Water Resources Sector
Technical Input – Interim Report
In Support of the
U.S. Global Change Research Program
2014 National Climate Assessment

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IWR INSTITUTE FOR WATER RESOURCES

U.S. Global Change Research Program
National Climate Assessment

The National Climate Assessment (NCA) is being conducted under the auspices of the Global Change Research Act of 1990. The GCRA requires a report to the President and the Congress every four years that integrates, evaluates, and interprets the findings of the U.S. Global Change Research Program (USGCRP); analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and analyzes current trends in global change, and projects major trends.

National climate assessments act as status reports about climate change science and impacts. They are based on observations made across the country and compare these observations to predictions from climate system models. The NCA aims to incorporate advances in the understanding of climate science into larger social, ecological, and policy systems, and with this provide integrated analyses of impacts and vulnerability.

What's New about the 2014 Assessment?

The 2014 NCA will set the stage for more comprehensive assessments in the future. It will differ from previous U.S. climate assessments by:

- Being an ongoing effort, rather than a periodic report-writing activity;
- Evaluating the nation's progress in adaptation and mitigation;
- Building long-term partnerships with entities in the public and private sectors;
- Identifying national indicators of change within regions and sectors, and establishing consistent and ongoing methods for evaluating them;
- Including new methods for documenting climate related risks and opportunities;
- Providing web-based information that supports decision making processes.

Objectives

The NCA is intended as an inclusive, nationwide process with key objectives, including:

- Synthesizing relevant climate science and information;
- Increasing understanding of what is known and not known about GCC;
- Informing climate science priorities;
- Building climate assessment capacity in regions and sectors;
- Supporting climate-literacy and skilled use of NCA findings.

Timeline

Because the last NCA was published in 2009, the next is due in 2014. A draft report will be completed by the NCA Development and Advisory Committee in 2012 so that it may be thoroughly reviewed by experts inside and outside the Federal government, the NAS, and the public. This document represents the water sector technical input into that process, and aimed at informing the water resources portion of the 2014 NCA.

More information at: http://www.globalchange.gov/what-we-do/assessment

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Note: This technical input report was commissioned by the USGCRP as input for the Water Resources Chapter of the 2014 National Climate Assessment. This report represents a summary of a larger intergovernmental document being finalized as an interagency report which is intended to be published later in 2014 as a USGS Circular.

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Introduction

An understanding of ongoing and anticipated effects of climate change on freshwater resources is critical for all aspects of human existence, including safe drinking water, food security, energy security, disaster preparedness planning and hazard response, ecosystem health, and the Nation's economy.

In support of the 2013 National Climate Assessment, as mandated by the Global Change Research Act, a Water Resources (WR) Sector technical input document is being developed. The overall NCA outline includes sector specific chapters on energy, transportation, agriculture, forestry, ecosystems and biodiversity, and human health, as well as water. The WR Sector Technical Input document will be used, along with other sources, to produce the Water Sector chapter. Other major components of the NCA include sectoral cross-cuts and region specific focus areas that include water related topics.

The purpose of the WR Sector technical input document is to summarize relevant recent information on effects of climate change on water resources with the context of USGCRP guidance. In particular the report seeks to identify key vulnerabilities, and to provide information required for future evaluation of adaptation and mitigation strategies. More detailed information on the U.S. Global Change Research Program, National Climate Assessment can be found at http://www.globalchange.gov/what-we-do/assessment.

This report is an assessment of recent, relevant information on the effects of climate change on freshwater resources. The body of scientific literature on climate change and water resources is vast and growing. The focus of this report is primarily on information that is well-documented, peer-reviewed, and useful to assess impacts of climate change on freshwater resources, including key vulnerabilities, and the development of adaptation and mitigation strategies. The report is organized by six key issues: (1) Precipitation patterns and intensity; (2) Surface water, including streamflow, snowmelt, and floods; (3) Groundwater, including soil moisture; (4) Water Quality; (5) Water Resources Management Implications, and (6) Adaptation. Information presented herein primarily is based on (1) observations and (2) projections of change.

Foundational Information

This assessment report is primarily based upon observations of the past and projections of the future. Observations and projections of various aspects related to water resources fundamentally differ in terms of degree of uncertainty, and usefulness, and applicability to support different decisions and actions and activities. Observations and projections are both critical for assessing and responding to the challenges that climate change is adding to the significant pressures already present on water resources.

Observations, both in situ and remotely sensed, represent conditions for a known time and location, and have reasonably well characterized uncertainties. Observations are limited to where observing networks exist and for the time for which they have been collecting data. Observations can be used to detect change, although changes in rare events (e.g., the frequency or magnitude of floods) may require long periods to detect.

Projections of future water resources conditions are generally based on Global Climate Models (GCMs) that are sometimes linked to earth systems models that couple the energy and water budgets of the land surface to the atmosphere. Applications to water resource studies utilize conversions of coarse-scale climate projections to fine scale predictions of water-resources impacts. There are large uncertainties associated with some aspects of climate projections, land-surface modeling, and the utilization of these projections with respect to adaptation is an active area of scientific development.

Both observations and projections should be used with some humility, recognizing the relatively short duration of the instrumental record, the spatial paucity of data, and the inherent uncertainties and information gaps in projections. GCMs, downscaling approaches, and statistical interpretation of both GCM results and measurements continue to improve. As an example, based on the work of Felzer and Heard (1999), the 2000 National Climate Assessment (NCA) (Jacobs, Adams, & Gleick, 2000) projected a potentially wetter Southwest under future conditions. Whereas more recent projections (e.g. Karl, Melillo, & Peterson, 2009) indicate a generally drier Southwest under future climate. Continuing and enhanced investments in observations, data analysis, research into hydrologic and climate processes, scenario development, and model improvements are critical to refining our understanding of how climate change will affect the nation's water resources.

"Long-term monitoring networks are critical for detecting and quantifying actual impacts, providing a basis for understanding hydrologic processes and trends, allowing calibration and validation of models used to project future conditions, and supporting design and evaluation of adaptation strategies" (Brekke et al., 2009). Monitoring should include both the natural system and the engineered system (i.e., withdrawals and use); (Brekke, et al., 2009). A comprehensive assessment of water-resources monitoring networks recently was completed (Federal Interagency Panel on Climate Change and Water Data and Information, 2011). As noted in the report, "the Nation invests considerable resources in monitoring, mapping, evaluating, assessing, modeling, and managing water resources…", however, "existing systems… (networks, methods, and models) were not designed to consider climate-induced stressors, to account for non-stationary hydroclimatic processes, or to evaluate the effectiveness of climate change mitigation and adaptation strategies." The report notes that improvements are needed in most of the Nation's water monitoring capabilities, including improved coordination among networks. Nevertheless, even relatively well-monitored systems, such as the Great Lakes, have shown that the information base is barely adequate to make good water management decisions based on the historical record (International Upper Great Lakes Study Board, 2012).

Observations support the development of hydroclimatic statistics, which underpin many water management decisions. Some hydroclimatic statistics are based on an assumption that hydroclimatic conditions have constant statistical properties through time (concept of stationarity). Although questioned for many years (e.g., Milly et al., 2008), the assumption of stationarity has prevailed in water-resources management and engineering design. Options for the application of hydroclimatic statistics to future conditions include continued use of the assumption of stationarity or development of new statistical methods (Griffis & Stedinger, 2007; Hirschboek, 2009; Koutsoyiannis & Montanari, 2007; Lins & Cohn, 2010; Luce & Holden, 2009). Long-term hydroclimatic patterns are not yet understood, so inclusion of these in statistical techniques is important but difficult. As engineers and planners establish new methods and re-evaluate current practices, they face the challenge of finding a balance between high projection uncertainties, risk reduction, and the costs of adaptation (Yang, 2010).

In addition to observations, findings in this report also rely on projections produced from GCMs used in the IPCC Fourth Assessment (IPCC, 2007b) and developed as part of the World Climate Research Program's Coupled Model Intercomparison Project phase 3 (WCRP CMIP3) or earlier. Efforts to develop the CMIP5 archive in support IPCC AR5 are underway but are not yet mature and available for use in impacts assessment. CMIP3 projections are thus regarded as the best available source for describing future global climate possibilities. Often these projections need to be regionalized from coarse geographic resolutions to appropriate scales for assessing impacts at a water-resource relevant scale.

There is a growing body of work that projects climate change impacts on water resources using output from GCMs (e.g., Cayan et al., 2010; Dettinger, Cayan, Meyer, & Jeton, 2004; Hanson & Dettinger, 2005; Hay & McCabe, 2010; Hayhoe et al., 2004; Hayhoe et al., 2007; Mauer, Hidalgo, Das, Dettinger, & Cayan, 2010; McCabe & Wolock, 2007; Zhang & Georgakakos, 2011). Although GCMs have shown an ability to simulate the influence of increasing greenhouse gas (GHG) emissions on global climate (IPCC, 2007b), there remain large uncertainties associated with coupling terrestrial to atmospheric processes, downscaling from GCM scales to hydrologically relevant scales, and utilization of GCM results for resource specific applications. GCM models have been used to evaluate uncertainty in hydrologic projections (Hay, McCabe, Clark, & Risley, 2009; Milly & Dunne, 2011), and it has been shown that there is a location dependent systematic bias in the long-term projections of streamflow. Projections of water-resources impacts are most appropriately used for relative comparisons rather than as forecasts of specific conditions at a given point in space and time. Despite past and current progress, a high degree of uncertainty in water-resources projections from GCM application likely will persist well into the future (Brekke, et al., 2009; Brekke et al., 2011; WUCA, 2009). There also are other methods for evaluating climate and water-resources conditions that differ from the observed record—primarily use of paleoclimatic information and stochastic hydrology. Paleoclimate data provide direct information or proxies for a longer period than is available in the instrumental record, thereby presumably accounting for greater variability in the hydro-climatic system. Stochastic hydrology provides a means for including additional variability in the climate record through the development of alternative futures based upon the statistics of the past. Both methods have been used effectively within water resources adaptation planning (e.g., International Upper Great Lakes Study Board, 2012).

Precipitation

a. Observational Data

Seasonal and annual precipitation totals across the continental U.S. (CONUS) have increased or remain unchanged (in the sole case of the winter season) over the period of record from 1895-2011. Average annual precipitation for the CONUS increased at a rate of 4.6 mm per decade (National Climatic Data Center, 2011). Both the Northeast and the Upper Midwest had their wettest years on record within the last five years. Notable dryness also has occurred during the last five years with near-lowest conditions in the West and the Southeast in 2007 and in the South in 2011.

There are climatological (Karl & Trenberth, 2003) and theoretical (Allan & Soden, 2008; Allen & Ingram, 2002; Trenberth, 2011) reasons that precipitation intensity is expected to change with a warming climate. There also is observational evidence for this change (Groisman et al., 2005; Groisman, Knight, & Karl, 2012; Karl, et al., 2009; Kunkel et al., 2010; 2011) as well as evidence from model output based on General Circulation Models (GCMs) (IPCC, 2007b; Min, Zhang, Zwiers, & Hegerl, 2011). Increases in the number and intensity of heavy (largest 5% of events), very heavy (largest 0.3%), and extreme (largest 0.1%) precipitation events of durations ranging from hourly to a few days have been detected at the CONUS and regional levels (Alexander et al., 2006; Groisman, et al., 2005; Groisman, Knight, & Karl, 2001; Groisman et al., 2004; Karl & Knight, 1998; Karl, Knight, Easterling, & Quayle, 1996; Karl, et al., 2009; Kunkel, Easterling, Redmond, & Hubbard, 2003; Kunkel et al., 2007) over the past several decades, compared to the previous decades of the 20th century (Figure 1).

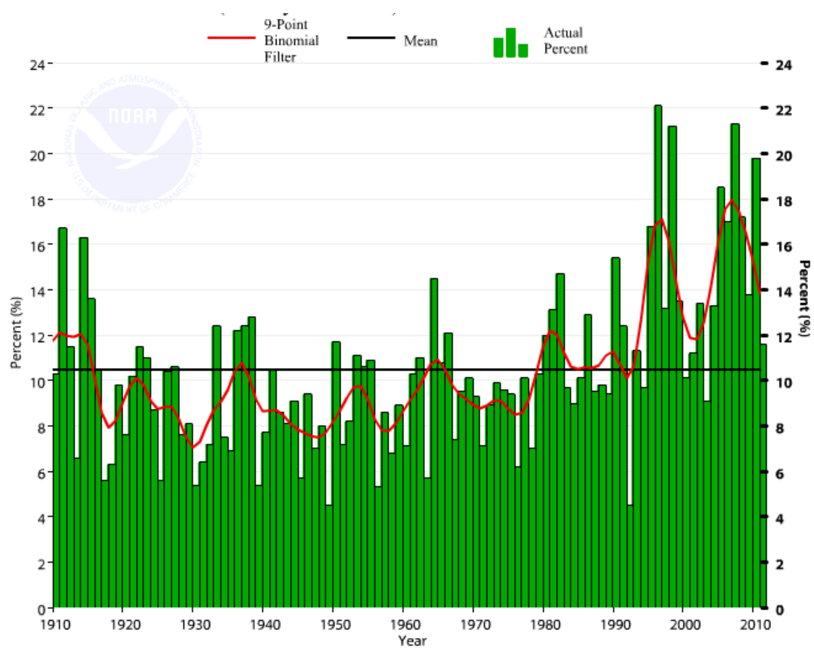

Figure 1: 1-day CONUS extreme precipitation events (top 10th percentile) as a percentage of total precipitation. Green bar is actual percent. Red line is running mean. Black line is mean. (see Gleason et al. (2008) for more detail.

At roughly two-thirds of the Historical Climatology Network stations across the CONUS, there is a positive trend in the 2-, 5-, and 10-year return-period for daily rainfall from 1950-2007 (DeGaetano, 2009). There is also a regional pattern to the trends with the Northeast, western Great Lakes, and the Pacific Northwest exhibiting dominantly positive trends. For most regions, there is a 20% reduction in the length of time between extreme events, which would be equivalent to a one in ten year event (based on data from 1950-1979) now occurring once every eight years when data from 1950-2007 are considered. There also has been an increase in the month or longer no-rain periods in the eastern U.S. in the summer over the past several decades (Groisman & Knight, 2007, 2008).

A northward shift of storm tracks has resulted in regional changes in the frequency of snowstorms in the U.S. (Karl, et al., 2009). The lower Midwest and South have seen a declining trend in frequency of snowstorms since 1900. The Northeast and upper Midwest, however, have seen increases, although there is considerable decade-to-decade variability. As ice coverage on the Great Lakes has decreased since 1950, there is evidence of increased lake-effect snowfall. The maximum seasonal ice coverage decreased about 30 percent from 1973 to 2008, creating conditions conducive to greater evaporation and thus heavier lake-effect snowstorms (Karl, et al., 2009).

Short-term droughts, generally of less than 6-months duration, primarily arise from natural variability; regional variations in sea-surface temperatures (SSTs) are a major factor forcing longer-term droughts. Warming can alter runoff timing from snowmelt (Barnett et al., 2008; Cayan, et al., 2010), exacerbating dry summer conditions. Land-use practices and effects of dust aerosols also can play important roles (B. R. Cook, Miller, & Seager, 2009), indicating that, in addition to climatological factors, multiple human influences must be considered in projecting drought occurrence (Pielke et al., 2011). There is an increasing trend in national areal coverage of drought conditions since 1971, but there is no trend for 1900-2011 (Figure 2).

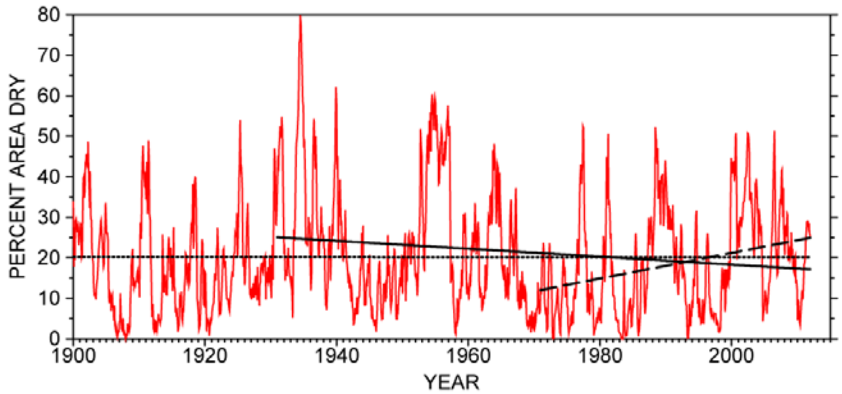

Figure 2: Percent of the contiguous U.S. experiencing moderate to extreme drought (PDSI ≤ -2.0), 1900 – 2011(red curve). Dotted line is linear regression over the period of record, solid line is for 1931-2011, and dashed line is for 1971-2011. (Data from NCDC)

For large parts of the CONUS, the droughts of record occurred during the 1930s and 1950s with 31.6% and 16.4%, respectively, of the nation having the driest, or near-record driest, Palmer Hydrological Drought Index (PHDI) in those two decades. For the period 1900 – 2011, the PHDI was driest, or tied for driest, for 12.8% of the country during the first decade of the 21st century (2001-2010) and 7.5% of the country in the first nine months of 2011.

Paleoclimate reconstructions based on tree-ring data suggest that drought in previous centuries has been more intense and of longer duration than the most extreme drought of the 20th and 21st centuries. The area in drought in the western U.S., for example, as measured by the Palmer Drought Severity Index (PDSI) reconstructed from tree rings, averaged 38% from AD 800-2005, but during AD 900-1300 the area was 42.4%, a significantly larger area experiencing drought than what was observed in the 20th century (E. R. Cook, Woodhouse, Eakin, Meko, & Stahle, 2004). This information suggests the importance of looking beyond the period of instrument records when evaluating changes in water-resource conditions.

b. Projected Changes

General circulation models (GCMs) agree in most locations and seasons on the sign of the changes in temperature, but projections of changes in precipitation are more uncertain. GCM agreement of at least 90% for projected changes in precipitation generally exists only for the High Latitudes. In much of the Tropics and Mid-Latitudes, agreement on the sign of the projected changes seldom exceeds 66% among the different IPCC models. Model agreement is also generally poor for other moisture related measures, such as soil moisture (Orlowsky & Seneviratne, 2012)

Wang and Zhang (2008) used the IPCC A2 scenario to examine 20-year return intervals for maximum daily precipitation. They found that both winter extreme precipitation and winter mean precipitation estimates from GCMs showed an increase in the northern U.S. and a decrease in the southern U.S. precipitation. Additionally, the increase in the extreme precipitation was greater than that for mean precipitation. The result suggest that a 1-in-20 year extreme precipitation event currently is likely to occur more frequently in the future, becoming a 1-in-5 to 1-in-15 year event. Model results also point to small, or no, shifts in circulation regime, indicating that the change in extreme precipitation events will be related to increased moisture in the air due to warmer temperatures (Wang & Zhang, 2008). This simple relationship has led to estimates of future precipitation possibilities of a 1.4 degree C increase in air temperature could lead to an increase of 20mm (0.8 in) per day in heavy precipitation events (Gutowski et al., 2008). Diffenbaugh et al. (2011) found a different trend based on increases in summer temperatures over the central United States. The authors noted increases in summer temperatures were associated with decreases in summer precipitation of up to 0.75mm (0.03 in) per day in the 2020–2039 period. As greenhouse gas forcing increases in the 21st century decreases of at least 0.5mm (0.02 in) per day in 2040–2049 in the central United States, and decreases of at least 1.0 mm (0.04 in) per day over much of the central and eastern United States in the 2080–2098 period is possible.

Surface Water

a. Observations

Streamflow represents the manifestation of a series of complex climatic and hydrologic interactions throughout the landscape. Primary climatic drivers of this interaction are radiation (temperature) and precipitation. These factors have been observed and are projected to change in future years for some locations and conditions.

Changes have been observed in streamflow timing (e.g., Aguado, Cayan, Riddle, & Roos, 1992; Dettinger & Cayan, 1995; Hamlet, Mote, Clark, & Lettenmaier, 2005; Pupacko, 1993; Regonda, Rajagopalan, Clark, & Pitlick, 2005; Roos, 1987, 1991; Stewart, Cayan, & Dettinger, 2005; Wahl, 1992) and quantity in snowmelt dominated systems of the Northeast and Western U.S. (e.g., Luce & Holden, 2009; Miller & Piechota, 2008; Regonda, et al., 2005). Declines in spring snowpack also have been observed in much of the mountain west (Mote, Hamlet, & Lettenmaier, 2005). Changes in the timing and seasonal volume of streamflow in snowmelt-dominated watersheds have been attributed to changes in the form of precipitation and temperature due to natural climate variability (Cayan, Redmond, & Riddle, 1999; Dettinger & Cayan, 1995; Hamlet, et al., 2005; Regonda, et al., 2005), including long-term persistence (e.g., Lins & Cohn, 2011) and to human-induced global warming (Barnett, et al., 2008; Dettinger, 2005; Hamlet, et al., 2005; Knowles, Dettinger, & Cayan, 2006; Mote, 2003; Mote, et al., 2005; Pierce et al., 2008; Regonda, et al., 2005; Stewart, et al., 2005). The detection and attribution of these changes is in early stages, but recent studies (e.g., Barnett, et al., 2008; Bonfils et al., 2008; Hidalgo et al., 2009; Pierce, et al., 2008) suggest that, at least in part, changes can be explained by anthropogenic influences on climate.

Snow water equivalent (SWE) is a measure of the water held in the snowpack. At many stations in the western U.S., there has been a decrease in SWE and general increase in winter precipitation over the past 50 years, indicating more precipitation occurring as rain rather than snow (Pierce, et al., 2008; Regonda, et al., 2005). Elevation can play a major role in observed changes in snowpack despite increased temperatures. Stewart (2009) notes that decreases in snowpack are observed at mid-elevations, regardless of increases in precipitation while at higher elevations temperatures remain cold enough to observe increased snowpacks with increased precipitation.

Based on tree ring records, the Missouri River basin appears to have had greater runoff (streamflow volume) during the 20th century than prior centuries, as well as relatively less annual variability (Stonefelt, Fontaine, & Hotchkiss, 2000; Watson, Barnett, Gray, & Tootle, 2009; Woodhouse, 2001). During the past century, the annual runoff in the Colorado River Basin has decreased (Reclamation, 2011). The period of 2000–2010 marked the lowest 11-year period on the Colorado River Basin over the past century. Yet, tree ring reconstructions show that the Colorado River Basin often experienced long-term, severe droughts prior to instrumental records (Meko et al., 2007; Woodhouse, Gray, & Meko, 2006). Tree-ring re-constructions for the Southeast U.S. show similar conditions (Seager, Tzanova, & Nakamura, 2009).

Flood producing precipitation increased over the latter half of the 20th century (Gutowski, et al., 2008; Karl & Knight, 1998). These changes have been attributed to anthropogenic climate change (Min, et al., 2011) and a warmer climate in general (Allan & Soden, 2008). Precipitation change along or in combination with changes in snowmelt processes (e.g., Hodgkins, Dudley, & Huntington, 2003; Knowles, et al., 2006; Mote, 2003, 2006) may result in increased flood magnitudes. However, there has been no large-scale regional detection of changes in flood statistics correlated with atmospheric CO2 concentrations (Hirsch & Ryberg, 2011). Detection of changes in rare events is difficult and likely will take many years of observations, (Brekke, et al., 2009), and attribution likely will be more difficult because of interannual and decadal ocean-atmosphere oscillations that affect flood events (e.g., Jain & Lall, 2000).

While detection is possible attribution of water-resources trends to climate change remains challenging, even for locations with very long systematic records (e.g., Hirsch, 2011). However, specific flood events have been tied to climate forcings (e.g., Dirmeyer & Kinter, 2010) and in one case in the UK tied to risks associated with anthropogenic atmospheric changes (Pall et al., 2011).

b. Projected Changes

Dettinger et al. (2004) projected that a 2.5^{o}C air temperature increase in the 21st century would result in peak snowmelt runoff occurring about one month earlier than present. Similarly, Adam et al. (2009) concluded that projected warming in the western U.S. would decrease snow accumulation and, thus, spring snowmelt, decreasing warm-season runoff in mid- to high-latitude regions. Similar changes to snowpack are expected in the Northeast U.S. (Hayhoe, et al., 2007). These projected changes to snowpack (e.g., Figure 3) and snowmelt likely would affect all aspects of water resources (Brekke, et al., 2009) in regions directly or indirectly (through interbasin transfers) dependent on snowmelt.

Streamflow projections indicate that significant changes are likely for the future throughout the U.S., but vary by region (e.g., Brekke, et al., 2009; Elsner et al., 2010; IPCC, 2007b; Markstrom et al., 2011; Milly, Dunne, & Vecchia, 2005; Moser, Franco, Pittiglio, Chou, & Cayan, 2009; Reclamation, 2011). However, projected changes in surface water runoff are more complex than projections of snowpack effects due in part to watershed hydrological processes. The Southwestern (Reclamation, 2011) and Southeastern U.S. (Zhang & Georgakakos, 2011) may experience reductions in annual runoff throughout the 21st century while the Northwest (Reclamation, 2011) to North-central U.S. (Reclamation, 2011) is projected to experience little change through the mid-21st century.

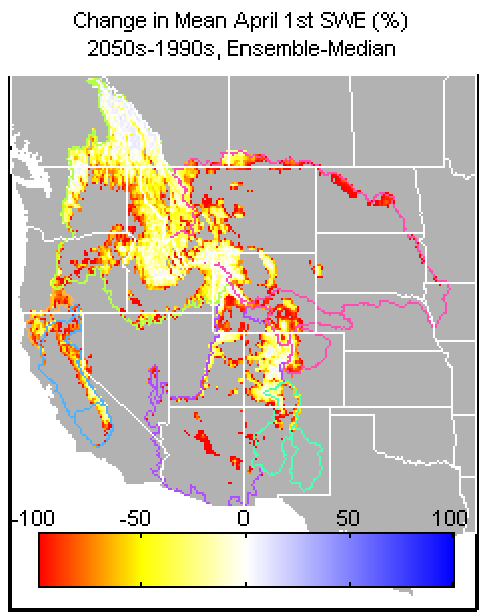

Figure 3: Projected changes in April 1st snowpack for western United States for 2050s from 1980s. Results are consistent with trends detected in observations (e.g. Stewart et al. 2005) (Reclamation, 2011).

In part, because of changes in snowmelt timing and increased rainfall relative to snow, cool season runoff is projected to increase over West Coast basins from California to Washington and over the North-Central U.S., but little change is projected for the Southwest. Warm season runoff is projected to experience substantial decreases over a region spanning southern Oregon, the Southwest, and Southern Rockies. However, north of this region, little change is projected for warm season runoff. In the Southeast, increased temperatures may be the dominant forcing for changes in runoff, regardless of changes to precipitation. Model projections suggest increasing precipitation and evaporation with a net decrease in annual runoff due to reductions in soil moisture (Seager, et al., 2009; Zhang & Georgakakos, 2011). Soil moisture reduction is expected to be more pronounced in summer and fall, impacting agriculture and leading to higher surface and groundwater withdrawals for irrigation. Increased extreme precipitation (IPCC, 2007b), including increased occurrence of flood-producing atmospheric rivers (Ralph et al., 2006) along the West Coast. Many studies suggest that, at least in some regions, there could be a tendency toward increased occurrence of floods (Das, Dettinger, Cayan, & Hidalgo, 2011; Dettinger, 2011; D. A. Raff, Pruitt, & Brekke, 2009).

Groundwater

a. Observational Data

Groundwater is the primary source of water supply for about 130 million Americans, including about 97 percent of the rural population (Dennehy, 2005). About 42 percent of irrigation water is supplied by groundwater (Hutson et al., 2004). Groundwater accounts for a large percentage of the total flow in most streams, with as much as 80 percent of streamflow originating from groundwater in some parts of the Nation (Winter, Harvey, Franke, & Alley, 1998). As locations for additional water-supply reservoirs become limited and availability of water from the Nation's streams becomes increasingly scarce, withdrawals from groundwater are likely to increase (Hutson, et al., 2004). In many areas, including California (Famiglietti et al., 2011) and the southeastern U.S., increases in groundwater use during surface water shortages have been dramatic. In addition, global groundwater depletion is in part contributing to sea level rise though aquifer impaction and land subsidence (e.g., Clark et al., 2012; Famiglietti, et al., 2011), as well as increased freshwater discharge to the ocean (Konikow, 2011; Figure 4).

Despite its importance, groundwater conditions and withdrawal rates in the U.S. generally are poorly monitored (Famiglietti, et al., 2011; Federal Interagency Panel on Climate Change and Water Data and Information, 2011). According to the U.S. Governmental Accountability Office (2004), no Federal agencies are collecting groundwater level data on a national scale. Data and models, which are data dependent, are needed to better understand the implications of precipitation variability, temperature change, and withdrawals on groundwater availability and, because of the tight coupling of surface and groundwater, on streamflows and aquatic ecosystems.

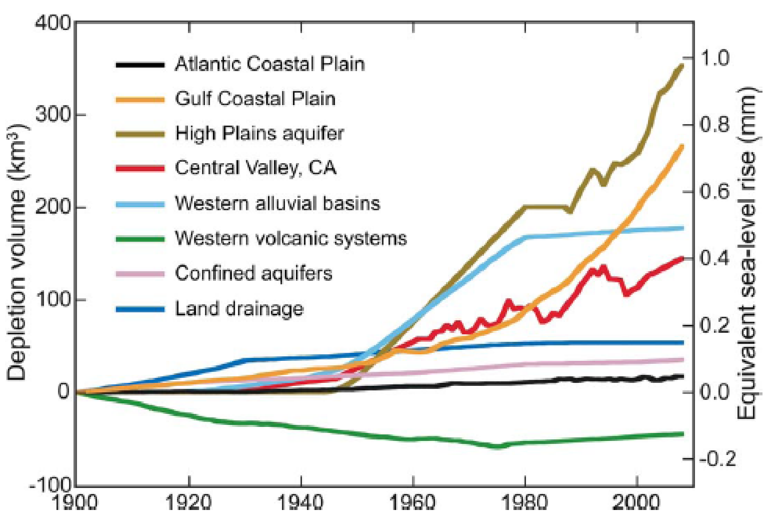

Figure 4: Cumulative net groundwater depletion in major United States aquifers, 1900 – 2008 (Konikow, 2011).

Soil moisture is critical for agricultural crop production. With climate change and the concomitant changes in the length of the growing season, irrigation practices will change in response to modified crop requirements, available precipitation, and the rate of evapotranspiration (ET; IPCC, 2007a). The amount of moisture stored in the soil is directly related to the balance between water saturation (through rainfall or irrigation) and ET, or the amount of water released to the environment through the growth of plants, trees, and vegetation. These factors, in conjunction with land use patterns and local hydrology influence the rate and extent of groundwater recharge and generation of runoff.

ET is the second largest component of the water cycle after precipitation and is a major determinant of the amount of groundwater recharge. Moreover, ET is one of the primary consumers of solar energy at the land surface, and couples the energy budget and the water budget at the land surface. This coupling makes it difficult to correctly model ET in downscaled global climate simulation models (e.g., Bae, Jung, & Lettenmaier, 2011; Mueller et al., 2011).

As the global air temperature has increased, one might expect an associated increase in pan evaporation, as higher temperatures provide more energy for evaporation. However, just the opposite has been observed (Roderick & Farquhar, 2002). There are at least three explanations for the observed decreases in pan evaporation: (1) higher humidity giving the atmosphere less capacity to take up water; (2) decreased winds (Vantard, Cattiaux, Yiou, Thépaut, & Ciais, 2010); and (3) reduced solar irradiance associated with increased cloud cover and aerosol concentration (Roderick & Farquhar, 2002). Reduced solar irradiance appears to be the best explanation for reduced pan evaporation in all settings (Roderick & Farquhar, 2002). It has been hypothesized that increased cloud cover and aerosols concentrations will be a result of global temperature increases.

b. GCM Projections

There have been few direct projections of groundwater conditions in response to climate change, but projections of surface water shortages likely mean greater reliance on groundwater for water supplies, which, in turn, could mean less groundwater discharge to the surface system. Hanson and Dettinger (2005) coupled a downscaled GCM to a regional groundwater flow model for the coastal aquifers of the Santa Clara-Calleguas Basin at Ventura, California, and demonstrated that the GCM – groundwater flow model could translate global-scale climate variations into realistic local groundwater responses. Although many climate assessments have identified saltwater intrusion into coastal aquifers as a potential impact of sea-level rise, it recently has been demonstrated that such an effect should not occur as long as groundwater recharge remains constant (ref) and that the effects of withdrawal greatly exceed potential effects of sea-level rise on saltwater intrusion.

Water Quality

Water quality is a result of natural physical, chemical, and biological processes interacting with human use and management of land and water resources. Changes in climate and hydrology can have direct and indirect effects on water quality. Direct effects include changes in stream temperature and hydrologic controls on sediment and nutrient movement into and within water bodies. Indirect effects result from changes in ecosystems, disease/wildfire, land-use (e.g., agricultural practices) and include a wide range of cumulative and cascading effects. For example, increased wildfire could affect water temperature, and water temperature changes could alter reaction rates, oxygen availability, and pollutant concentration gradients in water bodies.

Temperature is a fundamental control on biological processes in streams (Caissie, 2006; Poole & Berman, 2001). Water temperature directly affects biota (Brannon, Powell, Quinn, & Talbot, 2004; Dunham, Rosenberger, Luce, & Rieman, 2007; Holtby, 1988; Pörtner & Farrell, 2008; Torgersen, Price, Li, & McIntosh, 1999; Wenger, Isaak, Dunham, et al., 2011) and aquatic ecosystems through its effects on dissolved oxygen and nutrient cycling (Caissie, 2006; Kaushal et al., 2010; McCullough et al., 2009; Sweeny, 1993). Despite its ecological importance, long-term records of stream temperature are more restricted than streamflow (Isaak, Wollrab, Horan, & Chandler, 2011; Kaushal, et al., 2010). Historical trends in stream temperature show increases in many places in recent decades even without land cover or land use changes (Bartholow, 2005; Hari, Livingstone, Siber, Burkhardt-Holm, & Guttinger, 2006; Isaak et al., 2010; Isaak, et al., 2011; Kaushal, et al., 2010; Langan et al., 2001; Morrison, Quick, & Foreman, 2002; Petersen & Kitchell, 2001). Although stream temperatures have been rising with CO2 levels, rates of warming generally are slower than rates of increase in air temperature, and not all places are warming equally (e.g., van Vliet, Ludwig, Zwolsman, Weedon, & Kabat, 2011; Webb & Nobilis, 1997). Changes in riparian and watershed land cover associated with climate change create an important non-linear effect and have the capacity to locally mitigate or exacerbate the more direct changes in stream temperature associated with climate change.

Projected future changes in stream temperature tend to rely on correlations between air and stream temperature (Mohseni, Stefan, & Eaton, 2003; Rieman et al., 2007; Wenger, Isaak, Dunham, et al., 2011), although changes in air temperature generally are not the direct cause of major changes in stream temperature (Johnson, 2003, 2004). Projected declines in summer flows (e.g., Cayan, Kammerdiener, Dettinger, Caprio, & Peterson, 2001; Leppi, DeLuca, Solomon, & Running, 2011; Luce & Holden, 2009) mean that there is less water to heat in the months when the water is warmest. Temperature-driven disruption of the food web through effects on macroinvertebrates, amphibians, and algae (Caissie, 2006; Hossack & Pilliod, 2011; Kaushal, et al., 2010) may have much more widespread consequences for a variety of aquatic communities.

Increased air and water temperatures are likely to increase stratification in many lakes and reservoirs (Sahoo & Schladow, 2008; Sahoo, Schladow, Reuter, & Coats, 2011; Schneider & Hook, 2010). Increased thermal stability reduces mixing frequency and extent reducing oxygen in bottom waters. Declining oxygen concentrations drive important changes in redox chemistry, ultimately leading to release of nutrients (N and P), heavy metals (Hg, Mn, others) and sorbed toxics from bottom sediments (Sahoo & Schladow, 2008; Sahoo, et al., 2011).

A more vigorous hydrologic cycle including increased precipitation intensity will likely increase movement of sediment, nutrients and pollutants to downstream ecosystems. 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 & 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). Nutrients and contaminants associated with sediment will similarly increase with increasing hydrologic activity (Pruski & Nearing, 2002a, 2002b). Decreases in nitrogen removal by terrestrial ecosystems with increasing precipitation and consequent increases in nitrogen delivery to freshwater bodies has been demonstrated for the Northeast (Howarth et al., 2006), and California (Sobota, Harrison, & Dahlgren, 2009). In the Mississippi drainage basin, increased precipitation has resulted in increased nitrogen loads contributing to hypoxia in the Gulf of Mexico (Justic, Rabalais, & Turner, 2005; McIsaac, David, Gertner, & Goolsby, 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, Kirchner, & Clow, 2009).

The transmission and proliferation of microbial and chemical contaminants could increase as a result of changes in air and water temperatures and changes in runoff. The human pathogenic vibrio species V. parahaemolyticus, is now being detected in shellfish harvested from higher northern latitude waters than in the past (McLaughlin et al., 2005). Levels of fecal pathogens, such as Salmonella, Campylobacter, Cryptosporidium and human enteric viruses, have been reported to rise in surface waters as a result of heavy precipitation events (Boxall et al., 2009). According to (Brunkard, 2010), 68% of U.S. waterborne disease outbreaks during 1948-1994 were preceded by a precipitation event above the 80th percentile. Conversely, low cumulative rainfall and extended drought has also been linked with increases in waterborne outbreaks in England and Wales (Brunkard, 2010) presumably because of lower assimilative capacity and contaminant build-up between events.

Water Resources Management Implications

Future climate change can have wide-ranging effects on water management and use. Eight sets of implications are summarized here.

a. Water Infrastructure

The effects of climate change on water infrastructure range from the impacting the design of future systems to the operations and maintenance of long lived existing systems.

New Infrastructure: The design of new infrastructure including roads, bridges, dams, and levees rely upon estimates of frequency of hydrologic events, often obtained through either precipitation frequency analysis (NOAA NCDC http://www.ncdc.noaa.gov/oa/documentlibrary/rainfall.html) or through the "Guidelines for Determining Flood Flow Frequency" (IACWD, 1982). These documents provide frequency information based upon observational history. Climate change affecting that increase precipitation and or flood frequencies will require increased resource investment to new infrastructure design to be built larger or more robustly to keep to the engineering standard. Conversely if precipitation or flood frequencies are declining then designs for new infrastructure may require fewer resources to build to the engineering standard. Sizing of new infrastructure to ensure appropriate reliability in a changing climate also requires different assumptions based upon historic and future hydrology (e.g. Milly, et al., 2008).

Aging Infrastructure: Much of the water resources infrastructure in the United States is aging and needs maintenance, rehabilitation and repair (American Society of Civil Engineers, 2009). Infrastructure reliability for existing infrastructure is often evaluated relative to its ability to withstand unlikely flood events (Kenny, et al., 2009). This includes dams and levees, which are regularly evaluated against the potential of flood events or the management of flood risk through procedures defined by the "Guidelines for Determining Flood Flow Frequency" (IACWD, 1982). Legacy methodologies to assess infrastructure reliability and risk management have historically not included potential changes in future flood frequencies (Olsen, Kiang, & Waskom, 2010). Changes in flood frequencies as defined within Key Issue 2, thus changes may require either the investment of resources to modify existing infrastructure to maintain reliability or accept some change in reliability due to changing climatic conditions. Additionally existing infrastructure size included hydrologic assumptions of water supply and demand which, as has been articulated in Key Issues 2 – 4 may be altered in a changing climate.

Adaptation options exist including up-to-date maintenance, rehabilitation, and upgrades to ensure flexibility to a wide range of potential climate variability (Kenny, et al., 2009). Risks associated with not achieving the desired level of water supply given changes in supplies and demands from a changing climate can be adapt to through the creation of larger portfolios of water supply systems (Kenny, et al., 2009). This can include structural options including above ground, below ground storage, water treatment including desalination, as well as non-structural options including conjunctive management and water markets or changes to operations of existing facilities (e.g. P.L. 111-11 Subtitle F Section 9503). Adaptation can also include new methods of planning for existing and future water infrastructure. Planning can include the uncertainties of future climate through attempts to describe probability distributions associated with future climate scenarios, which may have significant difficulties with the existing sets of projections of future climate (e.g. Stainforth, Allen, Tredger, & Smith, 2007). Methods of describing scenarios (e.g. Lempert, Popper, & Bankes, 2003) that do not rely upon explicit probability distributions may allow for a broader characterization of uncertainty. Additionally, at the Federal level, changes to the discount rate and guidelines for making economic decisions can be sought with concurrence with the Office of Management and Budget, Office of Science and Technology Policy, the Office of Information and Regulatory Affairs, the Council of Environmental Quality, and the Council of Economics Advisors (Kenny, et al., 2009). Ultimately decisions can be sought to be robust to a wide range of future climates (Matalas, 1997) or be sought to be adaptive (e.g. Williams, Szaro, & Shapiro, 2007) as either better understanding of climate grows or changes manifest.

b. Aquatic environments

Changes in a stream's or river's thermal and flow regimes can cause changes in species abundance and modify ecosystem function (Olden & Naiman, 2010; Poff & Zimmerman, 2010), and can lead to shifts in species ranges (Poff, Olden, & Strayer, 2012; Poff & Zimmerman, 2010). For example, in the desert Southwest, a shift from perennial streams to intermittent ones is likely (Barnett, et al., 2008), with associated changes in riparian vegetation (Stromberg, Lite, & Dixon, 2010). In California's Central Valley, projected lower summer base flows and higher water temperatures are expected to increase summer mortality of adult Chinook salmon, which would contribute to population decline (Thompson et al., 2012). Further, a study of four trout species in the western U.S. indicates that changes in stream temperature and peak flows would lead to an average 47% range reduction by the 2080s due to warming under the A1B scenario (Wenger, Isaak, Luce, et al., 2011).

c. Flooding

Climate change may lead to increased flooding (see surface water section), as can land development. As a result of simulated future changes in flood regimes, the area inundated in 1% exceedance level floods (100-year flood) was projected to increase by roughly 45% above current levels by 2100. In populated areas, 30% of this increase is attributable to increased impervious area and 70% to climate change (Kollat, Kasprzyk, Thomas, Miller, & Divoky, in press).

d. Navigation

Hydrologic changes affect marine navigation primarily through impacts on inland shipping. In 2009, marine navigation accounted for some 677 billion ton-miles of shipping, of which 245 billion ton-miles traveled by inland waterways, and 30 billion ton-miles across the Great Lakes (USDOT and RITA 2009).

Inland shipping is particularly important for bulk commodities, particularly agricultural commodities, coal, and, on the Great Lakes, iron ore. There is a complex system of locks, dams, navigable waterways spanning the Missouri, Mississippi, and Ohio Rivers that is critical to the movement of corn, soy beans wheat, and other agricultural commodities from growing areas in the Mid West to export elevators along the Gulf Coast. This system is important not just to the U.S. economy, but to global food markets.

Recent warming has extended the navigation season in the Great Lakes (Millerd, 2007) and along the Upper Mississippi and additional warming is likely to further reduce the extent and duration of ice cover during the winter. However, climate change could also adversely affect navigation if changes result in lower lake and river levels, thereby reducing water levels in locks and lowering the tonnage barges can carry. Recent study indicates that decreases in Great Lake levels are more likely than increases by mid century (Angel & Kunkel, 2010). Expected increases in the frequency, intensity and duration of flooding in some parts of the U.S. (see section on surface water) could also result in the curtailment of shipping and damage to infrastructure.

e. Hydropower

Climate change will affect hydropower production primarily through changes in runoff (Sale et al., 2012). Changes in flow timing will also affect hydroelectric plants, in many cases requiring water managers to adjust operations and eventually to formally revise reservoir operating rules to address earlier spring snowmelt/runoff induced peak flows and lower summer flows and reservoir elevations – such changes are already being observed in the Pacific Northwest (Hamlet et al., 2010).

f. Water demand

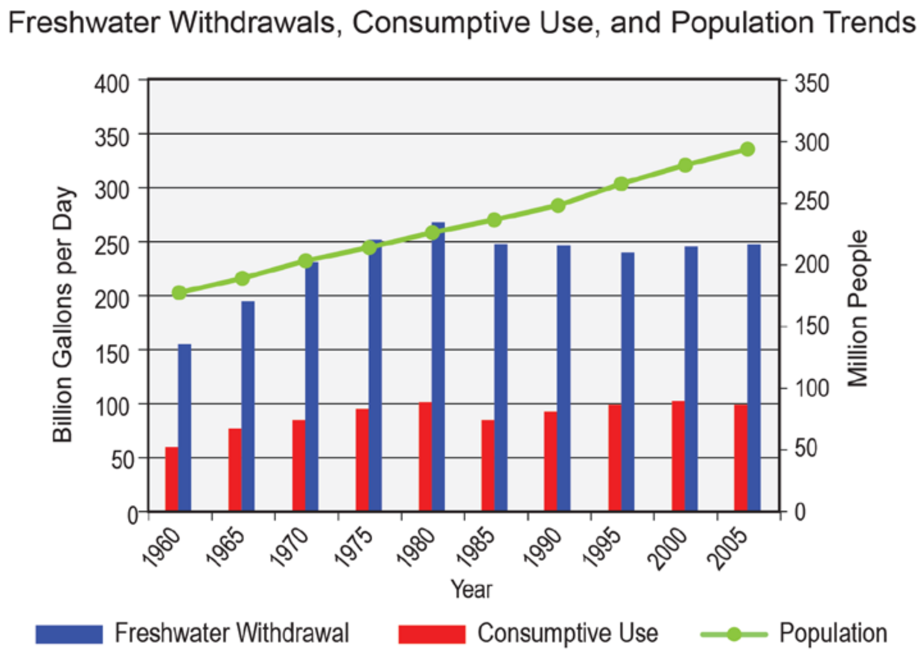

Figure 5: Trends in total freshwater withdrawal (equal to the sum of consumptive use and return flow) and population in the coterminous US. (Kenny, et al., 2009)

Aggregate water withdrawals in the U.S. have grown modestly in recent years (Kenny, et al., 2009; Figure 5) because of improving efficiency of water use (Brown, 2000). Largely because of expected further improvements in water use efficiency, in the absence of future climate change water withdrawals are projected to increase only about 5% to 10% over the next 50 years despite a projected increase in population of roughly 50% (Roy et al., 2010; U.S. Forest Service, 2012, Chapter 12). Total water withdrawals in the U.S. are dominated by energy production and agriculture (Figure 6). Climate change could substantially increase water demand in these and other water use sectors. Increases are expected in water withdrawals and consumptive use at thermoelectric plants to accommodate rising electricity demand for indoor space cooling, and in crop and landscape irrigation rates due to rising plant water demands as temperatures rise. Ignoring effects of warming on growing period and of ambient CO_2 increases on crop transpiration rates, the combined effect of these increased water demands are estimated to increase projected U.S. water withdrawals in 2060 by roughly 30% above the future levels expected without future climate change, with 75% of the increase attributable to agricultural irrigation (U.S. Forest Service, 2012, Chapter 12). However, some small scale modeling studies show that decreases in growing period plus CO_2 increases can substantially compensate for the effects of increasing temperatures on crop water demand (Guo, Lin, Mo, & Yang, 2010; Mo, Liu, Lin, & Guo, 2009), at least during the first half of the century (F., N.T., van Velthuizen, & Wiberg, 2007).

g. Water supply and shortage

Water supply depends on water yield and how that yield is managed. Recent studies of water supply and shortage show that the potential effects of climate change on available water supply vary widely across the U.S., with the most serious impacts expected in the larger Southwest (from California to the Central and Southern Great Plains) (U.S. Forest Service, 2012). Although some smaller-scale additions to reservoir storage capacity may help alleviate projected shortages, major additions to reservoir storage capacity would in many cases not address water supply shortages because of the lack of streamflow, as in the case of the Colorado River (Barnett & Pierce, 2009; Rajagopalan et al., 2009) and major basins in California (Harou et al., 2010). The ability to adapt to the impacts of climate change will depend most importantly on the ability to alter water demand, the flexibility to alter reservoir operating rules (e.g., Brekke, et al., 2009), the willingness to build new water infrastructure, and on the capacity to conjunctively manage surface and groundwater (e.g., Vicuna, Dracup, Lund, Dale, & Mauer, 2010). Georgakakos et al. (2011; northern California) and Georgakakos et al. (2010; Southeast U.S.) demonstrate that adaptive, risk based, and coordinated (system-wide) reservoir operating rules maintain robust performance under a changing and more variable climate.

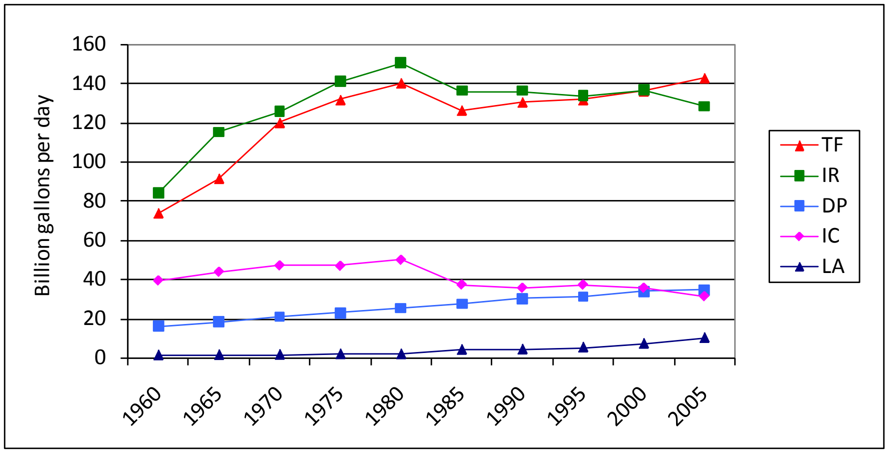

Figure 6: Trends by sector in freshwater withdrawal in the coterminous US. (Kenny et al., 2009)

Sectors: IR = agricultural irrigation, TF = freshwater thermoelectric, IC = industrial and commercial, DP = domestic and pubic, LA = livestock and aquaculture.

h. Water and wastewater treatment

Climate change could cause increases in costs of water treatment and wastewater treatment. Elevated steam temperatures (see section on water quality), which can be accompanied by lower flows in some areas (see section on surface water), will degrade the water quality of receiving waters, requiring wastewater facilities to increase treatment in order to meet stream water quality standards (U.S. Environmental Protection Agency, 2011; Whitehead, Wilby, Battarbee, Kernan, & Wade, 2009). Degraded source-water quality may require changes in drinking water treatment. More intense storms will increase the likelihood of combined sewer overflows and resulting downstream contamination (U.S. Environmental Protection Agency, 2008). In coastal areas, sea-level rise resulting in higher water tables can increase soil water pressure, leading to increased infiltration into wastewater collection systems and potential damage to wastewater distribution pipes (Flood & Cahoon, 2011). Sea level rise and storm surge can add damaging salt to the treatment system. Extensive reuse within a basin could decrease wastewater treatment plant contributions to streamflow with serious downstream NPDES and aquatic habitat impacts, as well as water-rights ramifications.

Adaptation

Adaptation is a managed response to change, to either reduce the impact of adverse change or take advantage of positive effects (Moser, 2010; National Research Council, 2011a). The focus of adaptation to climate change has been on the adverse effects, which, as demonstrated above, may be substantial and are becoming increasingly evident in some aspects of water resources. Adaptation performed prior to the change can be more cost effective than waiting until the need is obvious, but of course anticipatory adaptation would be performed with considerable uncertainty about its effectiveness, as demonstrated in the IUGLS Great Lakes study (2012).

The impacts of climate change on water resources in a particular location are difficult to predict with much precision, particularly when it is the rare events that are of most concern. Among the most significant implications of climate change for water resources management is the very real possibility that there will be increasing variability at the tails of the hydrograph – that is floods and/or droughts will become more frequent, of greater intensity, and longer duration within some regions of the U.S. As a result, water-resources adaptation should focus on increasing the resilience of human and natural systems—the ability of the systems to sustain function and recover from climate-induced perturbations (CCSP, 2008). The specific nature and degree of recommended adaptation depends on the vulnerability of human and natural systems to the impacts of climate change, which in turn depends on the sensitivity of the system to those effects and the capacity to adapt (Adger et al., 2007; Whitely Binder et al., 2010).

Two key aspects of adaptation in the face of uncertainty are adaptive management and robust decision making. Adaptive management is an iterative process of considering new information as it becomes available and revising management plans as needed, a process that relies on monitoring and flexible decision making (National Research Council, 2010). Robust decision making is an attempt to isolate strategies that will be successful under a range of plausible futures (Schwartz et al., 2011; Stakhiv, 2011).

Flexible adaptation, although eminently reasonable in theory, is difficult to perform in practice (Whitely Binder, et al., 2010). In addition to the difficulties of making decisions under much uncertainty, barriers to adaptation include the following: (1) institutional inflexibility due largely to the difficulties of changing existing water laws and management procedures (Gregory, Ohlson, & Arvai, 2006; Hamlet, et al., 2010; Lawler, 2009); (2) institutional fragmentation due to the multiple jurisdictions and ownerships—each potentially governed by distinct laws and regulations, and employing distinct management practices—typically involved in water issues (Hamlet, et al., 2010); (3) short planning horizons at odds with the longer term potential impacts of climate change; and (4) limited human and financial capital of the agencies charged with management of water management infrastructure (CCSP, 2008).

Adaptation entails two broad kinds of endeavors, those that build adaptive capacity and those that implement on-the-ground changes in response to specific vulnerabilities (Lawler, 2009). Building adaptive capacity increases the ability to then design and implement successful adaptive actions. Because there is little doubt that building an institution's adaptive capacity will be beneficial, it is considered a "no regrets" strategy (National Research Council, 2011b). Although such actions would be positive even if climate change were not to occur, the prospect of future climate change provides support for such win-win approaches to improving water management (Cullis et al., 2011).

Table 1: Approaches for adapting to impending water shortages.

Supply		
	Develop new water supplies	
		Rainwater harvesting
		Enhanced wastewater treatment and reuse
		Desalinization
	Improve existing water supplies	
		Add storage capacity (e.g., raise dam height)
		Remove sediment from reservoirs
		Amend reservoir operating rules to add flexibility
	Diversify existing water supplies	
		Build new canals to connect supply systems
		Alter trans-basin diversion agreements
		Purchase water rights
		Groundwater banking
		Dry-year options
Demand		
	Reduce demand	
		Reduce system losses
		Replace thirsty landscaping
	Encourage or improve withdrawal efficiency	
		Change pricing structure
		Educate public about conservation
		Update building codes
		Enhanced industrial recycling
		Improve irrigation practices
	Shift or avoid demand	
		Move demand to less stressed locations
		Use zoning to preclude demand

Options for building adaptive capacity, some of which

address the barriers to adaptation listed above, include the following five endeavors: (1) improve institutional capacity by actions such as removing obstacles to coordination across political jurisdictions and land ownerships, improving processes for conflict resolution, and enhancing technical expertise; (2) revisit past agreements that were established under conditions that no longer accurately reflect existing or expected hydrologic and socioeconomic conditions, as in the case of the Colorado River Compact (Schlager & Heikkila, 2011); (3) create flexible allocation systems through such actions as clarifying individual water rights, removing obstacles to water transfers, creating water banks, authorizing and simplifying procedures for acquisition of in-stream flow rights, and streamlining procedures for adjudication when conflicts arise; (4) improve monitoring capacity to facilitate adaptive management, which relies on monitoring to detect change and evaluate the effectiveness of adaptation actions (indeed, investment in water information infrastructure and seasonal forecasting capability is likely one of the most cost-effective adaptive measures available for water resource management); and (5) address existing infrastructure problems because many existing impediments to successful water management—such as aging water management infrastructure (e.g., leaky pipes, outmoded processes), unsafe bridges and levees, and lack of adequate water metering—could become greater impediments under an altered climate.

Approaches for adapting to impending water issues tend to be similar to those used in the past. For example, approaches for adapting to water shortages (); (Bates, Kundewicz, Wu, & Palutikof, 2008; Brekke, et al., 2009; Hanak & Lund, 2011) include, on the supply side, developing new supplies (e.g., desalinization); improving existing supplies (e.g., removing sediment from reservoirs), and diversifying existing supplies (e.g., installing new canals to connect supply systems), and, on the demand side, reducing system losses, improving efficiency (e.g., updating building codes; improving irrigation efficiency), and precluding some uses (e.g., via zoning). For other examples of adaptation options, see Palmer et al. (2009) on dealing with ecosystem impacts and Kunreuther & Michel-Kerjan (2009) on responding to increased flooding.

Clearly, successful adaptation in response to the substantial water-related challenges that future climate change may bring—given the uncertainty about the effects of climate change in a given location—is a formidable task. Yet, some optimism is reasonable given (1) the success, by-and-large, of past water management planning in the U.S. in designing infrastructure to accommodate future hydrologic variability and managing water systems using what has been called ad hoc, autonomous adaptation (Stakhiv, 1998); (2) the potential for comprehensive planning frameworks, such as Integrated Water Resource Management (GWP, 2009), to facilitate building adaptive capacity; and (3) the maturation of robust decision-making strategies – essentially the adaptation of proven principles and techniques for evaluating the risks and accounting for the uncertainties associated with a non-stationary climate in conjunction with demographic and other changes; (4) excellent examples of recent adaptation planning, such as that of New York City (New York City Panel on Climate Change, 2010); and (5) increased levels of interagency collaboration within the Federal water sector aimed at improving the institutional capacity for both evaluating risks and adaptively managing future adverse effects (Brekke, et al., 2009; IWRSS, 2011).

Research Needs

Despite the wealth of information that has been evaluated about climate change and water resources to date, there remain a number of research needs that, when addressed, will improve water resources management in the future.

a. Climate Information Needs:

One primary focus that has remained consistent over the past decades is to fundamentally improve projections of future climate both in terms of spatial and temporal scales as well as skill (e.g., Reclamation, 2011; WUCA, 2009). Included are better representations of global climate response through improved GCMs as well as improved capabilities with respect to statistical and dynamical downscaling techniques to represent climate information at scales relevant to water resources management. Additionally, better representation of hydrologic extremes in terms of both flood producing rainfall and periods of drought would be beneficial to the future.

b. Hydrologic Information

There also exists a need to better describe the natural system response to changes in climate as well as the social system response when conducting water resources planning studies (Brekke, et al., 2009; Brekke, et al., 2011). Included is how the natural system will both respond to changes in climate such as vegetation changes resulting, for example, in altered evapotranspiration, and how this affects watershed response to climatic drivers. Additionally increased knowledge of ecosystem response to changes in climatic drivers will provide more information about how best to manage water resources for integrated systems. Social system responses such as population dynamics, changes in prioritization of potentially competing objectives, land use changes all need to be better understood to better manage water resources for the future.

c. Water Resource Systems and Decision Making

There are needs that would benefit the operations of existing water resources systems as well. These needs have been categorized as a need for improved monitoring networks, forecasting of weather information from hours to weeks to months, improved understanding on product relationships and utilization in water management, and improvement of informational services from an enterprise approach (D. Raff, Brekke, Werner, Wood, & White, 2013).

There is also a broad category of research need related to decision making within the context of the uncertainty associated with future climate (Brekke, et al., 2009; Brekke, et al., 2011). This includes how to utilize traditional water resources planning techniques, or novel new techniques, with new assumptions about future climate. There are research needs associated with characterizing the uncertainties associated with approaches that utilize new assumptions of future climate. There are additional research needs associated with how to communicate these uncertainties to decision makers.

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Institute for Water Resources

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