Fifth National Climate Assessment: Chapter 4

Water

Chapter 4. Water

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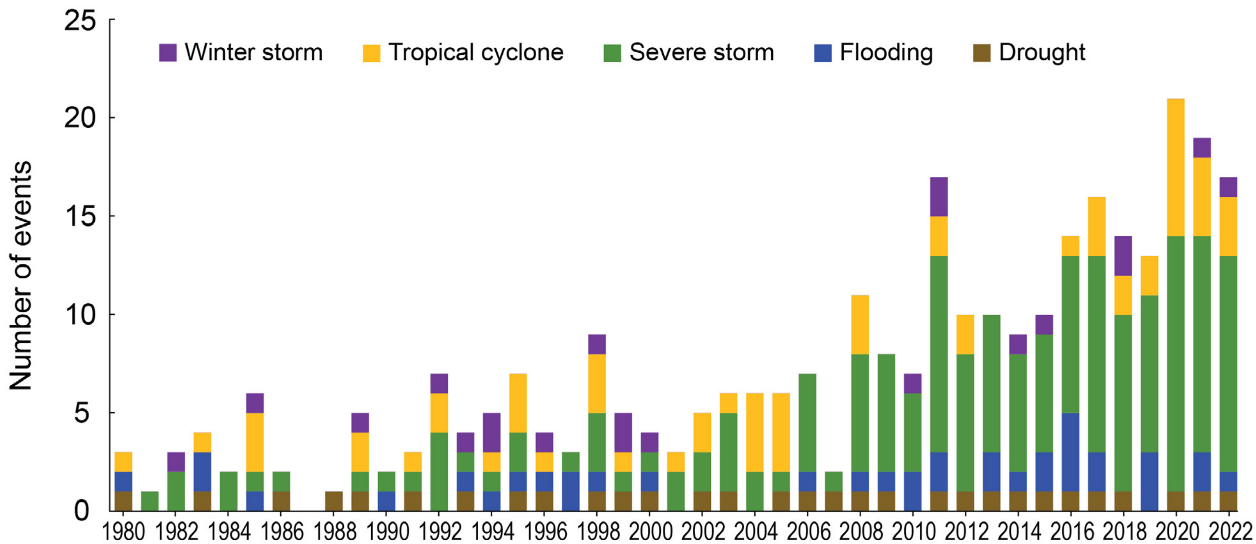
Introduction

Climate change is intensifying rainfall and floods, deepening droughts, and shifting weather patterns across the globe,[1] causing profound effects on terrestrial freshwater supplies and quality. Rising sea levels, reduced snowpacks, shrinking rivers, and declining groundwater threaten cities and rural communities and endanger forest, riverine, and other ecosystems across the United States.

Climate change, combined with greater exposure and vulnerability, is increasing the frequency of water-related disasters in the US (Figure 4.1).

Water-Related Billion-Dollar Disasters in the United States

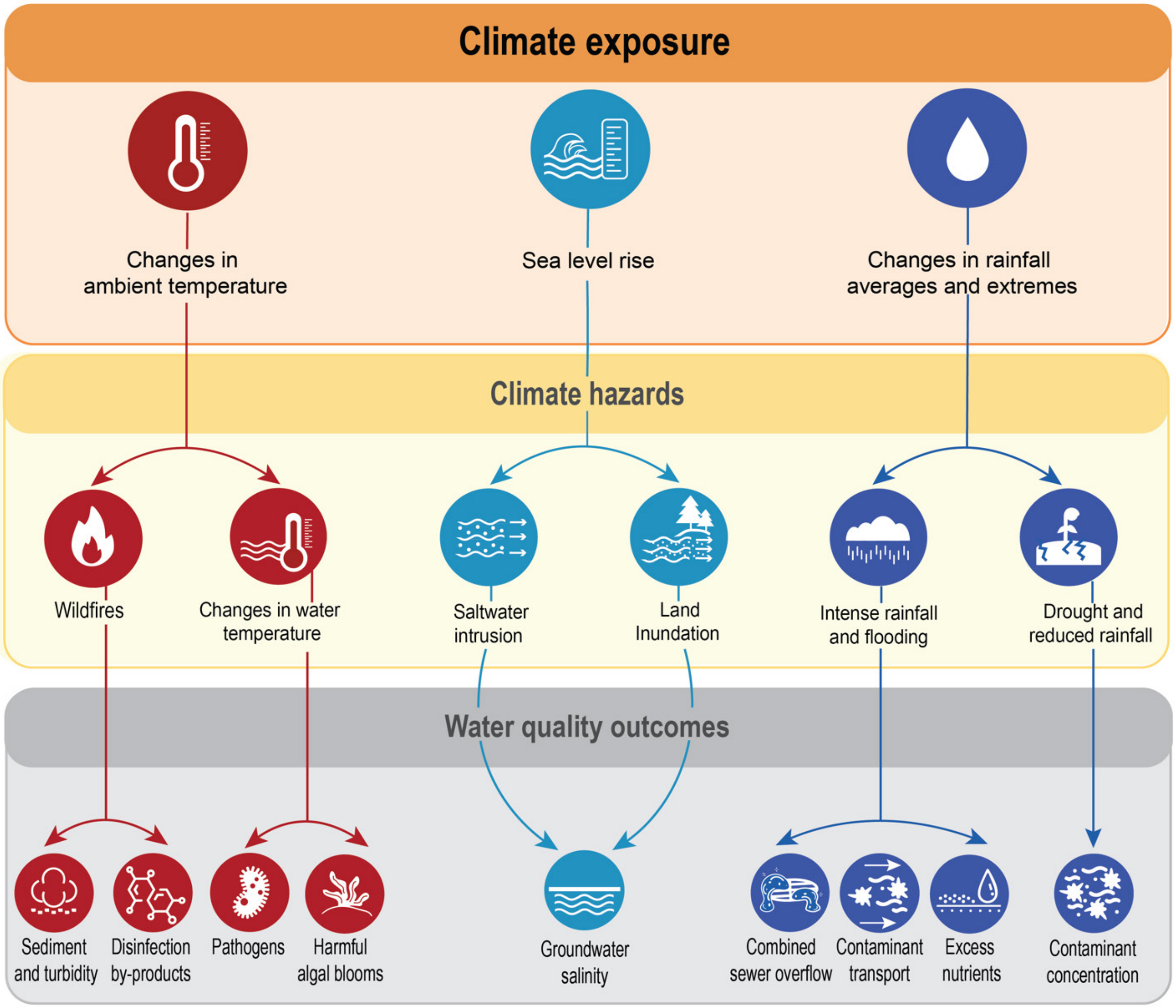


Water-related billion-dollar disasters are increasing in the United States.

Figure 4.1. Across the US, the number of water-related disasters with damages exceeding $1 billion (adjusted for inflation) during 1980–2022 rose due to increases in exposure, or assets at risk; vulnerability, or how much damage a hazard of a given intensity causes; and climate change-driven increases in the frequency of extremes. Adapted from NCEI 2023.[2]

While these events are primarily related to water *quantity*, impacts related to water *quality* are increasing as well, as predicted in the Fourth National Climate Assessment, released in 2018 (NCA4).[3] Temperature increases, sea level rise, and changes in precipitation are expected to continue to degrade water quality for people and ecosystems (Figure 4.2; KMs 4.2, 15.1, 15.2).[4,5,6]

Climate Change Impacts to Water Quality



Climate change threatens the quality of freshwater supplies.

Figure 4.2. Changes in ambient temperature, sea level, and rainfall (**top**) can create climate-related hazards, such as changes in water temperature and saltwater intrusion (**middle**) that can have negative impacts on water quality (**bottom**). Saltwater intrusion is an imminent threat to coastal and island communities dependent on groundwater for drinking water (KMs 30.1, 9.2); agricultural areas face risks to water supplies when fertilizers and pesticides are mobilized by flooding;[7] higher temperatures are putting many areas at risk of exposure to harmful algal blooms (e.g., KM 22.2) and increases in fecal coliform bacteria;[6] and treatment plants are challenged by sediments and debris from wildfires in their source waters (KM 6.1).[8,9] Adapted from Nijhawan and Howard 2022[6] [CC BY 4.0].

Climate change is forcing a reexamination of our concepts of rare events. Extreme precipitation incidents are more intense and more frequent (KM 2.2); extended droughts in the West appear to be due in part to long-term aridification in addition to episodic drying (KM 4.2); and compound hazards are increasing as the events that combine to create them become more frequent (Focus on Compound Events).

The US is slowly adapting to these changes. Utilities are exploring ways to integrate change into planning, and communities are cooperatively seeking solutions to water shortages and flooding (KM 4.3). But barriers arise from legal and regulatory institutions that have been in place for decades or even centuries, locking in practices that hinder adaptation (KM 4.3). The Nation's aging water infrastructure, designed under regulations and standards appropriate to an unchanging climate, is deteriorating and threatening public health, a situation little changed since it was highlighted in NCA4 (KM 4.2).[3]

Perhaps the most notable advance in recent years is the growing recognition of environmental injustices exacerbated by climate change (KM 1.2). Overburdened populations, including Black, Hispanic, Indigenous, Tribal and other communities, are suffering disproportionate impacts from climate-driven water quality and quantity hazards that threaten these communities' water security (KMs 4.2, 15.1, 15.2, 16.1).

The Nation is making some progress. The tools and data needed to support water resources planning and management have become more sophisticated and widely available, though gaps remain, particularly hydrologic projections for the US Caribbean, Hawai'i, and the US-Affiliated Pacific Islands, where water security concerns are high (KM 4.1; Box 23.2). Gaps in local projections of extreme event frequencies, magnitudes, and durations also hinder adaptation. There has been enormous growth in the availability of science-based climate information for water providers and natural resource managers, demonstrating increasing awareness and demand for solutions. These and similar efforts are the first steps toward building resilient human and natural systems in the face of climate-induced changes to the water cycle.

Key Message 4.1

Climate Change Will Continue to Cause Profound Changes in the Water Cycle

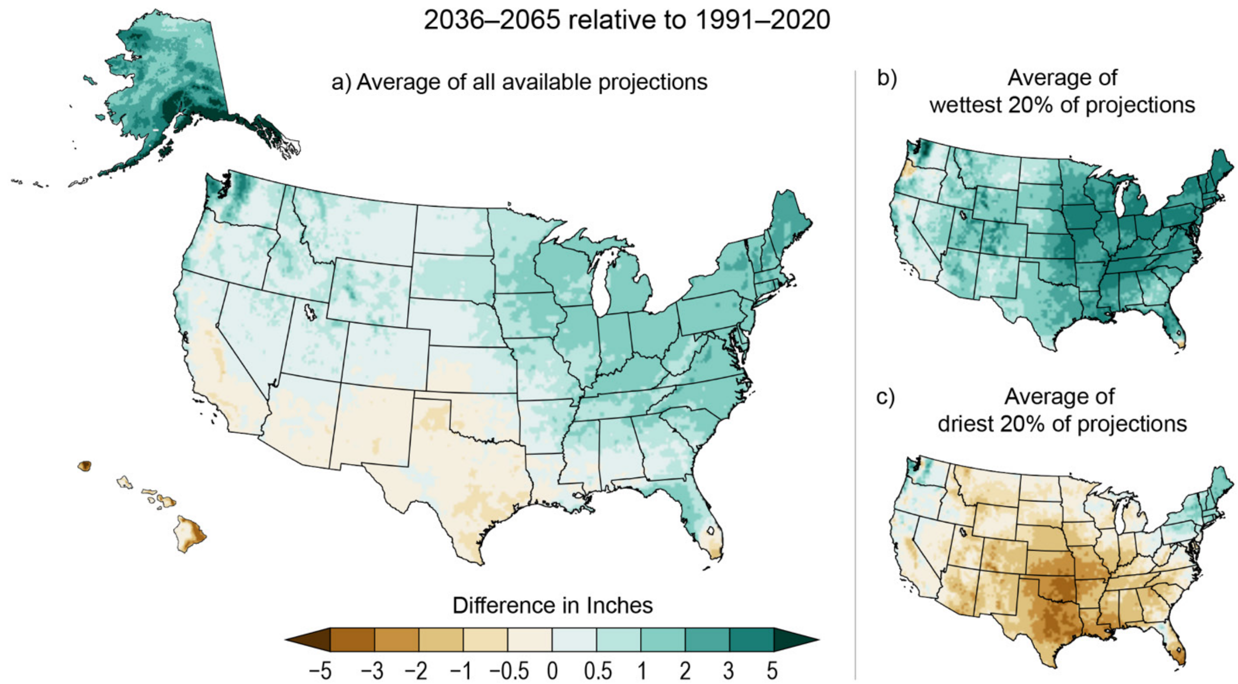
Changes to the water cycle pose risks to people and nature. Alaska and northern and eastern regions of the US are seeing and expect to see more precipitation on average, while the Caribbean, Hawai'i, and southwestern regions of the US are seeing and expect to see less precipitation (*medium confidence*). Heavier rainfall events are expected to increase across the Nation (*very likely*, *very high confidence*), and warming will increase evaporation and plant water use where moisture is not a limiting factor (*medium confidence*). Groundwater supplies are also threatened by warming temperatures that are expected to increase demand (*very likely*, *high confidence*). Snow cover will decrease and melt earlier (*very likely*, *high confidence*). Increasing aridity, declining groundwater levels, declining snow cover, and drought threaten freshwater supplies (*medium confidence*).

Freshwater availability is affected by the quantity of water in storage, the timing of water movement, how much water is used, and its quality,[10] all of which are governed by the interrelated hydrologic components of the water cycle. Changes to these components are occurring across the Nation as a result of human activities as well as human-caused climate change. These changes are superimposed on natural variability, resulting in changes to both water availability and water-related hazards (KMs 2.1, 2.2).

Precipitation Changes

Climate change has already shifted precipitation patterns across the country, including increased variability and elevated likelihood of extreme rainfall events (KMs 2.2, 3.5). These trends exhibit substantial regional and seasonal variations (KM 2.2).[11] Projected changes in annual precipitation also exhibit large regional differences (Figure 4.3). Precipitation trends and projections are discussed in more depth in Chapters 2 and 3.

Projected Changes in Annual Precipitation by Midcentury



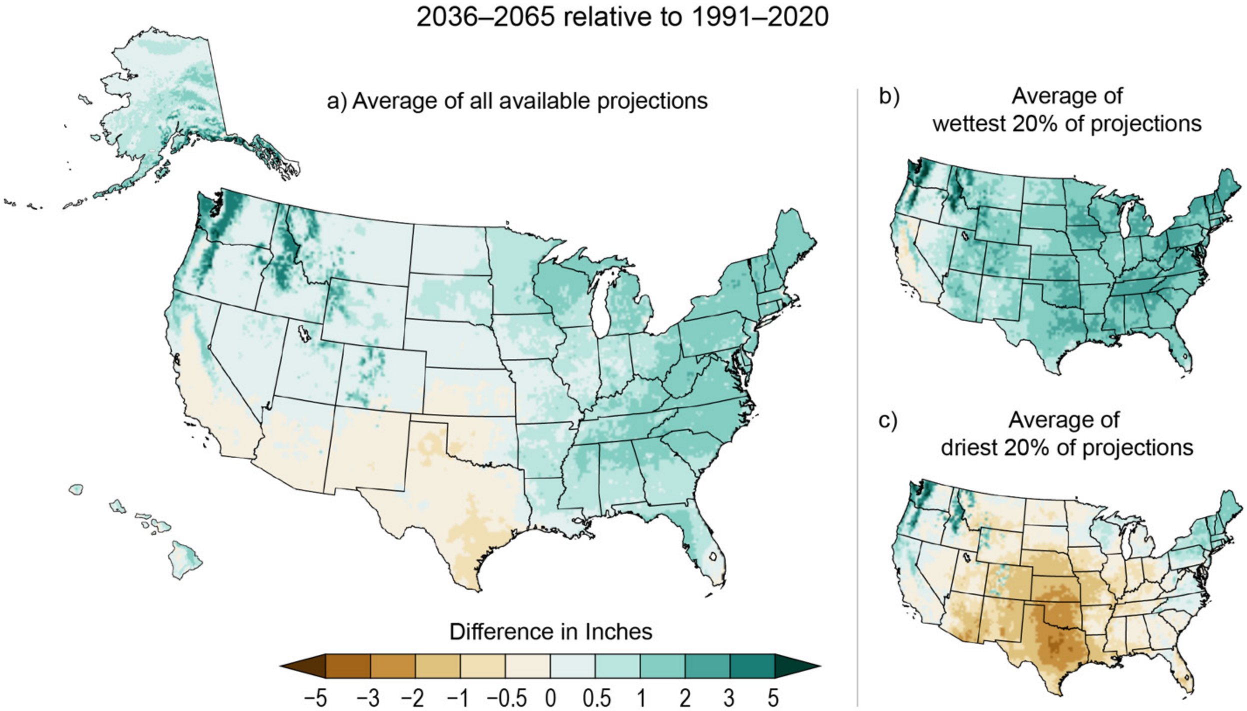
Annual precipitation projections show large regional differences.

Figure 4.3. Under an intermediate (RCP4.5) scenario, annual precipitation is projected to increase for much of the US (**a**), except for the Southwest, Hawai'i, and the US Caribbean (not shown; see Figure 23.2, which shows rainfall reductions of about 10% by midcentury, and increases in dry days during the wet season, for Puerto Rico). The wettest and driest 20% of projections (**b**, **c**) illustrate the range of uncertainty in annual precipitation projections. This figure shows projected changes in inches. In the Southwest, a half-inch change in annual precipitation has more influence on the region's hydrology than does a half-inch change in the Northeast (see Figure 2.10 for percent changes under different warming levels). Projections are not available for the US-Affiliated Pacific Islands. Figure credit: University of Colorado Boulder, NOAA NCEI, and CISESS NC.

Evapotranspiration Changes

Evapotranspiration is water that evaporates from soil, snow, and surface water or transpires from plants. It is a key component of the water budget and drives irrigation water demand. Increases in temperature and changes in other climate variables alter the evaporative demand (or potential evapotranspiration). In recent decades, evaporative demand has increased in much of the West, with few apparent trends in the East.[12] Actual evapotranspiration is evaporative demand limited by water availability. In the continental US, actual evapotranspiration has trended lower in the Southwest as water availability has declined, while the East and North show an increase. The greatest increase in actual evapotranspiration has been in the South from eastern Texas to northern Florida.[11,13] These trends are largely projected to continue with climate change (Figure 4.4).

Projected Changes in Annual Actual Evapotranspiration by Midcentury



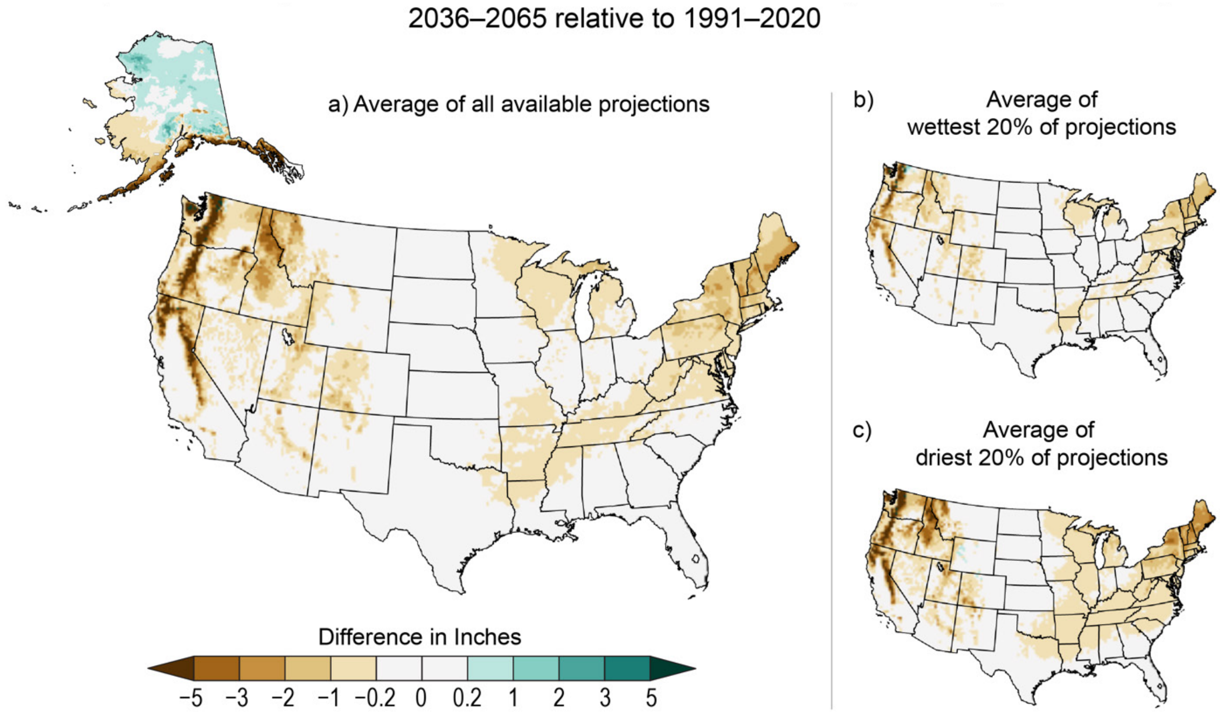
Actual evapotranspiration is projected to increase across most of the Nation but decrease in the Southern Great Plains and Southwest.

Figure 4.4. Actual evapotranspiration is the water that evaporates from soil and surface water or transpires from plants. Higher rates of evapotranspiration can reduce overall water availability even if precipitation does not change; conversely, low water availability can limit actual evapotranspiration. Under an intermediate scenario (RCP 4.5), actual evapotranspiration is expected to decrease in regions with decreasing or unchanging precipitation (**a**), such as the US Southwest, the Southern Great Plains, and the Caribbean (not shown; Box 23.2). Wetter regions, including the Northwest, Alaska, and the eastern half of the US, will see higher actual evapotranspiration. The wettest and driest projections (**b, c**) illustrate the range of uncertainty. Projections are not available for the US-Affiliated Pacific Islands. Figure credit: University of Colorado Boulder, NOAA NCEI, and CISESS NC.

Snow and Glacier Changes

Snow is a natural reservoir, storing cold-weather precipitation and later releasing water through snowmelt. With higher temperatures, the fraction of precipitation falling as rain instead of snow will increase.[14,15] Warming will also cause earlier snowmelt,[14,16] altered rates of snowmelt and evaporation directly from the snow,[17,18,19,20] and longer snow-free periods.[21,22] Most historical snow-observation records already show trends toward earlier peak snowpack, smaller volumes, and decreasing snow-season duration (Figure A4.7),[11] particularly for warmer maritime and lower-elevation regions.[23,24,25] In areas of the West where snow is the dominant source of runoff,[26] total seasonal snow water volume is projected to decrease by more than 24% by 2050 under intermediate (RCP4.5; Figure 4.5) and higher scenarios, with persistent low-snow conditions emerging within the next 60 years.[24] These snow reductions, combined with projected increases to water demand, are expected to stress water supplies, particularly in the West (KM 28.1), where snowmelt supplies a disproportionate amount of water for municipal water supplies and agriculture.[27,28,29] Reductions in snow cover are also accelerating the retreat of glaciers[30,31,32] that are critical for summer streamflow in Alaska[33] and the Pacific Northwest (Ch. 27).[34]

Projected Changes in Maximum Annual Snow Water Equivalent by Midcentury



Continued decreases in snowpack water content are projected across much of the US.

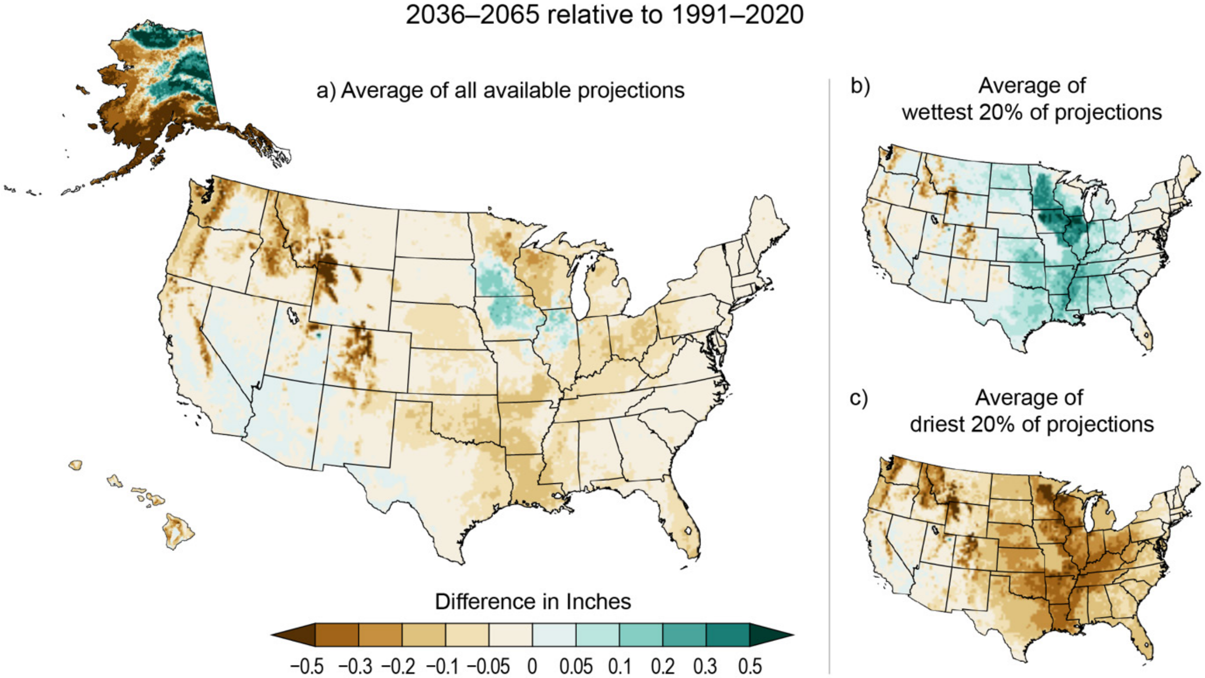
Figure 4.5. Snow water equivalent (SWE), the quantity of water stored in the snowpack, is key to regional water supplies. Under an intermediate scenario (RCP 4.5), peak SWE is projected to decline across much of the country except for some high-elevation interior locations in the contiguous United States and parts of Alaska (**a**). The largest snowpack declines are expected in warmer snow climates like coastal southern Alaska and the mountain ranges of California and the Northwest. The wettest (**b**) and driest (**c**) projections both show decreases in SWE, reflecting the influence of warming on future snowpack. Snow on the highest Hawaiian mountain peaks has important cultural and ecological significance, but projections at this resolution are not available. Figure credit: University of Colorado Boulder, NOAA NCEI, and CISESS NC.

Soil Moisture Changes

Soil moisture is water stored in the soil, usually close to the surface. It is a key component of the water cycle, supporting agriculture and ecosystem productivity, modifying streamflow by absorbing precipitation and snowmelt, and modulating climate.[35,36] A scarcity of soil moisture observations[37] has led to uncertainty regarding overall amounts, seasonality, and the direction of changes; however, there is consensus that soils are becoming drier in the Southwest.[38,39,40,41]

Projections suggest that summer soil moisture will decrease across most of the country (Figure 4.6), with parts of the upper Midwest and Alaska[42] as exceptions. The Northwest, parts of the central and eastern US, and Alaska can expect seasonal changes in total soil moisture, with wetter soils in winter.[42,43] Summer soil moisture in the Southwest could increase if summer precipitation is higher, but there is greater confidence in decreasing annual soil moisture in the region (Figure 2.4).[38,43]

Projected Changes in Average Summer (June–August) Soil Moisture by Midcentury



Projected decreases in summer soil moisture will have important implications for agriculture and ecosystems.

Figure 4.6. Summer soil moisture supports dryland agriculture and ecosystem functions and reduces irrigation demand and wildfire risk. Under an intermediate scenario (RCP 4.5), soil moisture is projected to decrease during the summer months (June, July, and August) for most of the country (**a**), with the West seeing decreases even under the wettest projections. Exceptions include portions of the Upper Midwest and Alaska. The range between the wettest (**b**) and driest (**c**) projections illustrate the uncertainty in summer soil projections. Projections are not available for the US Caribbean or US-Affiliated Pacific Islands. Figure credit: University of Colorado Boulder, NOAA NCEI, and CISESS NC.

Groundwater Changes

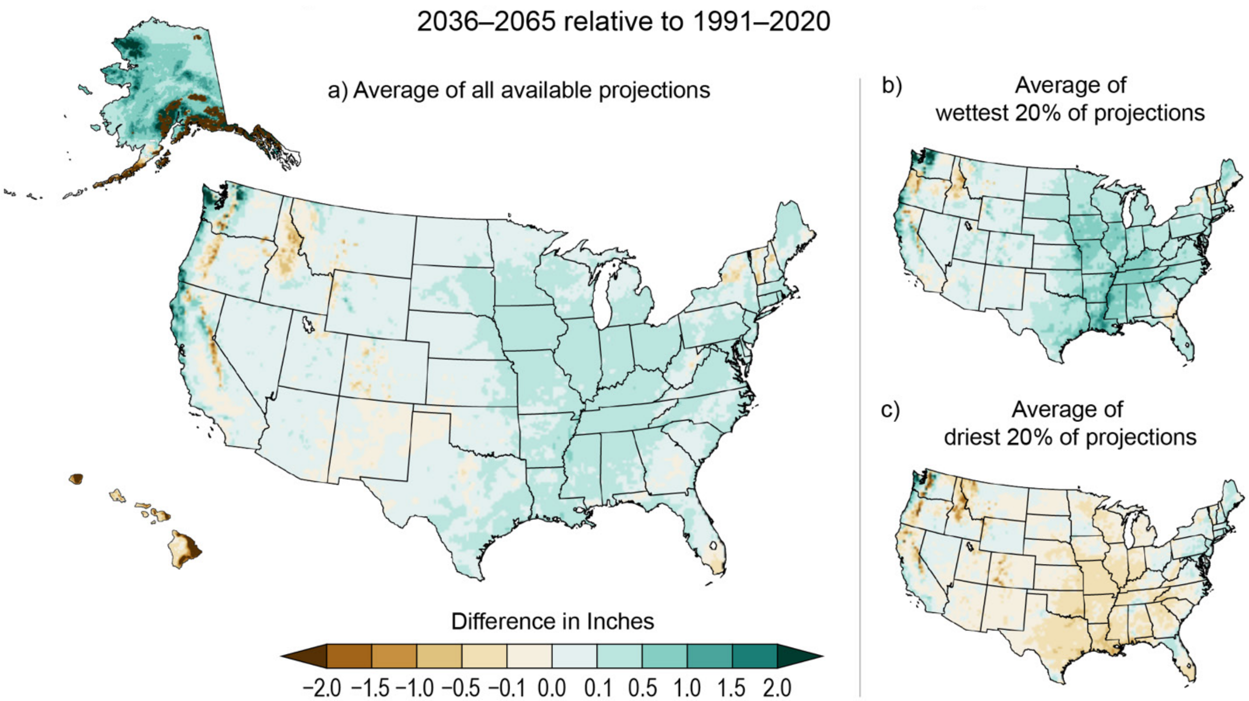
Groundwater is water stored below the land surface; it can be close to the surface or extend hundreds of feet deep. It is a crucial water supply for human systems and can moderate changes in temperature and precipitation.[44,45,46] NCA4 noted that groundwater depletions can increase drought risk and highlighted unsustainable groundwater usage and the likelihood of further declines in the future.[3] More recent work has emphasized the hydrologic connections between surface and groundwater that make surface water systems vulnerable to declining groundwater levels.[47,48]

Groundwater trends vary regionally and are difficult to project because the intensity of both groundwater withdrawals and recharge depends on human factors (e.g., land use, population, surface water allocations, and groundwater regulation) in addition to climate drivers.[49] Natural groundwater recharge varies from year to year but is projected to decrease slightly in the Southwest and increase slightly in the Northwest.[50,51] Higher temperatures will increase irrigation demand (Figure 4.9), which can lead to increased groundwater pumping in areas where groundwater is the primary water supply or where surface water supplies are limited.[52,53,54] Groundwater levels have already been declining in many major aquifers due to lack of management, overpumping, and decreased recharge; increased pumping could accelerate long-term storage losses, but those impacts will depend on the regional factors noted above.[49,52,55,56] Groundwater declines caused by increased drought severity and duration in the future are a concern in many parts of the country (KMs 23.3, 24.5, 28.1; Ch. 26).

Runoff Changes

Changes to the water cycle components discussed above combine with other factors to affect runoff (surface water flow). For example, snowpack changes impact the seasonality of runoff in snowmelt-dominated areas,[57] while soil moisture affects the amount of precipitation and snowmelt that becomes runoff.[58] In addition to direct precipitation and groundwater, runoff is a primary source of water supply for people and ecosystems. Annual runoff trends for the most part have tracked annual precipitation trends. Similarly, the trend toward increasing annual runoff variability in most of the eastern half of the US is consistent with increasing extreme precipitation events there.[11] Increases in heavy precipitation events are projected to increase annual runoff over much of the US (Figure 4.7).[59,60]

Projected Changes in Annual Runoff by Midcentury



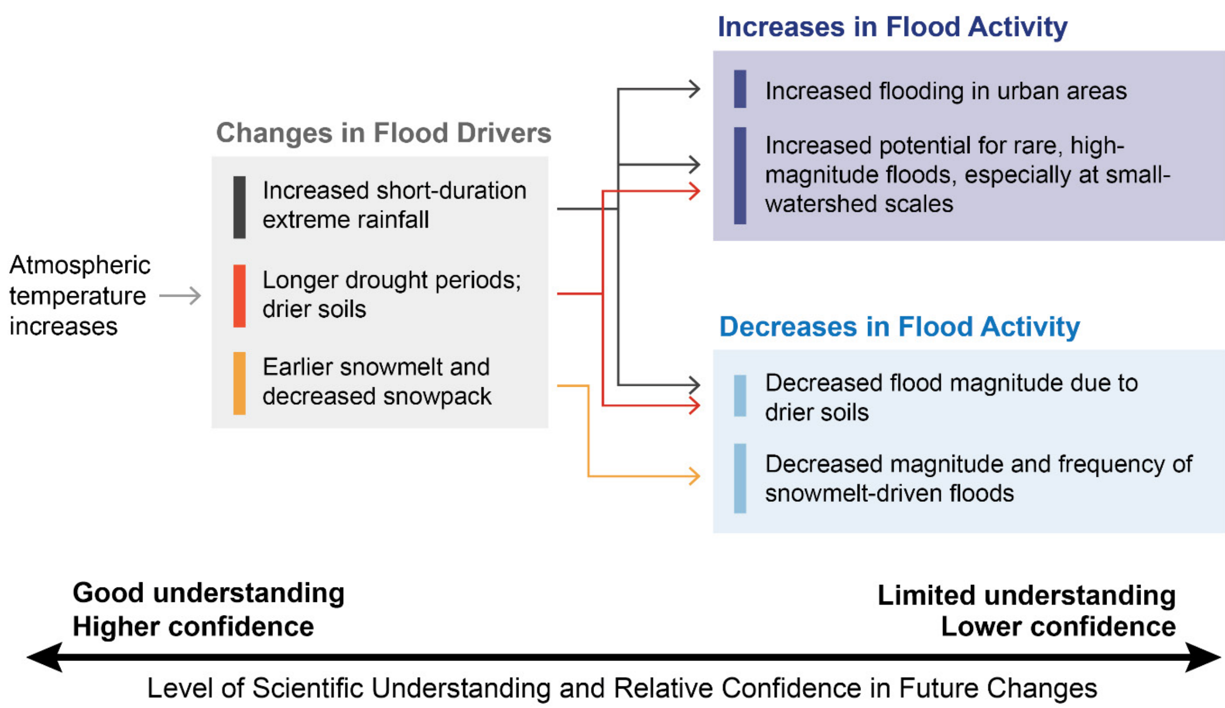
Projected changes in runoff vary across the Nation due to projected changes in multiple aspects of the water cycle.

Figure 4.7. Rivers and streams aggregate runoff across watersheds, and runoff integrates climate change impacts to the water cycle (Figures 4.3, 4.4, 4.5, 4.6); as a result, impacts to runoff over a watershed are commonly used as surrogates for impacts to streamflow. Under an intermediate scenario (RCP4.5), projections of annual runoff vary geographically depending on relative changes to precipitation, evapotranspiration, snow and ice, groundwater, and soil moisture. Decreases are projected in Hawai‘i and parts of the Nation supplied by snow (**a**). Projections are not available for US-Affiliated Pacific Islands or the US Caribbean; however, given projected decreases in precipitation and increases in temperature in the Caribbean, annual runoff is expected to decrease. The range between the wettest (**b**) and driest (**c**) projections illustrate the uncertainty in runoff projections. Figure credit: University of Colorado Boulder, NOAA NCEI, and CISESS NC.

Extreme Events: Floods and Droughts

Inland floods are driven by complex interactions among precipitation amount and timing, soil moisture, snowpack, and land cover (see KM 9.1 for coastal flooding). However, estimates of events such as the 100-year flood typically rely on historical observations and assumptions of an unchanging climate.[61] Methods that account for the added uncertainty of climate change are needed for infrastructure design, land use planning, and other purposes,[62,63,64] but future flood frequency is challenging to predict (Figure 4.8).[65,66] For example, some extreme precipitation events will be buffered by future reductions in soil moisture, which will allow more rainfall to be absorbed,[67,68,69] and some areas are projected to see increases in floods from rain falling on snow,[70,71] precipitation on wildfire-disturbed land,[72,73] and loss of natural water storage in urban landscapes.[74]

Climate Change Impacts to Inland Flood Drivers and Flood Activity

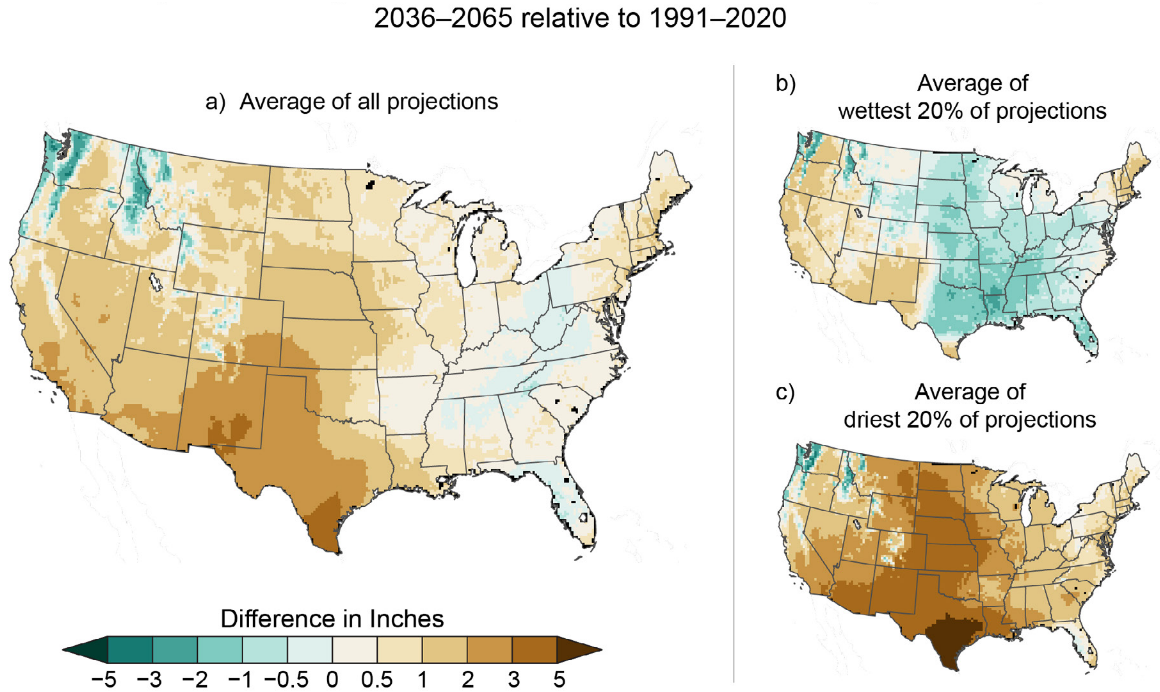


Climate change may cause both increases and decreases in inland flooding, depending on the location and time of year.

Figure 4.8. Inland floods result from combinations of factors, primarily extreme rainfall, soil moisture, and snow-pack and snowmelt conditions. Each of these are subject to substantial variability and change across a wide range of timescales, from daily to decadal, in a warming climate. Scientific confidence in how the climate drivers of flooding will change is higher than in how those drivers will combine to affect floods in particular locations and seasons. Adapted from Yu et al. 2020[66] [CC BY-NC 4.0].

Changes in future precipitation and temperature are expected to exacerbate drought across large portions of the US.[75] Observed trends in drought (Figure A4.9) and climatic water deficit reflect these changes,[13] as do projections, with the strongest drying signal occurring in the Southwest (Figure 4.9).[76]

Projected Changes in Annual Climatic Water Deficit by Midcentury



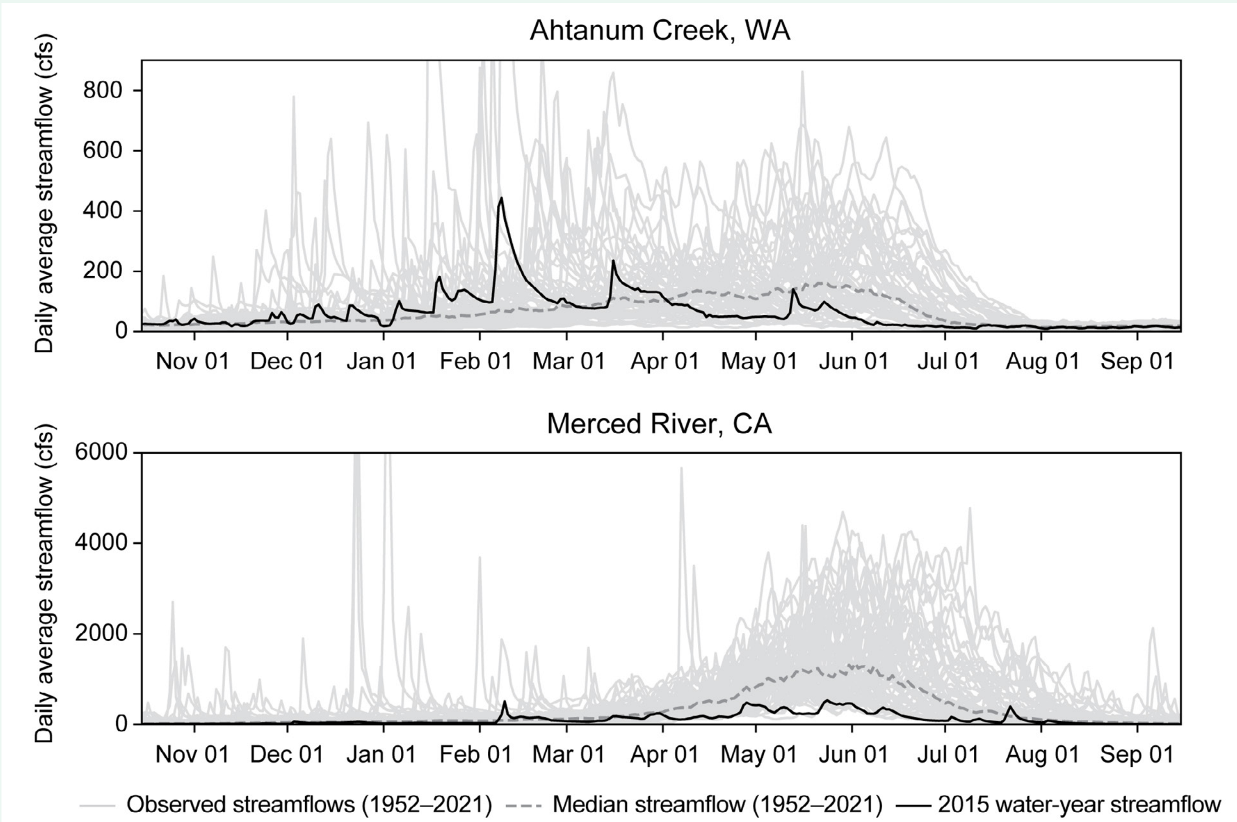
Water shortages to vegetation will increase across most of the Nation.

Figure 4.9. Climatic water deficit (CWD) is the shortfall of water necessary to fully supply vegetation requirements—CWD is zero if those needs are met, and a higher number indicates drier conditions. Vegetation water needs will increase with increases in temperature; as a result, in the absence of compensating increases in precipitation, CWD is projected to increase. Under an intermediate scenario (RCP4.5), CWD is expected to rise across much of the Nation, with the Great Plains and Southwest seeing the greatest increase (**a**, **c**). Even the wettest projections show increases in CWD in the West (**b**). Projections are not available for the US Caribbean, Alaska, Hawaiʻi, or US-Affiliated Pacific Islands; however, given expected temperature increases and annual precipitation decreases in Hawaiʻi and the US Caribbean, CWD is expected to increase in those regions, while Alaska is expected to see both increases and decreases similar to the pattern seen in the Northwest. Figure credit: University of Colorado Boulder.

Box 4.1. Washington–California 2015 Snow Drought

Snow droughts occurred across much of the western coastal mountain ranges during the 2014/15 winter. However, the climatic causes of these droughts varied. Western Oregon and Washington experienced a *warm* snow drought, wherein wintertime precipitation was 77%–113% of normal but elevated temperatures caused a larger proportion of that precipitation to fall as rain, which reduced snow accumulation and increased winter snowmelt.[15,77] As a result, wintertime streamflows were normal to high, but April to August flows were lower than normal (Figure 4.10).

Washington–California Snow Drought



In 2015, parts of Oregon and Washington experienced a warm snow drought while the California Sierra Nevada experienced a dry snow drought.

Figure 4.10. The timelines compare the 70-year (1952–2021) median streamflow (dashed line) with the 2015 water-year (October 2014–September 2015) streamflow (black line). Annual observed streamflows are also shown for 1952–2021 (gray lines). Values are daily average streamflows in cubic feet per second. Streamflow in summer 2015 was abnormally low, resulting from reduced snowpack during a warm snow drought (Ahtanum Creek) and a dry snow drought (Merced River). Daily streamflow is in cubic feet per second for each of the years 1952–2021 (gray lines). Merced River flows are lower year-round because of low total precipitation and little snowfall; Ahtanum Creek flows are shifted from summer to winter in 2014/15 because it was too warm for snow accumulation. Figure credit: University of Maryland, College Park and Lynker.

By contrast, the California Sierra Nevada experienced a *dry* snow drought, resulting in the shallowest snow volume ever recorded there.[15,78,79] Both the dry and warm droughts caused strain on water rights holders. In Oregon and Washington, irrigated crops—including valuable orchard crops—that depend on direct streamflow diversion water rights failed (Figure 4.11), but municipal water supplies that relied on storage rights that allow reservoirs to capture winter runoff were sufficient.[80] In California, total water supply was limited, resulting in severe or complete cutbacks to junior water rights and contract holders.[81]

Washington Apple Orchard Under Drought Stress

An apple orchard in the Roza Irrigation District in Washington shows extreme drought stress in September 2015.

Figure 4.11. This apple orchard suffered the effects of a warm snow drought the previous winter. The warm winter temperatures caused much of the precipitation to fall as rain instead of snow, producing a reduced snowpack, and led to early snowmelt, resulting in low streamflows during irrigation season. Photo credit: © Sonia A. Hall.

Key Message 4.2

Water Cycle Changes Will Affect All Communities, with Disproportionate Impacts for Some

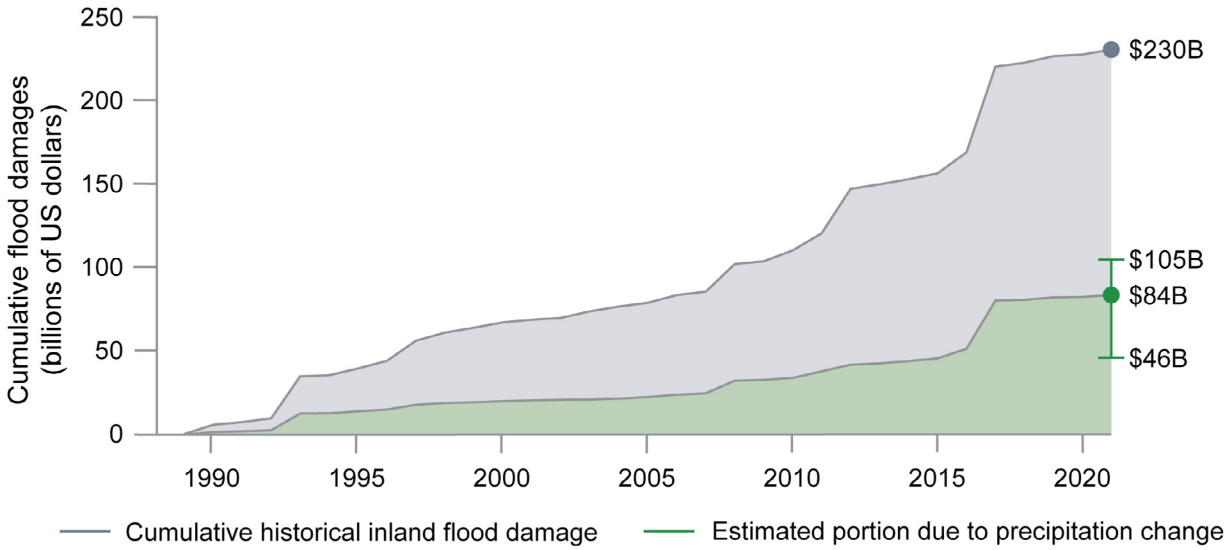
Natural and human systems have evolved under the water cycle's historical patterns, making rapid adaptation challenging. Heavier rainfall, combined with changes in land use and other factors such as soil moisture and snow, is leading to increasing flood damage (*likely, high confidence*). Drought impacts are also increasing (*medium confidence*), as are flood- and drought-related water quality impacts (*medium confidence*). All communities will be affected, but in particular those on the frontline of climate change—including many Black, Hispanic, Tribal, Indigenous, and socioeconomically disadvantaged communities—face growing risks from changes to water quantity and quality due to the proximity of their homes and workplaces to hazards and limited access to resources and infrastructure (*very likely, high confidence*).

Changes to the water cycle have manifold effects beyond those described in this chapter. See the Energy (Ch. 5), Ecosystems (Ch. 8), Agriculture (Ch. 11), Built Environment (Ch. 12), Transportation (Ch. 13), and Human Health (Ch. 15) chapters for more information.

Flood Impacts

Floods have important roles in creating and maintaining aquatic habitat, in regulating the reproductive cycles of fish and other river organisms, and in replenishing soil and nutrients in floodplains. Land-cover changes have limited these positive impacts and even exacerbated some of the negative consequences of floods. Climate change–driven changes in precipitation amount and duration, snowpack/snowmelt, and soil moisture have combined with land-cover change and increasing property values to increase overall economic damages from floods (Figure 4.12).[82]

Flood Damages Associated with Precipitation Change



A portion of observed increases in inland flood damages can be attributed to changes in precipitation.

Figure 4.12. Cumulative inland flood damages (in 2021 dollars) across the contiguous US (gray) and estimated portion due to changes in precipitation (green) are shown for 1988–2021. Over this period, heavy precipitation has increased over most of the US due to climate change (see Figure 2.8 for heavy precipitation changes over the 1958–2021 period). Error bars (in green) show the plausible range of cumulative damages in 2021, calculated using a 95% confidence level. Roughly 20%–46% of increases in observed flood damages can be attributed to increasing precipitation (assuming the same historical development patterns over the period 1988–2021). Other important contributors to flood damage include urbanization and land-use change, which can exacerbate runoff, and growth in the number and value of flood-affected buildings and other assets. Adapted from Davenport et al. 2021.[82]

In urban settings, pavements, roofs, and compacted soils do not absorb water as effectively as natural landscapes, amplifying the effects of heavy precipitation and concentrating flooding. In rural settings, lower amounts of impervious land cover allow soils to hold more rainfall. However, intensive agriculture can reduce the infiltration and water-holding capacity of soils and increase runoff, resulting in flooding.[83]

At major watershed scales, flooding along large river and lake systems causes numerous disruptions, including to rail, roadway, and river transportation; agricultural production; commodity deliveries; and industrial production, as seen during the Mississippi River flood of 2011 (KM 24.4).[84]

Increasing flood activity threatens water quality and ecosystems (Figure 4.2). As floodwaters inundate normally dry areas, they transport debris, chemicals, bacteria, and other contaminants (KM 23.1).[85,86] Heavy precipitation events are overwhelming aging combined stormwater–sewer systems, leading to discharges of contaminated water and raw sewage into receiving waters.[87,88] The upward trajectory of urban flooding impacts will likely continue with changing rainfall patterns and intensity.[89] Groundwater-sourced drinking water is becoming contaminated from standing floodwaters over wellheads and percolation into well-fields,[90] and in farmlands high runoff is discharging fertilizer into streams and lakes, causing harmful algal blooms.[91]

Drought Impacts

Droughts are driven by many factors, including unsupportable societal demands for water.[92] From a climate perspective, below-normal precipitation is a primary driver of drought, but there is growing acknowledgement that higher temperatures can cause drought to develop or become more intense than would be expected from precipitation deficits alone; higher temperatures drive increased atmospheric demand for moisture—a phenomenon known as hot drought.[75,93,94,95] Above-normal temperatures also contribute to snow drought (Box 4.1) and flash drought, which develops quickly over a few weeks.[96,97] Megadroughts are events of extraordinary duration and severity,[98] and many are documented in paleoclimate records.[99,100] Temperature's contribution to drought makes it clear that warming associated with climate change could increase the frequency, severity, and/or duration of drought[73,101,102] and drive aridification, a long-term shift toward a drier climate, which is a concern in already dry parts of the West.[76]

Between 1980 and 2022, drought and related heatwaves in the US caused $334.8 billion (in 2023 dollars as of July 2023) in damages; only tropical cyclones and severe storms were more costly (KM 22.1).[2] Droughts often reduce agricultural productivity and strain water systems,[103,104] driving shortages in water supplies and threatening power generation (KM 5.1).[105] River and lake transportation is also at risk due to drought (KM 24.4).

Drought stresses terrestrial and aquatic ecosystems[106] by leading to increased water temperature and salinity, reduced nutrients, lower oxygen levels, concentrated contaminants (Figure 4.2), loss of surface and groundwater connections, and declining productivity.[107,108] In addition, drought can exacerbate other disturbances such as pests and wildfire.[109] Ecosystems can be resilient under normal climate variability, but recovery after drought in a changed climate may not be possible, leading to the loss of ecosystem services and loss or migration of native and invasive species (Figure 8.6).[110,111]

Groundwater quality is also threatened by heat and drought. Warmer soil and groundwater temperatures can lead to decreased oxygen saturation, lower pH, and enhanced mineral weathering, all of which reduce water quality,[112] and coastal and island aquifers are at risk of seawater intrusion, rendering groundwater unpotable and potentially harming infrastructure (Figure 4.2; KMs 9.2, 21.2, 23.3, 28.2, 30.1).

Drought conditions have historically resulted in increased groundwater pumping in some regions of the US, a practice projected to increase with climate change.[55,56,113] Declining groundwater levels due to pumping can reduce streamflow (Figure 4.13)[48] and result in land subsidence.[114]

San Pedro River, Arizona

The San Pedro River in Arizona has been depleted by groundwater pumping, drying up wetlands and wildlife habitat.

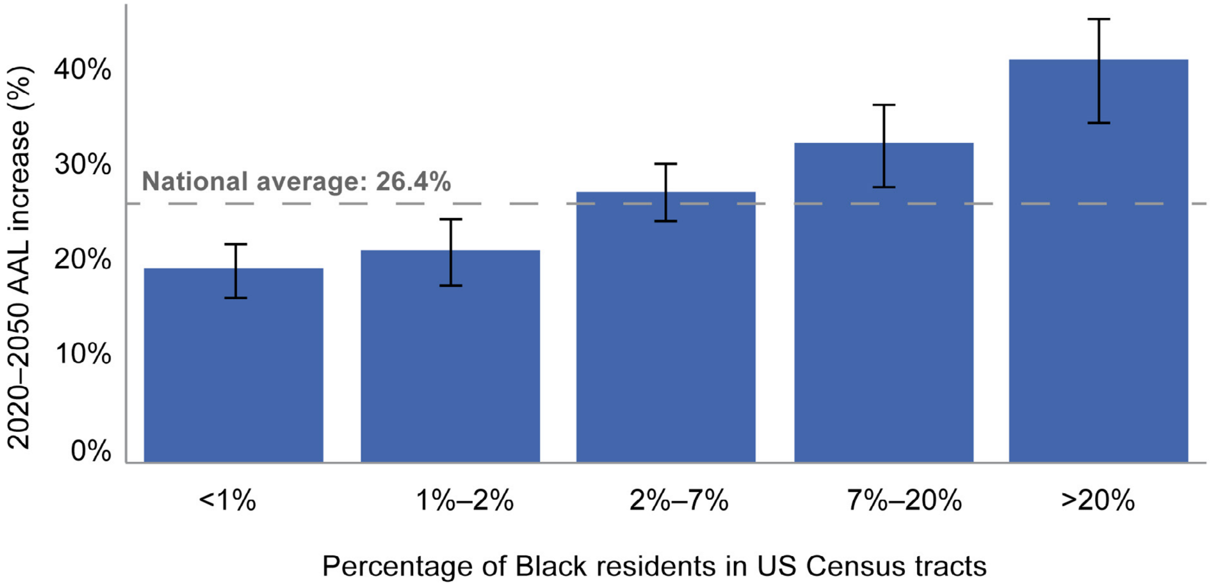
Figure 4.13. Groundwater pumping can reduce surface water supplies. One example is the San Pedro River in Arizona, where pumping that began in the 1940s has deprived wetlands and wildlife habitat of fresh water.[115] Photo credit: CochiseVista/iStock via Getty Images.

Disproportionate Impacts

Climate change creates unequal burdens on people and communities.[116,117,118] People who live along coasts and rivers or who work in agriculture and fisheries have increased exposure to water-related hazards.[119,120,121] Older adults, children, and residents of low-income neighborhoods and rural areas are at greatest risk of exposure to pathogens and pollutants from climate change–driven impacts to water quality.[122,123,124]

Many Tribal and Indigenous communities reside in areas subject to coastal and riverine flooding and risk displacement from lands with cultural significance.[125,126,127] Neighborhoods that are home to racial minorities and people with low incomes have the highest inland flood exposures in the South.[128] Hispanic residents are 50% more likely to live in the 500-year floodplain,[129] while Black communities are projected to bear a disproportionate share of future flood damages (Figure 4.14; Box 4.2).[130] Drought can also have unequal impacts depending on economic sector, access to water resources, ability to irrigate, reliance on electricity, and socioeconomic status.[131]

Projected Increases in Average Annual Losses (AALs) from Floods by 2050



Losses due to floods are projected to increase disproportionately in US Census tracts with higher percentages of Black residents.

Figure 4.14. Average annual losses—economic damages in a typical year—due to floods in census tracts with a Black population of at least 20% are projected to increase at roughly twice the rate of that in tracts where Black residents make up less than 1% of the population. Black bars represent 95% confidence intervals. Adapted from Wing et al. 2022[130] [CC BY 4.0].

Box 4.2. Climate Change, Urban Flooding, and Inequality

Hurricane Harvey dropped record-breaking rainfall onto the Houston and Beaumont–Port Arthur metropolitan areas in August 2017 (Figure 4.15). The flooding, exacerbated by extensive urbanization, killed more than 100 people and caused an estimated $147.6 billion in damages (in 2022 dollars).[132] Harvey's rainfall was estimated to be about 15% to 20% heavier than it would have been without human-caused warming,[133,134,135] which increased the flooded area in the Greater Houston area by 14%,[136] leading to 32% more homes being flooded.[137] Many of the flooded properties were located outside FEMA's designated 100-year floodplains and not covered by federal flood insurance. Such properties were disproportionately inhabited by Black and Hispanic residents.[138] People with disabilities and residents of subsidized housing were also disproportionately affected.[139,140] Climate change's impact on flooding is expected to worsen these types of inequalities.

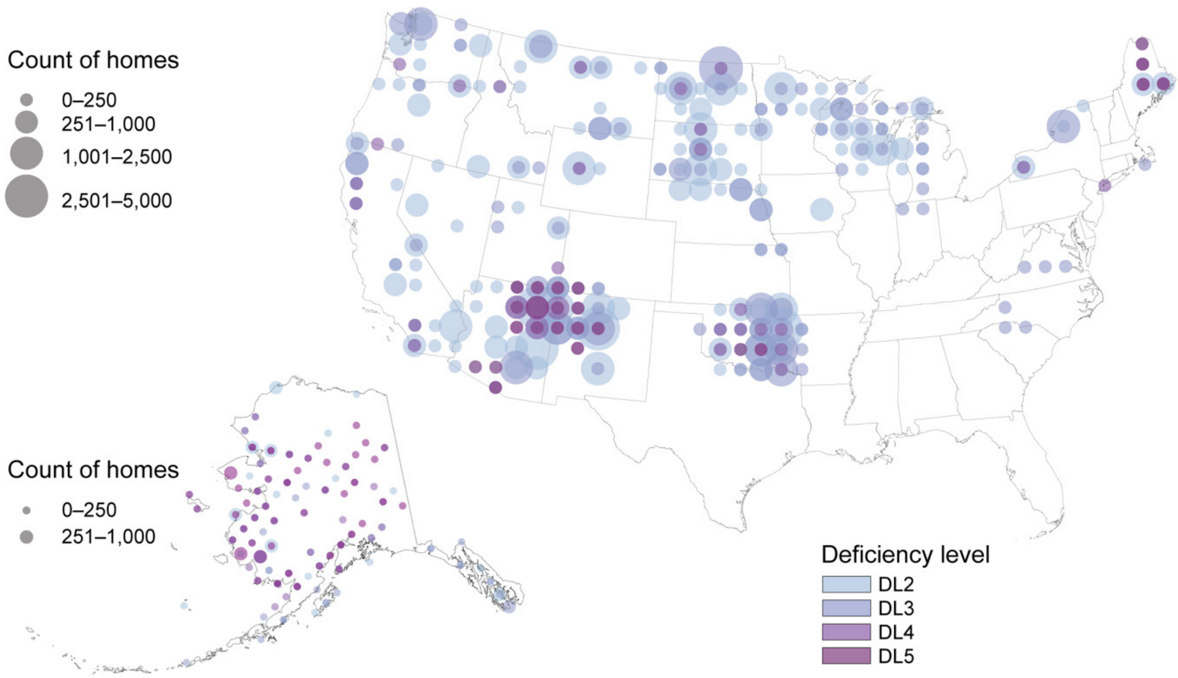
Residential Flooding from Hurricane Harvey

Flooding from Hurricane Harvey inundated residential neighborhoods in Port Arthur, Texas.

Figure 4.15. Photo credit: Staff Sgt. Daniel J. Martinez, US Air National Guard.

Across the Nation, drinking water delivery infrastructure is aging and deteriorating (KM 12.2), increasing the risks of contamination and delivery of unpotable water.[141] More than 1,000 community water systems—primarily serving older adults and people who are economically disadvantaged, rural, Indigenous, or with less education[142]—are already providing poor-quality water and are not prepared to cope with climate change-driven flooding, drought, and waterborne diseases (Figure 4.2; KMs 15.1, 15.2). For some Tribal and Indigenous communities, water infrastructure deficiencies threaten their social, physical, and mental well-being and impair their ability to thrive (KM 16.1).[143,144,145] Figure 4.16 shows the distribution and severity of sanitation facility deficiencies in American Indian and Alaska Native homes.[146]

American Indian and Alaska Native Homes Requiring Water and Sewer System Improvements



Water infrastructure supporting Tribal and Indigenous Peoples is particularly ill-equipped to handle increases in flooding and drought.

Figure 4.16. The Indian Health Service (IHS) maintains a database of American Indian and Alaska Native (AI/AN) homes requiring sanitation facility improvements within IHS service areas. The figure shows sanitation deficiency levels in AI/AN homes across the country ranging from level 2 (capital improvements are necessary to meet domestic sanitation needs) to level 5 (lacks a safe water supply and a sewage disposal system). The IHS does not collect data for Hawaiʻi, the US-Affiliated Pacific Islands, or the US Caribbean, but elevated rates of plumbing deficiencies are documented in those regions.[142] Figure credit: Indian Health Service.

Key Message 4.3

Progress Toward Adaptation Has Been Uneven

The ability of water managers to adapt to changes has improved with better data, advances in decision-making, and steps toward cooperation. However, infrastructure standards and water allocation institutions have been slow to adapt to a changing climate (*high confidence*), and efforts are confounded by wet and dry cycles driven by natural climate variability (*very likely*, *high confidence*). Frontline, Tribal, and Indigenous communities are heavily impacted but lack resources to adapt effectively, and they are not fully represented in decision-making (*high confidence*).

Approaches to Management and Planning

Uncertainty from natural variability has always been part of water resources planning, but as climate change affects different components of the water cycle, uncertainties around extreme events and water availability have increased. Responses to these growing uncertainties include climate adaptation and hazard mitigation through watershed management (KMs 6.1, 6.2);[147] nature-based solutions (KM 8.3); planned relocation;[148,149] floodplain management;[150] water conservation and reuse;[151,152] decision science;[153,154] reservoir optimization and artificial intelligence applications;[155,156,157] improved weather and streamflow forecasts;[158] municipal planning;[159,160,161] adaptive management systems;[162] stakeholder–scientist partnerships;[163] and adaptation guidance (KM 31.4).[164,165,166,167]

Adaptation Constraints

Climate change is overtaking water resources policymaking,[168,169] making risk reduction a continual exercise in catching up. For example, current rates of precipitation change outpace the regulatory changes needed to cope with them. Key rainfall metrics for design and decision-making are widely outdated;[170,171] updating these metrics is essential to protecting communities. While there have been recent advances in data collection, statistical methods, climate modeling, and weather forecasting, progress is difficult, in part because regulations, codes, and standards involve competing interests and often span multiple jurisdictions.[172,173,174]

Conflict, Competition, and Collaboration

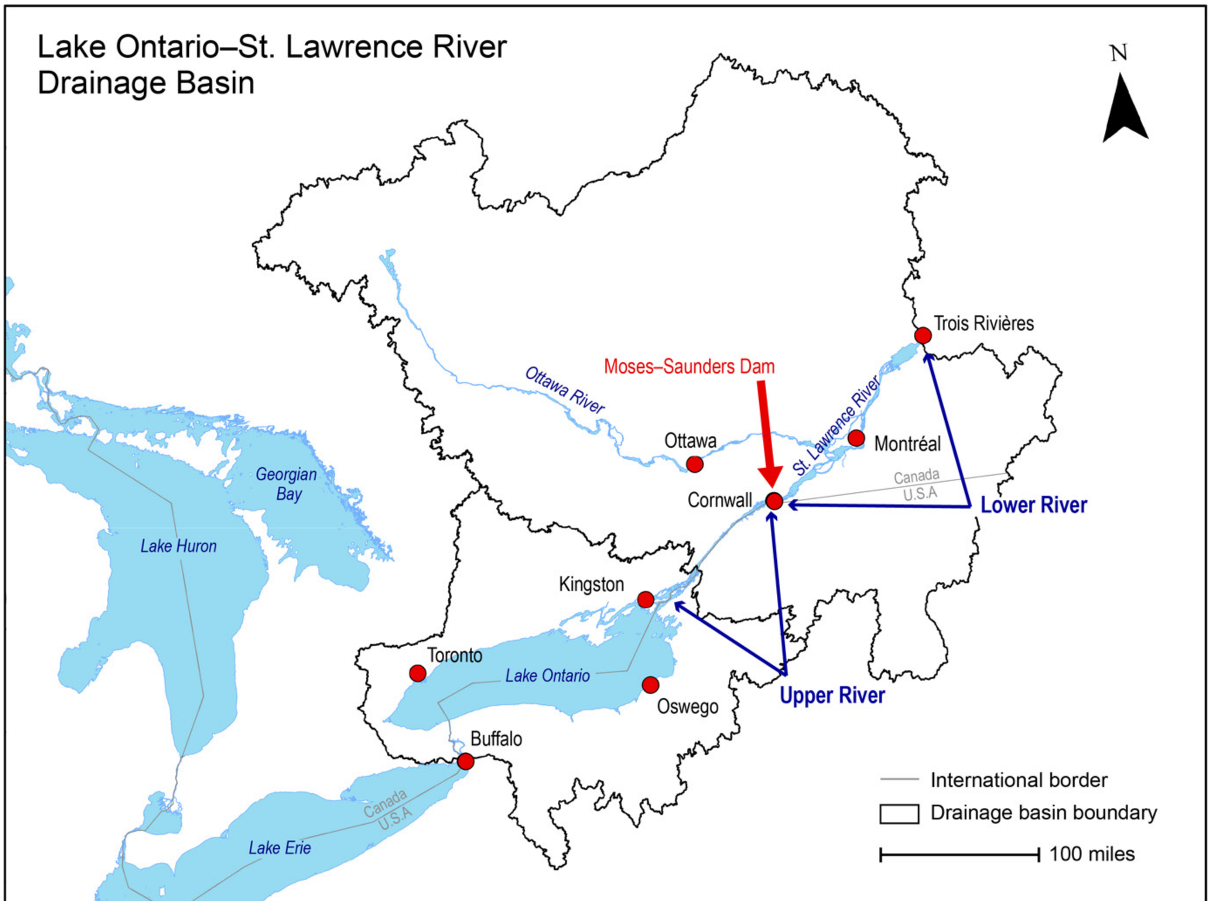
Climate change impacts to water supplies can result in competition, collaboration, or conflict. Frequently, water disputes in the western US are resolved through litigation.[175,176] However, under current severe drought conditions and in the context of existing legal frameworks, water interests in the Colorado River basin, including Mexico, are struggling to avoid litigation through negotiated settlements and voluntary use reduction (Box 28.1).[177,178,179] Some of these efforts now include Tribes and other water users who have traditionally been excluded from participation in negotiations, although representation remains uneven.[180]

In areas where flood risk is increasing, collaboration on flood hazard management at regional scales has become more urgent, as cooperation can provide solutions that are not available at the local scale (Box 4.3). This is especially true in the Midwest, where flooding is often regional and local solutions can push flood risks downstream.[181]

Box 4.3. International Cooperation in the Great Lakes

The Great Lakes, which contain the largest quantity of surface fresh water on Earth, are shared by two Canadian provinces, eight US states, and many sovereign Tribes and First Nations. Although ripe for conflict and competition, the waters have been equitably shared since the 1909 Boundary Waters Treaty.[182] In 2017, a management plan regulating Lake Ontario's levels and outflows was implemented (Figure 4.17).[183] It was the culmination of more than 16 years of scientific study, public engagement, and governmental review, including a collaboratively built model of the physical, environmental, and economic responses of the system to management and climate alternatives. Performance indicators yielded insights and quantified trade-offs, leading to a plan that balances flooding along the lake's New York and Ontario shorelines against flooding downstream on the St. Lawrence River at Montreal, Quebec. The plan also aims to restore the health and diversity of coastal wetlands and protect against extreme high and low water levels. An adaptive management committee evaluates the plan's performance under climate change and recommends adjustments.

Resolving Water Conflicts within the Lake Ontario–St. Lawrence River System



Plan 2014 determines outflows to the St. Lawrence River at Cornwall/Massena. Competing regions include Lake Ontario, Upper River, and Lower River. Interests include coastal flooding, erosion, shore protection, commercial navigation, hydropower, recreational boating, municipal and industrial water intakes, and ecological performance.

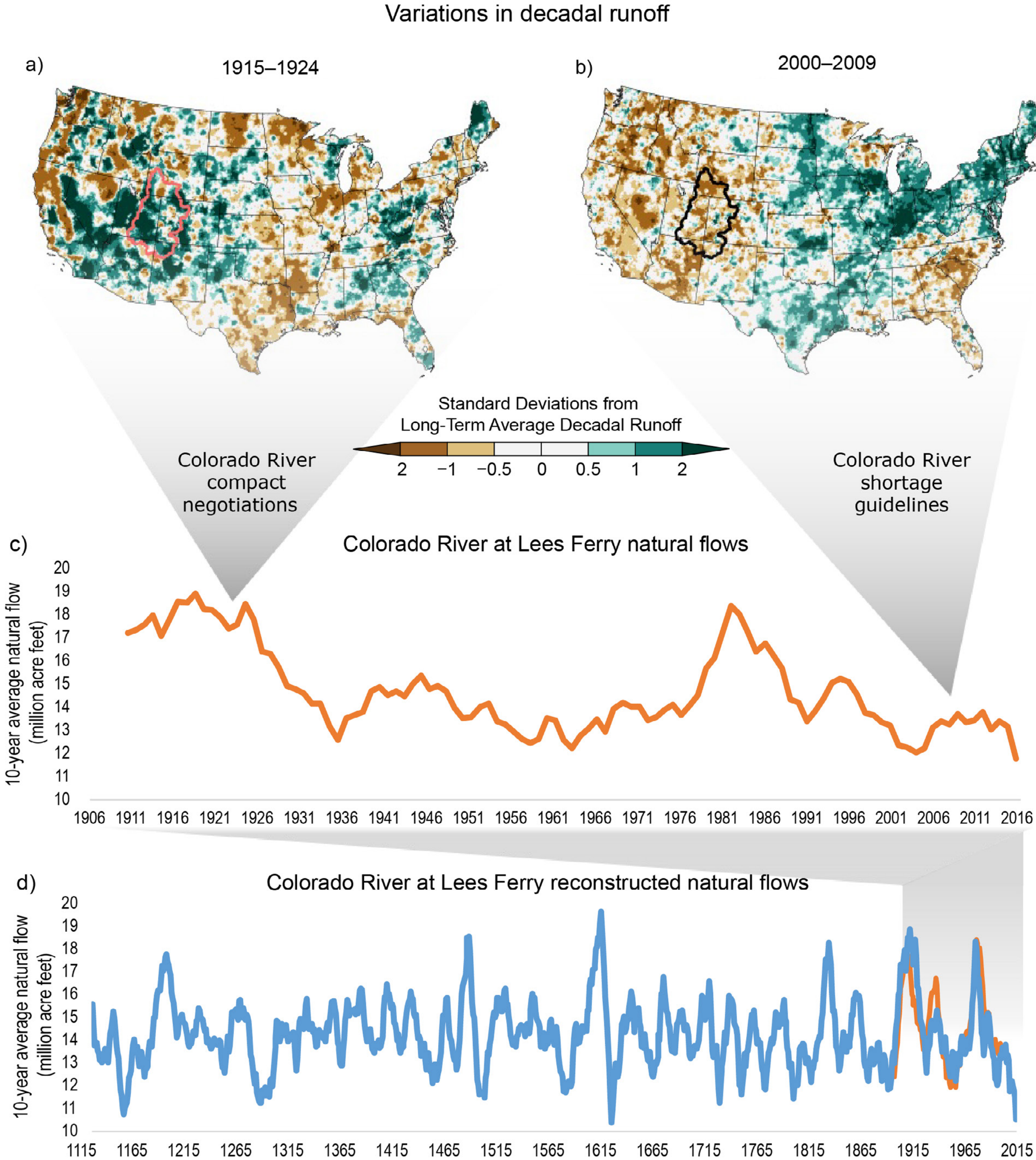
Plan 2014 was developed to manage Lake Ontario–St Lawrence River water levels, restore ecosystems, and account for climate change.

Figure 4.17. The map shows the geographic setting for an international plan between the US and Canada to cooperatively manage Lake Ontario. The plan balances interests upstream of the Moses-Saunders Dam with downstream interests. The collaborative framework used to develop the plan serves as a model of a successful approach to resolving water conflicts. Adapted from International Joint Commission 2014.[183]

The Effect of Natural Variability on Policy

Historical records and paleoecological evidence, such as tree ring data, show that natural variability in the climate system has resulted in multidecadal wet and dry spells in the past. [99] Climate projections indicate this pattern will continue, challenging planning and policy formulation for adaptation to climate change, and suggesting that durable and realistic long-term perspectives are necessary for robust policy development. For example, natural variability brought the wettest period in the past 1,200 years to the Colorado River in the early 20th century (Figure 4.18). The Colorado River Compact, negotiated in that period of relative abundance, allocated far more water than the river has since provided.[184] In the last years of the 20th century, sustained high reservoir levels prompted the development of guidelines for surplus allocation, but by the time those guidelines had been finalized, the current 22year drought had begun.[73] That drought has triggered unprecedented water use restrictions and is leading to more realistic policy discussions (Box 28.1).[177] Similar variability is present in climate and hydrology projections through the end of this century. The amplitude of projected 30-year-average wet and dry spells on the Colorado River may be twice the average projected decrease in streamflow by the end of this century;[185] as a result, multidecadal natural variability almost certainly will again lead to prolonged wet periods,[186] though diminished by higher temperatures.

Natural Hydrologic Variability Influences Policy



Natural hydrologic variability can promote urgency or complacency in long-term planning.

Figure 4.18. The figure shows hydrologic variability in both space and time: (**a**, **b**) runoff variability (a surrogate for streamflow variability) across the country between two decades, with the boundary of the Upper Colorado River Basin shown; and streamflow variability across time with (**c**) estimates of Colorado River flows from historical observations and (**d**) reconstructed flows from ancient tree rings (blue line), with data from (c) shown in orange. Wedges point to two negotiated policy events. Figure credit: Lynker and University of Colorado Boulder.

Adaptation Challenges Faced by Tribal and Indigenous Communities

To address water-related climate impacts, Tribes have voiced the need for climate impact assessments as a first step to resilience planning and identified information about climate change impacts to water as a top priority.[187] Many Indigenous communities lack data on water quality despite disproportionately experiencing water quality deficiencies.[188] Other data types critical to Tribal water management decisions are streamflow, temperature, precipitation, snowpack, and soil moisture, but these are not always available through federal information sources.[187]

Food security, protection of Traditional Knowledge, and Tribal capacity to implement adaptation plans, monitor and collect data, and conduct climate vulnerability assessments are also high priorities. Federally Recognized Tribes are eligible for federal assistance with climate change adaptation, but they face hurdles accessing these limited resources, including agency requirements (e.g., funding matches), lack of Tribal capacity, and navigating interagency processes.

Progress and Gaps in the Quality and Usability of Information

Water resources planning continues to be informed by past hydrologic records that do not reflect the impacts of climate change. Although some federal, state, and larger local agencies do use climate projections in planning, projections of precipitation, streamflow, water use,[189] and extreme events at the scale of local watersheds are rarely available, particularly outside of the contiguous US. Using projections is also costly because tools and techniques are specialized and not standardized. Finally, climate models project a wide range of uncertainty (Figure 4.3), requiring planners to use their best judgment about how to apply the information.

Data are foundational to adaptation. State and federal agencies have been collecting valuable climate, hydrology, and water use data for over a century, but these data are sparse in lightly populated and lower-income areas.[185] Increasingly, modeling and remote-sensing data are filling the gaps. High-resolution elevation and environmental data collected from airborne and spaceborne platforms provide detailed topographical and hydrological information that can be used to map flood hazards and snowpack[190,191] and refine real-time snow simulation.[192,193] Evapotranspiration is being estimated using satellite remote sensing combined with vegetation models,[194] providing early warning of emerging droughts,[195] and satellites are now being used to detect groundwater depletion.[196] Nevertheless, expanding direct observational data collection is still key to tracking environmental conditions and supporting development and testing of remotely sensed data and models.

Traceable Accounts

Process Description

With support from the chapter point of contact and the federal coordinating lead author, the chapter lead author selected authors for their expertise in assessing climate impacts to the Nation's surface and groundwater resources and the consequences of those impacts to human and natural systems, with an emphasis on the authors' ability to bring diverse perspectives to the team. The team comprises experts drawn from several regions across the country who work under various employment types (i.e., private business, academic institutions, and local, state, and federal governments), come from diverse backgrounds, and represent a range of combinations of age and gender. The team met virtually multiple times to scope the chapter, with each author offering their own priorities about what a chapter about the Nation's water resources should cover, taking into consideration the goals of this Assessment, the topics covered in previous National Climate Assessments (NCAs), and the topics of the other 31 chapters in the NCA5. The team's discussions revolved around these questions: How are changes in climate influencing water input volume and movement? How are extremes and the notion of extremes changing? How are changes in climate stressing both natural and human-made systems? What are the environmental justice considerations and the distribution of impacts? Are current climate data and tools adequate for decision-makers? And what are the interconnected climate risks? With these questions in mind, the team iteratively developed a draft outline for the chapter. That outline was made available online for public review and comment. The team presented and participated in a virtual, public, four-hour workshop and discussion, collecting comments and suggestions for the chapter from workshop participants. Workshop comments and formally submitted comments were taken into consideration in development of the chapter text. The Third Order Draft was presented to the public by five of the authors in a webinar hosted by Western Water Assessment at the University of Colorado. The author team met virtually at least twice per month during periods when the draft was not out for review. The team also met in person at the NCA5 All-Author Meeting held in April 2023 in Washington, DC. The meetings were used to set interim deadlines, assess the status of tasks, discuss language choices, find consensus on Key Messages and figures, develop responses to comments on drafts, and support each other with references and text reviews.

Key Message 4.1

Climate Change Will Continue to Cause Profound Changes in the Water Cycle

Description of Evidence Base

The hydrologic component maps shown in Figures 4.3, 4.5, 4.6, 4.7, and 4.9 constitute part of the evidence base. They show mid-21st-century projections of water cycle components based on an intermediate scenario (RCP4.5). Projections of water cycle components are available for both RCP4.5 and RCP8.5 scenarios, but both scenarios show similar hydrologic responses at midcentury, neither are available as 100-year projections, and space in this chapter is limited; as a result, only RCP4.5 projections are presented here. The central map of the contiguous US (CONUS) in each of these figures represents the average of all 32 Coupled Model Intercomparison Project Phase 5 (CMIP5) projections chosen for this discussion.[197] The Alaska and Hawai'i maps represent the average of 10 CMIP5 projections. The wettest and driest 20% of projections show the range of outcomes from the 32-projection set for CONUS, illustrating the uncertainty surrounding water cycle responses to climate change. Outside CONUS, downscaled climate projections are limited, especially those needed to map projected changes in hydrologic components for the US Caribbean and US-Affiliated Pacific Islands. The absence of projections for actual evapotranspiration, soil moisture, and runoff contribute to uncertainty when assessing future water security challenges for these regions. Further information about the data used to generate the maps can be found in the figure metadata.

Because the focus of this chapter is terrestrial fresh water, the authors relied heavily on Chapter 2 (Climate Trends) and Chapter 3 (Earth System Processes) for their assessments of precipitation trends and projections, particularly extreme precipitation trends and projections.

Regarding evapotranspiration, there is general consensus that warming temperatures will enhance evaporative demand (potential evapotranspiration, PET) across the Nation (Ch. 3);[43,44,75] however, uncertainties in vegetation response to warming reduce confidence in evapotranspiration (ET) projections.[75] In many parts of the country, projected changes in annual evapotranspiration by the end of this century are not robust, and there is disagreement among models across the southern states and parts of the central US.[43] The degree and sometimes direction of observed changes in PET and ET are also less certain, particularly east of the Rocky Mountains, due to differences in the trends of the variables that force PET.[12] Nor are these trends well supported by direct observation. There is a lack of information on more recent trends in pan evaporation across the US. Pan evaporation is a useful concept to estimate atmospheric evaporative demand but it is strongly affected by local environmental conditions, which can drive contradictory trends in pan evaporation across a broader region,[198] as is observed across the US.[199] For example, increases in local humidity (e.g., from irrigation) or land-use changes (e.g., changes in tree density near the pans) could affect evaporation from the pans. Therefore, pan evaporation may not provide a reliable indication of regional-scale trends in evaporative demand. The disagreement among observational data and reanalyses limits our confidence in past ET and PET trends. Complexities related to vegetation, as well as the competing effects of multiple evaporation drivers, make assigning nationally consistent likelihood and confidence challenging. However, the balance of evidence suggests with *medium confidence* that evaporation is expected to increase in places where moisture is not a limiting factor to atmospheric demand.

There is widespread consensus that increases in temperature will decrease the proportion of US precipitation that falls as snow,[14,15,24,43] decrease snow extents,[24,25] advance the timing of snowmelt rates and pulses,[16,27] increase the prevalence of rain-on-snow events,[70,71] and influence how snow water resources are partitioned to runoff.[19,20]

Since parts of Alaska and the highest elevations in the contiguous US may be cold enough to sustain snowfall in future climates, some studies have projected increases in snow volume in these locations with future increases in precipitation. However, those increases in snow are expected to be vastly outweighed by the future decreases in snow elsewhere, particularly across the western US and by the late 21st century for all intermediate (RCP4.5 and SSP2-4.5) and higher scenarios.

It is well established that groundwater and surface water are connected resources and that groundwater can help stabilize surface water supplies.[47,48] Similarly, there is agreement that loss of shallow groundwater can exacerbate droughts and decrease streamflow. There is also agreement that warmer temperatures will increase water demand and that this could increase groundwater pumping.[52,53,54]

Major Uncertainties and Research Gaps

Uncertainties stem from future projections of climate. This may be particularly true for late-21st-century projections that are dependent on the degree to which societies will respond to climate change. The literature employs different projections and emissions scenarios, as well as metrics and measurements that vary in their degree of climate sensitivity, resulting in studies that are not always directly comparable.

Understanding recent and potential future flood responses to climate change is difficult for several reasons. Floods are the product of complex subseasonal to interannual interactions between rainfall, soil moisture, evapotranspiration, snowpack/melt, and other processes. Isolating climate change impacts on inland flooding is further complicated by the hydrologic "replumbing" wrought by urbanization and dams. For these reasons, the translation of rainfall trends into flood changes is complex and poorly understood. National[65,200] and global[201] examination of historical flood records has concluded that climate influences have been relatively limited, contradicting an earlier study that argued that the largest floods have increased in severity.[202] This latter argument is further contradicted by evidence that floods in the central US have become more common but not more intense.[203,204]

However, major floods are by definition rare, making detection and attribution of changes difficult. Thus, a lack of statistically significant trends in observed floods does not necessarily indicate that such events are not changing. Indeed, a relatively limited number of geographically focused case studies have painted complex pictures of climate-related flood changes that are lacking in broader regional and national analyses. Additional place-based case studies—as opposed to regional- or national-scale analyses—could help unravel the complex interactions between climate and non-climate flood drivers.

Given the first-order influence of temperature and precipitation change on snowfall, there is high certainty that future US snow cover, snow volume, and snow persistence will change.[24] However, there is some disagreement in the literature about the extent and direction (positive or negative) of change in surface water availability with future changes in climate. Existing studies indicate both increases and decreases in future runoff for different US hydroclimatic regimes.

In particular, there is uncertainty in the degree to which temperature may impact flow in some major river systems in the West.[205,206] Significant disagreements in the direction of observed soil moisture trends remain,[38,39,40] largely because it can be challenging to estimate with remote sensing or models, and the existing in situ soil moisture–monitoring network is insufficient.[37] Uncertainties can also be introduced because not all products are directly comparable, capturing trends over slightly different depths, although modest differences are probably not a major source of error. There is also uncertainty in soil moisture projections related to model, season, and soil depth.[38,42,43]

Similarly, there is uncertainty in both the magnitude and direction of groundwater storage changes, primarily due to uncertainty in future groundwater management policy and uncertainty in future recharge. This is due to uncertainty in both the human response to changing climate conditions and research gaps in quantifying natural groundwater recharge. Groundwater pumping is controlled by a myriad of human factors such as population, water policy, crop choices, and irrigation technology. While it is well established that warmer temperatures can increase water demand,[52,53,54] and historical trends demonstrate unsustainable groundwater usage in the past (as discussed in NCA4), future groundwater pumping increases will depend on water management practices and policy. Groundwater recharge is similarly uncertain.[50,51] Projected increases in large precipitation and flooding events are expected to increase recharge (known as episodic recharge events). However, the quantity of this recharge is less certain and highly dependent on the nature and timing of the storms that occur. Also, while increases in recharge may be counteracted by changes in plant water usage and snowpack that can decrease natural recharge, the magnitude of these recharge changes has not been well quantified. Separating the impacts of groundwater pumping from climate trends is particularly challenging due to a lack of long-term groundwater monitoring wells, especially outside of the most heavily groundwater-developed areas.

Description of Confidence and Likelihood

The author team determined that the evidence points to *medium confidence* that there will continue to be increases in precipitation in Alaska and in the northern and eastern regions of the US and decreases in precipitation in the Caribbean and the Southwest. Despite lingering uncertainties around average precipitation, there is *very high confidence* from both observations and projections that extreme precipitation events are becoming more frequent nationwide, and that it is *very likely* this trend will continue in the future. The disagreement among observational data and reanalyses limits our confidence in past ET and PET trends. Complexities related to vegetation, as well as the competing effects of multiple evaporation drivers, make assigning nationally consistent likelihood and confidence challenging. However, the balance of evidence suggests with *medium confidence* that evaporation will increase in places where moisture is not a limiting factor to atmospheric demand. Based on current trends and climate model projections, there is *high confidence* and it is *very likely* that warming temperatures will increase the demand for surface and groundwater for crops and human use. Given the direct influence of rising temperatures on snow, there is *high confidence* and it is *very likely* that the extent, volume, and duration of snow cover and melt upon which human and natural systems rely is and will continue to be reduced by warming.

Key Message 4.2

Water Cycle Changes Will Affect All Communities, with Disproportionate Impacts for Some

Description of Evidence Base

Observational records now span time periods long enough to evaluate changes in the volume, variability, and timing of water availability.[11] The magnitude of these changes, and their agreement with model projections, vary with hydroclimate regimes across the US.

While it has been difficult to establish clear linkages between increases in extreme precipitation and trends in "traditional" measures of flood activity such as peak streamflow rate, attribution studies have apportioned some of the historical increases in flood damage to precipitation change.[68,69] It is probable that many of these increases have been concentrated in urbanized watersheds, which are more sensitive to rainfall than rural and natural settings.[74] Flood vulnerability, including in urbanized areas, tends to be concentrated in historically marginalized and socioeconomically disadvantaged neighborhoods.[130] There is increasing consensus that systematically disadvantaged communities have been and will continue to be most impacted by these hazards, due to factors such as inadequate climate/hydrological monitoring, deferred infrastructure maintenance, and insufficient access to recovery resources.[207]

There is ample literature describing the impacts of floods, fires, and drought events on a wide variety of water quality hazards.[6] These studies provide insights into impacts to water quality hazards from intensified events due to climate change, and studies specific to climate change impacts on water quality are becoming more prevalent. There are some reports of specific benefits to contaminant concentrations from increased or decreased precipitation, but there is no consensus that water quality will improve with climate change.

There is widespread consensus that increases in air temperature will impact water quality by increasing water temperatures, resulting in less oxygen-rich water, exacerbating harmful algal blooms, increasing pathogens, and creating problems with drinking water taste and odor.[6,7]

Similarly, there is consensus that increased precipitation and intensity will degrade water quality due to urban storm water and combined sewer overflows, increased agricultural runoff, and riverine flooding. There is less certainty in regions of the country where precipitation is not increasing or decreasing. Compounding factors of increasing temperatures and aging stormwater and sewer systems and water reservoirs can exacerbate problems due to too much or too little water.

The literature is rife with observations of segments of the population being negatively affected by climate change, especially water-related hazards. There is consensus that these negative impacts of water-related climate change will be felt disproportionately among marginalized and low-income people.[122]

Major Uncertainties and Research Gaps

There is moderate uncertainty about the degree to which land-surface changes will drive nonstationary changes to the volume and timing of water resources. There is a lack of research on the linkages between climate change and flooding.[68] There is uncertainty about the extent to which traditional design storms—that is, storms of particular intensity and duration, used in floodplain and built environment planning—and flooding assumptions based on older observations reflect current and future flood conditions.[171] Additional research into the effects of climate change on water quality would improve our understanding of impacts, particularly in the face of compounding factors such as aging infrastructure, wildfires, and increased agricultural runoff.

Description of Confidence and Likelihood

There is strong evidence that climate change imparts a number of important shifts in local and regional hydrologic cycles, and that when combined with land-use changes and other human factors, increases are *likely* in the frequency, severity, duration, and damages from floods (*high confidence*) and drought impacts are increasing (*medium confidence*). There is a more limited body of work on the effects of climate change on water quality; thus there is *medium confidence* that climate change is degrading water quality. However, there is still uncertainty about how climate drivers may shape harmful algal blooms, a significant factor in water quality. Based on the vast literature documenting current, disparate impacts to frontline communities from floods, droughts, and the exposures they bring, there is *high confidence* and it is *very likely* that frontline communities will be at disproportionate risk from water-related hazards exacerbated by climate change.

Key Message 4.3

Progress Toward Adaptation Has Been Uneven

Description of Evidence Base

There are many examples of climate change overtaking the speed of adaptation,[168,169] including communities caught off guard by extreme precipitation and drought events amplified by climate change.[96,133] A wide array of literature over the past decade has identified the safety and economic risks posed by aging water systems and changing hydrology.[87] Since the publication of NCA4, expanded data collection, improved climate projections, and better short- to midterm forecasts support better water resource management and planning. However, local water resource managers are still struggling to find accessible, usable science and data at the appropriate spatial scale, and they continue to rely on historical records that often do not reflect current and future water availability and timing. Disaster management literature contains many examples of public complacency and/or urgency in preparing for extreme events.[208]

A growing literature focuses on providing scientific information that is more usable for water resource planning and management.[164] There has been less work in assessing success and evaluating how equitable these approaches have been.[209]

A number of retrospective reviews highlight the omission of frontline, Tribal, and Indigenous voices and benefits from water projects.[180] Long-standing legal entitlements, established before climate change was a consideration, are well documented. The bulk of senior water rights and legal entitlements in the West are held by Tribes and agricultural water users but governed by state and federal decrees, agreements, and compacts that were not written to be flexible or responsive to a changing climate. Current literature is documenting these barriers and assessing emerging approaches to work past them.[177]

Major Uncertainties and Research Gaps

Building climate resilience in hydrologic systems is challenging given the high uncertainty of climate variability and change. Gaps in actionable local-scale water data are particularly problematic, especially translating projections from global climate models to the regional and local level. System-level approaches and the use of resilience metrics are also areas ripe for improvement.

There is moderate uncertainty about the degree to which changes to land surface characteristics will drive changes to the volume and timing of water resources, and the degree to which existing infrastructure and historically defined allocations will be able to adapt. A large part of this uncertainty is related to how quickly human actions and policies react to hydrologic hazards.

Description of Confidence and Likelihood

Rising water-related disaster costs, communities ill-prepared for floods and droughts, and basin water users deferring difficult water allocation decisions are just a few of the pieces of evidence leading to *high confidence* that adaptation efforts are proceeding unevenly relative to the rate of climate change and that this is *very likely* (with *high confidence*) due in part to natural climate variability masking long-term changes. The history of water resources decision-making rarely includes participation by frontline, Tribal, or Indigenous individuals or communities. Their exclusion from negotiations, compacts, decrees, and other allocation actions supports an assessment of *high confidence* that frontline, Tribal, and Indigenous communities have not had full representation in water resources decision-making in the past, despite being affected by those decisions.

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