# Water Resources

**Key Messages:**

- Climate change already has altered, and will continue to alter the water cycle, affecting where, when, and how much water is available.
- Floods and droughts will become more common and more intense.
- Precipitation and runoff are projected to increase in the Northeast and Midwest, while decreasing in the West, especially the Southwest.
- In mountain areas where snowpack dominates, the timing of runoff will shift to earlier in the spring and flows will be lower in late summer.
- Surface water quality and groundwater quantity will be affected by a changing climate.
- Climate change will place additional burdens on already stressed water systems.
- The past century is no longer a reasonable guide to the future for water management.

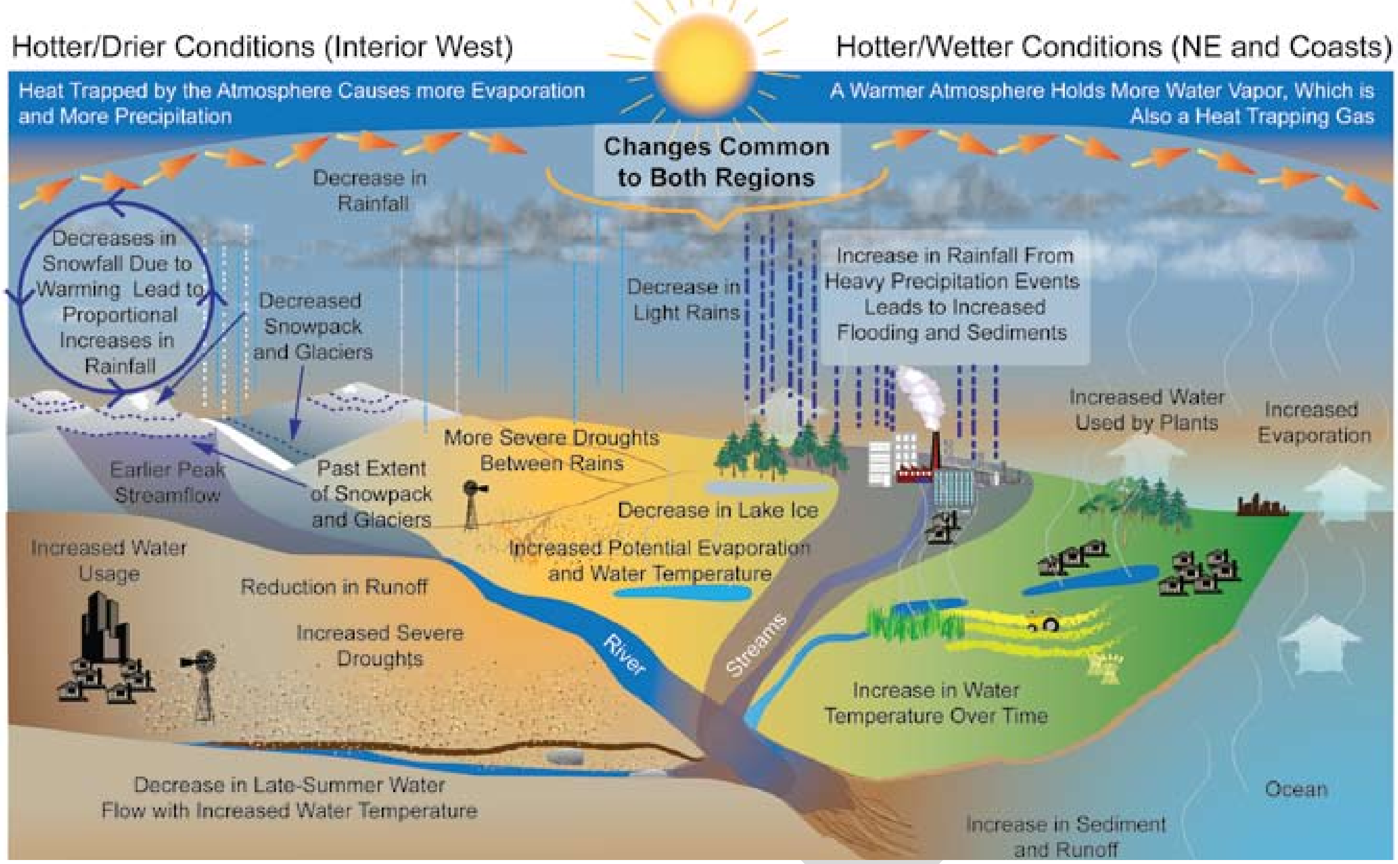
The warming observed over the past several decades is consistently associated with changes in the water cycle such as changes in precipitation patterns and intensity, incidence of drought, widespread melting of snow and ice, increasing atmospheric water vapor, increasing evaporation, increasing water temperatures, reductions in lake and river ice, and changes in soil moisture and runoff. Regional projections differ markedly with increases in precipitation, runoff, and soil moisture in the Midwest and Northeast, and declines in the West and Southwest. Climate change impacts include too little water, too much water, and degraded water quality. Water cycle changes are expected to continue and will adversely affect energy production and use, human health, transportation, agriculture, and ecosystems[1].

Skagit River and surrounding mountains in the Northwest

## Climate change has already altered, and will continue to alter the water cycle; affecting where, when, and how much water is available.

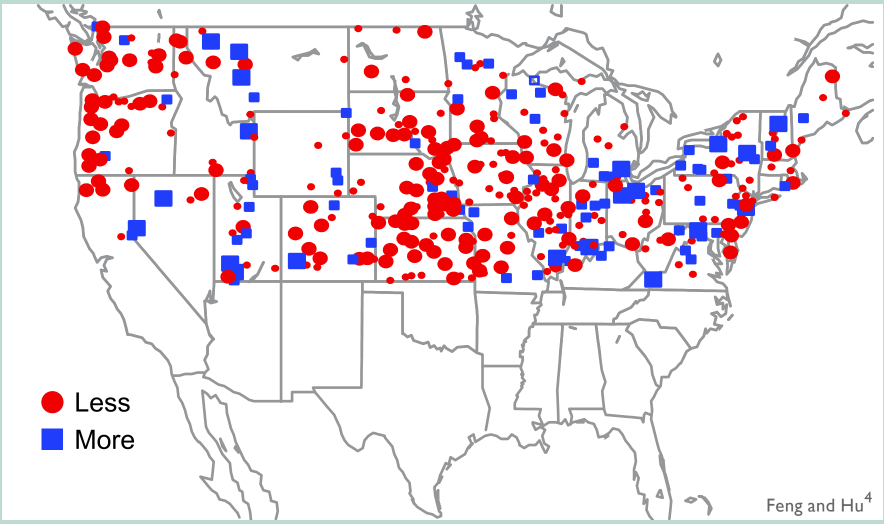
Substantial changes to the water cycle are expected as the planet warms because the movement of water in the atmosphere and oceans is one of the primary mechanisms for redistribution of heat around the world. Evidence is mounting that human-induced climate change is already altering many of the existing patterns of precipitation in the United States, including when, where, how much, and what kind of precipitation falls[1,2]. A warmer climate increases evaporation of water from land and sea, and allows more moisture to be held in the atmosphere. For every 1°F rise in temperature, the water holding capacity of the atmosphere increases by about 4 percent[3]. Coupled with other warming-related changes, this additional moisture-holding capacity tends to lead to more evaporation, and hence longer and more severe droughts in some areas, especially in arid and semi-arid areas such as the Southwest.

The additional atmospheric moisture contributes to more overall precipitation in some areas, especially in the Northeast and Alaska. Over the past century, Projected Changes in the Water Cycle



The water cycle exhibits many changes as the earth warms. Wet and dry areas respond differently. NOAA NCDC

Changes in Snowfall Contributions to Wintertime Precipitation
1949 to 2005



Trends in winter-snow-to-total-precipitation ratio from 1949-2005. Red circles indicate less snow, while blue squares indicate more snow. Large circles and squares indicate the most significant trends[4].

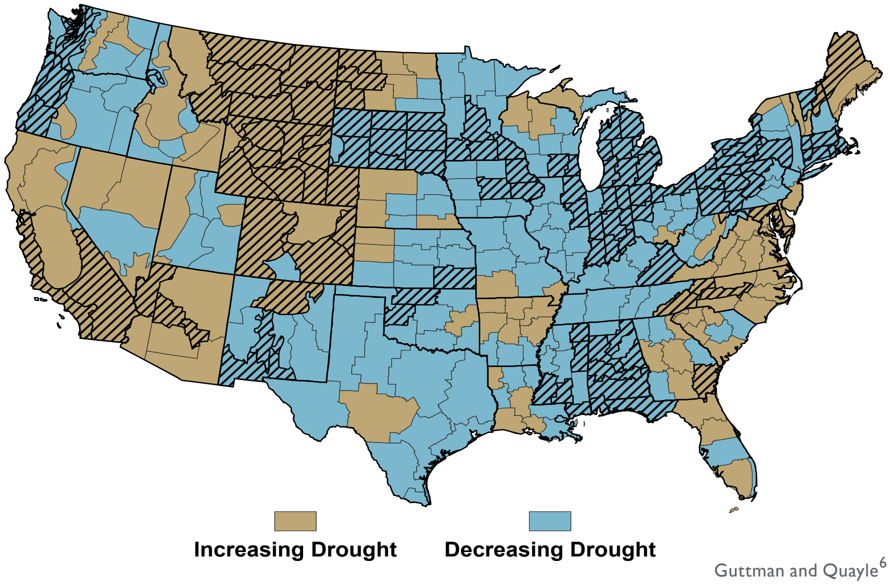
precipitation and streamflow have increased in the East and Midwest, with a reduction in drought duration and severity. The West has had reductions in precipitation and increases in drought severity and duration, especially in the Southwest.

In most areas of the country, the fraction of preciptation falling as rain versus snow has increased during the last 50 years. Despite this general shift from snow to rain, snowfalls along the downwind coasts of the Great Lakes have increased where reduced ice cover, due to warming lengthens the period of open water, allowing strong evaporation when temperatures are still cold enough to produce heavy snow. Heavy snowfall has increased in many northern parts of the United States. In the South however, where temperatures are already marginal for heavy snowfall, climate warming has lead to a reduction in heavy snowfall[2].

### Observed Changes in Water Resources During the Last Century[5]

| Observed Change | Direction of Change | Region Affected |
|---|---|---|
| One to four week earlier peak streamflow due to earlier warming-driven snowmelt | | West and Northeast |
| Proportion of precipitation falling as snow | Decreasing | West |
| Duration and extent of snow cover | Decreasing | Most of the United States |
| Mountain snow water equivalent | Decreasing | West |
| Annual precipitation | Increasing | Most of the United States |
| Annual precipitation | Decreasing | Southwest |
| Frequency of heavy precipitation events | Increasing | Most of the United States |
| Runoff and streamflow | Decreasing | Colorado and Columbia River Basins |
| Streamflow | Increasing | Most of East |
| Amount of ice in mountain glaciers | Decreasing | U.S. Western Mountains, Alaska |
| Water temperature of lakes | Increasing | Most of the United States |
| Ice cover | Decreasing | Great Lakes |
| Periods of drought | Increasing | West |
| Salinization of surface waters | Increasing | Florida, Louisiana |
| Widespread thawing of permafrost | Increasing | Alaska |

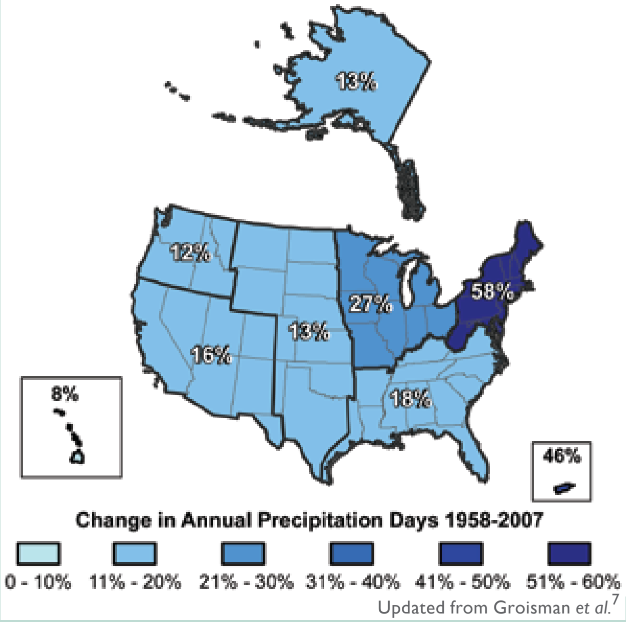
Observed Drought Trends 1900 to 2008



Guttman and Quayle[6]

Trends in end-of-summer drought as measured by the Palmer Drought Severity Index from 1900 through 2008 in each of 344 U.S. climate divisions. Areas with hatching indicates significant trends. Values are averaged in climate divisions of each U.S. state by averaging the corresponding station observations within each climate division beginning in January 1931. For data prior to 1931 values were calculated from a regression analysis of statewide values generated by averaging station observations within each state[6].

Increases in Very Heavy Precipitation Days
1958-2007



Updated from Groisman *et al.*[7]

The map shows the percentage increases in the average number of days with very heavy precipitation (defined as the heaviest 1 percent of all events) from 1958 to 2007 for each region, compared to a baseline period of 1961-1990. The clearest trends toward more very heavy precipitation days are evident at the national scale, and in the Northeast and Midwest.

## Floods and droughts will become more common and more intense.

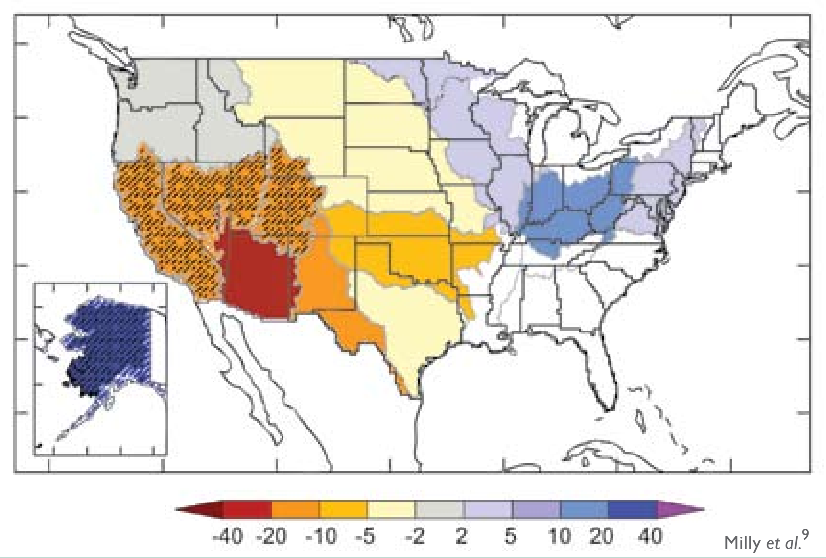
While it sounds counterintuitive, a warmer world produces both wetter and drier conditions because even though global precipitation increases, the regional distribution of precipitation changes. More precipitation comes in heavier rains (which can cause flooding) rather than light events. In the past century, averaged over the United States, total precipitation has increased by about 7 percent, while the heaviest 1 percent of rain events increased by nearly 20 percent[2]. This has been especially noteworthy in the East, where the annual number of days with very heavy precipitation has also increased in the past 50 years, as shown in the adjacent figure. Observations also show that over the past several decades, extended dry periods have become more frequent in parts of the United States, especially the Southwest[8]. Longer periods between rainfalls, combined with higher air temperatures, dry out soils and vegetation, causing drought.

For the future, precipitation intensity is projected to increase everywhere, with the largest increases occurring in areas in which average precipitation increases the most. For example, the Midwest and Northeast, where total precipitation is expected to increase the most, will also experience the largest increases in heavy precipitation events. The number of dry days between precipitation events is also projected to increase, especially in the more arid areas. Mid-continental areas and the Southwest are particularly threatened by future drought. The magnitude of the projected changes in extremes is expected to be greater than changes in averages, and hence detectable sooner[1-3,9].

## Precipitation and runoff are projected to increase in the Northeast and Midwest, while decreasing in the West, especially the Southwest.

Runoff, which accumulates as streamflow, is the amount of precipitation that is not evaporated, stored as snowpack or soil moisture, or filtered down to groundwater. The proportion of precipitation that runs off is determined by a variety of factors, including temperature, wind speed, humidity, Sun intensity, vegetation, and soil moisture. While runoff generally tracks precipitation, increases and decreases in precipitation do not necessarily lead to equal increases and

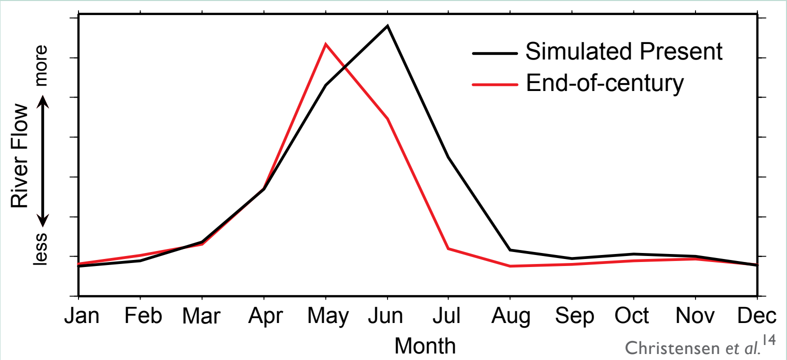
Projected Changes in Annual Runoff



Milly *et al.*[9]

Projected changes in median runoff for 2041 to 2060, relative to a 1901 to 1970 baseline, are mapped by water-resource region. Colors indicate percentage changes in runoff. Hatched areas indicate greater confidence. Based on emissions in between the lower and higher emissions scenarios[†].

Projected Changes in Annual Runoff Pattern



Christensen *et al.*[14]

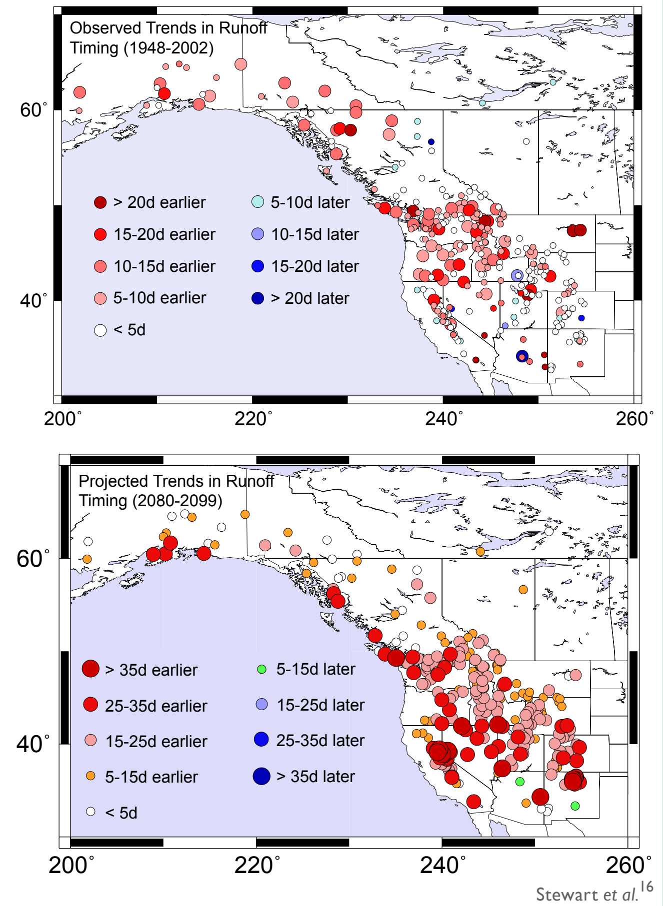
General schematic of changes in the annual pattern of runoff for snowmelt-dominated streams. Compared to the historical pattern, runoff peak is projected to shift to earlier in the spring and late summer flows are expected to be lower. The above example is for the Green River, which is part of the Colorado River watershed.

decreases in runoff. For example, droughts cause soil moisture reductions that can reduce expected runoff until soil moisture is replenished. Conversely, water-saturated soils can generate floods with only moderate additional precipitation. During the last century, consistent increases in precipitation have been found in the Midwest and Northeast along with increased runoff[11]. Climate models consistently project that the East will experience increased runoff, while there will be substantial declines in the interior West, especially the Southwest. Projections for runoff in California and other parts of the West also show reductions, although less than in the interior West. Climate models consistently project heat-related summer soil moisture reductions in the middle of the continent[1,8,11-13].

**In mountain areas where snowpack dominates, the timing of runoff will shift to earlier in the spring and flows will be lower in late summer.**

Large portions of the West rely on snowpack as a natural reservoir to hold winter precipitation until it later runs off as streamflow in spring, summer, and fall. Over the last 50 years, there have been widespread temperature-related reductions in snowpack in the West, with the largest reductions occurring in lower elevation mountains in the Northwest and California where snowfall occurs at temperatures close to the freezing point[1,15]. Observations indicate a transition to more rain and less snow during this period[4,5]. Runoff is occurring earlier in the year in snowmelt-dominated areas of the West, in some cases, up to 20 days earlier[16,17]. Future projections for most snowmelt-dominated basins in the West consistently indicate earlier spring runoff, in some cases up to 60 days earlier, which produces lower late-summer streamflows[16,18]. These lower streamflows stress human and environmental systems through less water availability and higher water temperatures[7]. Scientific analyses to determine the causes of recent changes in snowpack, runoff timing, and increased winter temperatures have attributed

Observed and Projected Trends in Peak Streamflow Timing



Stewart *et al.*[16]

Top map shows changes in runoff timing in snowmelt-driven streams during 1948-2002 with red circles indicating earlier runoff, and blue circles indicating later runoff. Bottom map shows projected changes in snowmelt-driven streams by 2080-2099, compared to 1951-1980, under a higher emissions scenario[†].

**Highlights of Water-Related Impacts by Sector**

| Sector | Impacts |
|---|---|
| Human Health | Heavy downpours increase incidence of water-borne disease and floods, resulting in hazards to human life and health[20]. |
| Energy Production and Use | Reductions in hydropower due to low flows in some regions. Reduced power generation in fossil fuel and nuclear plants due to increased water temperatures and reduced cooling water availability[21]. |
| Transportation | Floods and droughts disrupt transportation. Heavy downpours affect harbor infrastructure and inland waterways. Declining Great Lakes levels reduce freight capacity[22]. |
| Agriculture and Forests | Intense precipitation can delay spring planting and damage crops. Earlier spring snowmelt leads to increased number of forest fires[23]. |
| Ecosystems | Cold-water fish threatened by rising water temperatures. Some warm water fish will expand ranges[24]. |

these changes to human-caused climate change[19]. One to two week earlier spring runoff in snowmelt-dominated streams in the Northeast have also been recorded[1,10,18].

## Surface water quality and groundwater quantity will be affected by a changing climate.

### *Changes in water quality*

Increased air temperatures lead to higher water temperatures, which have already been detected in many streams, especially during low-flow periods. In lakes and reservoirs, higher water temperatures lead to longer periods of summer stratification (when surface and bottom waters don't mix). Dissolved oxygen is reduced in lakes, reservoirs, and rivers at higher temperatures. Oxygen is an essential resource for many living things, and its availability is reduced at higher temperatures both because the amount that can be dissolved in water is lower and because respiration rates of living things are higher. Low oxygen stresses aquatic animals such as cold-water fish and the insects and crustaceans on which they feed[1]. Lower oxygen levels also decrease the self-purification capabilities of rivers.

Many forms of water pollution, including sediments, nitrogen from agriculture, disease pathogens, pesticides, herbicides, salt, and thermal pollution, will be exacerbated by observed and projected increases in precipitation intensity and longer periods when streamflow is low[8]. The U.S. Environmental Protection Agency expects the number of waterways considered "impaired" by water pollution to increase[25]. However, regions that experience increased streamflow will have the benefit of pollution being more diluted. Heavy downpours lead to increased sediment in runoff and outbreaks of water-borne diseases[20,26]. Increases in pollution carried to lakes, estuaries, and the coastal ocean, especially when coupled with increased temperature, can result in blooms of harmful algae and bacteria. Water quality changes during the last century were likely to be attributable to causes other than climate change, primarily changes in pollutants[11]. There are only a few studies on the impacts of climate change on water quality; to date, water quantity impacts have been the focus of most climate change research.

### *Changes in groundwater*

Many parts of the United States are heavily dependent on groundwater for drinking, residential, and agricultural water supplies[27,28]. How climate change will affect groundwater is not well known, but increased water demands by society in regions that already rely on groundwater will clearly stress this resource, which is often drawn down faster than it can be recharged[29,30]. In many locations, groundwater is closely connected to surface water and thus trends in surface-water supplies over time affect groundwater. Changes in the water cycle that reduce precipitation or increase evaporation and runoff would reduce the amount of water available for recharge. Changes in vegetation and soils that occur as temperature changes or due to fire or pest outbreaks are also likely to affect recharge by altering evaporation and infiltration rates. Increased frequency and magnitude of floods are likely to increase groundwater recharge in semi-arid and

Heavy rain can cause sediments to become suspended in water, reducing its quality, as seen in the brown swath above in New York City's Ashokan reservoir following Hurricane Floyd in September 1999.

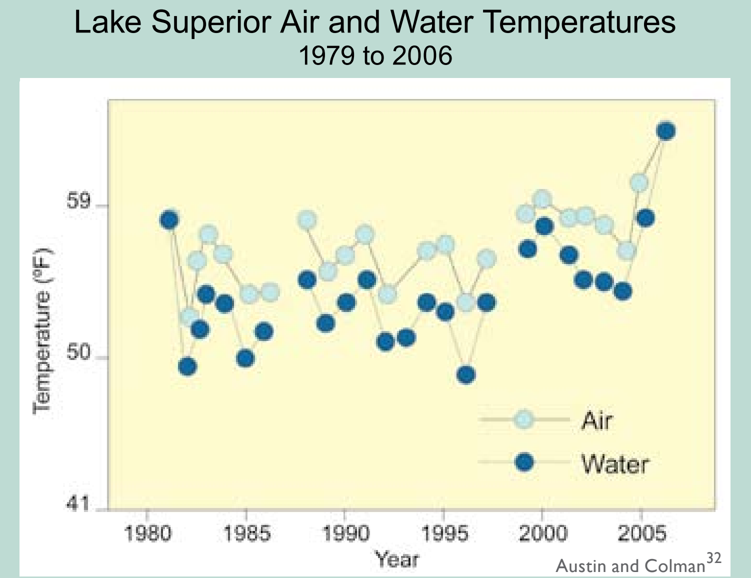
arid areas where most recharge occurs through dry streambeds after heavy rainfalls and floods[1]. Land subsidence (sinking) due to over-pumping of groundwater is a serious problem; the San Joaquin Valley in California, Houston, Texas, and areas in Arizona have suffered permanent declines of up to 30 feet after extended periods of over-pumping[31].

Sea-level rise is expected to increase salt water intrusion into coastal freshwater aquifers, making them unusable without desalination[8]. Increased evaporation or reduced recharge into coastal aquifers will exacerbate salt water intrusion. Shallow groundwater aquifers that exchange water with streams are likely to be the most sensitive part of the groundwater system to climate change[27]. Small reductions in groundwater levels can lead to large reductions in streamflow and increases in groundwater levels can increase streamflow[15]. Further, the interface between streams and groundwater is an important site for pollution removal by microorganisms. Their activity will change in response to increased temperature and increased or decreased streamflow as climate changes, and this will affect water quality. Like water quality, research on the impacts of climate change on groundwater has been minimal[11].

### Climate change will place additional burdens on already stressed water systems.

In many places, the nation's water systems are already taxed due to aging infrastructure, population increases, and conflicts between water for farming, municipalities, hydropower, recreation, and ecosystems[33-35]. Climate change will add another factor to many existing water management challenges, thus increasing vulnerability[36]. The U.S. Bureau of Reclamation has identified many areas in the West that are already at risk for serious conflict over water in the absence of climate change[37] (see figure on the following page). The Environmental Protection Agency has identified a potential funding shortfall for drinking water and waste water infrastructure of over $500 billion by 2020 if expenditures remain at current levels.

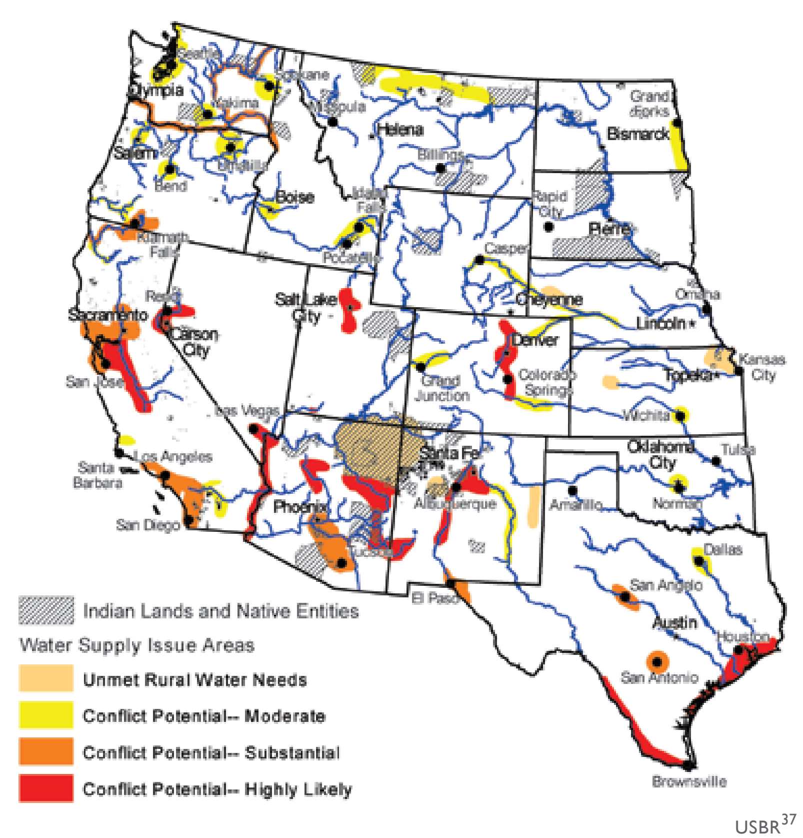
Adapting to gradual changes, such as changes in average amounts of precipitation, is less difficult than adapting to changes in extremes. Where extreme events, such as droughts or floods, become more intense or more frequent with climate change, the economic and social costs of these events will increase[38]. Water systems have lifetimes of many years and are designed with spare capacity. These systems are thus able to cope with small changes in average conditions[38]. Water resource planning today considers a broad range of stresses and hence adaptation to climate change will be one factor among



Austin and Colman[32]

The recent large jump in water temperature is related to the recent large reduction in ice cover (see *Midwest* region).

Potential Water Supply Conflicts by 2025



USBR[37]

The map shows regions in the West where water supply conflicts are likely to occur by 2025 based on a combination of factors including population trends and potential endangered species' needs for water. The red zones are where the conflicts are most likely to occur. This analysis does not factor in the effects of climate change[37].

many in deciding what actions will be taken to minimize vulnerability[38-40].

### Rapid regional population growth

Since the 2000 Census, the U.S. population is estimated to have grown to more than 300 million people, nearly a 7 percent increase from 2000 to today. Current Census Bureau projections are for this growth rate to continue, with the national population projected to reach 350 million by 2025 and 420 million by 2050. The highest rates of population growth to 2025 are projected to occur in areas such as the Southwest that are at risk for reductions in water supplies due to climate change[33].

### Aging water infrastructure

The nation's drinking water and wastewater infrastructure is aging. In older cities, some buried water mains are over 100 years old and breaks of these lines are a significant problem. Sewer overflows resulting in the discharge of untreated wastewater also occur frequently. The Environmental Protection Agency has identified a potential funding shortfall for drinking water and wastewater infrastructure of over $500 billion by 2020[34]. Heavy downpours will exacerbate existing problems in many cities, especially where stormwater catchments and sewers are combined. Drinking water and sewer infrastructure is very expensive to install and maintain. Climate change will present a new set of challenges for designing upgrades to the nation's water delivery and sewage removal infrastructure[34].

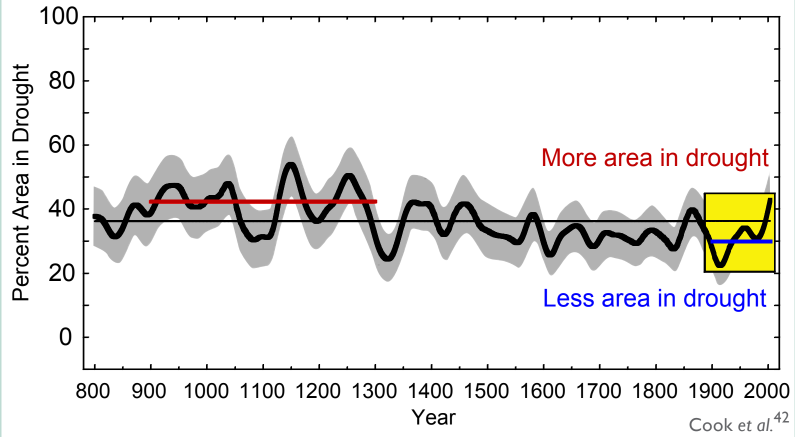
### Existing water disputes across the country

Many locations in the United States are already undergoing water stress. The Great Lakes states are establishing an interstate compact to protect against reductions in lake levels and potential water exports. Georgia, Alabama, and Florida are in a dispute over water for drinking, recreation, farming, environmental purposes, and hydropower in the Apalachicola–Chattahoochee–Flint River system[41]. The State Water Project in California is facing a variety of problems in the Sacramento Delta, including endangered species, salt water intrusion, and potential loss of islands due to flood- or earthquake-caused levee failures. A dispute over endangered fish in the Rio Grande has been ongoing for many years. The Klamath River in Oregon and California has been the location of a multi-year disagreement over native fish, hydropower, and farming. The Colorado River has

Damage to the city water system in Asheville, North Carolina, following a hurricane in 2004.

been the site of numerous interstate quarrels over the last century. Large, unquantified Native American water rights challenge existing uses in the West. By changing the existing patterns of precipitation and runoff, climate change will add another stress to existing problems.

Long-Term Aridity Changes in the West



Cook *et al.*[42]

Black line shows percent area affected by drought (Palmer Drought Severity Index less than –1) in the West over the past 1,200 years. The red line indicates the average drought area in the years 900 to 1300. The blue horizontal line in the yellow box indicates the average during the period from 1900 to 2000, illustrating that the most recent period, during which population and water infrastructure grew rapidly in the West, was wetter than the long-term average (thin horizontal black line)[42].

## The past century is no longer a reasonable guide to the future for water management.

Water planning has been based on the idea that supply and demand would fluctuate within historical levels. These levels were established based on measurements from stream gauges, lake levels, municipal meters, agricultural pumps, and other data collection methods over the past century. Reservoir flood operations, reservoir yields, urban stormwater runoff, and projected water demands are based on these data. Water managers have proven adept at managing supplies and demand through the significant climate variability of the past century[1]. Because climate change will significantly modify many aspects of the water cycle, the assumption of an unchanging climate is no longer appropriate for many aspects of water planning. Past assumptions derived from the historic record about supply and demand will need to be revisited for existing and proposed water projects[1,10,40].

Drought studies going back 1,200 years indicate that in the West, the last century was significantly wetter than most other centuries. Multi-decade "megadroughts" in the years 900 to 1300 were substantially worse than the worst droughts of the last century, including the Dust Bowl era. The causes of these events are only partially known; if they were to reoccur, they would clearly stress water management even in the absence of climate change[11,42,43].

The intersection of substantial changes in the water cycle with multiple stresses such as population growth and competition for water supplies means that water planning will be doubly challenging. The ability to modify operational rules and water allocations is likely to be critical for the protection of infrastructure, for public safety, to ensure reliability of water delivery, and to protect the environment. There are, however, many institutional and legal barriers to such changes in both the short and long term[44]. Four examples:

- The allocation of the water in many interstate rivers is governed by compacts, international treaties, federal laws, court decrees, and other agreements that are difficult to modify.
- Reservoir operations are governed by "rule curves" that require a certain amount of space to be saved in a reservoir at certain times of year to capture a potential flood. Developed by the Army Corps of Engineers based on historic flood data, many of these rule curves have never been modified, and modifications might require Environmental Impact Statements.
- In most parts of the West, water is allocated based on a "first in time means first in right" system, and because agriculture was developed before cities were established, large volumes of water typically are allocated to agriculture. Transferring agricultural rights to municipalities, even for short periods during drought, can involve substantial expense and time and can be socially divisive.
- Conserving water does not necessarily lead to a right to that saved water, thus creating a disincentive for conservation.

Total U.S. water diversions peaked in the 1980s, which implies that expanding supplies in many areas to meet new needs will not be a viable option, especially in arid areas likely to experience less precipitation. However, over the last 30 years, per capita water use has decreased significantly (due, for example, to more efficient technologies such as drip irrigation) and it is anticipated that per capita use will continue to decrease, thus easing stress[11]. A limited number of studies on adaptation indicate that water management can successfully adapt, albeit at some cost[45,46].

Reduced water levels on the Lake Powell reservoir leave a "bath tub ring" that shows the previous water level. This photograph was taken in July 2004, when the lake was at about 10 million acre feet (120 feet below full, 40 percent of capacity). In April 2005, the lake level was even lower, about 8 million acre feet or 33 percent of capacity.

## Spotlight on the Colorado River

The Colorado River system supplies water to over 30 million people in the Southwest including Los Angeles, Phoenix, Las Vegas, and Denver. Reservoirs in the system, including the giant lakes Mead and Powell, were nearly full in 1999, with almost four times the annual flow of the river stored. By 2007, the system had lost approximately half of that storage after enduring the worst drought in 100 years of record keeping. Runoff was reduced due to low winter precipitation, and warm, dry, and windy springs that substantially reduced snowpack.

Numerous studies over the last 30 years have indicated that the river is likely to experience reductions in runoff due to climate change. In addition, diversions from the river to meet the needs of cities and agriculture are approaching its average flow. Under current conditions, even without climate change, large year-to-year fluctuations in reservoir storage are possible[14]. If reductions in flow projected to accompany global climate change occur, water managers will be challenged to satisfy all existing demands, let alone the increasing demands of a rapidly growing population[33,47].

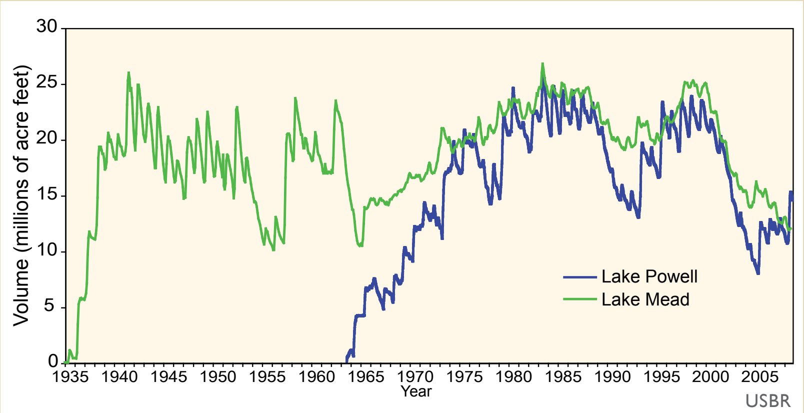
Efforts are underway to address these challenges. In 2005, the Department of Interior's Bureau of Reclamation began a process to formalize operating rules for lakes Mead and Powell during times of low flows and to apportion limited water among the states. As part of that process, the Bureau of Reclamation convened a Climate Technical work group to investigate how to incorporate climate change science into the Bureau's planning effort. Over the course of six months, the Work Group met several times and created a guidance document on the state of the science and on future research directions. These results were included in the Final Environmental Impact Statement released in December 2007[48].

June 29, 2002

December 23, 2003

Matching photographs taken 18 months apart during the most serious period of recent drought show a significant decrease in Lake Powell.

Change in Water Volume of Lakes Mead and Powell



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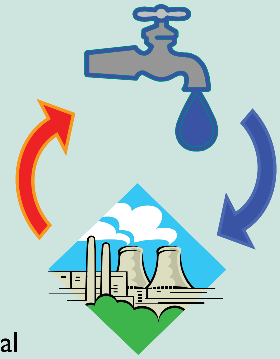
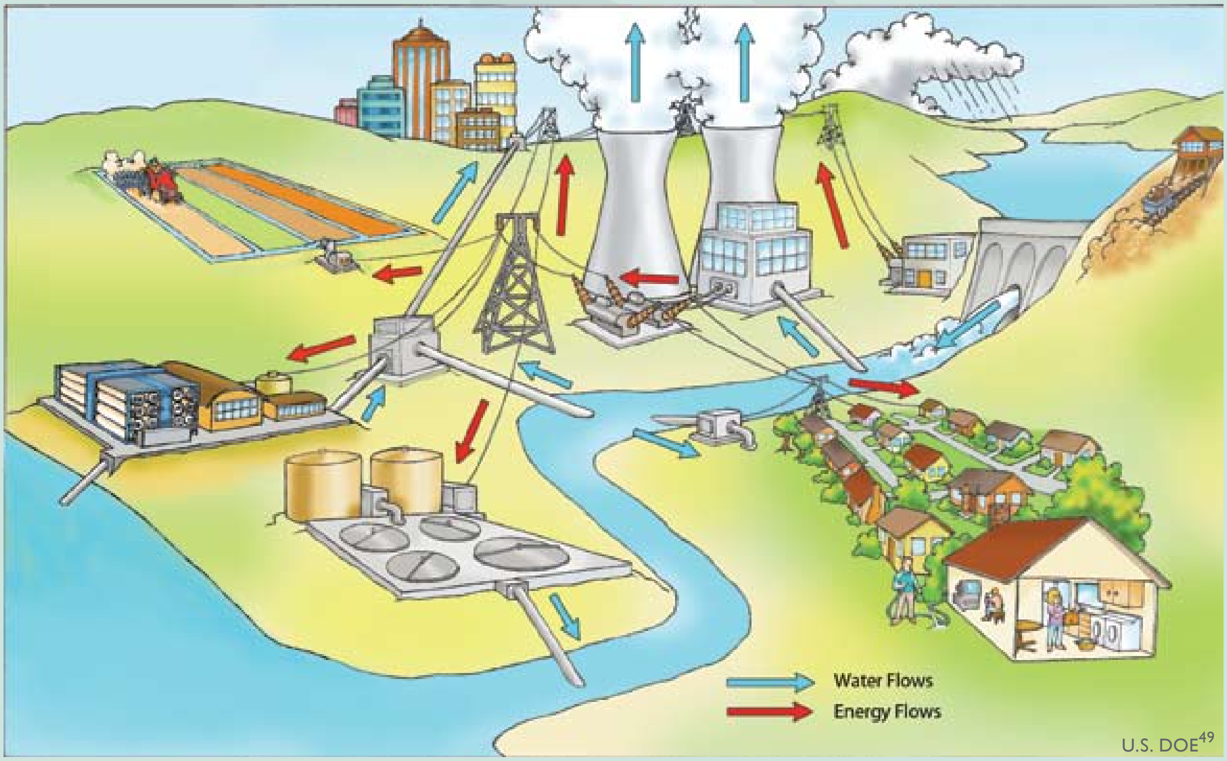
Lake Mead (green) was first filled in 1935, and Lake Powell (blue) was first filled in 1963. In 1999, the lakes were nearly full, but by 2007, the lakes had lost nearly half of their storage water after the worst drought in 100 years.

## Water and Energy Connections



Water and energy are tightly interconnected; water systems use large amounts of energy, and energy systems use large amounts of water. Both are expected to be under increasing pressure in the future and both will be affected by a changing climate. In the energy sector, water is used directly for hydropower, and cooling water is critical for nearly all other forms of electrical power generation. Freshwater withdrawals for thermoelectric cooling are very large, nearly equaling the water withdrawn for irrigation; water consumption by power plants is about 20 percent of all non-agricultural uses, or half that of all domestic use[49].

In the water sector, two very unusual attributes of water, significant weight and a high heat capacity, make water use energy intensive. Large amounts of energy are needed for pumping, heating, and treating drinking and wastewater. Water supply and treatment consumes roughly 4 percent of the nation's power supply, and electricity accounts for about 75 percent of the cost of municipal water processing and transport. In California, 30 percent of all non-power plant natural gas is used for water-related activities[50,51]. The energy required to provide water depends on its source (groundwater, surface water, desalinated water, treated wastewater, or recycled water), the distance the water is conveyed, the amount of water moved, and the local topography. Surface water often requires more treatment than groundwater. Desalination requires large amounts of energy to produce freshwater. Treated wastewater and recycled water (used primarily for agriculture and industry) require energy for treatment, but little energy for supply and conveyance. Conserving water has the dual benefit of conserving energy and potentially reducing greenhouse gas emissions if fossil fuels are the predominant source of that energy.



U.S. DOE[49]

Water and energy are intimately connected. Water is used by the power generation sector for cooling, and energy is used by the water sector for pumping, drinking, and waste water treatment. Without energy, there would be limited water distribution, and without water, there would be limited energy production.