CHAPTER 6

Climate Change and Associated Changes to the Water Budget

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Adequate supplies of clean water are fundamental requirements for human welfare and economic development. Conversely, water shortages and polluted waters limit human and economic growth. Indeed "Water availability may be the most important impact of global warming on human welfare." (Archer, 2007, p 164).

This chapter provides information on what scientists know, and don't know, about the future availability of water under changing climatic conditions. First, the water cycle and water budgets are explained. This is followed by documentation of historical climatic conditions and a look at possible future climatic conditions. The conclusions focus on the challenges to water-supply planners and managers of making decisions under conditions of risk and uncertainty.

Much is heard about global climate change, but everybody lives in a particular place on earth and the earth exhibits a myriad of regional and local climatic conditions. As it is impossible here to address all the regional climates of the world, we use as an example climatic conditions in Illinois, in the American Midwest.

Water cycle and water budgets

Water is found in all three phases – liquid (water), solid (snow and ice) and gas (water vapor) - in the atmosphere and within the surface layers of the earth. The water cycle (fig. 6.1) provides a conceptual model for understanding the flows and storage of water in any region of the world. Water at any given location and time can be accounted according to the familiar relationship:

$$\text{Precipitation} = \text{Evapotranspiration} + \text{Runoff} + \text{Percolation}$$

Precipitation is balanced by the return of water from the earth's surface (evapotranspiration) to the atmosphere, runoff to rivers, streams, lakes and oceans, and percolation into the soil. Some soil moisture is available to plants and some percolates deeper to recharge groundwater in

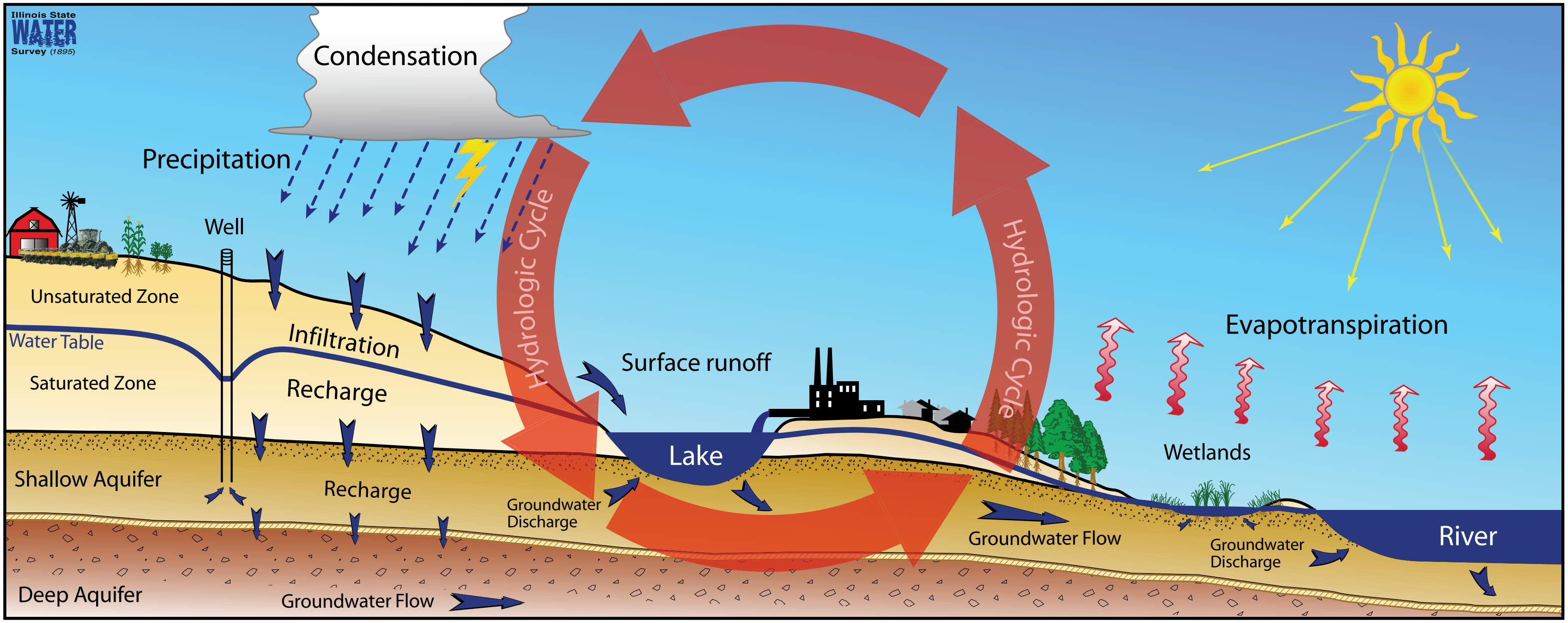


Figure 6.1: The Water Cycle
(http://www.sws.uiuc.edu/docs/watercycle/, accessed July 5, 2007).

underground aquifers. These processes are continuous with complex inter-relationships determined by such factors as precipitation, temperature, wind, soils, vegetation cover, and geology. However, the detailed partitioning of water flows and storage among streams and lakes, soil moisture or groundwater often remains a scientific challenge (Loescher et al., 2007; Bengtsson et al., 2007). Once precipitation enters the soil and aquifers, weeks, months or millennia can occur before the water re-enters surface waters or the atmosphere to complete the water cycle.

The accuracy and confidence associated with precipitation measurements depends the instruments, networks, and observers. As an example of the extent of water related observations, the National Weather Service (NWS) measures precipitation in an 8 in (20 cm) diameter can at about 290 sites in Illinois, each of which in general is representative of the area within, say, one mile (1.6 km) of the sensor. Precipitation rates vary from place to place within a storm, and further, clouds have edges that can cause rain to occur on one side of a street whereas the other side is dry. The measurements of snowfall totals are less reliable especially under windy conditions when the snowflakes easily blow over the gage as opposed to into the gage. Doppler radar currently can exhibit the areal distribution of precipitation rates, but calibration studies are still too few for accurate magnitudes. There are virtually no measurements of precipitation over the world's oceans, only estimates from satellites over the past couple of decades.

Since 1980, evaporation has been measured by the NWS at 4 - 9 sites in Illinois via pan evaporation, i.e., standing water in a pan fully exposed to the sun and wind. Evaporation from vegetation or urban surfaces can be dramatically different, but is not directly sensed.

The Illinois State Water Survey (ISWS) continuously monitors a variety of weather variables at 19 sites across the state, and from these data computes potential evapotranspiration, a numerical estimate of the amount of water evaporated (both as transpiration and evaporation from the soil) from an area of continuous, uniform vegetation that covers the whole ground and that is well supplied with water. In addition, the ISWS monitors soil moisture in the uppermost 6 ft of soil at 19 sites, monthly river flow at 26 stations (operated by the U. S. Geological Survey), reservoir levels at 39 locations, and shallow groundwater depths from 35 wells in Illinois (.http://www.sws.uiuc.edu/warm/). Two dense precipitation networks are operated in Cook County in northeast Illinois (25 gages) and McLean and Tazewell counties in central Illinois (24 gages).

There are two prerequisites for precipitation to occur: there must be adequate moisture in the atmosphere and the moist air must be lifted to condensation level to form clouds. Other things being constant, warmer air is able to contain more water vapor than colder air, thus representing a higher precipitation potential. Tropical and mountainous regions of the earth generally receive greater average precipitation, e.g., (60-80 in or more (1,524-2,032 mm)/year) than polar regions (<20 in (<50 mm)/year). On the summit of Mt. Waialeale, Kauai, Hawaii, the mean annual precipitation is 460 in (1,168 mm). Areas with little precipitation can be found distant from moisture sources and where the downward movement of air and/or cold surfaces inhibit the upward movement of air needed to create precipitation; for example, at Iquique, Chile, no precipitation was observed for 14 consecutive years!

A water budget quantifies systematically the flows and reservoirs of water in the water cycle based on the principle of the conservation of mass. That principle assumes that water is neither created nor destroyed in the system. 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.

Fig. 6.2 shows a water budget for Illinois. On average, an estimated 2000 billion gallons of water per day (bgd) ($8x10^9 m^3 d^{-1}$ (8 billion cubic meters of water per day) pass overhead in the atmosphere, 104 bgd ($394\ x10^6 m^3 d^{-1}$ (394 million cubic meters of water per day) fall as precipitation, 73 bgd ($276x10^6 m^3 d^{-1}$) return to the atmosphere through evapotranspiration, 31 bgd ($117x10^6 m^3 d^{-1}$) flow out of the state in rivers and streams, and groundwater recharge uses about 12 bgd ($44x10^6 m^3 d^{-1}$), of which about 11 bgd ($43x10^6 m^3 d^{-1}$) are returned as groundwater discharge to surface streams. Additional surface water flows into Illinois from rivers in Indiana and Wisconsin, and additional 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.

The escalating concern over global climate change is of great concern to water interests because of potential impacts on future water availability, water quality, and water demand. Here we focus on water availability.

There are two ways of looking at the future. The first approach is to document the past and assume that climatic conditions that have occurred in the past can recur in the future. The second approach is to use mathematical computer models to simulate possible future climatic and hydrologic conditions due to both natural and human factors. Both approaches yield data that can be used to show potential changes in water budgets at regional or local scales.

Historical climate

Higher temperature and wind speed increase evapotranspiration and reduce water

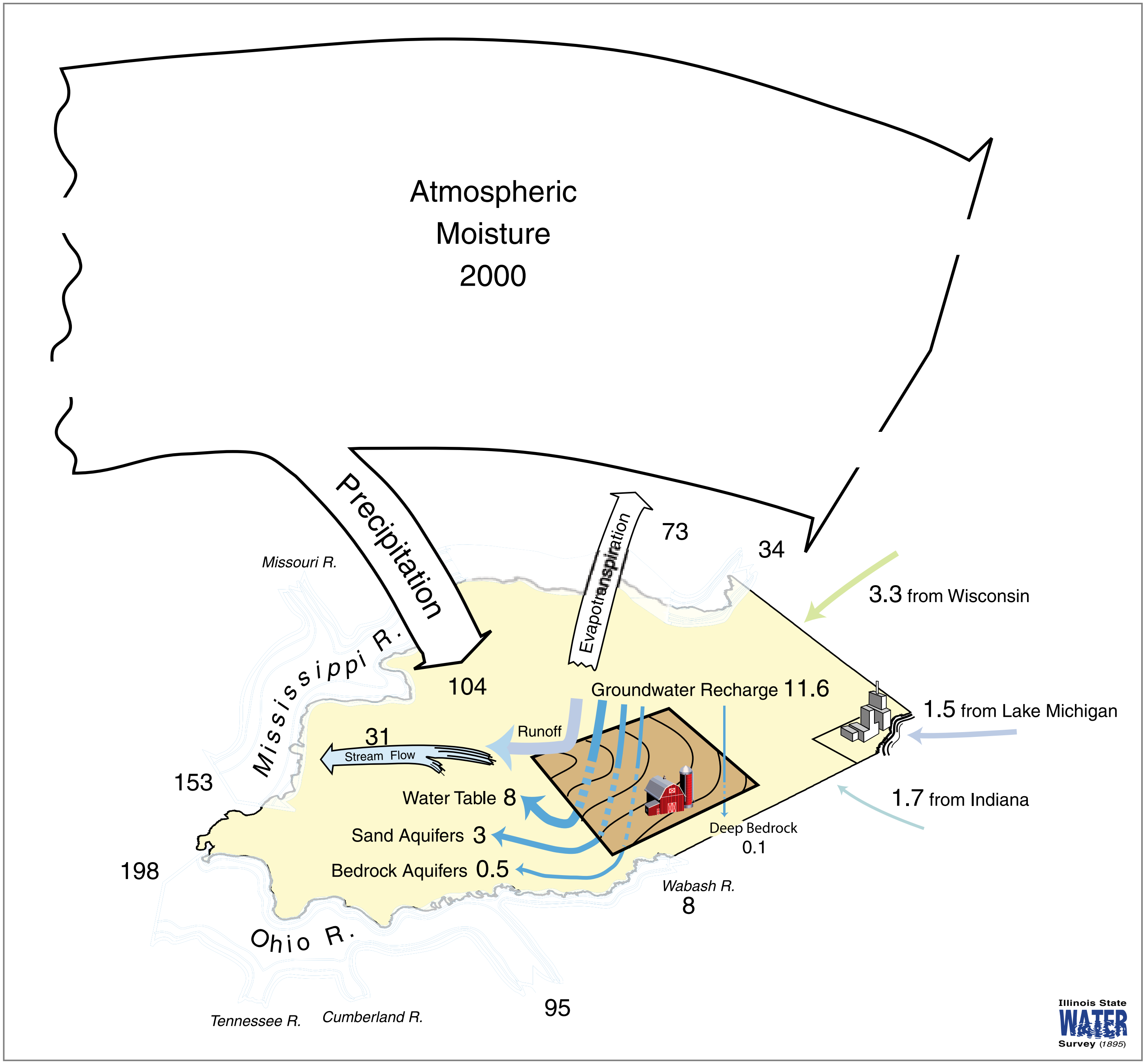


Figure 6.2: Water Budget for Illinois, 1971-2000
(http://www.sws.uiuc.edu/docs/watercycle/, accessed July 5, 2007).

availability, but experience shows that variations in precipitation have the largest impact on streamflow and groundwater levels; in Illinois, a 10 percent change in precipitation typically results in a 20-25 percent change in streamflow (Winstanley et al., 2006).

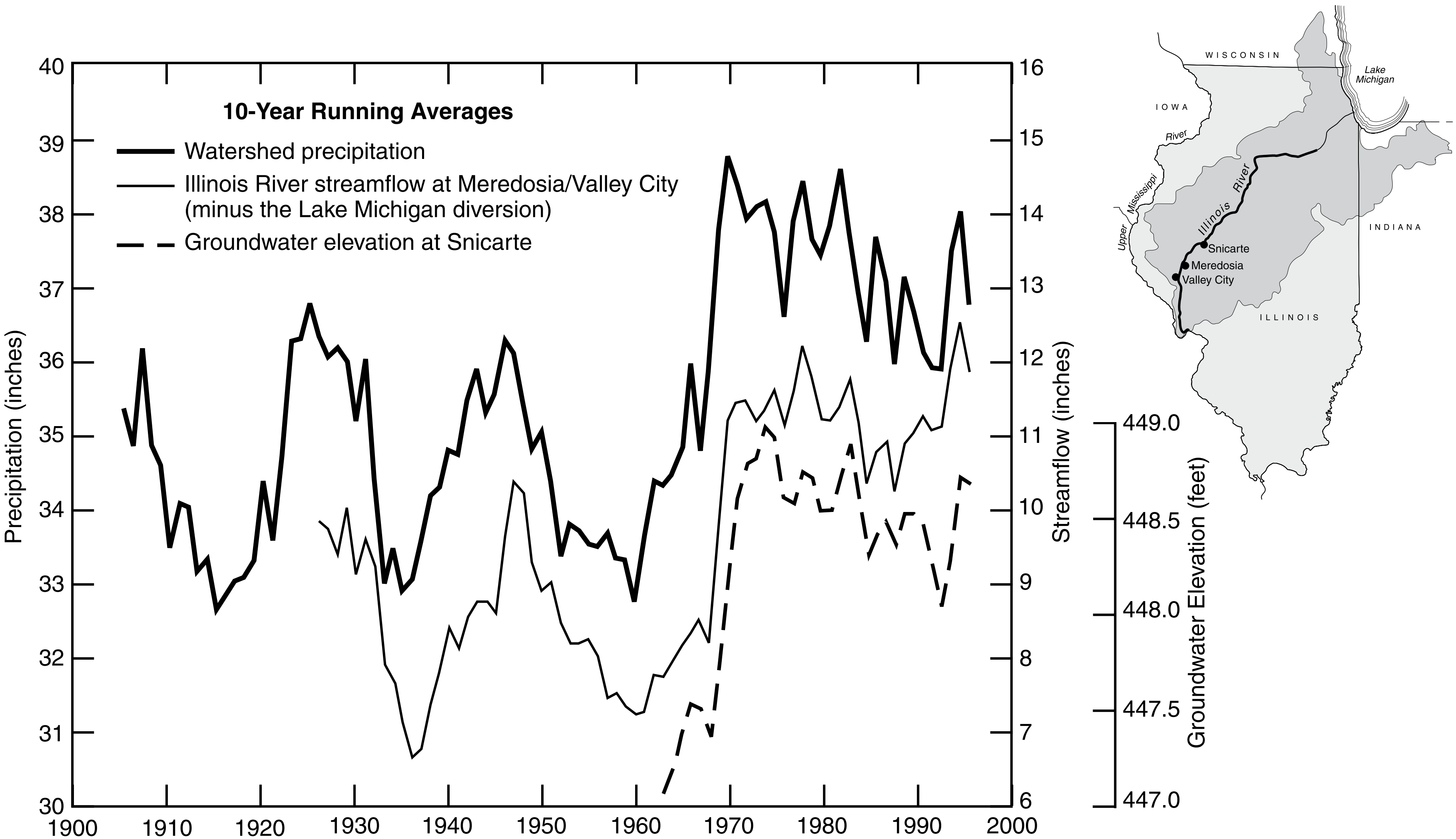
Temperature episodes of the past 12,000 years show that higher latitudes have exhibited greater temperature changes than lower latitudes largely associated with ice melting (Archer, 2007). Temperatures over Europe were about 0.9^{o}F (0.5^{o}C) warmer during the Little Climatic Optimum (A.D. 800-1200) and 1.8^{o}F (1.0^{o}C) cooler than today during the Little Ice Age (A.D. 1400-1800), but 9.0-10.8^{o}F (5.0-6.0^{o}C) colder than today during the Last Glacial Maximum (about 20,000 years before present) (Archer, 2007). Data are not available to show changes in global precipitation over these time scales, but proxy data from such as sediment and tree-ring analysis can be used to identify precipitation trends in some regions.

Although annual temperature in Illinois has increased since about 1980, it is no higher than in the 1920s to 1950s (http://www.sws.uiuc.edu/atmos/statecli/Climate_change/19century.htm). In Illinois a large increase in temperature of about 3.0^{o}F (1.7^{o}C) occurred from about 1870 to the 1930s, prior to the large increase in greenhouse gas concentrations in the 20th century. Since 1895 much of the Midwest and southern USA has cooled (http://www.sws.uiuc.edu/atmos/statecli/Climate_change/ustrends-maps.htm).

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 ground-water levels. The Midwest is a region with precipitation and hydrologic records extending back almost two centuries and these are used here to exemplify natural climate variability. There may have been human influences on regional climatic conditions prior to the 20th century, but we assume that the dominant agents for change were natural. In the 20th century human influences may have affected regional precipitation, but we cannot separate these from natural variations.

Fig.6.3. shows considerable interdecadal variability in precipitation, streamflow and shallow groundwater level in the Illinois River Basin over the last century. 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).

When we look at the longer precipitation and streamflow records in the Upper Mississippi River Basin (Fig. 6.4), it is evident that precipitation and streamflow were as high or higher in the mid 19th century as in recent decades. Also there was a high frequency of heavy precipitation events during portions of the late mid to late 19th century (Ken Kunkel, Illinois State Water Survey, personal communication, July 5, 2007). As there was no global warming at this time, high precipitation and streamflow probably due to natural factors. High precipitation and streamflow also occurred in the Ohio River Basin in the mid to late 19th century (Ken Kunkel, Illinois State Water Survey, personal communication, July 5, 2007) and the water level in Lake Michigan was high at this time (Winstanley et al., 2006). These records provide evidence of a high degree of natural variability in the regional climate system. To have credibility in projecting future regional climatic conditions, global climate models must demonstrate that they are capable of simulating historical regional changes in climate.



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 6.3: The 10-Year Moving Averages of Illinois River Watershed Precipitation, Streamflow (Minus Lake Michigan Diversion), and Groundwater Elevation (Winstanley et al., 2006, Figure A-14).

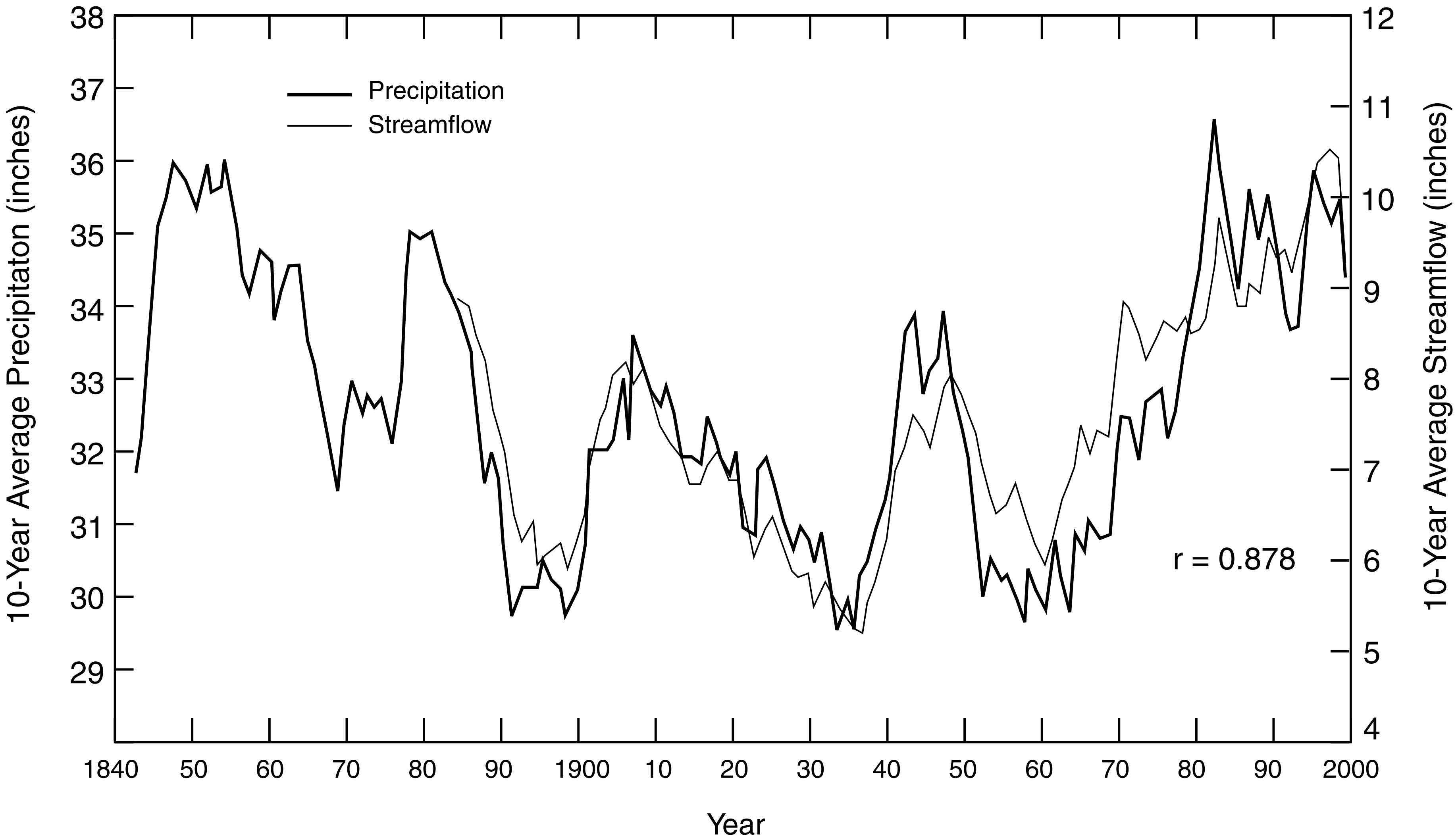


Figure 6.4: Comparison of 10-Year Moving Averages of Watershed Precipitation and Streamflow for the Mississippi River at Keokuk, Iowa, 1837-2002, Using 3-Precipitation Gages (Knapp, 2004 in Winstanley et al., 2006, Figure A-16).

Future Climate

Under the assumption that climate conditions that have occurred in the past can recur in the future, the range of possible future climatic conditions in any region of the world is wide. In Illinois, for example, annual precipitation could be as low as 25 in (63.5 cm) - about 34 percent below the 1971-200 average of 38 in (96.5 cm) - or as high as 54 in (137.2 cm) - about 42 percent above average. There could be a 10-year drought, similar to that which occurred in the 16th century (Winstanley et al., 2006). Extreme precipitation events could increase by 30 percent or more. Frosts and snow could occur in summer, as they did during the 19th Century (Wendland (2007).

During the 20th century, the atmospheric concentration of carbon dioxide ($CO_{2)}$ increased from 280 to 379 parts per million and global temperature increased 1.1^{o}F (0.6^{o}C) since the late 19th century. Beginning about 1940, however, global average temperature fell by about 0.5^{o}F (0.3^{o}C) until the 1970s when it began a climb of another 0.7^{o}F (0.4^{o}C). The early 20th century temperature increase, when CO_2 concentration was increasing only slowly, and the mid-20th century temperature decline, when CO_2 concentration was increasing quite rapidly, indicate that global average temperature is not solely a function of greenhouse gas emissions.

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 (6.7^{o}C) by the end of the 21st century and mean annual precipitation could increase or decrease by some 10 in (25.4 cm) (fig. 6.5.). Other models suggest that mean annual temperature could increase by only 2^{o}F (1.1^{o}C) and precipitation would not change significantly. Figure 6.5. shows the 5th and 95 percentiles of 140 global model runs from 21 global climate models driven by a range of emissions scenarios. These summaries of future scenarios were derived by scientists at the

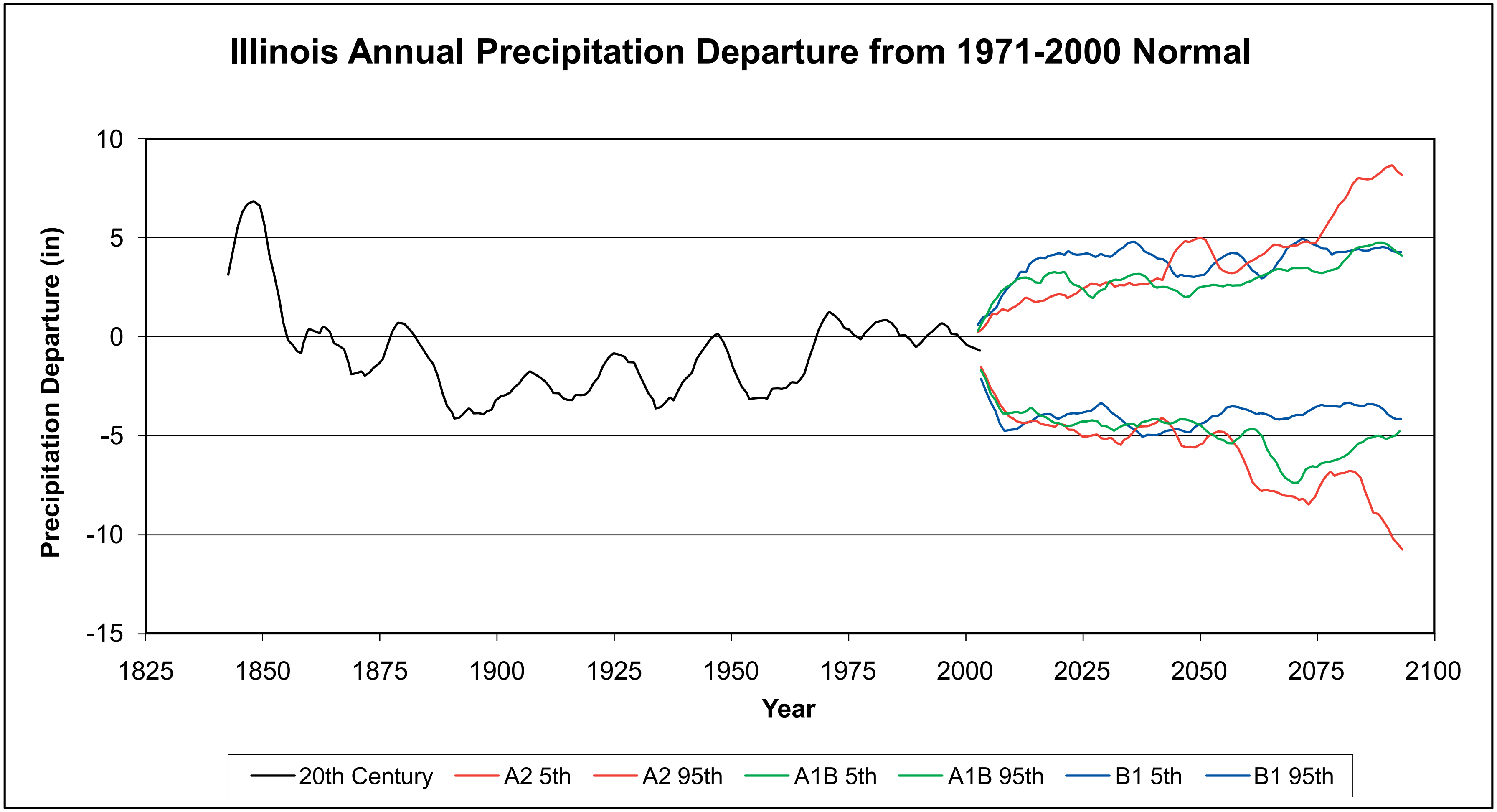


Figure 6.5: The instrumental record of precipitation variation in Illinois and summaries of future precipitation scenarios derived from a set of global climate model simulations produced for the Intergovernmental Panel on Climate change. The results of more than 120 model runs for 21 models and three greenhouse gas emissions scenarios were sorted and ranked. The plots show the smoothed 5th and 95th percentiles of the precipitation scenarios with departures from 1971-2000 "normal" conditions (http://www.sws.uiuc.edu/wsp/climate.asp, accessed July 11, 2007).

Illinois State Water Survey using the latest set of global climate model simulations produced for the IPCC's Fourth Assessment Report (http://www.sws.uiuc.edu/wsp/climate.asp, accessed July 12, 2007). 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 6.5 shows that precipitation scenarios have little dependence on emissions scenarios.

Perhaps the major weakness of global climate models is their difficulty in simulating clouds and precipitation; IPCC notes that even the uncertainties are difficult to quantify and assess (Forster et al., 2007). These difficulties mean that there is considerable uncertainty in the direction and magnitude of possible future precipitation changes over a high percentage of the earth (Wigley, 2002). Wigley also notes that there is some indication that the regions where we have most confidence in the temperature change signals also are the regions where we have least confidence in precipitation signals.

As the climatic conditions in a region incorporate a suite of precipitation, temperature and other variables, it is apparent that scientists cannot predict future regional climatic conditions with confidence. The more than 20 global climate models produce a wide range of climatic conditions dependent on the structure of the models and the assumptions about future emissions of greenhouse gases and land-cover changes.

Conclusions: Uncertainties in Water Availability

A consequence of the large uncertainties in future temperature and precipitation at the regional scale is that there are large uncertainties in future water availability. It is difficult for water supply planners and managers to accommodate such uncertainties. Realistically, it would be very expensive to provide water-supply infrastructure that could provide adequate water supplies under equally probable scenarios of mean annual precipitation increasing or decreasing by 10 in (25.4 cm). This is not the same as a drought with one year precipitation 10 in (25.4 cm) below average. We are faced with a situation where mean annual precipitation in Illinois could decrease from 38 in (96.5 cm) to 28 in (71.1 cm) and droughts could diminish precipitation in any particular year to perhaps 15 in (38.1 cm) by the end of the century. We do not know what the probability is 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 second strategy is for water supply managers to evaluate the capabilities of existing facilities to provide adequate supplies of water 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 could occur in the future than have occurred in the last 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 supplies of water during 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 and possibly 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 gives better expression of the uncertain science behind regional climate change.

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