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USACE DROUGHT CONTINGENCY PLANNING in the Context of Climate Change

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EXECUTIVE SUMMARY

The US Army Corps of Engineers (USACE) faces a number of challenges in the 21st century. Among these are increasing water demand from USACE reservoirs of river systems regulated by USACE projects and the potential for increased occurrences and severity of drought, including in areas of the country formerly thought to have exhaustive supplies of water. Following the Western droughts of the 1970's, USACE published Engineer Regulation (ER) 1110-2-1941, titled Drought Contingency Plans, in 1981 (USACE 1981). This ER provides policy and guidance for the preparation of drought contingency plans (DCPs) relative to water control management. Since that time, the combination of water control manuals, DCPs, and deviations has provided a great deal of flexibility to respond to short-term and long-term needs based on best available information and science.

Consistent with standard engineering practice in the years following the issuance of ER 1110-2-1941, DCPs were prepared based on observed periods of record with regard to temperature, precipitation and drought, and did not address the potential for changes in climate extremes in the future. However, as noted by the US National Climate Assessment (Melillo et al., 2014), climate is changing and is projected to continue to change. These changes vary regionally and include warming temperatures, altered precipitation patterns, increasing heat waves (particularly in the West), changing snow patterns (Walsh et al., 2014) and droughts (Georgakakos et al., 2014). Increases in summer drought are likely across the northern tier of states, including the Northeast, Northwest and Alaska, while increases in drought are likely in the southern Plains, Southeast, and Hawai'i. The already arid Southwest is anticipated to see large increases in drought frequency and severity. The Midwest and northern Plains, however, are anticipated to experience little change in drought frequency, and even reductions in drought in northern portions of these regions.

Given these observed and projected changes in drought conditions, USACE has undertaken a project to assess the state of drought contingency planning and develop methods to update DCPs to account for changing climate. The National Inventory of Dams reports that the U.S. Army Corps of Engineers (USACE) operates and maintains 707 dams at 557 projects, including 173 lock and dams. DCPs are typically only completed for projects with controllable storage, and thus are typically not developed for lock and dam projects and for the approximately 10% of the dams at USACE projects that do not maintain normal storage levels and typically have dry reservoirs. The team collected and reviewed 142 DCPs covering 301 projects. No DCPs were located for the remainder of the projects. This report contains an overview of climate, climate change, and drought in the United States to aid in planning for current and future droughts at USACE projects. The information summarized in this report sets the context for related work to develop methods and tools to improve understanding of projected conditions, and will serve as a guide for developing a strategy to update existing DCPs nationwide.

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USACE Drought Contingency Planning in the Context of Climate Change

BACKGROUND

The National Inventory of Dams reports that the U.S. Army Corps of Engineers (USACE) operates and maintains 707 dams at 557 projects, including 173 lock and dams. Approximately 10% of the dams at USACE projects that do not maintain normal storage levels typically have dry reservoirs. Other water control projects are typically multifunctional structures operated to meet several, sometimes competing missions, among which may be flood control, navigation, hydropower, water supply, water quality, recreation, and fish and wildlife benefit (USACE, 1987). Many of these purposes require identifying and sustaining the firm yield, the minimum outflow necessary for the project to meet its authorized purposes. Drought is one of many major threats to achieving this firm yield. Therefore, drought contingency planning is an important component of developing project-specific water control manuals.

The specifics of developing Drought Contingency Plans are detailed in Engineering Regulation (ER) 1110-2-1941, titled Drought Contingency Plans, dated 15 September 1981 (USACE 1981). The purpose of a DCP is to provide a basic reference for water management decisions and responses to a water shortage in a basin due to climatological drought. DCPs outline the process for identifying and monitoring drought at a facility, inform decisions water operations staff take to mitigate drought effects, and define the coordination needed to manage the (District) water resources to ensure that they are used in a manner consistent with the needs which develop. Because of the long-term nature of a drought and the uncertainties of the specific problems that may result, DCPs specify a minimum suite of actions that must be carried out related to water control, leaving open opportunities for additional action as the situation warrants.

Because climate change has been and is anticipated to continue to affect the frequency, duration, and spatial extent of drought in the United States (Brekke et al., 2009; Melillo et al., 2014), USACE Project Delivery Team (PDT), along with WEST Consultants, conducted a comprehensive analysis of existing DCPs to evaluate them, identify gaps, and determine whether existing DCPs are robust enough for projected future drought conditions. The last is important, because systematic preparation of DCPs was last undertaken in the 1980s and early 1990s, though some DCPs were finalized in 2011 and others are currently in the planning stage. While none of the available DCPs included information about drought projections under future climate change, further examination may identify some DCPs that are robust enough for projected future conditions. Given the recent droughts of 2012 in the middle US, and the drought of 2013-14 in the southwest, there is more pressure now to be sure that DCPs are up to date. This program will produce information that will support strategies to inform the systematic revision of DCPs to account for changing climate. This report documents the status of DCPs in USACE. It also provides an overview of how the frequency and duration of drought operations at USACE dams may be impacted by climate change, and highlights the need for updating DCPs to account for changing climate conditions and for changes in technology and drought monitoring over the last decade.

Objectives and Scope

The objectives of this report are as follows:

- Describe how drought is currently affecting the United States and how climate change is likely to alter drought intensity and frequency across the United States.

- Review the status of USACE DCPs.
- Compare and contrast DCP contents and methods previously used for forecasting drought frequency and intensity in order to evaluate gaps and robustness, develop analytical tools, and to set the stage for future updates to DCPs and DCP guidance if necessary.

As part of this effort, the team collected and reviewed 142 DCPs covering 301 projects. DCPs are not required for the 10% of projects that are dry reservoirs. No DCPs were located for the remainder of the projects. This report summarizes the findings with respect to drought determination, drought actions, water law, potential surplus water available, and drought history. The Project Development Team (PDT) is in the process of selecting five high priority projects and performing pilot updates on their DCPs to help test methods and tools and develop a framework for DCP updates. To facilitate transfer of information, an internal USACE secure web portal[1] was developed to capture the results of the PDT, including DCPs, deviations, pilot information, and other drought-related information.

The remainder of this chapter provides a brief overview of climate, climate change, and drought in the United States as a background to understanding the issues involved in planning for current and future drought at USACE projects in this country.

OVERVIEW OF DROUGHT AND CLIMATE CHANGE

Drought is a recurring extreme climate event over land characterized by below-normal precipitation over a period of months to years relative to the local normal condition (Dai, 2011). Although a lack of precipitation is the root cause of drought, the intensity can be exacerbated by high evaporation rates due to excessive temperatures, high winds, lack of cloudiness and /or low humidity (Figure 1) (Kunkel et al., 2008). Droughts can be classified into three types:

- **Meteorological drought** is a period of months to years in which precipitation is below normal. It can be accompanied by above-normal temperatures and other factors (Figure 1). It can precede and cause the other two types of drought.
- **Agricultural or soil-moisture drought** is a period with dry soils which can reduce crop production and plant growth. Soil-moisture drought can result from below-normal precipitation, above-normal evaporation, or intense but less-frequent precipitation events. Susceptibility to soil-moisture drought can depend on crop or vegetation type.
- **Hydrologic drought** refers to a period when river streamflow and water storages in aquifers, lakes and reservoirs fall below long-term mean levels. It can develop slowly as stored water is used but not replenished.

Both hydrologic and agricultural drought can be caused by meteorological drought, but can also be caused by other factors, including changes in precipitation frequency and intensity, poor water management, and land use changes affecting vegetative cover, runoff and erosion, such as overgrazing and large wildfires. Due to lack of clouds and lack of soil moisture, droughts are often accompanied by heat waves.

In many parts of the western U.S., large-scale water supply reservoir systems exist to buffer meteorological drought, mitigating the impacts of hydrologic drought and of soil-moisture drought in agricultural areas. These systems are therefore resilient to the short- and medium-term drought (months to a few years) common

[1] See https://maps.crrel.usace.army.mil/apex/f?p=875:1: (not accessible outside the USACE).

to these regions. Other areas of the United States typically receive abundant precipitation and tend to be less drought-resilient. Thus, short- and medium- term drought, including seasonal drought, are more significant issues in these regions. Few regions of the U. S, however, would be resilient to long-term drought on the scale evident in tree-ring records of past climate (see discussion on prehistoric drought below).

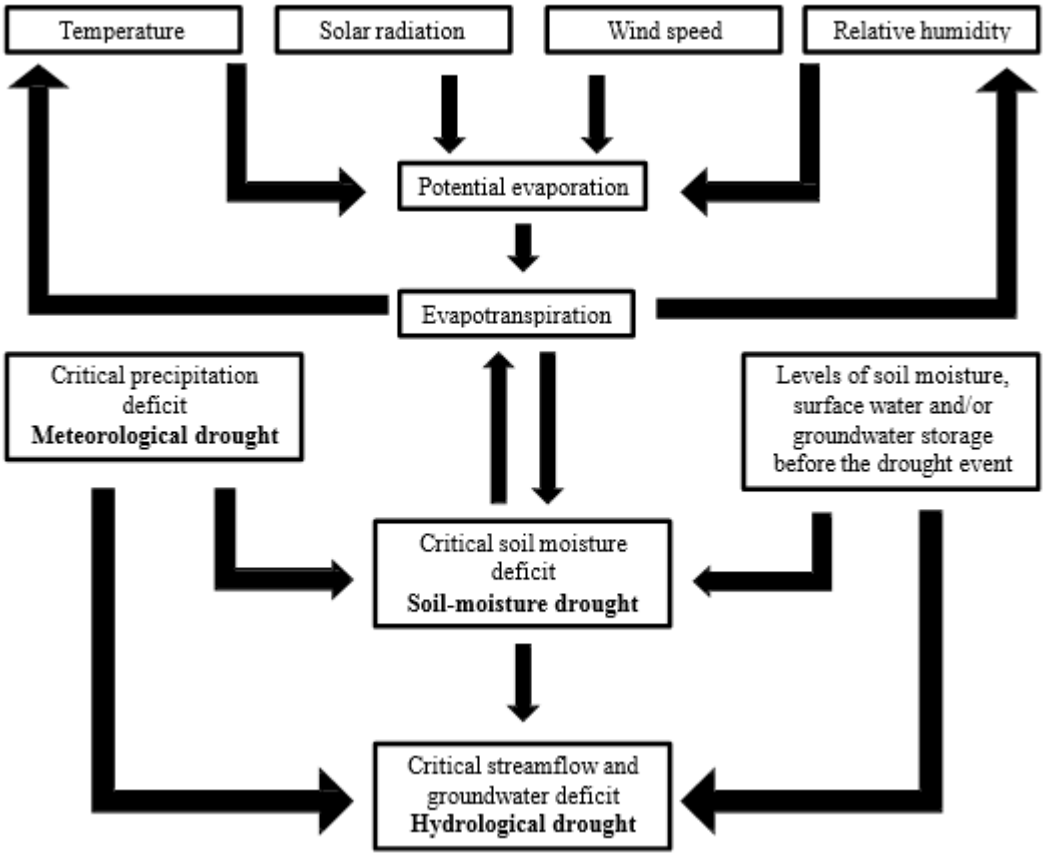

Figure 1 - The factors that drive drought
(after Seneviratne 2012)

Recent Drought Trends

Because of the latitudinal and topographic diversity of the U.S., observational data for the 20th century averaged over the whole country show no clear trend in drought (Kunkel et al., 2008). However, models of soil moisture and runoff for the period 1925-2003 suggest that droughts may have become shorter, less frequent, and spatially less extensive over the last 100 years (Andreadis and Lettenmaier, 2006; Kunkel et al., 2008), although these changes are not uniform: rising temperatures have contributed to increasing drought trends in the Southwest and portions of the interior West (Andreadis and Lettenmaier, 2006; Groisman et al., 2004), and increases in summer season drought in Canada and Alaska (Dai et al., 2004). Elsewhere in the United States, there has been a trend toward wetter conditions since the 1950s (Kunkel et al., 2008). In the upper Mississippi, Midwest, and Northwest, summer conditions have trended toward lesser drought (Kunkel et al., 2008). However, a net shift to drier conditions is evident in the Southwest, California in the spring, and over the Northeast (Kunkel et al., 2008).

The National Integrated Drought Information System (NIDIS) is an official source of drought information. The nucleus of NIDIS was PL 105-199, the National Drought Policy Act of 1998, which established the

National Drought Policy Commission. They in turn recommended a coordinated effort to integrate drought information and provide forecasts. As authorized by PL 109-430, the National Integrated Drought Information System Act of 2006, and reauthorized by PL 113-86, the National Integrated Drought Information System Reauthorization Act of 2014, the NIDIS is co-chaired by a Director (the NOAA Climate Program Office and Director) and Deputy Director (from the National Drought Mitigation Center at the University of Nebraska-Lincoln). Many Federal departments and agencies participate in NIDIS, including USACE.

Since 1999, the NIDIS drought monitor has provided weekly information about the status of drought in the US[2]. These status reports include a map of the US showing the current status of drought divided into the following classes, listed in order of increasing severity: abnormally dry, moderate drought, severe drought, extreme drought, and exceptional drought. The USACE drought contingency portal provides direct access to the current and past drought monitor maps, and also plots the extent of drought as a time series to support comparisons over time nationally. Figure 3 presents an overview of observed drought trends for USACE divisions contained in the drought portal based on information released by the NIDIS drought monitor.

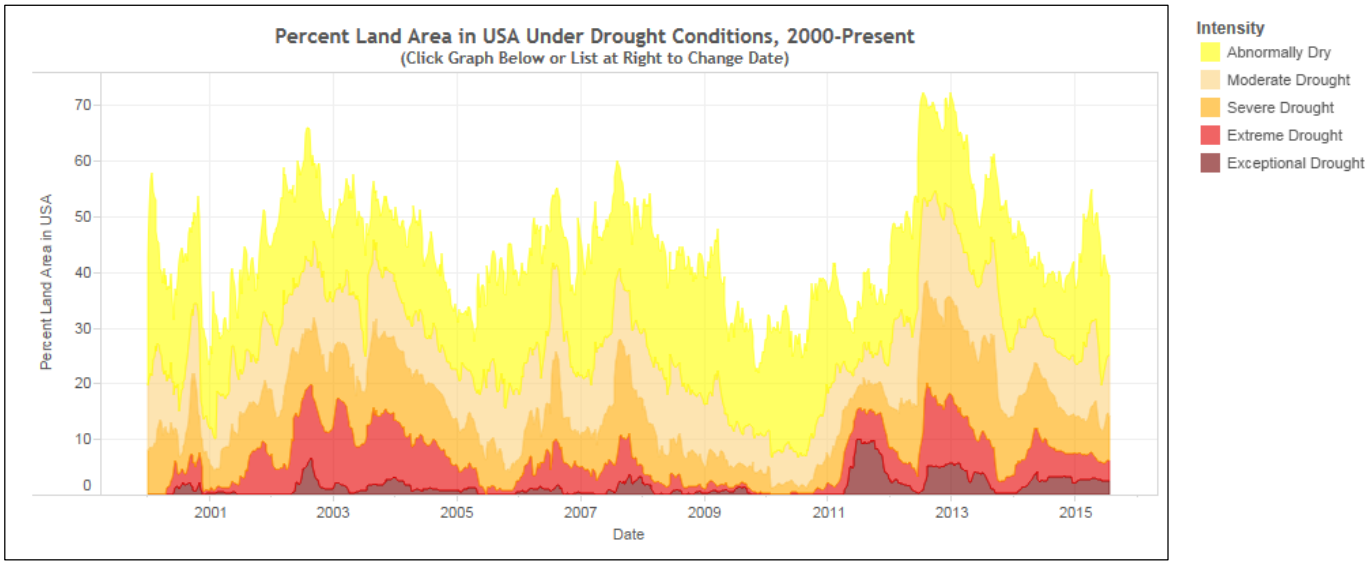

Figure 2 – Drought Trends for the Nation, 1999 - end of August 2015

[2] See http://www.drought.gov/drought/

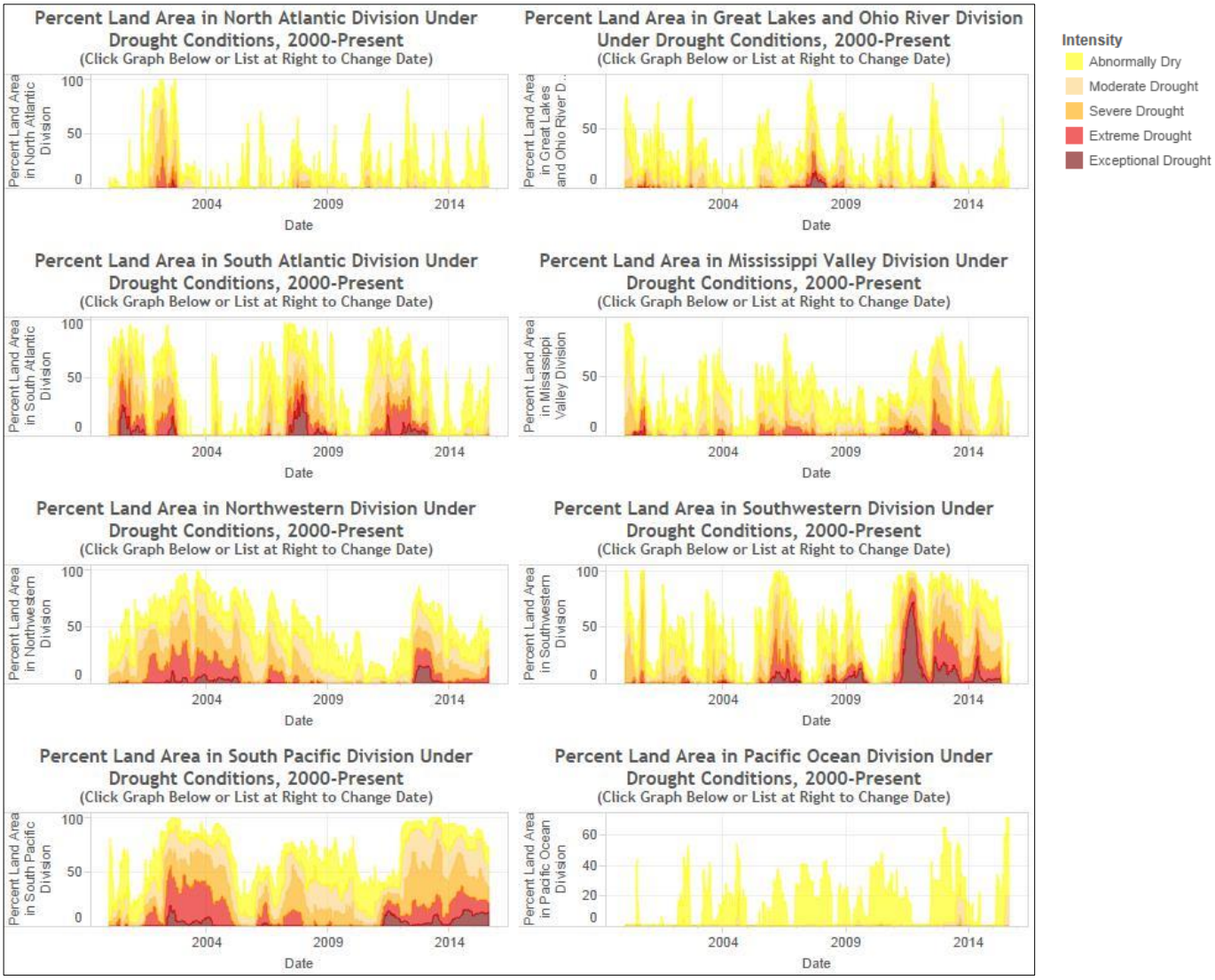

Figure 3 – Drought trends for USACE Divisions, 1999 – end of August 2015

Prehistoric Drought Trends

Although the droughts of the 1930s in the West, the 1950s in the Southwest, and 1987-1989 in the Pacific Northwest, northern Great Plains, and Midwest are recognized as the most severe historic droughts (NOAA, 2003), these droughts are dwarfed in extent and duration by prehistoric droughts evident in the tree ring records in the Southwest and elsewhere. For example, the drought of the mid- to late- 16th century appears to have impacted much of Mexico and the western United States, and may have been continent-wide. This drought was certainly longer-lasting and more widespread than the 1930s drought (Stahle et al., 2000). Longer and more severe droughts are also known from the period 1000-1470 (Grissino-Mayer, 1996; Laird et al., 1996; NOAA, 2003). The tree-ring record 1700-1978 in the United States indicates that droughts comparable to the 1950s drought, in terms of duration and spatial extent, have occurred once or twice a century (Cook, et al., 1999), although there are no other instances of droughts comparable to the 1930s drought in terms of its spatial extent and duration (Cook et al., 1999). However, in many parts of the United States, tree ring datasets spanning the last 500 to 2000 years record droughts lasting as long as several decades (NOAA, 2003), indicating that droughts of this magnitude are well within the range of natural variation for these regions.

Potential Drivers of Drought Change

Although there can be many factors that contribute to the emergence of drought in a region, three drivers dominate discussions of future drought: changes in the boundary between the subtropics and mid-latitudes; increasing temperatures driving up evaporation; and shifts in the frequency and intensity of precipitation. These are outlined briefly, below.

The biggest change in drought frequency is likely to occur due to already-underway shifts in the boundary between the subtropics and the mid-latitudes (Fu and Lin, 2011; Seidel et al., 2008). Warmer global temperatures cause stronger circulation of air between the equator and the poles. The zone of descending air / high pressure associated with the major deserts of the Northern Hemisphere (Chihuahuan, Sonoran, Sahara, Arabian, etc.) currently marks the northern boundary of the subtropics. This boundary shifts northward in summer and southward in winter. Warming is anticipated to strengthen this circulation, which would have the effect of expanding the subtropical dry zone poleward in all seasons. This mechanism is likely to be particularly important in the southern tier of states whose climates are already influenced by subtropical highs, including the Southeast, southern Great Plains, Southwest, and Hawai'i.

Increased temperatures, particularly in the warm season, are likely to drive up evaporation rates, changing the precipitation-evaporation balance in many areas (Trenberth et al., 2014). This mechanism is likely to lead to seasonal drought in some years, even in regions where precipitation increases are expected overall. Increased winter and spring temperatures in mountain headwaters regions are likely to contribute to hydrologic drought downstream due to reductions in the snowpack as a result of increased precipitation falling as rain instead of snow, advances in the timing and volume of spring runoff, and increased spring snowpack sublimation (Knowles et al., 2006; Mote et al., 2005; Stewart et al., 2004, 2005). This mechanism is particularly important for streams that head in the Sierra Nevada and Rocky Mountains, and for regions dependent on these streams.

The third major cause of drought change is likely to be the shift from frequent, small precipitation events to larger, more intense, but less frequent events. More intense precipitation events result in less infiltration / soil moisture recharge and more runoff than a comparable amount of precipitation delivered more slowly. In addition, as precipitation becomes concentrated into fewer events, longer dry spells between events becomes more likely.

The wild card in drought projections are the effects of changes in sea surface temperature on global climate, particularly changes in El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (Trenberth et al., 2014), which contribute significantly to drought by affecting the path of the jet stream over mid-latitude North America and elsewhere. Recent modeling suggests that ENSO teleconnections (global interaction) patterns may not change significantly (Maloney et al., 2013).

Drought Projections by Region

Although some researchers have projected dramatically greater increases in drought across the U.S. (e.g., Dai, 2013), considerable uncertainty surrounds these estimates (Trenberth et al., 2014). This uncertainty arises due to difficulties in measuring drought, difficulties calibrating model data with the historical record due to gaps and other problems with the historical dataset, and uncertainties about the evolution of ENSO (Trenberth et al., 2014). Droughts may or may not become more frequent, but when they set in they are likely to set in quicker, become more intense, last longer, and possibly become more extensive (Trenberth et al., 2014). Expanded drought is likely in the subtropical dry zone (Trenberth et al., 2014).

Across the U.S., seasonal summer drought is expected to intensify (Melillo et al., 2014). Although the magnitude differs among models, almost all recent models simulate summer drying in most parts of the northern subtropics (23-38°N latitude, from Hawai'i and the southern tip of Florida north to approximately the latitude of Richmond, VA and San Francisco, CA) and midlatitudes (from the subtropics north to 67°N latitude, or approximately the latitude of the Arctic Circle as it cuts across the Brooks Range in Alaska). Increasingly arid winters are also expected in subtropical areas excluding Hawai'i, with wetter winters projected for the Northwest, the northern Great Plains, the Midwest, and the Northeast (summarized in Table 1 for regions shown in Figure 4). More detailed descriptions of drought projections by region can be found in Appendix B.

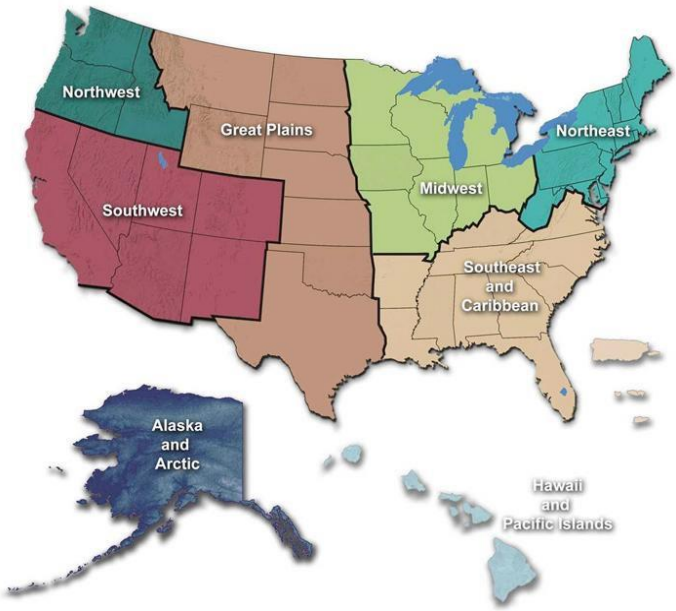

Figure 4 - Regions of the United States, as defined in the National Climate Assessment (Melillo et al., 2014)

Table 1: Increasingly Arid Regions

Region	Projected Drought Change
Northeast	Increased summer / fall drought (warmer and drier) Increased long-term drought (>6 months) in westernmost portion over time Decrease in incidence of severest drought
Midwest	No change in drought frequency North gets wetter; south dries a little in most models
Great Plains	Northern: Wetter climate, with decreased drought likely Central: No change in drought frequency Southern: Drier climate, with increased drought likely Late summer/fall hydrologic drought possible due to changes in monsoon
Northwest	Increased summer drought possible Increased hydrologic drought due to changes in mountain snowpack
Alaska	No change in meteorological drought incidence Higher summer temperatures and permafrost and glacier changes droughts, particularly in the south
Southeast	Drier west, with increased drought possible, especially in the south Increased chance of hydrologic drought across southern portion Increased precipitation northern and eastern portions
Southwest	Increased drought all seasons, with increased multi-year drought likely in the southern half of the region Complete loss of snowpack in NM below 36° south Central and northern California may get wetter
Hawai'i and Pacific Islands	Increased winter drought possible

Figures 5 through 8 show the projected changes in average drought severity index (an indicator developed for use in the USACE watershed vulnerability assessments based on downscaled CMIP5 projections) for 30-year periods centered on 2050 and 2085, compared to the historical baseline average for the period 1950-2004. The maps are based on 93 climate models binned as dry (driest 50% of models) or wet (wettest 50% of models). Drought severity here is estimated using the Thornthwaite (1948) method that takes into account the aridity or humidity of the soil and climate in the region and is calculated from the effects of precipitation, evapotranspiration, soil moisture deficit, and runoff. In general, the map shows that drought becomes more severe (more frequent and more intense) in almost all areas of the United States, with the greatest increases in the Southwest, southern Plains, and Southeast. Changes are least North and East of the Mississippi River.

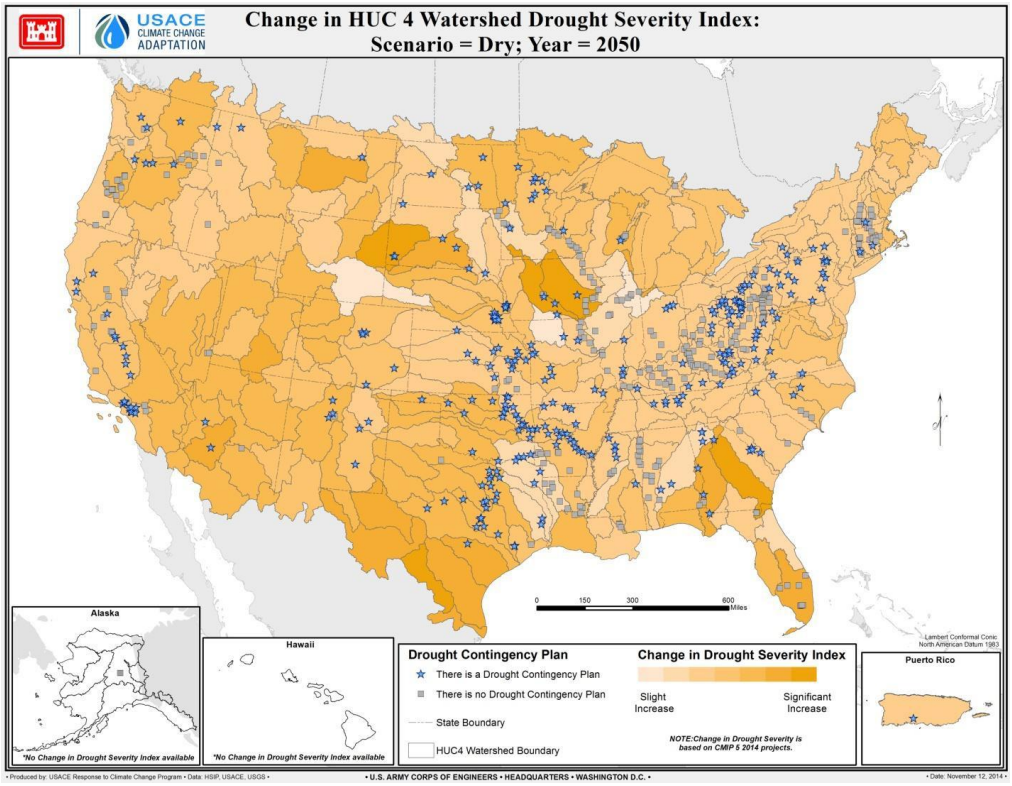

Figure 5 - Map showing DCP status and projected change in drought severity by HUC 4 code for the driest 50% of models for the 30-year period centered on 2050 (2035-2064)

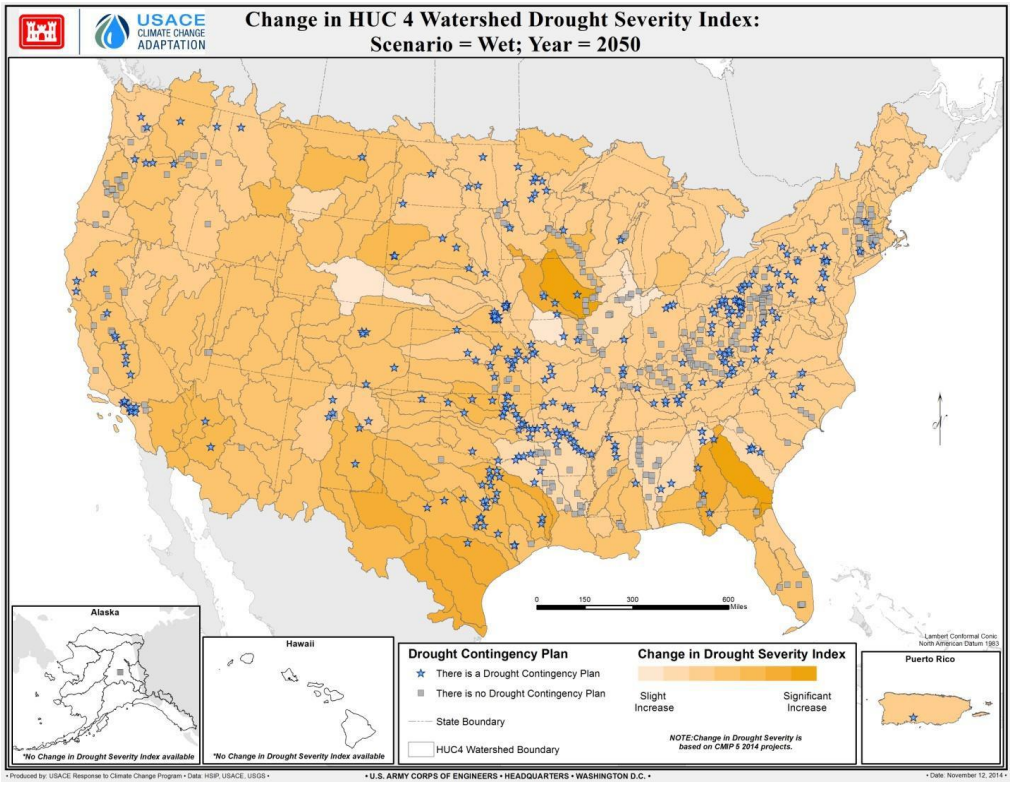

Figure 6 - Map showing DCP status and projected change in drought severity by HUC 4 code for the wettest 50% of models for the 30-year period centered on 2050 (2035-2064)

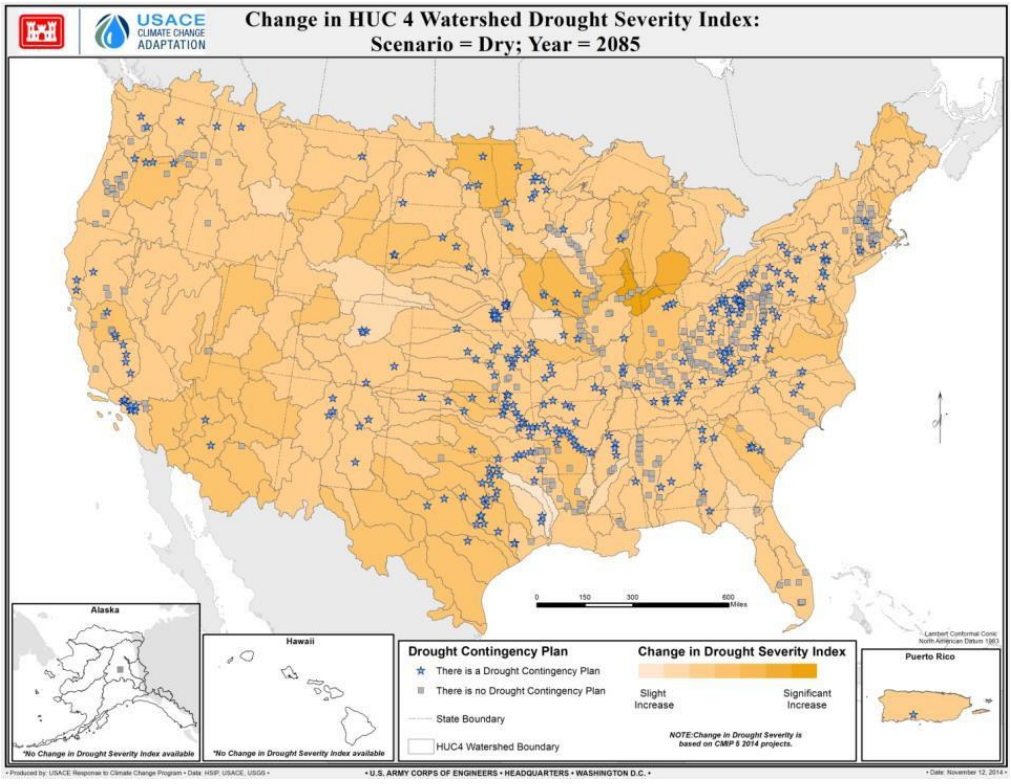

Figure 7 - Map showing DCP status and projected change in drought severity by HUC 4 code for the driest 50% of models for the 30-year period centered on 2085 (2070-2099)

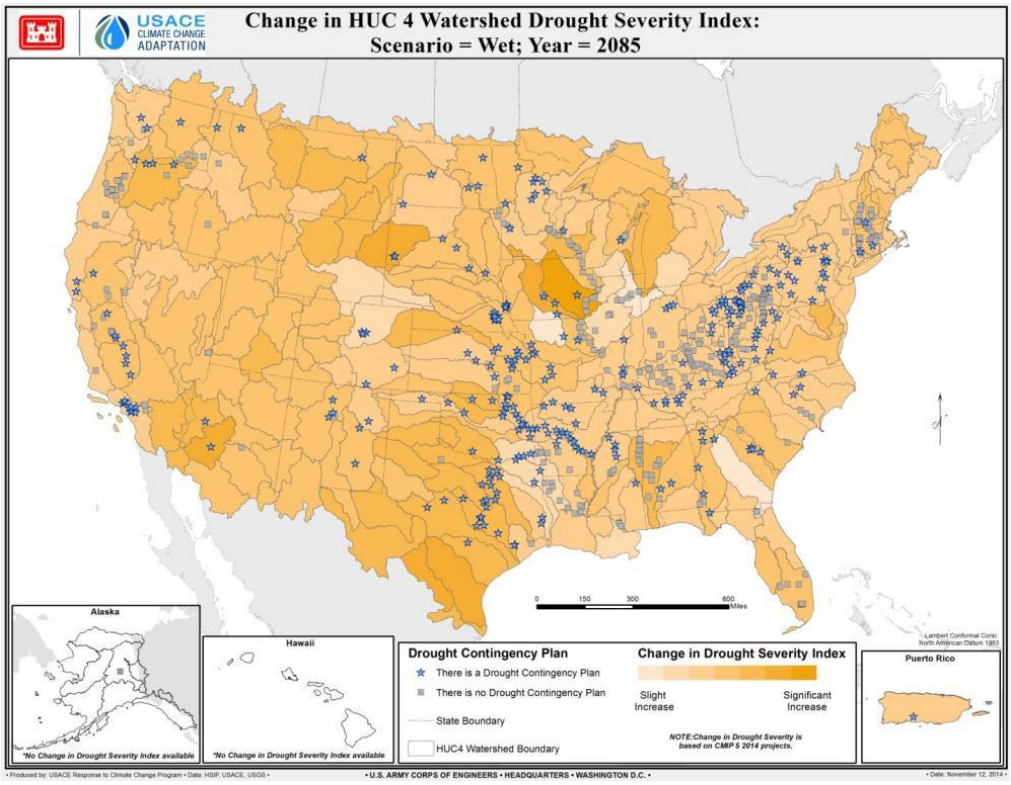

Figure 8 - Map showing DCP status and projected change in drought severity by HUC 4 code for the wettest 50% of models for the 30-year period centered on 2085 (2070-2099)

ASSESSMENT OF EXISTING DROUGHT CONTINGENCY PLANS

Purpose and Features of Drought Contingency Plans

DCPs are general guides for dynamic management of projects, or systems of projects, to address drought needs. DCPs are typically only completed for projects with controllable storage, and thus are not generally developed for lock and dam projects or dry reservoirs. A DCP should evaluate a project's capacity to address any aspect of drought, including issues relative to water supply, water quality, environment, fire protection, industry, recreation, power, and navigation. Drought impacts are difficult to measure; however, there are numerous concerns relative to drought that are commonly expressed. Those include: increasing municipal and industrial use of the water supply; competing uses of water supply amongst communities, industry, and fish/recreation interests; salt water intrusion and available fresh water supply; and impacts to agriculture.

In response to the droughts of the late 1970's, the USACE Institute for Water Resources (IWR) undertook a series of studies related to climate change and its implications for water resources planning (e.g., Stockton and Boggess, 1979; Beard and Maristany, 1979). In 1981, USACE published ER 1110-2-1941, Drought Contingency Plans. This regulation provides policy and guidance for the preparation of DCPs in the context of water control management, as a component of the project water control manual.

USACE reservoirs are operated according to water control manuals, including reservoir rule curves and drought contingency plans. With the passage of the Water Resources Development Act of 1990 (WRDA '90), public involvement became a requirement in the development of and modification to water control manuals (Section 310(b) of WRDA '90). A DCP approved after WRDA '90 that results in a change of the water control plan must comply with WRDA '90. It is the policy of the Chief of Engineers that water control plans be continually reviewed, updated, and adjusted as needed to ensure that the best use is made of available resources. Changes that have occurred over the intervening 30 years, most notably changes in climate affecting water supply and changes in water demand, stress the need for continual review and pertinent revision. USACE reservoir operations have proved relatively robust to observed climate changes. The combination of water control manuals, DCPs, and deviations provide a great deal of flexibility to respond to short-term and long-term needs based on best available information and science.

Significant features or objectives of DCPs are: drought monitoring and identification, implementation mechanisms, coordination procedures, and standard agreements between USACE and partner agencies. Monitoring reviews current conditions to assess whether defined trigger points (such as a particular water elevation) are being reached at a project. The term implementation mechanisms defines the actions that must occur when a particular trigger point is reached, and the processes established to implement these actions. Coordination with other Federal, state, and local agencies is essential to ensure that the DCPs reflect the public's needs during drought situations in order to make the maximum response based on current authorities.

Current Status of Drought Contingency Plans

The PDT conducted a comprehensive analysis of USACE DCPs. This review located 142 DCPs, covering only about half of the USACE projects that should have DCPs available (see Appendix A). Analysis of these DCPs found that seven topic areas were consistently covered in most of the documents. These topic areas include: water law, water supply and water users, surplus water available during a drought, drought history, drought monitoring and drought level determination, drought issues and drought actions, and drought coordination.

As shown in Figure 9, most of the DCP reports reviewed were completed prior to 2000, before information on climate change was widely available. None of the DCPs reviewed include information about drought projections under future climate change. Consequently, it is unlikely that these reports provide an adequate guide for preparing for future droughts that may be longer and more intense than recognized by these DCPs. However, following development of analysis tools in a later phase of this project, these will be evaluated for robustness to handle projected climate changes.

Need for Updating Drought Contingency Plans

Challenges facing USACE include increasing water demand and the potential for increased occurrences and severity of drought. This includes areas of the country formerly thought to have exhaustive supplies of water. In 1981, USACE published ER 1110-2-1941, Drought Contingency Plans (DCPs). This regulation provides policy and guidance for the preparation of DCPs in the context of water control management. These DCPs were directed to be prepared for each USACE project or system of projects having controlled reservoir storage. Updates to existing DCPs were required in the early 1990s. Consistent with contemporary approaches, these DCP updates assumed that historic patterns of temperature, precipitation, and drought provided a reasonably accurate model of future regional conditions. However, water resources planners are recognizing that this interpretation is not correct (e.g., Brekke et al., 2009; Georgakakos et al., 2014): climate change will affect future patterns of temperature,

precipitation, streamflow, and drought that in many regions will differ significantly from those conditions in the historic period. Consequently, USACE has recognized the necessity of using the best available and actionable science on climate change impacts to water resources in updating project Drought Contingency Plans (USACE, 2014)

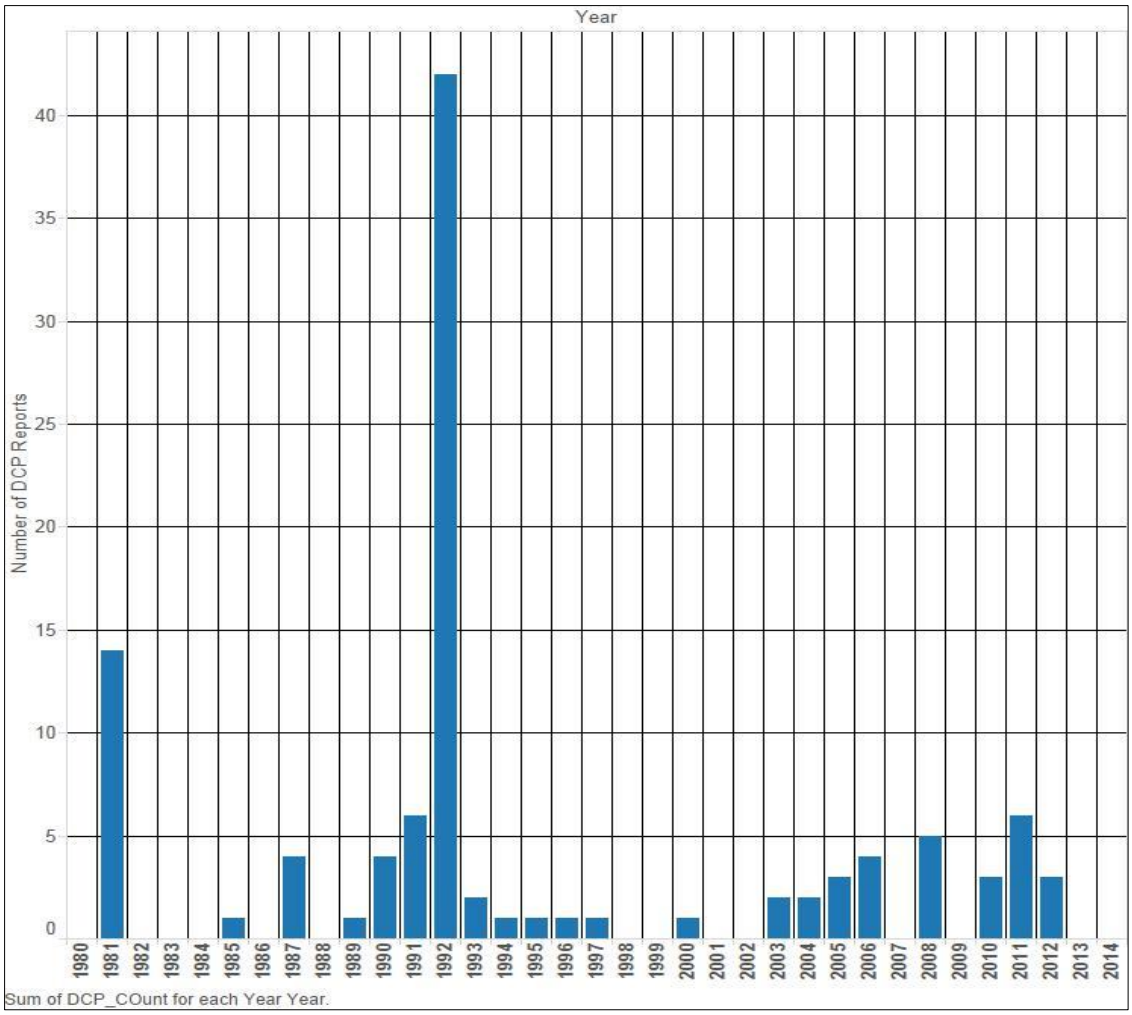

Figure 9 - Number of DCP reports finalized by year

Knowledge Gaps and Needs

Each district has unique operating issues and constraints. Operating issues may be impacted by factors such as the quantity of inactive storage and the ability to utilize it, the quantity of uncontracted water supply storage and the ability to use it, dam safety issues restricting changes in operations, the obligation for releases to support downstream water quality efforts, the obligation for releases to protect endangered species, and the determination of surplus water and use of it in relation to the overall sustainability of the project under given conditions. Constraints that impact project functions and DCPs can include the governing water rights and laws and corresponding rights of downstream users, minimum flow requirements for environmental or other concerns, and specific issues derived from the involvement and coordination with other federal, state, and local agencies.

Since the development of the existing DCPs, the products available for short-term forecasting (up to approximately 180 days) and characterization of drought have greatly improved. One example of this is from the National Weather Service Climate Prediction Center (CPC) (http://www.cpc.ncep.noaa.gov/). The CPC site provides outlooks on drought potential as well as the characterization of parameters such as precipitation and soil moisture anomalies. Future efforts of the PDT will include identification of all pertinent resources for short-term climate data, such as "Short-Term Water Management Decisions: User Needs for Improved Climate, Weather, and Hydrologic Information" (Raff et al., 2013), and provide suggestions on how to apply and disseminate this information during a drought.

In addition to improvements in short-term forecasting, the science of long-term climate change has also improved since many of these DCPs were developed (e.g., Brekke, 2011). Inclusion of this information in updated DCPs will aid in the long-term planning of the reservoir systems. The PDT is currently working with internal and external experts to develop an approach for incorporating these findings into the updated DCPs. Recommendations for how DCPs might be adjusted to reflect such changes will be comprehensively discussed in a follow-on report.

An additional gap is the lack of a standard method to evaluate DCP robustness to potential climate change impacts. This gap is being addressed by the PDT in a related work effort. Once the proper methods and tools are available, and a strategy for prioritization has been developed, DCP updates to account for climate change can be implemented for those with existing DCPs and projects that do not yet have a DCP. Ideally, the methods and tools developed by the PDT will streamline the development of these new DCPs as well as the process of updating existing DCPs.

DISCUSSION

Effective water management depends on adaptation to current while preparing for future conditions. The National Climate Assessment has identified observed changes in drought frequency, intensity and duration, and projected that, in the future, these are likely to fall outside the range of historical droughts used to design many USACE projects. DCPs are a critical element of flexible water management when combined with water control manuals and the deviation process. Therefore, it is critical that a strategy be developed providing a pathway for DCP updates to account for climate change. This document provides the foundation for the discussions needed to develop such a strategy.

To date, this effort has yielded a comprehensive overview of all available DCPs throughout the USACE. This information will be used to develop standard methods for updating DCPs to account for climate change if they do not exhibit robustness for projected changes in further analyses. It is recommended, however, that flexibility should be used in the development of DCPs since each project has unique requirements.

The next steps include the development of strategies for evaluating projects in light of projected short-term and long-term climate data. The short-term climate data can assist in a more robust determination of drought levels and in the development of more effective communication tools, while the long-term climate models can help predict changes decades into the future for long- term planning purposes.

The PDT is also conducting pilot DCP updates. These projects were chosen so as to represent each division with a variety of project uses. Pilot projects are currently planned for the following divisions: Lakes and Rivers, Mississippi Valley, Southwestern, South Pacific and Northwestern. Lessons learned from each of these updates will be applied to subsequent updates and will be included in the guidance developed for dissemination to the Districts.

ADDITIONAL INFORMATION

This technical note was prepared by PDT members including staff from districts, the USACE Engineer Research and Development Center, and the USACE Institute for Water Resources, under the Responses to Climate Change Program.

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APPENDIX A: Projects Reviewed for this Study

Appendix A contains two tables. Table A-1 provides a list of projects with DCPs that were reviewed for this study; DCP publication year was provided when available. Table A-2 provides a list of DCPs covering more than one USACE project; N is the number of projects included in the system DCP.

Table A-1 – Projects With DCPs Reviewed For This Study

DISTRICT	DAM NAME	DCP YEAR
Great Lakes & Ohio River Division		
Huntington	Alum Creek Dam	1989
Huntington	Atwood Dam	1992
Huntington	Beach City Dam	1992
Huntington	Beech Fork Lake Dam	2010
Huntington	Bluestone Dam	1989
Huntington	Bolivar Dam	1992
Huntington	Burnsville Lake Dam	2010
Huntington	Charles Mill Dam	1992
Huntington	Clendening Dam	1992
Huntington	Deer Creek Dam	1989
Huntington	Delaware Dam	1989
Huntington	Dewey Dam	1989
Huntington	Dillon Dam	1992
Huntington	Dover Dam	2010
Huntington	East Lynn Dam	2010
Huntington	Fishtrap Dam	1989
Huntington	Grayson Dam	2010
Huntington	John W Flannagan Dam	1989
Huntington	Leesville Dam	1992
Huntington	Mohawk Dam	1992
Huntington	Mohicanville Dam	1992
Huntington	N. Br. Of Kokosing Dam	1992
Huntington	N. Fork Of Pound Dam	1989
Huntington	Paint Creek Dam	1989
Huntington	Paintsville Dam	1989
Huntington	Piedmont Dam	1992
Huntington	Pleasant Hill Dam	1992
Huntington	R D Bailey Dam	1992
Huntington	Senecaville Dam	1989
Huntington	Summersville Dam	1989
Huntington	Sutton Dam	1989
Huntington	Tappan Dam	1992
Huntington	Tom Jenkins Dam	1992
Huntington	Wills Creek Dam	1992
Huntington	Yatesville Dam	1989
Louisville	Mississinewa Lake Dam	1995
Louisville	Salamonie Lake Dam	1995
Louisville	Taylorsville Lake	1995

DISTRICT	DAM NAME	DCP YEAR
Nashville	Barkley Dam	1994
Nashville	Center Hill Dam	1994
Nashville	Cheatham Dam	1994
Nashville	Cordell Hull Dam	1994
Nashville	Dale Hollow Dam	1994
Nashville	J Percy Priest Dam	1994
Nashville	Laurel Dam	1994
Nashville	Old Hickory Dam	1994
Nashville	Wolf Creek	1994
Pittsburgh	Berlin Dam	1992
Pittsburgh	Kinzua Dam	1992
Pittsburgh	Mahoning Creek Dam	1992
Pittsburgh	Michael J Kirwan Dam and Reservoir	1992
Pittsburgh	Mosquito Creek Dam	1992
Pittsburgh	Shenango Dam	1992
Pittsburgh	Stonewall Jackson Lake	1992
Pittsburgh	Tygart Dam	1992
Pittsburgh	Woodcock Creek Dam	1992
Pittsburgh	Youghiogheny Dam	1992
Mississippi Valley Division		
Rock Island	Coralville Dam	1996
Rock Island	Red Rock Dam	1992
Rock Island	Saylorville Dam	1992
St. Louis	Carlyle Lake Dam	1992
St. Louis	Clarence Cannon Dam	1992
St. Louis	Lake Shelbyville Dam	1992
St. Louis	Rend Lake Dam	1992
St. Paul	Baldhill	1992
St. Paul	Highway 75 Dam	1992
St. Paul	Lac Qui Parle Dam	1992
North Atlantic Division		
Baltimore	Almond Lake	1981
Baltimore	Alvin R Bush Dam	1991
Baltimore	Cowanesque Dam	1981
Baltimore	Curwensville Dam	1991
Baltimore	Foster Joseph Sayers Dam	1991
Baltimore	Raystown Dam	1981
Baltimore	Stillwater Dam	1981
Baltimore	Tioga Dam	1981
Baltimore	Whitney Point Dam	1981
Baltimore	York Indian Rock Dam	1981
New England	Black Rock Dam	1993
New England	Mansfield Hollow Dam	1992
New England	Otter Brook Dam	1992
Philadelphia	Beltzville Dam	1994
Philadelphia	Blue Marsh Dam	1994

DISTRICT	DAM NAME	DCP YEAR
Northwestern Division		
Omaha	Bear Creek	1987
Omaha	Big Bend Dam	2006
Omaha	Bowman Haley	1985
Omaha	Chatfield Dam	1987
Omaha	Cherry Creek Dam	1987
Omaha	Fort Peck Dam	2006
Omaha	Fort Randall Dam	2006
Omaha	Garrison Dam	2006
Omaha	Gavins Point Dam	2006
Omaha	Lake Traverse	1992
Omaha	Oahe Dam	2006
Omaha	Papillion Creek Site 11 - Glenn Cunningham Lake	1987
Omaha	Papillion Creek Site 16 - Standing Bear Dam	1987
Omaha	Pipestem Dam	2008
Omaha	Salt Creek Site 10 - Yankee Hill Dam	1987
Omaha	Salt Creek Site 12 - Conestoga	1987
Omaha	Salt Creek Site 13 - Twin Lakes Dam	1987
Omaha	Salt Creek Site 14 - Pawnee Dam-	1987
Omaha	Salt Creek Site 17 - Holmes Lake	1987
Omaha	Salt Creek Site 18 - Branched Oak	1987
Omaha	Salt Creek Site 2 - Olive Creek Dam	1987
Omaha	Salt Creek Site 4 - Bluestem	1987
Omaha	Salt Creek Site 8 - Wagon Train Dam	1987
Omaha	Salt Creek Site 9 - Stagecoach Dam	1987
Omaha	Wehrspann	1987
Omaha	Zorinsky Lake	1987
Seattle	Hiram M. Chittenden Locks & Dam	1992
South Atlantic Division		
Mobile	Allatoona Lake Dam and Powerhouse	2011
Mobile	Buford	2011
Mobile	Carters Main Dam	2011
Mobile	Claiborne Lock and Dam	2011
Mobile	Jim Woodruff Dam	2011
Mobile	Millers Ferry Lock,Dam & Powerhouse	2011
Mobile	Okatibbee Dam	1997
Mobile	Robert F. Henry Lock and Dam	2012
Mobile	Walter F George Lock,Dam,Powerhouse	2012
Mobile	West Point	2012
Wilmington	B. Everett Jordan Dam	2008
Wilmington	Falls Lake Dam	2008
Wilmington	John H Kerr Dam	1992
Wilmington	Philpott Dam	1991
Wilmington	W. Kerr Scott Dam	1991

DISTRICT	DAM NAME	DCP YEAR
South Pacific Division		
Albuquerque	Abiquiu Dam	1991
Albuquerque	Cochiti Lake	1991
Albuquerque	Conchas Dam	1991
Albuquerque	Jemez Canyon Dam	1991
Albuquerque	John Martin Dam & Reservoir	1990
Albuquerque	Santa Rosa Dam	1990
Albuquerque	Trinidad	1990
Albuquerque	Two Rivers Dam (Diamond A & Rocky)	1990
Los Angeles	Alamo Dam	1992
Los Angeles	Brea Dam	1992
Los Angeles	Carbon Canyon Dam	1992
Los Angeles	Fullerton Dam	1992
Los Angeles	Hansen Dam	1992
Los Angeles	Lopez Dam	1992
Los Angeles	Painted Rock Dam	1992
Los Angeles	Prado Dam	1992
Los Angeles	San Antonio Dam	1992
Los Angeles	Santa Fe Dam	1992
Los Angeles	Sepulveda Dam	1992
Los Angeles	Whittier Narrows Dam	1992
Sacramento	Black Butte Dam	1992
Sacramento	Buchanan Dam	2006
Sacramento	Hidden Dam	2004
Sacramento	Isabella Dam	2008
Sacramento	New Hogan Dam	1992
Sacramento	Pine Flat Dam	1992
Sacramento	Success Dam	1992
Sacramento	Terminus Dam	2005
San Francisco	Coyote Valley Dam	1993
San Francisco	Warm Springs Dam	1993

DISTRICT	DAM NAME	DCP YEAR
Southwestern Division		
Fort Worth	Aquilla Lake	1991
Fort Worth	Bardwell Lake	1991
Fort Worth	Belton Lake	1991
Fort Worth	Benbrook Lake	1991
Fort Worth	Canyon Lake	1991
Fort Worth	Granger Dam and Lake	1991
Fort Worth	Grapevine Lake	1991
Fort Worth	Hords Creek Lake	1991
Fort Worth	Joe Pool Lake	1991
Fort Worth	Lavon Lake	1991
Fort Worth	Lewisville Lake	1991
Fort Worth	Navarro Mills Lake	1991
Fort Worth	North San Gabriel Dam	1991
Fort Worth	O C Fisher Dam and Lake	1991
Fort Worth	Proctor Lake	1991
Fort Worth	Ray Roberts Dam	1991
Fort Worth	Sam Rayburn Dam and Reservoir	1991
Fort Worth	Somerville Lake	1991
Fort Worth	Stillhouse Hollow Dam	1991
Fort Worth	Town Bluff Dam	1991
Fort Worth	Waco Lake	1991
Fort Worth	Whitney Lake	1991
Little Rock	Beaver	1989
Little Rock	Blue Mountain	2006
Little Rock	Bull Shoals	1989
Little Rock	Clearwater Dam	1989
Little Rock	Dardanelle Lock & Dam	2006
Little Rock	David D. Terry Lock & Dam	2006
Little Rock	Emmett Sanders Lock & Dam	2006
Little Rock	Greers Ferry	1989
Little Rock	James W. Trimble Lock & Dam	2006
Little Rock	Joe Hardin Lock & Dam	2006
Little Rock	Murray Lock & Dam	2006
Little Rock	Nimrod	2006
Little Rock	Norfork	1989
Little Rock	Norrell Lock & Dam	2006
Little Rock	Ozark Lock & Dam	2006
Little Rock	Table Rock Dam	1989
Little Rock	Toad Suck Ferry Lock & Dam	2006
Little Rock	Wilbur D. Mills Dam	2006

DISTRICT	DAM NAME	DCP YEAR
Tulsa	Arcadia Lake	1990
Tulsa	Birch Lake	2003
Tulsa	Broken Bow Lake	1993
Tulsa	Canton Lake	1990
Tulsa	Chouteau Lock and Dam	1992
Tulsa	Copan Lake	2003
Tulsa	Council Grove Lake	1990
Tulsa	Denison Dam	2006
Tulsa	Eufaula Lake	1990
Tulsa	Fort Gibson Lake	1990
Tulsa	Fort Supply Lake	1990
Tulsa	Great Salt Plains Lake	2005
Tulsa	Heyburn Lake	2005
Tulsa	Hugo Lake	1993
Tulsa	Hulah Lake	2003
Tulsa	John Redmond Lake	1990
Tulsa	Kaw Lake	2005
Tulsa	Keystone Lake	2005
Tulsa	Marion Lake	1990
Tulsa	Newt Graham Lock and Dam	1992
Tulsa	Oologah Lake	2003
Tulsa	Optima Lake	1990
Tulsa	Pat Mayse Lake	1993
Tulsa	Pine Creek Lake	1993
Tulsa	Robert S.Kerr Lock and Dam	1992
Tulsa	Sardis	1993
Tulsa	Skiatook Lake	2003
Tulsa	Tenkiller Lake	1990
Tulsa	W.D.Mayo Lock and Dam	1992
Tulsa	Waurika Lake	2006
Tulsa	Webbers Falls Lock and Dam	1992
Tulsa	Wister Lake	1990

Table A-2 – System or Subsystem-Scale DCPs

Title	N	Dam Name	Operating Office	National Inventory of Dams ID
Great Lakes and Ohio River Division – Huntington District				
Manuals for Water Control Management, Muskingum River Basin, Annex II: Drought Contingency Plan, Muskingum River Basin	16	Atwood Dam Beach City Dam Bolivar Dam Charles Mill Dam Clendening Dam Dillon Dam Dover Dam Leesville Dam Mohawk Dam, Mohicanville Dam N. Br. of Kokosing Dam Piedmont Dam Pleasant Hill Dam Senecaville Dam Tappan Dam Wills Creek Dam	Huntington	OH00006 OH00005 OH00004 OH00020 OH00012 OH00007 OH00003 OH00014 OH00016 OH00019 OH00009 OH00011 OH00001 OH00013 OH00010 OH00002
Master Manual for Water Control Management, Scioto River Basin, Annex II: Scioto River Basin	4	Alum Creek Dam Deer Creek Dam Delaware Dam Paint Creek Dam	Huntington	OH00931 OH00008 OH00015 OH00017
Master Regulation Manual for Reservoirs in the Big Sand River Basin, Annex II: Drought Contingency Plan, Big Sand River Basin	5	Dewey Dam Fishtrap Dam John W. Flannagan Dam N. Fork of Pound Dam Paintsville Dam, Yatesville Dam	Huntington	KY03029 KY03028 VA05101 VA19501 KY82202 KY82201
Project Manual for Water Control Management, Bluestone Lake, Summersville Lake, Sutton Lake, Annex II: Drought Contingency Plan, Kanawha River Basin	3	Bluestone Dam Summersville Dam Sutton Dam	Huntington	WV08902 WV06702 WV00701
Project Manual for Water Control Management, East Lynn Lake, Beech Fork Lake, Annex II: Drought Contingency Plan Twelvepole Creek Basin	2	Beech Fork Lake Dam East Lynn Dam	Huntington	WV09903 WV09901

Title	N	Dam Name	Operating Office	National Inventory of Dams ID
Great Lakes & Ohio River Division – Louisville District				
Drought Management Plan Upper Wabash River Basin, Indiana	3	Huntington Lake Mississinewa Lake, Salamonie Lake	Louisville	*IN03004 IN03005
Great Lakes & Ohio River Division – Nashville District				
Cumberland River Basin Drought Contingency Plan	9	Barkley Dam Center Hill Dam Cheatham Dam Cordell Hull Dam Dale Hollow Dam J Percy Priest Dam Laurel Dam Old Hickory Dam Wolf Creek	Nashville	KY03001 TN04102 TN02101 TN15901 TN02702 TN03701 KY03046 TN03702 KY03010
Mississippi Valley Division – Rock Island District				
Drought Contingency Plan, Red Rock Lake and Saylorville Lake	2	Red Rock Dam Saylorville Dam	Rock Island	IA00013 IA00017
Mississippi Valley Division – St. Paul District				
Drought Contingency Plan, Bigstone Lake-Whetstone River Highway 75 Dam and Reservoir, Lac Qui Parle Reservoir, and Minnesota River-Channel Improvement, Reservoir Regulation Manual	2	Highway 75 Dam Lac Qui Parle Dam	St. Paul	MN00581 MN00580
North Atlantic Division – Baltimore District				
Drought Management Plan, Chemung River Basin		Almond Lake Cowanesque Dam Tioga Dam	Baltimore	NY01212 PA01134 PA01132
Drought Management Plan, West Branch Susquehanna River Basin		Alvin R Bush Dam Curwensville Dam Foster Joseph Sayers Dam	Baltimore	PA00002 PA00003 PA00005
North Atlantic Division - Philadelphia District				
Delaware River Basin Comprehensive Plan	2	Beltzville Dam Blue Marsh Dam	Philadelphia	PA00010 PA00921

Title	N	Dam Name	Operating Office	National Inventory of Dams ID
Northwestern Division – Omaha District				
Drought Contingency Fact Sheet Project: Salt Creek and Tributaries, 10 Salt Creek Dams and Lakes, Nebraska	9	Salt Creek Site 10 - Yankee Hill Dam Salt Creek Site 12 – Conestoga Salt Creek Site 13 - Twin Lakes Dam Salt Creek Site 14 - Pawnee Dam Salt Creek Site 17 - Holmes Lake Salt Creek Site 2 - Olive Creek Dam Salt Creek Site 4 – Bluestem Salt Creek Site 8 - Wagon Train Dam Salt Creek Site 9 - Stagecoach Dam	NWD Omaha	NE01058 NE01055 NE01060 NE01057 NE01061 NE01062 NE01064 NE01056 NE01059
Missouri River Mainstem Reservoir System Master Water Control Manual, Missouri River Basin	6	Big Bend Dam Fort Peck Dam Fort Randall Dam Garrison Dam Gavins Point Dam Oahe Dam	NWD Omaha	SD01092 MT00025 SD01093 ND00145 SD01094 SD01095
Papillion Creek Drought Contingency Plan	5	Papillion Creek Site 11 - Glenn Cunningham Lake Papillion Creek Site 16 - Standing Bear Dam Salt Creek Site 18 - Branched Oak Wehrspann Zorinsky Lake	NWD Omaha	NE01518 NE01065 NE01063 NE82201 NE82202
South Atlantic Division – Mobile District				
Drought Contingency Plan for the Alabama-Coosa- Tallapoosa River Basin	5	Allatoona Lake Dam and Powerhouse, Carters Main Dam Claiborne Lock and Dam Millers Ferry Lock, Dam & Powerhouse Robert F. Henry Lock and Dam	Mobile	GA03742 GA00821 AL01436 AL01435 AL01434
Drought Contingency Plan for the Apalachicola-	4	Buford Jim Woodruff Dam	Mobile	GA00824 FL00435
Chattahoochee-Flint River Basin		Walter F George Lock, Dam, Powerhouse West Point		AL01432 GA00820

Title	N	Dam Name	Operating Office	National Inventory of Dams ID
South Pacific Division – Albuquerque District				
Drought Contingency Plan: Arkansas River Basin	2	John Martin Dam & Reservoir Trinidad Lake	Albuquerque	CO01283 CO00050
Drought Contingency Plan: Pecos River Basin	2	Santa Rosa Dam Two Rivers Dam (Diamond A & Rocky)	Albuquerque	NM00158 NM00004
Drought Contingency Plan: Rio Grande Basin	3	Abiquiu Dam Cochiti Lake Jemez Canyon Dam	Albuquerque	NM00001 NM00404 NM00003
South Pacific Division – Sacramento District				
Coyote Valley Dam and Warm Springs Dam Water Control Manual	2	Coyote Valley Dam Warm Springs Dam	Sacramento	CA10201 CA82212
Southwestern Division – Fort Worth District				
Brazos River Basin Drought Contingency Plan, Appendix X, Brazos Master Manual	9	Aquilla Lake Belton Lake Granger Dam and Lake North San Gabriel Dam Proctor Lake Somerville Lake Stillhouse Hollow Dam Waco Lake Whitney Lake	Fort Worth	TX08004 TX00002 TX08005 TX08006 TX00010 TX00013 TX00014 TX00016 TX00017
Colorado River Basin, Texas, O.C. Fisher Lake, Hords Creek Lake, Drought Contingency Plan, Appendix III, Colorado Master Manual	2	Hords Creek Lake O C Fisher Dam and Lake	Fort Worth	TX00006 TX00012
Neches River Basin, Texas B.A. Steinhagen Lake, Sam Rayburn Reservoir Drought Contingency Plan	2	Sam Rayburn Dam and Reservoir Town Bluff Dam	Fort Worth	TX00011 TX00015
Trinity River Basin, Texas Benbrook Lake, Joe Pool Lake, Grapevine Lake, Ray Roberts Lake, Lewisville Lake, Lavon Lake, Navarro Mills Lake, Bardwell Lake Drought Contingency Plan	8	Bardwell Lake Benbrook Lake Grapevine Lake Joe Pool Lake Lavon Lake Lewisville Lake Navarro Mills Lake Ray Roberts Dam	Fort Worth	TX00001 TX00003 TX00005 TX08007 TX00007 TX00008 TX00009 TX08008

Title	N	Dam Name	Operating Office	National Inventory of Dams ID
Southwestern Division – Little Rock District				
Arkansas River Basin (Navigation Projects) Drought Contingency Plan	10	Dardanelle Lock & Dam David D. Terry Lock & Dam Emmett Sanders Lock & Dam James W. Trimble Lock & Dam Joe Hardin Lock & Dam Murray Lock & Dam Norrell Lock & Dam Ozark Lock & Dam Toad Suck Ferry Lock & Dam Wilbur D. Mills Dam	Little Rock	AR00162 AR00172 AR00167 AR00163 AR00168 AR00171 AR00161 AR00164 AR00170 AR00169
Drought Contingency Plan Appendix L-C to Master Water Control Manual Arkansas River Basin	2	Blue Mountain Nimrod	Little Rock	AR00157 AR00158
Drought Contingency Plan White River Basin	6	Beaver Bull Shoals Clearwater Dam Greers Ferry Norfork Table Rock Dam	Little Rock	AR00174 AR00160 MO30203 AR00173 AR00159 MO30202
Southwestern Division - Tulsa District				
Arkansas River - Navigation, Oklahoma Drought Contingency Plan	5	Chouteau Lock And Dam Newt Graham Lock And Dam Robert S.Kerr Lock And Dam W.D.Mayo Lock And Dam Webbers Falls Lock And Dam	Tulsa	OK10303 OK10302 OK10301 OK10305 OK10304
Drought Contingency Plan for Keystone KAW, Great Salt Plains, and Heyburn Lakes, Mid-Arkansas River Basin	4	Great Salt Plains Lake Heyburn Lake KAW Lake Keystone Lake	Tulsa	OK10319 OK10313 OK20509 OK10309
Drought Contingency Plan for Pat Mayse, Sardis, Hugo, Pine Creek and Broken Bow Lakes, Lower Red River Basin	5	Broken Bow Lake Hugo Lake Pat Mayse Lake Pine Creek Lake Sardis	Tulsa	OK10307 OK10300 TX04359 OK10306 OK21490
Drought Contingency Plan for Upper Neosho River, Kansas, Arkansas River Basin	3	Council Grove Lake John Redmond Lake Marion Lake	Tulsa	KS00001 KS00004 KS00006

Title	N	Dam Name	Operating Office	National Inventory of Dams ID
Southwestern Division - Tulsa District				
Eufaula, Arcadia, Canton, Fort Supply and Optima Lakes, Canadian River Basin, Drought Contingency Plan	5	Arcadia Lake Canton Lake Eufaula Lake Fort Supply Lake Optima Lake	Tulsa	OK22178 OK10316 OK10308 OK10318 OK20510
Lower Verdigris River, Oklahoma Drought Contingency Plan	5	Birch Lake Copan Lake Hulah Lake Oologah Lake Skiatook Lake	Tulsa	OK20508 OK21489 OK10312 OK10310 OK00037
Upper Red River Drought Contingency Plan	2	Denison Dam Waurika Lake	Tulsa	OK10317 OK20506
Wister, Tenkiller, and Fort Gibson Lakes, Arkansas Basin, Drought Contingency Plan	3	Fort Gibson Lake Tenkiller Lake Wister Lake	Tulsa	OK10314 OK10311 OK10315

APPENDIX B: Detailed Climate Change Discussion

Appendix B provides information about projected climate change impacts to drought frequency and severity in the U.S. This information expands on the summary presented in Table 1 of the main document. The discussion is organized by region as displayed in Figure 4 of the main report.

Northeast

Short-term drought lasting 1-3 months is anticipated to occur more frequently under projected warmer climate in the Northeast (Figure 4), particularly in the summer and fall. Increased temperatures during these seasons, coupled with precipitation decreases, are anticipated to play a significant role. Increases in medium and long term drought are projected by some models, with long-term drought projected to increase in frequency in the western portion of the region. These changes are discussed below.

The Northeast receives most of its precipitation from extratropical cyclones (midlatitude storm systems) that generally move from west to east across the region. The moisture source for these storms are humid subtropical tropical air masses that become entrained in the developing storm. Droughts commonly occur when the Bermuda High becomes entrenched over the eastern United States, pushing storms to the north of New England (Zielinski and Keim, 2003). Droughts can occur in any season of the year.

In the Northeast, soil moisture, streamflow and agricultural systems are dependent on natural rainfall to the extent that even short-term drought can have significant economic and other impacts (Hayhoe et al., 2007). Droughts lasting between one and three months are common, occurring every two or three years; severe droughts (such as the 1960s drought of record) are rare (Hayhoe et al., 2007).

In climate model projections by Hayhoe et al. (2007), short-term droughts (lasting 1 to 3 months) become more common under future climate scenarios, particularly the high emissions, fossil fuel intensive scenario (A1FI). Drought frequency increases in response to reductions in mean monthly soil moisture during summer and fall, driven by increased evapotranspiration and decreased precipitation. Evapotranspiration rises both because of the increase in temperature and an increase in the growing season length. By the end of the 21st century, under the A1FI scenario short-term droughts occur as frequently as once per year in the northern and eastern portions of the region (Hayhoe et al., 2007). Medium term (3-6 month) drought frequencies increase under the higher emissions (A1FI) scenario but are relatively unchanged under the low emissions (B1) scenario. Long term droughts (last longer than 6 months) become more frequent in western New York State and this area of increased frequency expands eastward by the end of the 21st century (Hayhoe et al., 2007).

Severe or extreme drought conditions, comparable to the historic 1960s drought, appear to become less intense over time although model skill in this area is relatively low (Hayhoe et al., 2007). The frequency and spatial extent of severe and persistent regionwide drought is not anticipated to change under any modeled future climate conditions (Hayhoe et al., 2007).

Streamflow in the Northeast is heavily depending on snowpack and the timing and speed of snowmelt, particularly as many surface water systems in the region have limited storage. Over the last century, significant changes in the timing of winter-spring streamflows have occurred in those parts of the Northeast that have a substantial annual snowpack (Hodgkins and Dudley, 2006; Hodgkins et al., 2003) due to changes in late winter air temperature (Hodgkins et al., 2003). Snowmelt-related streamflows are projected to continue to become earlier in the next century (Hayhoe et al., 2007; Kunkel et al., 2013d).

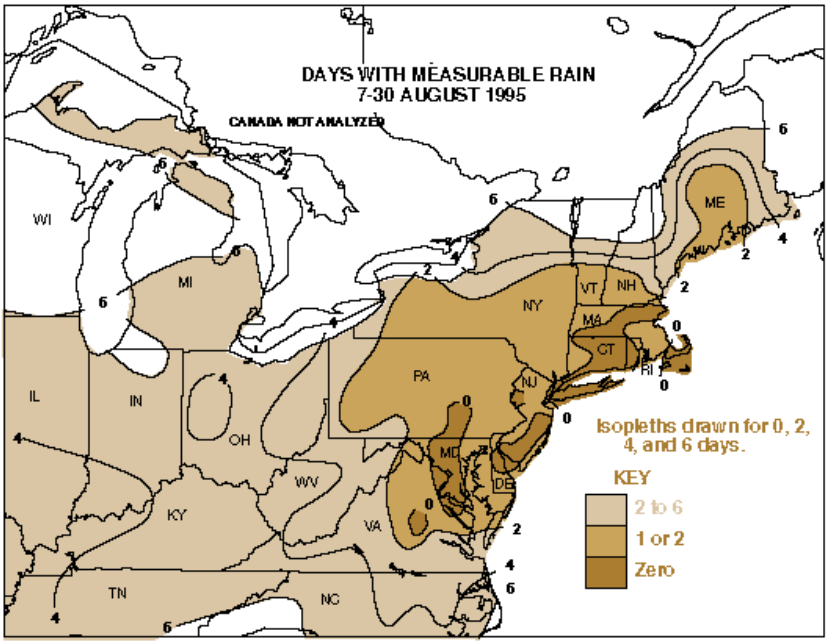

Figure B-1 - Days with measurable precipitation during 7-30 Aug 1995
(courtesy of the National Weather Service Climate Prediction Center)

Midwest

The Midwest (Figure 4) is anticipated to see little change to drought frequency, and in the northern portions may see declines in drought frequency, under projected warmer climates. Hotter temperatures are anticipated to lead to stronger and more frequent precipitation events, resulting in a net wetting of the region. These changes are detailed below.

Climate in the Midwest is influenced by its mid-latitude, continental interior location. Positioned far from the ameliorating effects of oceans, the region is subject to deep cold and snow conditions in winter, and humid, subtropical air masses in summer. In winter, the polar jet stream is often located near or over the region, enabling the regular movement of storms systems through the region (Kunkel et al., 2013b). In the spring, as the polar jet migrates northward and is replaced by warm, humid subtropical air masses. The combination of sharply contrasting air masses and strong winds aloft allow for frequent development of thunderstorms and tornadoes. In summer, the Bermuda High helps guide warm, humid air into the region from the Gulf of Mexico, and summer is typically the rainiest season (Kunkel et al., 2013b). Like the Northeast, agriculture in the region is typically not irrigated, and therefore the region is highly vulnerable to summer drought (Kunkel et al., 2013b). As with the southeast, the Bermuda High acts as a gateway to summer precipitation: in certain positions, it helps funnel moisture into the region, but if it moves farther west/inland, it can serve as a barrier to moisture entering the region, causing drought.

Climate model projections of mean annual precipitation mid-century (2041-2070) show the northern portion of the region becoming wetter by as much as 3-6%, increasing to 6-12% greater than current conditions by the end of this century (Kunkel et al., 2013b). Little change is projected for the southern part of the region. Increases in precipitation are simulated for fall, winter and spring throughout the region (Kunkel et al., 2013b), but in summer, there is a great deal more variation: decreases of up to 15% may occur in southwestern Missouri, and decreases of 5-10% may occur in a broad band across Missouri, Illinois, Indiana and Ohio (Kunkel et al., 2013b). By contrast, Minnesota, Wisconsin and

northern Michigan are projected to see a 0-10% increase in summer precipitation (Kunkel et al., 2013b). The models do not project significant increases in the average annual maximum number of consecutive days with less than trace precipitation (0.1 inches) (Kunkel et al., 2013b) in 2055 compared to 1980-2000. Significant decreases in the number of days with trace precipitation are modeled for northern Minnesota (Kunkel et al., 2013b). Together these indicate that models do not project significant increases in drought frequency for the region.

Great Plains

The Great Plains (Figure 4) are anticipated to see little change in drought frequency, and may see declines in drought frequency in northern areas under projected warmer climates. Hotter temperatures are anticipated to lead to stronger and more frequent precipitation events, resulting in a net wetting over much of the region, even in far western Texas where stronger monsoon precipitation is possible. Drier climates in the south may occur, leading to increased drought in that region. It is unclear whether there may be changes in the frequency of intense, protracted drought in the region. These changes are detailed below.

The Great Plains includes all the states sandwiched between Montana and North Dakota to the north and Texas to the South. With the exception of western Montana and western Wyoming, it is a continental interior region characterized by relatively flat topography. The Rocky Mountains to the west largely block moisture from the Pacific Ocean, so most of the moisture entering the region originates in the Gulf of Mexico. The distance from the Gulf influences the frequency and amount of the moisture reaching different portions of the region (Kunkel et al., 2013a). Because there are no significant mountain ranges to the north of this region, outbreaks of Arctic air can occur, bringing bitterly cold temperatures to the region in winter.

Precipitation is spatially variable, with some portions of the far southeastern part of the region receiving more than 60 inches per year, while portions of the far western region receive less than 10 inches per year (Kunkel et al., 2013a). Winter precipitation is typically in the form of midlatitude cyclones that follow the track of the jet stream. Summer is the rainiest season. In summer, the eastern and southern parts of the region tend to become warm and humid as the Bermuda High draws warm, humid air into the region, producing short-lived rainfall and thunderstorms. In the far southwestern portion of the region (esp. West Texas), summer precipitation peaks during the North American Monsoon. In coastal Texas, hurricanes in the late summer and fall provide the bulk of the precipitation (Kunkel et al., 2013a).

Drought is a common occurrence in the region with some portion of the region in drought every year (Kunkel et al., 2013a). Most recently in 2011, Texas and Oklahoma experienced severe drought conditions (Figure 5), although regionally the most significant long term drought occurred in the 1930s (the Dust Bowl era). An analysis of precipitation trends for the period 1895-2011, broken out by portion of the region, shows no trend in any season, or annually. However, a significant increase in the occurrence of extreme precipitation events over this time period was observed (Kunkel et al., 2013a). In addition, temperature increased approximately 0.13 to 0.33°F/decade in the northern Great Plains, and by a smaller amount in the winter and spring on the southern Great Plains (Kunkel et al., 2013a).

Climate model projections indicate a pronounced north-south gradient of future precipitation with southern areas showing a decrease in precipitation and northern areas showing an increase (Kunkel et al., 2013a). Seasonally, models project winter precipitation increases across most of the Great Plains; increases north and east and decreases south and west in the spring and summer, except for central

Texas where summer precipitation is projected to increase; and an increase in fall precipitation everywhere except the western-most portions of the region (Kunkel et al., 2013a).

The average annual maximum number of days with precipitation less than 0.1 inches is projected to increase significantly in the south, with increases of up to 13 days by 2055 (Kunkel et al., 2013a). The trend toward more dry days and higher temperatures across the southern Great Plains is likely to lead to increased evaporation, decreased water supplies, reduced electricity transmission capacity, and increased cooling demands (Melillo et al., 2014). However, it is unclear whether there may be changes in the frequency of intense, protracted drought in the region. By contrast, in the northern regions of Wyoming and Montana, a decrease by up to 8 days is anticipated in the number of days with trace precipitation (Kunkel et al., 2013a). However, over most of the region, the GCMs do not predict a statistically-significant change.

In addition to meteorological drought, hydrologic drought in the region may be exacerbated by losses to winter snowpack in the Rocky Mountains in the Southwestern states. Warmer winter and spring temperatures, and reduced winter precipitation, are anticipated to reduce spring runoff, cause that runoff to occur earlier in the year, and reduce late summer and fall base flows in streams heading in the Southern Rocky Mountains and traversing the Southern High Plains, including the Arkansas, Red, White, Canadian and Platte Rivers (see Southwest section).

Figure B-2 - Drought impacts to Lake Texoma, Texas, in 2013
(courtesy USACE Southwest Division)

Northwest

Like other regions encompassing the northern portion of the continental U.S., precipitation gains are anticipated for the Northwest (Figure 4) under a warmer climate. However, these gains are distributed unevenly over the year, with cool season gains partially offset by losses in summer precipitation, particularly in the interior regions. Seasonal drought and ENSO-related droughts are likely to occur in the future. These changes are detailed below.

The Northwest has a Mediterranean climate characterized by wet winters and dry summers. Rainfall is heaviest along the Pacific coast, but declines markedly as west-to-east moving storm systems traverse successive north-south trending mountain ranges (Coast Mountains, the Cascade Range, the Olympic Mountains, and the Rocky Mountains). Precipitation is heaviest on the windward (western) side of the mountains. For instance, on the western slopes of the Olympic Mountains, the annual precipitation may exceed 16.4 feet of water equivalent, while low elevation areas on the lee side of the Cascades may

receive less than 8 inches. ENSO is currently an important cause of regional drought (Mote et al., 2013).

Climate models project warming in the Northwest of 3-11°F by 2100, with the largest gains in the summer, and a 3-5% increase in average annual precipitation with a range of -10% to +18% for 2070–2099 (Mote and Salathé, 2010). The models exhibit great variation in fall, winter and spring precipitation, but strongly agree that summer precipitation will decline by as much as 30%, likely resulting in lower summer stream flows and greater wildfire incidence (Mote et al., 2013). Drying is more likely in some seasons in the interior Columbia Plateau area than elsewhere. Models projecting the warmest temperatures also project the greatest summertime drying (Mote et al., 2013). Model discrepancy in precipitation change is driven by uncertainty in how far north the boundary between the low and high latitudes will be: models agree that high latitude areas will get wetter, and low latitude areas drier, but disagree about where this boundary will lie (similar issues drive uncertainties across the central Great Plains).

If summer precipitation and stream flows decline as the models project, seasonal drought conditions are likely to occur, particularly in El Niño years. Consequently, climate models project an increase in the maximum run of days with precipitation less than 0.3 cm (0.1 in, trace) (Mote et al., 2013). Changes in meteorological drought frequency or intensity are not major features of climate projections (Kunkel et al., 2013c). However, a critical change across the Northwest may involve changes in snowmelt dominant watersheds where winter (October-March) precipitation falls as snow, is stored in the snowpack, and sustains late spring and summer flows throughout the region. Warmer winter air temperatures are likely to shift snowmelt-dominant and mixed rain-snow watersheds which are projected to gradually trend towards mixed rain-snow or rain-dominant watersheds (Raymondi et al., 2013). This is likely to result in reduced peak streamflow, increased winter flow, and reduced later summer flow in these watersheds. By the 2080s, a complete loss of snowmelt dominant basins is projected for the Northwest under the A1B (moderate emissions) scenario (Raymondi et al., 2013).

Alaska

In Alaska, precipitation is projected to increase across the state for all future periods; consequently meteorological drought is unlikely to increase in frequency in the future. However, declines in permafrost, extension of the growing season, loss of mountain glaciers, warmer temperatures, and increased evapotranspiration may contribute significantly to increases in hydrologic drought during the summer months. These changes are detailed below.

Alaska's climate is influenced by its high latitude location and topography (Stewart et al., 2013), which results in cold, short winter days and long summer days. Solar radiation is weak, even in summer. East-west trending mountain ranges are important topographic barriers to the northward movement of precipitation to the interior and northern portions of the state.

During the cooler months of the year, the climate across most of the state is dominated by cold, dry polar air; sea ice reduces evaporation, contributing both to cold and aridity, particularly in areas north of the Alaska and Aleutian Ranges. In winter, the Aleutian Low strengthens over the Gulf of Alaska, generating storms in southern Alaska from late fall to late spring (NOAA National Weather Service, n.d.). The Aleutian Low weakens in summer and retreats poleward, and climate in the Gulf of Alaska area is dominated by the North Pacific High pressure system (clear skies, few storms) (NOAA National Weather Service, n.d.).

Temperature trends in Alaska for the period 1949-2011 show warming of 2.5 to 9.0°F across the year, with the interior and north warming faster than other regions. Regardless of emissions scenario, models project continued significant warming across most of the state, with the highest rates of warming in the northern third of the state (Stewart et al., 2013). Warming is already increasing evaporation, melting the permafrost, and lengthening the growing season (Markon et al., 2012). These trends are anticipated to continue into the future, contributing to decreases in soil moisture and increases in wildfire (Markon et al., 2012). Warming is also accelerating mountain glacier melting, which in the short run may increase water availability to hydropower projects in the southeast, but in the long run may lead to increased hydrologic drought once glaciers melt completely (Markon et al., 2012).

Average annual precipitation has increased an average of 10 percent across the state over the period 1949-2005 (Shulski and Wendler, 2007). Increases have occurred primarily in the fall, winter and spring, while summer precipitation has decreased or remained near-average across much of the state (Shulski and Wendler, 2007). In addition, extreme precipitation events have also increased, with the greatest increase occurring in the summer. Precipitation is forecast to increase across the state for all future periods (Stewart et al., 2013). Consequently, meteorological drought is unlikely to increase in frequency under modeled future climate conditions in this region. However, declines in permafrost, extension of the growing season, loss of mountain glaciers, warmer temperatures, and increased evapotranspiration may contribute significantly to hydrologic and agricultural (soil moisture deficit) drought increases during the summer months (Markon et al., 2012).

Southeast

The Southeast (Figure 4) is projected to experience increases in drought frequency and intensity under warmer future climates in its southern and western regions, but see decreases in drought frequency in northern and eastern portions. These changes are detailed below.

The Southeast has a warm, humid climate with hot summers and generally mild. Precipitation over the Southeast is controlled by the location of the Bermuda High. In summer, the high is typically positioned off the Atlantic Coast. Its clockwise rotation pulls moisture from the Atlantic and Gulf of Mexico into the region and generates frequent thunderstorm activity in the afternoon and evening hours (Konrad and Fuhrmann, 2013). The Bermuda High shifts position within and between seasons. When the Bermuda High builds westward across the region, this shuts off the transport of humid air into the region, resulting in hot dry weather and, if it remains stationary, drought conditions typically develop (Konrad and Fuhrmann, 2013). Changes in the location of the Bermuda High also affect the tracks of hurricanes as they move across the region (Konrad and Fuhrmann, 2013). In winter, the Bermuda High shifts southeastward, enabling the jet stream to expand southward and with it, potentially generate cyclonic storm systems (Konrad and Fuhrmann, 2013). The combination of a cold front with humid air drawn in from the Gulf can produce snowstorms or ice storms, particularly in the northern part of the region above latitude 35°N.

The Southeast is prone to droughts as deficits of precipitation can rapidly lead to shortage of freshwater (particularly as demand is high due to rapid population growth and development). Droughts are typically of short duration (one to three years), and may be ameliorated during the late summer and fall by hurricanes (Konrad and Fuhrmann, 2013). Flooding and drought can occur simultaneously in the region. For example, in the lower Mississippi Valley in 2011, flooding due to large winter headwaters snowpacks and heavy rains in the Midwest coincided with extreme drought in Tennessee, Arkansas, Mississippi and Louisiana (Konrad and Fuhrmann, 2013).

The tree ring record in the Southeast, which extends back some 1,000 years, shows no long term trend in precipitation and soil moisture in the region, and indicates that the severity and duration of several prominent 20th and early 21st century droughts are not unusual: decade-long droughts have occurred periodically in the region (Konrad and Fuhrmann, 2013).

Model projections of future precipitation based on CMIP3 model data and downscaled data from the North American Regional Climate Change Assessment Program (NARCCAP) indicate a 2-4% decline in average annual precipitation in Louisiana and South Florida, with 6% increases in North Carolina and Virginia by mid-Century (Konrad and Fuhrmann, 2013). Precipitation may increase across most of the region except in summer, where a decrease of up to 15% occurs in parts of Arkansas, Louisiana, and South Florida (Konrad and Fuhrmann, 2013). The intensification and westward expansion of the Bermuda High during summer is a robust feature of several models (Konrad and Fuhrmann, 2013). In the Caribbean (including Puerto Rico), drying is projected to occur in both summer and winter months.

Hydrologic drought is expected to increase in frequency and intensity across the lower Mississippi River Valley and the Gulf Coast, but decrease in frequency across the northern tier and the mid-Atlantic (Strzepek et al., 2010). Significant model uncertainties exist, however (Konrad and Fuhrmann, 2013).

Figure B-3 - Drought impacts to Lake Hartwell, South Carolina
(courtesy of USGS)

Southwest

Under warmer climates, the Southwest (Figure 4) is projected to become increasingly arid, with fewer wet years and longer, more frequent, and more intense droughts. These changes are detailed below.

The Southwest (Figure 4) covers the six-state area of California, Nevada, Utah, Arizona, New Mexico and Colorado. The Southwest is currently positioned at the northern margin of the subtropics, which is one of the primary reasons for its aridity, the other being its continental interior location in the rainshadow of the Sierra Nevada and Rocky Mountains (Sheppard et al., 2002). Currently, most of the region lies within the subtropical dry zone during the summer, where it experiences warm, dry conditions. In Arizona and New Mexico, a monsoonal climate emerges in July, August and early September. However, California and Nevada experience largely dry summers. Eastern New Mexico and eastern

Colorado receive significant summer precipitation due to orographic effects and the interaction between mid-latitude cyclonic systems with moisture brought into the eastern plains by the Bermuda High (see Southeast, Great Plains section). Arizona and New Mexico receive most of their precipitation during the summer monsoon. ENSO currently exerts a significant influence on interannual precipitation variability in the region.

In winter, the boundary between the subtropics and the mid-latitudes diminishes equator-ward, permitting the jet stream to bring large storms to the region. California receives the bulk of its rain from storm systems that originate over the Pacific. These storms follow the jet stream eastward, bringing diminishing quantities of snow to the eastern portion of the Southwest until the high plains are reached. In the lee of the Rocky Mountains, winter storms tend to reform and gain strength, bringing severe winter conditions to eastern Colorado and New Mexico.

Historically and prehistorically, drought has been relatively common. Historically, the most significant drought in New Mexico was the drought of the 1950s (Gutzler, 2003). More recently, an attempt has been made to distinguish drought due to precipitation deficits – which characterized the 1950s drought – and droughts driven primarily by temperature increase, as seen in the first decade of the 2000s (Breshears et al., 2005; Cayan et al., 2010). As this early 21st century drought has evolved, precipitation deficits have become more significant (Figure 3).

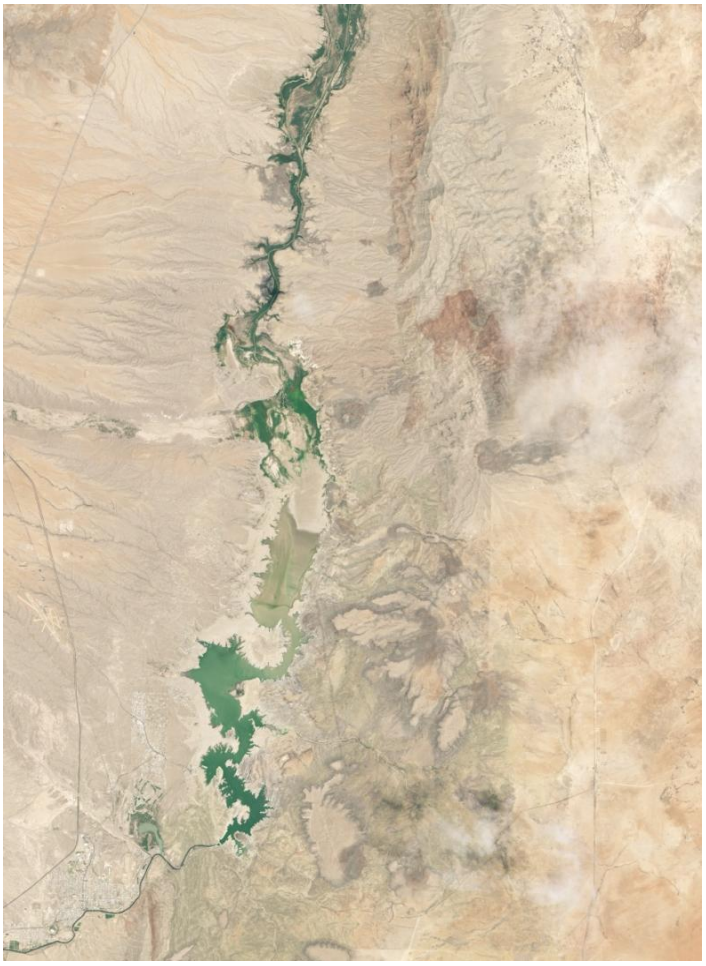

Figure B-4 - In the summer of 2013, drought reduced Elephant Butte Reservoir, NM, to its lowest level in forty years (courtesy of NASA Earth Observatory)

Of all the U.S. regions, drought conditions are expected to be the most persistent and severe in the Southwest U.S. in the future. This increase in frequency and intensity is likely to be due in part to increases in temperature and evaporation (Gutzler and Robbins, 2011; Seager et al., 2007; Seager and Vecchi, 2010) in most seasons of the year. Precipitation declines are also projected, particularly for the fall, winter, and spring (Melillo et al., 2014), with projected decreases in headwaters streamflow into the Rio Grande by approximately one-third, and diverted flow from the San Juan River by approximately one-fourth (Reclamation, USACE and Sandia, 2013).Modeling by Seager et al. (2007) projects that the average climate of the Southwest by the middle of the 21st century will resemble that of climate during a multi-year drought of today (e.g., Figure 8), with droughts much worse than any since the Medieval period. The median values across multiple model runs indicate steady declines in both winter and summer precipitation are anticipated over the 21st century (Seager and Vecchi, 2010). Temperature increases combined with precipitation decreases to produce increasingly arid winters across the region (Seager and Vecchi, 2010). Because of the gradual drying of the region, even the models with the wettest future climates failed to project a return to the wetter climate of the 1980s and 1990s (Seager and Vecchi, 2010). By the end of the twenty-first century, conditions similar to the droughts of the 1930s and 1950s are projected to become “normal” (Wehner et al., 2011).

Figure B-5 - California's ongoing drought has led to significant reductions in reservoir levels throughout the state in 2014 (courtesy of NASA’s Jet Propulsion Lab)

Hawai'i

Hawai'i is projected to experience an increase in precipitation in the southern part of the Hawaiian Islands and a decrease north across all emissions scenarios. However, the magnitudes of projected changes are small compared to interannual variation in precipitation, and the models are not in strong agreement. Precipitation is greater under higher emissions scenarios than lower. Finally, drought may occur more frequently in winter than in other seasons due to modeled shifts in sea surface temperature gradients and atmospheric circulation across the Pacific. These changes are detailed below.

Located in the central Pacific, Hawai’i is the only state located entirely within the tropics. Its climate is humid, characterized by equable temperatures (similar in all seasons). Because Hawai’i is a volcanic island chain, its steep vertical relief results in significant temperature differences along a topographic gradient. Summers are typically drier than winters.

Precipitation is carried to the islands on the trade winds, which blow predominantly from the north or northeast (NOAA, 1985). The trade winds are the result of outflow from the North Pacific High. In summer, the North Pacific High reaches its greatest spatial extent and northernmost position, steering the trade winds southeastward. This results in light to medium rainfall events resulting from orographic uplift of humid air (Keener et al., 2013). Consequently, there is a profound difference in especially summer precipitation between the windward and leeward sides that is most pronounced at lower elevations (NOAA, 1985). In winter, reductions in the strength of the North Pacific High and its more southerly position lead to reductions in trade wind flows, and permit mid-latitude storms, tropical cyclones and other storm systems to approach the islands from the west (Keener et al., 2013). There may be as many as two to seven major winter storms in a year (NOAA, 1985). The Hawaiian Islands are sensitive to the ENSO cycle: during El Niño events, weakened trade winds lead to reductions in rainfall and dry conditions throughout the island chain (Keener et al., 2013).

A general downward trend in precipitation has been noted statewide over the last century that is evident in both observations and GCMs (Keener et al., 2013). The decline in precipitation is associated with increasing frequency of trade wind inversions (which retard storm formation), a decline in trade wind occurrence, and higher rates of warming at high elevations (Keener et al., 2013). There has also been a trend toward fewer extremely high rainfall events and more frequent light intensity events (Keener et al., 2013). All the major Hawaiian Islands have also experienced more prolonged drought since 1980 compared to the period 1950-1979, estimated as the increase in the annual maximum number of consecutive dry days (Keener et al., 2013).

Analysis of CMIP3 model projections for future periods centered in 2035, 2055, and 2085 suggest an increase in precipitation in the southern part of the Hawaiian Islands and a decrease north across all emissions scenarios. However, the magnitudes of projected changes are small compared to interannual variation in precipitation, and the models are not in strong agreement (Keener et al., 2013). Precipitation overall is projected to be greater under the high emissions scenario than the low emissions scenario, possibly driven by higher sea surface temperatures in the former. Models also project a weakening of sea surface temperature gradients and atmospheric circulation across the Pacific, which may result in reductions in winter precipitation in Hawai'i resulting in more frequent wintertime drought. This is a continuation of an observed low weakening of the atmospheric circulation overlying much of the tropical Pacific during the 20th century (Keener et al., 2013).

Model projections of precipitation and drought in Hawai'i are complicated by the small geographic scale of the islands, their great relief, and the importance of localized processes (orographic lift, trade wind inversions, cloud formation, high altitude temperatures). All processes that occur are at spatial scales too small to be resolved by existing models. The projections for precipitation and drought must therefore be considered preliminary (Keener et al., 2013).

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14. ABSTRACT
This report contains an overview of climate, climate change, and drought in the United States to aid in planning for current and future droughts at USACE projects. It also reviews the status of the USACE project delivery team (PDT) that was established to compile drought contingency plan (DCP) information and compare and contrast DCP contents and methods previously used for forecasting drought frequency and intensity in order to evaluate gaps and robustness, develop analytical tools, and to set the stage for future updates to DCPs and DCP guidance if necessary.

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