3. Water Resources

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

Key Messages

Climate Change Impacts on the Water Cycle

1. **Annual precipitation and runoff increases are observed now in the Midwest and Northeast regions and are projected to continue or develop in northern states; decreases are observed and projected in southern states.**
2. **Summer droughts are expected to intensify in most regions of the U.S., with longer term reductions in water availability in the Southwest, Southeast, and Hawai‘i in response to both rising temperatures and changes in precipitation.**
3. **Floods are projected to intensify in most regions of the U.S., even in areas where average annual precipitation is projected to decline, but especially in areas that are expected to become wetter, such as the Midwest and the Northeast.**
4. **Expected changes in precipitation and land use in aquifer recharge areas, combined with changes in demand for groundwater over time, will affect groundwater availability in ways that are not well monitored or understood.**
5. **Sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to challenge the sustainability of coastal freshwater aquifers and wetlands.**
6. **Air and water temperatures, precipitation intensity, and droughts affect water quality in rivers and lakes. More intense runoff and precipitation generally increase river sediment, nitrogen, and pollutant loads. Increasing water temperatures and intensifying droughts can decrease lake mixing, reduce oxygen in bottom waters, and increase the length of time pollutants remain in water bodies.**

Climate Change Impacts on Water Resources

7. **In the Southwest, parts of the Southeast, the Great Plains, and the islands of the Caribbean and the Pacific, including the state of Hawai'i, surface and groundwater supplies are already affected and are expected to be reduced further by declining runoff and groundwater recharge trends, increasing the likelihood of water shortages for many off-stream and in-stream water uses.**
8. **Increasing flooding risk affects human safety and health, property, infrastructure, economy, and ecology in many basins across the U.S.**
9. **In most U.S. regions, water resources managers and planners will encounter new risks, vulnerabilities, and opportunities that may not be properly managed with existing practices.**
10. **Increasing resilience and enhancing adaptive capacity are useful strategies for water resources management and planning in the face of climate change. Challenges include: competing demands for water; a variety of institutional constraints; lack of scientific information or access to it; considerable scientific and economic uncertainties; inadequate information useful for practical applications; and difficulties in engaging stakeholders.**

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 to atmosphere through plant leaves, called "transpiration"), setting the stage for all life to exist. The water cycle is dynamic and naturally variable, and societies and ecosystems are adapted to this variability. However, climate change is altering the water cycle in multiple ways, presenting unfamiliar risks and opportunities.

Changing Rain, Snow, and Runoff

Annual precipitation and runoff increases are observed now in the Midwest and Northeast regions and are projected to continue or develop in the northern states; decreases are observed and projected in southern states.

Annual **average precipitation** over the continental U.S. as a whole increased by more than 2 inches (0.2 inches per decade) between 1895 and 2011 (Bales et al. 2012; NCDC 2011). In recent decades, annual average precipitation increases have been observed across the upper Midwest, northern Great Plains, and Northeast, moderate increases in the Northwest, and decreases in Hawai'i and parts of the Southeast and Southwest (IPCC 2007; NCDC 2011). Increases in the north and decreases in the Southwest are projected to continue in this century (Orlowsky and Seneviratne 2012).

Historically, the number and intensity of **heavy precipitation** events (top 1% or greater) have been increasing in all U.S. regions except the Southwest, Northwest, and Hawai'i. Further, the volume of precipitation from the heaviest daily events has increased across the U.S. (see Ch. 2:

Our Changing Climate). For example, during 1950-2007, daily precipitation totals with 2-, 5-, and 10-year return periods increased in the Northeast and western Great Lakes (DeGaetano 2009; Mishra and Lettenmaier 2011). Extreme daily precipitation events are projected to increase everywhere (see Ch. 2: Our Changing Climate), such that a heavy precipitation event that historically occurred once in 20 years would arrive as frequently as every 5 to 15 years by late in this century (Groisman et al. 2012; Wang and Zhang 2008).

Snowpack and snowmelt-fed rivers in much of the western U.S. have changed in response to warming trends since the middle of the last century, including the past decade (Fritze et al. 2011; Hoerling et al. 2012; Mote 2006; Pierce et al. 2008), showing declines in spring snowpack, earlier snowmelt-fed streamflow, more precipitation falling as rain instead of snow, and striking reductions in lake ice cover (Wang et al. 2012); several of these trends have now been shown to be due to human-induced warming trends (Barnett et al. 2008; Bonfils et al. 2008; Hidalgo et al. 2009; Pierce et al. 2008; Ch. 2: Our Changing Climate). Similar historical trends have been observed in the northern Great Plains, Midwest, and Northeast. 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 (Romanovsky et al. 2011; Smith et al. 2010). All of these trends are projected to become even more pronounced as the climate continues to warm.

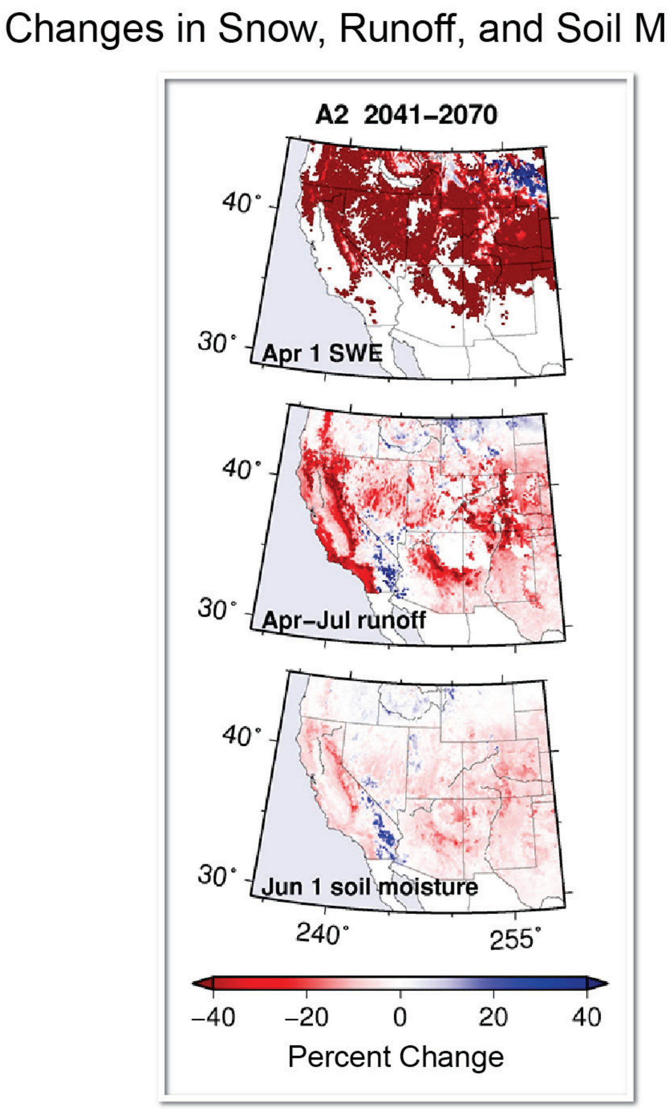

Figure 3.1: Changes in Snow, Runoff, and Soil Moisture

Caption: These projections, assuming continued increases in heat-trapping gas emissions (A2 scenario), illustrate: a) major losses in the water content of 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 1970-2000 conditions (Cayan et al. 2012).

Evapotranspiration (evaporation of water from soil and the release of water to the air from plant leaves) is the second largest component of the water cycle after precipitation. The evapotranspiration process responds to both solar energy and moisture availability at the land surface and regulates the amounts of soil moisture, groundwater recharge, and runoff (Mueller et al. 2011). This coupling of energy and water processes complicates the estimation of regional evapotranspiration and its modeling. Actual evapotranspiration depends on the potential of the atmosphere to absorb water vapor as well as on water availability for evapotranspiration at the land surface. The atmospheric potential for evapotranspiration is generally strongly dependent on temperature (Vautard et al. 2010); however, even though the Earth's surface temperature increased during the past 50 years, potential evaporation rates (as measured by pan-evaporation) have declined in many places (Peterson et al. 1995), including the U.S. (Roderick and Farquhar 2002). Decreasing wind speed (Vautard et al. 2010) has been proposed as a factor for this decreased evaporative demand (McVicar et al. 2012), while reduced solar irradiance at the land surface associated with increased cloud cover and aerosol concentration (Roderick and Farquhar 2002) and increasing humidity have also been identified as possible contributing factors in other parts of the globe (McVicar et al. 2012). In addition to the factors controlling evaporative demand, *actual* evapotranspiration also depends on the availability of soil moisture, which appears to have been declining over much of North America during the past few decades (BAMS 2012). However, much more research is needed to confidently identify historical trends, causes, and implications for future evapotranspiration trends. This represents a critical uncertainty in projecting the impacts of climate change on regional water cycles.

Soil moisture, on a regional scale, has historically been difficult to monitor and has often been inferred from models, but it is well-recognized that soil moisture plays a major role in the water cycle. In the last 20 years, soil moisture appears to have declined in parts of the Southeast (Georgakakos and Zhang 2011; Hamlet et al. 2007), southern Great Plains, and Southwest, and increased in the Northeast (Liu et al. 2011; Su et al. 2010). Based mostly on hydrologic simulations, soil moisture, especially in summer, is expected to decline with higher temperatures and attendant increases in the potential for evapotranspiration in much of the country, especially in the Southwest (Cayan et al. 2010; Ch. 2: Our Changing Climate) and Southeast (Georgakakos and Zhang 2011; Wehner et al. 2011).

Runoff and streamflow, at regional scales, declined during the last century in the Northwest (Luce and Holden 2009) and increased in the Mississippi basin and Northeast, with no clear trends in much of the rest of the continental U.S. (McCabe and Wolock 2011). Annual runoff in the Colorado River Basin has declined (U.S. Bureau of Reclamation 2011c), although tree-ring studies in the Colorado River basin and Southeast U.S. indicate that these regions have experienced even drier conditions in the past two thousand years (Hoerling et al. 2012; Meko et al. 2007; Woodhouse et al. 2006). Similarly, runoff from the Missouri River basin was greater and less variable during the 20th century than in previous centuries (Watson et al. 2009). Projected changes in runoff for eight basins in the Pacific Northwest, northern Great Plains, and Southwest are illustrated below.

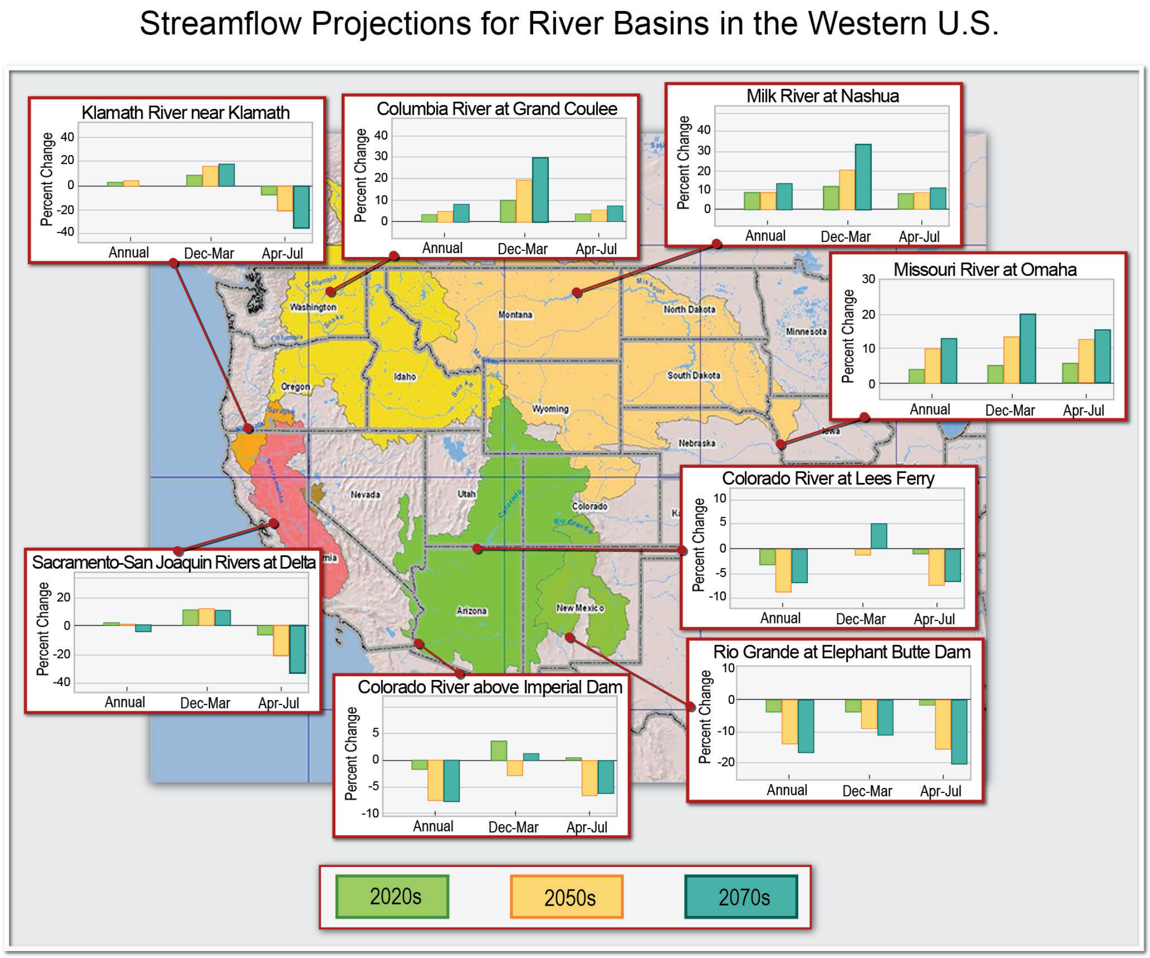

Figure 3.2: Streamflow Projections for River Basins in the Western U.S.

Caption: Streamflow projections associated with an ensemble of emissions scenarios and climate projections for eight river basins in the western U.S. 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 baseline conditions (1990s).

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

> and Rio Grande River basins) 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, Truckee, 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). The projected streamflow changes and associated uncertainties have water management implications, as the existing management systems have been designed to operate within the historical range of variability. (Source: U.S. Bureau of Reclamation 2011a).

Summer Droughts Intensify

Summer droughts are expected to intensify in most regions of the U.S., with longer-term reductions in water availability in the Southwest, Southeast, and Hawai‘i in response to both rising temperatures and changes in precipitation.

Averaged over recent climate models, annual runoff and streamflow are projected to decline in the Southwest (Milly et al. 2008; U.S. Bureau of Reclamation 2011b) and Southeast (Georgakakos and Zhang 2011), and to increase in the Northeast, Alaska, Northwest, and upper Midwest regions (Brekke 2011; Elsner et al. 2010; IPCC 2007; Markstrom et al. 2011; Milly et al. 2008; Moser et al. 2008; U.S. Bureau of Reclamation 2011b). Broadly, as warming changes the water cycle processes, the amount of runoff generated by each unit of precipitation is expected to decline (McCabe and Wolock 2011).

There has been no universal trend in the overall extent of drought across the continental U.S. since 1900. However, in the Southwest, there has been a trend towards more widespread drought during the 1901 to 2010 period, reflecting both precipitation deficits and higher temperatures (Hoerling et al. 2012). Drought conditions are also projected to increase in the Southeast, Hawai‘i, and the Pacific Islands. Generally – except where increases in summer precipitation compensate – summer droughts (see Ch. 2: Our Changing Climate) are expected to intensify almost everywhere in the continental U.S. (Trenberth et al. 2004). Basins watered by glacial melt in the Sierra Nevada, Glacier National Park, and Alaska may experience increased summer streamflows in the short term, until the amounts of glacial ice become too small (Basagic and Fountain 2011; Hall and Fagre 2003; Hodgkins et al. 2005).

Floods Intensify in Most Regions

Floods are projected to intensify in most regions of the U.S., even in areas where average annual precipitation is projected to decline, but especially in areas that are expected to become wetter, such as the Midwest and the Northeast.

Heavy precipitation increased over recent decades (Gutowski et al. 2008; Karl and Knight 1998) in most regions of the country, but **floods** are basin specific and dependent on existing moisture conditions among other factors. Annual flood magnitude trends (see figure in Ch. 2: Our Changing Climate) generally follow annual streamflow, except for the Northwest where there has been no trend in annual flood magnitude. Annual peak flows have increased at gauges in the upper Midwest and in the Northeast during the past 85 years, and have declined in the Rocky Mountains and the Southwest U.S., with other regions showing no consistent trends (Hirsch and Ryberg 2012). Seasonality of precipitation and antecedent conditions (especially soil moisture) are important determinants of runoff volume. If storms continue to intensify and catchment areas receive increasingly more precipitation as rain rather than snow, or more rain on snowpacks (Knowles et al. 2006; McCabe et al. 2007; Mote 2003, 2006), floods in some cases are expected to increase – even where precipitation and overall stream flows decline (see Ch. 2: Our Changing Climate).

Groundwater Availability

Expected changes in precipitation and land use in aquifer recharge areas, combined with changes in demand for groundwater over time, will affect groundwater availability in ways that are not well monitored or understood.

Groundwater storage or flow responses to climate change are not well understood. Despite their critical national importance as water supply sources, aquifers are not generally monitored in ways that allow for clear identification of climatic influences on groundwater storage or flows. Nearly all monitoring is focused in areas and aquifers where variations are dominated by groundwater pumping, which largely masks climatic influences (Hanson et al. 2006). In addition, climate models do not, in general, yet include dynamic representations of the groundwater reservoir and its connections to streams, the soil-vegetation system, and the atmosphere, hampering progress in understanding the potential impacts on groundwater and groundwater-reliant systems of climate change (Fan et al. 2007; Maxwell and Kollet 2008; Schaller and Fan 2009). Thus far, there have been few observations and projections of groundwater responses to climate change (Hanson et al. 2012), but surface water declines already have resulted in higher groundwater use in some areas (for example, in the Central Valley of California and the Southeast) and even more stress on both groundwater and surface water systems (NRC 2004). In many mountainous areas of the U.S., groundwater recharge derives disproportionately from snowmelt infiltration (Earman et al. 2006), suggesting that the loss of snowpack is likely to disrupt or change recharge rates and patterns (Earman and Dettinger 2011).

Spotlight on Groundwater

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 and food security and in sustaining ecosystems. Over the 2001 to 2008 period, the groundwater depletion rate was estimated at 145 ±39 km^3/yr worldwide, and 26±7 km^3/yr in North America (Konikow 2011; Taylor et al. 2012). 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.

During the 2006 – 2009 California drought, when the source of irrigation shifted from surface water to predominantly groundwater, the groundwater storage in the California Central Valley declined by 24 km^3 to 31 km^3, equivalent to the storage capacity of Lake Mead, the largest reservoir in the U.S. (Famiglietti et al. 2011).

As the risk of drought increases, groundwater can play a key role in enabling adaptation to climate variability and change – for example, through conjunctive management strategies that use surface water for irrigation and water supply during wet periods, and groundwater during drought. However, the current understanding of the dynamic relationship between groundwater and climate is limited by the dearth of measurements of groundwater recharge and discharge variations and changes.

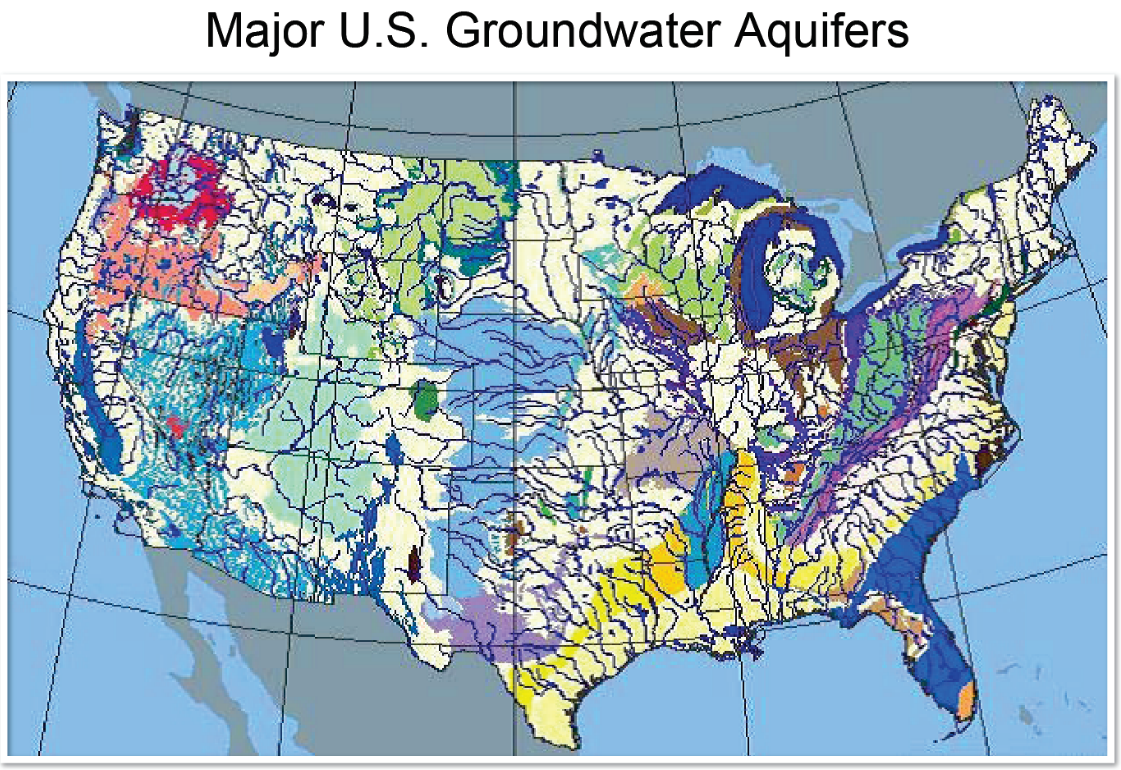

Figure 3.3: Major U.S. Groundwater Aquifers

Caption: Groundwater aquifers are found throughout the U.S., but they vary dramatically in terms of ability to store and recharge water. On this map, differences in geology are illustrated: blue is unconsolidated sand and gravel; yellow is semi-consolidated sand; green is sandstone; brown is carbonate-rock; and red is igneous and metamorphic rock.

(Source: DOI 2012)

Risks to Coastal Aquifers and Wetlands

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

With so much of the nation's population concentrated near coasts, coastal aquifers and wetlands are precious resources. These aquifers and wetlands, which are extremely important from a biological/biodiversity perspective (see Ch. 8: Ecosystems and Biodiversity, Ch. 25: Coastal Zone), may be particularly at risk due to the combined effects of inland droughts, increased surface water impoundments and diversions, increased groundwater pumping, and accelerating sea level rise and greater storm surges (Chang et al. 2011; Heimlich and Bloetscher 2011). Several coastal areas (see Ch. 25: Coastal Zone), including Apalachicola Bay in Florida, the Mississippi River delta in Louisiana, and the delta of the Sacramento-San Joaquin rivers in northern California, are particularly vulnerable.

Lakes and Rivers at Risk

Air and water temperatures, precipitation intensity, and droughts affect water quality in rivers and lakes. More intense runoff and precipitation generally increase river sediment, nitrogen, and pollutant loads. Increasing water temperatures and intensifying droughts can decrease lake mixing, reduce oxygen in bottom waters, and increase the length of time pollutants remain in water bodies.

Water temperature has increased in many rivers (Kaushal et al. 2010), a trend generally expected to persist with climate warming (Cloern et al. 2011; Van Vliet et al. 2011). Thermal lake and reservoir stratification is increasing with increased air and water temperatures (Sahoo and Schladow 2008; Sahoo et al. 2012; Schneider and Hook 2010), and mixing may be eliminated in shallow lakes, decreasing dissolved oxygen and releasing excess nutrients (nitrogen and phosphorous), heavy metals (such as mercury), and other toxics into lake waters (Sahoo and Schladow 2008; Sahoo et al. 2012; Schneider and Hook 2010).

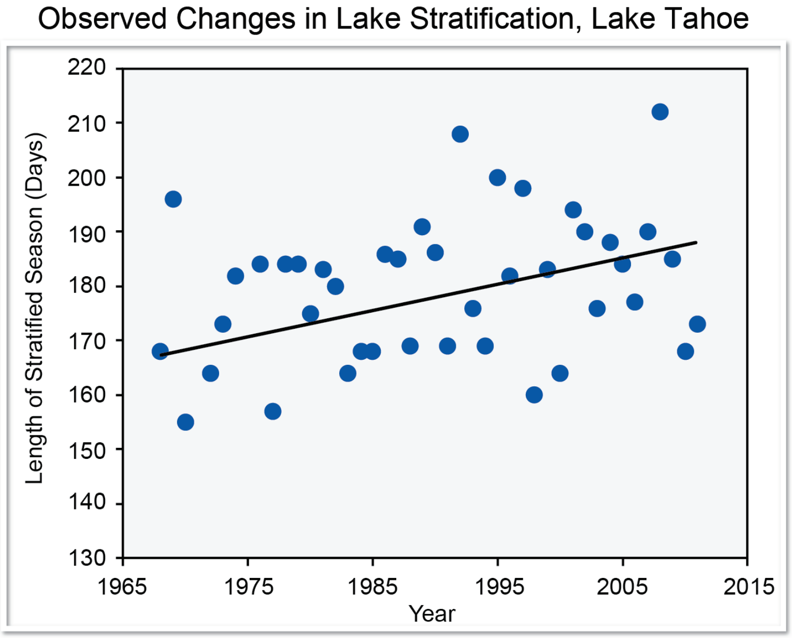

Figure 3.4: Observed Changes in Lake Stratification, Lake Tahoe

Caption: Thermal stratification of lakes, in this case, Lake Tahoe, has been increasing since the 1960s in response to increasing air and surface water temperatures. Temperature differences cause changes in density, leading to longer stratification seasons (on average, by 20 days in Lake Tahoe), decreasing the opportunities for deep lake mixing, reducing oxygen levels, and causing impacts to many species and numerous aspects of aquatic ecosytems. (UC Davis and Tahoe Environmental Research Center 2012)

Increased low flows under drought conditions as well as increased overland flow during floods have the potential to 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 for downstream water users (Pruski and Nearing 2002a, 2002b) and ecosystems. Mineral weathering products, like calcium, magnesium, sodium, and silicon and nitrogen loads (Justic et al. 2005; McIsaac et al. 2002) have been increasing with higher streamflows (Godsey et al. 2009). Changing land cover, flood frequencies, and flood magnitudes are expected to increase mobilization of sediments in large river basins (Osterkamp and Hupp 2010). Changes in sediment transport will vary regionally and by land-use type, but may increase by 25% to 55% over the next century (Nearing et al. 2005). 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 (Whitehead et al. 2009).

Climate Change Impacts on Water Resources

Climate change-induced water cycle changes are affecting water supplies in a variety of ways that affect ecosystems and livelihoods by altering reliability of water availability, demand, competition between sectors, and management responses in many regions. The direction and magnitude of the projected impacts are expected to vary by type of use, region, and adaptation responses.

Water benefits derive from freshwater withdrawals (from streams, rivers, lakes, and aquifers) for municipal, industrial, agricultural, and re-circulating electric power plant cooling water supply (*off-stream* water uses). Water benefits also come from *in-stream* water flows, levels, and quality suitable for hydropower production, once-through electric power plant cooling water supply, navigation, recreation, and healthy ecosystems. 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. 13: Land Use and Land Cover Change, Ch. 4: Energy Supply and Use, and Ch. 6: Agriculture). 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 re-assessment of the water infrastructure and institutional responses (Bales et al. 2012).

Off-stream Water Uses

At the national level, total freshwater withdrawals (including both water that is withdrawn and eventually consumed and amounts that return to the original surface or groundwater source) and consumptive uses have leveled off since 1980 at 350 and 100 billion gallons per day respectively, despite the addition of 68 million people from 1980 to 2005 (Kenny et al. 2009). Irrigation and all electric power plant cooling withdrawals currently 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 used up 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%).

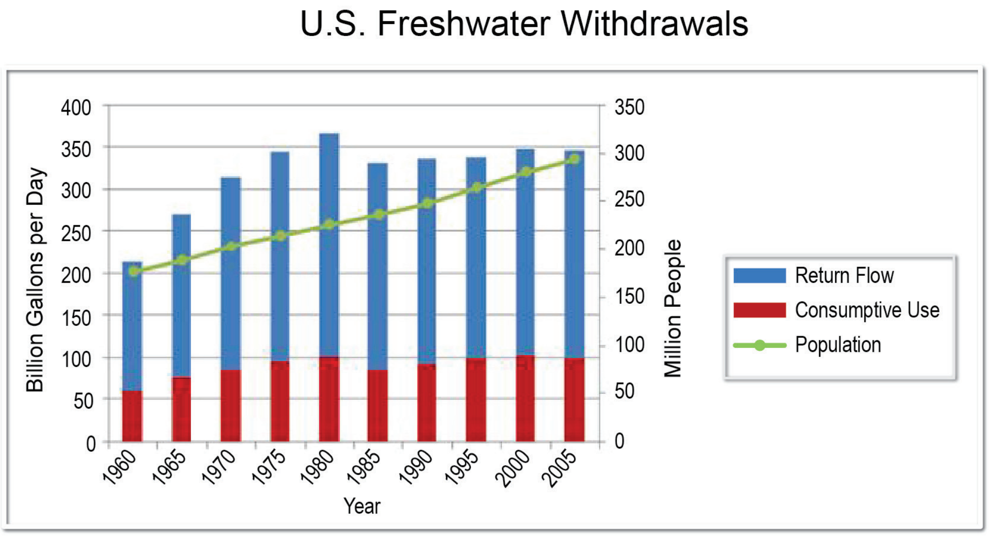

Figure 3.5: U.S. Freshwater Withdrawals

Caption: Trends in total freshwater withdrawal (equal to the sum of consumptive use and return flows to rivers) and population in the contiguous U.S. 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, reductions in exterior landscape watering in commercial and residential properties. While efficiency improvements have effectively decoupled water use from population growth and have resulted in more flexibility in meeting water demand, in some cases they have also reduced the flexibility to scale back water use in times of drought. With drought stress projected to increase in summer months in most of the U.S., drought vulnerability is also expected to rise (Bales et al. 2012).

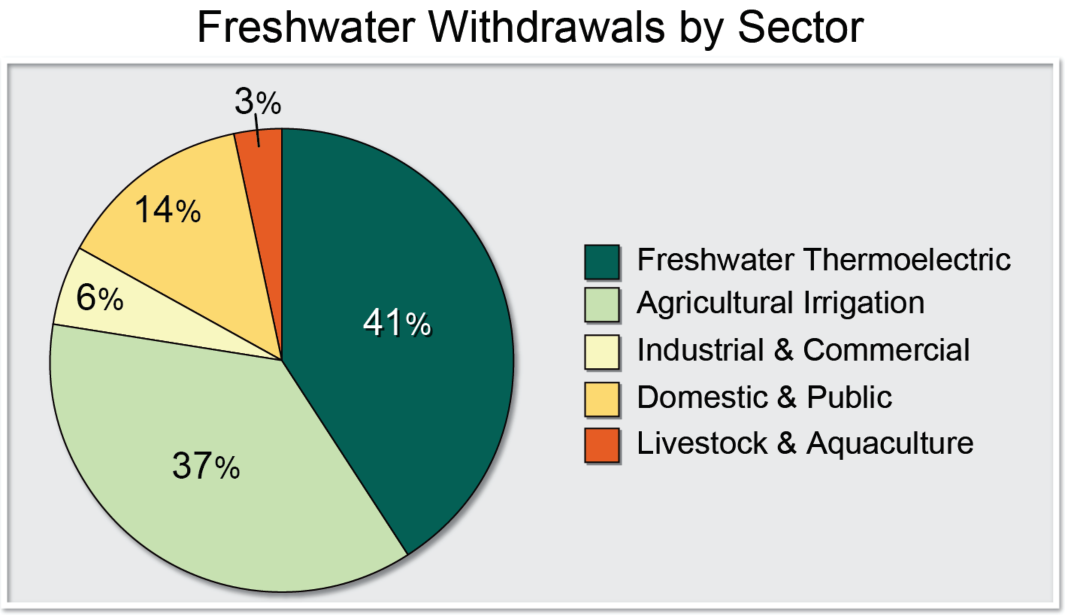

Figure 3.6: Freshwater Withdrawals by Sector

Caption: Total water withdrawals 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) (Figure source: USGS, 2005.)

Per capita water withdrawal and use are decreasing due to many factors, including (Brown et al. 2012): demand management, efficiency improvement programs, and pricing strategies (Groves et al. 2008; Jeffcoat et al. 2009; Rockaway et al. 2011) (*in the municipal sector*); changes from water intensive manufacturing and other heavy industrial activities to service-oriented businesses (David 1990), and enhanced water use efficiencies in response to environmental pollution legislation (*in the industrial and commercial sector*); replacement of older once-through-cooling electric power plants by plants that recycle their cooling water (*in the thermoelectric sector*); switching from flood irrigation to more efficient methods in the western U.S. (Brown 2000; Foti et al. 2012a) (*in the irrigation sector*); and decreasing consumer demands for meat (Haley 2001) (*in the livestock sector*). Notwithstanding the overall national trends, regional water withdrawal and use are strongly correlated with climate (Balling and Gober 2007); 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.

In the absence of climate change but in response to a projected 60% to 85% population increase, simulations indicate that the demand for water withdrawals in the U.S. will increase respectively by 3% to 8% over the next 50 years (Foti et al. 2012; USFS 2012). If, however, climate-change projections are also factored in, the increase in demand for water withdrawals has been estimated to rise by 25% to 35% (Foti et al. 2012) over the same period, with three-quarters of the increase attributed to irrigation demand and the rest to landscape watering and electricity generation.

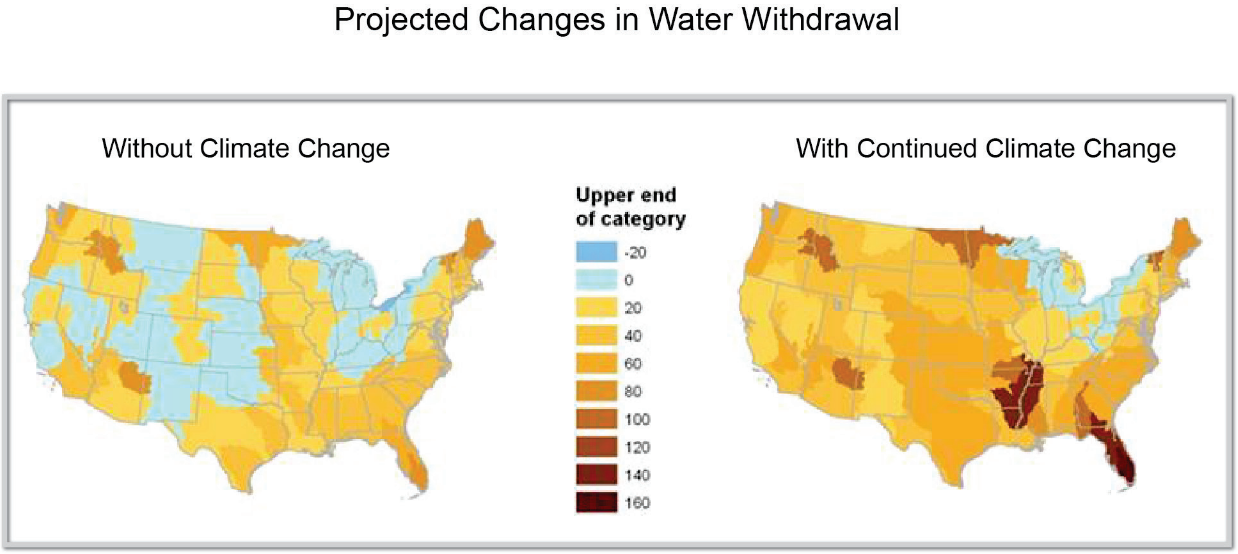

Figure 3.7: Projected Changes in Water Withdrawals

Caption: Percent change from 2005 to 2060 in projected withdrawals assuming no change in climate (left) and continued growth in heat-trapping gas emissions (A2 scenario, right). The effects of climate change, primarily associated with increasing temperatures, are projected to significantly increase water demand across most of the U.S. (Foti et al. 2012).

Power plant cooling is expected to be affected by changes in water supply availability in areas where surface water supplies are diminishing and by increasing water temperatures. Higher water temperatures affect both the effectiveness of electric generation and cooling processes and the ability to discharge heated water to streams from once-through cooled power systems due to regulatory requirements and concerns about ecosystem impacts (see Ch. 4: Energy Supply and Use) (Wilbanks and al. 2007)).

Flooding and Instream Water Uses

Extreme precipitation events have intensified in recent decades in most U.S. regions, and this trend is projected to continue (Ch. 2: Our Changing Climate). Reported flood frequency and severity increases are generally consistent with observed and projected water cycle changes in many U.S. regions (Brekke et al. 2009a; Das et al. 2012; Raff et al. 2009; Shaw and Riha 2011; Walker et al. 2011), especially in the Northeast and Midwest. This trend, combined with the devastating toll of large floods (in human life, property, environment, and infrastructure; see "Spotlight on Flooding"), suggests that proactive management measures could minimize changing future flood risks and consequences. New York, Boston, Miami, Savannah, New Orleans, the San Francisco Bay area, and many other U.S. cities located along coasts are threatened by flooding and seawater intrusion due to sea level rise. Increasing flooding risk may also increase health risk, and poses safety risks, when critical infrastructure fails (Ebi et al. 2006; Kessler 2011; Patz et al. 2000; Wright et al. 2012). Though numerous flood risk reduction measures are possible, including levees, land-use zoning, flood insurance, and restoration of natural flood plain retention capacity (FEMA 1994), economic conditions may constrain implementation. The effective use of these measures would require significant investment in many cases, as well as updating policies and methods to account for climate change (Milly et al. 2008; Villarini et al. 2011) in the planning, design, operation, and maintenance of flood risk reduction infrastructure (Brekke et al. 2009a; Yang 2010).

Spotlight on Flooding

The 2011 floods in the Northeast and the Mississippi basin, and the 2009 floods in the Southeast set new precipitation and flood stage records in many locations, causing fatalities, property damage, and devastating economic losses of several billion dollars.

There was widespread flooding along the Susquehanna River in Binghamton, N.Y. in September 2011, disrupting road and rail transportation (*top*; photo credit: NWS Forecast Office, Binghamton, NY); the Fort Calhoun Nuclear Power Plant in eastern Nebraska was surrounded by a Missouri River flood, June 8, 2011, that also affected Louisiana, Mississippi, Missouri, Illinois, Kentucky, Tennessee, and Arkansas (*middle*; photo credit: Larry Geiger); and the R.M. Clayton sewage treatment plant in Atlanta, Georgia, September 23, 2009, was engulfed by floodwaters forcing it to shut down and discharge raw sewage into the Chattahoochee River.

The 2009 Southeast floods affected several counties throughout northern Georgia (*bottom*; photo credit: NASA), Tennessee, Alabama, Mississippi and Arkansas, caused eleven fatalities, and cost more than a billion dollars (NOAA, Southeast Floods, 18-23 2009). Interestingly, the 2009 Southeast flood occurred in the wake of a record setting drought (2006-2008), illustrating the continuing potential high risks and vulnerabilities associated with both floods and droughts.

Hydropower contributes 6% of electricity generation nationwide, but up to 60% to 70% in the Northwest and 20% in California, Alaska, and the Northeast (EIA 2011). 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. One-quarter of all hydropower facilities nationwide, especially in the Southeast, Southwest, and the Great Plains, are expected to face water availability constraints (EPRI 2011), and these challenges will rise as aging hydropower infrastructure needs to be replaced (Brekke 2011).

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 (Bales et al. 2012; DOT 2011). Navigation is affected by ice cover and by floods and droughts. Seasonal ice cover on the Great Lakes has been decreasing (Wang et al. 2012) and may allow increased shipping (Millerd 2011). However, lake level declines are also possible in the long term, decreasing vessel draft and cargo capacity, but projections of lake levels are uncertain, with even the direction of change undetermined (see Ch. 18: Midwest and Ch. 6: Transportation). Similarly, although the river ice cover period has been decreasing (Hodgkins et al. 2005) (extending the inland navigation season), seasonal ice cover changes (Beltaos and Prowse 2009; Hawkes et al. 2010; Prowse et al. 2011; Weyhenmeyer et al. 2011) could impede lock operations (Hawkes et al. 2010). Intensified floods are likely to hinder shipping by causing waterway closures and damaging or destroying ports and locks. Intensified droughts can decrease reliability of flows or channel depth. Both floods and droughts can disrupt rail and road traffic and increase shipping costs (DOT 2012) and result in commodity price volatility (Ch. 19: Great Plains).

Recreation activities associated with water resources, including boating, fishing, swimming, skiing, camping, and wildlife watching, are a strong regional and national economic driver, valued at between $700 billion and $1.1 trillion annually (DOC 2012; U.S. Census Bureau 2012). Recreation is sensitive to weather and climate (Yu et al. 2009), and climate change impacts to recreation can be difficult to project (Scott and Becken 2010). Rising temperatures affect extent of snowcover and mountain snowpack, with impacts on skiing (Dawson et al. 2009) and snowmobiling (Frumhoff et al. 2008). As the climate warms, changes in precipitation and runoff are expected to result in both beneficial (in some regions) and adverse impacts (Yu et al. 2009) to water sports, with potential for considerable economic and job losses (Frumhoff et al. 2008; Union of Concerned Scientists 2009).

Changing climate conditions are projected to impact **water and wastewater treatment and disposal** in several ways, both positively and negatively. Elevated stream temperatures, combined with lower flows, may require wastewater facilities to increase treatment to meet stream water quality standards (EPA 2011). 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 (Whitehead et al. 2009).

Conversely, increasing, but not extreme, precipitation could result in increased stream flows, improving capacity to absorb wastewater in some regions. Sea level rise and more frequent coastal flooding could damage wastewater utility infrastructure and lower treatment efficiency (Flood and Cahoon 2011; Ch. 25: Coastal Zone).

Changes in streamflow temperature and flow regimes can affect **aquatic ecosystem** structure and function (see Ch. 8: Ecosystems and Biodiversity). 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 (Maurer et al. 2010). Hydrologic alterations due to human interventions have without doubt impaired riverine ecosystems in most U.S. regions and globally (Poff et al. 2010). If the rate of climate change (Loarie et al. 2009) outpaces plant and animal species adjustment to temperature change, additional biodiversity loss may occur. Furthermore, climate-induced water cycle alterations may exacerbate existing ecosystem vulnerability, especially in the western U.S. (Falke et al. 2011; Rood et al. 2008; Stromberg et al. 2010; Thomson et al. 2010) where droughts and shortages are likely to rise. But areas receiving additional precipitation, such as the northern Great Plains, may benefit.

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.

Drought is Affecting Water Supplies

In the Southwest, the Southeast, the Great Plains, and the islands of the Caribbean and the Pacific, including the state of Hawai'i, surface and groundwater supplies are already affected and expected to be reduced by declining runoff and groundwater recharge trends, increasing the risk of water shortages for many off-stream and in-stream water uses.

Many southwestern and western watersheds, including the Colorado, Rio Grande (U.S. Bureau of Reclamation 2011b, 2011c; Ward et al. 2006), and Sacramento-San Joaquin (Brekke et al. 2009b; Connell-Buck et al. 2012; Georgakakos et al. 2012), are experiencing increasingly drier conditions with even larger runoff reductions (in the range of 10% to 20%) expected over some of these watersheds the next 50 years (Cayan et al. 2010). Declining runoff and groundwater recharge are expected to affect surface and groundwater supplies (Earman and Dettinger 2011) and increase the risk of water shortages for many off-stream and in-stream 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 challenge the management of reservoirs, aquifers, and other water infrastructure (Rajagopalan et al. 2009). 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 (Backlund et al. 2008).

Flood Effects on People and Communities

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

Observations and projections suggest that heavy precipitation, peak flows, and flooding may become more frequent and intense in this century across the country and even more pronounced in the Midwest and Northeast, and that sea levels will continue to rise.

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 "Spotlight on Flooding"). Climate change and its impacts on water supply can result in both increased uncertainty and decreased accuracy of flood forecasting, in the short term (Raff et al. 2012) and long term (Brekke 2011). This will hinder effective preparedness (such as evacuations) and the effectiveness of structural and nonstructural flood risk reduction measures. Increasing flooding risk will also exacerbate human health risks associated with failure of critical infrastructure (Ebi et al. 2006; Huang et al. 2011; Kessler 2011; Patz et al. 2000; Wright et al. 2012), waterborne disease (Curriero et al. 2001; Ch. 9: Health), and airborne diseases (Ziska et al. 2008). Thus, effective climate change adaptation planning requires an integrated approach (Frumhoff et al. 2008; Kundzewicz et al. 2002; Moser et al. 2008) that addresses public health and safety issues (City of New York 2012; Kirshen et al. 2008). 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 should begin soon. Lastly, in coastal areas, sea level rise may act in parallel with inland climate changes to exacerbate water use impacts and challenges (Obeysekera et al. 2011; Ch. 17: Southeast).

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 with existing practices.

Water managers and planners strive to balance water availability and demand and secure adequate supplies for all off-stream and in-stream water uses and users. The management process involves complex tradeoffs among water use benefits, consequences, and risks, and, by altering water availability *and* demand, climate change is likely to present new challenges. For example, the California Bay-Delta experience indicates that managing risks and sharing benefits requires re-assessment of very complex ecosystems, infrastructure systems, water rights, stakeholder preferences, reservoir operation strategies, and significant investments, all of which are subject to large uncertainties (NRC 2010, 2011b, 2012). 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 "Spotlight on Water Management").

Recent assessments illustrate the water management challenges facing California (Brekke et al. 2009b; Connell-Buck et al. 2012; Georgakakos et al. 2007; Georgakakos et al. 2012; Vicuna et al. 2010), the Southwest (Barnett and Pierce 2009; Rajagopalan et al. 2009), Southeast

(Georgakakos et al. 2010; Obeysekera et al. 2011; Ch. 17: Southeast), Northwest (Payne et al. 2004; Vano et al. 2010a; Vano et al. 2010b), Great Plains (Brikowski 2008), and Great Lakes (International Upper Great Lakes Study Board 2012). 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: demand management; more flexible, risk-based, better-informed, and adaptive operating rules; and combined surface and groundwater resources management (Brekke et al. 2009b; Georgakakos et al. 2007; Means et al. 2010a; NRC 2011a; Vicuna et al. 2010). Water management and planning would benefit from better coordination between the national, state, and local levels, with participation of all relevant stakeholders in well-informed, fair, and equitable decision-making processes.

Spotlight on Water Management

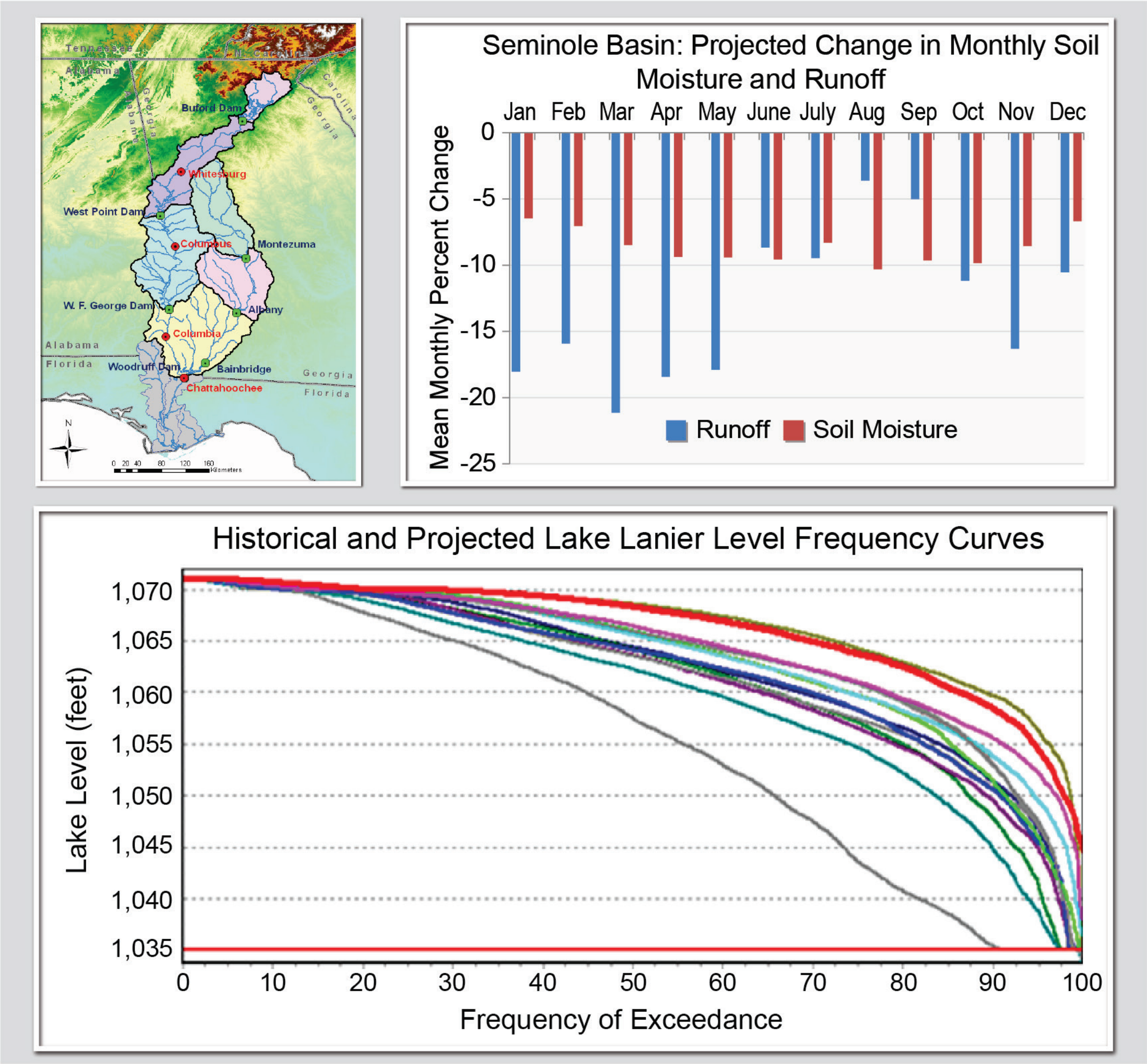

Figure 3.8: Water Challenges in a Southeast River Basin

Caption: The Apalachicola-Chattahoochee-Flint (ACF) River Basin faces several climate-related challenges. **Top:** Comparison of monthly simulated soil moisture and runoff for 50 historical (1960-2009) and future years (2050-2099) based on a scenario of continued increases in emissions (A2) for the Seminole sub-basin of the ACF Basin in the southeastern U.S. Mean soil moisture is projected to decline in all months (droughts), especially during the crop growing season from April to October. Mean runoff declines are also projected throughout the year and especially from November to May. Runoff is projected to exhibit higher wet extremes and flooding risks (not shown). Similar findings apply to all other ACF sub-basins. **Bottom:** Historical (1960-2010; thick red line) and projected Lake Lanier levels under the A2 emission scenario and projected water demands (2050-2099). The frequency curve comparison shows that future lake levels are projected to be lower (by as much as 15 feet) than historical levels throughout the frequency range, particularly during droughts. Figure provided by A. Georgakakis.

Adaptation and Institutional Responses

Increasing resilience and enhancing adaptive capacity are useful strategies for water resources management and planning in the face of climate change. Challenges include: competing demands for water; a variety of institutional constraints; lack of scientific information or access to it; considerable scientific and economic uncertainties; inadequate information useful for practical applications; and difficulties in engaging stakeholders.

Climate change will stress the nation’s aging water infrastructure to varying degrees by location and over time. Current drainage infrastructure may be overwhelmed during heavy precipitation and high runoff events anticipated as a result of climate change. 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 (Nilsen et al. 2011; Wilbanks et al. 2012). Infrastructure planning 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 (Brekke et al. 2009a; Means et al. 2010b; Wilbanks et al. 2012).

Adaptation strategies for water infrastructure may include elements of structural *and* non-structural approaches (for example, instituting operational and/or demand management changes) that focus on both adapting physical structures and innovative management (Brekke et al. 2009a; Brown 2010; Wilbanks et al. 2012). Such strategies could take advantage of conventional (“gray”) infrastructure upgrades, adjustments to reservoir operating rules, new demand management strategies, land-use management that enhances adaptive capacity, increased reliance on benefits achieved through ecosystem restoration and watershed management, hybrid strategies that blend “green” infrastructure with gray infrastructure, and pricing strategies (Bales et al. 2012; Brekke et al. 2009a; Solecki and Rosenzweig 2012; Wilbanks et al. 2012; Wilby and Keenan 2012).

In addition to physical adaptation, capacity-building activities can build knowledge and enhance communication and collaboration within and across sectors (Bales et al. 2012; Liverman et al. 2012; Wilby and Keenan 2012). In particular, building networks, partnerships, and support systems has been identified as a major asset in building adaptive capacity (Lackstrom et al. 2012; Ch. 26: Decision Support; Ch. 28: Adaptation).

Just as climate change may stress the physical infrastructure of water systems, it also may challenge water laws that are based on an assumption of unchanging regimes of stream flows, water levels, water temperature, or water quality. Existing laws, policies, and regulations, and their current implementation, may limit water management capacity in the context of novel and dynamic conditions (Berry 2012; Brekke et al. 2009a).

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") (Craig 2010). 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 (Brekke et al. 2009a). As a result, stationarity is no longer reliable as the central assumption in water-resource risk assessment and planning (Craig 2010). Instead, a new paradigm that provides additional flexibility in institutional and legal processes will need to be developed, rather than relying on one that narrowly optimizes the distribution of water based on historical experience (Craig 2010).

In the past few years, many federal, state, and local agencies have begun to address climate change adaptation, including it in existing decision-making, planning, or infrastructure-improvement processes (Adelsman and Ekrem 2012; NOAA 2011; State of Oregon 2010; U.S. Bureau of Reclamation 2011b; Ch. 28: Adaptation). Water utilities are increasingly utilizing climate information to prepare assessments of their supplies (EPA 2010), and utility associations and alliances, such as the 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 U.S. (Barsugli et al. 2009; Carpenter 2011; EPA 2011; Means et al. 2010a).

The economic, social, and environmental implications of climate change-induced water cycle changes are very significant, as is the cost of inaction. Adaptation responses will 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.

Traceable Accounts

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: 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 (Bales et al. 2012), 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 #1/10	**Annual precipitation and runoff increases are observed now in the Midwest and Northeast regions and are projected to continue or develop in northern states; decreases are observed and projected in southern states.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document (Bales. et al, 2012), Ch. 2: Our Changing Climate and Ch. 20: Southwest (2013), (Bales et al. 2012; Garfin et al. 2012; Kunkel et al. 2012a) Garfin et al, 2012, Kunkel et al, 2012, 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 and runoff trends (Diaz et al. 2005; Garfin et al. 2012; Georgakakos and Zhang 2011); see Ch. 2: Our Changing Climate. Notably, the broad trends described in this message and in Ch. 2: Our Changing Climate and Ch. 20: Southwest are trends that are shared by the majority of projections by available climate models and projections (Orlowsky and Seneviratne 2012), lending confidence that the projected precipitation responses (trends) to increasing greenhouse gases are robust in a wide variety of models and depictions of climate at the geographic scale described. There are also many long-term NWS/NCDC weather monitoring networks, USGS streamflow monitoring networks, and analyses of records therefrom, most recently for precipitation as part of NCDC (2011) report and Ch. 2: Our Changing Climate and numerous studies including McCabe and Wolock (2011), Georgakakos & Zhang (2011), and Luce and Holden (2009), that have identified these broad observed trends in precipitation and runoff increases. Projections by ensembles of climate models, reported by Milly et al. (2008), Orlowsky & Seneviratne (2012), and Ch. 2: Our Changing Climate and Ch. 20: Southwest (2013), and Garfin et al. (2012), are basis for the reported projections of trends.
New information and remaining uncertainties	Important new evidence (cited above) confirmed many of the findings from the prior National Climate Assessment (http://www.globalchange.gov/publications/reports/scientific-assessments/saps). **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 extremely 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 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 runoff 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 precipitation and runoff increases will continue in northern states with increasing fractions of precipitation falling as rain than snow. Confidence is therefore judged to be **high** that precipitation and runoff decreases will continue in southern states.

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

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: See key message #1.

Key message #2/10	**Summer droughts are expected to intensify in most regions of the U.S., with longer term reductions in water availability in the Southwest, Southeast, and Hawai'i in response to both rising temperatures and changes in precipitation.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document Bales et al.,(2012), Garfin et al., (2012), Ch. 16: Northeast, Ch 17: Southeast and Caribbean, Ch. 2: Our Changing Climate, Ch. 18: Midwest, Ch. 19: Great Plains, Ch, 20 Southwest, Ch. 21: Northwest, and Ch. 23: Hawaii 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 (e.g., Wehner et al. (2011), from hydrologic models responding to projected climate trends in others (e.g., Reclamation, (2011c); Cayan et al (2010)), from considerations of the interactions between precipitation deficits and either warmer or cooler temperatures in historical (observed) droughts (Cayan et al. 2010) and from combinations of these approaches (for example, (Trenberth et al. 2004; Trenberth and Dai 2007)) in still other studies.
New information and remaining uncertainties	Important new evidence (cited above) confirmed many of the findings from the prior National Climate Assessment (http://www.globalchange.gov/publications/reports/scientific-assessments/saps). Warmer temperatures, especially in summer and in interior parts of North America, 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, and net surface radiation, 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 potential increases, less overall water will remain on the landscape and droughts will intensify and become more common
Assessment of confidence based on evidence	The expectation of future intensification of droughts is supported strongly in the southern regions by a strong consensus of existing climate models towards less precipitation, along with the expectation that ET demands will increase nearly everywhere with rising temperatures. In the northern regions, uncertainties regarding the eventual balance between increased ET demands and increased precipitation (discussed previously), leads to the greatest reductions in confidence in the expectation of more intense drought regimes (although there is still confidence about increasing drought conditions in the summer). Other uncertainties derive from the possibility that changes in other variables or influences of CO_2-fertilization may also partly ameliorate drought intensification. Furthermore in many parts of the country, El Nino-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. Confidence in the expectation of future intensification of droughts is therefore judged to be **medium-high** except in the Southwest and the lower Great Plains where it is

	high.

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

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: See key message #1.

Key message #3/10	**Floods are projected to intensify in most regions of the U.S., even in areas where average annual precipitation is projected to decline, but especially in areas are expected to be wetter, such as the Midwest and the Northeast.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document Bales et al.(2012), Garfin et al.(2012), Ch. 16: Northeast, Ch 17: Southeast and Caribbean, Ch. 2: Our Changing Climate, Ch. 18: Midwest, Ch. 19: Great Plains, Ch, 20 Southwest, Ch. 21: Northwest, and Ch. 23: Hawaii 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. Annual peak-flow records from 200 USGS streamflow gaging stations measuring flows from catchments that are minimally influenced by upstream water uses, diversions, impoundments, or land-use changes (from the USGS HCDN network), with more than 85 years of records, were the basis for careful national-scale flood-trend analysis by Hirsch & Rhyberg (2012), which provide the principal observational basis for the flood message. Projections of future flood-frequency changes result from detailed hydrologic (for example (Walker et al. 2011); Das et al. (2012); Raff et al. (2009)) models 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 prior National Climate Assessment (http://www.globalchange.gov/publications/reports/scientific-assessments/saps). Large uncertainties still exist as to how well climate models can represent and project future extremes of precipitation, which has—until recently—limited attempts to be specific about 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. Rising sea levels and potentials for intensification of tropical storms and hurricanes provide first-principles bases for expecting intensified flood regimes in Florida and other Southeastern 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, upstream managements). Consequently, flood frequency changes may not be simple nor regionally homogeneous, and basin by basin projections may need to be developed. Nonetheless, the 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 therefore judged to be **medium**.

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

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: See key message #1.

Key message #4/10	**Expected changes in precipitation and land use in aquifer recharge areas, combined with changes in demand for groundwater over time, will affect groundwater supplies in ways that are not well monitored or understood.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document Bales et al.(2012), Garfin et al.(2012), NCA regional chapters (2013), 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. For many aquifers in the Southwest region, 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 (Earman and Phillips 2003; Earman et al. 2006; Liu et al. 2004; Manning and Solomon 2003; Manning et al. 2012; Phillips et al. 2004; Rademacher et al. 2002; Rose et al. 2003); 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, and simply spatial redistribution.
New information and remaining uncertainties	The observations and, even, modeling evidence for making projections of future responses of groundwater recharge and discharge to long-term climate changes are thus far very limited, primarily because of limitations in data availability and in the models themselves. Additional monitoring and modeling studies of the responses of groundwater recharge and discharge to climate change are needed to increase confidence. Despite the low confidence 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	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 systems. The nature of these changes, however, remains unexplored. Confidence is therefore judged to be **high** that groundwater aquifers will be influenced by climate change at aquifer recharge areas and by increased groundwater use in ways that remain unexplored.

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

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: See key message #1.

Key message #5/10	**Sea level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to challenge the sustainability of coastal freshwater aquifers and wetlands.**
Description of evidence base	Considerable historical experience with seawater intrusion into many of the Nation's coastal aquifers under the influence of heavy pumpage, some experience with the influences of droughts and some storms on seawater intrusion in at least some coastal aquifers, and experience with seepage of seawater into shallow coastal aquifers under storm and storm surges conditions that lead to coastal inundations with seawater provide a strong basis for both practical, and theoretical, expectations expressed by this message. The likely influences of sea level rise on seawater intrusion into coastal (and island) aquifers are somewhat less certain, as discussed below, although it is often assumed that sea level rise may increase tendencies for higher sea levels to increase opportunities for saltwater intrusion (see Ch. 25: Coastal Zone).
New information and remaining uncertainties	Chang et al. (2011) have recently provided theoretical and modeling arguments that sea level rise need not generally induce significantly greater seawater intrusion unless freshwater recharge and discharge also change. In essence, Chang et al. (2011) show that the lens of freshwater in coastal aquifers may essentially float atop the rising saline waters in ways that preserve the lens and prevent significant intrusion, unless the water balance of the freshwater lens is altered by changing recharge and/or water use patterns. Other than the findings of Chang et al. (2011), 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. Studies in the literature and historical experience demonstrate the detrimental impacts of alterations to the water budgets of the freshwater lenses in coastal aquifers (most often, by groundwater development) around the world, 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, intensifying storms and larger storm surges may challenge the sustainability of coastal freshwater aquifers and wetlands (see Ch. 25: Coastal Zone).

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

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: See key message #1.

Key message #6/10	**Air and water temperatures, precipitation intensity, and droughts affect water quality in rivers and lakes. More intense runoff and precipitation generally increase river sediment, nitrogen, and pollutant loads. Increasing water temperatures and intensifying droughts can decrease lake mixing, reduce oxygen in bottom waters, and increase the length of time pollutants remain in water bodies.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document Bales et al.,(2012), Ch. 8: Ecosystems and Biodiversity, 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 (Bales et al. 2012; Coats et al. 2006; Sahoo and Schladow 2008; Sahoo et al. 2011; Schneider and Hook 2010), and may be eliminated in shallow lakes. Increased stratification reduces mixing, resulting in reduced oxygen in bottom waters. Oxygen solubility decreases as temperature increases (Wetzel 2001). 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 result in a degraded aquatic ecosystem. Major precipitation events and resultant water flows increase watershed pollutant scour and thus increase pollutant loads. Models predict and observations confirm that continued warming will have increasingly negative effects on lake water quality and ecosystem health (Sahoo and Schladow 2008; Sahoo et al. 2011). Although not yet observed, warming lake water has the potential to cross important temperature thresholds, allowing invasion by non-native species. In the Mississippi drainage basin, increased precipitation has resulted in increased nitrogen loads contributing to hypoxia in the Gulf of Mexico (Justic et al. 2005; McIsaac et al. 2002). Fluxes of mineral weathering products (e.g., Ca, Mg, Na, and Si) have also been shown to increase in response to higher discharge (Godsey et al. 2009). 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 (Osterkamp and Hupp 2010). 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% (Nearing et al. 2005).
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/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 this, other 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. However, projected declines in

	summer flows mean that there will be less water to heat in the months when the water is warmest (Cayan et al. 2001; Leppi et al. 2011).
Assessment of confidence based on evidence	Based on the evidence base: 1) Confidence is **very high** that lake temperatures will increase and dissolved oxygen will decrease due to climate change. Confidence is **very high** that temperatures will increase and dissolved oxygen will decline in many streams; however, place to place (among streams and along streams) differences are likely. 2) Confidence is **high** there will be decreases in mixing in some lakes and reservoirs due to climate change. 3) Confidence is **medium** that sediment, nitrogen, and pollutant loads will increase due to climate change.

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

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: See key message #1.

Key message #7/10	**In the Southwest, parts of the Southeast, the Great Plains, and the islands of the Caribbean and the Pacific, including the state of Hawai‘i, surface and groundwater supplies are already affected and expected to be reduced by declining runoff and groundwater recharge trends, increasing the likelihood of water shortages for many off-stream and in-stream water uses.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document, Bales. et al. (2012), Ch. 2: Our Changing Climate, Ch. 17: Southeast and Caribbean, Ch. 19: Great Plains, Ch. 20: Southwest, Ch. 23: Hawaii and Pacific Islands (2013), Garfin et al. (2012), 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 U.S. has been changing toward dryer conditions (Barnett and Pierce 2009; Georgakakos et al. 2010; Hirsch and Ryberg 2012; Rajagopalan et al. 2009; Ch. 17: Southeast). Furthermore, paleo-climate 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 (Meko et al. 2007). **Projected Trends and Consequences:** GCM projections indicate that this trend is likely to persist, with runoff reductions in the range 10-20% over the next 50 years, and intensifying droughts (Cayan et al. 2010). The drying water cycle is expected to affect all human and ecological water uses, especially in the Southwest. This region extends over six states (Colorado, New Mexico, Utah, Arizona, Nevada, and California) and is inhabited by more than 60 million people. 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 35% by 2060 under the A2 climate scenario (Foti et al. 2012). Decreasing runoff and groundwater recharge are expected to reduce surface and groundwater supplies (Earman and Dettinger 2011), increasing the annual risk of water shortages from 25 to 50% by 2060 (Rajagopalan et al. 2009). 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 (Rajagopalan et al. 2009). Rising water temperatures and longer low flow periods may make thermoelectric water withdrawals unreliable, and aquatic and riparian ecosystems susceptible to degraded habitats and invasive, non-native species (Backlund et al. 2008). Such impacts and consequences have been identified for several Southwest river basins including the Colorado (U.S. Bureau of Reclamation 2011c), Rio Grande (Ward et al. 2006), and Sacramento-San Joaquin (Brekke et al. 2009b; Connell-Buck et al. 2012; Georgakakos et al. 2012).
New information and remaining uncertainties	The drying climate trend observed in southern California, 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, at some future time, it will reverse direction. However, the rate of change and the comparative GCM assessment results with and without historical

	CO2 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(Georgakakos and Zhang 2011; U.S. Bureau of Reclamation 2011a) provides confidence that these projections are robust.
Assessment of confidence based on evidence	Confidence is **high** that in the Southwest, the Southeast, the Great Plains, and the islands of the Caribbean and the Pacific, including the state of Hawai'i, surface and groundwater supplies will be affected by declining runoff and uncertain groundwater recharge changes, increasing the risk of water shortages for many groundwater, off-stream, and in-stream water uses.

1

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

2

1 **Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)**

2 **Key Message Process:** See key message #1.

Key message #8/10	**Increasing flooding risk affects human safety and health, property, infrastructure, economy, 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 (Bales. et al, 2012), the the chapters Our Changing Climate, Northwest, Great Plains, Midwest, Northeast and multiple others (2013), 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:** Annual peak-flow records from 200 USGS streamflow gaging stations measuring flows from catchments that are minimally influenced by upstream water uses, diversions, impoundments, or land-use changes (from the USGS HCDN network), with more than 85 years of records, were the basis for careful national-scale flood-trend analysis (Hirsch and Ryberg 2012), providing the observational basis for this message. Additional observational evidence that heavy precipitation events are increasing in the northern states can be found in Ch. 2: Our Changing Climate. **Projected Trends:** Projections of future flood-frequency changes result from detailed hydrologic (Das et al. 2012; Raff et al. 2009; Walker et al. 2011) and hydraulic models of rivers that simulate responses to projected precipitation and temperature changes from climate models. **Consequences:** Floods already impact 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: Coastal Zone). 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 (Ebi et al. 2006; Kessler 2011; Patz et al. 2000; Wright et al. 2012) (see Ch. 11 Urban and Infrastructure), from waterborne disease that can persist well beyond the occurrence of extreme precipitation (Curriero et al. 2001) (see Ch. 9: Human Health), from water outages associated with infrastructure failures that cause decreased sanitary conditions (Huang et al. 2011), and also from ecosystem changes that can affect airborne diseases (Ziska et al. 2008; Ch. 8: Ecosystems and Biodiversity).
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 exacerbates this effect. This trend is broadly expected to increase in frequency under general warming trends, particularly in mountainous catchments.

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, upstream managements). Consequently, flood frequency changes may not be 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 flooding risk will increase, potentially affecting human safety and health, property, infrastructure, economy, and ecology in most regions across the U.S.

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

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: See key message #1.

Key message #9/10	**In most U.S. regions, water resources managers and planners will encounter new risks, vulnerabilities, and opportunities that may not be properly managed with existing practices.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document (Bales et al. 2012), NCA chapters (2013), 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. South Florida's groundwater supplies, ecology, and coastal communities are becoming increasingly vulnerable to sea level rise and drought impacts, but many GCMs cannot capture the regional climate trends (Obeysekera et al. 2011). The Sacramento – San Joaquin Bay Delta is already threatened by flooding, sea water intrusion, and changing needs for environmental, municipal, and agricultural water uses. Managing these risks and uses requires re-assessment 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 (NRC 2010, 2011b, 2012). Given the projected climate changes in this area (Cayan et al. 2008; Cloern et al. 2011), adherence to historical management and planning practices may not be a long-term viable option (Brekke et al. 2009b; Georgakakos et al. 2012), but the supporting science is not yet fully actionable (Milly et al. 2008), 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, but it has been fraught by litigious conflicts for more than 20 years. An inclusive stakeholder coalition offers new hope that a shared vision plan may still be formulated, but climate change presents new stresses and uncertainties (Georgakakos et al. 2010). Intense water management challenges have also been reported in the Southwest (Barnett and Pierce 2009; Rajagopalan et al. 2009), Northwest (Vano et al. 2010a; Vano et al. 2010b), Great Plains, and Great Lakes (International Upper Great Lakes Study Board 2012).
New information and remaining uncertainties	Climate, demand, land use, and demographic changes 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, benefits, and vulnerabilities that may not be properly managed with existing practices.

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

Chapter 3: Water Resources (Climate Change Impacts on the Water Cycle)

Key Message Process: See key message #1.

Key message #10/10	**Increasing resilience and enhancing adaptive capacity are useful strategies for water resources management and planning in the face of climate change. Challenges include: competing demands for water; a variety of institutional constraints; lack of scientific information or access to it; considerable scientific and economic uncertainties; inadequate information useful for practical applications; and difficulties in engaging stakeholders.**
Description of evidence base	The key message and supporting chapter text summarizes extensive evidence documented in the inter-agency prepared foundational document (Bales et al. 2012), Garfin et al.(2012), 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 key message is a restatement of conclusions derived from the peer-reviewed literature as cited in the reference list for the chapter. The two parts of the key message are described separately below. Increasing resilience and adaptive capacity is a crucial and low-regrets strategy for water resources management and planning in the face of climate change. Water utilities appear to be benefiting from various efforts to assess their potential vulnerabilities and long term planning options for responding to climate change (EPA 2010). Building human and social capital through networks and partnerships is identified as both major assets and continued needs; building networks of colleagues is identified as important sources of accessible, relevant and trusted information (Lackstrom et al. 2012). Building adaptive capacity ultimately increases the ability to develop and implement adaptation strategies and is considered a no-regrets strategy (Bales et al. 2012). A very useful strategy for risk management in an uncertain future “is to build the capacity to address climate change impacts in the future, including improving understanding of the problem, educating and building awareness among citizens, establishing collaborative ties with others, improving data sharing and communication, setting up stakeholder engagement processes, and developing funding mechanism” (Liverman et al. 2012). Challenges include competing water uses; considerable uncertainties; insufficient actionable science ready for practical application; the challenges of stakeholder engagement; and a lack of agreement on alternative paradigms to “post-stationarity” on which to base water laws, regulations, and policies. Additional support for this part of this key message is as follows: Climate change will stress the current state-based water allocation systems and create new conflicts between consumptive and non-consumptive, especially environmental, uses (Tarlock 2010). With a very few exceptions, water users have no right to take water other than in accordance with state law. Laws differ from the East’s riparianism and regulated riparianism, to the West’s prior appropriation doctrines, with differing ability to accommodate the stress of climate change (Adler 2010; Hall and Abrams 2010). Adaptation management will have to cope with many layers of government, because many adaptation problems and strategies will be local in implementation while

	adaptation principles and goals may arise and be organized at larger state, watershed, regional or national scales. Key principles suggested for adaption legal regimes are to: 1) increase monitoring and study; 2) eliminate or reduce non-climate change stress and promote resilience; 3) encompasses immediate, "no regrets" changes; 4) plan for the long term increased coordination across media, sectors, interests, and governments; 5) promote principled flexibility in regulatory goals and natural resource management, and 6) accept that adaptation may require loss (Craig 2010). There are many examples of federal, state and local adaptation efforts including interstate institutions (Hall and Abrams 2010), regionalization of supplies (Heimlich et al. 2009), adaptive management of existing supply systems (Short et al. 2012; Solecki and Rosenzweig 2012), decision support planning methods (Adams et al. 2012), initiatives to balance instream and off stream benefits (Hall and Abrams 2010; Tarlock 2010; U.S. Bureau of Reclamation 2012; Washington State Department of Ecology 2011) and innovative international engagement with Mexico (IBWC 2010; Megdal and Scott 2011; Transboundary Aquifer Assessment Act 2009; Vickery 2009; Wilder et al. 2012). (see Ch. 28: Adaptation).
New information and remaining uncertainties	Jurisdictions at the state and local level are addressing climate change related legal and institutional issues on an individual basis. An on-going assessment of these efforts may show more agreement and practical applications.
Assessment of confidence based on evidence	Confidence is **very high** that increasing resilience and adaptive capacity is a useful strategy for water resources management and planning in the face of climate change. Confidence is **very high** that there are challenges to realizing increased resilience and adaptive capacity.

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

References

Adams, A., D. Behar, K. Brooks, P. Fleming, and L. Stickel, 2012: Water Utility Climate Alliance's Technical Input to the 2012 NCA

Adelsman, H. and J. Ekrem, 2012: Ch. 7 Water Resources. *Preparing for a Changing Climate: Washington State's Integrated Climate Response Strategy* L. Geller, Ed., State of Washington, Department of Ecology, 99-120. [Available online at https://fortress.wa.gov/ecy/publications/publications/1201004i.pdf]

Adler, R.W., 2010: Climate Change and the Hegemony of State Water Law. *Stanford Environmental Law Journal*, **29,** 283

Backlund, A., A. Janetos, D. Schimel, J. Hatfield, K. Boote, P. Fay, L. Hahn, C. Izaurralde, B.A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thomson, D. Wolfe, M.G. Ryan, S.R. Archer, R. Birdsey, C. Dahm, L. Heath, J. Hicke, D. Hollinger, T. Huxman, G. Okin, R. Oren, J. Randerson, W. Schlesinger, D. Lettenmaier, D. Major, L. Poff, S. Running, L. Hansen, D. Inouye, b.P. Kelly, L. Meyerson, b. Peterson, and R. Shaw, 2008: *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research.* Vol. SAP 4.3, U.S. Environmental Protection Agency, 362 pp.

Bales, J., D. Raff, C. McNutt, M. Brewer, T. Johnson, and T. Brown, 2012: Water Resources Sector Technical Input Report in Support of the U.S. Global Change Research Program, National Climate Assessment, 2013

Balling, J.R.C. and P. Gober, 2007: Climate variability and residential water use in the city of Phoenix, Arizona. *Journal of Applied Meteorology and Climatology*, **46,** 1130-1137

BAMS, cited 2012: State of the Climate Reports. NCDC. [Available online at http://www.ncdc.noaa.gov/bams-state-of-the-climate/]

Barnett, T.P. and D.W. Pierce, 2009: Sustainable water deliveries from the Colorado River in a changing climate. *Proceedings of the National Academy of Sciences of the United States of America*, **106,** 7334-7338 doi: 10.1073/pnas.0812762106, [Available online at http://www.pnas.org/content/106/18/7334.short]

Barnett, T.P., D.W. Pierce, H.G. Hidalgo, C. Bonfils, B.D. Santer, T. Das, G. Bala, A.W. Wood, T. Nozawa, A.A. Mirin, D.R. Cayan, and M.D. Dettinger, 2008: Human-induced changes in the hydrology of the western United States. *Science*, **319,** 1080-1083 doi: 10.1126/science.1152538, [Available online at http://www.sciencemag.org/cgi/content/abstract/1152538]

Barsugli, J., C. Anderson, J.B. Smith, and J.M. Vogel, 2009: Options for improving climate modeling to assist water utility planning for climate change. Final Report., Water Utility Climate Alliance. [Available online at http://www.wucaonline.org/assets/pdf/pubs_whitepaper_120909.pdf]

Basagic, H.J. and A.G. Fountain, 2011: Quantifying 20th Century Glacier Change in the Sierra Nevada, California. *Arctic, Antarctic, and Alpine Research*, **43,** 317-330 doi: 10.1657/1938-4246-43.3.317

Beltaos, S. and T. Prowse, 2009: River-ice hydrology in a shrinking cryosphere. *Hydrological processes*, **23,** 122-144 doi: 10.1002/hyp.7165

Berry, L., 2012: Florida Water Management and Adaptation in the Face of Climate Change: A white paper on climate change and Florida's resources. .

Bonfils, C., B.D. Santer, D.W. Pierce, H.G. Hidalgo, G. Bala, T. Das, T.P. Barnett, D.R. Cayan, C. Doutriaux, A.W. Wood, A. Mirin, and T. Nozawa, 2008: Detection and attribution of temperature changes in the mountainous western United States. *Journal of Climate*, **21,** 6404-6424 doi: 10.1175/2008JCLI2397.1 [Available online at http://journals.ametsoc.org/doi/abs/10.1175/2008JCLI2397.1]

Brekke, L.D., 2011: *Addressing Climate Change in Long-Term Water Resources Planning and Management: User Needs for Improving Tools and Information.* DIANE Publishing.

Brekke, L.D., J.D. Anderson, M.D. Dettinger, A. Harrison, E.P. Maurer, T. Pruitt, and E.S. Townsley, 2009b: Assessing reservoir operations risk under climate change. *Water resources research*, **45,** 16 doi: 10.1029/2008WR006941 [Available online at http://www.agu.org/pubs/crossref/2009/2008WR006941.shtml]

Brekke, L.D., J.E. Kiang, J.R. Olsen, R.S. Pulwarty, D.A. Raff, D.P. Turnipseed, R.W. Webb, and K.D. White, 2009a: *Climate change and water resources management: a federal perspective.* DIANE Publishing.

Brikowski, T.H., 2008: Doomed reservoirs in Kansas, USA? Climate change and groundwater mining on the Great Plains lead to unsustainable surface water storage. *Journal of Hydrology*, **354,** 90-101 doi: 10.1016/j.jhydrol.2008.02.020

Brown, C., 2010: The end of reliability. *Journal of Water Resources Planning and Management*, **136,** 143-145 doi: 10.1061/(ASCE)WR.1943-5452.65

Brown, T.C., 2000: Projecting US freshwater withdrawals. *Water resources research*, **36,** 769-780

Brown, T.C., R. Foti, and J.A. Ramirez, 2012: Projecting fresh water withdrawals in the United States under a changing climate. *Water resources research*, **in review**

Carpenter, A., 2011: Selected Climate-Change Related Water Sector References, Technical Input 2011-0057 to the National Climate Assessment, 2012.

Cayan, D.R., S.A. Kammerdiener, M.D. Dettinger, J.M. Caprio, and D.H. Peterson, 2001: Changes in the onset of spring in the western United States. *Bulletin of the American Meteorological Society*, **82,** 399-416 doi: 10.1175/1520-0477(2001)082<0399:citoos>2.3.co;2, [Available online at <Go to ISI>://WOS:000167228500001]

Cayan, D.R., P.D. Bromirski, K. Hayhoe, M. Tyree, M.D. Dettinger, and R.E. Flick, 2008: Climate change projections of sea level extremes along the California coast. *Climatic Change*, **87,** 57-73 doi: 10.1007/s10584-007-9376-7, [Available online at http://dx.doi.org/10.1007/s10584-007-9376-7]

Cayan, D.R., T. Das, D.W. Pierce, T.P. Barnett, M. Tyree, and A. Gershunov, 2010: Future dryness in the southwest US and the hydrology of the early 21st century drought. *Proceedings of* *the National Academy of Sciences of the United States of America*, **107,** 21271-21276 doi: 10.1073/pnas.0912391107

Cayan, D.et al., 2012: Ch. 6: The Southwest climate of the future—Projections of mean climate. *Assessment of Climate Change in the Southwest United States: A Technical Report Prepared for the U.S. National Climate Assessment*, G. Garfin, Ed., 153-173

Chang, S.W., T. Prabhakar Clement, M.J. Simpson, and K.K. Lee, 2011: Does sea-level rise have an impact on saltwater intrusion? *Advances in Water Resources*, **34,** 1283-1291 doi: 10.1016/j.advwatres.2011.06.006

City of New York, 2012: PlaNYC Progress Report 2012. A Greener, Greater New York, City of New York. [Available online at http://nytelecom.vo.llnwd.net/o15/agencies/planyc2030/pdf/PlaNYC_Progress_Report_2012_Web.pdf]

Cloern, J.E., N. Knowles, L.R. Brown, D. Cayan, M.D. Dettinger, T.L. Morgan, D.H. Schoellhamer, M.T. Stacey, M. van der Wegen, R.W. Wagner, and A.D. Jassby, 2011: Projected Evolution of California's San Francisco Bay-Delta-River System in a Century of Climate Change. *PLoS ONE*, **6,** e24465 doi: 10.1371/journal.pone.0024465

Coats, R., J. Perez-Losada, G. Schladow, R. Richards, and C. Goldman, 2006: The warming of lake Tahoe. *Climatic Change*, **76,** 121-148 doi: 10.1007/s10584-005-9006-1

Connell-Buck, C.R., J. Medellín-Azuara, J.R. Lund, and K. Madani, 2012: Adapting California’s water system to warm vs. dry climates. *Climatic Change*, **109,** 133-149 doi: 10.1007/s10584-011-0302-7

Craig, R., 2010: 'Stationarity is Dead'-Long Live Transformation: Five Principles for Climate Change Adaptation Law. *Harvard Environmental Law Review*, **34,** 9-75, [Available online at http://ssrn.com/abstract=1357766]

Curriero, F.C., J.A. Patz, J.B. Rose, and S. Lele, 2001: The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948–1994. *American Journal of Public Health*, **91,** 1194-1199 doi: 10.2105/AJPH.91.8.1194

Das, T., M.D. Dettinger, D.R. Cayan, and H.G. Hidalgo, 2012: Potential increase in floods in California’s Sierra Nevada under future climate projections. *Climatic Change*, **109,** 71-94 doi: 10.1007/s10584-011-0298-z

David, E.L., 1990: Manufacturing and mining water use in the United States, 1954-83. *National Water Summary 1987 - Hydrologic events and water supply and use* United States Government Printing

Dawson, J., D. Scott, and G. McBoyle, 2009: Climate change analogue analysis of ski tourism in the northeastern USA. *Climate Research*, **39,** 1-9

DeGaetano, A.T., 2009: Time-Dependent Changes in Extreme-Precipitation Return-Period Amounts in the Continental United States. *Journal of Applied Meteorology and Climatology*, **48,** 2086-2099 doi: 10.1175/2009jamc2179.1

Diaz, H.F., P.S. Chu, and J.K. Eischeid, 2005: Rainfall changes in Hawaii during the last century. *16th Conference on Climate Variability and Change*, San Diego, CA.

DOC, cited 2012: ITA. U.S. Department of Commerce. [Available online at http://www.tinet.ita.doc.gov/pdf/2010-year-in-review.pdf]

DOI, cited 2012: National Atlas. U.S. Department of the Interior. [Available online at http://www.nationalatlas.gov]

DOT, 2011: National Transportation Statistics, Bureau of Transportation Statistics, U.S. Department of Transportation, Research and Innovative Technology Administration, Bureau of Transportation Statistics. [Available online at www.bts.gov/publications/national_transportation_statistics/]

——, 2012: Climate Impacts and Transportation: Technical Input Report for the National Climate Assessment. DOT OST/P-33 (Draft, February 2012).

Earman, S. and F.M. Phillips, 2003: Groundwater Recharge and Movement in the Central Chiricahua Mountains, Arizona. *The Geological Society of America 2003 Annual Meeting*, Seattle, Washington.

Earman, S. and M. Dettinger, 2011: Potential impacts of climate change on groundwater resources-a global review. *Journal of water and climate change*, **2,** 213-229

Earman, S., A.R. Campbell, F.M. Phillips, and B.D. Newman, 2006: Isotopic exchange between snow and atmospheric water vapor: Estimation of the snowmelt component of groundwater recharge in the southwestern United States. *Journal of Geophysical Research*, **111,** 18 doi: 10.1029/2005JD006470

Ebi, K.L., D.M. Mills, J.B. Smith, and A. Grambsch, 2006: Climate Change and Human Health Impacts in the United States: An Update on the Results of the U.S. National Assessment. *Environmental Health Perspectives*, **114,** 1318-1324 doi: 10.1289/ehp.8880

EIA, 2011: Net Generation by Energy Source, U.S. Energy Information Administration

Elsner, M.M., L. Cuo, N. Voisin, J.S. Deems, A.F. Hamlet, J.A. Vano, K.E.B. Mickelson, S.Y. Lee, and D.P. Lettenmaier, 2010: Implications of 21st century climate change for the hydrology of Washington State. *Climatic Change*, **102,** 225-260 doi: 10.1007/s10584-010-9855-0

EPA, 2010: Climate Change Vulnerability Assessments: A Review of Water Utility Practices. U.S. EPA Report 800-R-10-001 U.S. Environmental Protection Agency.

EPA 2011: Climate change vulnerability assessments: four case studies of water utility practices, U.S. Environmental Protection Agency. [Available online at http://www.epa.gov/ncea.]

EPRI, 2011: Water Use for Electricity Generation and Other Sectors: Recent Changes (1985-2005) and Future Projections (2005-2030). 2011 Technical Report. http://my.epri.com/portal/server.pt?Abstract_id=000000000001023676

Falke, J.A., K.D. Fausch, R. Magelky, A. Aldred, D.S. Durnford, L.K. Riley, and R. Oad, 2011: The role of groundwater pumping and drought in shaping ecological futures for stream fishes in a dryland river basin of the western Great Plains, USA. *Ecohydrology*, **4,** 682-697 doi: 10.1002/eco.158

Famiglietti, J., M. Lo, S. Ho, J. Bethune, K. Anderson, T. Syed, S. Swenson, C. de Linage, and M. Rodell, 2011: Satellites measure recent rates of groundwater depletion in California's Central Valley. *Geophysical Research Letters*, **38,** L03403

Fan, Y., G. Miguez-Macho, C.P. Weaver, R. Walko, and A. Robock, 2007: Incorporating water table dynamics in climate modeling: 1. Water table observations and equilibrium water table simulations. *Journal of Geophysical Research*, **112,** 17 doi: 10.1029/2006JD008111

FEMA, 1994: A Unified National Program for Floodplain Management, The Federal Emergency Management Agency, Interagency Task Force on Floodplain Management

Flood, J.F. and L.B. Cahoon, 2011: Risks to Coastal Wastewater Collection Systems from Sea-Level Rise and Climate Change. *Journal of coastal research*, **27,** 652-660 doi: 10.2112/JCOASTRES-D-10-00129.1

Foti, R., T.C. Brown, and J.A. Ramirez, 2012: *Vulnerability of future United States water supply to shortage.* U.S. Forest Service.

Foti, R., J.A. Ramirez, and T.C. Brown, 2012a: Vulnerability of future United States water supply to shortage

Fritze, H., I.T. Stewart, and E.J. Pebesma, 2011: Shifts in Western North American snowmelt runoff regimes for the recent warm decades. *Journal of Hydrometeorology*, **12,** 989-1006 doi: 10.1175/2011JHM1360.1

Frumhoff, P.C., J.J. McCarthy, J.M. Melillo, S.C. Moser, D.J. Wuebbles, C. Wake, and E. Spanger-Siegfried, 2008: An integrated climate change assessment for the Northeast United States. *Mitigation and Adaptation Strategies for Global Change*, **13,** 419-423

Garfin, G., A. Jardine, R. Merideth, M. Black, and J. Overpeck, 2012: Assessment of Climate Change in the Southwest United States: a Technical Report Prepared for the U.S. National Climate Assessment. A report by the Southwest Climate Alliance, National Climate Assessment 2013: Tuscon, AZ, Southwest Climate Alliance, p. 805.

Georgakakos, A. and F. Zhang, 2011: Climate Change Scenario Assessment for ACF, OOA, SO, ACT, TN, and OSSS Basins in Georgia. Georgia Water Resources Institute (GWRI) Technical Report. Sponsored by NOAA, USGS, and the Georgia EPD; Georgia Institute of Technology, Georgia Institute of Technology 229 pp

Georgakakos, A.P., F. Zhang, and H. Yao, 2010: Climate Variability and Change Assessment for the ACF River Basin, Southeast US. Technical Input Report submitted to the National Climate Assessment 2013 321 pp

Georgakakos, K.P., N.E. Graham, A.P. Georgakakos, C. Spencer, M. Yao, and M. Kistenmacher, 2007: Integrated Forecast and Reservoir Management (INFORM) for Northern California: System Development and Initial Demondstration: PIER Final Project Report., California Energy Commission, Public Interest Energy Research 263 pp. [Available online at http://www.energy.ca.gov/pier/project_reports/CEC-500-2006-109.html]

Georgakakos, K.P., F.Y. Cheng, A.P. Georgakakos, N.E. Graham, M. Kistenmacher, C. Spencer, E. Shamir, and H. Yao, 2012: Value of adaptive water resources management in northern

California under climatic variability and change: Dynamic hydroclimatology. *Journal of Hydrology*, **412-413,** 47-65 doi: 10.1016/j.jhydrol.2011.04.032

Godsey, S.E., J.W. Kirchner, and D.W. Clow, 2009: Concentration–discharge relationships reflect chemostatic characteristics of US catchments. *Hydrological processes*, **23,** 1844-1864 doi: 10.1002/hyp.7315

Groisman, P.Y., R.W. Knight, and T.R. Karl, 2012: Changes in Intense Precipitation over the Central United States. *Journal of Hydrometeorology*, **13,** 47-66 doi: 10.1175/JHM-D-11-039.1 [Available online at http://journals.ametsoc.org/doi/abs/10.1175/JHM-D-11-039.1]

Groves, D.G., D. Yates, and C. Tebaldi, 2008: Developing and applying uncertain global climate change projections for regional water management planning. *Water resources research*, **44,** 16 doi: 10.1029/2008WR006964 [Available online at http://www.agu.org/pubs/crossref/2008/2008WR006964.shtml]

Gutowski, W.J., G.C. Hegerl, G.J. Holland, T.R. Knutson, L.O. Mearns, R.J. Stouffer, P.J. Webster, M.F. Wehner, and F.W. Zwiers, 2008: Causes of observed changes in extremes and projections of future changes. *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and US Pacific Islands. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*, T. R. Karl, G. A. Meehl, C. D. Miller, S. J. Hassol, A. M. Waple, and W. L. Murray, Eds., 81-116

Haley, M.M., 2001: Changing consumer demand for meat: the US example, 1970-2000. *Changing Structure of Global Food Consumption and Trade*, A. Regmi, Ed., U.S. Department of Agriculture, Economic Research Service, 41-48

Hall, M.H.P. and D.B. Fagre, 2003: Modeled climate-induced glacier change in Glacier National Park, 1850-2100. *BioScience*, **53,** 131-140 doi: 10.1641/0006-3568(2003)053[0131:MCIGCI]2.0.CO;2

Hall, N.D. and R.H. Abrams, 2010: Framing Water Policy in a Carbon Affected and Carbon Constrained Environment. *Natural Resources Journal*, **50,** 68-69, [Available online at http://works.bepress.com/noahhall/11]

Hamlet, A.F., P.W. Mote, M.P. Clark, and D.P. Lettenmaier, 2007: Twentieth-Century Trends in Runoff, Evapotranspiration, and Soil Moisture in the Western United States*. *Journal of Climate*, **20,** 1468-1486 doi: 10.1175/JCLI4051.1

Hanson, R.T., M.D. Dettinger, and M.W. Newhouse, 2006: Relations between climatic variability and hydrologic time series from four alluvial basins across the southwestern United States. *Hydrogeology Journal*, **14,** 1122-1146 doi: 10.1007/s10040-006-0067-7

Hanson, R.T., L.E. Flint, A.L. Flint, M.D. Dettinger, C.C. Faunt, D. Cayan, and W. Schmid, 2012: A method for physically based model analysis of conjunctive use in response to potential climate changes. *Water resources research*, **48,** 23 doi: 10.1029/2011WR010774

Hawkes, P.J., H. Moser, Ø.A. Arntsen, P. Gaufres, S. Mai, and K. White, 2010: Impacts of climate change on navigation. *Proceedings of the ICE - Civil Engineering*.

Heimlich, B. and F. Bloetscher, 2011: Effects of sea level rise and other climate change impacts on southeast Florida's water resources: Florida Water Resources Journal, 36-46

Heimlich, B.N., F. Bloetscher, D.E. Meeroff, and J. Murley, 2009: Southeast Florida's Resilient Water Resources: Adaptation to sea level rise and other climate change impacts, Florida Atlantic University. *Center for Urban and Environmental Solutions and Department of Civil Engineering, Environmental, and Geomatics Engineering*, [Available online at www.ces.fau.edu/files/projects/climate_change/SE_Florida_Resilient_Water_Resources.pdf]

Hidalgo, H., T. Das, M. Dettinger, D. Cayan, D. Pierce, T. Barnett, G. Bala, A. Mirin, A. Wood, and C. Bonfils, 2009: Detection and attribution of streamflow timing changes to climate change in the western United States. *Journal of Climate*, **22,** 3838-3855

Hirsch, R.M. and K.R. Ryberg, 2012: Has the magnitude of floods across the USA changed with global CO_2 levels? *Hydrological Sciences Journal*, **57,** 1-9 doi: 10.1080/02626667.2011.621895, [Available online at http://www.tandfonline.com/doi/abs/10.1080/02626667.2011.621895]

Hodgkins, G.A., R.W. Dudley, and T.G. Huntington, 2005: Changes in the number and timing of days of ice-affected flow on northern New England rivers, 1930–2000. *Climatic Change*, **71,** 319-340

Hoerling, M.P., M. Dettinger, K. Wolter, J. Lukas, J. Eischeid, R. Nemani, B. Liebmann, and K.E. Kunkel, 2012: Evolving Weather and Climate Conditions of the Southwest United States. *Assessment of Climate Change in the Southwest United States: a Technical Report Prepared for the U.S. National Climate Assessment*, G. Garfin, A. Jardine, R. Merideth, M. Black, and J. Overpeck, Eds.

Hostetler, S. and E. Small, 1999: Response of north American freshwater lakes to simulated future climates1. *JAWRA Journal of the American Water Resources Association*, **35,** 1625-1637

Huang, L.Y., Y.C. Wang, C.M. Liu, T.N. Wu, C.H. Chou, F.C. Sung, and C.C. Wu, 2011: Water outage increases the risk of gastroenteritis and eyes and skin diseases. *BMC public health*, **11,** 726

IBWC, 2010: International Boundary and Water Commission (IBWC) Minute 317 "Conceptual Framework for U.S. Mexico Discussions on Colorado River Cooperative Actions," signed on June 17, 2010.

International Upper Great Lakes Study Board, 2012: Lake Superior Regulation: Addressing Uncertainty in Upper Great Lakes Water Levels. Final Report to the International Joint Commission pp. 215 pp

IPCC, 2007: Summary for Policymakers. *Climate Change 2007: The Physical Science Basis*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, Eds., Cambridge University Press, 1-18. [Available online at http://ds.heavyoil.utah.edu/dspace/bitstream/123456789/9951/1/ClimateChange2007-1.pdf]

Jeffcoat, S., D. Baughman, and P.M. Thomas, 2009: Total water management strategies for utility master planning. *Journal American Water Works Association*, **101,** 56-64

Justic, D., N.N. Rabalais, and R.E. Turner, 2005: Coupling between climate variability and coastal eutrophication: Evidence and outlook for the northern Gulf of Mexico. *Journal of Sea*

Research, **54,** 25-35 doi: 10.1016/j.seares.2005.02.008, [Available online at <Go to ISI>://WOS:000230298200004]

Karl, T.R. and R.W. Knight, 1998: Secular Trends of Precipitation Amount, Frequency, and Intensity in the United States. *Bulletin of the American Meteorological Society*, **79,** 231-241

Kaushal, S.S., G.E. Likens, N.A. Jaworski, M.L. Pace, A.M. Sides, D. Seekell, K.T. Belt, D.H. Secor, and R.L. Wingate, 2010: Rising stream and river temperatures in the United States. *Frontiers in Ecology and the Environment*, **8,** 461-466 doi: 10.1890/090037, [Available online at <Go to ISI>://000284159700016]

Kenny, J.F., N.L. Barber, S.S. Hutson, K.S. Linsey, J.K. Lovelace, and M.A. Maupin, 2009: Estimated use of water in the United States in 2005 52 pp

Kessler, R., 2011: Stormwater Strategies: Cities Prepare Aging Infrastructure for Climate Change. *Environmental Health Perspectives*, **119,** a514

Kirshen, P., M. Ruth, and W. Anderson, 2008: Interdependencies of urban climate change impacts and adaptation strategies: a case study of Metropolitan Boston USA. *Climatic Change*, **86,** 105-122

Knowles, N., M.D. Dettinger, and D.R. Cayan, 2006: Trends in Snowfall Versus Rainfall in the Western United States. *Journal of Climate*, **19,** 4545-4559

Konikow, L.F., 2011: Contribution of global groundwater depletion since 1900 to sea-level rise. *Geophysical Research Letters*, **38** doi: L17401 10.1029/2011gl048604

Kundzewicz, Z.W., S. Budhakooncharoen, A. Bronstert, H. Hoff, D. Lettenmaier, L. Menzel, and R. Schulze, 2002: Coping with variability and change: floods and droughts. Wiley Online Library, 263-274.

Kunkel, K.E., L. E. Stevens, S. E. Stevens, E. Janssen, and D. Wuebbles, 2012a: Climate of the Contiguous United States, U.S. National Oceanic and Atmospheric Administration, National Climatic Data Center (in press)

Lackstrom, K., K. Dow, B. Haywood, A. Brennan, N. Kettle, and A. Brosius, 2012: Engaging Climate-sensitive sectors in the Carolinas. Technical Report: CISA-2012-03: Carolinas Integrated Sciences and Assessments 180 pp

Leppi, J.C., T.H. DeLuca, S.W. Harrar, and S.W. Running, 2011: Impacts of climate change on August stream discharge in the Central-Rocky Mountains. *Climatic Change*, 1-18

Liu, F., M.W. Williams, and N. Caine, 2004: Source waters and flow paths in an alpine catchment, Colorado Front Range, United States. *Water resources research*, **40,** W09401

Liu, Y., R. Parinussa, W. Dorigo, R. De Jeu, W. Wagner, A. Van Dijk, M. McCabe, and J. Evans, 2011: Developing an improved soil moisture dataset by blending passive and active microwave satellite-based retrievals. *Hydrology and Earth System Sciences*, **15,** 425

Liverman, D., S. Moser, P. Weiland, L. Dilling, M. Boykoff, H. Brown, D. Busch, E. Gordon, C. Greene, E. Holthaus, D. Niemeier, S. Pincetl, J. Steenburgh, and V. Tidwell, 2012: Climate Choices for a Sustainable Southwest. *Assessment of Climate Change in the Southwest United States: a Technical Report Prepared for the U.S. National Climate Assessment. A report by the*

Southwest Climate Alliance, G. Garfin, A. Jardine, R. Merideth, M. Black, and J. Overpeck, Eds., Southwest Climate Alliance, pp. 684-734

Loarie, S.R., P.B. Duffy, H. Hamilton, G.P. Asner, C.B. Field, and D.D. Ackerly, 2009: The velocity of climate change. *Nature*, **462,** 1052-1055

Luce, C. and Z. Holden, 2009: Declining annual streamflow distributions in the Pacific Northwest United States, 1948–2006. *Geophysical Research Letters*, **36** doi: 10.1029/2009GL039407

Manning, A.H. and D.K. Solomon, 2003: Using noble gases to investigate mountain-front recharge. *Journal of Hydrology*, **275,** 194-207

Manning, A.H., J.F. Clark, S.H. Diaz, L.K. Rademacher, S. Earman, and L. Niel Plummer, 2012: Evolution of groundwater age in a mountain watershed over a period of thirteen years. *Journal of Hydrology*

Markstrom, S.L., L.E. Hay, C. Ward-Garrison, J.C. Risley, W.A. Battaglin, D.M. Bjerklie, and J.F. Walker, 2011: An integrated watershed scale response to climate change for selected basins across the United States: U.S. Geological Survey Scientific Investigations Report

Maurer, E., H. Hidalgo, T. Das, M. Dettinger, and D. Cayan, 2010: Assessing climate change impacts on daily streamflow in California: the utility of daily large-scale climate data. *Hydrology and Earth Systems Sciences Discussions*, **7,** 1209-1243

Maxwell, R.M. and S.J. Kollet, 2008: Interdependence of groundwater dynamics and land-energy feedbacks under climate change. *Nature Geoscience*, **1,** 665-669

McCabe, G.J. and D.M. Wolock, 2011: Independent effects of temperature and precipitation on modeled runoff in the conterminous United States. *Water resources research*, **47,** W11522

McCabe, G.J., M.P. Clark, and L.E. Hay, 2007: Rain-on-snow events in the western United States. *Bulletin of the American Meteorological Society*, **88,** 319-328

McIsaac, G.F., M.B. David, G.Z. Gertner, and D.A. Goolsby, 2002: Relating net nitrogen input in the Mississippi River basin to nitrate flux in the lower Mississippi River: A comparison of approaches. *Journal of Environmental Quality*, **31,** 1610-1622, [Available online at <Go to ISI>://WOS:000178156800022]

McVicar, T.R., M.L. Roderick, R.J. Donohue, L.T. Li, V.N. T.G., A. Thomas, J. Grieser, D. Jhajharia, Y. Himri, N.M. Mahowald, A.V. Mescherskaya, A.C. Kruger, S. Rehman, and Y. Dinpashoh, 2012 Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. *Journal of Hydrology***,** 416-417; 182-205 doi: 10.1016/j.jhydrol.2011.10.024

Means, E., M. Laugier, J.A. Daw, and D.M. Owen, 2010b: Impacts of climate change on infrastructure planning and design: Past practices and future needs. *Journal of the American Water Works Association*, **102**

Means, E., M. Laugier, J. Daw, L. Kaatz, and M. Waage, 2010a: Decision support planning methods: Incorporating climate change uncertainties into water planning, Water Utility Alliance. [Available online at http://www.wucaonline.org/assets/pdf/pubs_whitepaper_012110.pdf]

Megdal, S.B. and C.A. Scott, 2011: The Importance of Institutional Asymmetries to the Development of Binational Aquifer Assessment Programs: The Arizona-Sonora Experience. *Water*, **3**

Meko, D.M., C.A. Woodhouse, C.A. Baisan, T. Knight, J.J. Lukas, M.K. Hughes, and M.W. Salzer, 2007: Medieval drought in the upper Colorado River Basin. *Geophysical Research Letters*, **34,** 10705

Millerd, F., 2011: The Potential Impact of Climate Change on Great Lakes International Shipping. *Climatic Change*, **104,** 629-652

Milly, P.C.D., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer, 2008: Stationarity Is Dead: Whither Water Management? *Science*, **319,** 573-574 doi: 10.1126/science.1151915, [Available online at http://www.sciencemag.org/content/319/5863/573.short]

Mishra, V. and D.P. Lettenmaier, 2011: Climatic trends in major US urban areas, 1950–2009. *Geophysical Research Letters*, **38,** L16401

Moser, S.C., R.E. Kasperson, G. Yohe, and J. Agyeman, 2008: Adaptation to climate change in the Northeast United States: opportunities, processes, constraints. *Mitigation and Adaptation Strategies for Global Change*, **13,** 643-659 doi: 10.1007/s11027-007-9132-3, [Available online at <Go to ISI>://000207969900014]

Mote, P.W., 2003: Trends in snow water equivcalent in the Pacific Northwest and their climatic causes

——, 2006: Climate-Driven Variability and Trends in Mountain Snowpack in Western North America*. *Journal of Climate*, **19,** 6209-6220

Mueller, B., S.I. Seneviratne, C. Jiminez, T. Corti, M. Hirschi, G. Balsamo, P. Ciais, P. Dirmeyer, J.B. Fisher, Z. Guo, M. Jung, F. Maignan, M.F. McCabe, R. Reichle, M. Reichstein, M. Rodell, J. Sheffield, A.J. Teuling, K. Wang, E.F. Wood, and Y. Zhang, 2011: Evaluation of global observations-based evapotranspiration datasets and IPCC AR4 simulations. *Geophysical Research Letters*, **38,** 7 doi: 10.1029/2010GL046230

NCDC, 2011.

Nearing, M., V. Jetten, C. Baffaut, O. Cerdan, A. Couturier, M. Hernandez, Y. Le Bissonnais, M. Nichols, J. Nunes, and C. Renschler, 2005: Modeling response of soil erosion and runoff to changes in precipitation and cover. *Catena*, **61,** 131-154

Nilsen, V., J. Lier, J. Bjerkholt, and O. Lindholm, 2011: Analysing urban floods and combined sewer overflows in a changing climate. *Journal of water and climate change*, **2,** 260-271

NOAA: Western Governors/NOAA MOU. [Available online at http://www.noaanews.noaa.gov/stories2011/pdfs/WGA_NOAA_MOU_6.30.11.pdf]

NRC, 2004: Ch. 3: Interactions of groundwater with climate *Groundwater Fluxes Across Interfaces*, National Academies Press, 32-41

——, 2010: A Scientific Assessment of Alternatives for Reducing Water Management Effects on Threatened and Endangered Fishes in California's Bay Delta. National Academies Press.

——, 2011a: America's Climate Choices, National Academy of Sciences Committee on America's Climate Choices

——, 2011b: A Review of the Use of Science and Adaptive Management in California's Draft Bay Delta Conservation Plan0309212316, National Research Council

——, 2012: Sustainable Water and Environmental Management in the California Bay-Delta, National Research Council

Obeysekera, J., M. Irizarry, J. Park, J. Barnes, and T. Dessalegne, 2011: Climate change and its implications for water resources management in south Florida. *Stochastic Environmental Research and Risk Assessment*, **25,** 495-516

Orlowsky, B. and S.I. Seneviratne, 2012: Global changes in extreme events: regional and seasonal dimension. *Climatic Change***,** 1-28

Osterkamp, W. and C. Hupp, 2010: Fluvial processes and vegetation--Glimpses of the past, the present, and perhaps the future. *Geomorphology*, **116,** 274-285

Paerl, H.W., J.D. Bales, L.W. Ausley, C.P. Buzzelli, L.B. Crowder, L.A. Eby, J.M. Fear, M. Go, B.L. Peierls, and T.L. Richardson, 2001: Ecosystem impacts of three sequential hurricanes (Dennis, Floyd, and Irene) on the United States' largest lagoonal estuary, Pamlico Sound, NC. *Proceedings of the National Academy of Sciences*, **98,** 5655-5660

Patz, J.A., M.A. McGeehin, S.M. Bernard, K.L. Ebi, P.R. Epstein, A. Grambsch, D.J. Gubler, P. Reither, I. Romieu, and J.B. Rose, 2000: The potential health impacts of climate variability and change for the United States: executive summary of the report of the health sector of the US National Assessment. *Environmental Health Perspectives*, **108,** 367

Payne, J.T., A.W. Wood, A.F. Hamlet, R.N. Palmer, and D.P. Lettenmaier, 2004: Mitigating the Effects of Climate Change on the Water Resources of the Columbia River Basin. *Climatic Change*, **62,** 233-256

Peterson, T., V. Golubev, and P.Y. Groisman, 1995: Evaporation losing its strength

Phillips, F.M., M.A. Walvoord, and E.E. Small, 2004: Effects of environmental change on groundwater recharge in the desert Southwest. *Groundwater Recharge in a Desert Environment: The Southwestern United States, Water Sci. Appl. Ser*, **9,** 273-294

Pielke, R.A., M.W. Downton, and J.Z.B. Miller, 2002: *Flood damage in the United States, 1926-2000: a reanalysis of National Weather Service estimates.* University Corporation for Atmospheric Research Boulder, CO.

Pierce, D.W., T.P. Barnett, H.G. Hidalgo, T. Das, C. Bonfils, B.D. Santer, G. Bala, M.D. Dettinger, D.R. Cayan, and A. Mirin, 2008: Attribution of declining western US snowpack to human effects. *Journal of Climate*, **21,** 6425-6444 doi: 10.1175/2008JCLI2405.1 [Available online at http://journals.ametsoc.org/doi/abs/10.1175/2008JCLI2405.1]

Poff, N.L., B.D. Richter, A.H. Arthington, S.E. Bunn, R.J. Naiman, E. Kendy, M. Acreman, C. Apse, B.P. Bledsoe, and M.C. Freeman, 2010: The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology*, **55,** 147-170

Prowse, T., K. Alfredsen, S. Beltaos, B. Bonsal, C. Duguay, A. Korhola, J. McNamara, R. Pienitz, W.F. Vincent, and V. Vuglinsky, 2011: Past and future changes in Arctic lake and river ice. *AMBIO: A Journal of the Human Environment*, **40,** 53-62

Pruski, F. and M. Nearing, 2002a: Climate-induced changes in erosion during the 21st century for eight US locations. *Water resources research*, **38,** 1298

——, 2002b: Runoff and soil-loss responses to changes in precipitation: a computer simulation study. *Journal of Soil and Water Conservation*, **57,** 7-16

Rademacher, L., J. Clark, and G. Hudson, 2002: Temporal changes in stable isotope composition of spring waters: Implications for recent changes in climate and atmospheric circulation. *Geology*, **30,** 139-142

Raff, D., T. Pruitt, and L. Brekke, 2009: A framework for assessing flood frequency based on climate projection information. *Hydrology and Earth System Sciences*, **13,** 2119

Raff, D.A., L.D. Brekke, K. Werner, and A. Wood, 2012: Short-term water management decisions: user needs for improved climate, weather, and hydrologic information (in review).

Rajagopalan, B., K. Nowak, J. Prairie, M. Hoerling, B. Harding, J. Barsugli, A. Ray, and B. Udall, 2009: Water supply risk on the Colorado River: Can management mitigate. *Water resources research*, **45,** W08201

Rockaway, T.D., P.A. Coomes, J. Rivard, and B. Kornstein, 2011: Residential water use trends in North America. *Journal AWWA - American Waterworks Association*, **103**

Roderick, M.L. and G.D. Farquhar, 2002: The cause of decreased pan evaporation over the past 50 years. *Science*, **298,** 1410-1411

Romanovsky, V.E., S.L. Smith, H.H. Christiansen, N.I. Shiklomanov, D.S. Drozdov, N.G. Oberman, A.L. Kholodov, and S.S. Marchenko, 2011: Permafrost: Arctic Report Card, Update for 2011. *Bulletin of the American Meteorological Society*, **in press,** 6, [Available online at http://www.arctic.noaa.reportcard/permafrost.html]

Rood, S.B., J. Pan, K.M. Gill, C.G. Franks, G.M. Samuelson, and A. Shepherd, 2008: Declining summer flows of Rocky Mountain rivers: Changing seasonal hydrology and probable impacts on floodplain forests. *Journal of Hydrology*, **349,** 397-410

Rose, T., G. Eaton, and A. Kersting, 2003: Hydrologic Resources Management Program and Underground Test Area Project FY2001-2002 Progress Report, Lawrence Livermore National Laboratory

Sahoo, G. and S. Schladow, 2008: Impacts of climate change on lakes and reservoirs dynamics and restoration policies. *Sustainability Science*, **3,** 189-199

Sahoo, G., S. Schladow, J. Reuter, and R. Coats, 2011: Effects of climate change on thermal properties of lakes and reservoirs, and possible implications. *Stochastic Environmental Research and Risk Assessment*, **25,** 445-456

Sahoo, G., S. Schladow, J. Reuter, R. Coats, M. Dettinger, J. Riverson, B. Wolfe, and M. Costa-Cabral, 2012: The response of Lake Tahoe to climate change. *Climatic Change*, 1-25

Schaller, M.F. and Y. Fan, 2009: River basins as groundwater exporters and importers: Implications for water cycle and climate modeling. *Journal of Geophysical Research*, **114,** D04103

Schneider, P. and S.J. Hook, 2010: Space observations of inland water bodies show rapid surface warming since 1985. *Geophysical Research Letters*, **37** doi: Artn L22405

Doi 10.1029/2010gl045059, [Available online at <Go to ISI>://000284702800003]

Scott, D. and S. Becken, 2010: Adapting to climate change and climate policy: progress, problems and potentials. *Journal of Sustainable Tourism*, **18,** 283-295

Shaw, S.B. and S.J. Riha, 2011: Assessing possible changes in flood frequency due to climate change in mid ‐ sized watersheds in New York State, USA. *Hydrological processes*, **25,** 2542-2550

Short, M.D., W.L. Peirson, G.M. Peters, and R.J. Cox, 2012: Managing Adaptation of Urban Water Systems in a Changing Climate. *Water resources management***,** 1-29

Smith, S., V. Romanovsky, A. Lewkowicz, C. Burn, M. Allard, G. Clow, K. Yoshikawa, and J. Throop, 2010: Thermal state of permafrost in North America: a contribution to the International Polar Year. *Permafrost and Periglacial Processes*, **21,** 117-135

Solecki, W. and C. Rosenzweig, 2012: U.S. Cities and Climate Change: Urban, Infrastructure, and Vulnerability Issues. Technical Report in Support of the National Climate Assessment.

State of Oregon, 2010: The Oregon Climate Change Adaptation Framework, State of Oregon, Environmental Quality Commission

Stromberg, J., S. Lite, and M. Dixon, 2010: Effects of stream flow patterns on riparian vegetation of a semiarid river: implications for a changing climate. *River research and applications*, **26,** 712-729

Su, Z., W. Dorigo, D. Fernández-Prieto, M. Van Helvoirt, K. Hungershoefer, R. de Jeu, R. Parinussa, J. Timmermans, R. Roebeling, and M. Schröder, 2010: Earth observation Water Cycle Multi-Mission Observation Strategy (WACMOS). *Hydrology and Earth Systems Sciences Discussions*, **7,** 7899-7956

Tarlock, D., 2010: How Well Can Water Law Adapt to the Potential Stresses of Global Climate Change? *The University of Denver Water Law Review*, **14,** 1-173

Taylor, R.G., B. Scanlon, P. Döll, M. Rodell, R. van Beek, Y. Wada, L. Longuevergne, M. Leblanc, J.S. Famiglietti, and M. Edmunds, 2012: Ground water and climate change. *Nature Climate Change*, **2** doi: 10.1038/NCLIMATE1744

Thomson, L.C., M.I. Escobar, and M.D. Dixon, 2010: Water management adaptations to prevent loss of spring-run Chinook salmon in California under climate change. . *Journal of Water Resources Planning and Management* doi: doi: 10.1061/(ASCE)WR.1943-5452.0000194.

Timm, O. and H.F. Diaz, 2009: Synoptic-Statistical Approach to Regional Downscaling of IPCC Twenty-First-Century Climate Projections: Seasonal Rainfall over the Hawaiian Islands*. *Journal of Climate*, **22,** 4261-4280

Timm, O.E., H. Diaz, T. Giambelluca, and M. Takahashi, 2011: Projection of changes in the frequency of heavy rain events over Hawaii based on leading Pacific climate modes. *Journal of Geophysical Research*, **116,** D04109

Transboundary Aquifer Assessment Act, 2009: Transboundary Aquifer Assessment Act (U.S. Public Law 109-448), signed December 22, 2009. *The intent is to provide scientific information useful to policymakers and water managers*

Trenberth, K., J. Overpeck, and S. Solomon, 2004: Exploring drought and its implications for the future. *EOS Transscripts, AGU*, **85,** 27

Trenberth, K.E. and A. Dai, 2007: Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering. *Geophysical Research Letters*, **34,** L15702

U.S. Bureau of Reclamation, 2011a: SECURE Water Act Section 9503(c) - Reclamation Climate Change and Water, Report to Congress. U.S. Bureau of Reclamation, Ed.

——, 2011b: SECURE Water Act Section 9503(c) – Reclamation Climate Change and Water, Report to Congress, U.S. Department of Interior, Bureau of Reclamation, , p. 226.

——, 2011b: West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections, Technical Memorandum No. 86-68210-2011-01. U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, 138.

——, 2011c: Interim Report No. 1, Colorado River Basin Water Supply and Demand Study, Status Report. ed. Colorado River Basin Water Supply and Demand Study Team.

——: Pacific Northwest Region and the Washington State Department of Ecology, Yakima River Basin Integrated Water Resource Plan Final Programmatic Environmental Impact Statement, March 2012. [Available online at http://www.ecy.wa.gov/programs/wr/cwp/YBIP.html]

U.S. Census Bureau: The 2012 Statistical Abstract: Arts, Recreation & Travel. [Available online at http://www.census.gov/compendia/statab/cats/arts_recreation_travel.html]

UC Davis and Tahoe Environmental Research Center, 2012: State of the Lake Report. [Available online at http://terc.ucdavis.edu/stateofthelake/StateOfTheLake2012.pdf]

Union of Concerned Scientists, 2009: Climate Change in the United States: The Prohibitive Costs of Inaction. [Available online at http://www.ucsusa.org/global_warming/science_and_impacts/impacts/climate-costs-of-inaction.html]

USFS, 2012: Future of America's forest and rangelands: 2010 Resources Planning Act assessment. General Technical Report WO-XX. . U. S. F. Service, Ed.

Van Vliet, M., F. Ludwig, J. Zwolsman, G. Weedon, and P. Kabat, 2011: Global river temperatures and sensitivity to atmospheric warming and changes in river flow. *Water resources research*, **47,** W02544

Vano, J.A., M.J. Scott, N. Voisin, C.O. Stöckle, A.F. Hamlet, K.E.B. Mickelson, M.M.G. Elsner, and D.P. Lettenmaier, 2010a: Climate change impacts on water management and irrigated agriculture in the Yakima River Basin, Washington, USA. *Climatic Change*, **102,** 287-317

Vano, J.A., N. Voisin, L. Cuo, A.F. Hamlet, M.M.G. Elsner, R.N. Palmer, A. Polebitski, and D.P. Lettenmaier, 2010b: Climate change impacts on water management in the Puget Sound region, Washington State, USA. *Climatic Change*, **102,** 261-286

Vautard, R., J. Cattiaux, P. Yiou, J.N. Thépaut, and P. Ciais, 2010: Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness. *Nature Geoscience*, **3,** 756-761

Vickery, H., 2009: Secretary Kempthorne, Mexican Ambassador Sarukhan Sign Declaration Commending On-Going Partnership in the Management of the Colorado River.Office of the U.S. Department of the Interior. http://www.doi.gov/news/pressreleases/2009_01_15_release.cfm?renderforprint=1&

Vicuna, S., J.A. Dracup, J.R. Lund, L.L. Dale, and E.P. Maurer, 2010: Basin-scale water system operations with uncertain future climate conditions: Methodology and case studies. *Water resources research*, **46,** W04505

Villarini, G., J.A. Smith, M.L. Baeck, and W.F. Krajewski, 2011: Examining Flood Frequency Distributions in the Midwest US 1. *JAWRA Journal of the American Water Resources Association*, **47,** 447-463

Walker, J.F., L.E. Hay, S.L. Markstrom, and M.D. Dettinger, 2011: Characterizing climate-change impacts on the 1.5-yr flood flow in selected basins across the United States: A probabilistic approach. *Earth Interactions*, **15,** 1-16

Wang, J. and X. Zhang, 2008: Downscaling and projection of winter extreme daily precipitation over North America. *Journal of Climate*, **21,** 923-937

Wang, J., X. Bai, H. Hu, A. Clites, M. Colton, and B. Lofgren, 2011: Temporal and spatial variability of Great Lakes ice cover, 1973-2010. *Journal of Climate*, [Available online at http://journals.ametsoc.org/doi/abs/10.1175/2011JCLI4066.1]

Ward, F.A., B.H. Hurd, T. Rahmani, and N. Gollehon, 2006: Economic impacts of federal policy responses to drought in the Rio Grande basin. *Water resources research*, **42,** 41-53

Washington State Department of Ecology: Publication Number: 11-11-07: Focus on Carpenter-Fisher subbasin - Carpenter-Fisher subbasin water reservation closed to new uses. [Available online at http://www.ecy.wa.gov/pubs/1111075.pdf and more generally, http://www.ecy.wa.gov/programs/wr/instream-flows/skagitbasin.html]

Watson, T.A., F. Anthony Barnett, S.T. Gray, and G.A. Tootle, 2009: Reconstructed Streamflows for the Headwaters of the Wind River, Wyoming, United States1. *JAWRA Journal of the American Water Resources Association*, **45,** 224-236

Wehner, M., D.R. Easterling, J.H. Lawrimore, R.R. Heim Jr, R.S. Vose, and B.D. Santer, 2011: Projections of Future Drought in the Continental United States and Mexico. *Journal of Hydrometeorology*, **12,** 1359-1377 doi: 10.1175/2011JHM1351.1 [Available online at http://journals.ametsoc.org/doi/abs/10.1175/2011JHM1351.1]

Wetzel, R., 2001: Limnology, 3 E. Lake and River Ecosystems. *Academic Press***,** 850

Weyhenmeyer, G.A., D.M. Livingstone, M. Meili, O. Jensen, B. Benson, and J.J. Magnuson, 2011: Large geographical differences in the sensitivity of ice‐covered lakes and rivers in the Northern Hemisphere to temperature changes. *Global Change Biology*, **17,** 268-275

Whitehead, P., A. Wade, and D. Butterfield, 2009: Potential impacts of climate change on water quality in six UK rivers. *Hydrological Research*, **40,** 113-122

Wilbanks, T., S. Fernandez, G. Backus, P. Garcia, K. Jonietz, P. Kirshen, M. Savonis, B. Solecki, L. Toole, M. Allen, R. Bierbaum, T. Brown, N. Brune, J. Buizer, J. Fu, O. Omitaomu, L. Scarlett, M. Susman, E. Vurgin, and R. Zimmerman, 2012: Climate Change and Infrastructure, Urban Systems, and Vulnerabilities. Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment, Oak Ridge National Laboratory

Wilbanks, T.J. and e. al., 2007: Executive Summary. *Effects of climate change on energy production and use in the United States*, T. J. Wilbanks, V. Bhatt, D. E. Bilello, S. R. Bull, J. Ekmann, W. C. Horak, Y. J. Huang, M. D. Levine, M. J. Sale, D. K. Schmalzer, and M. J. Scott, Eds., U.S. Climate Change Science Program, x-xii

Wilby, R.L. and R. Keenan, 2012: Adapting to flood risk under climate change. *Progress in Physical Geography*, **36,** 348-378

Wilder, M., C. Scott, N. Pineda-Pablos, R. Varady, and G. Garfin, 2012: Moving Forward from Vulnerability to Adaptation: Climate Change, Drought, and Water Demand in the Urbanizing Southwestern United States and Northern Mexico. Casebook. *Udall Center for Studies in Public Policy*

Woodhouse, C.A., S.T. Gray, and D.M. Meko, 2006: *Updated streamflow reconstructions for the Upper Colorado River basin.* American Geophysical Union.

Wright, L., P. Chinowsky, K. Strzepek, R. Jones, R. Streeter, J.B. Smith, J.M. Mayotte, A. Powell, L. Jantarasami, and W. Perkins, 2012: Estimated effects of climate change on flood vulnerability of US bridges. *Mitigation and Adaptation Strategies for Global Change***,** 1-17

Yang, Y.J., 2010: Redefine Water Infrastructure Adaptation to a Nonstationary Climate. *Journal of Water Resources Planning and Management*, **136,** 297

Yu, G., Z. Schwartz, and J. Walsh, 2009: A weather-resolving index for assessing the impact of climate change on tourism related climate resources. *Climatic Change*, **95,** 551-573 doi: 10.1007/s10584-009-9565-7, [Available online at http://dx.doi.org/10.1007/s10584-009-9565-7]

Ziska, L.H., P.R. Epstein, and C.A. Rogers, 2008: Climate change, aerobiology, and public health in the Northeast United States. *Mitigation and Adaptation Strategies for Global Change*, **13,** 607-613