4 Water Resources

Chapter Lead Author
Dennis P. Lettenmaier[a]

Contributing Authors:
Katharine Hayhoe[b]
David Major[c]
Leroy Poff[d]
Steven Running[e]

[a]Department of Civil and Environmental Engineering, University of Washington
[b]Department of Geosciences, Texas Tech University
[c]Columbia University Earth Institute
[d]Department of Biology, Colorado State University
[e]School of Forestry, University of Montana

4.1 Introduction

Water managers have long understood the implications of variability in water sources resulting from weather and climatic variations at time scales ranging from days to months and years, and have developed sophisticated methods to simulate and respond to such variability in water resource system design and operation. A distinguishing feature of these methods is that they assume that an observed record of streamflow is statistically stationary, that is, the probability distribution(s) from which the observations are drawn does not change with time. *In the era of climate change this assumption is no longer tenable*. The challenge facing water managers is to determine reasonable ways of assessing plausible ranges of future conditions for purposes of hydrologic design and operation. Such assessments are also needed to understand how changes in the availability and quality of water will affect animals, plants, and ecosystems.

4.2 Hydroclimatology of the U.S, and the role of water management

The primary driver of the land surface hydrologic system is precipitation. Precipitation varies widely, not only in total annual amount, but in seasonal distribution, and space-time variability across the United States. Proceeding from east to west, the semi-humid conditions of the eastern U.S. yield to drier conditions to the west, with the increasing dryness eventually interrupted by the Rocky Mountains, and then amplified in the intermountain west and Southwest. These extremely arid conditions give way as one proceeds west and north to the more humid conditions of the coastal west. Runoff patterns, for the most part, follow those of precipitation. The runoff ratio (runoff divided by precipitation) decreases from east to west, and the decline in runoff with aridity is sharper than it is for precipitation. The ratio of maximum annual snow accumulation to annual runoff is an index to the relative fraction of runoff that is derived from snowmelt. This number is high in the mountainous areas of the West, and to a more limited extent, in the northern tier of states, and low elsewhere. The coefficient of variation of annual runoff is a measure of the variability of runoff. Its spatial pattern generally follows that of precipitation coefficient of variation; it is highest where runoff (and precipitation) is lowest.

The water resources of the continental U.S. are heavily managed, mostly by surface water reservoirs. The most important metric of storage is the ratio of usable reservoir storage to mean annual reservoir inflows. Storage to runoff ratio of one is usually taken as the division between reservoirs that are primarily used to shape within-year variations in runoff, and those that are primarily used to buffer interannual variations in runoff. Within the United States, most reservoir storage can be classified as within-year; the major exceptions where reservoir storage is over-year are the Colorado, and upper Missouri River basins.

4.3 Trends in U.S. water use

With respect to water use, U.S. water withdrawals have decreased (slightly) over the last 20 years in virtually all categories. This is despite substantial population growth during the same period, which suggests that per capita water withdrawals (and by implication, consumptive use) have decreased markedly. These changes follow a period of rapid growth in water withdrawals in the mid-20th century. The reasons for these reductions in water withdrawals arise both from regulatory considerations (e.g., imposition of minimum instream flow standards, and higher WUE appliances), and economic considerations. For instance, in the case of irrigation, there has been a transition from flood to sprinkler irrigation. Irrigation water use has also been affected by the cost of electric power. Industrial water use efficiency gains have been driven by pollution control regulations, which encourage reduction of wastewater discharge, and hence more recycling.

4.4 Observed trends in U.S. water resources

Over most of the United States, streamflow increased over the second half of the 20th century. This is true for all but the highest (flood) flows, for which there were relatively few statistically significant trends. Those trends that have been observed cannot necessarily be attributed to climatic warming, however the spatial coherence in the trends suggests that non-climatic causes (e.g., land cover change), are not likely the cause. The western U.S. constitutes an important apparent reversal in the trend toward increasing U.S. streamflow, with an indication of an onset of dry conditions beginning in the 1980s. However, this apparent pattern may well be associated with decadal scale climate variability. There has, however, been a trend toward reduced mountain snowpack, and earlier spring snowmelt runoff peaks across much of the western U.S., and this trend increasingly appears to be attributable to long-term warming, rather than to decadal scale variability. Furthermore, there is some indication that the variability of streamflow in the western U.S. has increased over the last two decades.

Several studies have found that pan evaporation decreased over the last 50 years, whereas some studies suggest that actual evapotranspiration during the same period has increased. Two explanations have been advanced; one is the so-called evaporation paradox, which holds that microclimatic conditions in the vicinity of evaporation pans lead to decreased pan evaporation as actual evaporation increases. The second is that actual ET may also have declined due to reduced net radiation, resulting from increased cloud cover. The latter hypothesis appears to be inconsistent with some published work that has found that actual evaporation, as estimated by the difference between river basin precipitation and runoff, has increased in many river basins.

With respect to drought, consistent with streamflow and precipitation observations, most of the continental U.S. became wetter over the 20th century, with inferred reductions in drought severity and duration. However, there was some evidence of trends in the opposite direction (that is, increases) in drought severity and duration in the western and southwestern U.S., which apparently results from increased actual evaporation dominating the trend towards increased soil wetness. Paleo reconstructions of droughts show that much more severe droughts have occurred over the last 2,000 years than those that have been observed in the instrumental record (notably, the Dust Bowl drought of the 1930s, and extensive drought in the 50s).

Water quality is sensitive both to increased water temperatures, and changes in patterns of precipitation. However, most observed changes in water quality across the continental U.S. are attributable to causes other than climate change. These include, for instance, changes in land cover, and changes in pollutant loadings. Some work has, however, shown that temperatures have increased in some western U.S. streams over the second half of the 20th century. Some of these changes are associated with changes in runoff patterns, e.g., earlier snowmelt runoff leads to reduced summer flows, at a time when radiative and other forcings leading to increased water temperatures are the greatest.

4.5 Projected future changes in U.S. water resources

The most recent (IPCC AR4) climate model simulations project increased runoff over the eastern U.S., gradually transitioning to little change in the Missouri and lower Mississippi, to substantial decreases in annual runoff in the interior of the west (Colorado and Great Basin). Runoff changes along the west coast (Pacific Northwest and California) are also negative, but smaller in absolute value than in the western interior basins. The projected drying in the interior of the West is quite consistent among models (the only projections that are more consistent among models are for runoff increase in Alaska). These changes are, very roughly, consistent with observed trends in the second half of the 20th century, which show increased streamflow over most of the United States, but sporadic decreases in the West.

4.6 Findings and conclusions

1) Precipitation over much of the continental U.S. increased in recent decades, and this trend toward increased wetness is evident in a predominance of upward trends in stream discharge, especially for flows from the lower end to the middle of the streamflow distribution (that is, extreme low flows, through median flows). The preponderance of upward trends vanishes toward the upper end of the streamflow distribution (floods), and there is no evidence of increases in floods within the range of basin sizes represented by the USGS Hydroclimatic Data Network (HCDN; mostly thousands to tens of thousands of square km drainage area).

2) The trend toward increased wetness is also evident in simulated soil moisture (unfortunately not verifiable from observations due to short record lengths) over most of the country, and as a consequence, drought severity and duration declined over most of the United States during the 20th century. However, there are some trends in the opposite direction in the western and southwestern U.S., where increased temperatures and resultant increases in evaporative demand more than counteracted increased precipitation.

3) Pan evaporation declined over most of the United States over the second half of the 20th century. These declines are consistent with the "complementary hypothesis" that states that trends in actual and pan evaporation should be in opposite directions (i.e., actual evaporation should be increasing if pan evaporation is decreasing). Furthermore, some analyses support this hypothesis by showing trends toward increased precipitation minus runoff (inferred actual evaporation) at the river basin level.

4) Snowpacks in the mountainous headwaters regions of the western U.S. generally declined over the second half of the 20th century, especially at lower elevations and in locations where average winter temperatures are close to or above zero degrees C ("transient" rain-snow conditions). These trends toward reduced winter snow accumulation, and earlier spring melt are also reflected in a tendency toward earlier runoff peaks in the spring, a shift that has not occurred in rainfall-dominated watersheds in the same region.

5) Warmer summer temperatures in the western U.S. have led to longer growing seasons, but have also increased summer drought stress. This has led to conditions that are conducive to increased fire hazard. This tendency is, however, confounded by the effects of fire suppression over the same period.

6) Climate model projections for increased temperatures, and (averaged across many models) modest increases in precipitation are expected to lead to streamflow declines.

Because of the uncertainty in climate model projections of precipitation change, the hydrologic consequences are highly uncertain across most of the United States One exception is watersheds that are dominated by spring and summer snowmelt, most of which are in the western U.S. In these cases, where shifts to earlier snowmelt peaks and reduced summer and fall low flows have already begun to be detected, continuing shifts in this direction are quite likely, and may have substantial impacts on the performance of reservoir systems, especially when the active reservoir storage volume is much less than mean annual streamflow, as is the case across much of the western U.S.

7) Stream temperature increases have begun to be detected across much of the United States, although a comprehensive analysis similar to those reviewed for long-term streamflow trends has yet to be conducted. Stream temperature is a change agent that has both direct and indirect effects on aquatic ecosystems. Changes that will be most evident during low flow periods, when stream temperature changes are of greatest concern.

8) U.S. consumptive use of water per capita has declined over the last two decades, and total water use has declined slightly as well. This is due to various improvements in water use efficiency related both the legal mandates and water pricing, as well as some changes in water laws that have facilitated reallocation of water, especially in the western U.S., and especially during droughts. These trends seem likely to continue in the coming decades. Pressures for reallocation of water will be greatest in areas of highest population growth, notably the Southwest. These trends toward declining water consumption will help to mitigate the impacts of climate change on water resources.

4.7 Background

Water is essential to life and is central to society's welfare and to sustainable economic growth. Plants, animals, natural and managed ecosystems, and human settlements are sensitive to variations in the storage, fluxes, and quality of water at the land surface – notably storage in soil moisture and groundwater, snow, and surface water in lakes, wetlands, and reservoirs, and precipitation, runoff, and evaporative fluxes to and from the land surface, respectively. These, in turn, are sensitive to climate change.

Water managers have long understood the implications of variability in water sources at time scales ranging from days, to months and years on the reliability of water resources systems, and have developed many sophisticated methods to simulate and respond to such variability in water system design and operation. The distinguishing feature of all such streamflow synthesis, or stochastic hydrology methods, however, is that they assume that an observed record of streamflow is statistically stationary – that is, the probability distribution(s) from which the observations are drawn does not change with time. As noted by Arnell (2002), Lettenmaier (2003), NRC (1998), and others, in the era of climate change this assumption is no longer tenable. The challenge at this point is to determine reasonable ways of assessing plausible ranges of future conditions for purposes of hydrologic design and operation. Such assessment is also needed to understand how changes in the availability and quality of water will affect animals, plants, and ecosystems.

In this chapter, we first briefly review the current status of U.S. water resources, both in terms of characteristics of the physical system(s), trends in water use, and observed space-time variability in the recent past. We then review changes to the natural hydrologic system (primarily streamflow, but also evapotranspiration and snow water storage) over recent decades for four regions of the United States (the West, Central, Northeast, and South and Southeast, each of which is defined as aggregates of USGS Hydrologic Regions). Finally, we review recent studies, based on climate model projections archived for the 2007 IPCC report, which project the implications of climate change for these four major U.S. regions.

4.8 Hydroclimatic variability in the United States

The primary driver of the land surface hydrologic system is precipitation. Figure 4.1 shows variations in mean annual precipitation and its variability (expressed as the coefficient of variation, defined as the standard deviation divided by the mean) across the continental U.S. As is well known, the semi-humid conditions of the eastern U.S. yield to drier conditions to the west, with the increasing dryness eventually interrupted by the Rocky Mountains. The driest climates, however, exist in the Intermountain West, and the Southwest, which give way as one proceeds west and north to more humid conditions on the upslope areas of the Cascade and Coast mountain ranges, especially in the Pacific Northwest. The bottom panel of Figure 4.1, which shows the coefficient of variation of precipitation, indicates that precipitation variability generally is lowest in the humid areas, and highest in the arid and semi-arid West, with a tendency toward lower variability in the Pacific Northwest, which is more similar to that of the East than the rest of the West.

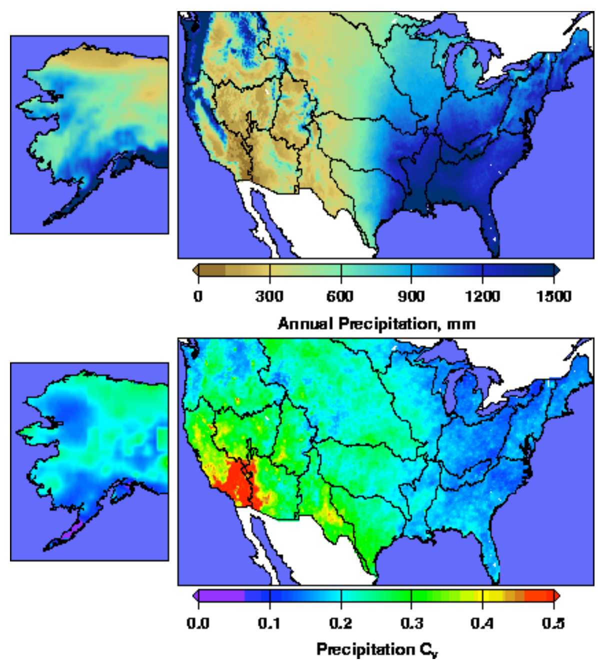

Figure 4.1 Mean and coefficient of variation of annual precipitation in the continental U.S. and Alaska. Data replotted from Maurer et al. (2002).

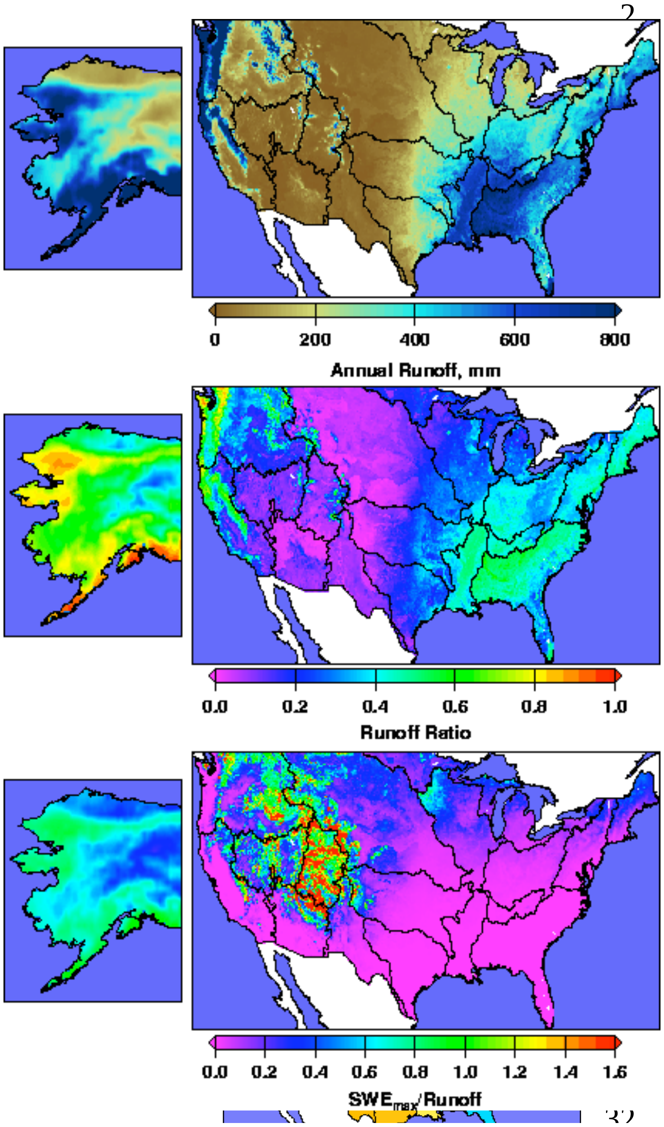

Figure 4.2 Mean annual runoff, runoff ratio (annual mean runoff divided by annual mean precipitation), and ratio of maximum mean snow accumulation to mean annual runoff in the continental U.S. and Alaska. Data replotted from Maurer et al. (2002).

Figure 4.2 (upper panel) shows that runoff patterns, for the most part, follow those of precipitation. The runoff ratio (annual runoff divided by annual precipitation; second panel in Figure 4.2) generally decreases from east to west, which suggests that the decline in runoff with aridity is sharper than it is for precipitation. The runoff ratio increases in headwaters regions of the mountainous source areas of the west, and more generally in the Pacific Northwest. This increase in runoff ratio with elevation is critical to the hydrology of the West, where a large fraction of runoff originates in a relatively small fraction of the area – much more so than in the semi-humid East and Southeast, where runoff generation is relatively uniform spatially. The bottom panel in Figure 4.2 shows the ratio of maximum annual snow accumulation to annual runoff, and can be considered an index to the relative fraction of runoff that is derived from snowmelt. This panel emphasizes the critical roll of snow processes to the hydrology of the western U.S., and to a more limited extent, in the northern tier of states.

Upper panel replotted from Maurer et al. (2002);
lower panel from Vogel et al. (1998)

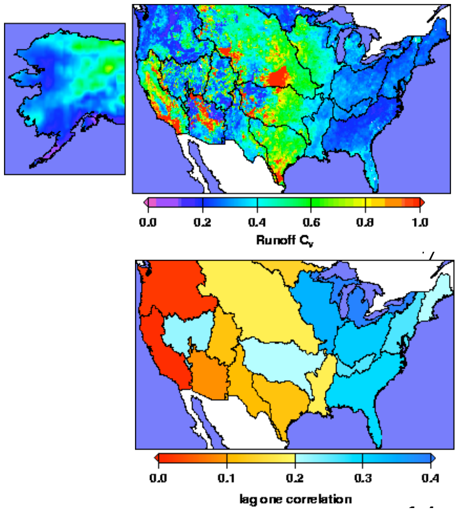

Figure 4.3 Coefficient of variation of annual runoff (upper panel) and lag one correlation of annual runoff (lower panel). Upper panel replotted from Maurer et al. (2002); lower panel from Vogel et al. (1998)

Figure 4.3 shows two key aspects of runoff variability – the coefficient of variation of annual runoff, and its persistence in time (the latter expressed as the lag one correlation coefficient). The coefficient of variation of annual runoff generally follows that of precipitation; however, it is higher for the most part as the hydrologic system tends to amplify variability (due in part to the fact that the runoff ratio is less than one-half over most of the United States). Annual runoff persistence is generally low, but tends to be higher in the East (and generally in more humid areas) than in the western U.S. The differences between regions are, however, slight, and Vogel et al. (1998) argue in terms of homogeneity that most of the United States can be considered to be a "homogeneous region" in terms of the serial correlation of runoff. It is nonetheless interesting that there is a general gradient downward in serial correlation of runoff from east to west, which is not reversed in the generally more humid areas of the northwest and Pacific Coast regions.

4.8.1 Characteristics of managed water resources in the United States

The water resources of the continental U.S. are heavily managed, mostly by surface water reservoirs. During the period from about 1930 through 1980, dams were constructed at most technically feasible locations, with the result that aside from headwater regions, the flow of most rivers, especially in the western U.S., has been heavily altered by reservoir management. Figure 4.4 (modified from Graf, 1999) shows the extent of reservoir storage across the continental U.S. From the standpoint of water management, the lower panel in Figure 4.4, which shows variations in the ratio of reservoir storage to mean annual flow, is most relevant. Although the figure scale is in terms of quartiles, the lowest quartile has storage divided by mean annual runoff ratios in the range 0.25 – 0.36, and the upper quartiles 2.18-3.83 (see Graf, 1999; Table 4.1). A storage to runoff ratio of one is usually taken as the division between reservoirs that are primarily used to shape within-year variations in runoff (small storage to runoff ratios; orange colors in Figure 4.4, lower panel) and those that are primarily used to smooth interannual variations in runoff (large storage to runoff ratios; dark blue I Figure 4.4 lower panel). As we will see in subsequent sections, these differences in storage capacity, coupled with the characteristics of the hydrologic systems, are critical in defining the sensitivity of water resources to climate change.

4.8.1.1 U.S. water use and water use trends

The U.S. Geological Survey compiles, at five-year intervals, information about the use of water in the United States. The most recent publication (USGS 2004) is for the period through 2000. The update to this publication, through 2005, unfortunately was not available as of the time of this writing. The data compiled by the USGS are somewhat limiting in that they are for water withdrawals, rather than consumptive use. The distinction is important, as one of the largest uses of water is for cooling of thermoelectric power plants, and much of that water is returned to the streams from which it is withdrawn (use of water for hydroelectric power generation, virtually none of which is consumptively used, is not included in this category). On the other hand, a much higher fraction of the water withdrawn for irrigation is consumptively used.

Despite these limitations, the two key figures in the 2004 USGS publication, reproduced here as Figure 4.4, are instructive in that they further define the trends noted by Gleick et al. (2000) – U.S. water withdrawals have decreased slightly over the last 20 years in virtually all categories, and appear to have stabilized since about 1985. This is despite substantial population growth during the same period (see Figure 4.4, upper panel).

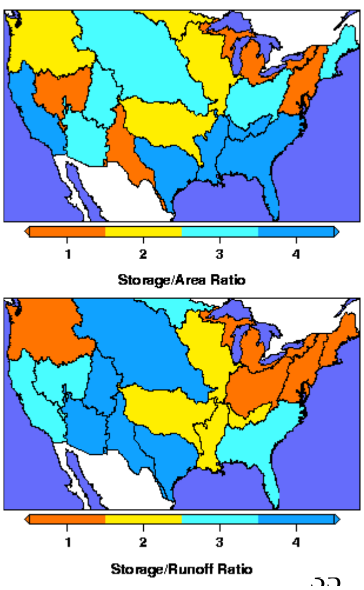

Figure 4.4 Reservoir storage in the continental U.S. per unit area (upper panel) and storage/runoff ratio (lower panel). Colors are for four quartiles of cumulative probability distribution. Replotted from Graf (1999).

These changes, which follow a 30-year period of rapid growth in water withdrawals, have occurred for somewhat different, but related reasons. Water withdrawals from many streams are now limited, particularly during periods of low flow, by environmental regulations. Furthermore, economic considerations have driven more efficient use of water. In the case of irrigation, there has been a transition from flood to sprinkler irrigation, and (albeit in a much smaller number of cases) much more efficient drip irrigation. Irrigation water use has also been affected by economic considerations, such as the cost of electric power to pump irrigation water.

Industrial water use efficiency gains have been driven by pollution control regulations, which encourage reduction of wastewater discharge, and hence more recycling. Municipal water use reductions have been driven by improved efficiency of in-house appliances and plumbing fixtures, as well as trends to higher density housing which reduces use of water for landscape irrigation. Economic considerations have also had an effect on municipal water use, especially in municipalities where the cost of wastewater treatment is linked to water use. The combined result, as shown in Figure 4.5, is that total U.S. water withdrawals have been stable, which implies that per capita water use has declined.

One might ask whether continuation of this trend toward reduced per capita water use is feasible. Comparison of U.S. per capita water use (see Gleick 1996) with that elsewhere globally shows that U.S. water use is much higher than elsewhere globally, even comparing with other industrialized parts of the world like Europe. Therefore, it does not seem unreasonable that this overall trend toward reduced per capita use of water will continue, at least over the next decade or two.

4.9 Observed changes in U.S. water resources

We review briefly in this section observed trends in U.S. water resources – both physical aspects, and water quality. In general, much more work has been done evaluating trends in physical aspects of the land surface hydrologic cycle than for water quality, and more attention has been focused on the western U.S. than elsewhere. For this reason, we review studies of physical aspects by region, but water quality in aggregate.

4.9.1 Observed streamflow trends

The most comprehensive study of trends in U.S. streamflow to date is reported by Lins and Slack (1999; 2005). It follows an earlier study by Lettenmaier et al. (1994) that dealt also with precipitation and temperature, but in less detail with streamflow. Given that the Lins and Slack study concentrates more directly on streamflow, and is somewhat more current, we focus on it. Although the methodologies, record lengths, locations, etc differ somewhat for the two studies, to the extent that the results can be compared they are generally consistent.

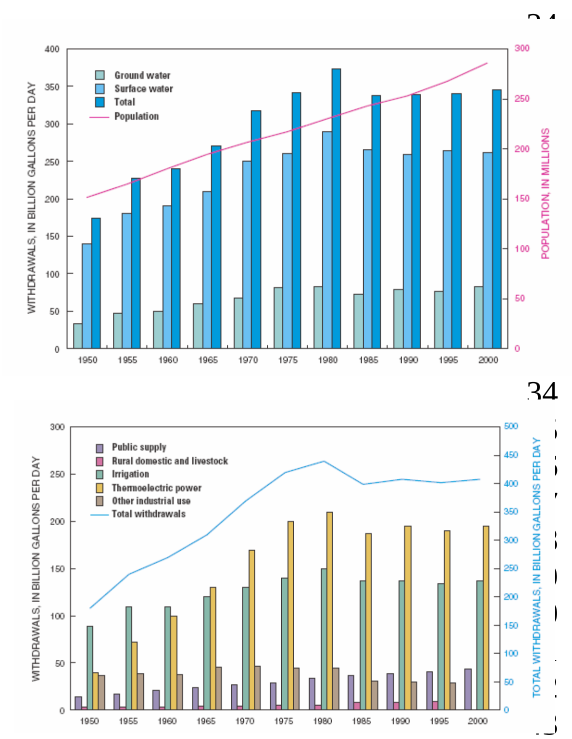

Figure 4.5 Trends in U.S. water withdrawals, 1950-2000. Upper panel: trends in population, groundwater, and surface water withdrawals. Lower panel: withdrawals by sector. Figure from Hutson et al., 2004.

Lins and Slack (1999) analyzed long-term streamflow records for a set of 395 stations across the continental U.S. for which upstream effects of water management were minimal, and which had continuous (daily) records for the period 1944-93 (updated to 435 stations for the period 1940-99 by Lins and Slack (2005). For each station, they formed time series of minimum and maximum flows, as well as flows at the 10th, 30th, 50th, 70th, and 90th percentiles of the flow duration curve. They found, consistent with Lettenmaier et al. (1994) that there was a preponderance of upward trends (many more than would be expected due to chance) in all but the highest flows (see Figure 4.6), for which the number of upward and downward trends was about the same. In addition to the 50-year period

1944-93, similar analyses were conducted for the smaller number of stations having 60, 70, and 80 years of record (all ending in 1993), and the fraction of upward and downward trends was about the same as for the analysis of the larger number of stations with at least 50 years of record. Lins and Slack (2005) update the analysis to a "standard" 60-year period, 1940-99, but unlike their earlier paper, do not consider longer periods with smaller numbers of stations. Neither the 1999 nor the 2005 papers attempt to attribute the observed trends to climatic warming, although the spatial coherence in the trends suggest that non-climatic causes (e.g., land cover change), are not likely the cause. However, as noted in Cohn and Lins (2006), hydroclimatic records by nature reflect long term persistence associated with climate variability over a range of temporal scales, as well as low frequency effects associated with land processes, so the mere existence of trends in and of itself does not necessarily imply a causal link with climate change. Summaries of the Lins and Slack results are shown in Figure 4.7a-c, which plot the location and strength (as significance level) of trends at a subset of HCDN stations, with the longest records (note that in Figure 4.7, green indicates no significant trend at the 0.05 significance level).

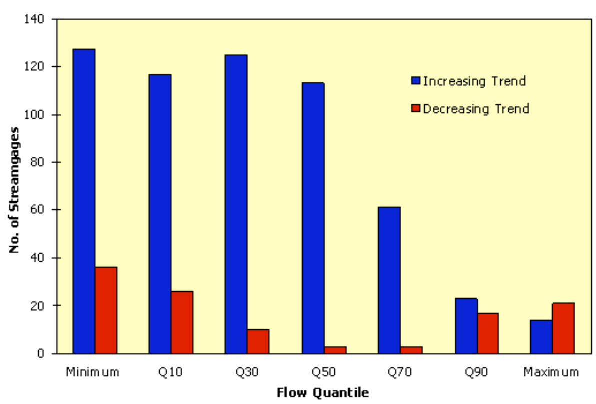

Figure 4.6 Number of increasing and decreasing trends in continental U.S. streamflow records for a range of flow quantiles. From Lins and Slack (1999).

Mauget (2003) used a method based on running time windows of length six to 30 years applied to streamflow records for the 1939-98 period extracted from the same USGS Hydro-Climatic Data Network as were used by Lins and Slack (1999). The Mauget et al. (2003) analysis was based only on the 167 stations for which data were available for the period 1939-98, and hence make up a somewhat different station set than was used by Lins and Slack. (It is worth noting that many of the stations used in the Mauget et al. study are likely the same as those used by Lins and Slack in their 60-year (1934-93) set of 193 stations. It should also be noted that the Mauget study is based on mean annual flow, and Lins and Slack use percentiles of the annual flow distribution, including the median). The results of the Mauget et al. (2003) study are broadly similar to Lins and Slack (1999) to the extent that comparisons are possible. Mauget finds evidence of high streamflows being more likely toward the end of the record than the beginning in the eastern U.S., especially in the 1970s, and "a coherent pattern of high-ranked annual flow … beginning during the later 1960s and early 1970s, and ending in either 1997 o 1998." By contrast, he found a more or less reverse pattern in the western U.S., with an onset of dry conditions beginning in the 1980s.

4.9.2 Evaporation trends

Several studies have been performed to assess changes in evapotranspiration, another major term in the land surface water balance. Unfortunately, there are no long-term ET observations – methods that enable direct measurements, e.g., via eddy flux methods, have only been available for about 20 years, and are still used more in the realm of intensive research observations than long-term. Another source of evaporation data are records from evaporation pans, which are generally located in agricultural areas and have been used as an index to potential evaporation. These records are generally longer; a number (several hundred over the continental U.S.) have record lengths approaching 50 years. Several studies (e.g., Peterson et al. 1995; Golubev et al. 2001) have shown that pan evaporation records over the United States generally had downward trends over the second half of the 20th century. This is contrary to the expectation that a generally warming climate would increase land surface evaporation.

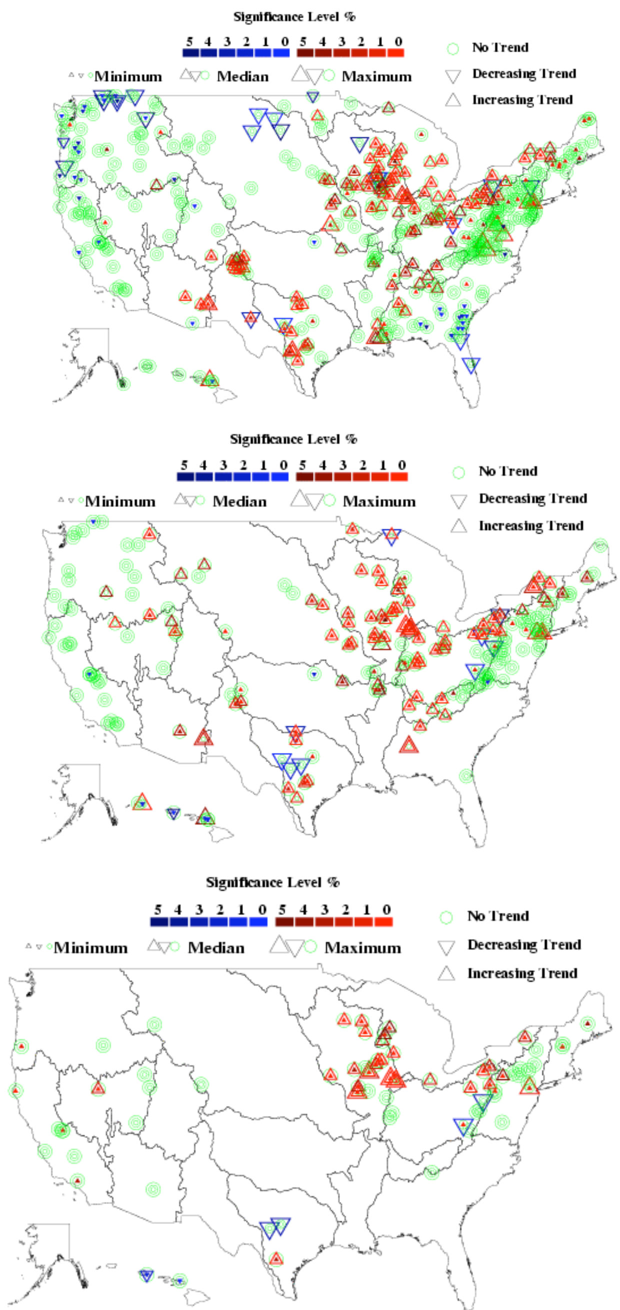

Figure 4.7. Statistically significant trends in streamflow across the continental U.S. At each station location, direction of trend and significance level (if statistically significant at less than 0.05 level) are plotted for minimum, median, and maximum of the annual flows. Upper panel: 393 stations at which data were available from 1944-93; middle panel: same for 1934-93; lower panel: same for 1924-93. Data replotted from Lins and Slack (1999).

Two explanations have been advanced. The first is the so-called evaporation paradox (Brutsaert and Parlange, 1998), which holds that increasing evaporation alters the humidity regime surrounding evaporation pans, causing the air over the pan to be cooler and more humid. This "complementary hypothesis" suggests that trends in pan and actual evaporation should be in the opposite direction. Observational evidence, using U.S. pan evaporation data and basin-scale actual evaporation, inferred by differencing annual precipitation and runoff, suggests that trends in U.S. pan and actual evaporation have in fact been in opposite directions (Hobbins et al. 2004).

The second hypothesis is that actual ET may also have declined due to reduced net radiation, resulting from increased cloud cover. This hypothesis is consistent with observed downward trends in the daily temperature range (daily minimum temperatures have generally increased over the last 50 years, while daily maxima have increased more slowly, if at all), and the temperature range is generally related to downward solar radiation, which would therefore have decreased. Unfortunately, as with actual evaporation, long-term records of surface solar radiation are virtually nonexistent, so indirect estimates (such as cloud cover, or daily temperature range) must be relied on. Roderick and Farquahr (2002) argue that decreasing net solar irradiance resulting from increased cloud cover and aerosol concentrations is a more likely cause for the observed changes, and that actual evaporation should generally have decreased, consistent with the pan evaporation trends.

Brutsaert (2006) argues that “the significance of this negative trend [in pan evaporation], as regards terrestrial evaporation, is still somewhat controversial, and its implications for the global hydrologic cycle remain unclear. The controversy stems from the alternative views that these evaporative changes resulted either from global radiative dimming, or from the complementary relationship between pan and terrestrial evaporation. Actually, these factors are not mutually exclusive, but act concurrently. He derives a theoretical relationship between trends in actual evaporation, net radiation, surface air temperature, and pan evaporation, and shows that the observed trends are generally consistent, accounting for the generally observed downward trend in net radiation (“global dimming,” albeit from sparse observations),

4.9.3 U.S. drought trends

Andreadis and Lettenmaier (2006) investigated trends in droughts in the continental U.S. using a method that combined long-term observations with a land surface model. Their approach was to use gridded observations of precipitation and temperature that were adjusted to have essentially the same decadal variability as the Hydroclimatic Data Network (HCDN) stations – which have been carefully quality controlled for changes in observing methods – to force a land surface model, and then used to evaluate trends in several drought characteristics, in both model-derived soil moisture and runoff. Results show that the spatial character of trends in the model-derived runoff is in general consistent with the observed streamflow trends from Lins and Slack (1999). Andreadis and Lettenmaier also show that, generally, the continental U.S. became wetter over the period analyzed (1915-2003), which was reflected in trends in soil moisture as well as drought severity and duration. However, there was some evidence of trends in the opposite direction (that is, increases) in drought severity and duration in the western and southwestern U.S., which was interpreted as increased actual evaporation dominating the trend toward increased soil wetness, which was evident through the rest of the United States.

Prior to the instrumental record of roughly 100 years, there is evidence that much more severe droughts have occurred in North America. For instance, Woodhouse and Overpeck (1998), using paleo indicators (primarily tree rings) find that many droughts over the last 2,000 years have eclipsed the major U.S. droughts of the 1930s and 1950s, with much more severe droughts occurring as recently as the 1600s. Although the nature of future drought stress remains unclear, for those areas where climate models suggest drying, such as the Southwest (see e.g., Seager et al. 2007), droughts more severe than those encountered in the instrumental record may be increasingly likely.

4.9.4 Regional assessment of changes in U.S. water resources

For purposes of this section, we partition the United States into four "super-regions" using aggregations of the USGS hydrologic regions (Figure 4.8) as follows: West (Pacific Northwest, California, Great Basin, Upper Colorado, Lower Colorado, Rio Grande, and upper Missouri); Central (Arkansas-Red, lower Missouri, Upper Mississippi, Souris-Red-Rainy, and Great Lakes); Northeast (New England, Mid Atlantic, Ohio, and northern half of South Atlantic-Gulf); and South and Southeast (Tennessee, Lower Mississippi, Texas-Gulf, and southern half of South Atlantic-Gulf), as well as Hawaii and Alaska, which are treated separately. Observed changes over each of these parts of the country are summarized below.

4.9.4.1 West

As noted above, the western U.S. has been more studied than any of the other regions in terms of both observed climate-related changes in hydrology and water resources, and the future implications. This is probably because a) the western U.S. is, in general, more water-limited than is the rest of the United States, hence any changes in the availability of water have more immediate and widespread consequences, and b) much of the runoff in the western U.S. is derived from snowmelt, and therefore western U.S. streamflow is more sensitive to ongoing and future climate change in ways that are more readily observable than elsewhere in the United States

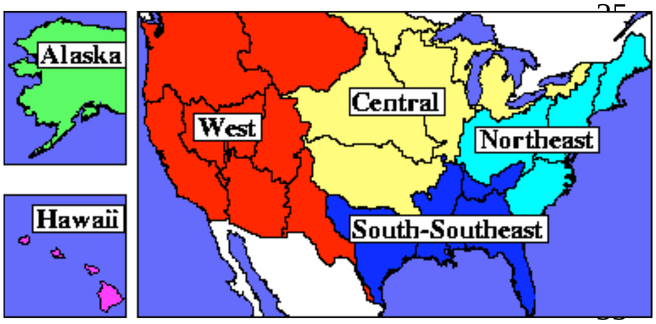

Figure 4.8 Super-regions as aggregates of USGS hydrologic regions.

Much of the recent work on observed changes in the hydrology of the western U.S. has focused on changes in observed snowpack. Mote (2003) analyzed 230 time series of snow water equivalent in the Pacific Northwest (defined as the states of Washington, Oregon, Idaho, and Montana west of the Continental Divide, and southern British Columbia) for the period 1950 to 2000 (and in some cases longer). These records orginate mostly from manual snow courses at which snow cores were taken at about the same time each year (in some cases, more than once, but at most locations around April 1), primarily for the purpose of predicting subsequent spring and summer runoff for water management purpose. Mote (2003) found that over this region, there was a strong preponderance of downward trends, especially in the Cascade Mountains, where winter temperatures were generally higher than elsewhere in the region. Also, the decreases were generally larger in absolute value at lower than at higher elevations. He noted that changes in precipitation, as well as decadal scale variability (especially the widely acknowledged shift in the Pacific Decadal Oscillation (PDO) in about 1977) may have contributed to the observed trends, but argued that the PDO shift alone could not explain changes in SWE over the period analyzed. He also concluded that while regional warming has played a role in the decline in SWE, "… regional warming at the spatial scale of the Northwest cannot be attributed statistically to increase in greenhouse gasses."

Mote et al. (2005) expanded the analysis of Mote (1999) to the western U.S., and used a combination of modeling and data analysis (similar to the approach used by Andreadis and Lettenmaier in their continental U.S. drought analysis) to analyze changes in SWE over the western U.S. for the period 1915 to 2003. They used the snow accumulation and ablation model in the Variable Infiltration Capacity (VIC) macroscale hydrology model (Liang et al. 1994) to simulate SWE over the entire western U.S. for the period of interest, and then compared simulated trends and their dependence on elevation and average winter temperature with snow course observations. They found, notwithstanding considerable variability at the scale of individual snow courses, that the spatial and elevation patterns of trends agreed quite well over the region. They then analyzed reconstructed records for the entire period 1915-2003 and evaluated trends in the reconstructed records. The advantage of this approach is that the longer 1915 to 2003 period spans several phase changes in the PDO, and therefore effectively filters our its effect on long-term trends. They found that over the nearly 80-year period, there had been a general downward trend in SWE over most of the region. The exception was the southern Sierra Nevada, where an apparent upward trend in SWE, especially at higher elevations, appeared to have resulted from increased precipitation, which more than compensated for the generally warming over the period.

Hamlet et al. (2005) extended the work of Mote et al. (2005) and through sensitivity analysis, determined that most of the observed SWE changes in the western U.S. can be attributed to temperature, rather than precipitation changes. Hamlet et al. (2007) used a similar strategy of driving the VIC hydrological model with observed precipitation and temperature and found, over the 1916 to 2003 period, that trends in soil moisture, ET, and runoff generally can be traced to shifts in snowmelt timing associated with a general warming over the period. In a companion paper, Hamlet and Lettenmaier (2007) assessed changes in flood risk using a similar approach. This analysis

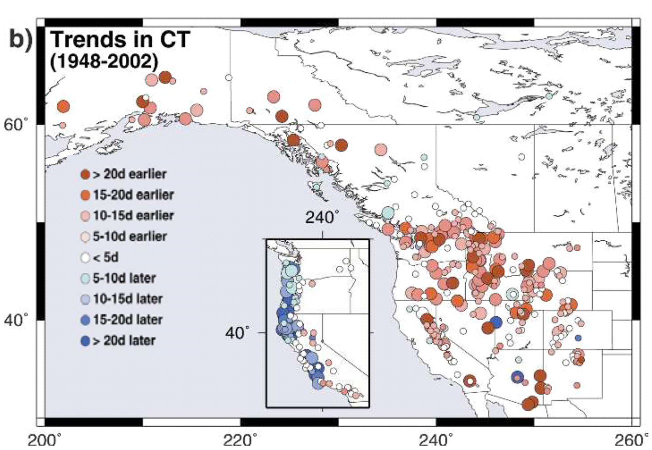

Figure 4.9 Changes in western U.S. snowmelt runoff timing, 1948-2002. Source: Stewart et al. (2005).

showed that in cold (high elevation, and continental interior) river basin flood risk was reduced due to overall reductions in spring snowpack. In contrast, for relatively warm rain-dominant basins (mostly coastal and/or low elevation) where snow plays little role, little systematic change in flood risk was apparent. For intermediate basins, a range of competing factors such as the amount of snow prior to the onset of major storms, and the contributing basin area during storms (i.e., that fraction of the basin for which snowmelt was present) controlled flood risk changes, which were less easily categorized.

Stewart et al. (2005) analyzed changes in the timing of spring snowmelt runoff across the western U.S. They computed several measures of spring runoff timing using 302 streamflow records across the western U.S., western Canada, and Alaska for the period 1948 to 2002. The most useful was the center of mass timing (CT), which is the centroid of the time series of daily flows for a year. As shown in Figure 4.9, they found consistent shifts earlier in time of CT for snowmelt dominated (mostly mountainous) river basins, but little change (or changes toward later runoff) for coastal basins without a substantial snowmelt component. Although they noted the existence of the PDO shift part way through their period of record, Stewart et al. (2005) argue that the variance in CT is explained both by temporal changes in the PDO and a general warming in the region, and that variations in PDO alone are insufficient to explain the observed trends. This finding is supported by the absence of coherent shifts in CT for non-snowmelt dominated streams.

Pagano and Garen (2005) found that the variability of April-September streamflow at 141 unregulated sites across the western U.S. has generally increased from about 1980 onward. This contrasts with a period of markedly low variability over much of the region from about 1930 through the 1970s. Although such shifts at decadal time scales have been observed before, and are even expected due to the nature of decadal scale variability, increased streamflow variability is a major concern for water managers, as it tends to diminish the reliability with which water demands can be satisfied.

4.9.4.2 Central

There has been relatively little work evaluating hydrologic trends in the central U.S. more specific than the U.S.-wide work of Lins and Slack (1999), and Mauget (2003). Garbrecht et al. (2004) analyzed trends in precipitation, streamflow, and evapotranspiration over the Great Plains. They found, in an analysis of 10 watersheds in Nebraska, Kansas, and Oklahoma with streamflow records starting from 1922 to 1950 (median start year about 1940) and all ending in 2001, a common pattern of increasing annual streamflow in all watersheds, most of which occurred in spring and winter (notwithstanding that most of the annual precipitation in these basins occurs in spring and summer). Garbrecht et al. also found that the relative changes in annual streamflow were much larger than in annual precipitation, with an average 12-percent increase in precipitation, leading to and average 64-percent increase in streamflow, but only a 5-percent increase in evapotranspiration. They also note that the large increases in streamflow had mostly occurred by about 1990, and in some (but not all) of the basins appeared to have reversed in the last decade of the record. Mauget (2004) analyzed annual streamflow records at 42 USGS Hydro-Climatic Data Network stations in a large area of the central and southern U.S. (stations included were as far west as eastern Montana and Colorado, as far east as Ohio, as far north as North Dakota, and as far south as Texas). They used an approach somewhat similar to that of Mauget (2003), based on a moving average (six to 30 year window) of the non-parametric Mann-Whitney U-statistic computed from the annual streamflow series for the same 1939-98 period used by Mauget (2003). Although the patterns vary somewhat across the stations, in general higher flow periods tended to occur more toward the end of the period than the beginning, indicating general increases in streamflow over the period. A more detailed analysis of daily streamflows indicate negative changes in the incidence of drought events (defined as sequences of days with flows below a station-dependent threshold) and increases in the incidence of “surplus” days (days with flows above a station-dependent surplus threshold). These results are broadly consistent with those of Lins and Slack (1999), and Andreadis and Lettenmaier (2006).

4.9.4.3 Northeast

The Northeast region is distinctive in that many records relating to hydrologic phenomena are relatively long. Burns et al. (in press) report that, based on data from 1952 to 2005, in the Catskill region of New York State (the source of most of New York City’s water supply), peak snowmelt generally shifted from early April at the beginning of the record, to late March at the end of the record, “consistent with a decreasing trend in April runoff and an increasing trend in maximum March air temperature.” Burns et al. also report increases in regional mean precipitation and regional mean potential evapotranspiration (PE), with generally increased regional runoff.

Hodgkins et al. (2003) and Hodgkins and Dudley (2006) studied high flows in rural, unregulated rivers in New England, where snowmelt dominates the annual hydrological cycle. They showed significantly earlier snowmelt runoff (using methods similar to those applied in the western U.S. by Stewart et al. (2005), with most of the change (advances of center of volume of runoff by one to two weeks) occurring in the last 30 years. Hodgkins et al. (2002) also noted reductions in ice cover in New England. Spring ice-out (when lake ice-cover ends) records between 1850 and 2000 indicate an advancement of nine days for lakes in northern and mountainous regions, and 16 days for lakes in more southerly regions. These changes were generally found to be related to warmer air temperatures.

Huntington et al. (2004), analyzed the ratio of snow to precipitation (S/P) for Historical Climatology Network (HCN) sites in New England and found a general decrease in the ratio, and decreasing snowfall amounts, which are consistent with warming trends. Hodgkins and Dudley (2006) found that 18 of 23 snow course sites in and near Maine with records spanning at least 50 years had decreases in snowpack depth, or increases in snowpack density, changes that are also consistent with a warming climate.

The Ohio Basin, also included within our northeast “super-region,” is relatively understudied in terms of climate change (Liu et al. 2000) despite its economic and demographic (population 25 million) importance, and the significance of its flow (it contributes 49 percent of the total Mississippi flow at Vicksburg). The Lins and Slack (1999) study of streamflow trends across the United States found increases in minimum and median flows at several locations in the Ohio basin, but no trend in maximum flows. McCabe and Wolock (2002) describe a step change (increases) in about 1970 in U.S. streamflow, which was most prevalent in the eastern U.S., including the Ohio. They related this apparent shift to a possible change in climate regime. Easterling and Karl (2001) note that during the 20th century there was a cooling of about 0.6°C in the Ohio basin, with warming in the northern Midwest of about 2°C for the same period. But they also report that the length of the snow season in the Ohio Valley over the second half of the 20th century decreased by as much as 16 days. In a study of evaporation and surface cooling in the Mississippi basin (including the Ohio), Milly and Dunne (2001) suggest that high levels of precipitation were caused by an internal forcing, and that a return to normal precipitation could reveal warming in the basin.

Moog and Whiting (2002) studied the relationship of hydrologic variables (precipitation, streamflow and snow cover) to nutrient exports in two basins adjacent to the northern boundary of the Ohio (Maumee and Sandusky Rivers). While not focused on climate-related changes directly, it is nonetheless of interest since it allows inferences to be made of how climate change might impact water quality in the basin. Antecedent precipitation and streamflow were found to be negatively correlated to pollution loading, and snow cover to be correlated with deferring loads. These results suggest how shifts in seasonal streamflow, and the increases in low and median flows observed by Lins and Slack (1999), might impact nutrient export from the basin.

4.9.4.4 South and Southeast

No studies were found that dealt specifically with hydrologic trends in the South and Southeast, although the national study of Lins and Slack shows generally increasing streamflow over most of this region in the second half of the 20th century. This result is consistent with Mauget (2003) and the part of the domain studied by Mauget (2004) that lies in the South and Southeast super-region. A related study by Czikowsky and Fitzjarrald (2004) analyzed several aspects of seasonal and diurnal streamflow patterns at several hundred USGS stream gauge stations in the east and southeastern U.S., as they might be related to evapotranspiration changes that occur at the onset of spring. These measures included the difference between precipitation minus runoff, the median of the daily runoff hydrographs recession time constant following storms, and the amplitude of diurnal streamflow variations. They found a general shift in runoff patterns earlier in the spring in Virginia (as well as in New England, and New York), but not in Pennsylvania and New Jersey.

4.9.4.5 Alaska

Hinzman et al. (2005) review evidence of changes in the hydrology and biogeochemistry of northern Alaska (primarily arctic regions). They showed decreases in warm season surface water supply, defined as precipitation minus potential evapotranspiration, at several sites on the Arctic coastal plain over the last 50 years. Precipitation was observed, and potential evapotranspiration was computed using observed air temperature. These downward trends were related primarily to increased air temperature, as precipitation trends generally were not statistically significant over the period. Permafrost temperatures (from borehole measurements at 20-meter depth) have increased over the last half century, with the increases most marked over the last 20 years. The authors also found some evidence of increasing discharge of Alaskan Arctic rivers over recent decades, although short records precluded a rigorous trend analysis. Records of snow cover at Barrow indicate that the last day of snow cover has become progressively earlier, by about two weeks over 60 years. Stewart et al. (2005), in their study of seasonal streamflow timing, included stations in Alaska (mostly south and southeast), and found that the shifts toward earlier timing of spring runoff in the western U.S. extended into Alaska (see Figure 4.8). Lins and Slack (1999) included a handful of HCDN stations in southeast Alaska, for which there did not appear to be significant trends over the periods they analyzed.

4.9.4.6 Hawaii

Oki (2004) analyzed 16 long-term USGS streamflow records from the islands of Hawaii, Maui, Molokai, Oahu, and Kauai for the period 1913 to 2002. They found that for all stations, there were statistically significant downward trends in low flows, but that trends were generally not significant in the annual or higher flows. When segregated into baseflow and total flow, baseflow trends were significant across almost the entire distribution (mean as well has high and low percentiles). In general, low and base flows increased from 1913 to about the early 1940s, and decreased thereafter. Oki also found that streamflow was strongly linked to the El Niño-Southern Oscillation (ENSO), with winter flows tending to be low following El Niño events, and high following La Niña events, a signal that is modulated to some extent by the PDO, and is most apparent in the total flows, and to a lesser extent in baseflows. Oki (2004) noted that changes in ENSO patterns could be responsible for the observed long-term trends, but did not attempt to isolate the portion of the observed trends that could be attributed to interannual and interdecadal variability attributable to ENSO and the PDO.

4.10 Water quality

Water quality reflects the chemical inputs from air and landscape and their biogeochemical transformation within the water (Murdoch et al. 2000). The inputs are determined by atmospheric processes and movement of chemicals via various hydrologic flowpaths of water through the watershed, as well as the chemical nature of the soils within the watershed. Water quality is also broadly defined to include indicators of ecological health (e.g. sensitive species). Regional scale variation in natural climatic conditions (precipitation pattern, and temperature) and local variation in soils generates spatial variation in "baseline" water quality and specific potential response to a given scenario of climate change. A warming climate is, in general, expected to increase water temperatures and modify regional patterns of precipitation, and these changes can have direct effects on water quality. However, a major challenge in attributing altered water quality to climate change is the fact that water quality is very sensitive to other, nonstationary human activities, particularly land use practices that alter landscapes and modify flux of water as well as thermal and nutrient characteristics of water.

In general, water quality is sensitive to temperature and water quantity. Higher temperatures enhance rates of biogeochemical transformation and physiological processes of aquatic plants and animals, thereby influencing measures of water quality. As temperature increases, the ability of water to hold dissolved oxygen declines, and as water becomes anoxic, animal species begin to experience suboptimal conditions. Nutrients in the water enhance biological productivity of algae and plants, which increases oxygen concentration by day, but at night these producers consume oxygen and oxygen sags can impose suboptimal anoxic conditions. Greater volumes of water can dilute nutrient concentrations and thus diminish excessive biological production, and higher flows can flush excess nutrients from sources of origin in a stream.

Most studies examining the responses of water quality over time have focused on nutrient loading, as this factor has changed significantly over time and there are specific U.S. laws (Clean Water Act) designed to reduce nutrient inputs into surface waters to increase their quality. For example, Alexander and Smith (2006) examined trends in concentrations of total phosphorus and total nitrogen and the related change in the probabilities of trophic conditions from 1975 to 1994 at 250 river sites in the United States with drainage areas > 1,000 km^2. Concentrations in these nutrients generally declined over the period, and most improvements were seen in forested and shrub-grassland watersheds compared to agricultural and urban watersheds. Ramstack et al. (2004) reconstructed water chemistry before European settlement for 55 Minnesota lakes. They found that lakes in forested regions showed very little change in water quality since 1800. By contrast, about 30 percent of urban lakes and of agricultural lakes showed significant increases in chloride (urban) or phosphorus (agricultural). These results indicate the strong influence of land use on water quality indicators. Detecting the effects of climate change requires the identification of reference sites that are not influenced by the very strong effects of human land use activities.

Recent historical assessments of changes in water quality due to temperature trends have largely focused on salmonid fishes in the western U.S. For example, Bartholow (2005) used USGS temperature gauges to document a 0.5°C per decade increase in water temperatures in the lower Klamath River from the early 1960s to 2001, driven by basin-wide increase in air temperatures. Such changes may be related to Pacific Decadal Oscillation. Increases in water temperature can directly and indirectly influence salmon through negatively affecting different life stages. Crozier and Zabel (2006) reported that air temperatures have risen 1.2°C from 1992 to 2003 in the Salmon River Basin in Idaho. Because water temperatures show a correlation with air temperature, smaller snowpacks that reduce autumn flows and cause higher water temperatures are expected to reduce salmon survival. Temperature effects can be indirect as well. For example, Petersen and Kitchell (2001) examined climate records for the Columbia River from 1933-1996 and observed variations of up to a 2°C between "natural" warm periods and cold periods. Using a bioenergetics model, they showed that warmer water temperatures are associated with an expected higher mortality rate of young salmon due to fish predators.

4.11 Attribution of changes

Trend attribution essentially amounts to attempting to answer the question "if trends were observed, what caused them?" Among the various agents of hydrologic change, the most plausible are a) changing climate, b) changing land cover and/or land use, c) water management, and d) instrumentation changes, or effects of other systematic errors – although certainly others could be hypothesized. Among the causes of streamflow trends (the variable assessed by most studies reviewed in this chapter), water management changes are the easiest to deal with. With respect to changes in streamflow (the variable analyzed by most of the studies reviewed above), the studies cited have all used streamflow records selected to be as free as possible of water management effects. For instance, USGS HCDN stations, used by Lins and Slack (1999; 2005), as well as several other studies reviewed, were selected specifically based on USGS metadata that indicate the effects of upstream water management. Certainly, it is not impossible for the metadata to be in error. An earlier study by Lettenmaier et al. (1994) used a set of USGS records that pre-dated HCDN, which was selected using similar methods, identified some stations where there were obvious water management effects upstream, despite metadata entries to the contrary. However, the number of such stations was small, and in any event the clear spatial structure in the Lins and Slack results shown in Figure 4.7, for instance, if attributable to water management, would require a corresponding spatial structure to errors in the metadata, which seems unlikely. In short, while it could be that some of the detected trends are attributable to undocumented water management effects, it is highly unlikely that the same could be said for the general patterns, or conclusions.

Changes in instrumentation are always of concern in trend detection studies, as shifts in instrumentation often are implemented at a particular time, and hence can easily be confounded with other trend causes. This is a problem, for instance, with precipitation measurement, where changes in gauge types, wind shields, and other particulars complicate trend attribution (it should be noted that these problems are addressed in precipitation networks like the U.S. Historical Climatology Network, which has had adjustments made for observing system biases). For streamflow observations, in contrast, the methods are relatively straightforward – the measured variable is river stage, which is converted to discharge via a stage-discharge relationship, formed from periodic coincident measurements of discharge and stage. The USGS has well established protocols for updating stage-discharge relationships, especially following major floods, which may affect the local hydraulic control. Therefore, while there almost certainly are cases where bias is introduced into discharge records following rating curve shifts, it is unlikely that such shifts would persist though a multi-decadal record, and even more unlikely that observed spatial patterns in trends could be caused by rating curve errors.

Distinguishing between the two remaining possible causes of trends – land cover and/or land use change and climate – is a much more difficult problem. Some land cover/land use change effects have striking effects on runoff. Urbanization is one such change agent, which typically decreases storm response time (the time between peak precipitation and peak runoff), increases peak runoff following storms, and decreases base flows (as a result of decreased infiltration). However, urban areas are generally avoided in selection of stations to be included in networks like HCDN, so urbanization is probably not a major contributor. Other aspects of land cover change, however, such as conversion of land use to or from agriculture, and forest harvest tend to affect much larger areas, and often occur over many decades, hence have time constants that are similar to decadal and longer scale climate variability. Relatively few studies have been performed that have attempted to quantify the effects on runoff of large-scale vegetation change. Matheussen et al. (2000) studied land cover change in the Columbia River basin from 1900 to 1990, and estimated that changes to annual runoff from forest harvest and fire suppression were at most 10 percent (to one of eight sub-basins analyzed, more typical changes were of order five percent) over this time period. On the other hand, studies of smaller basins, where a large fraction of the basin can be perturbed over relatively short periods of time, have projected or measured much larger changes (see, e.g., Bowling and Lettenmaier (2001) for an example of modeled changes of forest harvest, and Jones and Grant (1996) for an observational study). Over basins the size of which have been analyzed within networks like HCDN, however, more modest changes are likely, and over such moderate (typical drainage areas hundreds to thousands of km^2 and up) efforts to isolate vegetation change from climate variability have been complicated by signal-to-noise ratios that are usually smaller for the vegetation than the climatic signal (see Bowling et al. 2000 for an example). In so arguing, though, it must be acknowledged that some studies have reported changes in the hydrologic response of intermediate sized drainage basins, such as those included in the HCDN, that appear to be attributable to land cover, rather than climate change (see e.g. Potter, 1991). In summary, we view it as unlikely that the hydrologic trends detected in the various studies reviewed above can be attributed, at least in large part, to land cover and land use change – but we cannot refute such a contention definitively.

The final cause to which long-term hydrological trends might be attributed is climate change. Although it is essentially impossible to demonstrate cause and effect, streamflow (and other land surface hydrological variables) clearly are highly sensitive to climate, especially precipitation. Hence, it is possible to compare trends in precipitation, for instance, with those in runoff, and in fact most efforts to do so (some explicit, others more indirect) show a general correspondence, at least in the continental U.S., between changes in precipitation and runoff. Certainly, this effect is clear in the Lins and Slack (1999; 2005) results, where generally increased streamflow over most percentiles of the flow frequency distribution (and to the annual minima) seem to correspond to generally upward trends in precipitation across much of the continental U.S. For the annual maxima (floods), the correspondence to precipitation is less obvious. While various studies have shown increases in intense precipitation across the continental U.S. (e.g., Groisman et al., 1999), the absence of corresponding increases in flood incidence has remained a somewhat open question. Groisman et al. (2001) performed an analysis to show that shifts in the probability distribution of extreme precipitation in general correspond to shifts in flood distributions, however the fact remains that few changes were detected in extreme floods in the Lins and Slack analysis, and of those changes the number of downtrends and uptrends was nearly equal. One possible reason for the discrepancy is that the "floods" analyzed by Groisman et al. (2001) are not of the same general magnitude as the annual maxima series analyzed by Lins and Slack (1999) (which is the basis for estimation of the frequency distribution of extreme floods commonly used for risk analysis, e.g., the 100-year flood plain used for land use planning). Another reason that has been advanced is that the shifts in intense precipitation observed by Groisman et al. (1999) and others occur mostly during periods of the year when extreme floods are uncommon.

Notwithstanding these difficulties related to the upper tail of the streamflow distribution, most streamflow trends do, at least generally, correspond to observed trends in precipitation. The question then becomes, are these changes evidence of climate change, or decadal (or longer) scale variability. This is a question that cannot be addressed through hydrologic analysis alone. There is a close link between decadal and longer scale variability. As just one example, observed downward trends in streamflow in the Pacific Northwest are difficult to discriminate from changes associated with a mid-70s shift in the PDO, especially because this change occurred at about the mid-point of many streamflow records (many stations in the Pacific Northwest date to the late 1940s). The most promising way to deal with this issue is through use of model reconstructions (see e.g. Mote et al. 2005; Hamlet et al. 2007), which attempt to segregate decadal scale variability from longer term (century or longer) shifts. Most of the studies reviewed in this chapter do not incorporate such methods, however, and must be qualified (as the authors have explicitly in many cases) to the effect that while the studies identify trends, they do not attempt attribution.

4.12 Future changes and impacts

We review briefly in this section recent work that has assessed potential impacts of climate change over the next several decades (formally, to the mid-21st century) on the water resources and water quality of the United States. Numerous studies of the impacts of climate change on U.S. water resources have been performed, many of which are reviewed in, for instance, special issues of journals (see, for instance, Gleick 2000) and IPCC reports (e.g. Arnell and Liu 2001). An exhaustive review of this considerable body of research is beyond the scope of this chapter, and in any event, would be duplicative. Instead, we limit our review here to work that derives directly from climate scenarios archived for the 2007 IPCC assessment.

This recent work has several particular features. First, the global greenhouse gas emissions scenarios used in global model runs archived for use with the 2007 IPCC assessment are, in general, more consistent across models than in previous IPCC studies. Most models were run with transient scenarios (that is, global greenhouse gases increasing over time from an initial condition that typically is consistent with conditions as of about 2000) as specified in the IPCC (2000) Special Report on Emissions Scenarios (SRES). Although this report was issued prior to the 2001 IPCC Third Assessment Report, the full effect of the SRES report was not felt until the IPCC Fourth Assessment Report (2007) because of the lag time of several years that is required to run GCMs (often incorporating model improvements) and to archive their output. Second, the GCM physical parameterizations have improved with time, as has the spatial resolution, notwithstanding that the spatial resolution of most models is still coarse relative to the spatial scales required for regional impact assessments. Third, the length of GCM model runs has generally increased, with most modeling centers that have made runs available for IPCC analyses now producing simulations of length at least 100 years, and in many cases with multiple ensembles for each of several emissions scenarios. Finally, archiving model runs at the Lawrence Livermore National Laboratory's Program for Climate Model Diagnosis and Intercomparison (PCMDI) in common formats has greatly facilitated user access to the climate model scenarios.

Milly et al. (2005) evaluated global runoff from a set of 24 model runs (some were multiple ensembles from the same GCM, and global emission scenarios) archived for the IPCC AR4. They pre-screened model results by comparing model-estimated runoff from 20th century retrospective runs (GCM runs using estimated global emissions during the 20th century) with observations. The 12 models (total of 65 model runs, including multiple ensembles for some models) that had the lowest root means square error (RMSE) of runoff per unit area over 165 large river basins globally, for which observations were available, were retained for evaluation of 21st century projections. The rationale for retaining only those models with plausible reproductions of 20th century runoff globally was that future projections for models that are unable to reproduce past runoff characteristics may be called into question. For the same 12 models, a set of 24 model runs was extracted from the PCMDI archive. Each of the model runs was performed by the parent global modeling center using the IPCC A1B global emissions scenario, which reflects modest reductions in current global greenhouse gas emissions trends over the 21st century (somewhat similar to what has been termed "business as usual" scenarios in the past). There were 24 runs for the 12 models because multiple ensembles were available for some models.

Milly et al. (2005) show, in Figure 4.4, projected changes in runoff globally for the 24 model runs, as both mean changes in fractional runoff for the future period 2041 to 2060 relative to the period 1900 to 1970 in the same model's 20th century run, and in the difference between the number of models showing increases less the number showing decreases. In Figure 4.10, we show the same results, plotted by Dr. Milly's group at Geophysical Fluid Dynamics Laboratory (GFDL) for the 18 USGS water resources regions in the continental U.S., plus Alaska. In Figure 4.10, the shading identifies the median fractional change in runoff over the 24 model run pairs for 2041 to 2060 relative to 1901-1970 (using the median, rather than the mean as in the original paper, which results in slightly improved statistical behavior). Figure 4.10 shows that, taken over all 24 of the model run pairs, the projections are for increased runoff over the eastern U.S., gradually transitioning to little change in the Missouri and lower Mississippi, to substantial (median decreases in annual runoff approaching 20 percent) in the interior of the West (Colorado and Great Basin). Runoff changes along the West Coast (Pacific Northwest and California) are also negative, but smaller in absolute value than in the Western Interior basins.

Figure 4.10 also shows, in a manner similar to Figure 4.4 in Milly et al. (2005), the consistency in the direction of changes across the 24 model pairs. In particular, the percentages given in the figure body are the fraction of model pairs for which the change was in the same direction as the indicated change in the model median. Hence, for Alaska, all 24 model pairs (100 percent) showed runoff increases, whereas for the Pacific Northwest, 16 pairs (67 percent) showed runoff decreases, whereas eight pairs (33 percent) showed runoff increases.

It is important to note several caveats and clarifications with respect to these results. First, the results for the various GCMs were interpolated to the USGS water resources regions, and some of the regions are small and are not well resolved by the GCMs (the highest resolution GCMs are somewhat less than three degrees latitude-longitude; most are somewhat coarser). Therefore, important spatial characteristics, such as mountain ranges in the western U.S., are only very approximately accounted for in these results. Second, there is, for some regions, considerable variability across the models as indicate above. In some cases (for instance, see the example for the Pacific Northwest above), there may be a substantial number of models that do not agree with the median change direction (on the other hand, it is impressive that 23 of 24 model pairs showed runoff decreases for the upper Colorado, which is the source of most of the runoff for the entire Colorado basin).

In the remainder of this section, we review studies that have used essentially the same model results pool (although not necessarily the same specific group of models) as in Milly et al. (2005). These studies use downscaling methods (generally statistical, meaning that relationships between a higher spatial resolution grid mesh and the lower resolution GCM grid are "trained" using historical observations) to produce forcings (usually precipitation and temperature, as well as, in some cases, other variables downscaled from the GCMs) for a land hydrology model. The advantage of these "off line" approaches is that the higher resolution land scheme is able to resolve spatial features,

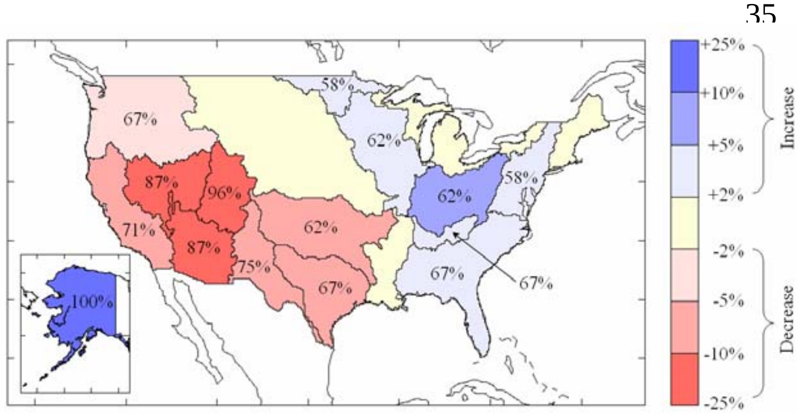

Figure 4.10 Median changes in runoff interpolated to USGS water resources regions from Milly et al. (2005) from 24 pairs of GCM simulations for 2041-2060 relative to 1901-1970. Percentages are fraction of 24 runs for which differences had same sign as the 24-run median. Results replotted from Milly et al. (2005) by Dr. P.C.D. Milly, USGS.

such as topography in the western U.S., which may control runoff response. As just one example, in mountainous areas, there are strong seasonal differences in the period of maximum runoff generation and ET with elevation, and these differences are not captured at the coarse spatial resolution of the GCM. Therefore, the regional simulations may capture certain negative feedbacks in the response to global warming (e.g., warming leads to earlier snowmelt runoff, hence earlier maximum soil moisture, which occurs at a time when net radiation is lower, hence reducing ET, and arguably reducing the sensitivity of runoff to increasing temperatures). The downside of the off-line approaches, however, is that they do not, in general, preserve the water balance at the large (GCM) scale. At this point, the nature of high-resolution feedbacks to the large (continental and global) scale remains an area for research. We believe it is important to view results of the regional studies discussed below in the context of the continental scale results shown in Figure 4.10, however.

4.13 Hydrology and water resources

As in Section 2.4, we partition the United States into the four "super-regions" shown in Figure 4.7. For each of these super-regions, we review the relatively small number of recent studies that have evaluated hydrologic and water resources implications of the IPCC AR4 archived model results.

Western United States

Two recent studies have used IPCC AR4 multimodel ensembles to evaluate climate change effects on hydrology of the western U.S. Maurer (2007) used statistical downscaling methods applied to eleven 21st century AR4 simulations to produce one-eighth degree latitude-longitude forcings for the VIC macroscale hydrology model over the Sacramento and San Joaquin River basins of California. The GCM runs used reflected SRES A2 and B1 emissions scenarios. They focused on four river basins draining to California's Central Valley from the Sierra Nevada, more or less along a transect from north to south: The Feather, American, Tolumne, and Kings Rivers. Their work primarily emphasized the variability across the ensembles relative to current conditions, and statistical significance of implied future changes given natural variability. All ensembles for both emissions scenarios are warmer than the current climate, whereas changes in precipitation are much more variable from model to model – although in the ensemble mean there are increases in winter precipitation and decreases in spring precipitation. These result in shifts in peak runoff earlier in the year, most evident in the higher elevation basins in the southern part of the domain. Notwithstanding variability across the ensembles, these runoff shifts are generally statistically significant, i.e., outside the bounds of natural variability, especially later in the 21st century (three periods are considered: 2011 to 2041, 2041 to 2070, and 2071 to 2100).

Although not considered explicitly in the paper, the results presented for 2041-2070 and emissions scenario A2 (which generally yields larger precipitation and temperature changes than B1) imply changes in ensemble mean runoff for the four basins as follows: +6.8 percent (increase) for the Feather; +3.1 percent for the American, +2.2 percent for the Tolumne, and -3.4 percent for the Kings River. By comparison, the Milly et al. results (for emissions scenario A1B, which results in slightly less warming than the A2 scenario used by Maurer) indicate reductions in annual runoff of -5 to -10 percent for California.

Christensen and Lettenmaier (2007) used similar methods to Maurer (2007) for the Colorado River basin. The eleven GCM scenarios, two emissions scenarios, and the statistical downscaling methods used in the two studies were identical. Christensen and Lettenmaier (2006) found that in the multimodel ensemble average for emission scenario A2 for 2040 to 2069, discharge for the Colorado River at Lees Ferry was predicted to decrease by about six percent, with a larger decrease of 11 percent indicated for 2070-2099. By comparison, the Milly et al. results suggest approximately 20 percent reductions in Colorado River runoff by mid-century.

The differences in the two downscaled studies as compared with the global results raise the question of why the off-line simulations (that is, simulations in which a hydrology model is forced with GCM output, rather than extracting hydrologic variables directly from a coupled GCM run) imply less severe runoff reductions (or in the case of three of the four California basins, increases rather than decreases) than do the GCM results. First, it must be said that the comparisons between Milly et al.'s (2005) global results and the off-line results from Maurer (2007) and Christensen and Lettenmaier (2007) should be interpreted with care; as indicated above, the emissions scenarios are slightly different, as are the models that make up the ensembles in the two studies. However, these factors do not seem likely to be the primary reason for the differences. As noted above, there is a negative feedback, reflected in the macroscale hydrology model results for snowmelt runoff under rising temperatures. Because this feedback is specific to the relatively high elevation headwaters portions of western U.S. watersheds, it is not well resolved at the GCM scale. However, while this feedback does appear to be present in the model results, it remains to evaluate whether the extent of the feedback in the model is consistent with observations. Second, spatial resolution issues also imply that precipitation (and temperature) gradients are less in the GCM than in either the off-line simulations or the true system, for instance the GCM resolution tends to "smear out" precipitation over a larger area, and hence nonlinear effects (such as much higher runoff generation efficiency at high elevations) are lost at the GCM scale. A third factor is the role of the seasonal shift (present in both California and the Colorado basin) from spring and summer to winter precipitation. Although this shift is present in the GCMs, the differential effect may well be amplified in the off-line, higher resolution runs, where increased winter precipitation leads to much larger increases in runoff than would the same amount of incremental precipitation spread uniformly over the entire basin. It should be emphasized, as indicated in Section 4.0, that these possible explanations should be cast as hypotheses, and not as definitive explanations.

4.13.1 Central

However, a general idea of potential impacts of climate change on the Central super-region can be obtained from the global results from Milly et al. (2005) as plotted to the USGS regions in Figure 4.9. This figure shows a general gradation in the ensemble mean from increased runoff toward the eastern part of the Central super-region (e.g., Ohio, which has the largest ensemble mean runoff increases within the continental U.S.), to neutral (slightly lower to slightly higher) in the upper Mississippi, to moderately negative in the Arkansas-Red. The concurrence among models is generally modest – i.e., typically at most two-thirds of the models are in agreement as to the direction of runoff changes, so even in the Ohio basin where the ensemble mean shows increased annual runoff of 10-25 percent, about one-third of the models show downward annual runoff (this contrasts, for instance, to the higher preponderance of models showing drying in the southwestern U.S.). Also, the results shown in Figure 4.9 are for annual runoff, and seasonal patterns vary. Due to increased summer evaporative stress, some (although certainly not all) models that predict increases in annual runoff may predict decreased summer runoff.

Jha et al. (2004) used a regional climate model to downscale a mid-21st century global simulation of the HADCM2 global climate model to the upper Mississippi River basin. This is a relatively old GCM simulation (not included in AR4), and as the authors note, is generally wetter and slightly cooler than other GCMs (and relative to the AR4 ensemble means shown in Figure 4.10). Their simulations showed that a 21-percent increase in future precipitation lead to a 50-percent net increase in surface water yield in the upper Mississippi River basin (this contrasts with the much smaller two to five percent increase in the multimodel mean runoff in Figure 4.10). Takle et al. (2006), using an ensemble of seven IPCC AR4 models, showed results that are more consistent with Figure 4.10 for the Upper Mississippi basin, specifically a multimodel mean increase in runoff of about three percent for the end of the 21st century. They found that these hydrologic changes would likely decrease sediment loading to streams, but that the implications for stream nitrate loading were indeterminate.

Schwartz et al. (2004) analyzed projections of Great Lakes levels associated produced by three GCMs run in the late 1990s for the IPCC TAR. Two of the three GCMs projected declines in lake levels, and one projected a slight increase. Declining lake levels were associated with increased harbor dredging costs, and some loss in vessel capacity. However, low confidence must be ascribed to the projected declines in lake levels, as FAR model output shows runoff changes in the multimodel mean (see Figure 4.10) to be on the margin between slightly negative and slightly positive, with nearly as many models projecting increases as decreases.

4.13.2 Northeast

Several studies have evaluated potential future climate changes and impacts in the Northeast using climate model simulations performed for the IPCC's AR4. Hayhoe et al. (2006) produced climate scenarios for the Northeast (which they defined as the 9-state area from Pennsylvania through Maine) using output from nine atmosphere-ocean general circulation models (AOGCMs) archived in the IPCC AR4 data base. Three IPCC emissions scenarios were included: B1, A2, and A1F1, which represent low, moderately high, and high global greenhouse gas emissions over the next century. Results were presented as model ensemble averages for two time periods: 2035 to 2064 and 2070 to 2099. For the earlier period, the model ensemble averages for increases in temperature (°C) are from 2.1 to 2.9, and for increases in annual precipitation, five percent to eight percent. The authors also used hydrologic modeling methods to evaluate the corresponding range of hydrologic variables for the period 2035-2064. They found increases in ET ranging from +0.10 to +0.16 mm/day; increases from 0.09 to 0.12 mm/day; advances in the timing of the peak spring flow centroid from five to eight days; and decrease in the mean number of snow days/month ranging from 1.7 to 2.2. The authors conclude that "the model-simulated trends in temperature and precipitation-related indicators …are reasonably consistent with both observed historical trends as well as a broad range of future model simulations."

Rosenzweig et al. (in press) use a similar approach applied to a smaller geographic region to determine how a changing climate might impact the New York City watershed region, which feeds one of the largest water systems in the United States. The authors used five models, also from the IPCC AR4 archive. Three emissions scenarios were used: B2, A1B and A2, representing low, moderate and relatively high emissions, respectively (A2 is also used in Hayhoe et al. 2006). The scenarios were downscaled to the New York watershed region using a weighting procedure for adjacent AOGCM gridboxes, and were evaluated using observed data. For the 2050s, temperature increases (°F) in the range 2 to 5.5°F were indicated relative to the 1970-1999 baseline period, with a median range of 3.5 to 4°F. Precipitation changes ranged from -2.5 percent to +12.5 percent, compared to the baseline, with the median in the range five to 7.5 percent. This study also produced scenarios of local sea level rise, a factor that impacts groundwater through salt water intrusion, river withdrawals for water use through the encroachment of the salt front, and sewer systems of coastal cites and wastewater treatment facilities (typically located on the coasts) through higher sea levels and storm surges.

Several studies have been performed of potential future climate change and impacts that are relevant to the Ohio River basin, but none are based on the most recent IPCC AR4 scenarios with multiple models and emissions scenarios. McCabe and Wolock (2002b) used prescribed future changes in climate, in this case an increase in monthly temperatures of 4°C, to examine changes in mean annual precipitation minus mean annual potential evapotranspiration (P-PE) and potential evapotranspiration (PE). In the Ohio basin, the drop in the first is relatively low, and the increase in the latter is moderate, reflecting the greater impact on PE (and thus P-PE) in warm regions as compared to cooler regions. Another study used a 4°C benchmark to examine land use effects relating to climate change. It found that land use conversion from commercial to low-density residential use decreased runoff (Liu et al. 2000). The early scenarios cited by Easterling and Karl (2001) suggest decreases of up to 50 percent in the snow cover season in the 21st century, and it is possible that by the end of the 21st century sustained snow cover (more than 30 continuous days of snow cover) could disappear from the entire southern half of the Midwest. However, these scenario results and others given by Easterling and Karl are based on earlier GCMs, and a comprehensive multimodel, multi-emissions AR4 scenario evaluation for the Ohio needs to be undertaken.

4.13.3 South and Southeast KH

No studies were identified that have assessed the implications of IPCC AR4 scenarios for the hydrology of the South and Southeast super-region. However, a general idea of potential impacts can be obtained from the global results of Milly et al. (2005) as plotted to the USGS regions in Figure 4.10. This figure shows a general gradation in the ensemble mean from east to west, with slightly increased runoff in the Southeast, near zero change in the lower Mississippi, and moderate decreases in the Texas drainages. As for the Central super-region, the concurrence among models is modest – for all regions within the South and Southeast super-region, two-thirds of the models are in agreement as to the direction of runoff changes, meaning that even for the Texas basins where moderate decreases in runoff are predicted in the ensemble mean, one-third of the models predicted increases. Furthermore, as for the Central sub-region, it should be emphasized that these results are for annual runoff, and shifts in the seasonality of runoff (generally higher summer evaporative stress will tend to decrease the fraction of runoff occurring in summer, and increase the fraction occurring at other times of the year, especially winter and spring, although this pattern certainly will not be present in all models).

4.13.4 Alaska

No studies were identified that have assessed hydrologic changes for Alaska associated with the AR4 scenarios. However, Figure 4.10 shows that relatively large runoff increases are suggested in the global model output for Alaska, a result that is consistent with the generally higher increases in temperature expected toward the poles. This, in turn, results in higher precipitation, in part because of increased moisture holding capacity of the atmosphere at higher temperatures, which results, in most model physics, in increased precipitation. Large increases in runoff (10-25 percent, larger than anywhere in the continental U.S.) are predicted in the ensemble mean, and all models (100 percent) concur that runoff will increase over Alaska (note also that such 100 percent agreement is not present anywhere else in the continental U.S.). Nonetheless, it should be noted that Alaska is a large area that covers several much different climatic regions, so considerable subregional, as well as seasonal, variability in these results should be expected.

4.13.5 Hawaii

No studies were identified that have assessed hydrologic changes for Hawaii associated with the AR4 scenarios. Furthermore, the Hawaiian Islands are far too small to be represented explicitly within the GCMs, so any results that are geographically appropriate to Hawaii are essentially for the ocean, and not the land. This is important as precipitation, and hence runoff, over this region are strongly affected by orography, and the nature of broader shifts in precipitation, as well as evaporative demand over land, interact in ways that can only be predicted accurately with regional scale modeling – an exercise that has not yet, to our knowledge, been undertaken.

4.14 Water quality

The larger scale implications for increasing water temperature across the nation are illustrated by a couple of modeling studies. Eaton and Scheller (1996) calculated that cool-water and cold-water fishes will shift their distributions nationwide, and streams and rivers currently supporting salmonids may become inhospitable as temperatures cross critical thresholds (see Keleher and Rahel 1996). Stefan et al. (2001) simulated the warming effects of a doubling of CO_2 on 27 lake types (defined by combinations of three categories of depth, area, and nutrient enrichment) across the continental United States, and examined the responses of fish species to projected changes in lake temperature and dissolved oxygen. They found that suitable habitat would be reduced by 45 percent for coldwater fish, and 30 percent for cool-water fish, relative to historical conditions (before 1980). Shallow and medium-depth lakes (maximum depths of four meters and 13 meters, respectively) were most affected. Habitat for warm-water fish was projected to increase in all lake types investigated.

Warmer temperatures will also enhance algal production, and most likely the growth of nuisance species, such as bluegreen algae, which diminish water quality. Modeling results suggest that increased temperatures associated with climate warming will increase the abundance of bluegreen algae, and thus reduce water quality. This effect is exacerbated by nutrient loading, pointing to the importance of human response to climate change in mediating some aspects of water quality (Elliott et al. 2006). Increased temperatures, coupled with lower water volumes and increased nutrients, would further exacerbate the problem.

Because warmer waters support more production of algae, many lakes may become more eutrophic due to increased temperature alone, even if nutrient supply from the watershed remains unchanged. Warm, nutrient-rich waters tend to be dominated by nuisance algae, so water quality will decline in general under climate change (Murdoch et al. 2000; Poff et al. 2002). The possible increase in episodes of intense precipitation projected by some climate change models implies that nutrient loading to lakes from storm-related erosion could increase. Further, if freshwater inflows during the summer season also are reduced, the dissolved nutrients will be retained for a longer time in lakes, effectively resulting in an increase in productivity. These factors will independently and interactively contribute to a likely increase in algal productivity.

A warmer and dryer climate will reduce streamflows and increase water temperatures. Expected consequences would be a decrease in the amount of dissolved oxygen in surface waters and an increase in the concentration of nutrients and toxic chemicals due to a reduced flushing rate (Murdoch et al. 2000). Reduced inputs of dissolved organic carbon from watershed runoff into lakes can increase the clarity of lake surface waters and allow biological productivity to increase at depth and ultimately deplete oxygen levels and increase the hypolimnetic stress in deeper waters (Schindler et al. 1996).

A warmer-wetter climate could ameliorate poor water quality conditions in places where human-caused concentration of nutrients and pollutants currently degrades water quality (Murdoch et al. 2000). However, a wetter climate, characterized by greater storm intensity and long inter-storm duration, may act to episodically increase flushing of nutrients or toxins into freshwater habitats. For example, Curriero et al. (2001) reported that 68 percent of the 548 reported outbreaks of waterborne diseases during the period of 1948 to 1994 were statistically associated with the 80 percent increase in precipitation intensity, implying that increased precipitation intensity in the future carries a health risk via polluted runoff into surface waters.

In general, an increase in extreme events will likely reduce water quality in substantial ways. More frequent floods and prolonged low flows would be expected to induce water quality problems through either episodic flushing of accumulated nutrients/toxins on the landscape followed by their retention in water bodies (Murdoch et al. 2000, Senhorst and Zwolsman 2005). Clearly, human actions in response to climate change will influence the ultimate affect of climate on water quality. In a modeling example, Chang (2004) used the HadCM2 scenario for five subbasins in southeastern Pennsylvania for projected changes in 2030 and found that climate change alone would slightly increase mean annual nitrogen and phosphorus loads, but concurrent urbanization would further increase N loading by 50 percent. This example illustrates how human land use activity interacts with warming climate and altered precipitation patterns to induce synergistic water quality changes.

4.14.1 Hydrology-landscape interactions

Across much of the continental U.S., annual precipitation increased during the 20th century, and especially in the second half of the century (the average precipitation increase was estimated as about seven percent by Groisman (2004)). Andreadis and Lettenmaier (2006) found that as a result, droughts generally became shorter, less frequent, and covered a smaller part of the country toward the end of the 20th century than toward the beginning (although they noted that the West and Southwest were apparent exceptions). Dai (2004) found that the fraction of the country under extreme (either wet or dry) conditions was increasing. Walter et al. (2004) found that ET has increased (by an average of about 55-millimeters) in the last 50 years in the conterminous U.S., but that stream discharge in the Colorado and Columbia River basins has decreased since 1950 (also coincidentally a period of major reservoir construction).

The most direct and observable connection between climate and terrestrial ecosystems is in life cycle timing of seasonal phenology, and in plant growth responses, annually in primary productivity, and decadally over changes in biogeographical range. These impacts on seasonality and primary productivity then cascade down to secondary producers and wildlife populations. The vegetation growing season as defined by continuous frost-free air temperatures has increased by, on average, two days/decade since 1948 in the conterminous U.S., with the largest change in the West, and with most of the increase related to earlier warming in the spring (Easterling 2002; Feng and Hu 2004). Global daily satellite data, available since 1981, has detected similar changes in earlier onset of spring “greenness” of 10-14 days in 19 years , particularly over temperate latitudes of the Northern Hemisphere (Myeni et al., 1997; Lucht et al. 2002). Honeysuckle first bloom dates have advanced 3.8 days/decade at phenology observation sites across the western United States (Cayan et al. 2001) and apple and grape leaf onset have advanced two days/decade at 72 sites in the northeastern U.S. (Wolfe et al. 2004).

As a result of these climatic and hydrologic changes, forest growth appears to be slowly accelerating (<1 percent/decade) in regions of the United States where tree growth is limited by low temperatures and short growing seasons, which are gradually being alleviated (McKenzie et al. 2001; Joos et al. 2002; Casperson et al. 2000). On the other hand, radial growth of white spruce in Alaska has decreased over the last 90 years due to increased drought stress on the dry, southern aspects they occupy (Barber et al. 2000). Semi-arid forests of the Southwest also showed a decreasing growth trend since 1895, which appears to be related to drought effects from warming temperatures (McKenzie 2001).

Climatic constraints on ecosystem activity can be generalized as variable limitations of temperature, water availability, and solar radiation, the relative impacts of which vary regionally and even locally (e.g., south vs north aspects) (Nemani et al. 2003; Jolly et al. 2005). Where a single climatic limiting factor clearly dominates, such as low temperature constraints on the growing season at high latitudes, or water limitations of deserts, ecosystem responses will be fairly predictable. However, where a seasonally changing mix of temperature and water constraints is possible, projection of ecosystem responses depends both on temperature trends, and the land surface water balance. While temperature warming trends for North America are well documented, the land water balance trends over the past half century suggest that roughly, the western half of the continent is getting drier and the eastern half wetter (see e.g. Andreadis and Lettenmaier 2006).

These changes have important implications for wildfires, especially in the western U.S., but elsewhere as well. From 1920 to 1980, the area burned in wildfires in the continental U.S. averaged about 13,000 km^2/yr. Since 1980, average annual burned area has almost doubled to 22,000 km^2 /yr, and three major fire years have exceeded 30,000km^2 (Schoennagel et al. 2004). The forested area burned from 1987-2003 is 6.7 times the area burned for the period 1970-1986, with a higher fraction burning at higher elevations (Westerling et al. 2006). Warming climate encourages wildfires by drying of the land surface, allowing more fire ignitions, and desiccated vegetation, and hot dry weather allow fires to grow exponentially more quickly, ultimately determining the area burned (Westerling et al. 2003). Relating climatic trends to fire activity is complicated by regional differences in seasonality of fire activity. Most fires occur in April to June in the Southwest and Southeast, and July to August in the Pacific Northwest and Alaska. Earlier snowmelt, longer growing seasons, and higher summer temperatures observed particularly in the western U.S. are synchronized with increase of wildfire activity, along with dead fuel buildup from previous decades of fire suppression activity (Westerling et al. 2006).

Insects and diseases are a natural part of all ecosystems; however, in forests periodic insect epidemics can erupt and kill millions of hectare of trees, providing dead, desiccated fuels for large wildfires. The dynamics of these epidemic outbreaks are related to insect life cycles that are tightly tied to climate fluctuations and trends (Williams and Liebhold 2002). Many of the northern insects have a two-year life cycle, and warmer winter temperatures now allow a higher percentage of overwintering larvae to survive. Recently, Volney and Flemming (2000) found that spruce budworm in Alaska have successfully completed their life cycle in one year, rather than two. Earlier warming spring temperatures allow a longer active growing season, and higher temperatures directly accelerate the physiology and biochemical kinetics of the life cycles of the insects (Logan et al. 2003). The mountain pine beetle has expanded its range in British Columbia into areas previously too cold to support their survival (Carroll et al. 2003). Multi-year droughts also reduce the available carbohydrate balance of trees, and their ability to generate defensive chemicals to repel insect attack (Logan et al. 2003).

Figure 4.11 Number of HCDN active stations 1905-2005 (upper panel), and location of discontinued stations as of 2005. Figure courtesy U.S. Geological Survey.

4.14.2 Observing system

Essentially no aspect of the current hydrologic observing system was designed specifically for purposes of detecting climate change or its effects. However, a major purpose of the stream gauging network when it was first established in the late 1800s was to provide basic information on water resource availability, a major aspect of which was water supply. More specifically, stream gauges were installed to help determine the natural variability of runoff, from which decisions about how much water could be extracted from a reservoir or reservoirs of a given size could be made. Over time, as the era of dam construction waned in the 1960s and 1970s, the purpose of the stream gauge network shifted as well, to focus more on water management than on design. Arguably, the network now is configured more to address accounting issues (i.e., stations are situated above and below major water management structures and/or diversions) than to address questions of long-term change, which requires location of stations where the confounding effects of water management, as well as other anthropogenic influences, are minimized. The HCDN is a subset of the USGS stream gauges first identified by Langbein and Slack (1982), with (then) record lengths of at least 20 years, which were considered “suitable for the study of variation of surface-water conditions in relation to climate variation” (see also Slack et al. 1993). The stations are intended to be mostly free of major anthropogenic influences, especially regulation by dams. Originally, more than 1,600 stations were included in this network, however the number of active stations is now substantially smaller (see Figure 4.11) due to discontinuation of stations over the years. (In most cases, HCDN stations are not supported, at least in their entirety, by federal funds. The most common funding mechanism is the USGS Cooperative (Co-op) Program, in which states and local agencies share the cost of station operation. Although the Co-op program allows leveraging of federal funds and hence operation of a much larger stream gauging program than would be possible from federal funds alone, it makes the station network susceptible to short-term budget issues in the cooperating agencies, and the loss of stations indicated in Figure 4.11 is, in large part, the result of such issues.) It is important to note that essentially all of the studies reviewed in this chapter that have analyzed long-term streamflow trends in the United States (e.g., Lettenmaier et al. 1994; Lins and Slack, 1999, 2005; Garbrecht et al. 2004; Mauget 2004; and McCabe and Wolock 2002a, among others) have been based on subsets of the HCDN network, hence the absence of a long-term strategy is of critical concern, and needs to be addressed.

Another key hydrologic variable that especially affects the western U.S. (in addition to parts of the upper Midwest and Northeast) is snow, and specifically snow water equivalent or SWE. In the western U.S., SWE has historically been observed at manual snow courses, at which observations were mostly taken by Natural Resources Conservation Service (NRCS) (in California, observations have been taken by the Department of Water Resources). These observations are relatively costly to collect, as they involve travel to remote, mostly mountainous areas, and for this reason observations were collected only a few times per year (usually around April 1, at about the time of maximum snow accumulation. In the early 1980s, NRCS began to transition to an automated network of snow pillows (which essentially record the weight of snow on a pressure sensor, which is then converted to SWE). In California, there has been a similar transition from manual snow course to snow pillows, although California’s Department of Water Resources continues to collect manual snow course data as well. The major advantage of the snow pillows is that data are essentially continuous, and the data transmission system provides additional channels that allow other variables (typically temperature and precipitation) to be transmitted as well. Analyses of long-term snow trends have faced the problem of merging the snow course and SNOTEL data. There are a variety of problems in so doing – for instance, thermodynamic properties of snow sensors are different from those of the surrounding natural landscape, and this can affect the rate of spring melt, and hence statistics like “last date of snow.” Furthermore, standard protocol for snow course measurements is to average a number (usually at least 10) of manual cores taken along a transect – or transects – that cover a larger area than do the snow pillows, so the representation of local spatial variability differs (see e.g.

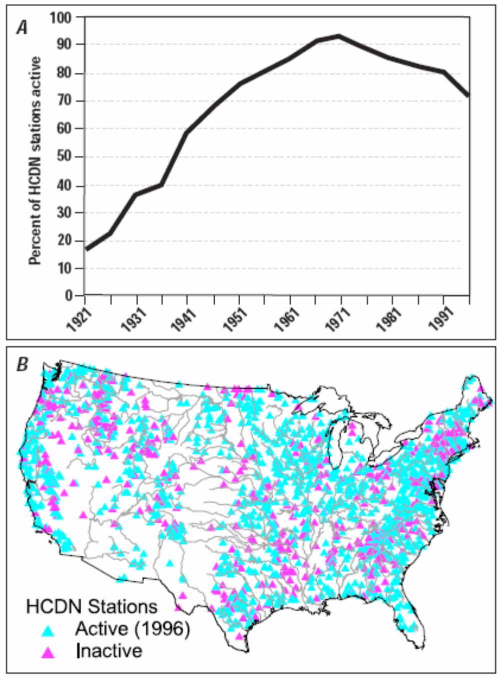

Figure 4.12 Number of HCDN active stations 1921-1996, and location of discontinued stations (Figure courtesy USGS, to be updated).

Dressler et al. 2006). Pagano et al. (2004) have shown how the transition from manual snow courses to the SNOTEL network has affected the accuracy of seasonal streamflow forecasts across the west.

Like HCDN, the purpose of the snow course (and SNOTEL) networks was not monitoring of climate change and variability, but rather support of water management through provision of basic data used in water supply forecasting. However, as demands for information related to long-term climate-related shifts in snow properties have grown, the network(s) have begun to be used increasingly for these purposes. NRCS' National Water and Climate Center has initiated a study to evaluate effects of changes in SNOTEL instrumentation (e.g. metal or hypalon pillows), their comparison with manual snow courses, as well as systematic changes in snow courses and SNOTEL sites related to changes in vegetation and other site-specific characteristics, to provide better background information as to sources of systematic errors in long-term SWE records. A significant number of SNOTEL sites have been augmented with soil moisture and soil temperature sensors to improve spring runoff forecasts and basin-specific water management. The SNOTEL network also supports snow depth, relative humidity, wind speed/direction, and solar radiation measurements.

As noted in Section 4.4, evaporation pans do not provide a direct measurement of either actual or potential evaporation. Nonetheless, they provide a relatively uncomplicated measuring device, and the existing long-term records, taken together with the analyses discussed in Section 4.4, do provide a land surface data record that has some value. Pan evaporation data are most commonly collected at agricultural experiment stations, and are archived by the National Climatic Data Center.

Actual evaporation can be measured in several ways. One is weighing lysimeters, which, generally, are only practical for relatively short vegetation, such as crops, and are complicated by the disturbance to the surface inherent in their construction. The second is Bowen ratio sensors, which measure the gradient of humidity and air temperature close to the surface, the ratio of which, under an assumption that bulk transfer coefficients for latent and sensible heat are identical, is equal to the ratio of sensible to latent heat (the Bowen ratio). The Bowen ratio is used to partition the residual of net radiation and ground heat flux (both of which must be measured) into latent heat (equal to evapotranspiration, when adjusted by a proportionality factor) and sensible heat. Another method of estimating evapotranspiration (or more accurately, latent heat) directly is through eddy correlation, which essentially measures high frequency variations in the vertical component of wind and humidity, the product of which, when averaged over time, is the latent heat flux. Both the Bowen ratio and eddy correlation methods require some assumptions (see Shuttleworth, 1993), however the eddy correlation method, which is somewhat more direct, seems to have gained favor recently. The AmeriFlux network consists of about 200 stations across the continental U.S. at which evapotranspiration (mostly by the eddy correlation method) is measured. The longest term records at these stations are somewhat longer than 10 years – not nearly long enough for meaningful trend analysis. Furthermore, instrumentation has evolved over time, and there is a need for careful calibration and maintenance of the instrumentation, as well as quality control to assure, for instance, that the measured energy flux terms (some, but not all, Ameriflux stations measure downward and reflected solar and longwave radiation, as well as latent, sensible, and ground heat flux) balance. In the long-term, however, the quality (and reliability) of the instrumentation will improve, and this network appears to offer the best hope for direct, long-term measurements of evapotranspiration.

Soil moisture is a key indicator of the hydrologic state of the land system. However, until recently, there was no national soil moisture network, and the NRCS SCAN (Soil Climate and Analysis Network) dates only to 1998, and at present consists of fewer than 150 stations (although eventually, if fully funded, plans exist to create 1,000 stations). The most established soil moisture network is operated by the state of Illinois, and for about 25 years has produced data at about 20 stations statewide. More recently, the Oklahoma Mesonet network has observed soil moisture on a county by county basis in Oklahoma, and a few other state networks have been initiated. These networks will become increasingly important as time passes, particularly given concerns over possible effects of climate change on drought, and steps are needed to assure the longevity of a core network of soil moisture stations with an appropriate national distribution.