Climate Change Impacts in the United States

CHAPTER 3
WATER RESOURCES

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3 WATER RESOURCES

KEY MESSAGES

Climate Change Impacts on the Water Cycle


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1. **Annual precipitation and river-flow increases are observed now in the Midwest and the Northeast regions. Very heavy precipitation events have increased nationally and are projected to increase in all regions. The length of dry spells is projected to increase in most areas, especially the southern and northwestern portions of the contiguous United States.**
2. **Short-term (seasonal or shorter) droughts are expected to intensify in most U.S. regions. Longer-term droughts are expected to intensify in large areas of the Southwest, southern Great Plains, and Southeast.**
3. **Flooding may intensify in many U.S. regions, even in areas where total precipitation is projected to decline.**
4. **Climate change is expected to affect water demand, groundwater withdrawals, and aquifer recharge, reducing groundwater availability in some areas.**
5. **Sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to compromise the sustainability of coastal freshwater aquifers and wetlands.**
6. **Increasing air and water temperatures, more intense precipitation and runoff, and intensifying droughts can decrease river and lake water quality in many ways, including increases in sediment, nitrogen, and other pollutant loads.**

Climate Change Impacts on Water Resources Use and Managment

7. **Climate change affects water demand and the ways water is used within and across regions and economic sectors. The Southwest, Great Plains, and Southeast are particularly vulnerable to changes in water supply and demand.**
8. **Changes in precipitation and runoff, combined with changes in consumption and withdrawal, have reduced surface and groundwater supplies in many areas. These trends are expected to continue, increasing the likelihood of water shortages for many uses.**
9. **Increasing flooding risk affects human safety and health, property, infrastructure, economies, and ecology in many basins across the United States.**

Adaptation and Institutional Responses

10. **In most U.S. regions, water resources managers and planners will encounter new risks, vulnerabilities, and opportunities that may not be properly managed within existing practices.**
11. **Increasing resilience and enhancing adaptive capacity provide opportunities to strengthen water resources management and plan for climate change impacts. Many institutional, scientific, economic, and political barriers present challenges to implementing adaptive strategies.**

This chapter contains three main sections: climate change impacts on the water cycle, climate change impacts on water resources use and management, and adaptation and institutional responses. Key messages for each section are summarized above.

> *The cycle of life is intricately joined with the cycle of water.*
>
> — Jacques-Yves Cousteau

Climate Change Impacts on the Water Cycle

Water cycles constantly from the atmosphere to the land and the oceans (through precipitation and runoff) and back to the atmosphere (through evaporation and the release of water from plant leaves), setting the stage for all life to exist. The water cycle is dynamic and naturally variable, and societies and ecosystems are accustomed to functioning within this variability. However, climate change is altering the water cycle in multiple ways over different time scales and geographic areas, presenting unfamiliar risks and opportunities.

Key Message 1: Changing Rain, Snow, and Runoff

Annual precipitation and river-flow increases are observed now in the Midwest and the Northeast regions. Very heavy precipitation events have increased nationally and are projected to increase in all regions. The length of dry spells is projected to increase in most areas, especially the southern and northwestern portions of the contiguous United States.

Annual average precipitation over the continental U.S. as a whole increased by close to two inches (0.16 inches per decade) between 1895 and 2011.[1,2] In recent decades, annual average precipitation increases have been observed across the Midwest, Great Plains, the Northeast, and Alaska, while decreases have been observed in Hawai'i and parts of the Southeast and Southwest (Ch. 2: Our Changing Climate, Figure 2.12). Average annual precipitation is projected to increase across the northern U.S., and decrease in the southern U.S., especially the Southwest. (Ch. 2: Our Changing Climate, Figures 2.14 and 2.15).[3]

The number and intensity of very heavy precipitation events (defined as the heaviest 1% of all daily events from 1901 to 2012) have been increasing significantly across most of the United States. The amount of precipitation falling in the heaviest daily events has also increased in most areas of the United States (Ch. 2: Our Changing Climate, Figure 2.17). For example, from 1950 to 2007, daily precipitation totals with 2-, 5-, and 10-year average recurrence periods increased in the Northeast and western Great Lakes.[4] Very heavy precipitation events are projected to increase everywhere (Ch. 2: Our Changing Climate, Figure 2.19).[5] Heavy precipitation events that historically occurred once in 20 years are projected to occur as frequently as every 5 to 15 years by late this century.[6] The number and magnitude of the heaviest precipitation events is projected to increase everywhere in the United States (Ch. 2: Our Changing Climate, Figure 2.13).

Dry spells are also projected to increase in length in most regions, especially in the southern and northwestern portions of the contiguous United States (Ch. 2: Our Changing Climate, Figure 2.13). Projected changes in total average annual precipitation are generally small in many areas, but both wet and dry extremes (heavy precipitation events

Projected Changes in Snow, Runoff, and Soil Moisture

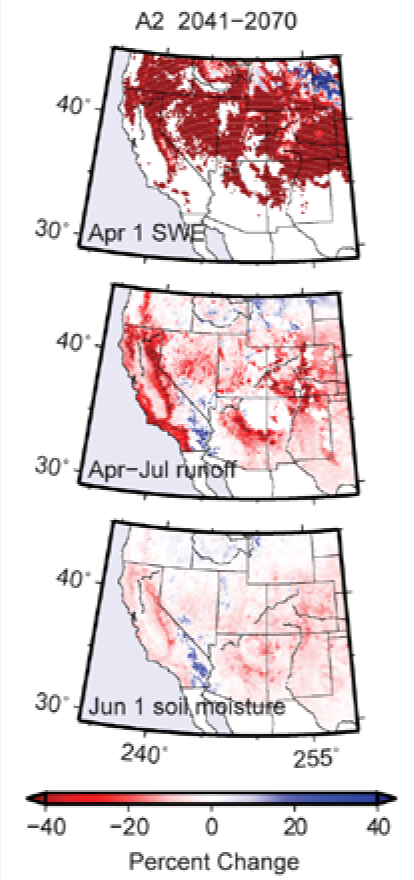
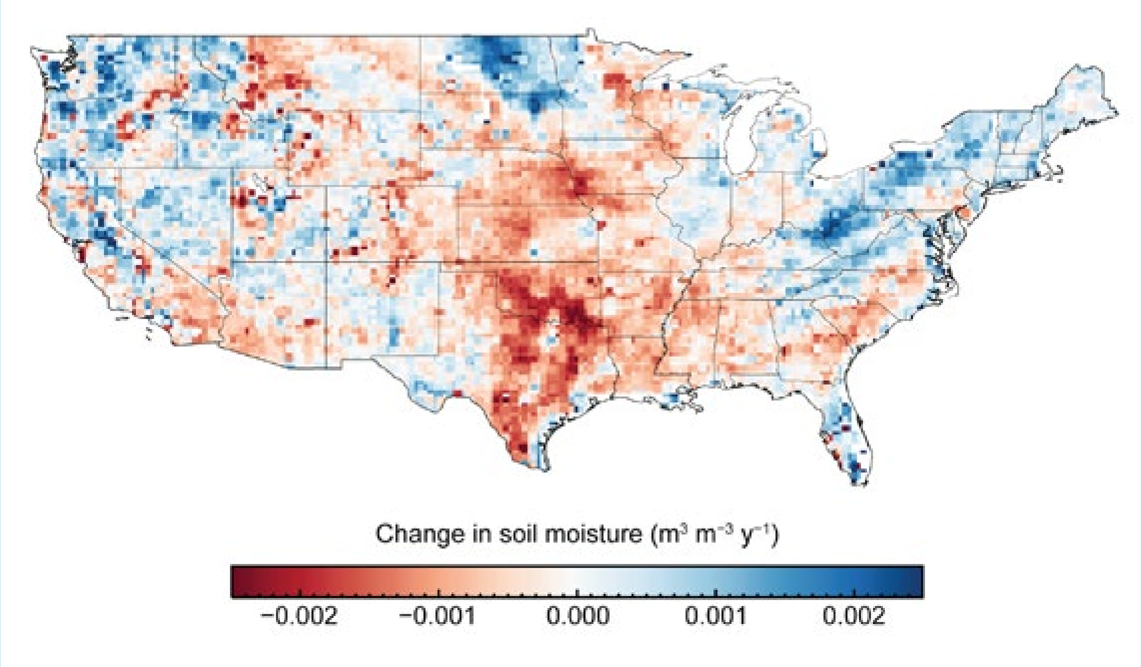


Figure 3.1. These projections, assuming continued increases in heat-trapping gas emissions (A2 scenario; Ch. 2: Our Changing Climate), illustrate: a) major losses in the water content of the snowpack that fills western rivers (snow water equivalent, or SWE); b) significant reductions in runoff in California, Arizona, and the central Rocky Mountains; and c) reductions in soil moisture across the Southwest. The changes shown are for mid-century (2041-2070) as percentage changes from 1971-2000 conditions (Figure source: Cayan et al. 2013[18]).



Annual Surface Soil Moisture Trends

Figure 3.2. Changes in annual surface soil moisture per year over the period 1988 to 2010 based on multi-satellite datasets. Surface soil moisture exhibits wetting trends in the Northeast, Florida, upper Midwest, and Northwest, and drying trends almost everywhere else. (Images provided by W. Dorigo[35]).

and length of dry spells) are projected to increase substantially almost everywhere.

The timing of peak river levels has changed in response to warming trends. Snowpack and snowmelt-fed rivers in much of the western U.S. have earlier peak flow trends since the middle of the last century, including the past decade (Ch. 2: Our Changing Climate).[7,8] This is related to declines in spring snowpack, earlier snowmelt-fed streamflow, and larger percentages of precipitation falling as rain instead of snow. These changes have taken place in the midst of considerable year-to-year variability and long-term natural fluctuations of the western U.S. climate, as well as other influences, such as the effects of dust and soot on snowpacks.[7,9] There are both natural and human influences on the observed trends.[10,11] However, in studies specifically designed to differentiate between natural and human-induced causes, up to 60% of these changes have been attributed to human-induced climate warming,[10] but only among variables that are more responsive to warming than to precipitation variability, such as the effect of air temperature on snowpack.[12]

Other historical changes related to peak river-flow have been observed in the northern Great Plains, Midwest, and Northeast,[13,14] along with striking reductions in lake ice cover (Ch. 2: Our Changing Climate).[15,16]

Permafrost is thawing in many parts of Alaska, a trend that not only affects habitats and infrastructure but also mobilizes subsurface water and reroutes surface water in ways not previously witnessed.[17] Nationally, all of these trends are projected to become even more pronounced as the climate continues to warm (Figure 3.1).

Evapotranspiration (ET – the evaporation of moisture from soil, on plants and trees, and from water bodies; and transpiration, the use and release of water from plants), is the second largest component of the water cycle after precipitation. ET responds to temperature, solar energy, winds, atmospheric humidity, and moisture availability at the land surface and regulates amounts of soil moisture, groundwater recharge, and runoff.[19] Transpiration comprises between 80% and 90% of total ET on land (Ch. 6: Agriculture).[20] In snowy settings, sublimation of snow and ice (loss of snow and ice directly into water vapor without passing through a liquid stage) can increase these returns of water to the atmosphere, sometimes in significant amounts.[21] These interactions complicate estimation and projection of regional losses of water from the land surface to the atmosphere.

Globally-averaged ET increased between 1982 and 1997 but stopped increasing, or has decreased, since about 1998.[22] In North America, the observed ET decreases occurred in water-rich rather than water-limited areas. Factors contributing to these ET decreases are thought to include decreasing wind

Seasonal Surface Soil Moisture Trends

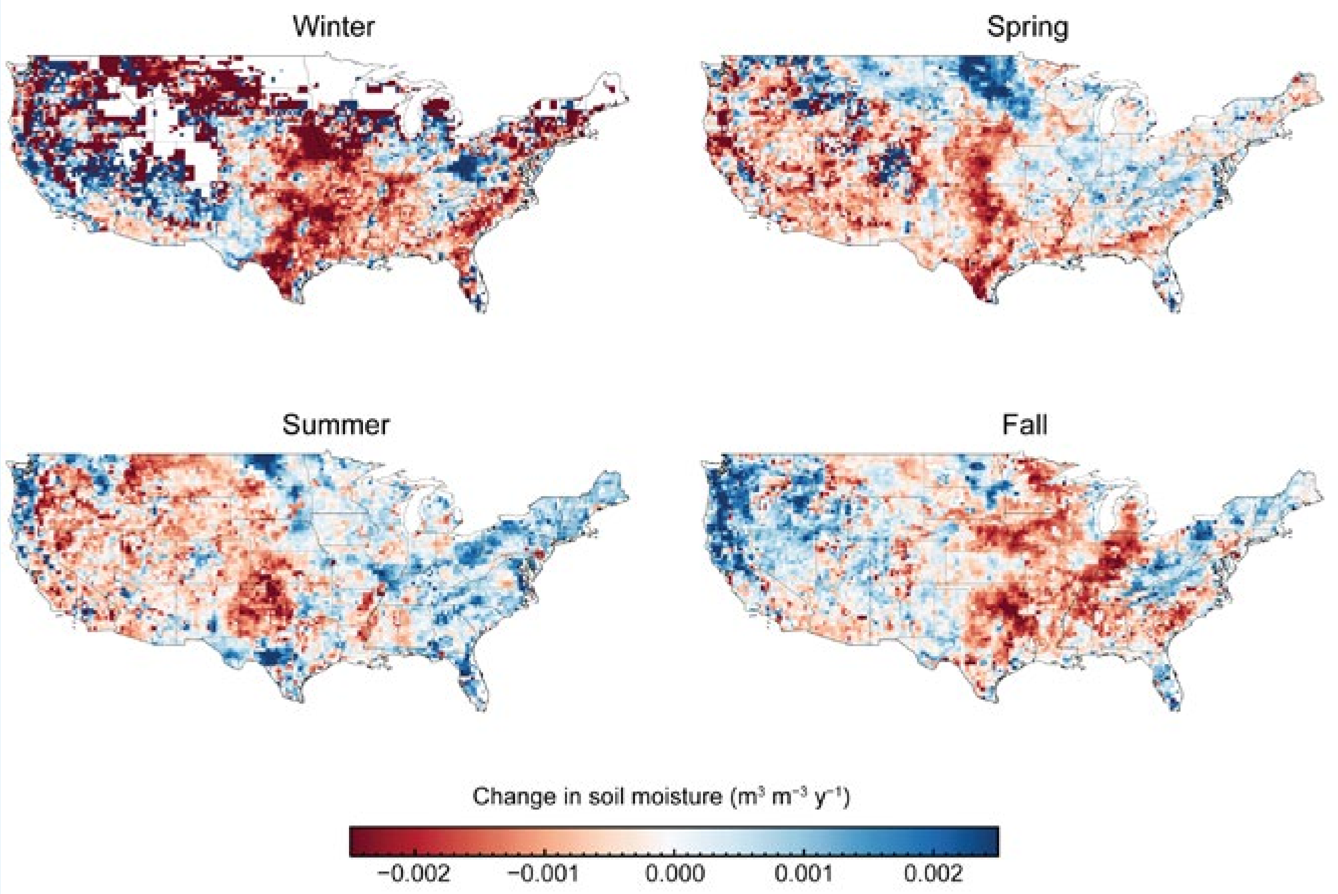


Figure 3.3. Changes in seasonal surface soil moisture per year over the period 1988 to 2010 based on multi-satellite datasets.[35] Seasonal drying is observed in central and lower Midwest and Southeast for most seasons (with the exception of the Southeast summer), and in most of the Southwest and West (with the exception of the Northwest) for spring and summer. Soil moisture in the upper Midwest, Northwest, and most of the Northeast is increasing in most seasons. (Images provided by W. Dorigo).

speed,[23,24] decreasing solar energy at the land surface due to increasing cloud cover and concentration of small particles (aerosols),[25] increasing humidity,[23] and declining soil moisture (Figure 3.2).[26]

Evapotranspiration projections vary by region,[27,28,29,30] but the atmospheric potential for ET is expected to increase; actual ET will be affected by regional soil moisture changes. Much more research is needed to confidently identify historical trends, causes, and implications for future ET trends.[31] This represents a critical uncertainty in projecting the impacts of climate change on regional water cycles.

Soil moisture plays a major role in the water cycle, regulating the exchange of water, energy, and carbon between the land surface and the atmosphere,[22] the production of runoff, and the recharge of groundwater aquifers. Soil moisture is projected to decline with higher temperatures and attendant increases in the potential for ET in much of the country, especially in the Great Plains,[29] Southwest,[18,32,33] and Southeast.[28,34]

Runoff and streamflow at regional scales declined during the last half-century in the Northwest.[36] Runoff and streamflow increased in the Mississippi Basin and Northeast, with no clear trends in much of the rest of the continental U.S.,[37] although a declining trend is emerging in annual runoff in the Colorado River Basin.[38] These changes need to be considered in the context of tree-ring studies in California's Central Valley, the Colorado River and Wind River basins, and the southeastern U.S. that indicate that these regions have experienced prolonged, even drier and wetter conditions at various times in the past two thousand years.[8,39,40] Human-caused climate change, when superimposed on past natural variability, may amplify these past extreme conditions. Projected changes in runoff for eight basins in the Northwest, northern Great Plains, and Southwest are illustrated in Figure 3.4.

Basins in the southwestern U.S. and southern Rockies (for example, the Rio Grande and Colorado River basins) are projected to experience gradual runoff declines during this century. Basins in the Northwest to north-central U.S. (for example, the

Streamflow Projections for River Basins in the Western U.S.

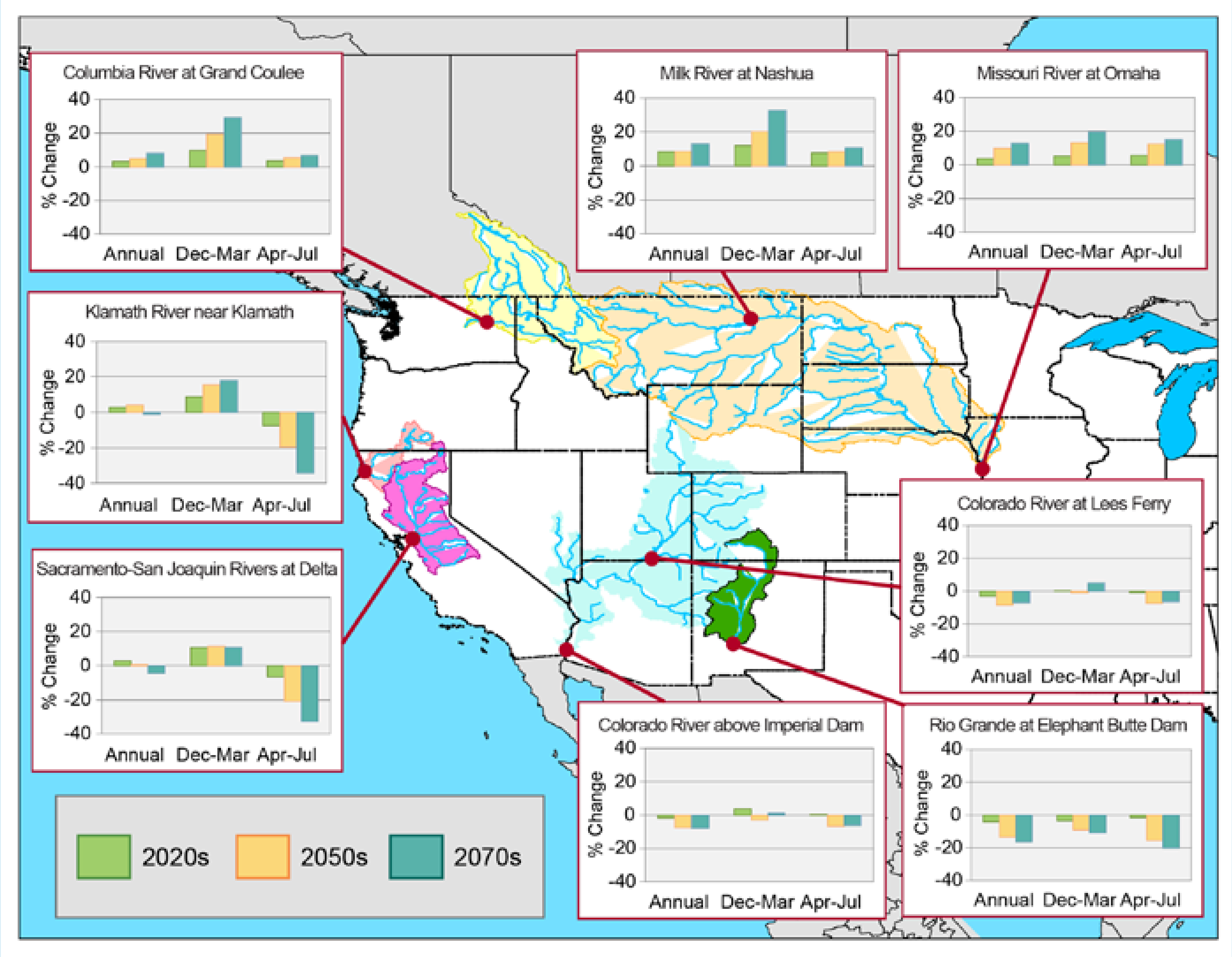


Figure 3.4. Annual and seasonal streamflow projections based on the B1 (with substantial emissions reductions), A1B (with gradual reductions from current emission trends beginning around mid-century), and A2 (with continuation of current rising emissions trends) CMIP3 scenarios for eight river basins in the western United States. The panels show percentage changes in average runoff, with projected increases above the zero line and decreases below. Projections are for annual, cool, and warm seasons, for three future decades (2020s, 2050s, and 2070s) relative to the 1990s. (Source: U.S. Department of the Interior – Bureau of Reclamation 2011;[41] Data provided by L. Brekke, S. Gangopadhyay, and T. Pruitt)

Columbia and the Missouri River basins) are projected to experience little change through the middle of this century, and increases by late this century.

Projected changes in runoff differ by season, with cool season runoff increasing over the west coast basins from California to Washington and over the north-central U.S. (for example, the San Joaquin, Sacramento, Klamath, Missouri, and Columbia River basins). Basins in the southwestern U.S. and southern Rockies are projected to see little change to slight decreases in the winter months.

Warm season runoff is projected to decrease substantially over a region spanning southern Oregon, the southwestern U.S., and southern Rockies (for example, the Klamath, Sacramento, San Joaquin, Rio Grande, and the Colorado River basins), and change little or increase slightly north of this region (for example, the Columbia and Missouri River basins).

In most of these western basins, these projected streamflow changes are outside the range of historical variability, especially by the 2050s and 2070s. The projected streamflow changes and associated uncertainties have water management implications (discussed below).

Key Message 2: Droughts Intensify

Short-term (seasonal or shorter) droughts are expected to intensify in most U.S. regions. Longer-term droughts are expected to intensify in large areas of the Southwest, southern Great Plains, and Southeast.

Annual runoff and related river-flow are projected to decline in the Southwest[42,43] and Southeast,[34] and to increase in the Northeast, Alaska, Northwest, and upper Midwest regions,[42,43,44,45] broadly mirroring projected precipitation patterns.[46] Observational studies[47] have shown that decadal fluctuations in average temperature (up to 1.5°F) and precipitation changes of 10% have occurred in most areas of the U.S. during the last century. Fluctuations in river-flow indicate that effects of temperature are dominated by fluctuations in precipitation. Nevertheless, as warming affects water cycle processes, the amount of runoff generated by a given amount of precipitation is generally expected to decline.[37]

Droughts occur on time scales ranging from season-to-season to multiple years and even multiple decades. There has been no universal trend in the overall extent of drought across the continental U.S. since 1900. However, in the Southwest, widespread drought in the past decade has reflected both precipitation deficits and higher temperatures[8] in ways that resemble projected changes.[48] Long-term (multi-seasonal) drought conditions are also projected to increase in parts of the Southeast and possibly in Hawaiʻi and the Pacific Islands (Ch. 23: Hawaiʻi and Pacific Islands). Except in the few areas where increases in summer precipitation compensate, summer droughts (Ch. 2: Our Changing Climate) are expected to intensify almost everywhere in the continental U.S.[49] due to longer periods of dry weather and more extreme heat,[33] leading to more moisture loss from plants and earlier soil moisture depletion in basins where snowmelt shifts to earlier in the year.[50,51] Basins watered by glacial melt in the Sierra Nevada, Glacier National Park, and Alaska may experience increased summer river-flow in the next few decades, until the amounts of glacial ice become too small to contribute to river-flow.[52,53]

Key Message 3: Increased Risk of Flooding in Many Parts of the U.S.

Flooding may intensify in many U.S. regions, even in areas where total precipitation is projected to decline.

There are various types of floods (see “Flood Factors and Flood Types”), some of which are projected to increase with continued climate change. Floods that are closely tied to heavy precipitation events, such as flash floods and urban floods, as well as coastal floods related to sea level rise and the resulting increase in storm surge height and inland impacts, are expected to increase. Other types of floods result from a more complex set of causes. For example, river floods are basin specific and dependent not only on precipitation but also on pre-existing soil moisture conditions, topography, and other factors, including important human-caused changes to watersheds and river courses across the United States.[54,55,56,57]

Significant changes in annual precipitation (Ch. 2: Our Changing Climate) and soil moisture (Figures 3.2 and 3.3), among other factors, are expected to affect annual flood magnitudes (Figure 3.5) in many regions.[58] River floods have been increasing in the Northeast and Midwest, and decreasing in the Southwest and Southeast.[56,57,58,59] These decreases are not surprising, as short duration very heavy precipitation events often occur during the summer and autumn when rivers are generally low. However, these very heavy precipitation events can and do lead to flash floods, often exacerbated in urban areas by the effect of impervious surfaces on runoff.

Heavy rainfall events are projected to increase, which is expected to increase the potential for flash flooding. Land cover, flow and water-supply management, soil moisture, and channel conditions are also important influences on flood generation[55] and must be considered in projections of future flood risks. Region-specific storm mechanisms and seasonality also affect flood peaks.[57] Because of this, and limited capacity to project future very heavy events with confidence, evaluations of the relative changes in various storm mechanisms may be useful.[57,60,61] Warming is likely to directly affect flooding in many mountain settings, as catchment areas receive increasingly more precipitation as rain rather than snow, or more rain falling on existing snowpack.[62] In some such settings, river flooding may increase as a result – even where precipitation and overall river flows decline (Ch. 2: Our Changing Climate).

Trends in Flood Magnitude

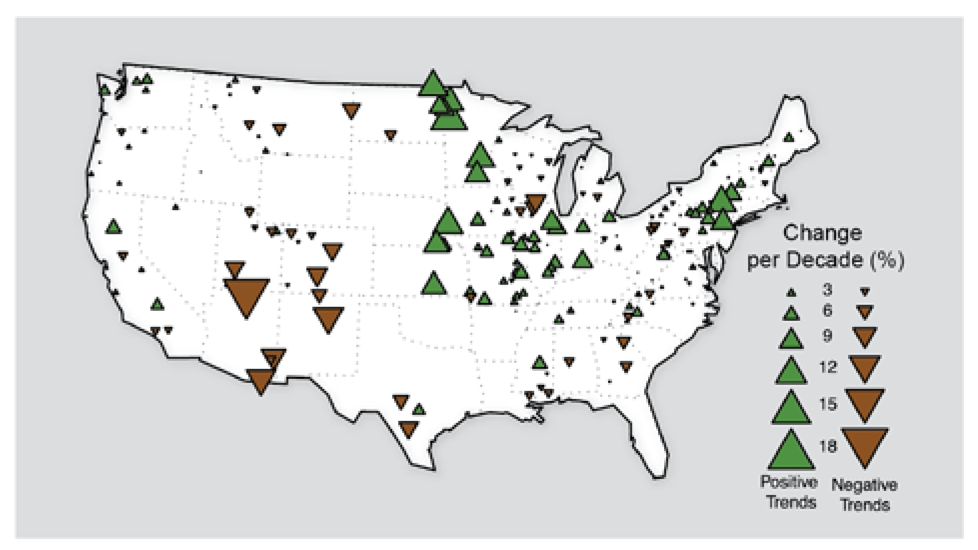


Figure 3.5. Trend magnitude (triangle size) and direction (green = increasing trend, brown = decreasing trend) of annual flood magnitude from the 1920s through 2008. Flooding in local areas can be affected by multiple factors, including land-use change, dams, and diversions of water for use. Most significant are increasing trends for floods in Midwest and Northeast, and a decreasing trend in the Southwest. (Figure source: Peterson et al. 2013[63]).

Key Message 4: Groundwater Availability

Climate change is expected to affect water demand, groundwater withdrawals, and aquifer recharge, reducing groundwater availability in some areas.

Groundwater is the only perennial source of fresh water in many regions and provides a buffer against climate extremes. As such, it is essential to water supplies, food security, and ecosystems. Though groundwater occurs in most areas of the U.S., the capacity of aquifers to store water varies depending on the geology of the region. (Figure 3.6b illustrates the importance of groundwater aquifers.) In large regions of the Southwest, Great Plains, Midwest, Florida, and some other coastal areas, groundwater is the primary water supply. Groundwater aquifers in these areas are susceptible to the combined stresses of climate and water-use changes. For example, during the 2006–2009 California drought, when the source of irrigation shifted from surface water to predominantly groundwater, groundwater storage in California's Central Valley declined by an amount roughly equivalent to the storage capacity of Lake Mead, the largest reservoir in the United States.[64]

Climate change impacts on groundwater storage are expected to vary from place to place and aquifer to aquifer. Although precise responses of groundwater storage and flow to climate change are not well understood nor readily generalizable, recent and ongoing studies[65,66,67,68] provide insights on various underlying mechanisms:

1) Precipitation is the key driver of aquifer recharge in water-limited environments (like arid regions), while evapotranspiration (ET) is the key driver in energy-limited environments (like swamps or marshlands).

2) Climate change impacts on aquifer recharge depend on several factors, including basin geology, frequency and intensity of high-rainfall periods that drive recharge, seasonal timing of recharge events, and strength of groundwater-surface water interaction.

3) Changes in recharge rates are amplified relative to changes in total precipitation, with greater amplification for drier areas.

With these insights in mind, it is clear that certain groundwater-dependent regions are projected to incur significant climate change related challenges. In some portions of the country, groundwater provides nearly 100% of the water supply (Figure 3.6b). Seasonal soil moisture changes are a key aquifer recharge driver and may provide an early indication of general aquifer recharge trends. Thus, the observed regional reductions in seasonal soil moisture for winter and spring (Figure 3.3) portend adverse recharge impacts for several U.S. regions, especially the Great Plains, Southwest, and Southeast.

Despite their critical national importance as water supply sources (see Figure 3.6), aquifers are not generally monitored

Principal U.S. Groundwater Aquifers and Use

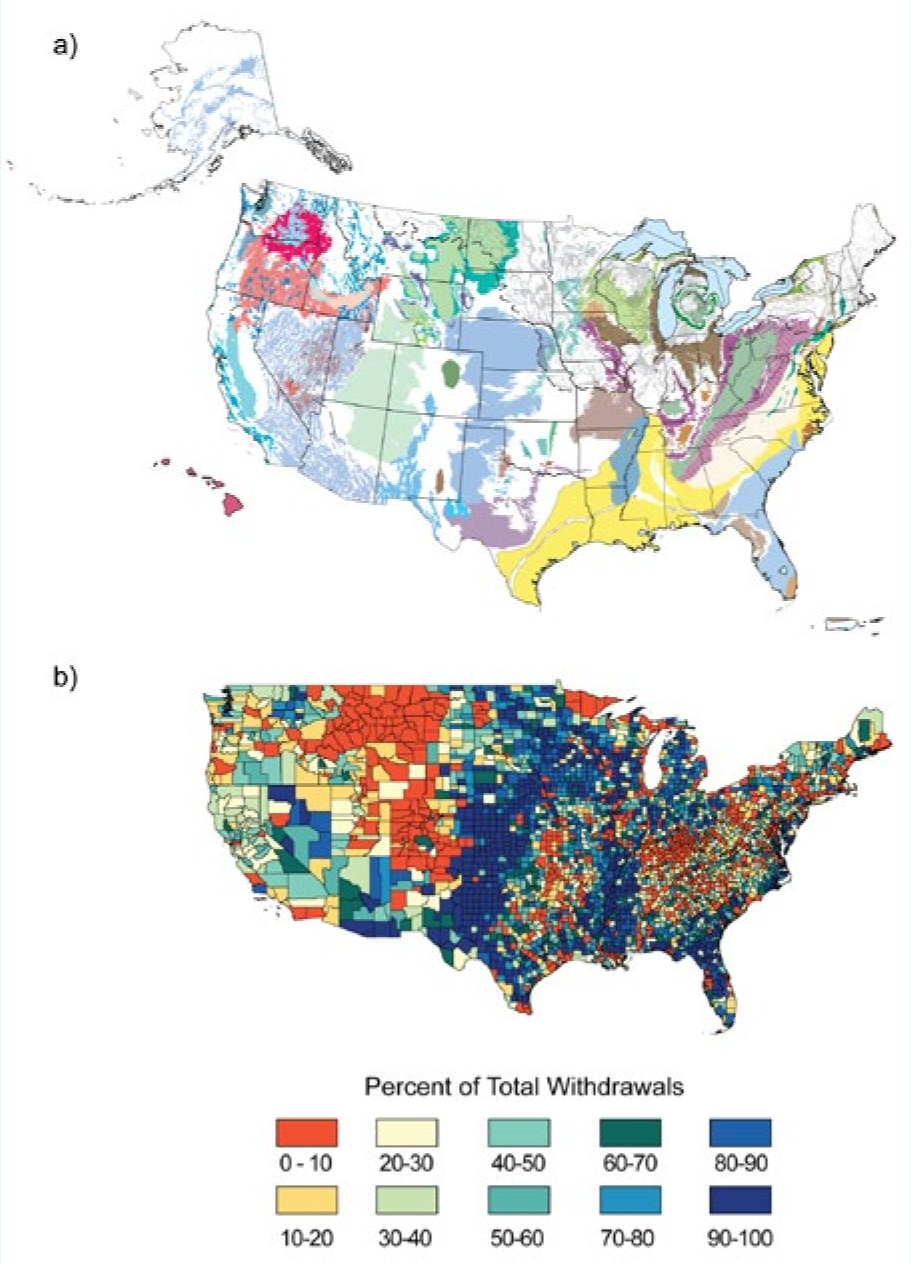


Figure 3.6. (**a**) Groundwater aquifers are found throughout the U.S., but they vary widely in terms of ability to store and recharge water. The colors on this map illustrate aquifer location and geology: blue colors indicate unconsolidated sand and gravel; yellow is semi-consolidated sand; green is sandstone; blue or purple is sandstone and carbonate-rock; browns are carbonate-rock; red is igneous and metamorphic rock; and white is other aquifer types. (Figure source: USGS). (**b**) Ratio of groundwater withdrawals to total water withdrawals from all surface and groundwater sources by county. The map illustrates that aquifers are the main (and often exclusive) water supply source for many U.S. regions, especially in the Great Plains, Misssissippi Valley, east central U.S., Great Lakes region, Florida, and other coastal areas. Groundwater aquifers in these regions are prone to impacts due to combined climate and water-use change. (Data from USGS 2005).

in ways that allow for clear identification of climatic influences on groundwater recharge, storage, flows, and discharge. Nearly all monitoring is focused in areas and aquifers where variations are dominated by groundwater pumping, which largely masks climatic influences,[69] highlighting the need for a national framework for groundwater monitoring.[70]

Generally, impacts of changing demands on groundwater systems, whether due directly to climate changes or indirectly through changes in land use or surface-water availability and management, are likely to have the most immediate effects on groundwater availability;[67,71] changes in recharge and storage may be more subtle and take longer to emerge. Groundwater models have only recently begun to include detailed representations of groundwater recharge and interactions with surface-water and land-surface processes,[50] with few projections of groundwater responses to climate change.[68,72] However, surface water declines have already resulted in larger groundwater withdrawals in some areas (for example, in the Central Valley of California and in the Southeast) and may be aggravated by climate change challenges.[73] In many mountainous areas of the U.S., groundwater recharge is disproportionately generated from snowmelt infiltration, suggesting that the loss of snowpack will affect recharge rates and patterns.[50,51,66,74] Models do not yet include dynamic representations of the groundwater reservoir and its connections to streams, the soil-vegetation system, and the atmosphere, limiting the understanding of the potential climate change impacts on groundwater and groundwater-reliant systems.[75]

As the risk of drought increases, groundwater can play a key role in enabling adaptation to climate variability and change. For example, groundwater can be augmented by surface water during times of high flow through aquifer recharge strategies, such as infiltration basins and injection wells. In addition, management strategies can be implemented that use surface water for irrigation and water supply during wet periods, and groundwater during drought, although these approaches face practical limitations within current management and institutional frameworks.[71,76]

Key Message 5: Risks to Coastal Aquifers and Wetlands

Sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to compromise the sustainability of coastal freshwater aquifers and wetlands.

With more than 50% of the nation's population concentrated near coasts (Chapter 25: Coasts),[77] coastal aquifers and wetlands are precious resources. These aquifers and wetlands, which are extremely important from a biological/biodiversity perspective (see Ch. 8: Ecosystems; Ch. 25: Coasts), may be particularly at risk due to the combined effects of inland droughts and floods, increased surface water impoundments and diversions, increased groundwater withdrawals, and accelerating sea level rise and greater storm surges.[78,79] Estuaries are particularly vulnerable to changes in freshwater inflow and sea level rise by changing salinity and habitat of these areas.

Several coastal areas, including the Delaware, Susquehanna, and Potomac River deltas on the Northeast seaboard, most of Florida, the Apalachicola and Mobile River deltas and bays, the Mississippi River delta in Louisiana, and the delta of the Sacramento-San Joaquin rivers in northern California, are particularly vulnerable due to the combined effects of climate change and other human-caused stresses. In response, some coastal communities are among the nation's most proactive in adaptation planning (Chapter 25: Coasts).

Key Message 6: Water Quality Risks to Lakes and Rivers

Increasing air and water temperatures, more intense precipitation and runoff, and intensifying droughts can decrease river and lake water quality in many ways, including increases in sediment, nitrogen, and other pollutant loads.

Water temperature has been increasing in some rivers.[80] The length of the season that lakes and reservoirs are thermally stratified (with separate density layers) is increasing with increased air and water temperatures.[81,82] In some cases, seasonal mixing may be eliminated in shallow lakes, decreasing dissolved oxygen and leading to excess concentrations of nutrients (nitrogen and phosphorous), heavy metals (such as mercury), and other toxins in lake waters.[81,82]

Lower and more persistent low flows under drought conditions as well as higher flows during floods can worsen water quality. Increasing precipitation intensity, along with the effects of wildfires and fertilizer use, are increasing sediment, nutrient, and contaminant loads in surface waters used by downstream water users[84] and ecosystems. Mineral weathering products, like calcium, magnesium, sodium, and silicon and nitrogen loads[85] have been increasing with higher streamflows.[86] Changing land cover, flood frequencies, and flood magnitudes are expected to increase mobilization of sediments in large river basins.[87]

Increasing air and water temperatures, more intense precipitation and runoff, and intensifying droughts can decrease water quality in many ways. Here, middle school students in Colorado learn about water quality.

Changes in sediment transport are expected to vary regionally and by land-use type, with potentially large increases in some areas,[88] resulting in alterations to reservoir storage and river channels, affecting flooding, navigation, water supply, and dredging. Increased frequency and duration of droughts, and associated low water levels, increase nutrient concentrations and residence times in streams, potentially increasing the likelihood of harmful algal blooms and low oxygen conditions.[89] Concerns over such impacts and their potential link to climate change are rising for many U.S. regions including the Great Lakes,[90] Chesapeake Bay,[91] and the Gulf of Mexico.[85,86] Strategies aiming to reduce sediment, nutrient, and contaminant loads at the source remain the most effective management responses.[92]

Observed Changes in Lake Stratification and Ice Covered Area

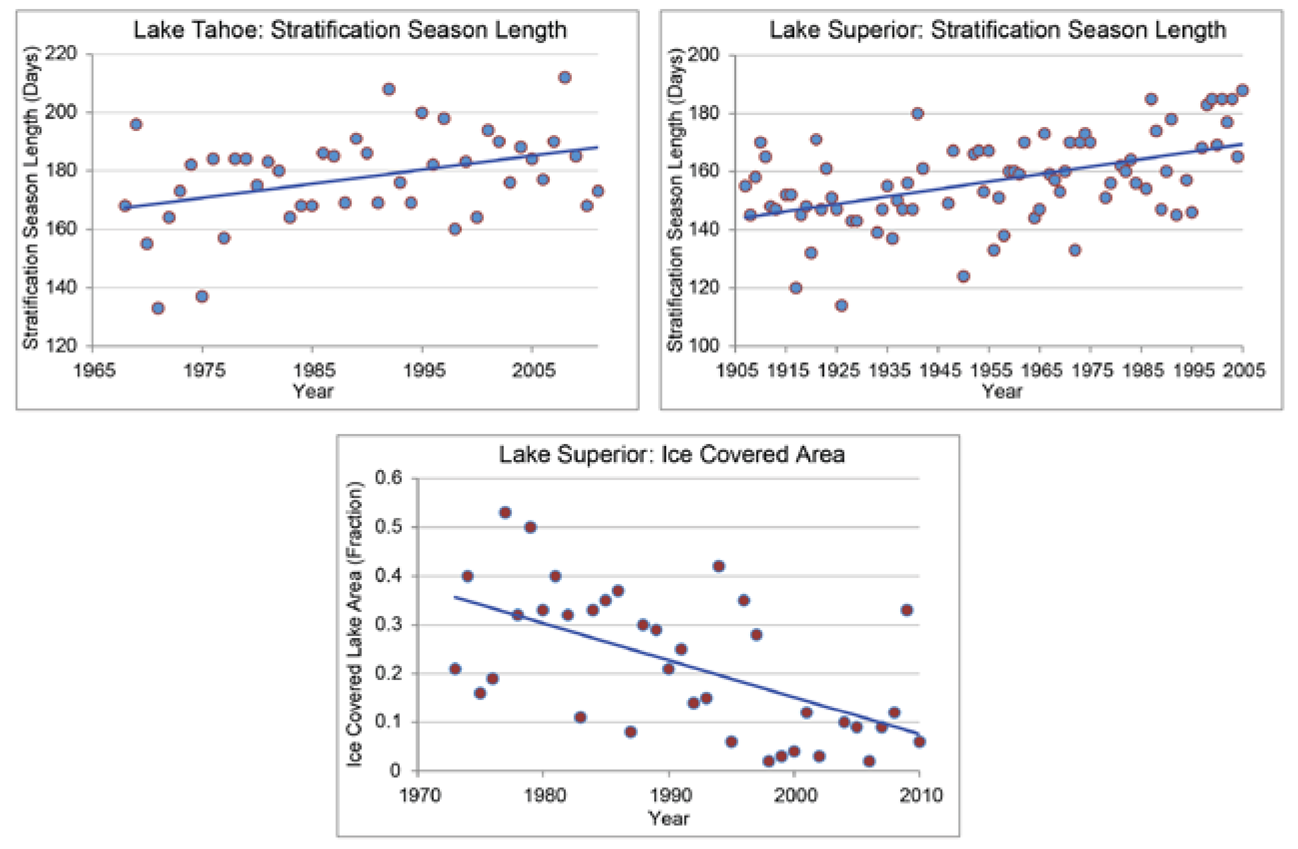


Figure 3.7. The length of the season in which differences in lake temperatures with depth cause stratification (separate density layers) is increasing in many lakes. In this case, measurements show stratification has been increasing in Lake Tahoe (top left) since the 1960s and in Lake Superior (top right) since the early 1900s in response to increasing air and surface water temperatures (see also Ch. 18: Midwest). In Lake Tahoe, because of its large size (relative to inflow) and resulting long water-residence times, other influences on stratification have been largely overwhelmed, and warming air and water temperatures have caused progressive declines in near-surface density, leading to longer stratification seasons (by an average of 20 days), decreasing the opportunities for deep lake mixing, reducing oxygen levels, and causing impacts to many species and numerous aspects of aquatic ecosystems.[83] Similar effects are observed in Lake Superior,[16] where the stratification season is lengthening (top right) and annual ice-covered area is declining (bottom); both observed changes are consistent with increasing air and water temperatures.

Relationship between Historical and Projected Water Cycle Changes

Natural climate variations occur on essentially all time scales from days to millennia, and the water cycle varies in much the same way. Observations of changes in the water cycle over time include responses to natural hydroclimatic variability as well as other, more local, human influences (like dam building or land-use changes), or combinations of these influences with human-caused climate change. Some recent studies have attributed specific observed changes in the water cycle to human-induced climate change (for example, Barnett et al. 2008[10]). For many other water cycle variables and impacts, the observed and projected responses are consistent with those expected by human-induced climate change and other human influences. Research aiming to formally attribute these responses to their underlying causes is ongoing.

FLOOD FACTORS AND FLOOD TYPES

A flood is defined as any high flow, overflow, or inundation by water that causes or threatens damage.[93] Floods are caused or amplified by both weather- and human-related factors. Major weather factors include heavy or prolonged precipitation, snowmelt, thunderstorms, storm surges from hurricanes, and ice or debris jams. Human factors include structural failures of dams and levees, inadequate drainage, and land cover alterations (such as pavement or deforestation) that reduce the capacity of the land surface to absorb water. Increasingly, humanity is also adding to weather-related factors, as human-induced warming increases heavy downpours, causes more extensive storm surges due to sea level rise, and leads to more rapid spring snowmelt.

Worldwide, from 1980 to 2009, floods caused more than 500,000 deaths and affected more than 2.8 billion people.[94] In the U.S., floods caused 4,586 deaths from 1959 to 2005[95] while property and crop damage averaged nearly $8 billion per year (in 2011 dollars) over 1981 through 2011.[93] The risks from future floods are significant, given expanded development in coastal areas and floodplains, unabated urbanization, land-use changes, and human-induced climate change.[94]

Major flood types include flash, urban, riverine, and coastal flooding:

Flash floods occur in small and steep watersheds and waterways and can be caused by short-duration intense precipitation, dam or levee failure, or collapse of debris and ice jams. Snow cover and frozen ground conditions can exacerbate flash flooding during winter and early spring by increasing the fraction of precipitation that runs off. Flash floods develop within minutes or hours of the causative event, and can result in severe damage and loss of life due to high water velocity, heavy debris load, and limited warning. Most flood-related deaths in the U.S. are associated with flash floods.

Flash Flooding: Cave Creek, Arizona (Photo credit: Tom McGuire).

Urban flooding can be caused by short-duration very heavy precipitation. Urbanization creates large areas of impervious surfaces (such as roads, pavement, parking lots, and buildings) and increases immediate runoff. Stormwater drainage removes excess surface water as quickly as possible, but heavy downpours can exceed the capacity of drains and cause urban flooding.

Flash floods and urban flooding are directly linked to heavy precipitation and are expected to increase as a result of projected increases in heavy precipitation events. In mountainous watersheds, such increases may be partially offset in winter and spring due to projected snowpack reduction.

Riverine Flooding: In many regions, infrastructure is currently vulnerable to flooding, as demonstrated in these photos. Left: The Fort Calhoun Nuclear Power Plant in eastern Nebraska was surrounded by a Missouri River flood on June 8, 2011, that also affected Louisiana, Mississippi, Missouri, Illinois, Kentucky, Tennessee, and Arkansas (photo credit: Larry Geiger). Right: The R.M. Clayton sewage treatment plant in Atlanta, Georgia, September 23, 2009, was engulfed by floodwaters forcing it to shut down and resulting in the discharge of raw sewage into the Chattahoochee River (photo credit: Reuters/David Tulis). Flooding also disrupts road and rail transportation, and inland navigation.

Riverine flooding occurs when surface water drains from a watershed into a stream or a river exceeds channel capacity, overflows the

Continued

FLOOD FACTORS AND FLOOD TYPES (CONTINUED)

banks, and inundates adjacent low lying areas. Riverine flooding is commonly associated with large watersheds and rivers, while flash and urban flooding occurs in smaller natural or urban watersheds. Because heavy precipitation is often localized, riverine flooding typically results from multiple heavy precipitation events over periods of several days, weeks, or even months. In large basins, existing soil moisture conditions and evapotranspiration rates also influence the onset and severity of flooding, as runoff increases with wetter soil and/or lower evapotranspiration conditions. Snow cover and frozen ground conditions can also exacerbate riverine flooding during winter and spring by increasing runoff associated with rain-on-snow events and by snowmelt, although these effects may diminish in the long term as snow accumulation decreases due to warming. Since riverine flooding depends on precipitation as well as many other factors, projections about changes in frequency or intensity are more uncertain than with flash and urban flooding.

Coastal flooding is predominantly caused by storm surges that accompany hurricanes and other storms. Low storm pressure creates strong winds that create and push large sea water domes, often many miles across, toward the shore. The approaching domes can raise the water surface above normal tide levels (storm surge) by more than 25 feet, depending on various storm and shoreline factors. Inundation, battering waves, and floating debris associated with storm surge can cause deaths, widespread infrastructure damage (to buildings, roads, bridges, marinas, piers, boardwalks, and sea walls), and severe beach erosion. Storm-related rainfall can also cause inland flooding (flash, urban, or riverine) if, after landfall, the storm moves slowly or stalls over an area. Inland flooding can occur close to the shore or hundreds of miles away and is responsible for more than half of the deaths associated with tropical storms.[93] Climate change affects coastal flooding through sea level rise and storm surge, increases in heavy rainfall during hurricanes and other storms, and related increases in flooding in coastal rivers.

Hurricane Sandy coastal flooding in Mantoloking, N.J. (Photo credit: New Jersey National Guard/Scott Anema).

In some locations, early warning systems have helped reduce deaths, although property damage remains considerable (Ch. 28: Adaptation). Further improvements can be made by more effective communication strategies and better land-use planning.[94]

Climate Change Impacts on Water Resource Uses and Management

People use water for many different purposes and benefits. Our water use falls into five main categories: 1) municipal use, which includes domestic water for drinking and bathing; 2) agricultural use, which includes irrigation and cattle operations; 3) industrial use, which includes electricity production from coal- or gas-fired power plants that require water to keep the machinery cool; 4) providing ecosystem benefits, such as supporting the water needs of plants and animals we depend on; and 5) recreational uses, such as boating and fishing.

Water is supplied for these many uses from two main sources:

- freshwater withdrawals (from streams, rivers, lakes, and aquifers), which supply water for municipal, industrial, agricultural, and recirculating thermoelectric plant cooling water supply;
- instream surface water flows, which support hydropower production, once-through thermoelectric plant cooling, navigation, recreation, and healthy ecosystems.

Key Message 7: Changes to Water Demand and Use

Climate change affects water demand and the ways water is used within and across regions and economic sectors. The Southwest, Great Plains, and Southeast are particularly vulnerable to changes in water supply and demand.

Climate change, acting concurrently with demographic, land-use, energy generation and use, and socioeconomic changes, is challenging existing water management practices by affecting water availability and demand and by exacerbating competition among uses and users (see Ch. 4: Energy; Ch. 6: Agriculture; Ch. 10: Energy, Water, and Land; Ch. 12: Indigenous Peoples; and Ch. 13: Land Use & Land Cover Change). In some regions, these current and expected impacts are hastening efficiency improvements in water withdrawal and use, the deployment of more proactive water management and adaptation approaches, and the reassessment of the water infrastructure and institutional responses.[1]

Water Withdrawals

Total freshwater withdrawals (including water that is withdrawn and consumed as well as water that returns to the original source) and consumptive uses have leveled off nationally since 1980 at 350 billion gallons of withdrawn water and 100 billion gallons of consumptive water per day, despite the addition of 68 million people from 1980 to 2005 (Figure 3.8).[96] Irrigation and all electric power plant cooling withdrawals account for approximately 77% of total withdrawals, municipal and industrial for 20%, and livestock and aquaculture for 3%. Most thermoelectric withdrawals are returned back to rivers after cooling, while most irrigation withdrawals are consumed by the processes of evapotranspiration and plant growth. Thus, consumptive water use is dominated by irrigation (81%) followed distantly by municipal and industrial (8%) and the remaining water uses (5%). See Figure 3.9.

Water sector withdrawals and uses vary significantly by region. There is a notable east-west water use pattern, with the largest regional withdrawals occurring in western states (where the climate is drier) for agricultural irrigation (Figure 3.10a,d). In the east, water withdrawals mainly serve municipal, industrial, and thermoelectric uses (Figure 3.10a,b,c). Irrigation is also dominant along the Mississippi Valley, in Florida, and in southeastern Texas. Groundwater withdrawals are especially intense in parts of the Southwest, Southeast, Northwest, and

U.S. Freshwater Withdrawal, Consumptive Use, and Population Trends

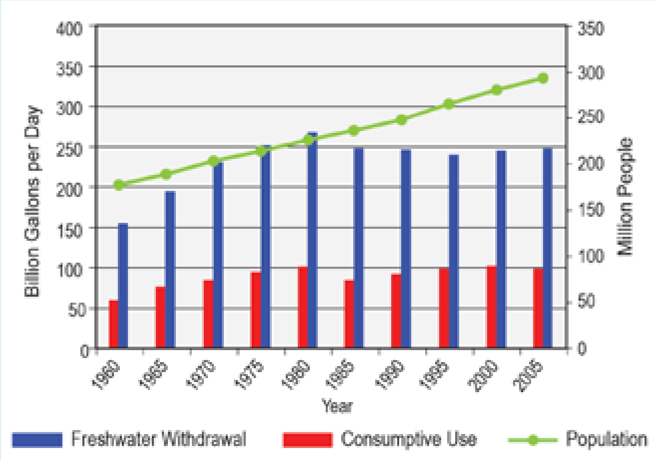


Figure 3.8. Trends in total freshwater withdrawal (equal to the sum of consumptive use and return flows to rivers) and population in the contiguous United States. This graph illustrates the remarkable change in the relationship between water use and population growth since about 1980. Reductions in per capita water withdrawals are directly related to increases in irrigation efficiency for agriculture, more efficient cooling processes in electrical generation, and, in many areas, price signals, more efficient indoor plumbing fixtures and appliances, and reductions in exterior landscape watering, in addition to shifts in land-use patterns in some areas.[97] Efficiency improvements have offset the demands of a growing population and have resulted in more flexibility in meeting water demand. In some cases these improvements have also reduced the flexibility to scale back water use in times of drought because some inefficiencies have already been removed from the system. With drought stress projected to increase in many U.S. regions, drought vulnerability is also expected to rise.[1]

Freshwater Withdrawals by Sector

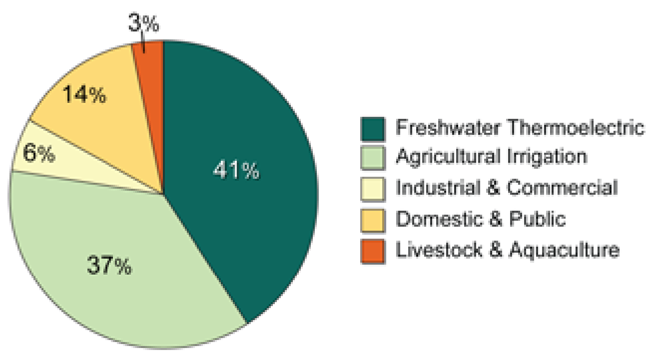


Figure 3.9. Total water withdrawals (groundwater and surface water) in the U.S. are dominated by agriculture and energy production, though the primary use of water for thermoelectric production is for cooling, where water is often returned to lakes and rivers after use (return flows). (Data from Kenny et al. 2009[96])

U.S. Water Withdrawal Distribution

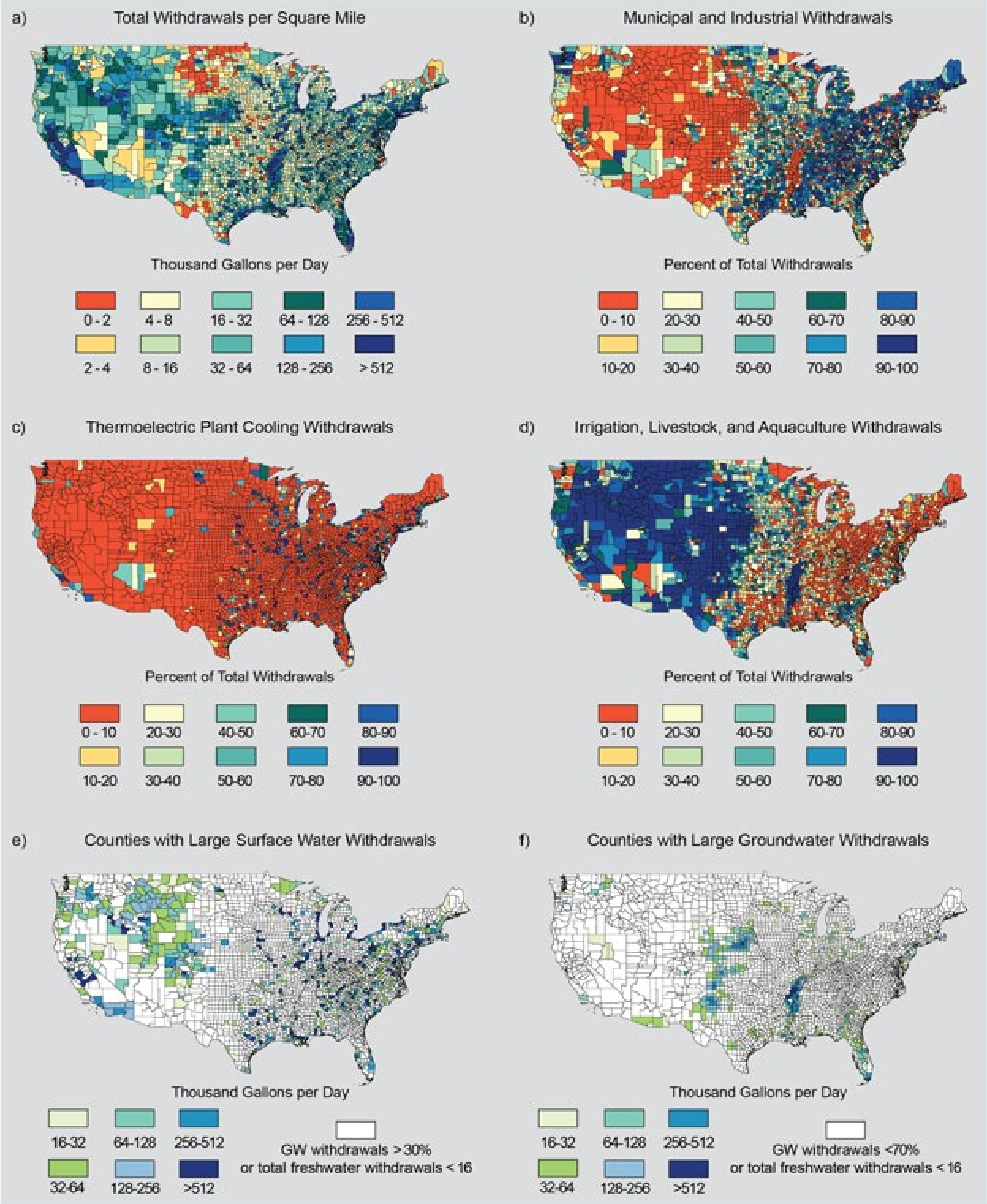


Figure 3.10. Based on the most recent USGS water withdrawal data (2005). This figure illustrates water withdrawals at the U.S. county level: (a) total withdrawals (surface and groundwater) in thousands of gallons per day per square mile; (b) municipal and industrial (including golf course irrigation) withdrawals as percent of total; (c) irrigation, livestock, and aquaculture withdrawals as percent of total; (d) thermoelectric plant cooling withdrawals as percent of total; (e) counties with large surface water withdrawals; and (f) counties with large groundwater withdrawals. The largest withdrawals occur in the drier western states for crop irrigation. In the east, water withdrawals mainly serve municipal, industrial, and thermoelectric uses. Groundwater withdrawals are intense in parts of the Southwest and Northwest, the Great Plains, Mississippi Valley, Florida and South Georgia, and near the Great Lakes (Figure source: Georgia Water Resources Institute, Georgia Institute of Technology; Data from Kenny et al. 2009;[96] USGS 2013[98]).

Great Plains, the Mississippi Valley, Florida and South Georgia, and near the Great Lakes (Figure 3.10f). Surface waters are most intensely used in all other U.S. regions.

Per capita water withdrawal and use are decreasing due to many factors.[99] These include demand management, new plumbing codes, water-efficient appliances, efficiency improvement programs, and pricing strategies, especially in the municipal sector.[100] Other factors contributing to decreasing per capita water use include changes from water-intensive manufacturing and other heavy industrial activities to service-oriented businesses,[101] and enhanced water-use efficiencies in response to environmental pollution legislation (in the industrial and commercial sector). In addition, replacement of older once-through-cooling electric power plants by plants that recycle their cooling water, and switching from flood irrigation to more efficient methods in the western United States[102] have also contributed to these trends.

Notwithstanding the overall national trends, regional water withdrawal and use are strongly correlated with climate;[103] hotter and drier regions tend to have higher per capita usage, and water demand is affected by both temperature and precipitation on a seasonal basis (see also Ch. 28: Adaptation).

Water demand is projected to increase as population grows, and will increase substantially more in some regions as a result of climate change. In the absence of climate change but in response to a projected population increase of 80% and a 245% increase in total personal income from 2005 to 2060, simulations under the A1B scenario indicate that total water demand in the U.S. would increase by 3%.[99] Under these conditions, approximately half of the U.S. regions would experience an overall decrease in water demand, while the other half would experience an increase (Figure 3.11a). If, however, climate change projections based on the A1B emissions scenario (with gradual reductions from current emission trends beginning around mid-century) and three climate models are also factored in, the total water demand is projected to rise by an average of 26% over the same period (Figure 3.11b).[99] Under the population increase scenario that also includes climate change, 90% of the country is projected to experience a total demand increase, with decreases projected only in parts of the Midwest, Northeast and Southeast. Compared to an 8% increase in demand under a scenario without climate change, projections under the A2 emissions scenario (which assumes continued increases in global emissions) and three climate models over the 2005 to 2060 period result in a 34% increase in total water demand. By 2090, total water demand is projected to increase by 42% over 2005 levels under the A1B scenario and 82% under the higher A2 emissions scenario.

Crop irrigation and landscape watering needs are directly affected by climate change, especially by projected changes in temperature, potential evapotranspiration, and soil moisture. Consequently, the projected climate change impacts on water demand are larger in the western states, where irrigation dominates total water withdrawals (see Figure 3.10). Uncertainties in the projections of these climate variables also affect water demand projections.[99] However, it is clear that the impacts of projected population, socioeconomic, and climate changes amplify the effects on water demand in the Southwest and Southeast, where the observed and projected drying water cycle trends already make these regions particularly vulnerable.

This vulnerability will be exacerbated by physical and operational limitations of water storage and distribution systems. River reservoirs and associated dams are usually designed to handle larger-than-historical streamflow variability ranges. Some operating rules and procedures reflect historical seasonal and interannual streamflow and water release patterns, while others include information about current and near-term conditions, such as snowpack depth and expected snowmelt volume. Climate change threatens to alter both the streamflow variability that these structures must accommodate and their opportunities to recover after doing so (due to permanent changes in average streamflow). Thus, as streamflow and demand patterns change, historically based operating rules and procedures could become less effective in balancing water supply with other uses.[104]

Some of the highest water demand increases under climate change are projected in U.S. regions where groundwater aquifers are the main water supply source (Figure 3.11b), including the Great Plains and parts of the Southwest and Southeast. The projected water demand increases combined with potentially declining recharge rates (see water cycle section) further challenge the sustainability of the aquifers in these regions.

Power plant cooling is a critical national water use, because nearly 90% of the U.S. electrical energy is produced by thermoelectric power plants.[105] Freshwater withdrawals per kilowatt hour have been falling in recent years due to the gradual replacement of once-through cooling of power plant towers with plants that recycle cooling water. Thermal plant cooling is principally supported by surface water withdrawals (Figure 3.10e,f) and has already been affected by climate change in areas where temperatures are increasing and surface water supplies are diminishing, such as the southern United States. Higher water temperatures affect the efficiency of electric generation and cooling processes. It also limits the ability of utilities to discharge heated water to streams from once-through cooled power systems due to regulatory requirements and concerns about how the release of warmer water into rivers and streams affects ecosystems and biodiversity (see Ch. 4: Energy).[106]

Projected Changes in Water Withdrawals

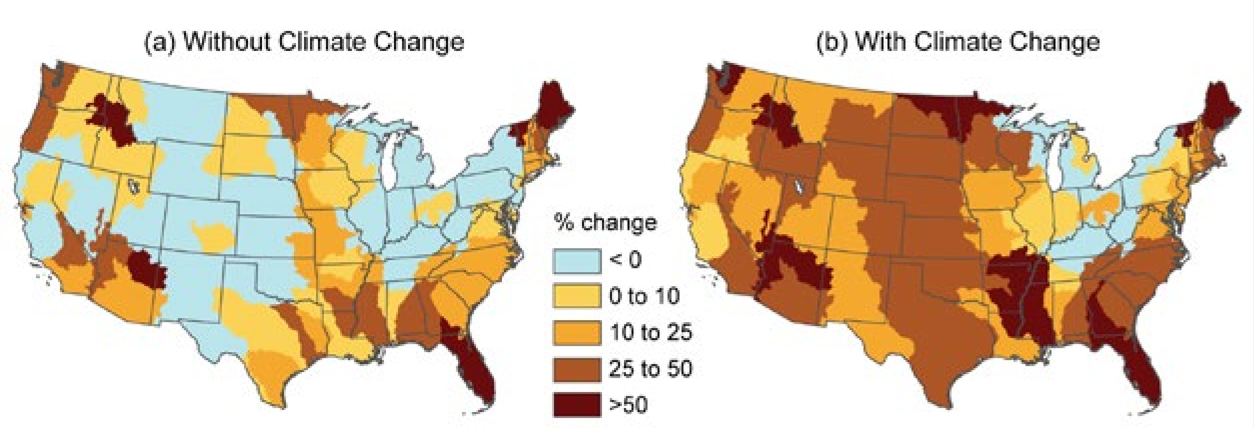


Figure 3.11. The effects of climate change, primarily associated with increasing temperatures and potential evapotranspiration, are projected to significantly increase water demand across most of the United States. Maps show percent change from 2005 to 2060 in projected demand for water assuming (a) change in population and socioeconomic conditions based on the underlying A1B emissions scenario, but with no change in climate, and (b) combined changes in population, socioeconomic conditions, and climate according to the A1B emissions scenario (gradual reductions from current emission trends beginning around mid-century). (Figure source: Brown et al. 2013[99]).

Instream Water Uses

Hydropower contributes 7% of electricity generation nationwide, but provides up to 70% in the Northwest and 20% in California, Alaska, and the Northeast.[107] Climate change is expected to affect hydropower directly through changes in runoff (average, extremes, and seasonality), and indirectly through increased competition with other water uses. Based on runoff projections, hydropower is expected to decline in the southern U.S. (especially the Southwest) and increase in the Northeast and Midwest (though actual gains or losses will depend on facility size and changes in runoff volume and timing). Where non-power water demands are expected to increase (as in the southern U.S.), hydropower generation, dependable capacity, and ancillary services are likely to decrease. Many hydropower facilities nationwide, especially in the Southeast, Southwest, and the Great Plains, are expected to face water availability constraints.[108] While some hydropower facilities may face water-related limitations, these could be offset to some degree by the use of more efficient turbines as well as innovative new hydropower technologies.

Inland navigation, most notably in the Great Lakes and the Missouri, Mississippi, and Ohio River systems, is particularly important for agricultural commodities (transported from the Midwest to the Gulf Coast and on to global food markets), coal, and iron ore.[1,109] Navigation is affected by ice cover and by floods and droughts. Seasonal ice cover on the Great Lakes has been decreasing[16] which may allow increased shipping.[110] However, lake level declines are also possible in the long term, decreasing vessel draft and cargo capacity. Future lake levels may also depend on non-climate factors and are uncertain both in direction and magnitude (see Ch. 2: Our Changing Climate; Ch. 5: Transportation; and Ch. 18: Midwest). Similarly, although the river ice cover period has been decreasing[53] (extending the inland navigation season), seasonal ice cover changes[111,112] could impede lock operations.[112] Intensified floods are likely to hinder shipping by causing waterway closures and damaging or destroying ports and locks. Droughts have already been shown to decrease reliability of flows or channel depth, adversely impacting navigation (Ch. 5: Transportation)**.** Both floods and droughts can disrupt rail and road traffic and increase shipping costs[113] and result in commodity price volatility (Ch. 19: Great Plains).

Recreational activities associated with water resources, including boating, fishing, swimming, skiing, camping, and wildlife watching, are strong regional and national economic drivers.[114] Recreation is sensitive to weather and climate,[115] and climate change impacts to recreation can be difficult to project.[116] Rising temperatures affect extent of snowcover and mountain snowpack, with impacts on skiing[117] and snowmobiling.[118] As the climate warms, changes in precipitation and runoff are expected to result in both beneficial (in some regions) and adverse impacts[115] to water sports, with potential for considerable economic dislocation and job losses.[118]

Changing climate conditions are projected to affect water and wastewater treatment and disposal in ways that depend on system-specific and interacting attributes. For example, elevated stream temperatures, combined with lower flows, may require wastewater facilities to increase treatment to meet stream water quality standards.[119] More intense precipitation and floods, combined with escalating urbanization and associated increasing impermeable surfaces, may amplify the likelihood of contaminated overland flow or combined sewer overflows.[120] Moderate precipitation increases, however, could result in increased stream flows, improving capacity to dilute contaminants in some regions. Sea level rise and more frequent coastal flooding could damage wastewater utility infrastructure and reduce treatment efficiency (Ch. 25: Coasts).[121]

Changes in streamflow temperature and flow regimes can affect aquatic ecosystem structure and function (see Ch. 8: Ecosystems). Water temperature directly regulates the physiology, metabolism, and energy of individual aquatic organisms, as well as entire ecosystems. Streamflow quantity influences the extent of available aquatic habitats, and streamflow variability regulates species abundance and persistence. Flow also influences water temperature, sediment, and nutrient concentrations.[122] If the rate of climate change[123] outpaces plant and animal species' ability to adjust to temperature change, additional biodiversity loss may occur. Furthermore, climate change induced water cycle alterations may exacerbate existing ecosystem vulnerability, especially in the western United States[124] where droughts and water shortages are likely to increase. But areas projected to receive additional precipitation, such as the northern Great Plains, may benefit. Lastly, hydrologic alterations due to human interventions have without doubt impaired riverine ecosystems in most U.S. regions and globally.[125] The projected escalation of water withdrawals and uses (see Figure 3.11) threatens to deepen and widen ecosystem impairment, especially in southern states where climate change induced water cycle alterations are pointing toward drier conditions (see Ch. 8: Ecosystems). In these regions, balancing socioeconomic and environmental objectives will most likely require more deliberate management and institutional responses.

Major Water Resource Vulnerabilities and Challenges

Many U.S. regions are expected to face increased drought and flood vulnerabilities and exacerbated water management challenges. This section highlights regions where such issues are expected to be particularly intense.

Key Message 8: Drought is Affecting Water Supplies

Changes in precipitation and runoff, combined with changes in consumption and withdrawal, have reduced surface and groundwater supplies in many areas. These trends are expected to continue, increasing the likelihood of water shortages for many uses.

Many southwestern and western watersheds, including the Colorado, Rio Grande,[38,43,126] and Sacramento-San Joaquin,[127,128] have recently experienced drier conditions. Even larger runoff reductions (about 10% to 20%) are projected over some of these watersheds in the next 50 years.[48,129] Increasing evaporative losses, declining runoff and groundwater recharge, and changing groundwater pumpage are expected to affect surface and groundwater supplies[65,66,67,71] and increase the risk of water shortages for many water uses. Changes in streamflow timing will exacerbate a growing mismatch between supply and demand (because peak flows are occurring earlier in the spring, while demand is highest in mid-summer) and will present challenges for the management of reservoirs, aquifers, and other water infrastructure.[130] Rising stream temperatures and longer low flow periods may make electric power plant cooling water withdrawals unreliable, and may affect aquatic and riparian ecosystems by degrading habitats and favoring invasive, non-native species.[131]

Key Message 9: Flood Effects on People and Communities

Increasing flooding risk affects human safety and health, property, infrastructure, economies, and ecology in many basins across the U.S.

Flooding affects critical water, wastewater, power, transportation, and communications infrastructure in ways that are difficult to foresee and can result in interconnected and cascading failures (see "Flood Factors and Flood Types"). Very heavy precipitation events have intensified in recent decades in most U.S. regions, and this trend is projected to continue (Ch. 2: Our Changing Climate). Increasing heavy precipitation is an important contributing factor, but flood magnitude changes also depend on specific watershed conditions (including soil moisture, impervious area, and other human-caused alterations).

Projected changes in flood frequency based on climate projections and hydrologic models have recently begun to emerge (for example, Das et al. 2012;[60] Brekke et al. 2009;[132] Raff et al. 2009;[133] Shaw and Riha 2011;[134] Walker et al. 2011[135]), and suggest that flood frequency and severity increases may occur in the Northeast and Midwest (Ch. 16: Northeast; Ch. 18: Midwest). Flooding and sea water intrusion from sea level rise and increasing storm surge threaten New York, Boston, Philadelphia, Virginia Beach, Wilmington, Charleston, Miami, Tampa, Naples, Mobile, Houston, New Orleans, and many other cities on U.S. coasts (Chapter 25: Coasts).

The devastating toll of large floods (human life, property, environment, and infrastructure) suggests that proactive management measures could minimize changing future flood risks and consequences (Ch. 28: Adaptation). In coastal areas, sea level rise may act in parallel with inland climate changes to intensify water-use impacts and challenges (Ch. 12: Indigenous Peoples; Ch. 17: Southeast).[136] Increasing flooding risk, both coastal and inland, could also exacerbate human health risks associated with failure of critical infrastructure,[137,138] and an increase in both waterborne diseases (Ch. 9: Human Health)[139] and airborne diseases.[140]

Changes in land use, land cover, development, and population distribution can all affect flood frequency and intensity. The nature and extent of these projected changes results in increased uncertainty and decreased accuracy of flood forecasting in both the short term[133] and long term.[141] This lack of certainty could hinder effective preparedness (such as evacuation planning) and the effectiveness of structural and non-structural flood risk reduction measures. However, many climate change projections are robust (Ch. 2: Our Changing Climate), and the long lead time needed for the planning, design, and construction of critical infrastructure that provides resilience to floods means that consideration of long-term changes is needed.

Effective climate change adaptation planning requires an integrated approach[45,118,142] that addresses public health and safety issues (Ch. 28: Adaptation).[143] Though numerous flood risk reduction measures are possible, including levees, land-use zoning, flood insurance, and restoration of natural floodplain retention capacity,[144] economic and institutional conditions may constrain implementation. The effective use of these measures would require significant investment in many cases,[145] as well as updating policies and methods to account for climate change[42,146] in the planning, design, operation, and maintenance of flood risk reduction infrastructure.[132,147]

Adaptation and Institutional Responses

Key Message 10: Water Resources Management

In most U.S. regions, water resources managers and planners will encounter new risks, vulnerabilities, and opportunities that may not be properly managed within existing practices.

Water managers and planners strive to balance water supply and demand across all water uses and users. The management process involves complex tradeoffs among water-use benefits, consequences, and risks. By altering water availability and demand, climate change is likely to present additional management challenges. One example is in the Sacramento-San Joaquin River Delta, where flooding, sea water intrusion, and changing needs for environmental, municipal, and agricultural water uses have created significant management challenges. This California Bay-Delta experience suggests that managing risks and sharing benefits requires re-assessment of very complex ecosystems, infrastructure systems, water rights, stakeholder preferences, and reservoir operation strategies – as well as significant investments. All of these considerations are subject to large uncertainties.[54,148] To some extent, all U.S. regions are susceptible, but the Southeast and Southwest are highly vulnerable because climate change is projected to reduce water availability, increase demand, and exacerbate shortages (see "Water Management").

Recent assessments illustrate water management challenges facing California,[127,129,149,150] the Southwest,[130,151] Southeast (Ch. 17: Southeast),[136,152] Northwest,[153] Great Plains,[154] and Great Lakes.[155] A number of these assessments demonstrate that while expanding supplies and storage may still be possible in some regions, effective climate adaptation strategies can benefit from innovative management strategies. These strategies can include domestic water conservation programs that use pricing incentives to curb use; more flexible, risk-based, better-informed, and adaptive operating rules for reservoirs; the integrated use of combined surface and groundwater resources; and better monitoring and assessment of statewide water use.[129,149,156,157] Water management and planning would benefit from better coordination among public sectors at the national, state, and local levels (including regional partnerships and agreements), and the private sector, with participation of all relevant stakeholders in well-informed, fair, and equitable decision-making processes. Better coordination among hydrologists and atmospheric scientists, and among these scientists and the professional water management community, is also needed to facilitate more effective translation of knowledge from science to practice (Ch. 26: Decision Support; Ch. 28: Adaptation).[158]

WATER CHALLENGES IN A SOUTHEAST RIVER BASIN

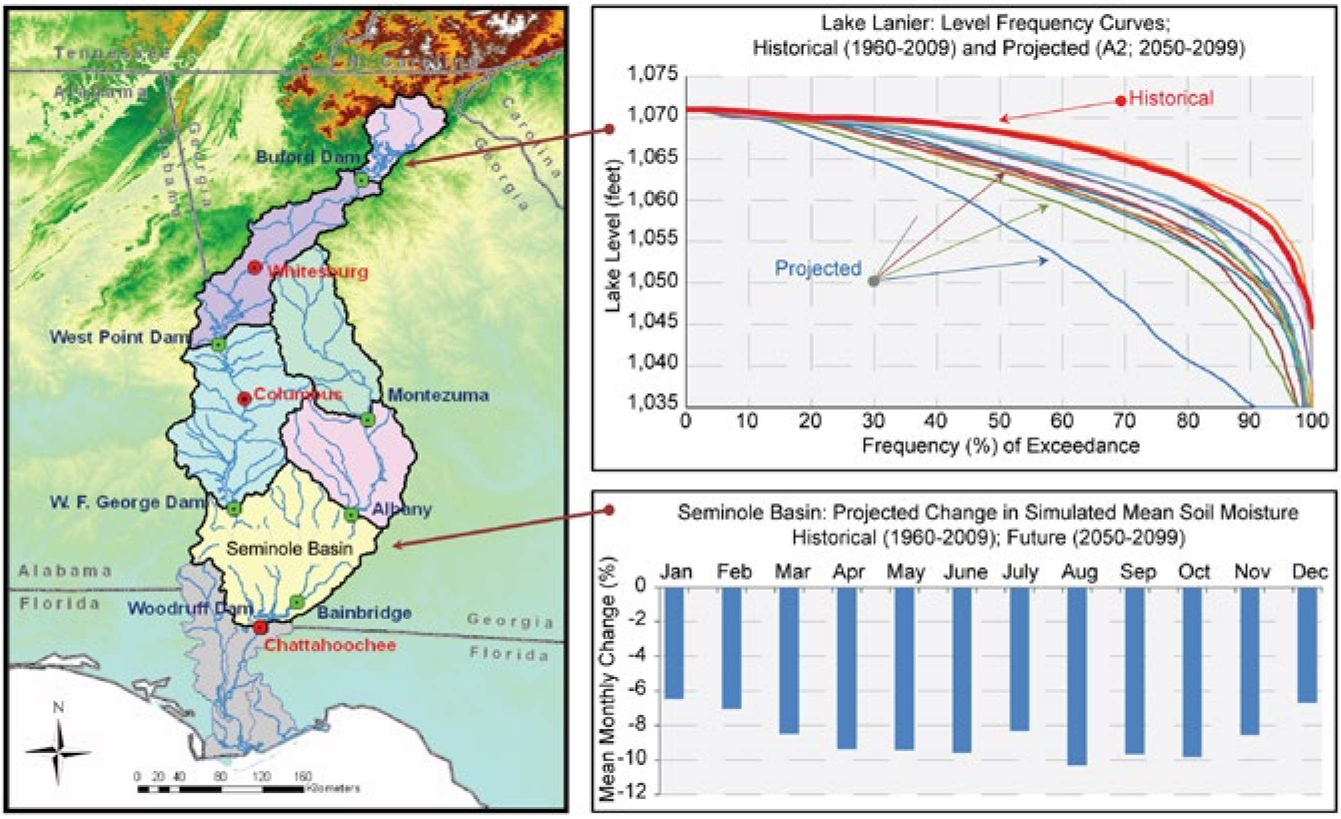


Figure 3.12. The Apalachicola-Chattahoochee-Flint (ACF) River Basin supports many water uses and users, including municipal, industrial, and agricultural water supply; flood management; hydroelectric and thermoelectric energy generation; recreation; navigation; fisheries; and a rich diversity of environmental and ecological resources. In recent decades, water demands have risen rapidly in the Upper Chattahoochee River (due to urban growth) and Lower Chattahoochee and Flint Rivers (due to expansion of irrigated agriculture). At the same time, basin precipitation, soil moisture, and runoff are declining, creating challenging water sharing tradeoffs for the basin stakeholders.[159] The historical water demand and supply trends are expected to continue in the coming decades. Climate assessments for 50 historical (1960-2009) and future years (2050-2099) based on a scenario of continued increases in emissions (A2) for the Seminole and all other ACF sub-basins[152] show that soil moisture is projected to continue to decline in all months, especially during the crop growing season from April to October (bottom right). Mean monthly runoff decreases (up to 20%, not shown) are also projected throughout the year and especially during the wet season from November to May. The projected soil moisture and runoff shifts are even more significant in the extreme values of the respective distributions. In addition to reduced supplies, these projections imply higher water demands in the agricultural and other sectors, exacerbating management challenges. These challenges are reflected in the projected response of Lake Lanier, the main ACF regulation project, the levels of which are projected (for 2050-2099) to be lower, by as much as 15 feet, than its historical (1960-2009) levels, particularly during droughts (top right). Recognizing these critical management challenges, the ACF stakeholders are earnestly working to develop a sustainable and equitable management plan that balances economic, ecological, and social values.[160] (Figure source: Georgia Water Resources Institute, Georgia Institute of Technology.[152]).

Key Message 11: Adaptation Opportunities and Challenges

Increasing resilience and enhancing adaptive capacity provide opportunities to strengthen water resources management and plan for climate change impacts. Many institutional, scientific, economic, and political barriers present challenges to implementing adaptive strategies.

Climate adaptation involves both addressing the risks and leveraging the opportunities that may arise as a result of the climate impacts on the water cycle and water resources. Efforts to increase resiliency and enhance adaptive capacity may create opportunities for a wide-ranging public discussion of water demands, improved collaboration around water use, increased public support for scientific and economic information, and the deployment of new technologies supporting adaptation. In addition, adaptation can promote the achievement of multiple water resource objectives through improved infrastructure planning, integrated regulation, and planning and management approaches at regional, watershed, or ecosystem scales. Pursuing these opportunities may require assessing how current institutional approaches support adaptation in light of the anticipated impacts of climate change.[161]

Climate change will stress the nation's aging water infrastructure to varying degrees by location and over time. Much of the country's current drainage infrastructure is already overwhelmed during heavy precipitation and high runoff events, an impact that is projected to be exacerbated as a result of climate change, land-use change, and other factors. Large percentage increases in combined sewage overflow volumes, associated with increased intensity of precipitation events, have been projected for selected watersheds by the end of this century in the absence of adaptive measures.[106,162] Infrastructure planning, especially for the long planning and operation horizons often associated with water resources infrastructure, can be improved by incorporating climate change as a factor in new design standards and in asset management and rehabilitation of critical and aging facilities, emphasizing flexibility, redundancy, and resiliency.[106,132,163]

Adaptation strategies for water infrastructure include structural and non-structural approaches. These may include changes in system operations and/or demand management changes, adopting water conserving plumbing codes, and improving flood forecasts, telecommunications, and early warning systems[164] that focus on both adapting physical structures and innovative management.[106,132,165] Such strategies could take advantage of conventional ("gray") infrastructure upgrades (like raising flood control levees); adjustments to reservoir operating rules; new demand management and incentive strategies; land-use management that enhances adaptive capacity; protection and restoration at the scale of river basins, watersheds, and ecosystems; hybrid strategies that blend "green" infrastructure with gray infrastructure; and pricing strategies.[1,106,132,166,167] Green infrastructure approaches that are increasingly being implemented by municipalities across the country include green roofs, rain gardens, roadside plantings, porous pavement, and rainwater harvesting (Ch. 28: Adaptation). These techniques typically utilize soils and vegetation in the built environment to absorb runoff close to where it falls, limiting flooding and sewer backups.[168] There are numerous non-infrastructure related adaptation strategies, some of which could include promoting drought-resistant crops, flood insurance reform, and building densely developed areas away from highly vulnerable areas.

In addition to physical adaptation, capacity-building activities can build knowledge and enhance communication and collaboration within and across sectors.[1,167,169] In particular, building networks, partnerships, and support systems has been identified as a major asset in building adaptive capacity (Ch. 26: Decision Support; Ch. 28: Adaptation).[170]

In addition to stressing the physical infrastructure of water systems, future impacts of climate change may reveal the weaknesses in existing water law regimes to accommodate novel and dynamic water management conditions. The basic paradigms of environmental and natural resources law are preservation and restoration, both of which are based on the assumption that natural systems fluctuate within an unchanging envelope of variability ("stationarity").[171] However, climate change is now projected to affect water supplies during the multi-decade lifetime of major water infrastructure projects in wide-ranging and pervasive ways.[132] Under these circumstances, stationarity will no longer be reliable as the central assumption in water-resource risk assessment and planning.[42,171] For example, in the future, water rights administrators may find it necessary to develop more flexible water rights systems conditioned to address the uncertain impacts of climate change.[172] Agencies and courts may seek added flexibility in regulations and laws to achieve the highest and best uses of limited water resources and to enhance water management capacity in the context of new and dynamic conditions.[132,173]

In the past few years, many federal, state, and local agencies and tribal governments have begun to address climate change adaptation, integrating it into existing decision-making, planning, or infrastructure-improvement processes (Ch. 28: Adaptation).[43,174] Drinking water utilities are increasingly utilizing climate information to prepare assessments of their supplies,[175] and utility associations and alliances, such as the Water Research Foundation and Water Utility Climate Alliance, have undertaken original research to better understand the implications of climate change on behalf of some of the largest municipal water utilities in the United States.[119,156,176]

The economic, social, and environmental implications of climate change induced water cycle changes are very significant, as is the cost of inaction. Adaptation responses need to address considerable uncertainties in the short-, medium-, and long-term; be proactive, integrated, and iterative; and be developed through well-informed stakeholder decision processes functioning within a flexible institutional and legal environment.

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SUPPLEMENTAL MATERIAL

TRACEABLE ACCOUNTS

Process for Developing Key Messages:

The chapter author team engaged in multiple technical discussions via teleconferences from March – June 2012. These discussions followed a thorough review of the literature, which included an inter-agency prepared foundational document,[1] over 500 technical inputs provided by the public, as well as other published literature. The author team met in Seattle, Washington, in May 2012 for expert deliberation of draft key messages by the authors wherein each message was defended before the entire author team before this key message was selected for inclusion in the Chapter. These discussions were supported by targeted consultation with additional experts by the lead author of each message, and they were based on criteria that help define "key vulnerabilities." Key messages were further refined following input from the NCADAC report integration team and authors of Ch. 2: Our Changing Climate.

KEY MESSAGE #1 TRACEABLE ACCOUNT

Annual precipitation and river-flow increases are observed now in the Midwest and the Northeast regions. Very heavy precipitation events have increased nationally and are projected to increase in all regions. The length of dry spells is projected to increase in most areas, especially the southern and northwestern portions of the contiguous United States.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 2: Our Changing Climate, Ch. 20: Southwest, other technical input reports,[2] and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

Numerous peer-reviewed publications describe precipitation trends (Ch. 2: Our Changing Climate)[4,7,8,34] and river-flow trends.[13,41] As discussed in Chapter 2, the majority of projections available from climate models (for example, Orlowsky and Seneviratne 2012;[3] Kharin et al. 2013[5]) indicate small projected changes in total average annual precipitation in many areas, while heavy precipitation[6] and the length of dry spells are projected to increase across the entire country. Projected precipitation responses (such as changing extremes) to increasing greenhouse gases are robust in a wide variety of models and depictions of climate.

The broad observed trends of precipitation and river-flow increases have been identified by many long-term National Weather Service (NWS)/National Climatic Data Center (NCDC) weather monitoring networks, USGS streamflow monitoring networks, and analyses of records therefrom (Ch. 2: Our Changing Climate;[34,36,37]). Ensembles of climate models[3,42](see also Ch. 2: Our Changing Climate, Ch. 20: Southwest) are the basis for the reported projections.

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings from the 2009 National Climate Assessment.[177]

Observed trends: Precipitation trends are generally embedded amidst large year-to-year natural variations and thus trends may be difficult to detect, may differ from site to site, and may be reflections of multi-decadal variations rather than external (human) forcings. Consequently, careful analyses of longest-term records from many stations across the country and addressing multiple potential explanations are required and are cornerstones of the evidentiary studies described above.

Efforts are underway to continually improve the stability, placement, and numbers of weather observations needed to document trends; scientists also regularly search for other previously unanalyzed data sources for use in testing these findings.

Projected trends: The complexity of physical processes that result in precipitation and runoff reduces abilities to represent or predict them as accurately as would be desired and with the spatial and temporal resolution required for many applications; however, as noted, the trends at the scale depicted in this message are very robust among a wide variety of climate models and projections, which lends confidence that the projections are appropriate lessons from current climate (and streamflow) models. Nonetheless, other influences not included in the climate change projections might influence future patterns of precipitation and runoff, including changes in land cover, water use (by humans and vegetation), and streamflow management.

Climate models used to make projections of future trends are continually increasing in number, resolution, and in the number of additional external and internal influences that might be confounding current projections. For example, much more of all three of these directions for improvement are already evident in projection archives for the next IPCC assessment.

Assessment of confidence based on evidence

Observed trends have been demonstrated by a broad range of methods over the past 20+ years based on best available data; projected precipitation and river-flow responses to greenhouse gas increases are robust across large majorities of available climate (and hydrologic) models from scientific teams around the world.

Confidence is therefore judged to be **high** that annual precipitation and river-flow increases are observed now in the Midwest and the Northeast regions.

Confidence is **high** that very heavy precipitation events have increased nationally and are projected to increase in all regions.

Confidence is **high** that the length of dry spells is projected to increase in most areas, especially the southern and northwestern portions of the contiguous United States.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key message #2 Traceable Account

Short-term (seasonal or shorter) droughts are expected to intensify in most U.S. regions. Longer-term droughts are expected to intensify in large areas of the Southwest, southern Great Plains, and Southeast.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 16: Northeast, Ch 17: Southeast, Ch. 2: Our Changing Climate, Ch. 18: Midwest, Ch. 19: Great Plains, Ch. 20: Southwest, Ch. 21: Northwest, Ch. 23: Hawai'i and Pacific Islands, and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

Projected drought trends derive directly from climate models in some studies (for example, Hoerling et al. 2012;[8] Wehner et al. 2011;[30] Gao et al. 2012;[32] Gao et al. 2011;[33]), from hydrologic models responding to projected climate trends in others (for example, Georgakakos and Zhang 2011;[38] Cayan et al. 2010;[48]), from considerations of the interactions between precipitation deficits and either warmer or cooler temperatures in historical (observed) droughts,[48] and from combinations of these approaches (for example, Trenberth et al. 2004[49]) in still other studies.

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings from the 2009 National Climate Assessment.[177]

Warmer temperatures are robustly projected by essentially all climate models, with what are generally expected to be directly attendant increases in the potentials for greater evapotranspiration, or ET (although it is possible that current estimates of future ET are overly influenced by temperatures at the expense of other climate variables, like wind speed, humidity, net surface radiation, and soil moisture that might change in ways that could partly ameliorate rising ET demands). As a consequence, there is a widespread expectation that more water from precipitation will be evaporated or transpired in the warmer future, so that except in regions where precipitation increases more than ET increases, less overall water will remain on the landscape and droughts will intensify and become more common. Another widespread expectation is that precipitation variability will increase, which may result in larger swings in moisture availability, with swings towards the deficit side resulting in increased frequencies and intensities of drought conditions on seasonal time scales to times scales of multiple decades. An important remaining uncertainty, discussed in the supporting text for Key Message #1, is the extent to which the types of models used to project future droughts may be influencing results with a notable recent tendency for studies with more complete, more resolved land-surface models, as well as climate models, to yield more moderate projected changes.

Other uncertainties derive from the possibility that changes in other variables or influences of CO_2-fertilization and/or land cover change may also partly ameliorate drought intensification. Furthermore in many parts of the country, El Niño-Southern Oscillation (and other oceanic) influences on droughts and floods are large, and can overwhelm climate change effects during the next few decades. At present, however, the future of these oceanic climate influences remains uncertain.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties:

Confidence is judged to be **medium-high** that short-term (seasonal or shorter) droughts are expected to intensify in most U.S. regions. Confidence is **high** that longer-term droughts are expected to intensify in large areas of the Southwest, southern Great Plains, and Southeast.

KEY MESSAGE #3 TRACEABLE ACCOUNT

Flooding may intensify in many U.S. regions, even in areas where total precipitation is projected to decline.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 16: Northeast, Ch 17: Southeast, Ch. 2: Our Changing Climate, Ch. 18: Midwest, Ch. 19: Great Plains, Ch. 20: Southwest, Ch. 21: Northwest, Ch. 23: Hawai'i and Pacific Islands, and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

The principal observational bases for the key message are careful national-scale flood-trend analyses[58] based on annual peak-flow records from a selection of 200 USGS streamflow gaging stations measuring flows from catchments that are minimally influenced by upstream water uses, diversions, impoundments, or land-use changes with more than 85 years of records, and analyses of two other subsets of USGS gages with long records (including gages both impacted by human activities and less so), including one analysis of 50 gages nationwide[56] and a second analysis of 572 gages in the eastern United States.[57] There is some correspondence among regions with significant changes in annual precipitation (Ch. 2: Our Changing Climate) and soil moisture (Figures 3.2 and 3.3), and annual flood magnitudes (Figure 3.5).[58]

Projections of future flood-frequency changes result from detailed hydrologic models (for example, Das et al. 2012;[60] Raff et al. 2009;[133]Walker et al. 2011[135]) of rivers that simulate responses to projected precipitation and temperature changes from climate models; such simulations have only recently begun to emerge in the peer-reviewed literature.

New information and remaining uncertainties

Important new evidence (cited above) confirmed many of the findings from the 2009 National Climate Assessment.[177]

Large uncertainties remain in efforts to detect flood-statistic changes attributable to climate change, because a wide range of local factors (such as dams, land-use changes, river channelization) also affect flood regimes and can mask, or proxy for, climate change induced alterations. Furthermore, it is especially difficult to detect any kinds of trends in what are, by definition, rare and extreme events. Finally, the response of floods to climate changes are expected to be fairly idiosyncratic from basin to basin, because of the strong influences of within-storm variations and local, basin-scale topographic, soil and vegetation, and river network characteristics that influence the size and extent of flooding associated with any given storm or season.[54,55,56,57]

Large uncertainties still exist as to how well climate models can represent and project future extremes of precipitation. This has – until recently – limited attempts to make specific projections of future flood frequencies by using climate model outputs directly or as direct inputs to hydrologic models. However, precipitation extremes are expected to intensify as the atmosphere warms, and many floods result from larger portions of catchment areas receiving rain as snowlines recede upward. As rain runs off more quickly than snowfall this results in increased flood potential; furthermore, occasional rain-on-snow events exacerbates this effect. This trend is broadly expected to increase in frequency under general warming trends, particularly in mountainous catchments.[62] Rising sea levels and projected increase in hurricane-associated storm intensity and rainfall rates provide first-principles bases for expecting intensified flood regimes in coastal settings (see Ch. 2: Our Changing Climate).

Assessment of confidence based on evidence

Future changes in flood frequencies and intensities will depend on a complex combination of local to regional climatic influences, and the details of complex surface-hydrologic conditions in each catchment (for example, topography, land cover, and upstream management). Consequently, flood frequency changes may be neither simple nor regionally homogeneous, and basin by basin projections may need to be developed. Early results now appearing in the literature have most often projected intensifications of flood regimes, in large part as responses to projections of more intense storms and increasingly rainy (rather than snowy) storms in previously snow-dominated settings. Confidence in current estimates of future changes in flood frequencies and intensities is overall judged to be **low**.

KEY MESSAGE #4 TRACEABLE ACCOUNT

Climate change is expected to affect water demand, groundwater withdrawals, and aquifer recharge, reducing groundwater availability in some areas.

Description of evidence base
The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] regional chapters of the NCA, and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

Several recent studies[65,66,67,68,71,72] have evaluated the potential impacts of changes in groundwater use and recharge under scenarios including climate change, and generally they have illustrated the common-sense conclusion that changes in pumpage can have immediate and significant effects in the nation's aquifers. This has certainly been the historical experience in most aquifers that have seen significant development; pumpage variations usually tend to yield more immediate and often larger changes on many aquifers than do historical climate variations on time scales from years to decades. Meanwhile, for aquifers in the Southwest, there is a growing literature of geochemical studies that fingerprint various properties of groundwater and that are demonstrating that most western groundwater derives preferentially from snowmelt, rather than rainfall or other sources.[50,51,66,74] This finding suggests that much western recharge may be at risk of changes and disruptions from projected losses of snowpack, but as yet provides relatively little indication whether the net effects will be recharge declines, increases, or simply spatial redistribution.

New information and remaining uncertainties
The precise responses of groundwater storage and flow to climate change are not well understood, but recent and ongoing studies provide insights on underlying mechanisms.[65,66,67] The observations and modeling evidence to make projections of future responses of groundwater recharge and discharge to climate change are thus far very limited, primarily because of limitations in data availability and in the models themselves. New forms and networks of observations and new modeling approaches and tools are needed to provide projections of the likely influences of climate changes on groundwater recharge and discharge. Despite the uncertainties about the specifics of climate change impacts on groundwater, impacts of reduced groundwater supply and quality would likely be detrimental to the nation.

Assessment of confidence based on evidence
Given the evidence base and remaining uncertainties, confidence is judged to be **high** that climate change is expected to affect water demand, groundwater withdrawals, and aquifer recharge, reducing groundwater availability in some areas.

KEY MESSAGE #5 TRACEABLE ACCOUNT

Sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to compromise the sustainability of coastal freshwater aquifers and wetlands.

Description of evidence base
This message has a strong theoretical and observational basis, including considerable historical experience with seawater intrusion into many of the nation's coastal aquifers and wetlands under the influence of heavy pumpage, some experience with the influences of droughts and storms on seawater intrusion, and experience with seepage of seawater into shallow coastal aquifers under storm and storm surge conditions that lead to coastal inundations with seawater. The likely influences of sea level rise on seawater intrusion into coastal (and island) aquifers and wetlands are somewhat less certain, as discussed below, although it is projected that sea level rise may increase opportunities for saltwater intrusion (see Ch. 25: Coasts).

New information and remaining uncertainties
There are few published studies describing the kinds of groundwater quality and flow modeling that are necessary to assess the real-world potentials for sea level rise to affect seawater intrusion.[78] Studies in the literature and historical experience demonstrate the detrimental impacts of alterations to the water budgets of the freshwater lenses in coastal aquifers and wetlands around the world (most often by groundwater development), but few evaluate the impacts of sea level rise alone. More studies with real-world aquifer geometries and development regimes are needed to reduce the current uncertainty of the potential interactions of sea level rise and seawater intrusion.

Assessment of confidence based on evidence
Confidence is **high** that sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to compromise the sustainability of coastal freshwater aquifers and wetlands.

KEY MESSAGE #6 TRACEABLE ACCOUNT

Increasing air and water temperatures, more intense precipitation and runoff, and intensifying droughts can decrease river and lake water quality in many ways, including increases in sediment, nitrogen, and other pollutant loads.

Description of evidence base
The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 8: Ecosystems, Ch. 15: Biogeochemical Cycles, and over 500 technical inputs on a wide range of topics that were reviewed as part of the Federal Register Notice solicitation for public input.

Thermal stratification of deep lakes and reservoirs has been observed to increase with increased air and water temperatures,[1,81,82] and may be eliminated in shallow lakes. Increased stratification reduces mixing, resulting in reduced oxygen in bottom waters. Deeper set-up of vertical thermal stratification in lakes and reservoirs may reduce or eliminate a bottom cold water zone; this, coupled with lower oxygen concentration, results in a degraded aquatic ecosystem.

Major precipitation events and resultant water flows increase watershed pollutant scour and thus increase pollutant loads.[84] Fluxes of mineral weathering products (for example, calcium, magnesium, sodium, and silicon) have also been shown to increase in response to higher discharge.[86] In the Mississippi drainage basin, increased precipitation has resulted in increased nitrogen loads contributing to hypoxia in the Gulf of Mexico.[85] Models predict and observations confirm that continued warming will have increasingly negative effects on lake water quality and ecosystem health.[81]

Future re-mobilization of sediment stored in large river basins will be influenced by changes in flood frequencies and magnitudes, as well as on vegetation changes in the context of climate and other anthropogenic factors.[87] Model projections suggest that changes in sediment delivery will vary regionally and by land-use type, but on average could increase by 25% to 55%.[88]

New information and remaining uncertainties

It is unclear whether increasing floods and droughts cancel each other out with respect to long-term pollutant loads.

It is also uncertain whether the absolute temperature differential with depth will remain constant, even with overall lake and reservoir water temperature increases. Further, it is uncertain if greater mixing with depth will eliminate thermal stratification in shallow, previously stratified lakes. Although recent studies of Lake Tahoe provide an example of longer stratification seasons,[83] lakes in other settings and with other geometries may not exhibit the same response.

Many factors influence stream water temperature, including air temperature, forest canopy cover, and ratio of baseflow to streamflow.

Assessment of confidence based on evidence

Given the evidence base, confidence is **medium** that increasing air and water temperatures, more intense precipitation and runoff, and intensifying droughts can decrease river and lake water quality in many ways, including increases in sediment, nitrogen, and pollutant loads.

KEY MESSAGE #7 TRACEABLE ACCOUNT

Climate change affects water demand and the ways water is used within and across regions and economic sectors. The Southwest, Great Plains, and Southeast are particularly vulnerable to changes in water supply and demand.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 2: Our Changing Climate, Ch. 17: Southeast, Ch. 19: Great Plains, Ch. 20: Southwest, Ch. 23: Hawai‘i and Pacific Islands, and many technical inputs on a wide range of topics that were received and reviewed as part of the Federal Register Notice solicitation for public input.

Observed Trends: Historical water withdrawals by sector (for example, municipal, industrial, agricultural, and thermoelectric) have been monitored and documented by USGS for over 40 years and represent a credible database to assess water-use trends, efficiencies, and underlying drivers. Water-use drivers principally include population, personal income, electricity consumption, irrigated area, mean annual temperature, growing season precipitation, and growing season potential evapotranspiration.[99] Water-use efficiencies are also affected by many non-climate factors, including demand management, plumbing codes, water efficient appliances, efficiency improvement programs, and pricing strategies;[100] changes from water intensive manufacturing and other heavy industrial activities to service-oriented businesses,[101] and enhanced water-use efficiencies in response to environmental pollution legislation; replacement of older once-through-cooling electric power plants by plants that recycle their cooling water; and switching from flood irrigation to more efficient methods in the western United States.[102]

Projected Trends and Consequences: Future projections have been carried out with and without climate change to first assess the water demand impacts of projected population and socioeconomic increases, and subsequently combine them with climate change induced impacts. The main findings are that in the absence of climate change total water withdrawals in the U.S. will increase by 3% in the coming 50 years,[99] with approximately half of the U.S. experiencing a total water demand decrease and half an increase. If, however, climate change projections are also factored in, the demand for total water withdrawals is projected to rise by an average of 26%,[99] with more than 90% of the U.S. projected to experience a total demand increase, and decreases projected only in parts of the Midwest, Northeast, and Southeast. When coupled with the observed and projected drying water cycle trends (see key messages in “Climate Change Impacts on the Water Cycle” section), the water demand impacts of projected population, socioeconomic, and climate changes intensify and compound in the Southwest and Southeast, rendering these regions particularly vulnerable in the coming decades.

New information and remaining uncertainties

The studies of water demand in response to climate change and other stressors are very recent and constitute new information on their own merit.[99] In addition, for the first time, these studies make it possible to piece together the regional implications of climate change induced water cycle alterations in combination with projected changes in water demand. Such integrated assessments also constitute new information and knowledge building.

Demand projections include various uncertain assumptions which become increasingly important in longer term (multi-decadal) projections. Because irrigation demand is the largest water demand component most sensitive to climate change, the most important climate-related uncertainties are precipitation and potential evapotranspiration over the growing season. Non-climatic uncertainties relate to future population distribution, socioeconomic changes, and water-use efficiency improvements.

Assessment of confidence based on evidence

Considering that (a) droughts are projected to intensify in large areas of the Southwest, Great Plains, and the Southeast, and (b) that these same regions have experienced and are projected to experience continuing population and demand increases, confidence that these regions will become increasingly vulnerable to climate change is judged to be **high**.

Key message #8 Traceable Account

Changes in precipitation and runoff, combined with changes in consumption and withdrawal, have reduced surface and groundwater supplies in many areas. These trends are expected to continue, increasing the likelihood of water shortages for many uses.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 2: Our Changing Climate, Ch. 17: Southeast, Ch. 19: Great Plains, Ch. 20: Southwest, Ch. 23: Hawai'i and Pacific Islands, and over 500 technical inputs on a wide range of topics that were received and reviewed as part of the Federal Register Notice solicitation for public input.

Observed Trends: Observations suggest that the water cycle in the Southwest, Great Plains, and Southeast has been changing toward drier conditions (Ch. 17: Southeast).[130,151,152] Furthermore, paleoclimate tree-ring reconstructions indicate that drought in previous centuries has been more intense and of longer duration than the most extreme drought of the 20th and 21st centuries.[40]

Projected Trends and Consequences: Global Climate Model (GCM) projections indicate that this trend is likely to persist, with runoff reductions (in the range of 10% to 20% over the next 50 years) and intensifying droughts.[48]

The drying water cycle is expected to affect all human and ecological water uses, especially in the Southwest. Decreasing precipitation, rising temperatures, and drying soils are projected to increase irrigation and outdoor watering demand (which account for nearly 90% of consumptive water use) by as much as 34% by 2060 under the A2 emissions scenario.[99] Decreasing runoff and groundwater recharge are expected to reduce surface and groundwater supplies,[66] increasing the annual risk of water shortages from 25% to 50% by 2060.[130] Changes in streamflow timing will increase the mismatch of supply and demand. Earlier and declining streamflow and rising demands will make it more difficult to manage reservoirs, aquifers, and other water infrastructure.[130]

Such impacts and consequences have been identified for several southwestern and western river basins including the Colorado,[38] Rio Grande,[126] and Sacramento-San Joaquin.[127,128,129]

New information and remaining uncertainties

The drying climate trend observed in the Southwest and Southeast in the last decades is consistent across all water cycle variables (precipitation, temperature, snow cover, runoff, streamflow, reservoir levels, and soil moisture) and is not debatable. The debate is over whether this trend is part of a multi-decadal climate cycle and whether it will reverse direction at some future time. However, the rate of change and the comparative GCM assessment results with and without historical CO_2 forcing (Ch. 2: Our Changing Climate) support the view that the observed trends are due to both factors acting concurrently.

GCMs continue to be uncertain with respect to precipitation, but they are very consistent with respect to temperature. Runoff, streamflow, and soil moisture depend on both variables and are thus less susceptible to GCM precipitation uncertainty. The observed trends and the general GCM agreement that the southern states will continue to experience streamflow and soil moisture reductions[34,41] provides confidence that these projections are robust.

Assessment of confidence based on evidence

Given the evidence base and remaining uncertainties, confidence is **high** that changes in precipitation and runoff, combined with changes in consumption and withdrawal, have reduced surface and groundwater supplies in many areas. Confidence is **high** that these trends are expected to continue, increasing the likelihood of water shortages for many uses.

Key message #9 Traceable Account

Increasing flooding risk affects human safety and health, property, infrastructure, economies, and ecology in many basins across the U.S.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] Ch. 2: Our Changing Climate, Ch. 21: Northwest, Ch. 19: Great Plains, Ch. 18: Midwest, Ch. 16: Northeast, and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

Observed Trends: Very heavy precipitation events have intensified in recent decades in most U.S. regions, and this trend is projected to continue (Ch. 2: Our Changing Climate). Increasing heavy precipitation is an important contributing factor for floods, but flood magnitude changes also depend on specific watershed conditions (including soil moisture, impervious area, and other human-caused alterations). There is, however, some correspondence among regions with significant changes in annual precipitation (Ch. 2: Our Changing Climate), soil moisture (Figures 3.2 and 3.3), and annual flood magnitudes (Figure 3.5).[58]

Flooding and seawater intrusion from sea level rise and increasing storm surge threaten New York, Boston, Philadelphia, Virginia Beach, Wilmington, Charleston, Miami, Tampa, Naples, Mobile, Houston, New Orleans, and many other coastal cities (Chapter 25: Coasts).

Projected Trends: Projections of future flood-frequency changes result from detailed hydrologic[60,133,135] and hydraulic models of rivers that simulate responses to projected precipitation and temperature changes from climate models.

Consequences: Floods already affect human health and safety and result in substantial economic, ecological, and infrastructure damages. Many cities are located along coasts and, in some of these cities (including New York, Boston, Miami, Savannah, and New Orleans), sea level rise is expected to exacerbate coastal flooding issues by backing up flood flows and impeding flood-management responses (see Ch. 16: Northeast and Ch. 25: Coasts).[136]

Projected changes in flood frequency and severity can bring new challenges in flood risk management. For urban areas in particular, flooding impacts critical infrastructure in ways that are difficult to foresee and can result in interconnected and cascading failures (for example, failure of electrical generating lines can cause pump failure, additional flooding, and failure of evacuation services). Increasing likelihood of flooding also brings with it human health risks associated with failure of critical infrastructure (Ch. 11: Urban),[137] from waterborne disease that can persist well beyond the occurrence of very heavy precipitation (Ch. 9: Human Health),[139] from water outages associated with infrastructure failures that cause decreased sanitary conditions,[138] and from ecosystem changes that can affect airborne diseases (Ch. 8: Ecosystems).[140]

New information and remaining uncertainties

Large uncertainties still exist as to how well climate models can represent and project future precipitation extremes. However, precipitation extremes are expected to intensify as the atmosphere warms, and many floods result from larger portions of catchment areas receiving rain as snowlines recede upward. As rain runs off more quickly than snowfall, this results in increased flood potential; furthermore occasional rain-on-snow events exacerbate this effect. This trend is broadly expected to increase in frequency under general warming trends, particularly in mountainous catchments.[62]

Assessment of confidence based on evidence

Future changes in flood frequencies and intensities will depend on a complex combination of local to regional climatic influences and on the details of complex surface-hydrologic conditions in each catchment (for example, topography, land cover, and upstream managements). Consequently, flood frequency changes may be neither simple nor regionally homogeneous, and basin by basin projections may need to be developed. Nonetheless, early results now appearing in the literature have most often projected intensifications of flood regimes, in large part as responses to projections of more intense storms and more rainfall runoff from previously snowbound catchments and settings.

Therefore, confidence is judged to be **medium** that increasing flooding risk affects human safety and health, property, infrastructure, economies, and ecology in many basins across the U.S.

KEY MESSAGE #10 TRACEABLE ACCOUNT

In most U.S. regions, water resources managers and planners will encounter new risks, vulnerabilities, and opportunities that may not be properly managed within existing practices.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document,[1] other chapters of the NCA, and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

Observed and Projected Trends: Many U.S. regions are facing critical water management and planning challenges. Recent assessments illustrate water management challenges facing California,[127,128,129,149] the Southwest,[130,151] Southeast (Ch. 17: Southeast),[136,152] Northwest,[153] Great Plains,[154] and Great Lakes.[155]

The Sacramento-San Joaquin Bay Delta is already threatened by flooding, seawater intrusion, and changing needs for environmental, municipal, and agricultural water uses. Managing these risks and uses requires reassessment of a very complex system of water rights, levees, stakeholder consensus processes, reservoir system operations, and significant investments, all of which are subject to large uncertainties.[54,148] Given the projected climate changes in the Sacramento-San Joaquin Bay Delta, adherence to historical management and planning practices may not be a long-term viable option,[128,129] but the supporting science is not yet fully actionable,[42] and a flexible legal and policy framework embracing change and uncertainty is lacking.

The Apalachicola-Chattahoochee-Flint (ACF) River basin in Georgia, Alabama, and Florida supports a wide range of water uses and the regional economy, creating challenging water-sharing tradeoffs for the basin stakeholders. Climate change presents new stresses and uncertainties.[152] ACF stakeholders are working to develop a management plan that balances economic, ecological, and social values.[160]

New information and remaining uncertainties

Changes in climate, water demand, land use, and demography combine to challenge water management in unprecedented ways. This is happening with a very high degree of certainty in most U.S. regions. Regardless of its underlying causes, climate change poses difficult challenges for water management because it invalidates stationarity – the perception that climate varies around a predictable mean based on the experience of the last century – and increases hydrologic variability and uncertainty. These conditions suggest that past management practices will become increasingly ineffective and that water management can benefit by the adoption of iterative, risk-based, and adaptive approaches.

Assessment of confidence based on evidence

The water resources literature is unanimous that water management should rely less on historical practices and responses and more on robust, risk-based, and adaptive decision approaches.

Therefore confidence is **very high** that in most U.S. regions, water resources managers and planners will face new risks, vulnerabilities, and opportunities that may not be properly managed with existing practices.

KEY MESSAGE #11 TRACEABLE ACCOUNT

Increasing resilience and enhancing adaptive capacity provide opportunities to strengthen water resources management and plan for climate change impacts. Many institutional, scientific, economic, and political barriers present challenges to implementing adaptive strategies.

Description of evidence base

The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document[1] and over 500 technical inputs on a wide range of topics that were received as part of the Federal Register Notice solicitation for public input.

There are many examples of adaptive strategies for water infrastructure[106,132,164,165] as well as strategies for demand management, land-use and watershed management, and use of "green" infrastructure.[1,106,132,166,167]

Building adaptive capacity ultimately increases the ability to develop and implement adaptation strategies and is considered a no-regrets strategy.[1,169] Building networks, partnerships, and support systems has been identified as a major asset in building adaptive capacity (Ch. 26: Decision Support; Ch. 28: Adaptation).[170]

Water utility associations have undertaken original research to better understand the implications of climate change on behalf of some of the largest municipal water utilities in the United States.[119,156,176]

Challenges include "stationarity" no longer being reliable as the central assumption in water-resource planning,[171] considerable uncertainties, insufficient actionable science ready for practical application, the challenges of stakeholder engagement, and a lack of agreement on "post-stationarity" paradigms on which to base water laws, regulations, and policies.[42] Water administrators may find it necessary to develop more flexible water rights and regulations.[132,172,173]

New information and remaining uncertainties

Jurisdictions at the state and local levels are addressing climate change related legal and institutional issues on an individual basis. An ongoing assessment of these efforts may show more practical applications.

Assessment of confidence based on evidence

Confidence is **very high** that increasing resilience and enhancing adaptive capacity provide opportunities to strengthen water resources management and plan for climate change impacts.

Confidence is **very high** that many institutional, scientific, economic, and political barriers present challenges to implementing adaptive strategies.