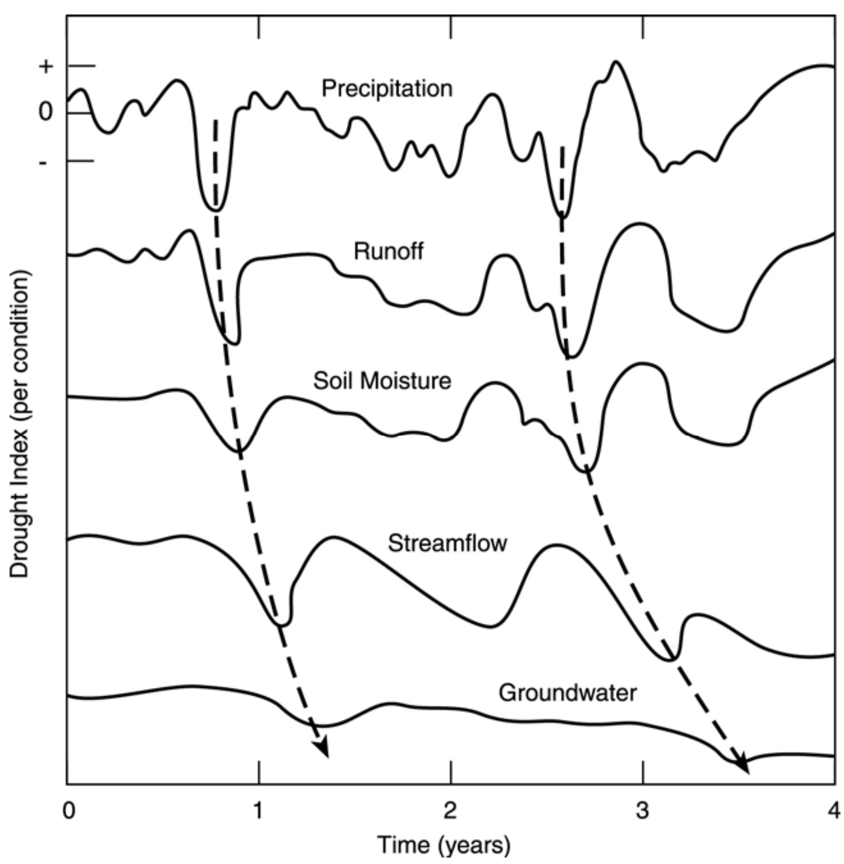
Climate change is any systematic and statistically significant change in the long-term statistics of climate elements, such as precipitation, temperature, pressure, or winds, sustained over several decades or longer. Thus, climate change can be an expression of changes in long-term average precipitation or temperature, and/or changes in the frequency of extreme climate events. A wet or warm 10-year period would not be sufficient to be classified as climate change.

Climate change may be due to natural external factors, such as changes in the emission of solar radiation or slow changes in the Earth's orbital elements, natural internal processes of the Earth's climate system, anthropogenic forcing, such as an increase in the concentration of greenhouse gases, or combinations of these factors.

General Relationships between Climate Variability and Change and Hydrology

Figure 1 (Figure A-3 in Winstanley et al., 2006) shows the effects of hypothetical fluctuations in precipitation over a four-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).

Figure 1. Schematic showing precipitation deficiencies during a hypothetical 4-year period are translated through other physical components of the water cycle



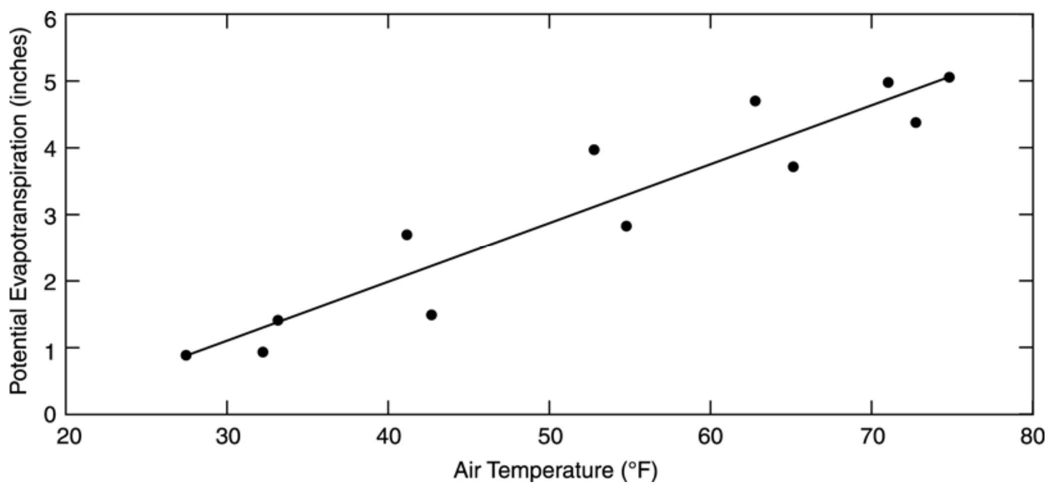
Changnon (2003) used an existing watershed model developed and calibrated on a well instrumented, small, rural basin in central Illinois to estimate the distribution of additional water from three levels of increased summer rainfall simulated to occur during actual sequences of recent dry and wet years. Results showed that about half of the added water percolated into groundwater storage, which would have major benefits because many urban and rural water-supply systems in central Illinois depend on groundwater sources.

In wet years, 35-40% of added water became runoff, compared to 13-22% in dry years. The simulated rain increase, consisting of a 25% increase on moderate to heavy rain days, exhibited the greatest affects on the basin’s hydrologic components. In dry years, 10 to 15% of the additional water went through transpiration, reflecting water use by crops and potential crop yield increases.

Temperature also affects the water budget by its influence on the physical phase of water, evapotranspiration, and 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 reduced.

An approximately linear relationship between 13-year monthly average air temperature and potential evapotranspiration for the period 1992-2004 is shown in Figure 2 (Figure A-7 in Winstanley et al., 2006). Potential evapotranspiration increases approximately 1 inch for each 10^{o}F increase in temperature.

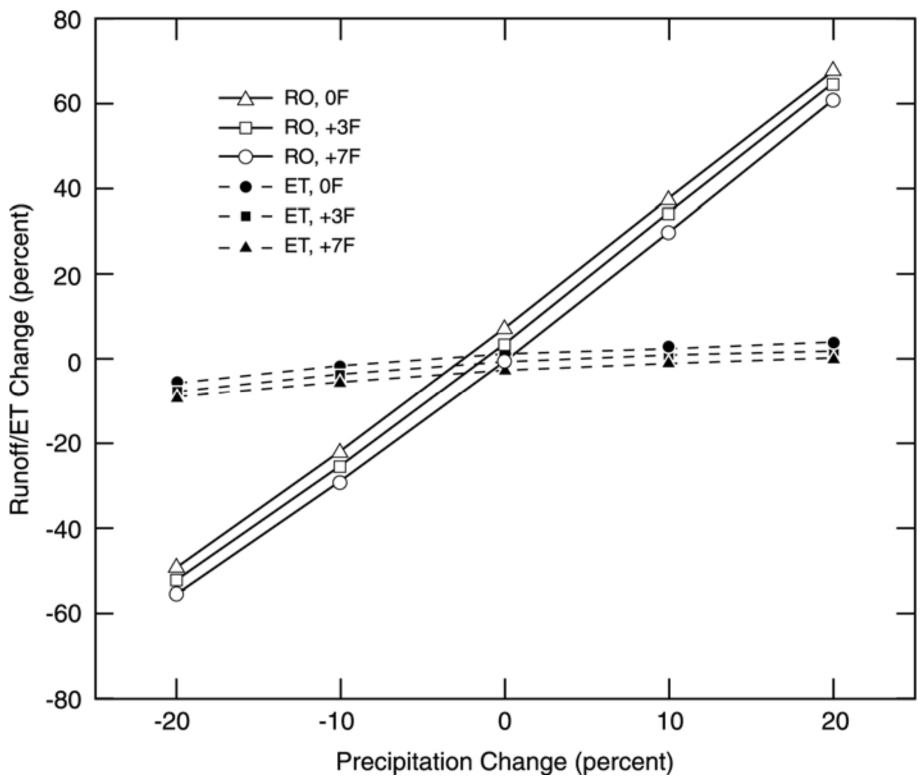
Figure 2. Relationship between 13-year monthly average air temperature and potential evapotranspiration in Illinois, 1992-2004



As the range in annual temperature in Illinois since 1895 is about 7^{o}F and the range in annual precipitation is about 24 inches, it is apparent that precipitation plays a much larger role than temperature in changing water availability from year to year.

Change in runoff and evapotranspiration for various prescribed changes in precipitation and temperature can be derived from a soil-water-balance model and are shown in Figure 3 (Figure A-13 in Winstanley et al., 2006). The figure shows that runoff is very sensitive to precipitation. A 20% decrease in precipitation results in more than a 50% decrease in runoff, and a 20% increase in precipitation results in more than a 60% increase in runoff. Changes in evapotranspiration are less sensitive to precipitation, and neither runoff nor evapotranspiration is as sensitive to temperature as precipitation.

Figure 3. Change in runoff and evapotranspiration for various prescribed changes in precipitation and temperature derived from a soil-water-balance model for Illinois



As a reality check on these calculations, Winstanley et al. (2006) selected the only five-year period in the past 150 years when average annual precipitation was close to 20% below normal. In 1952-1956, average annual precipitation across Illinois averaged 18% below normal. For that five-year period, average annual temperature was 2.1^{o}F above normal. Average annual runoff for Illinois during the five-year period was approximately 48% below normal. 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.

Winstanley et al. (2006) concluded that relationships between precipitation and evapotranspiration or runoff shown in Figure 3 provide a reasonable basis for evaluating first-order affects of changes in precipitation and temperature on streamflow in Illinois.

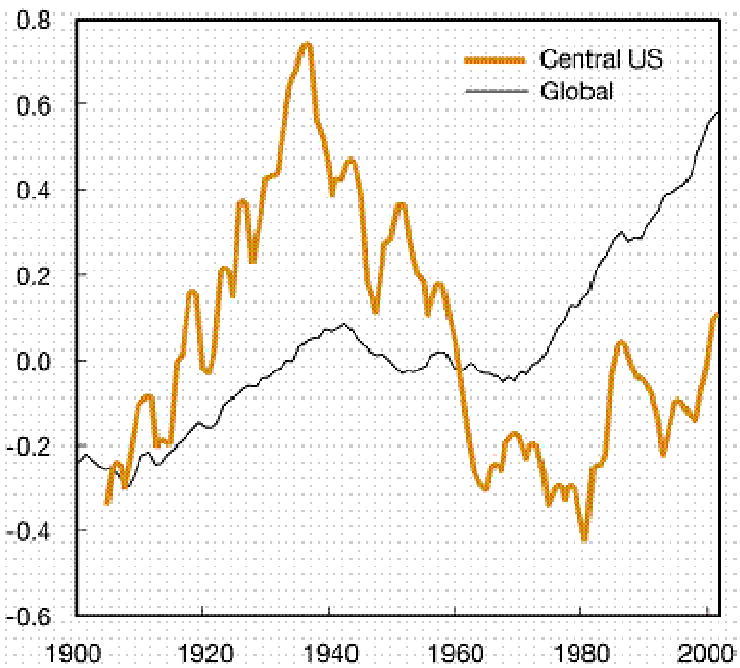
In summer, high evaporation exceeds precipitation and subsurface water storage acts as a moisture source to the atmosphere. Upward movement of water from shallow aquifers outweighs gravity drainage downward, replenishes the root zone soil moisture, and results in a steep decline of the water table.

Precipitation exceeds evaporation the rest of the year and 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. In Illinois, snowmelt in spring has a relatively minor impact on river flow, which peaks then in association with higher precipitation and groundwater levels.

Historical Climate and Hydrological Records in Illinois and the Midwest

The mean annual temperature averaged over the whole Earth has increased significantly during the past century. In Illinois and in much of the east-central U.S., however, the mean annual temperature is cooler than it was in the 1930s, even though the concentration of greenhouse gasses in the atmosphere has increased by about 50%. This fact (Figure 4, Kunkel, Illinois State Water Survey, personal communication, June 7, 2007) illustrates the value of long-term climate records and the complexity of understanding regional climate variations in the context of global climate change.

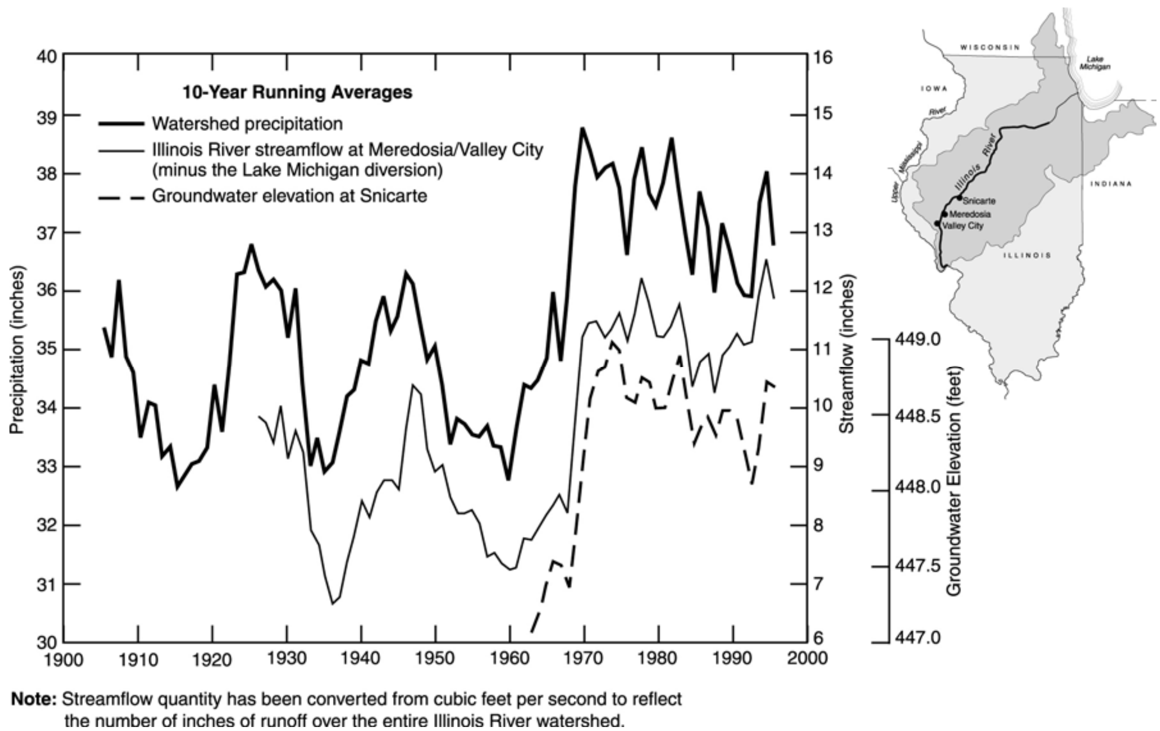
Figure 4. East-central USA temperature changes differ from global trends



Century-scale natural variations in water availability are difficult to determine due to the relatively short length of most observational records of precipitation, streamflow, and groundwater levels. Fortunately, the Midwest is a region with precipitation and hydrologic records extending back 160 years. These records are used to exemplify natural climate variability and change. Human factors may have influenced regional climatic conditions, but we assume that the dominant change agents have been natural. In the twentieth century human influences may have affected regional precipitation and temperature, but we cannot separate these from natural variations (Winstanley and Wendland, 2007: http://www.sws.uiuc.edu/docs/books/ww/WintanleyWendland07.pdf).

Figure 5 (Figure A-14 in Winstanley et al., 2006) shows considerable interdecadal variability in precipitation, streamflow, and shallow groundwater level in the Illinois River Basin over the past century.

Figure 5. The 10-year moving averages of Illinois River watershed precipitation, streamflow (minus Lake Michigan diversion), and groundwater elevation



"As all the components of the water cycle are linked closely, it is not surprising to find that fluctuations in precipitation, streamflow, and shallow groundwater level are highly correlated. In Illinois and across most of the USA, precipitation increased about 10-15 percent over the last century. The Intergovernmental Panel on Climate Change (IPCC) relates the increase in precipitation in mid-latitudes to an increase in the intensity of the water cycle associated with an enhanced greenhouse effect and global warming (Solomon et al., 2007)."

In the Illinois River Basin, precipitation increased about 15% from the 1950s to 1980s, and streamflow increased more than 50%. The modeled relationship between runoff and precipitation for the Illinois River Basin is nearly linear in the range for which observations are available.

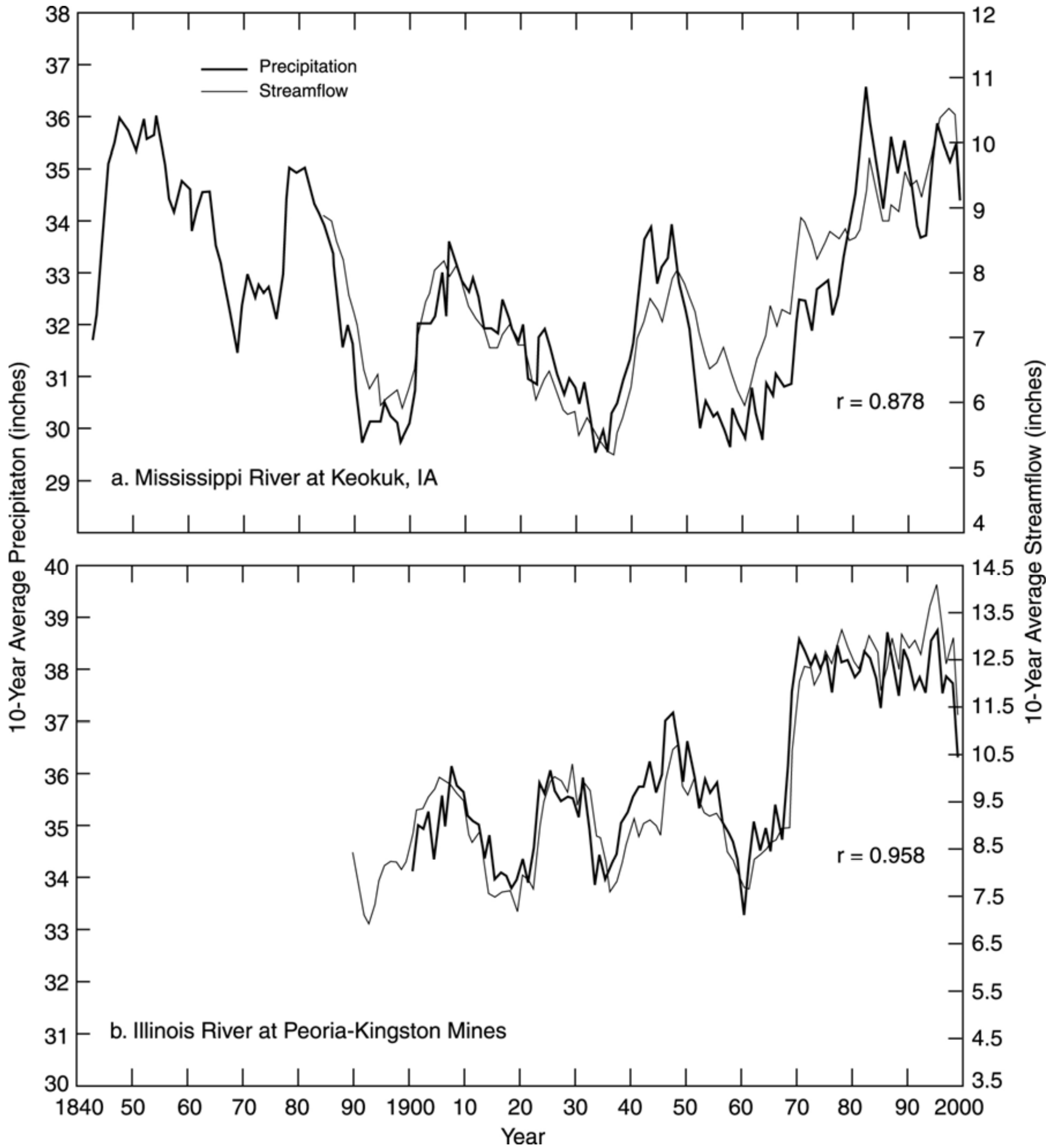
The Illinois State Water Survey maintains long-term records of groundwater levels in shallow wells throughout the state (http://www.sws.uiuc.edu/warm/sgwdata/wells.aspx). Observation wells typically are located in areas remote from pumping, so only natural fluctuations in the water table, undisturbed by pumping, are measured. These data allow scientists to assess both short-term and long-term water table trends.

Groundwater level at Snicarte near the Illinois River rose by about 2 feet from the 1950s to1980s due to an increase in precipitation. Since the 1950s, groundwater level at Snicarte has varied by about 12 feet in response to seasonal and annual climatic conditions (http://www.sws.uiuc.edu/warm/sgwdata/graph.aspx?well=91&name=Snicarte&icn=n&bdate=1/9/1950&edate=1/9/2008). This amount of variation in groundwater level is typical throughout the state.

We do not have continuous groundwater level records prior to the 1950s, but we do have some long-term climate and streamflow records in the region. Records in the Upper Mississippi River Basin arguably provide the best examples of long-term flow records in the United States for studying long-term relationships between climate and streamflow.

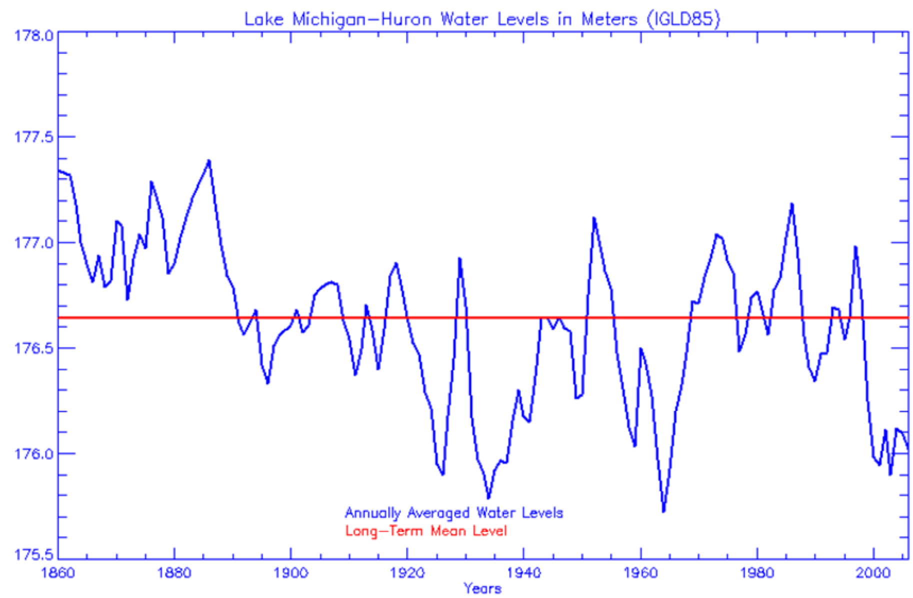
The time series of precipitation and streamflow shown in Figure 6 (Figure A-16 in Winstanley et al., 2006) show that precipitation and streamflow are closely correlated from the 1880s to the present. Knapp (2004) found that the 10-year average correlation coefficient between precipitation and streamflow in the Upper Mississippi River Basin during this time period was 0.878.

Figure 6. 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 this close correlation it can be reasonably assumed that streamflow also closely paralleled precipitation from the 1840s to the 1880s. It thus appears that precipitation and streamflow were as high or higher in the mid-nineteenth century as in recent decades. Winstanley and Wendland (2007) concluded that, as there was very little global warming in the mid-nineteenth century, high precipitation and streamflow probably were due to natural factors. High precipitation and streamflow also occurred in the Ohio River Basin in the mid- to late-nineteenth century (Ken Kunkel, Illinois State Water Survey, personal communication, July 5, 2007), and the water level in Lake Michigan was high at this time (Figure 7).

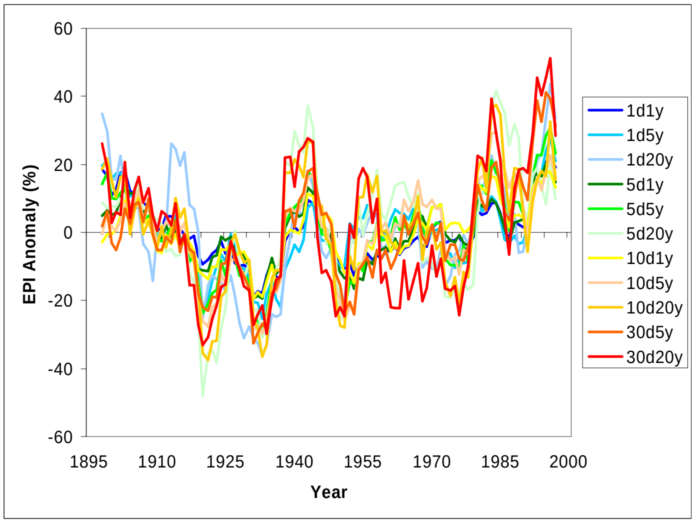
Figure 7. Lake Michigan-Huron water levels (Source: National Oceanic Atmospheric Administration, Great Lakes Environmental Research Laboratory)



In the Upper Mississippi River Basin it appears that precipitation decreased by about 14% from the 1840s to the 1930s and streamflow decreased by about 45%. These trends were reversed over the subsequent 70 years.

The frequency of heavy precipitation events also appears to have changed systematically during a 160-year period. Figure 8 shows that across the U.S., the frequency of heavy precipitation events with varying durations and return periods was low during the low precipitation years of the 1920s and 1930s and increased as precipitation increased during the past 70 years (Kunkel, 2003).

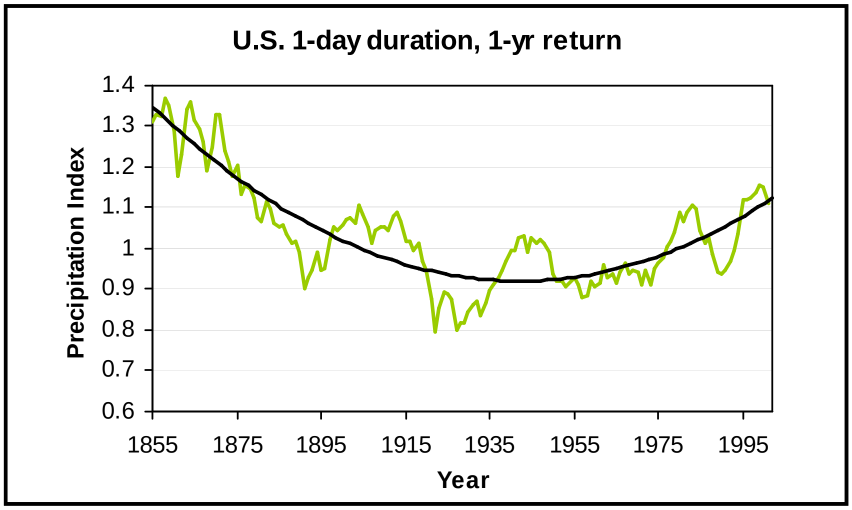
Figure 8. Frequency of heavy precipitation events across the U.S.



This record starts in 1895, but the19th Century Forts and Voluntary Observers Database Build Project of the National Oceanic and Atmospheric Administration (NOAA) Climate Database Modernization Program (CDMP) is allowing a reconstruction of earlier climatic conditions. The Midwestern Regional Climate Center at the Illinois State Water Survey is collaborating with the National Climatic Data Center to extend the digital climate record and is analyzing severe climate events during the nineteenth century.

Preliminary data from this new database (Figure 9) indicate that the frequency of 1-day/1-year heavy precipitation events was much higher across the U.S. during the mid-nineteenth century (Ken Kunkel and James Angel, Illinois State Water Survey, personal communication, July 5, 2007).

Figure 9. U.S. 1-day duration, 1-year return



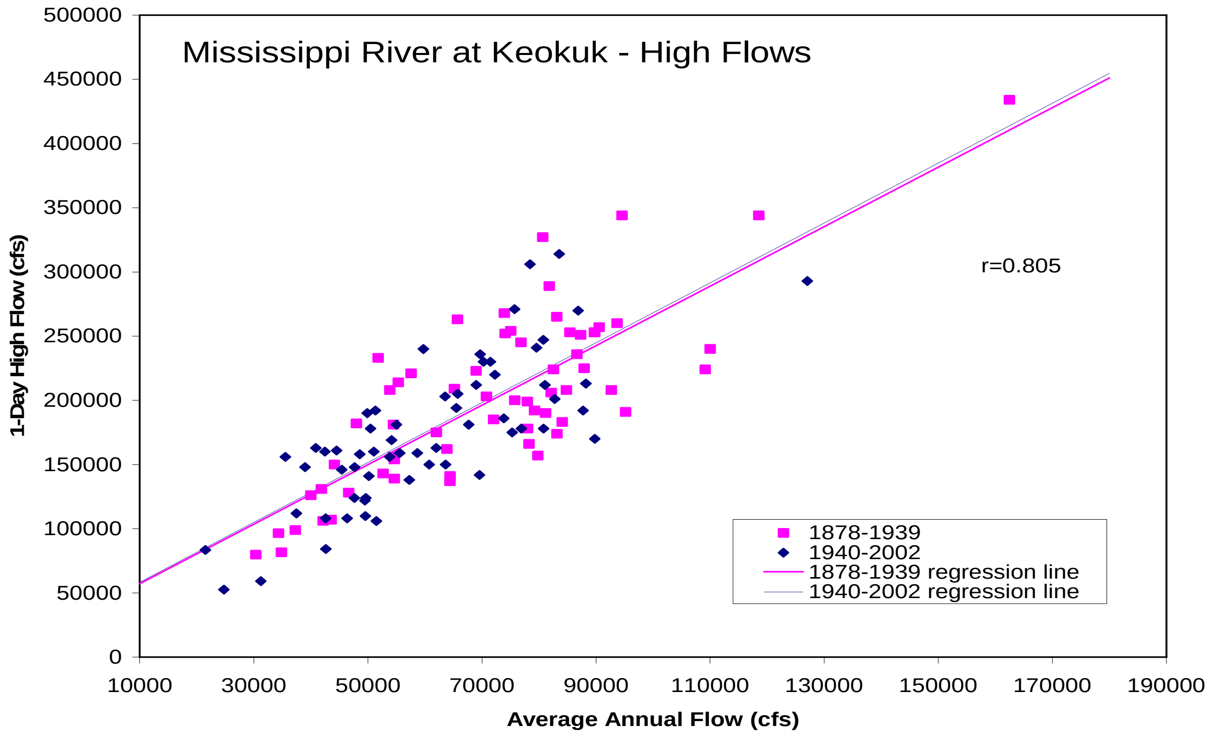
As Figure 8 shows that other heavy precipitation events have followed closely the 1-day/1-year heavy precipitation events since 1895, it is reasonable to assume that they also have followed changes in the 1-day/1-year events since the 1850s. If this is true, then all heavy precipitation events from 1-day/1-year to 30-days/20-years were much more frequent during the mid-nineteenth century than any time since.

Since the nineteenth century was relatively cold and there was little enhanced greenhouse effect, one can challenge the IPCC interpretation that the twentieth century precipitation increase in mid-latitudes can be attributed to an increase in the intensity of the water cycle associated with an enhanced greenhouse effect (Solomon et al., 2007). In the Midwest, it appears that higher precipitation, a greater frequency of heavy precipitation events, and higher streamflow occurred in the nineteenth century with an intensified water cycle. From these historical records it can be concluded that intensification of the water cycle is not necessarily caused by an enhanced greenhouse effect and warmer temperatures.

The IPCC did not produce reconstructions of precipitation and streamflow in the nineteenth century and, hence, did not have the advantage of evaluating twentieth century climate changes in the context of longer-term natural changes in climate.

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, major hydrologic droughts and lowest flow events occurred in 1890 to 1970, when average precipitation and streamflow were well below the long-term average. Figure 10 shows a linear relationship between the average annual flow of the Upper Mississippi River at Keokuk and the 1-day high flow over the period 1878 to 2002. The lowest 1-day high flows occur in dry years and the highest 1-day high flows occur in wet years.

Figure 10. Relationship between the average annual flow and the 1-day high flow, Mississippi River at Keokuk, 1878-2002 (Knapp, 2004)



These records provide evidence of a high degree of natural variability in the regional climate system. The dominant signal in the regional precipitation and hydrological records since the 1840s in an area from the Tennessee and Kanawha Rivers across Illinois to the Upper Mississippi River has been a 160 oscillation from wet to dry and a return to wet conditions. In a study of the Great Lakes levels during the past 4,700 years, Wilcox et al. also noted that high lake levels occurred in longer quasi-periodic cycles of about 160 years (http://www.climatescience.gov/workshop2005/posters/P-CO2.5_Wilcox.pdf).

Future Climate

The Past as a Guide to the Future

Under the assumption that past climate conditions can recur in the future, the range of possible future climatic conditions is broad, even before an enhanced greenhouse effect is considered.

In Illinois, Winstanley and Wendland (2007) reported from a purely statistical analysis of historical records that annual precipitation could be as low as 25 inches, which is about 34 percent below the 1971-2000 'normal' of 38 inches, or as high as 54 inches, which is about 42 percent above 'normal.' There even could be a 10-year drought, similar to that which occurred in the sixteenth century (Winstanley et al., 2006). Heavy precipitation events could increase by 30% or decrease by 20%.

The 2005 drought in Northern Illinois and the current near-record low level of Lake Michigan (http://www.lre.usace.army.mil/_kd/Items/actions.cfm?action=Show&item_id=3887&destination=ShowItem) raise the question of whether the 160-year oscillation is again on the downturn. Annual precipitation in Northeastern Illinois peaked in the 1990s and has since declined, although summer precipitation still shows an upward trend, as evident in the heavy precipitation and floods of 2007 (Figures 11 and 12, respectively). At this point, it is impossible to determine whether historical trends will continue or be reversed, or whether natural variability or global warming, or a combination of the two, is the cause of precipitation changes in Illinois.

Figure 11. Northeast Illinois annual precipitation (Source: James Angel, Illinois State Water Survey, personal communication, October 12, 2007)

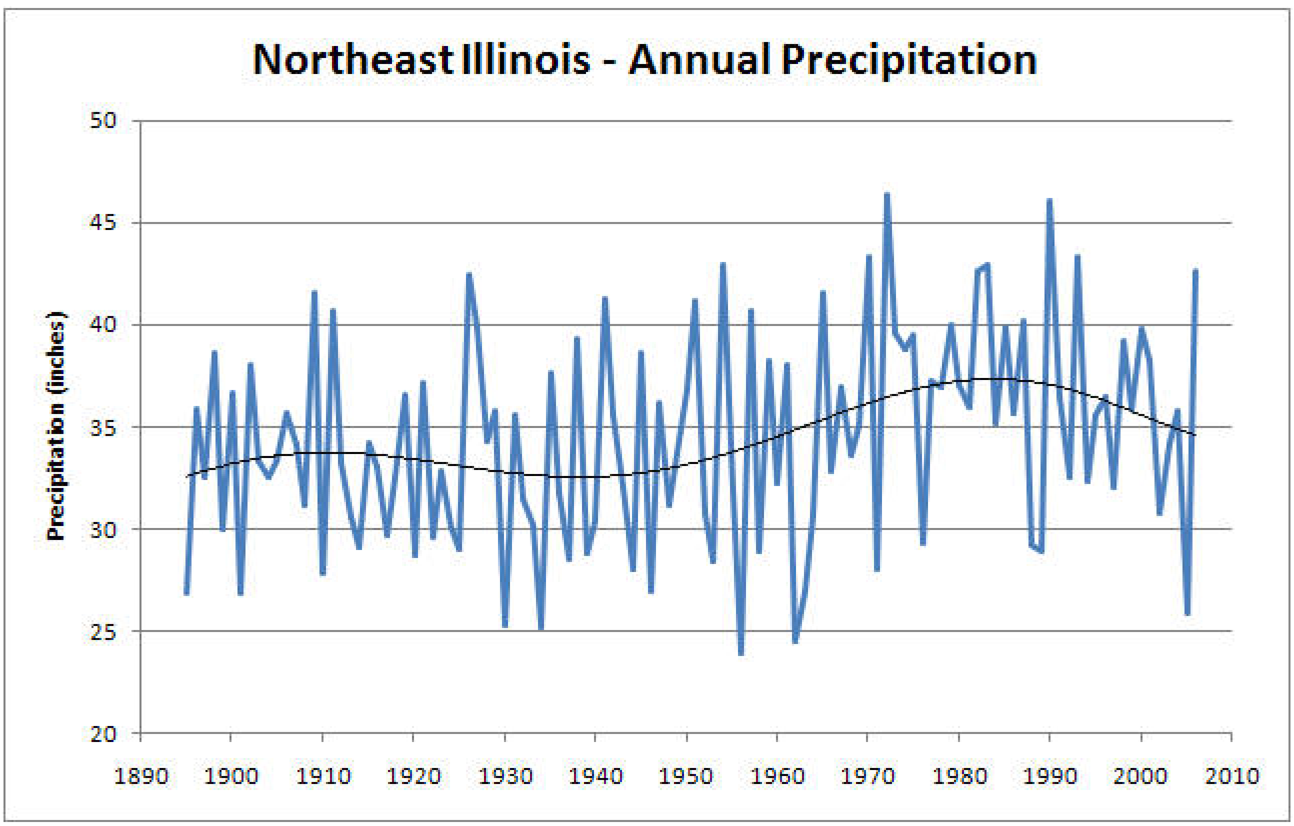
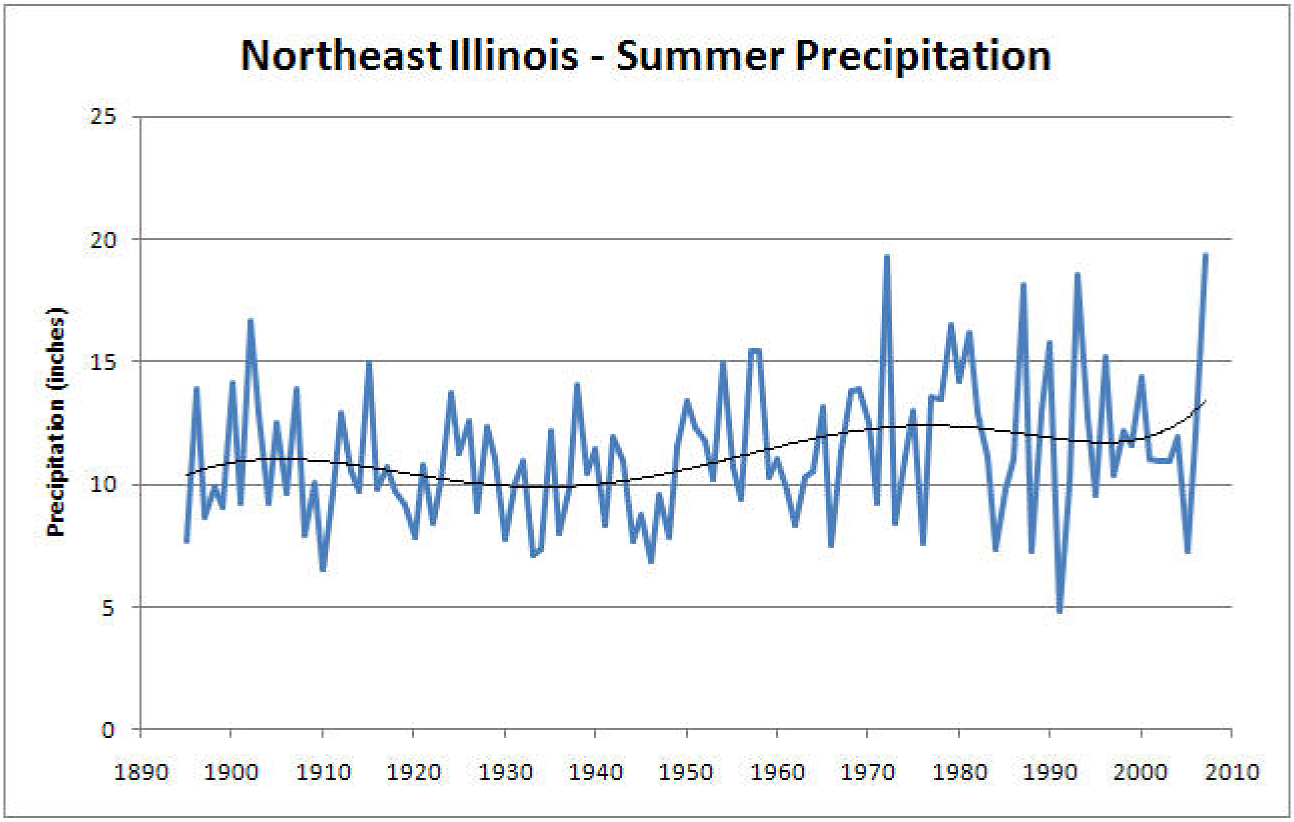


Figure 12. Northeast Illinois Summer Precipitation (Source: James Angel, Illinois State Water Survey, personal communication October 12, 2007)



Climate Model Scenarios

With an enhanced greenhouse effect and global warming, global climate models suggest that mean annual temperature in Illinois could increase by up to 12^{o}F by the end of the twenty-first century and mean annual precipitation could increase or decrease by some 9 or 10 inches. Other models suggest that mean annual temperature could increase by only 2^{o}F and precipitation would not change significantly.

Figure 13 shows the 5th and 95th percentiles of 140 global model runs from 21 global climate models driven by a range of scenarios derived by Illinois State Water Survey scientists using the latest set of global climate model simulations produced for the IPCC’s Fourth Assessment Report. The modeling groups produced simulations for three different scenarios about how emissions may change in the future: moderately high scenario (denoted as ‘A2’), an intermediate scenario (denoted as ‘A1B’), and a low scenario (denoted as “B1”).

Figure 13. Illinois annual temperature departure from 1971-2000 normal

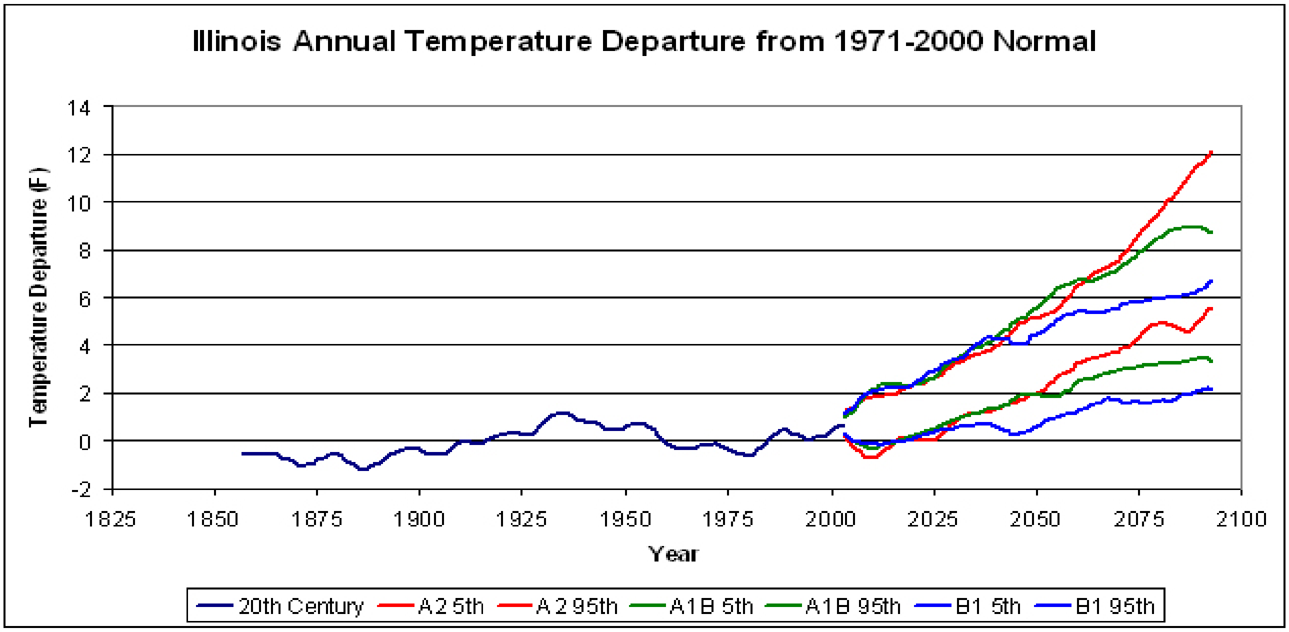
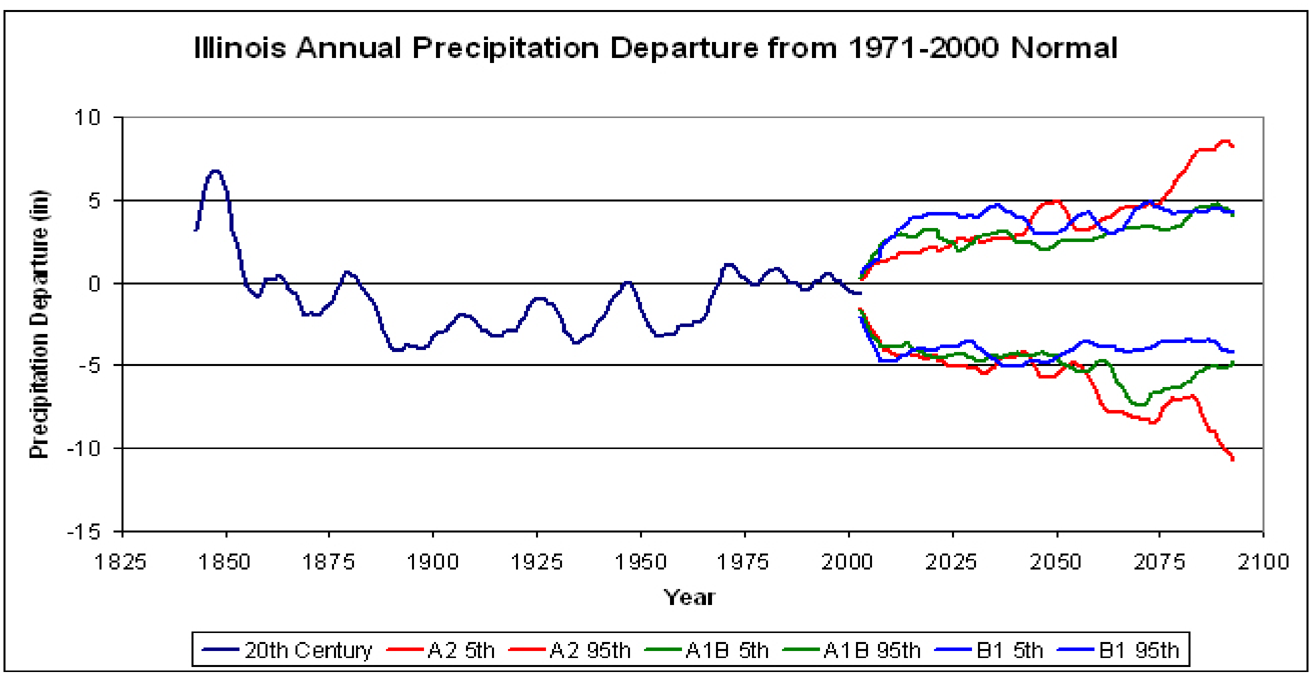


Figure 14 shows that precipitation in Illinois could either increase or decrease by 9 to 10 inches by the end of the century. Precipitation scenarios show little dependence on emissions scenarios and the concentration of greenhouse gases in the atmosphere.

Figure 14. Illinois annual precipitation departure from 1971-2000 normal



Perhaps the major weakness of global climate models is their difficulty in simulating clouds and precipitation. As a result, there is considerable uncertainty in the direction and magnitude of possible future precipitation changes over a high percentage of the Earth (Wigley, 2002).

Uncertainties in Climate Change and Impacts of Climate Change on Water Availability

Scientists cannot predict future Illinois climatic conditions with confidence. The historical climate and hydrological records since the nineteenth century show that climate has changed significantly in the past and, even without human interference, could change significantly in the future. More than 20 global climate models produce a wide range of future climatic conditions depending on the models' structure, assumptions about future greenhouse gas emissions and land-cover changes, and initial conditions when the model runs are started. Possible future natural and human-modified climate conditions range widely.

A consequence of large uncertainties in future climatic conditions at the regional scale is that there are large uncertainties in future hydrological conditions and water availability. It is difficult for water supply planners and managers to accommodate such a large range of uncertainties. Realistically, it would be expensive to provide water-supply infrastructure that could provide adequate water supplies under scenarios of mean annual precipitation increasing or decreasing by 10 inches by 2100. This is not the same as a drought with one-year precipitation 10 inches below average.

We are faced with a situation in which mean annual precipitation in Illinois could decrease from 38 inches to 28 inches and droughts could diminish precipitation in any particular year to perhaps 15 inches by the end of the century. We do not know the probability of such occurrences.

Facing such uncertainties, a number of strategies could be considered. The first strategy is for scientists to improve climate models and reduce the magnitude of climate uncertainty. The Illinois State Water Survey is developing an improved climate model that is expected to reduce climate uncertainty and, when applied, hydrological uncertainty (http://www.sws.uiuc.edu/atmos/modeling/caqims/).

The second strategy is for water supply managers to evaluate the capabilities of existing facilities to provide adequate water supplies during severe droughts that have occurred in the past and could recur in the future. Even in the absence of human-induced climate change, more severe droughts are likely to occur in the future than have occurred in the past 30 years, and it would be wise to be prepared. Currently, the ability of many water-supply facilities to cope with worst-case historical droughts is unknown.

The third strategy would be to evaluate the capabilities of existing facilities to provide adequate water supplies during even more severe droughts that could occur in the future in association with global warming. Difficult decisions will have to be made when constructing new water-supply facilities. Such decisions will have to consider the risks and unknown probabilities of possible climate changes and the high costs of mitigation strategies, as well as the possible high costs of doing nothing.

It would not be wise for water supply managers to base their decisions on the output of one climate model and one set of assumptions of future greenhouse gas emissions. A large number of global climate models running a range of emissions scenarios provides better expression of the uncertain science behind regional climate change. The large range of natural variations and changes in regional climatic conditions also need to be considered.

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