ANL/EVS/R-11/14

Analysis of Drought Impacts on Electricity Production in the Western and Texas Interconnections of the United States

In Support of Interconnection-wide Transmission Planning

Environmental Science Division

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Sponsor:
U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability

December 2011

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Acknowledgments

The authors would like to thank Tom Iseman and Alex Schroeder at the Western Governors Association, Heidi Pacini, Jamie Austin, Tom Chisholm, and Stan Holland at the Western Electric Coordination Council, Doug Murray, Kevin Hanson, and Niveditha Reddy at the Electric Reliability Council of Texas, and Carey King at the University of Texas for their invaluable guidance, feedback and support throughout this effort (and for their uncanny ability to endure countless conference calls!). We would also like to thank Caitlin Callaghan, Mathew Rosenbaum, Adriana Kocornik-Mina, David Meyer and John Schnagl with the Department of Energy's Office of Electricity Delivery and Energy Reliability and Raymond Lopez at the National Energy Technology Laboratory for sponsoring this work and for their valuable feedback on the many previous iterations of this document. We would like to thank Jan Gilbreath with the US EPA Office of Policy, Policy and Regulatory Analysis Division for taking the time to provide constructive feedback on an early draft of this report. Finally, we would like to thank our Argonne colleagues John Gasper for helping to manage this effort and Liz Stefanski and Robert Horner for the thankless job of providing a thorough edit and technical review of this document.

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1. Executive Summary

Electricity generation relies heavily on water resources and their availability. To examine the interdependence of energy and water in the electricity context, the impacts of a severe drought to assess the risk posed by drought to electricity generation within the western and Texas interconnections has been examined. The historical drought patterns in the western United States were analyzed, and the risk posed by drought to electricity generation within the region was evaluated. The results of this effort will be used to develop scenarios for medium- and long-term transmission modeling and planning efforts by the Western Electricity Coordination Council (WECC) and the Electric Reliability Council of Texas (ERCOT). The study was performed in response to a request developed by the Western Governors' Association in conjunction with the transmission modeling teams at the participating interconnections. It is part of a U.S. Department of Energy-sponsored, national laboratory-led research effort to develop tools related to the interdependency of energy and water as part of a larger interconnection-wide transmission planning project funded under the American Recovery and Reinvestment Act. This study accomplished three main objectives. It provided a thorough literature review of recent studies of drought and the potential implications for electricity generation. It analyzed historical drought patterns in the western United States and used the results to develop three design drought scenarios. Finally, it quantified the risk to electricity generation for each of eight basins for each of the three drought scenarios and considered the implications for transmission planning.

Literature on drought impacts on electricity generation describes a number of examples where hydroelectric generation capacity has been limited because of drought but only a few examples of impact on thermoelectric generation. In all documented cases, shortfalls of generation were met by purchasing power from the market, albeit at higher prices. However, sufficient excess generation and transmission must be available for this strategy to work. Although power purchase was the most commonly discussed drought mitigation strategy, a total of 12 response strategies were identified in the literature, falling into four main categories: electricity supply, electricity demand response, alternative water supplies, and water demand response.

Three hydrological drought scenarios were developed based on a literature review and historical data analysis. The literature review helped to identify key drought parameters and data on drought frequency and severity. Historical hydrological drought data were analyzed for the western United States to identify potential drought correlations and estimate drought parameters. The first scenario was a West-wide drought occurring in 1977; it represented a severe drought in five of the eight basins in the study area. A second drought scenario was artificially defined by selecting the conditions from the 10^{th}-percentile drought year for each individual basin; this drought was defined in this way to allow more consistent analysis of risk to electricity generation in each basin. The final scenario was based upon the current low-flow hydro modeling scenario defined by WECC, which uses conditions from the year 2001.

These scenarios were then used to quantify the risk to electricity generation in each basin. The risk calculations represent a first-order estimate of the maximum amount of electricity generation that might be lost from both hydroelectric and thermoelectric sources under a worst-

case scenario. Even with the conservative methodology used, the majority of basins showed a limited amount of risk under most scenarios. The level of risk in these basins is likely to be amenable to mitigation by known strategies, combined with existing reserve generation and transmission capacity. However, the risks to the Pacific Northwest and Texas Basins require further study. The Pacific Northwest is vulnerable because of its heavy reliance on hydroelectric generation. Texas, conversely, is vulnerable because of its heavy dependence on thermoelectric generation, which relies on surface water for cooling, along with the fact that this basin seems to experience more severe drought events on average. Further modeling analysis will be performed in conjunction with the modeling teams at the participating interconnections (WECC and ERCOT) to explore the transmission implications of the drought scenarios in more detail.

Given the first-order nature of this analysis, more detailed study of the potential impacts of drought on electricity generation is recommended. Future analyses should attempt to model the potential impacts of drought at the power-plant level, including potential mitigation strategies; include the effects of drought duration; understand the impacts of climate change; and consider economic impacts. While it is recommended that future studies initially focus on the basins that have been identified as having highest risk, it may also be important to study other areas not normally associated with drought or water-related stress, as generators in these areas may be more dependent upon surface water sources and may be less likely to have adequate contingency plans in place.

2. Introduction

Over the past decade, concerns about the risks to the electric grid from severe drought have grown. Recent drought events in the Pacific Northwest and California in 2001, in the Southeastern U.S. in 2007 and 2008 and in Texas in 2011, along with the uncertain impacts of climate change, have heightened these concerns. This study seeks to improve understanding of the potential impacts that drought may have on electricity production and transmission resources, explore mitigation strategies, and identify areas for more detailed analyses. It has been implemented in response to the study request developed by the Western Governors' Association (WGA) in conjunction with the transmission modeling teams at the Western Electricity Coordination Council (WECC) and Electric Reliability Council of Texas (ERCOT). The results of the analysis will be used as input into long-term transmission modeling and planning efforts by the participating interconnections. Therefore, the study focuses exclusively on eight hydrological basins covering the western United states and Texas.

This effort is part of a research effort to develop tools related to the interdependency of energy and water, sponsored by the U.S. Department of Energy (DOE), in conjunction with DOE's interconnection-wide transmission planning initiative funded under the American Recovery and Reinvestment Act, and led by national laboratories. These tools will be used to support decision-making for infrastructure and resource planning. The leading laboratory for this effort is Sandia National Laboratory, supported by other national laboratories including Argonne National Laboratory (Argonne), Pacific Northwest National Laboratory, the National Renewable Energy Laboratory (NREL), and Idaho National laboratory, as well as the Electric Power Research Institute and the University of Texas.

While hundreds of studies have been performed that have evaluated drought patterns and their impacts, very few have taken a comprehensive look at the impact of drought on electricity production. This study uses a simplified, first-order approach and is only a first step towards a comprehensive understanding of drought impacts on electricity production. A thorough review of the literature on drought, including the impact on electricity production, has been performed. Data on historical drought events were analyzed and used to develop three separate drought scenarios. The risk to both hydroelectric and thermoelectric power generation was then quantified for each of the eight hydrological basins within the study area for each of the three drought scenarios.

The remainder of this report is structured as follows:

- Literature Review: reviews and summarizes the results from drought analyses performed in the past five years, previous studies on drought impacts on electricity production, drought contingency plans, and drought impacts on electricity demand;
- Methodology: describes the methodologies used to analyze historical drought patterns, develop design drought scenarios, and quantify the impacts of drought on electricity production;
- Results and Analysis: presents and analyzes the results of the study and explores the implications;

- Conclusions and Recommendations: summarizes the key conclusions and provides recommendations for drought impact mitigation and future study.

3. Literature Review

Numerous studies on drought analysis have been conducted in the last five years. In this screening analysis, we have performed an extensive literature search and review. This review is split into four sections. The first section looks at drought analyses with a focus on drought parameters and how drought is defined, to support the development of a design drought for this study. The second section summarizes the literature on drought impacts on electricity production, including historical accounts and modeling analyses, to support the development of a modeling approach. The third section summarizes information gathered from utilities and power producers about their drought contingency plans and provides insights into potential drought mitigation strategies. The fourth section gives an overview of the possible impacts of climate parameters associated with drought on electricity demand.

A brief summary for each study reviewed is provided in Appendix A, *List of Ongoing and Current Drought Studies*. The *List of Ongoing and Current Drought Studies* mainly includes studies published in 2006-2011. A few valuable publications prior to 2006 are also included.

3.1 Review of Recent Drought Analyses

In this section we summarize the main findings of studies on drought that have potential impacts on electricity generation availability. The literature review indicated that most drought analyses have not specifically targeted potential impacts on electricity generation. The literature review mainly focused on drought characteristics and parameters that would lead to a set of reasonable assumptions for a design drought to be used as a bassis for drought impact analysis.

3.1.1 Drought Characteristics

Many recent studies have included extensive analyses of the drought characteristics of the western United States in the 20th century (e.g., Andreadis and Lettenmaier 2006; Easterling et al. 2007; Sheffield and Wood 2007; Groisman and Knight 2008; Luce and Holden 2009; Woodhouse et al. 2009; Cook et al. 2010; McCabe et al. 2010). Cayan et al. (2010) identified a general pattern of drought development in the western United States by compiling measured data and simulation results for 11 extreme drought years identified in 1916-2008 across California, the Great Basin, and the Upper and Lower Colorado water resource regions. They analyzed monthly data on temperature, precipitation, snow water equivalent (SWE), soil moisture (SM), and runoff over a 48-month period starting two years before each drought year and ending one year after the drought year. Their results demonstrated that most extreme drought events have the following similar pattern:

- The greatest precipitation shortage occurs during the winter months.
- The largest reduction in SWE occurs in March and April.
- The worst deficit of SM and runoff comes in May and June.
- The SM and runoff may not be fully recovered, typically to the 80% level of the average value, in the May and June following the extreme drought year.

- Monthly mean temperature in the drought summer increases by +0.1°C to +5°C.

Several studies have also identified climate change over the 20th century, including an increase of 1-3°C in spring temperature (Cayan et al. 2001), a decline in spring snow pack and SWE (Knowles et al. 2007) and a shift to early peak runoff (Regonda et al. 2005). These trends would amplify the deficit of warm-season runoff in drought years, on the basis of the drought characteristics discussed above. The increased drought effects were confirmed by the study of Luce and Holden (2009), which showed significant trends in annual stream flow reduction during dry years over the period of 1948-2006.

The climate change observed in the 20th century has been projected to continue throughout the 21st century in much of the western United States. Recent studies performed for the Reclamation Climate Change and Water Program under the SECURE Water Act suggest that losses of snow pack will be persistent over the western United States (Bureau of Reclamation 2011a). This change in snow-pack dynamics would exacerbate future droughts by reducing warm-season runoff in the southern part of the western United States. Projected increases in precipitation in the northern part of the western United States, however, could counteract the decrease in warm-season runoff (Bureau of Reclamation 2011b).

3.1.2 General Considerations in the Design Drought

Drought analyses have identified and measured historical droughts in various ways, depending on which impacts of droughts are to be managed. A drought measurement for agricultural risk management would be different from one for hydro-power risk management. However, in general, the key elements of a design drought for impact analysis are similar across different risk managements, including its duration, frequency, severity, and spatial pattern, as well as temperature deviation during the drought. In this section, we present the results of the literature review in the context of those elements associated with design drought.

Duration and frequency

Drought duration has been analyzed by using variables that include soil moisture, stream flow and various indices. Prolonged droughts lasting for a single year or multiple years may impact electricity generation. The stream flow data could be either measured by instrumented gauges or derived on the basis of reconstruction from tree rings. The tree-ring-based reconstructions of several major river flows in the western United States have identified century-long medieval megadroughts and several sporadic, extended drought episodes in the 1600s. Because of these exceptional droughts in the past, recurring prolonged droughts are a concern for the 21st century (Woodhouse et al. 2010).

Table 3.1 lists droughts varying from 1 to 11 years in duration in the major water resource regions in the western United States. The long-term historical drought analyses indicated that a five-year drought recurred every 20-30 years through the 20th century and the beginning of the 21th century. However, a 10-year prolonged drought occurred only once in the last century. A single-year drought was found at an average frequency of once every 8 years over the period 1750-2000.

One of the Palmer Indices, the Palmer Hydrologic Drought Index (PHDI), reflects a relatively longer-term hydrologic condition. Severe (PHDI < -3) and extreme (PHDI < -4) droughts represent water shortages that could potentially affect electricity generation. Figure 3.1 shows the frequency of the severe or extreme drought condition, based on PHDI observations for the period of 1895-2008. The frequency of severe or worse droughts is 11-20% of observations over 114 years for most of the water resource regions in the western United States.

For a water resource region that has significant storage capacity, a one-year drought is expected to have a limited impact. For example, in the Colorado River system, the total storage capacity is more than four times the river's average annual runoff of ~60 million acre feet (MAF). However, about 85% of the water stored in the river system is located within the two largest reservoirs, Lake Powell and Lake Mead (Bureau of Reclamation 2011b). During the early-21st-century drought, after five consecutive years of below-average inflows, the reservoir storage decreased by 50% in volume. However, the system still had two years of annual Colorado River flows (Fulp 2005). For a river system that has limited storage capacity, it is likely that droughts with durations of 1-5 years would have significant impacts on flow reduction.

Severity

Several indices have been used to define drought severity, such as Palmer indices, including the Palmer Drought Severity Index (PDSI), PHDI, etc.; the standardized runoff index; and the surface water supply index. The National Drought Mitigation Center (2011) uses some of these indices to monitor and evaluate the severity of droughts. The severe (PHDI < -3) and extreme (PHDI < -4) droughts are associated with water shortages, which may affect electricity generation. The droughts defined by soil moisture or stream flow commonly use a particular threshold, such as the 10th to 20th percentiles.

Spatial pattern

The spatial pattern of droughts in the western United States has been related to modes of climate variability and Pacific and Atlantic sea surface temperature (SST) anomalies that are influenced by the El Niño-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO), and the Atlantic Multidecadal Oscillation (AMO) (e.g., Cayan et al. 1999; Dettinger and Diaz 2000; Enfield et al. 2001; Hunter et al. 2006; McCabe et al. 2008). The recurring features and spatial variation of large-scale droughts have been found to be correlated with dynamic changes among and the magnitude of ENSO, NAO, PDO, and AMO.

A regional distribution of the PDSI over the eight water resource regions for the period of 1895-2004 indicates a significant geographic variation of drought pattern. The National Drought Mitigation Center calculated the PDSI for every year from 1895 to 2004 and plotted the annual percentage of drought area at the severity of PDSI < -3 over the total area of each of eight water resource regions (Appendix B, Figure B.1). A high percentage of drought-affected area suggests occurrence of regional-scale drought. The duration and frequency of regional-scale drought vary over the eight water resource regions. Drought events in the Pacific Northwest and Great Basin

regions show a longer duration and lower frequency, whereas droughts in the Texas Gulf have shorter duration and higher frequency.

Deviation from average temperatures during drought

Only limited information is available in the current literature on temperature deviation during drought. Recently, Cayan et al. (2010) constructed a composite anomaly of temperature for 11 droughts in the 20th century and the beginning of the 21st century. Annual temperatures during drought years have increased by 0.3^{o}C (minimum daily temperature) and 0.8^{o}C (maximum daily temperature). A higher temperature deviation, ranging from +0.5^{o}C to +1.0^{o}C, was observed in summer during droughts.

Table 3.1 Drought durations analyzed from various studies.

Basin	Drought Duration[a]	Time Period of Records	Drought Definition
Pacific Northwest	1 yr: 32 events 5 yr: 1840s, 1930s, 1890s, 1775, and 1805 11 yr: 1840s, 1930s	1750 -2000	Below 15th percentile of 1-yr, 5-yr, and 11-yr mean stream flow, respectively. Data: tree ring and stream flow (Dalles)
	5 yr: 1627-39, 1999-2005, 1930-35, 1988-92, 1895-1905 10 yr: 1625-40, 1642-52, 1930-41,1895-1905	1591 -2006	Below 2 standard devationsfrom 5-yr and 10-yr mean stream flow, respectively. Data: tree ring and stream flow (Snake)
Colorado	5 yr[b]: 1896-1907, 1930-36, 1953-65, 1974-78, 1988-93, 1999-2002	1884 -2002	Below-average stream flow over 1884-2002. Data: stream flow (5 United States Geological Survey gauges)
	5 yr: 1999-2004, 1844-48, 1622-26 10 yr: 1622-31	1569 -2003	Top rank of driest periods using 5-yr and 10-yr mean stream flow, respectively. Data: tree ring and stream flow
California	6 yr: 1930-35, 1976-81, 1987-92	1906 -2000	Below 20th percentile of 6-yr mean stream flow. Data: stream flow
Great Basin Colorado California	47–123 months (4-10 yr) in six extreme drought events	1916 –2008	Top 6 of 11 drought events, which are defined as below the 10th percentile. Data: soil moisture

[a] Listed in an order of drought intensity
[b] Chronological order (not in an order of drought intensity)

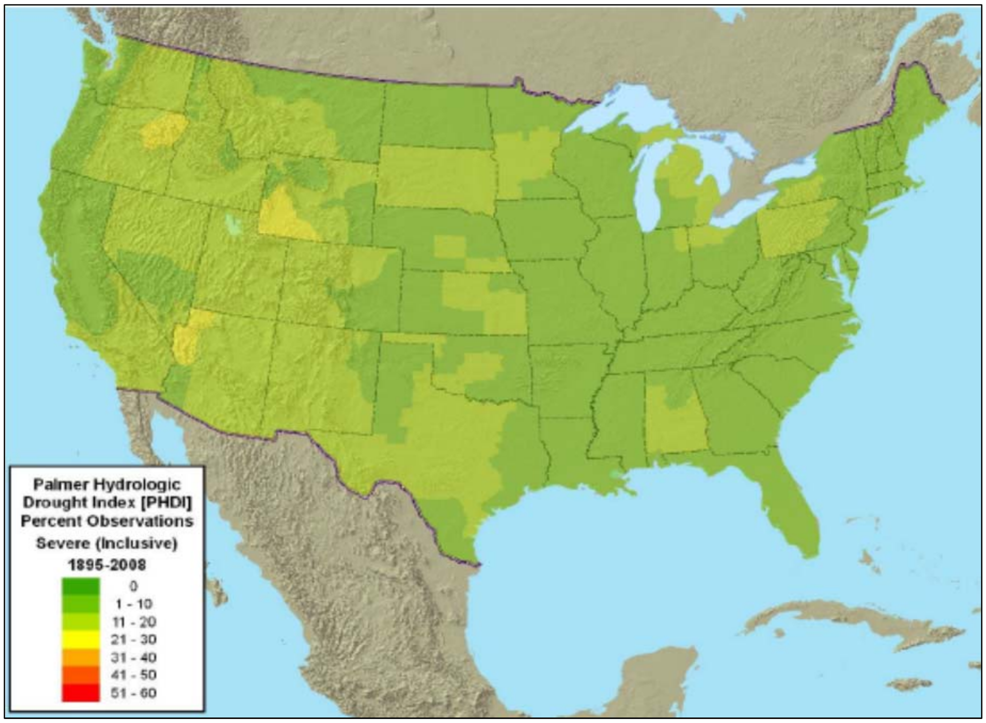

Figure 3.1 Frequency of severe and extreme droughts by percent of PHDI observations in 1895-2008.

3.2 Drought Impacts on Electricity Production

This section outlines the literature on historical drought events and modeling analyses focused on impacts on electricity production. A few recent events have led to increased concerns over the risks that drought poses to electricity production. The most significant was the Western energy crisis that resulted from a drought in 2001. Severe drought in California and the Pacific Northwest significantly reduced hydroelectric power generation, resulting in tight electricity supplies and high prices. While outages were largely avoided, there were significant financial impacts (BPA 2002). The Northwest Power and Conservation Council (2005) estimated the total regional economic impact of the drought to be between $2.5 and $6 billion.

In addition, prolonged drought occurred between 2007 and 2008 in the Southeast and posed a substantial risk to large-base-load thermoelectric generation facilities in the region. The Union of Concerned Scientists (2007) reported that the Tennessee Valley Authority (TVA) was forced to temporarily shut down its Brown’s Ferry facility, and a few others were forced to reduce generation during a particularly acute period of drought in August 2007. During this period, TVA was forced to purchase electricity from the grid to meet demand. This outage, however, appears to have been more a result of an increase in the temperature of the cooling-water source than due to limitations in the availability of water (Union of Concerned Scientists 2007). In addition, over the course of the drought period, water sources for a few key facilities dropped to within a few feet of the levels at which curtailed generation would have been

required. Water levels in lakes used as sources of cooling water have been identified as a key indicator of drought risk for certain large thermoelectric plants (Milazi 2009).

In general, the literature indicates that hydro generation is far more significantly affected by drought than thermoelectric generation. While hydro generation has been shown to vary by large margins depending upon hydrological conditions, there have been limited reports of thermoelectric facilities being forced to shut down involuntarily because of water limitations. In addition to the TVA facilities impacted in 2007, the same report mentioned an outage at a plant in Quad Cities, Illinois, in 2006, along with a few additional thermoelectric plants in Illinois and Minnesota that were forced to reduce generation at the same time. Drought events in 2003 and 2006 in Europe required the shutdown or curtailment of a number of thermoelectric units as well. During the 2003 event, France was forced to shut down as much as 25% of its nuclear fleet (Union of Concerned Scientists 2007).

Two studies published by Lawrence Berkeley National Laboratory in 1977 and 1978 evaluated the impacts on electricity supply in California from a drought spanning 1976 and 1977. The main impact observed from this drought was a significant decrease in the availability of hydroelectric generation. No impact on thermoelectric generation was mentioned, but the report pointed out that the majority of thermoelectric generation in California in 1977 was coastal, utilizing sea water for cooling. Overall grid reliability was maintained throughout the drought period; however, electricity prices and emissions increased because of increased reliance on oil and natural gas for electricity generation. In 1977, total electricity demand was also lower than previously anticipated. This reduction in demand growth was attributed to higher electricity costs, a cooler summer, and a public relations campaign that helped increase conservation efforts. Overall success in managing this crisis was attributed to early anticipation, coordination, and planning, along with the use of transmission to transfer electricity from areas not impacted by the drought. The researchers speculated that while the impacts of drought had been managed reasonable well, a third consecutive year of drought would have had more severe impacts (Sathaye 1977, 1978). This last statement indicates that the impact on thermoelectric generation may be linked to not only the severity but also the duration of a drought. The availability of water storage within lakes and reservoirs may provide a buffer that minimizes impacts from droughts of short duration.

Reports on drought events in the West in 1976-1977 and 2001 do not indicate significant impacts on thermoelectric generation. The greater risk, at least in California and the Pacific Northwest, appears to result from significant reliance on hydroelectric generation. A representative from APS, an electric utility in Arizona, stated that they had never experienced a forced outage at any of their thermoelectric facilities as a result of water shortages (Day 2011). Significant monitoring and planning efforts appear to be the main drivers in limiting the impact on thermoelectric generation from water shortages. This observation may indicate that areas that are more prone to drought are in fact more resilient than areas with less experience with drought, because utilities in drought-prone areas are likely to have put more effort into planning and developing mitigation strategies.

Three recent studies from Argonne have looked at potential impacts of drought on power generation. The first study looked at cooling-water intake heights as an indicator of drought risk for thermoelectric power plants. A total of 423 plants were analyzed. Of these, 43% were identified as having cooling-water intake heights of less than 10 ft below the typical water level of their water source (Kimmel and Veil 2009). The second study looked at coal plants in the United States and ranked them by their vulnerability on the basis of 18 different water supply- and demand-related indicators. Of the 580 plants evaluated, 60% (representing approximately 90% of total coal generating capacity) were deemed to be vulnerable on the basis of either supply- or demand-related criteria (Elcock and Kuiper 2010). However, the definition of vulnerability used in this study includes but is not limited to drought so that a plant could have a water supply or demand vulnerability even if it is not in a drought prone area. A third study modeled a drought scenario in the western United States to estimate the impact on electricity prices and CO_2 emissions. The model simulated supply to match historical hourly load data. The results showed increases in electricity prices ranging from 4% to 35%, depending on the month and year. The largest price increases were observed during summer months, and the lowest price increase was in the fall. The researchers also estimated a small (5%) increase in CO_2 emissions in the drought scenario, resulting from an increase in natural gas generation to make up for lost hydroelectric generation (Poch et al. 2009).

Overall, the literature and historical experience shows that impacts from drought manifest themselves most often economically, in terms of increased costs that can significantly impact local economies. True involuntary power shortages that result in supply disruptions appear to be quite rare. A representative of BC Hydro commented that in 20 years he has never seen a situation where needed power could not be purchased from another utility (Ketchum 2011). Much of this can be attributed to the availability of transmission to transfer power over long distances, which adds resilience to the grid. However, for such transfers to be possible, there still must be sufficient transmission capacity, and connected areas must not all experience shortages at the same time.

3.3 Drought Contingency Plans

In addition to the literature review, a total of 22 utilities, power producers, and government agencies responsible for power production and management in the West were contacted regarding plans for dealing with drought conditions. The original goal of this effort was to obtain information that would be useful in modeling the impacts of the design drought scenarios on electricity production. Unfortunately, the information and documents obtained did not provide enough detail to be of much use for this purpose. However, from these discussions and the review of obtained documents, a clear picture emerged of the range of strategies expected to be used by these organizations to minimize risk from drought.

A number of state and local drought plans were also reviewed. State plans reviewed included those of California, Arizona, Colorado, New Mexico, Idaho, Montana, and Wyoming. These plans rarely addressed electricity production directly; however, they did outline drought response options and mitigation strategies at the state and local levels. Activities outlined typically include monitoring, modeling, and planning, as well as mechanisms for coordination between state and local authorities. Some of the plans include specific actions to reduce water

demand, tied to measures of drought severity. These range from education and outreach activities to encourage conservation, to working with local water agencies to implement use restrictions (such as lawn watering limitations). While the state and local plans do not specifically address energy consumption, state and local actions to conserve water during drought conditions are likely to benefit electricity producers indirectly by freeing up more water for use in electricity generation.

Multiple operators commented that traditional drought planning (periodically producing a well-documented, static, and deterministic drought plan) has decreased in recent years. Sophisticated integrated monitoring, modeling, and planning processes appear to have taken the place of more static drought plans. In the case of hydroelectric generators, their operations are planned to balance a wide range of competing objectives in addition to electricity production, including flood control, water supply, fish protection, recreation, and navigation. In many cases, power production is low on this list of priorities. Their primary response strategy is to buy power from the market, and concerns are more about costs than availability. We note, however, that their ability to purchase power is contingent on the availability of both power for purchase and transmission to transport the power to where it is needed.

In addition to power purchases, 12 different response strategies were identified that could be used to reduce risk to power supplies during drought events. These strategies fall into four main categories: electricity supply, electricity demand response, alternative water supplies, and water demand response. These response strategies are outlined in Table 3.2. Although it is not listed in Table 3.2, the most critical element for minimizing drought risk appears to be adequate monitoring, modeling, and planning to anticipate shortages well in advance of when they are likely to occur.

Table 3.2 Drought response strategies.

Response Strategy	Summary
Electricity Supply	
Electricity Purchase from the Spot Market	This is the most common strategy, but it requires that there be significant supply in the market and sufficient transmission available. It also can be costly, as prices tend to spike at exactly the times when purchases need to be made.
Option Purchases	Options can be purchased in advance for periods when supply is expected to fall short of demand. This approach can potentially reduce costs and limit risk attributable to a volatile spot market.
Power Exchanges	Agreements can be set up to exchange power between utilities. Power is received in times of high demand and returned when demand is lower. This approach works best when different utilities have different load profiles. Sufficient transmission is necessary for these agreements to work.
Electricity Demand Response	
Energy Efficiency and Conservation	Many utilities already provide incentives for energy efficiency and conservation activities. These can be increased during critical times to further accelerate conservation.
Demand Exchange	Utilities pay program participants to reduce load in times of peak demand.
Interruptible-Load Contracts	Interruptible-load contracts between utilities and industrial consumers typically allow the utility to cut power on short notice in exchange for reduced electricity rates or payments for interruptions.
Alternative Water Supplies	
Water Banks	Many states operate water banks or similar mechanisms to facilitate transfers of water between rights holders in times of shortage.
Water Supply Contracts	Water supply contracts, typically between a farmer or group of farmers and a water utility or industrial user, allow for the temporary transfer of water during drought periods. These contracts can be negotiated independently between the two parties or facilitated by a state water bank or similar water market entity.
Groundwater Wells	Some power plants that primarily rely on surface water maintain groundwater wells as a backup water supply in the event that their surface water source becomes unavailable.
Water Demand Response	
Education and Conservation Campaigns	Publicity campaigns to encourage voluntary conservation measures have been shown to be effective at temporarily reducing demand.
Water Use Restrictions	Mandatory water use restrictions can be implemented by state and local water authorities for specific activities. The most common restriction is on lawn watering.
Rate Surcharges	Cost mechanisms can be implemented to encourage conservation. Tiered or increasing rate structures, which significantly increase water prices with increased consumption, when triggered by drought conditions.

3.4 Drought Impacts on Electricity Demand

There is no single *standard* and widely accepted energy demand adjustment that reflects an increase in temperature. Changes in energy demand vary seasonally and regionally, and estimates of these changes vary. Estimates of a change in annual energy use are not necessarily representative of seasonal changes (e.g., if temperatures are warmer all year, cooling demand may increase in the summer, but heating demand may decrease in the winter, and the average annual effect might be minimal; in some regions, the overall effect might be a decrease in energy demand). Differing climatic characteristics and socioeconomic conditions can cause different regions to respond differently to an increase in temperature. In addition to temperature, wind speed and humidity can affect cooling demand (although these variables seem to matter more in the Southeast than in the West). Existing air-conditioning market saturation, affects cooling loads varies across the U.S. and within states,. Increases in air-conditioning saturation affect future impacts of temperature on peak and total energy demand. Some estimates in the literature suggest that a several-degree increase in temperature will lead to less than a 1% increase in electricity demand, while others suggest that an increase of 1^{o}C would result in closer to an 8% increase in electricity use. Annotations to the relevant literature reviewed are included in Appendix A.

4. Methodology

This section describes the methodologies used to analyze historical drought events, develop design drought scenarios and quantify the risk to electricity production on the basis of these drought scenarios. The study area includes eight water resource regions, each defined as a two-digit Hydrologic Unit Code (HUC-2) by the United States Geological Survey (USGS). The eight regions cover the majority of the WECC and ERCOT area (Figure 4.1).

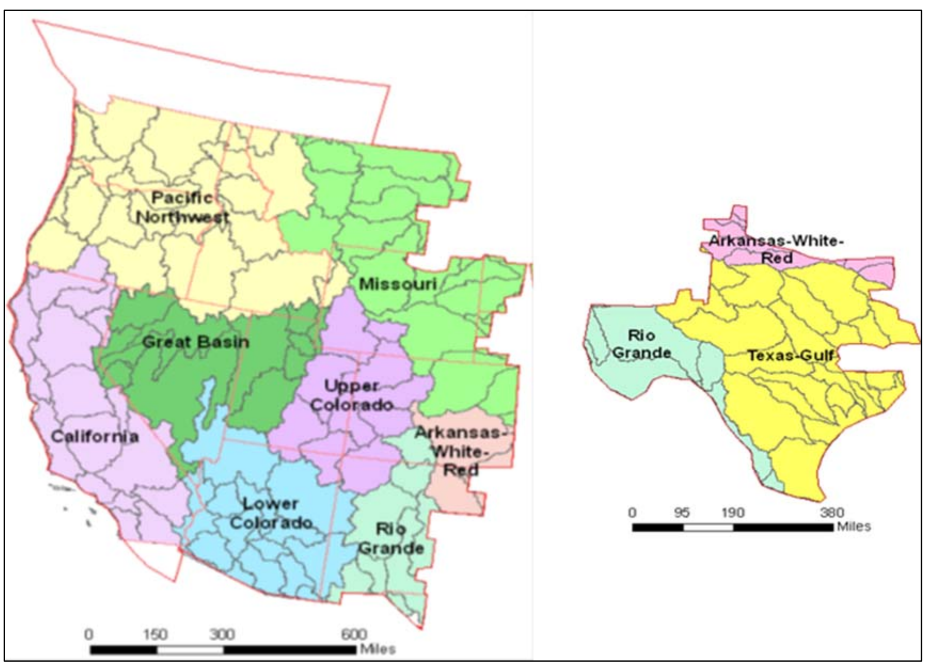

Figure 4.1 Water resource regions (HUC-2) in WECC and ERCOT.

4.1 Analysis of Historical Droughts

The results of the literature review indicate that no design drought is available for a direct impact analysis over the entire western United States. A screening analysis of historical droughts was conducted to identify design drought scenarios.

Approach to define historical droughts

Defining a drought event is a key step in drought analysis. A generally accepted definition of drought is elusive (Andreadis and Lettenmaier 2006). Wilhite and Glantz (1985) found more than 150 published definitions of drought, which could be classified in a number of categories. The choice of event definition may depend on the specific problem under study, regional drought characteristics, and data availability. In general, four different types of droughts are considered: meteorological drought (precipitation), agricultural drought (soil moisture), hydrologic drought (stream flow and groundwater), and socio-economic drought (water demand for an economic good). In this initial screening study, we define drought events in terms of stream flow, which is one of the major sources of water supply for electricity generation. In addition, stream flow results from an integrated response to multiple factors including meteorological forcing, basin transfer and storage, agricultural processes, and human activity and consumption. To some degree, stream-flow deficit during drought events reflects an overall system response to drought impacts.

Assumptions in determining design drought parameters

As discussed in Section 3, general consideration of a design drought includes the following key parameters in drought: (1) duration, (2) frequency, (3) severity, (4) spatial pattern, and (5) temperature deviation. The determination of these parameters was specifically requested by the DOE and WGA in their study request.

To derive parameters of a design drought, we have made the following assumptions:

1. Droughts of single-year duration are considered for analysis as design droughts of interest that have potential impacts on electricity generation, even though some studies show that a single-year drought may have little impact on a river system with high storage capacity. This was done for consistency with the concurrent drought modeling being conducted by WECC which only considers single-year droughts..
2. The frequency of drought was assumed at about every 10 years over the period of 109 years, which is equivalent to defining droughts at the 10th percentile or worse. This assumption was based on the frequency of severe and extreme drought conditions observed by using PHDI for the western United States (Figure 3.1).
3. Temperature deviation in droughts was assumed to be +0.5^{o}C to +1.0^{o}C in the warm season over the average observations, on the basis of 11 extreme droughts analyzed by Cayan et al. (2010). No additional analysis was conducted.
4. Eight water resource regions were used as the regional base of analysis that could capture reasonable spatial variations for this initial screening study. The eight water

resource regions are USGS HUC-2 basins; they include the Pacific Northwest, Great Basin, California, Upper Colorado, Lower Colorado, Missouri, Rio Grande, and Texas-Gulf basins (Figure 4.1).

On the basis of the assumptions above, the regional stream flow data were analyzed to identify design drought scenarios and their parameters, such as drought severity, as well as their spatial variation. The results are discussed in Section 5.

Data sources

As pointed out by Rossi et al. (1992), drought definition includes an at-site event definition and a regional event definition. The at-site drought is defined by a point value, while the regional drought is determined by integrated spatial variation over the study region. We used the HUC-2 basins as a base of our regional drought screening. A data set of regional stream flow over each HUC-2 basin from 1901 to 2009 was calculated by combining gauge data within the region from the USGS stream gauge network, weighted by the drainage area fraction of the entire basin for each gauge. The annual regional stream flow data were collected from the USGS WaterWatch website (http://waterwatch.usgs.gov/) and are listed in Appendix B, Table B.1. In this study, we used these regional stream flow data to perform the screening analysis.

4.2 Consensus Drought Definition

The screening analysis was used to develop drought scenarios with specifics for the following parameters:

- Drought frequency
- Spatial variation of drought
- Drought severity

The parameters of the specific design drought scenarios are presented in the results and analysis section.

4.3 Quantification of Drought Risk to Electricity Generation

The primary goal of this effort was to estimate the potential impacts of the design drought scenarios on electricity generation in the West. Impacts were calculated on an annual basis for each of the eight basins included in the study area by using separate methodologies for hydroelectric and thermoelectric generation. Estimating impacts on electricity production on the basis of hydrological data is challenging at best. Given the limitations of schedule and budget for this effort, a large number of assumptions needed to be made to quantify these impacts. The current approach does not come close to considering the full complexity of the system or the impact of drought response and mitigation activities. Overall, the results of this analysis should be viewed as a first-order estimate of the worst-case scenario and an indicator of relative risk, rather than definitive quantitative predictions of what would actually occur in any specific drought.

4.3.1 Categorization of Power Plants

The first step in estimating the potential impact of drought on electricity generation was to categorize the risk for individual power plants. Data were compiled by NREL and the University of Texas on individual generating units within WECC and ERCOT, respectively. These data sets were used to categorize generation into one of three categories: hydroelectric, low-risk generation, and at-risk thermoelectric generation. Low-risk generation was defined either as requiring no water for cooling (solar photovoltaic, wind, combustion turbine, dry cooling) or as using non-surface water sources (wells, ocean, treated wastewater). All generation that utilized fresh surface water or unspecified water sources was assumed to be at risk for drought impacts. A breakdown of generation by type for each basin is shown in Figure 4.2. Maps illustrating the locations of hydroelectric and at-risk thermoelectric generators are provided in Appendix C.

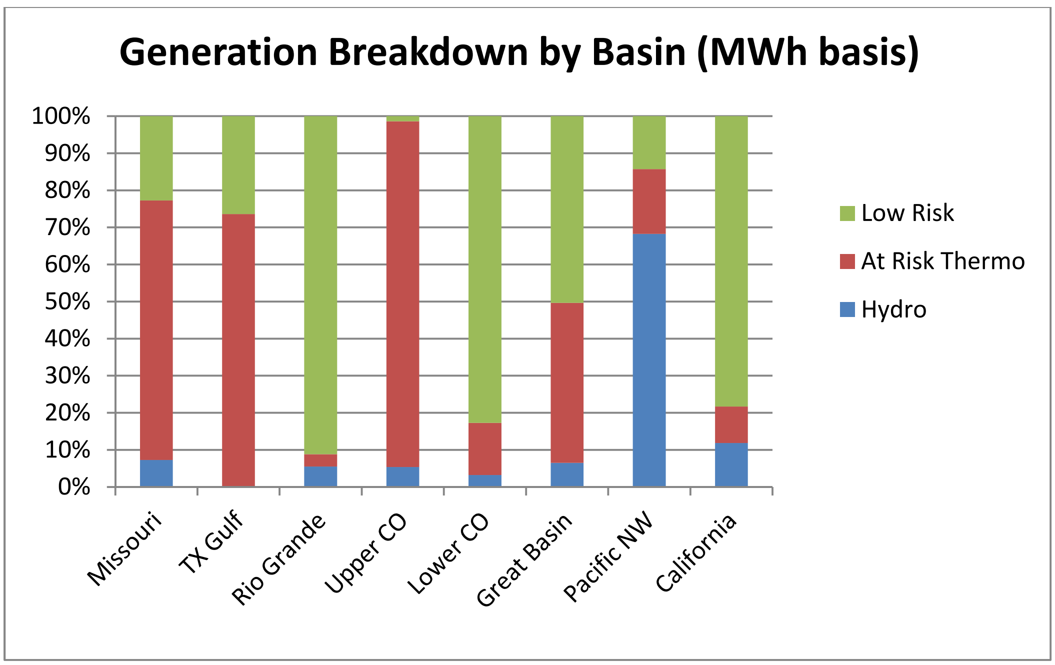

Figure 4.2 Breakdown of total electricity generation for each basin by risk.

4.3.2 Impacts on Hydroelectric Generation

Attempts to estimate impacts on hydroelectric generation started with the hypothesis that generation is proportional to flow within a basin. This hypothesis was then investigated for its validity. To test this hypothesis, annual flow data from the USGS (Appendix B, Table B.1) was compared to annual hydroelectricity generation from Bureau of Reclamation projects for the years 2000-2008 (Bureau of Reclamation 2011c). Annual values of both flow and generation were compared to the 9-year average values to generate dimensionless ratios for comparison.

Data were adequate for evaluation of the correlation between generation and flow in five of the eight total basins in the study area. Of the five basins analyzed, three showed strong correlation between generation and flow, with fit values $R^2 > 0.7$. However, two basins, the Lower Colorado and Missouri, both showed very poor correlations, with $R^2 < 0.3$. Figures 4.3-4.7 compare ratios of flow and generation for each basin considered.

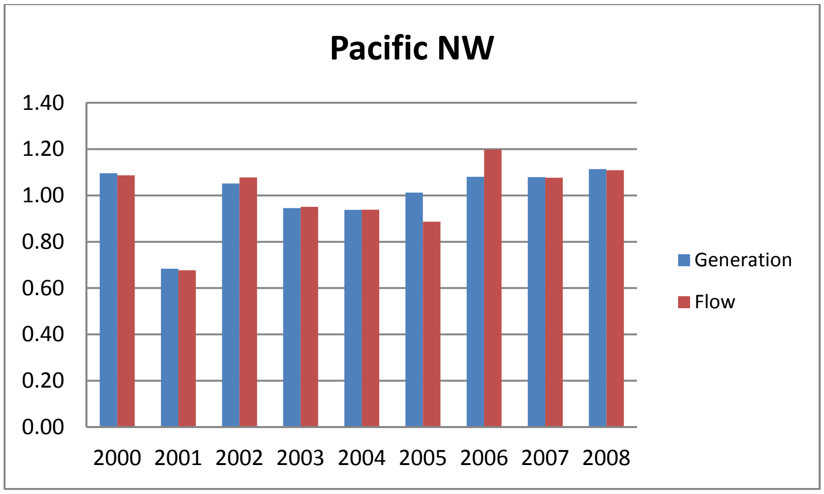

Figure 4.3 Correlation between flow and hydroelectric generation in the Pacific Northwest Basin.

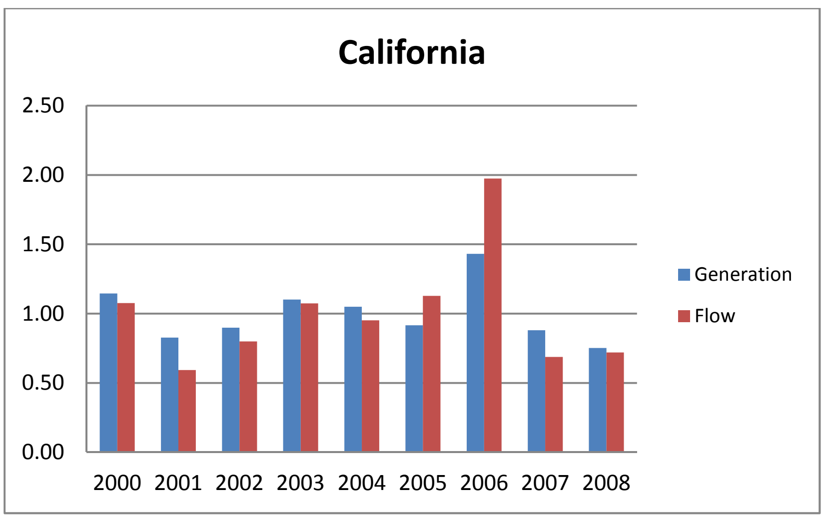

Figure 4.4 Correlation between flow and hydroelectric generation in the California Basin.

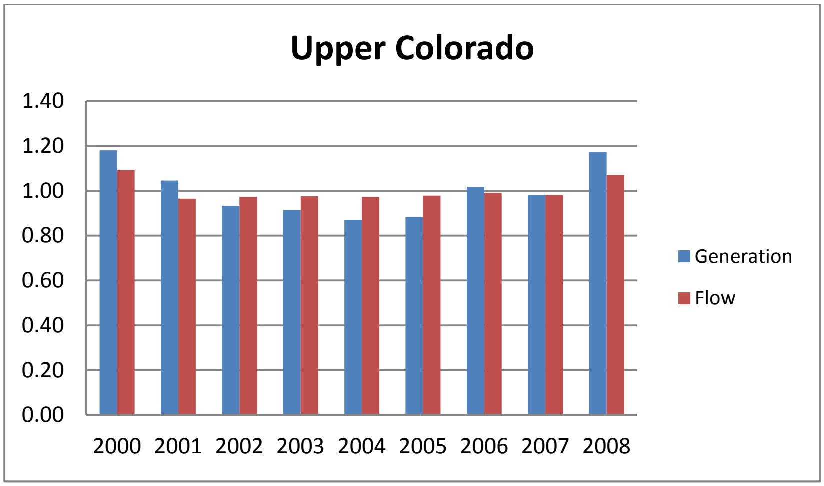

Figure 4.5 Correlation between flow and hydroelectric generation in the Upper Colorado Basin.

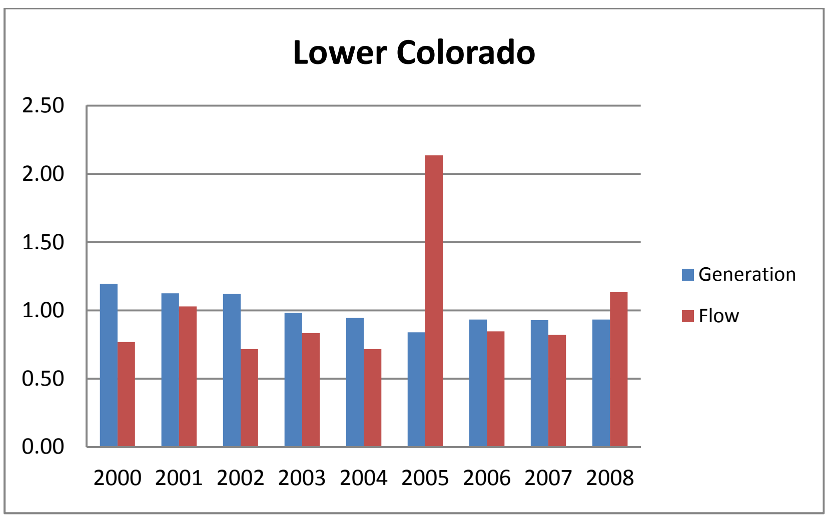

Figure 4.6 Correlation between flow and hydroelectric generation in the Lower Colorado Basin.

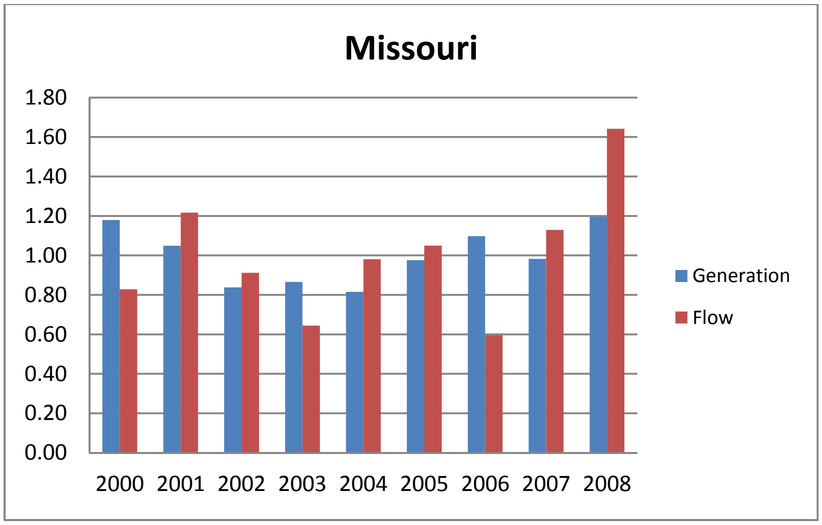

Figure 4.7 Correlation between flow and hydroelectric generation in the Missouri Basin.

Factors identified that could lead to poor correlation between generation and flow in some basins include the drawdown of reservoir storage in low-flow periods, upper limits on generation capacity in high-flow periods, and competing demands for reservoir resources such as fish, water supply, and flood control. The most significant factor is likely the role of reservoir storage in buffering generation from changes in flow. This buffering effect is likely to be greater in basins where storage is large relative to flow, such as the Lower Colorado. In comparison, the Pacific Northwest has a much lower ratio of storage to flow. Use of reservoir storage will result in an increase in generation relative to flow in most dry years and decrease generation relative to flow in most wet years. If this is truly the case, then an assumption that the ratio of drought flow to average flow is equal to the ratio of drought generation to average generation would represent a reasonable worst-case scenario for impacts on hydroelectric generation under drought conditions.

To look more closely at this assumption, the data for all basins were plotted in a scatter plot, with the flow ratio (annual flow/average flow) on the x-axis and generation ratio (annual generation/average generation) on the y-axis, as shown in Figure 4.8. If the assumed model fit perfectly, we would expect all of the data points to line up exactly on the black line which shows where the flow ratio is exactly equal to the generation ratio. However, in reality, from what we know about the impact of reservoir storage, we expect points to generally fall below the black line in periods with high flow (flow ratio > 1) and to lie above the black line for periods of low flow (flow ratio < 1).

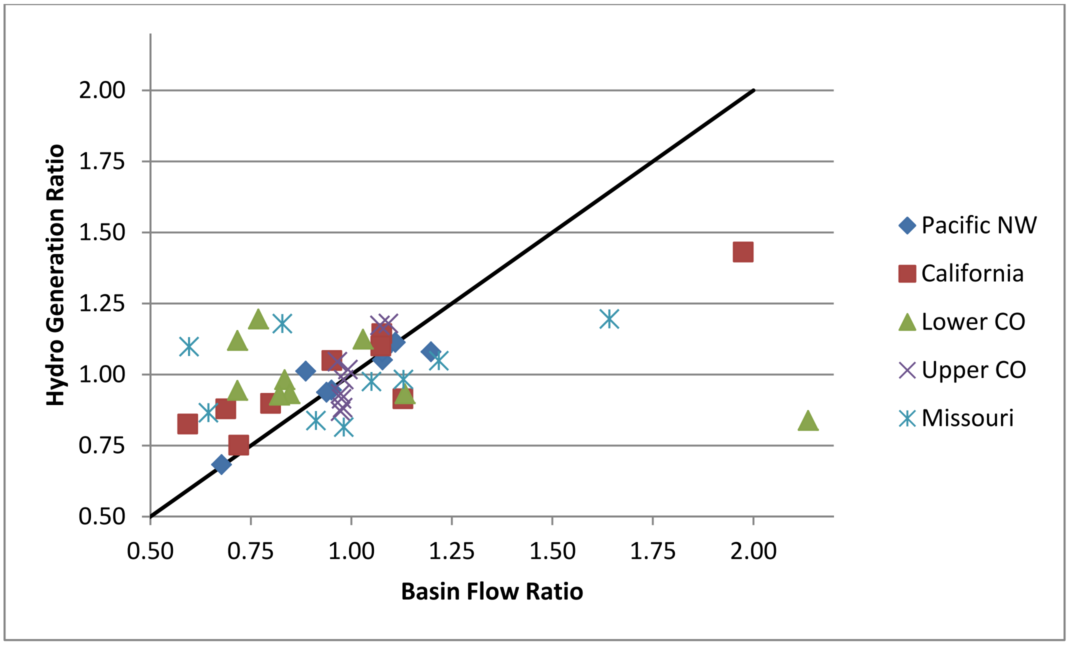

Figure 4.8 Correlation of hydro generation to basin flow for all basins. Each data point represents a single year between 2000-2008 for the specified basin.

Since we are most concerned about periods of low flow, a second plot (Figure 4.9) focuses on the data when the flow ratio is < 0.9; in this case, all points lie on or above the black line. This result shows that making the assumption that the ratio of drought flow to average flow is equal to the ratio of drought generation to average generation would, in fact, represent a reasonable worst-case scenario, with a limited probability of underestimating losses in hydroelectric generation. On the basis of this core assumption, a worst-case hydroelectric generation factor was defined as follows:

$$Hydro\ Generation\ Factor = \frac{Drought\ Generation}{Average\ Generation} = \frac{Drought\ Flow}{Average\ Flow} \quad (1)$$

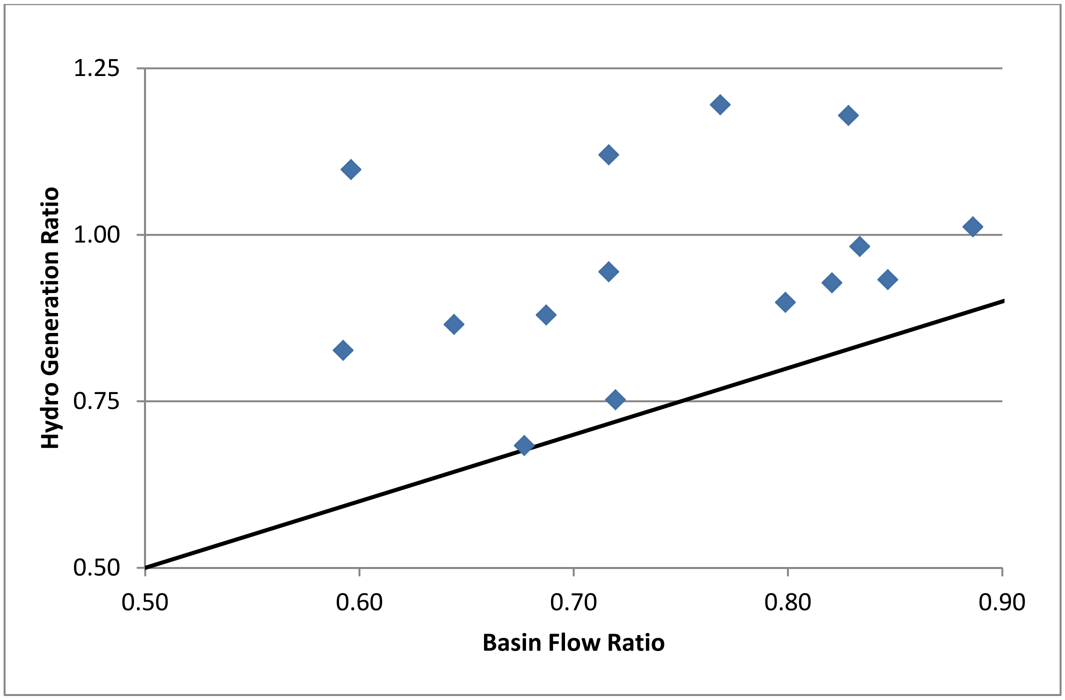

Figure 4.9 Correlation of hydro generation to basin flow for all basins under drought conditions.

The hydro generation factor can then be used to calculate the worst case loss of electricity generation from the average annual hydro generation in the basin:

$$Loss\ of\ Gen = Avg\ Annual\ Hydro\ Generation \times (1 - Hydro\ Generation\ Factor) \quad (2)$$

Note that the hydro generation factor was limited to values of 0-1. Although flow in some basins can exceed the average basin flow in some scenarios, the purpose of this analysis is to estimate any loss of generation. No estimation of excess generation is attempted in these cases.

4.3.3 Impacts on Thermoelectric Generation

While identifying the fraction of thermoelectric generation that is at risk is the first step, the more difficult question is how much of that generation will actually be curtailed during a drought. A number of potential triggers have been identified for drought-related outages for thermoelectric plants. If water levels drop below cooling-water intake structures, generation is likely to be curtailed. In addition, even when water levels are above intake structures, if water levels drop too low in certain lakes or reservoirs within the watershed, water withdrawals may have to be curtailed because of regulatory requirements or use agreements with local authorities. During drought conditions, the combination of lower water levels and potentially higher temperatures can also lead to situations where discharge temperatures for once-through cooling systems exceed permitted limits, resulting in requirements to reduce generation. In some areas, water rights also represent a potential risk. During severe drought, junior water-rights holders may temporarily lose their right to withdraw water.

Modeling these specific curtailment triggers for individual plants within the study area was beyond the scope of this analysis. In addition, basing the analysis on a historical correlation between drought and generation curtailment, as was done for hydroelectric generation, was not possible because of the limited number of reported incidents of drought impacts on thermoelectric generation. For this reason, significant simplifying assumptions had to be made.

Two methods for estimating the worst-case loss of at-risk thermoelectric generation from drought were initially considered. The first assumed that the loss of at-risk generation was proportional to the loss of flow, relative to the average flow, within the basin during drought conditions. This approach, however, assumes no excess flow relative to total water demand in the basin during normal years—a poor assumption in most basins. The second method assumed that the loss of at-risk generation was proportional to the shortfall of flow during the drought period relative to total basin water demand in 2010. This approach, however, assumes that all normal water demand within the basin is met by surface water flows—a poor assumption in some dryer basins like the Lower Colorado and Rio Grande where demand frequently exceeds flows. Both approaches assume no prioritization of water consumption toward electricity generation and no mitigation actions.

A hybrid approach was developed to eliminate the weaknesses of the two approaches discussed above. The hybrid approach assumes that loss of generation is proportional to the loss of flow relative to the minimum of the average basin flow or 2010 water demand. Use of the minimum value ensures that generation will not be assumed to be lost when there is excess flow in the basin relative to demand. It also avoids overestimating the loss of generation in areas where normal demand already exceeds normal flows, as these areas are likely to have alternative sources of water in addition to surface flows (groundwater, desalination, interbasin transfers, etc.). The equation for calculating the loss of thermoelectric generation is shown below:

$$Loss\ of\ Gen = At\ Risk\ Thermo\ \times \left(1 - \left(\frac{Drought\ Flow}{Min\ (Average\ Flow, 2010\ Water\ Demand)}\right)\right) \qquad (3)$$

5. Results and Analysis

This section details the major study results and provides analysis of the implications. It includes analysis of historical drought events in the West and Texas, descriptions of the consensus design drought scenarios and their parameters, and quantification of the risk to electricity generation for each drought scenario, along with the implications for transmission planning.

5.1 Analysis of Historical Drought Events

Regional stream-flow data sets over the period of 1901-2009 from the USGS were analyzed to (1) identify drought scenarios of interest, (2) select a drought year with most widely spatial coverage as a West-wide drought scenario on the basis of spatial variation over the eight HUC-2 basins, and (3) evaluate the parameters of the design drought scenarios.

5.1.1 Defining Design Drought Scenarios

In this study, a threshold approach was used to define drought events. We chose the 10^{th} percentile of the annual average stream flow over the 109 annual stream flow records as a threshold to identify droughts. These drought events are likely to occur at an average frequency of once every 10 years. On the basis of the distribution of PHDI calculated by the National Drought Mitigation Center over the similar period of 1895-2008, stream flows at the 10^{th} percentile were typically considered as severe (PHDI < -3) or extreme (PHDI < -4) droughts in the western United States (Figure 3.1). Therefore, the criterion of using stream flow at the 10th percentile or worse would reasonably capture most severe and extreme droughts in the western United States. With this drought definition, we identified 11 drought years for each basin and 50 drought years in total for the eight basins. In some of the drought years, severe drought occurred at multiple basins. This is explored in more detail in the next few sections.

The first design drought scenario was artificially constructed by assuming the 10^{th} percentile drought flow condition occurred simultaneously in each of the 8 basins. This drought scenario is deemed highly unlikely to occur based upon the historical record. However, it was selected in order to provide a consistent basis of comparison of the risk to electricity generation between different basins to a drought of the same frequency. The flow conditions for the 10^{th}-percentile drought scenario are listed in Table 5.1.

A more realistic West-wide drought scenario was determined on the basis of the spatial distribution of drought events is discussed separately in Section 5.1.3. The drought year selected for this scenario was 1977.

The final scenario is based upon the conditions selected by the WECC hydro-modeling group for its low hydroelectricity sensitivity study. The year selected for their study was 2001. For consistency the year 2001 was also selected as a third scenario to evaluate for impact on electricity generation. The flow condition for 2001 in each basin is listed in Table 5.1.

Table 5.1 Summary of drought scenarios.

		HUC-2 Basin							
Scenarios	**Description**	**Texas**	**Rio Grande**	**Upper Colorado**	**Lower Colorado**	**Great Basin**	**Pacific Northwest**	**California**	**Missouri**
Normal	Mean historical flow, 1950-2009 (MAF)	20.55	3.39	10.36	3.00	13.60	202.55	92.59	61.74
Recent Mean	Mean historical flow, 2001-2009 (MAF)	20.06	2.81	9.00	2.21	11.21	179.32	71.71	53.09
10^{th}-Percentile Drought	Year	1913	1963	1966	2000	1954	1929	2009	1955
	Flow (MAF)	6.61	1.92	8.27	1.74	7.27	132.08	48.51	34.56
West-wide Drought	1977 flow (MAF)	22.83	1.36	8.68	1.41	6.73	127.19	27.56	41.53
WECC Low Flow	2001 flow (MAF)	29.51	2.79	8.70	2.32	8.10	121.13	44.01	62.46
Worst Drought	Year	1917	1964	1964	1904	1961	1926	1977	1934
	Flow (MAF)	3.21	1.31	2.55	1.06	4.47	119.09	27.56	21.79

Figure 5.1 shows historical hydrographs of stream flow for all eight regional basins. At the beginning of the 20^{th} century, surface stream water had a high rate of flow in 6 of the 8 basins (the exceptions were Pacific Northwest and Texas). A significant decreasing trend followed until the 1950s. For comparison, a normal flow condition was estimated on the basis of average stream flow over the period 1950-2009. Use of flow records in this period to calculate normal flow rate can also minimize effects of large reservoirs constructed in early 20^{th} century. This normal flow rate for each basin is listed in Table 5.1 and shown as a straight red line in Figure 5.1. The water deficit in the drought-year scenario can be calculated as the deviation of flow rate from the normal flow.

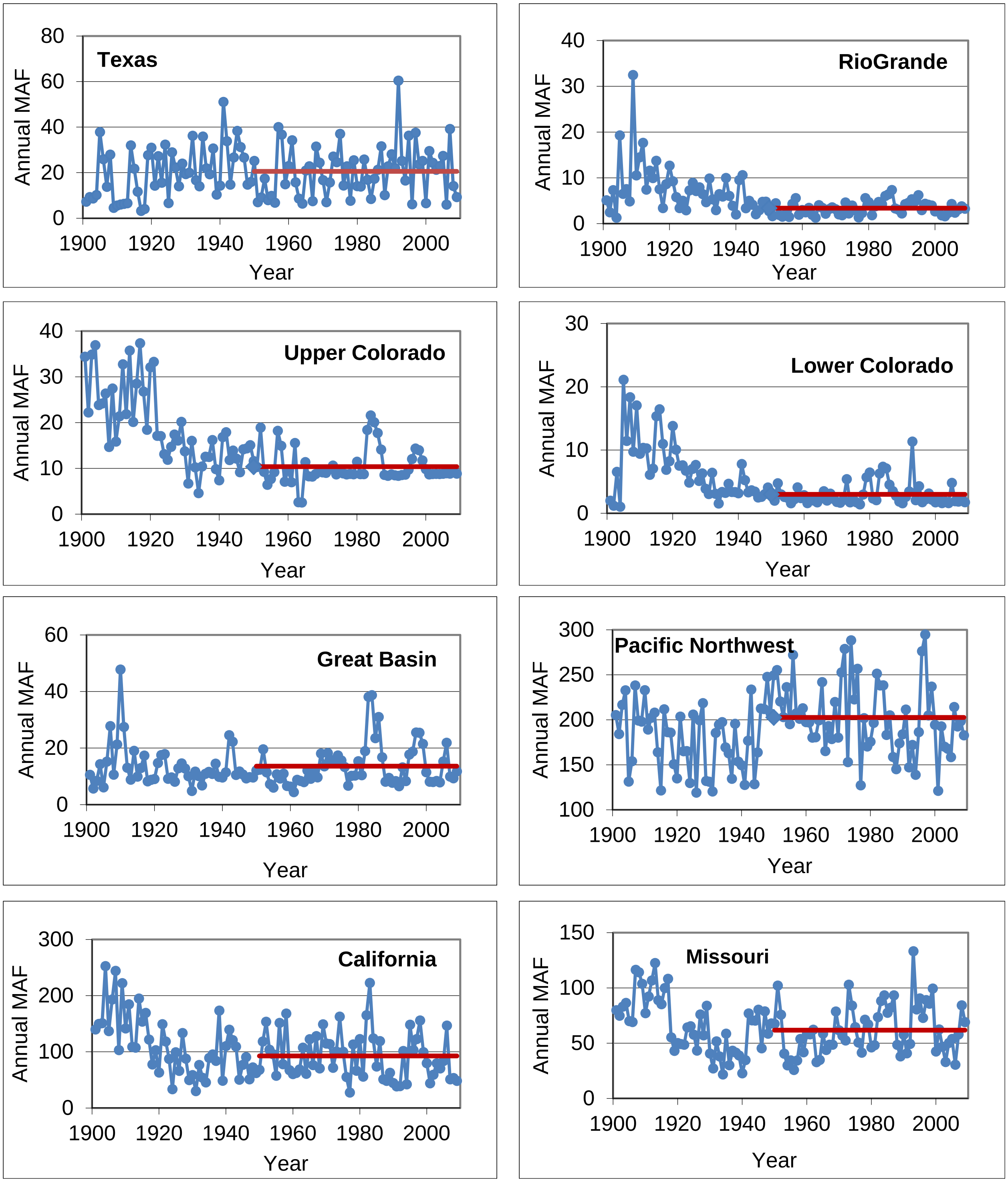

Figure 5.1 Hydrographs of regional stream flow in the eight water resource regions over the period of 1901-2009. The red line indicates the average stream flow over the period 1950-2009.

5.1.2 Spatial Variation of Drought

On the basis of drought events defined in Section 5.1.1, 11 severe to extreme droughts over the 109-year period (1901-2009) were identified for each water resource region. Because of the geographic variation of droughts in the western United States, we found 11 extreme droughts over the eight water resource regions, spread among 50 of the 109 recorded years. To better understand the geographic relationships of drought among the eight regions, two correlation analyses were performed, as discussed below.

Geographic correlations of stream flow for all recorded years

A spatial correlation analysis of stream flow among the eight regions was conducted by using all records over the 109-year period. The computed correlation coefficients are listed in Appendix B, Table B.2. The geographic correlation among the eight regions is illustrated in Figure 5.2. We divided the water resource regions into the following three groups on the basis of their relative correlations:

- The Lower Colorado, Upper Colorado, and Rio Grande water resource regions have a good, positive correlation (> 0.6), illustrated in the upper left part of the diagram (Group I in Figure 5.2).
- The Missouri, Great Basin, California, and Pacific Northwest regions have a medium, positive correlation (0.3-0.6), as shown in the lower right part of the diagram (Group II in Figure 5.2). However, the correlation between Missouri and Pacific Northwest is weak (< 0.3), below the range of 0.3-0.6.
- The Texas-Gulf region has no apparent correlation with any of the other regions, except for a medium negative correlation (-0.4) with the Pacific Northwest (Appendix B, Table B.2).

Geographic correlations of stream flow in drought years

An additional spatial correlation analysis was conducted by using only stream flow during drought years. Because of the geographic variation of droughts, extreme droughts identified in the eight regions were widely spread over 50 years. The correlation coefficients derived from the 50-year stream flow records are listed in Appendix B, Table B.3. The visual correlations are shown in Figure 5.3. The general pattern of three groups of drought regions remains the same. However, the geographic correlation of droughts is slightly changed and members of two groups are adjusted, compared to correlation of all stream flow records, as follows:

- The Missouri water resource region is more correlated with the first group of regions (Lower Colorado, Upper Colorado, and Rio Grande regions) than with the rest of the second group (Great Basin, California, and Pacific Northwest regions) in drought years (Figure 5.3).

- A negative correlation between the Texas-Gulf region and the second group of regions (Great Basin, California, and Pacific Northwest regions) is enhanced during drought years (-0.5 to -0.6; Appendix B, Table B.3).

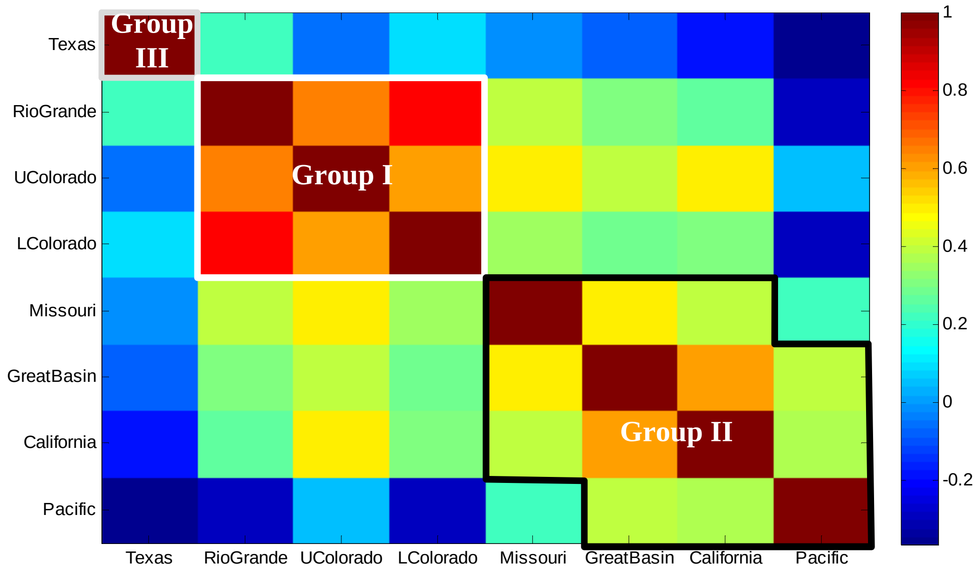

Figure 5.2 Spatial correlations among the eight regions, determined by using stream flow records over all recorded years

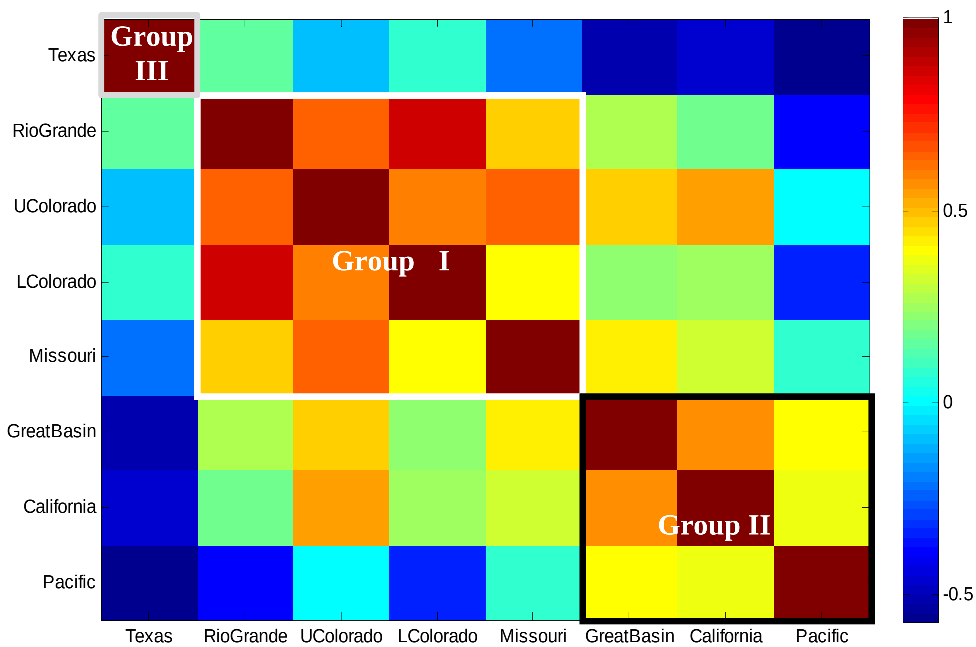

Figure 5.3 Spatial correlations among the eight regions, determined by using stream flow records during drought years.

5.1.3 West-Wide Drought Scenario

As analyzed in Section 5.1.2, the historical severe-drought events apparently do not occur widely over the entire western United States. Drought years may vary from one group of regions to another. This spatial variation of severe drought may reflect a geographic footprint that is likely influenced by spatial and temporal variability of climate and hydrology. To identify the West-wide drought, we conducted an analysis of spatial occurrences in eight regions for each drought year. Figure 5.4 shows that extreme droughts in 1931, 1934, and 1977 affected the greatest number of regions. Among the three drought years that were widely spread in five regions, a recent 1977 drought was selected as a West-wide drought year for drought design. The drought-affected regions in 1977 include the Lower Colorado and Rio Grande regions in the first geographic group and the Great Basin, California, and Pacific Northwest regions in the second geographic group. Apparently, the Upper Colorado region was less affected because variations in stream flow were significantly mitigated after 1967, when the major reservoirs in the Colorado River system were filled up. Figure 5.4 shows that no drought was defined in the Upper Colorado basin after 1967. The flow condition in the 1977 drought is summarized in Table 5.1.

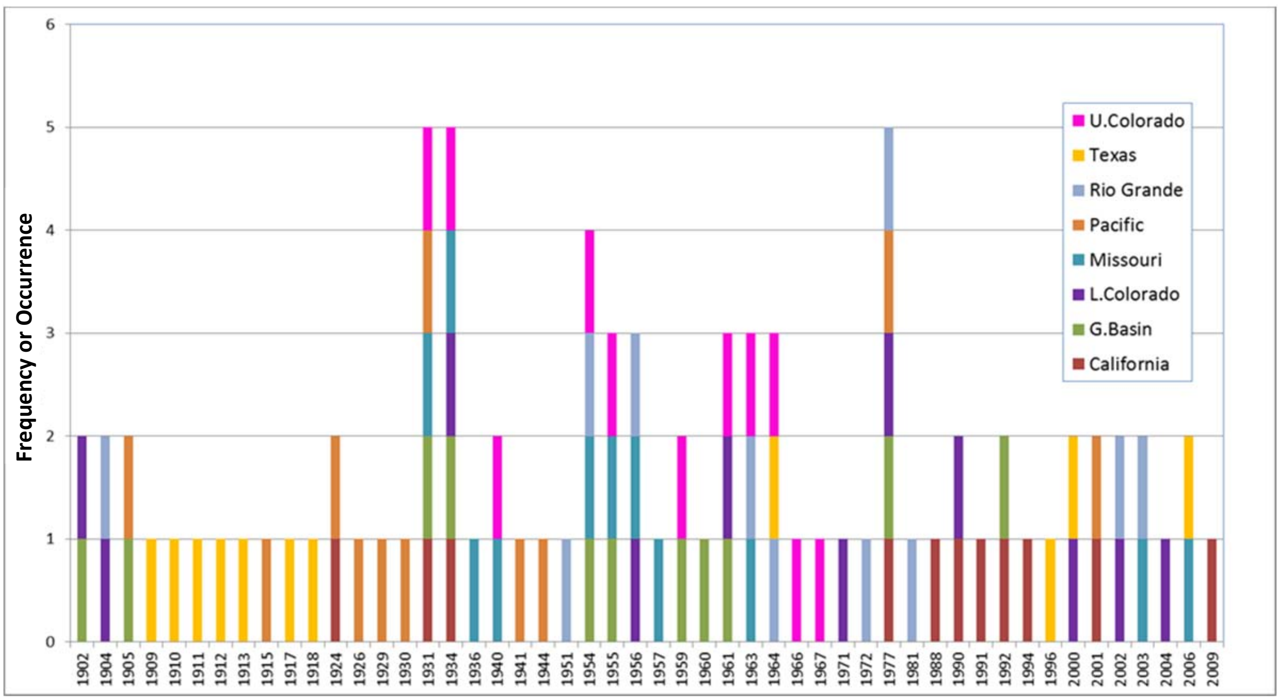

Figure 5.4 Spatial occurrences of extreme droughts (10th percentile or worse) within the eight water resource regions studied in each possible drought year.

5.2 Consensus Drought Definition

5.2.1 Summary of Design Drought Scenarios

On the basis of the discussions above, three design drought scenarios are recommended for further impact analysis. These three design drought scenarios include (1) droughts at the 10th percentile or worse, (2) the West-wide drought of 1977, and (3) WECC's low-flow drought of 2001. A comparison of drought parameters among the three scenarios is summarized below.

Drought frequency

- Droughts defined by the 10th percentile or worse have a recurring frequency of ~ 10 years.
- The West-wide drought of 1977 has a recurring frequency of ~ 35 years over five out of eight regions at the same year.
- Droughts at the WECC's low-flow scenario of 2001 or worse conditions have a recurring frequency of ~ 10 years in two regions and a higher frequency in the other six regions.

Spatial variation of drought

- Three groups of regions represent the geographic variation of drought: (1) Lower Colorado, Upper Colorado, Rio Grande, and Missouri River Basins; (2) Great Basin, California, and Pacific Northwest River Basins; and (3) Texas-Gulf Basin.
- The West-wide drought scenario (1977) affects the majority of regions in the first and second groups at the level of the 10th percentile or worse, while WECC's low-flow scenario of 2001 only severely affects two regions; California and Pacific Northwest, at level of 10th percentile or worse. .

Drought severity

- In the drought scenario at the 10th percentile or worse, severe drought is assumed to occur in all eight regions. The surface water flow is 32–80% of normal flow during the drought year, with an overall average water shortage of 43% (Figure 5.5).
- The West-wide drought scenario of 1977 has the lower stream flow than normal in 7 out of 8 regions (Figure 5.5). The reduction of stream flow over the affected regions reaches 30-84% of normal flow, with an overall average water shortage of 39%.
- The WECC's low-flow-year (2001) scenario has the lower flow than normal in 6 out of 8 regions (Figure 5.5). The decrease in stream flow ranges from 48% to 84%, with an overall average flow shortage of 18%.

5.2.2 Further Considerations and Recommended Future Analyses

This screening analysis is limited to a review of existing studies and a quick analysis based on readily available data. The results of the screening indicated that some key factors need to be considered further and that future analyses might be required. The following are some recommendations:

- A decreasing trend of stream flow has been identified in five out of eight regions over a 109-year period. The effect of the decreasing trend in the subsequent 10 and 20 years needs to be considered.
- Spatial variation is likely present within each water resource region (HUC-2). To evaluate the impact of drought at the plant level, a detailed drought analysis using stream flow data may be required at the HUC-8 watershed level.
- Drought duration of longer than one year and up to five years is probable, on the basis of historical droughts. Methods to incorporate effects of longer drought duration might need to be developed for impact analysis.
- For drought impacts 20 years into the future, the effects of climate change might need to be evaluated for the western United States.

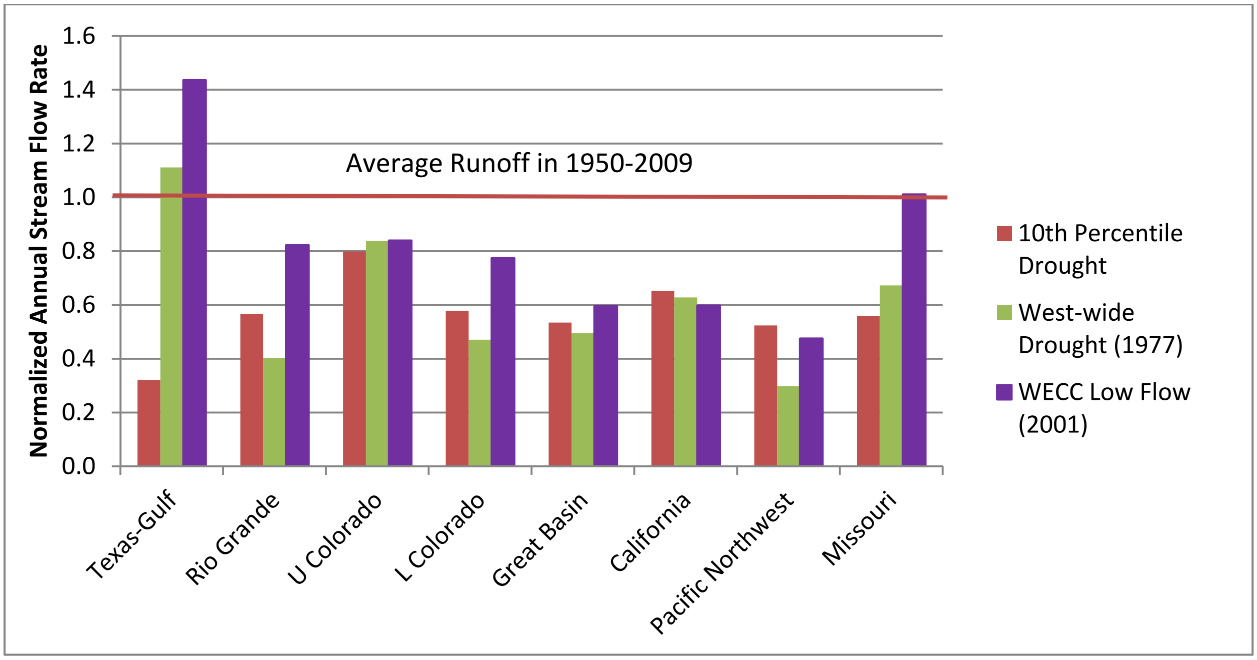

Figure 5.5 Comparison of normalized annual flow rates for three design drought scenarios. The normalized annual flow rates were calculated based on the annual stream flow rates divided by the average annual stream flow rate in 1950-2009 for each of eight water resource regions.

5.3 Quantification of Drought Risk to Electricity Generation

This section describes the estimated impact of the design drought scenarios on electricity generation. The potential impacts on both hydroelectric and thermoelectric generation are analyzed for the three drought scenarios described in section 5.2.

Impacts were calculated on an annual basis for each of the eight basins included in the study area. Estimating impacts on electricity production on the basis of hydrological data is challenging at best. Overall, the results of this analysis should be viewed as a worst-case scenario, given the number of simplifying assumptions that needed to be made. The analysis does not consider the impact of drought response and mitigation activities, owing to the complexity required to adequately model them.

5.3.1 Impacts on Hydroelectric Generation

Equation (1), described in Section 4.3.2, was used to calculate hydroelectric generation factors for each basin for the three drought scenarios. These factors, in turn, are used to calculate the worst-case generation during the drought scenarios. In calculating these factors, the average flow is taken as the average flow between 2000 and 2009, rather than the average flow over the entire historical record. This is because of significant differences in these two values for some basins; operations at hydroelectric facilities are likely to be more closely calibrated toward recent flows than toward long-term average flows. These factors are shown in Table 5.2.

Table 5.2 Hydroelectric generation factors for drought scenarios.

Basin	10th Percentile	West-Wide (1977)	WECC Low Flow (2001)
Texas Gulf	0.31	1	1
Rio Grande	0.70	0.49	1
Upper Colorado	0.92	0.96	0.97
Lower Colorado	0.77	0.63	1
Great Basin	0.65	0.60	0.73
Pacific	0.74	0.71	0.68
California	0.65	0.37	0.59
Missouri	0.67	0.81	1

The total loss of electrical generation was calculated for each of the basins and for each scenario as a fraction of the total annual generation. These values are shown in Figure 5.6. The most significant impact on overall electrical generation occurs in the Pacific Northwest, with 18-22% of total electrical generation lost in the three drought scenarios. This significant impact is driven by the large percentage of total electricity generation from hydroelectric sources in this basin, as illustrated in Figure 4.2. Although other basins experience more severe drought in the

various scenarios, the impact is attenuated by the small fraction of total generation that is from hydroelectric sources.

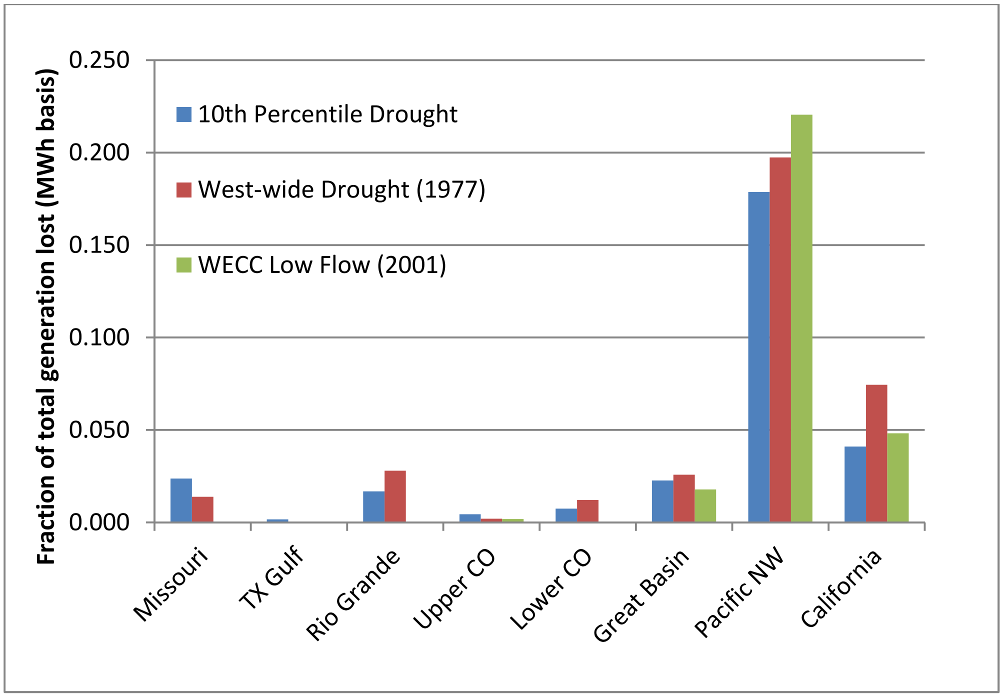

Figure 5.6. Worst-case loss of total basin generation from hydroelectric sources for drought scenarios.

5.3.2 Impacts on Thermoelectric Generation

The methodology described in Section 4.3.3 was used to calculate the fraction of total electricity generation lost from thermoelectric sources for each of the three drought scenarios. The results are shown in Figure 5.7. Except for Texas during the 10^{th}-percentile drought, this methodology results in relatively low amounts of lost thermoelectric generation. In most of the basins and scenarios, no loss of generation is calculated. This is actually somewhat reasonable, given the limited number of reported drought-related outages for thermoelectric generation units (Section 3.2). The high risk in Texas appears to result from a very significant loss of flow in the 10^{th}-percentile drought scenario, combined with the large percentage of total electricity generation that is at risk for thermoelectric generation as defined in Section 4.3.1. We reiterate that these values are to be considered worst-case estimates. They do not consider the buffering impacts of water storage in lakes and reservoirs or the range of mitigation strategies that would almost certainly be employed to minimize the lost generation during actual drought events.

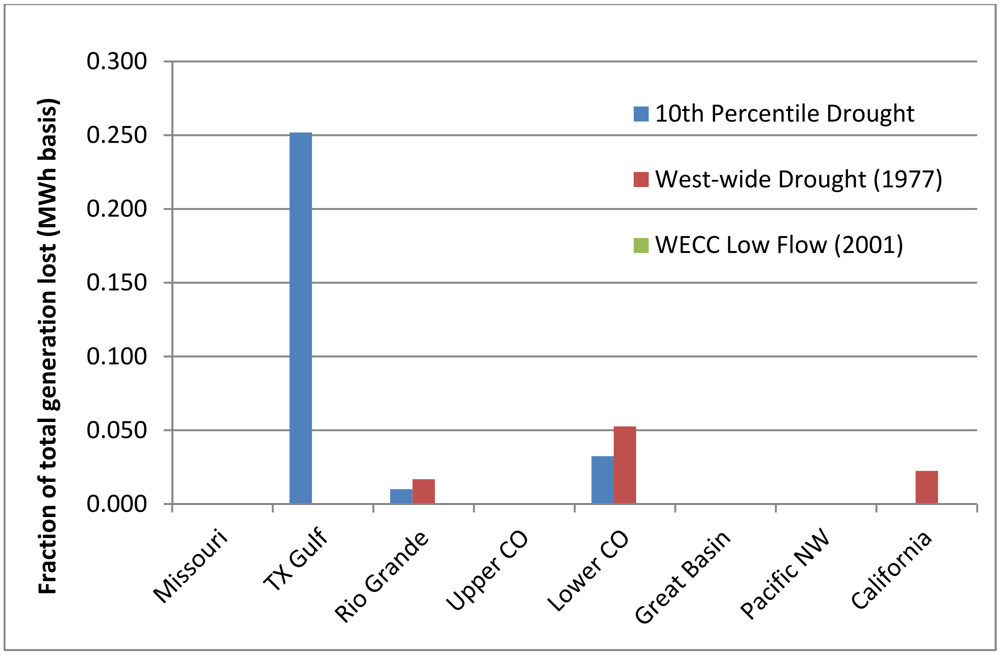

Figure 5.7 Worst-case loss of total basin generation from thermoelectric sources for drought scenarios.

5.3.3 Comparison of Generation Risk by Basin

Here, the results from the hydroelectric and thermoelectric analyses are combined to determine the maximum total percentage of electricity generation that might be lost for each scenario. The results for each scenario are shown in Figures 5.8-5.10. These figures show the worst-case loss of electricity generation for the basin as a fraction of the total annual electricity generation in a normal year, in terms of megawatt hours generated. The results represent the amount of replacement generation or reduction in load that would be required if no reserve capacity were available and mitigation actions were not taken. Given the number of assumptions required and the worst-case nature of these calculations, the results are likely to be more valuable as a measure of relative risk between the different basins than as quantitative predictions.

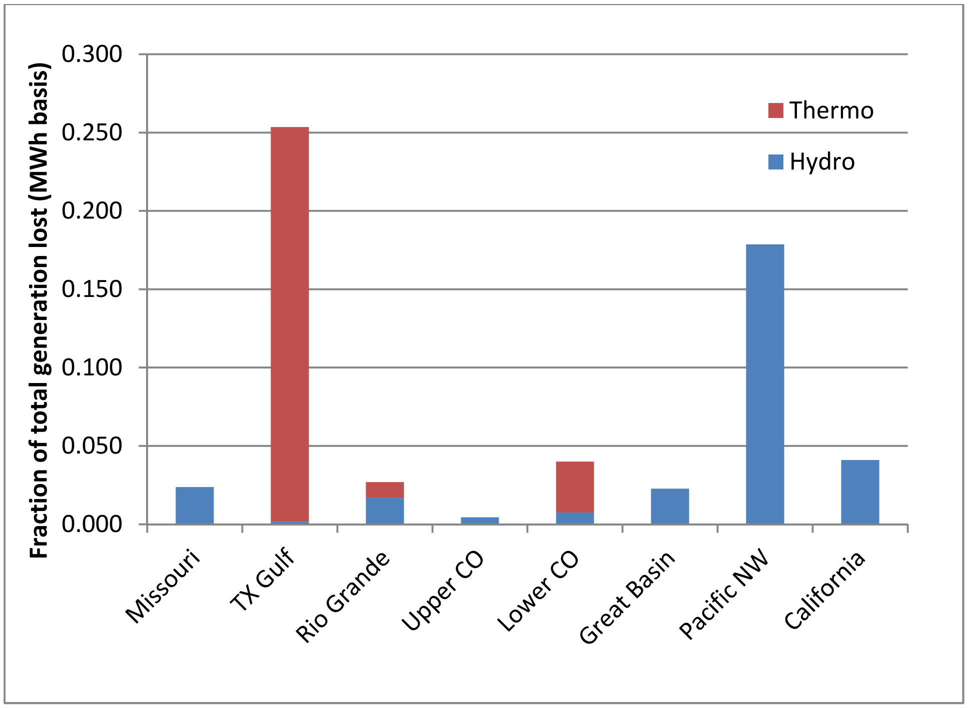

Figure 5.8 Fractional loss of total annual electricity generation for the 10th-percentile drought scenario.

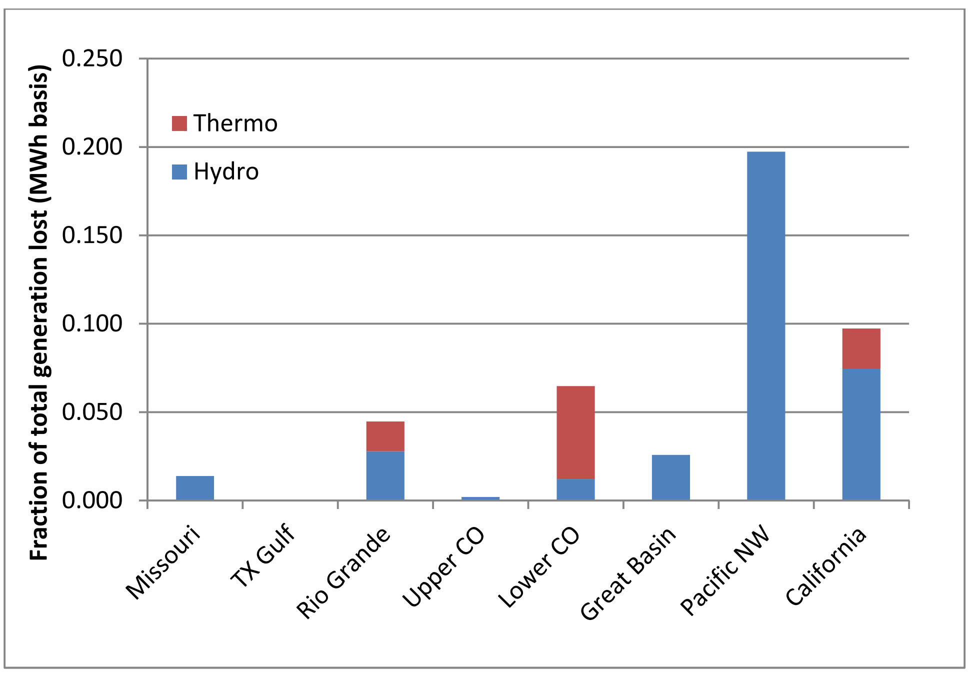

Figure 5.9 Fractional loss of total annual electricity generation for the West-wide drought scenario.

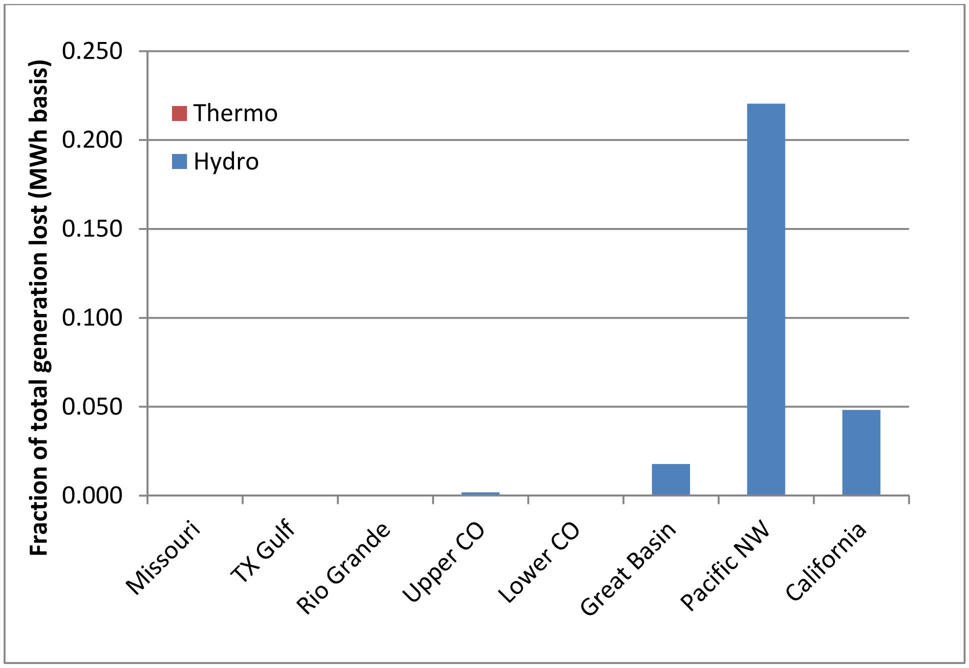

Figure 5.10 Fractional loss of total annual electricity generation for the WECC low-flow scenario.

The 10th-percentile drought scenario is the best scenario for analyzing the relative risks to generation in the different basins, because they all experience drought with the same probability of occurrence. The results for two of the basins are striking, for different reasons. The Pacific Northwest basin shows an 18% loss of generation, entirely from lost hydroelectric generation. This risk is driven by the extreme reliance on hydroelectric generation in the basin. The Texas Gulf Coast basin, on the other hand, shows a 25% loss of generation, almost entirely from lost thermoelectric generation. This risk appears to be driven by the extreme nature of the drought in this basin, with drought flows equaling only 31% of normal levels. In addition, over 70% of electricity generation in this basin relies on fresh surface water for cooling. The remaining basins all show total losses of around 5% or less, which indicates that risk from drought in these basins may in fact be small, at least under the relatively frequent 10th-percentile drought conditions. In the cases of the Lower Colorado and Rio Grande basins, which are mostly arid and prone to drought, this result is somewhat surprising. However, this counterintuitive result is due to the fact that shortages of water have already forced generators in these basins to think about water and minimize their water footprint and drought risk. In most basins, the risks to hydroelectric generation outweigh the risks to thermoelectric generation, but the former is limited by the relatively small fraction of total generation from hydroelectric sources in most basins.

The West-wide drought scenario represents a more severe drought in the California, Lower Colorado, and Rio Grande Basins. This observation logically translates to significant increases in impacts on generation in these basins. It also may indicate that while risks can appear to be limited under more common drought conditions, they may increase significantly in extreme drought events. Therefore, planning based on extreme drought events may be more

useful than planning based on more common drought conditions such as a 10-year drought. This interpretation is supported by the fact that at least two operators (BC Hydro and Avista Corp) reported that they do planning on the basis of the most severe drought on record.

The WECC low-flow scenario impacts only California, the Pacific Northwest, and the Great Basin and does not result in any loss of thermoelectric generation. However, this case does represent the most severe impact on hydroelectric generation in the Pacific Northwest. Grid system modeling under this scenario is likely to provide a good indication of risks to this basin, but it might miss potential risks in other areas such as the Missouri and Upper and Lower Colorado Basins. This may, in fact, be a reasonable tradeoff, given that WECC only models the loss of hydroelectric generation in its low-flow hydroelectric sensitivity study and these basins do not rely significantly on hydroelectric generation.

With the exception of the Pacific Northwest and Texas, the risks to most basins, in most scenarios, appear to be limited and within a range that can be managed with known mitigation strategies, along with existing reserve and transmission capacity. We note, however, that the analysis considers only average annual losses. While the analysis shows relatively low generation losses in most basins under most scenarios, it does not consider the potential for and the impact of shorter-term, more acute events. Such events are unlikely to impact hydroelectric generation, which is buffered by storage reservoirs, but they might have an impact on thermoelectric generation. It also does not consider the cumulative impact of extended, severe drought, which is likely to draw down water storage and may exceed the capabilities of short-term mitigation efforts. These differential and nonlinear impacts are challenging to model or predict, but represent important risks for planners to take into consideration.

The risk to the Pacific Northwest and Texas Basins requires further study. The Pacific Northwest is vulnerable because of its heavy reliance upon hydroelectric generation, which has been shown to be highly correlated with surface water flows. However, because of this history, the region is experienced in dealing with variability in the annual supply of hydropower. In addition, drought is an important consideration for WECC in its resource planning process. The results of this analysis will be adapted in collaboration with researchers at WECC to develop model scenarios to explore the resource adequacy and transmission implications of extreme drought conditions.

Texas is currently in the process of becoming a case study for the impact on thermoelectric generation from drought. The state is in the midst of one of its most severe droughts on record. To date, the curtailment of thermoelectric generation has been kept to a minimum, but recent statements by ERCOT indicate that the risk will increase significantly if the drought continues far into 2012. At ERCOT's October 2011 board meeting, it was reported that only one small 24-MW unit had been curtailed at that point, but that without a return to normal precipitation patterns, between 400 and 3000 MW could be curtailed by May 2012. It was reported that operators were reducing the impact of the drought by building pipelines to alternative water sources, acquiring additional water rights, and installing additional groundwater pumping capacity (ERCOT 2011a). In its December 2011 assessment of resource adequacy for winter 2011/2012, ERCOT stated that the water sources for over 11,000 MW of generation were at historically low levels (ERCOT 2011b). This amount represents 15% of the total available

resource (compared to 25% estimated as a worst case for the 10^{th}-percentile scenario). Further increasing the reliability risk is the fact that Texas and ERCOT are poorly connected with the rest of the nation's electric grid; this fact limits the potential for purchasing power to make-up any shortfall.

Thus far, the impacts from the current drought in Texas, despite the severity, have been significantly less than the worst-case scenario predicted by the 10^{th}-percentile scenario. However, these reports from ERCOT indicate that the impacts may grow significantly over time if the drought continues as water storage reservoirs are depleted and mitigation strategies reach their limits. If this eventuality occurs, it is possible that the risk may approach or even exceed those estimated in this study. The researchers will continue to work closely with ERCOT to gain an improved understanding of the impacts of drought on thermoelectric generators as they adapt to the continuing drought conditions within Texas.

6. Conclusions and Recommendations

A conservative, first-order analysis of the risk to electricity generation from drought in the western United States has been performed. Even with these conservative risk estimates, the majority of basins evaluated showed a limited amount of risk under most scenarios. The level of risk in these basins is likely to be amenable to mitigation by known strategies, combined with existing reserve generation and transmission capacity. At least in some of the more arid basins, such as the Lower Colorado and Rio Grande, this is the result of proactive planning that has minimized the number of generators that depend upon fresh surface water sources. The risks to the Pacific Northwest and Texas basins, however, do appear to be significant and require more detailed study. The Pacific Northwest is vulnerable because of its heavy reliance on hydroelectric generation. Texas, conversely, is vulnerable because of its heavy dependence on thermoelectric generation, which relies on surface water for cooling, along with the fact that this basin seems to experience more severe drought events on average. Further increasing the risk to Texas is the fact that its electric grid is largely independent of the rest of the country, so it has limited capacity for importing power in times of shortage.

From the perspective of individual power producers or generating units, the most important strategy to minimize risk appears to be to have proactive monitoring, modeling, and planning processes in place in order to anticipate risks well in advance, so as to provide adequate time to implement mitigation strategies. Many operators in arid states have developed sophisticated internal systems to manage water and water-related risks. However, it is unclear whether operators in other states where drought is not as common have done so. It is possible that generators in states that experience drought infrequently may in fact be more vulnerable than those that deal with drought on a regular basis.

The results of this analysis will be adapted in collaboration with researchers at WECC to develop a modeling scenario to explore transmission implications further under the worst-case-scenario conditions considered here. In most of the basins, the WECC low-flow hydroelectric scenario currently modeled showed less significant generation impacts than either the West-wide drought scenario or the 10^{th}-percentile drought scenario. Modeling a more severe drought scenario will help improve understanding of the resilience of the existing system to severe conditions and will help inform future transmission planning efforts. The researchers will also continue to work closely with ERCOT to gain an improved understanding of the impacts of drought on thermoelectric generators as they adapt to the continuing drought conditions within Texas.

In addition to the ongoing work described above, we recommend more detailed study of the potential impacts of drought on electricity generation. Future analyses should include (1) effects of the decreasing trend in stream flow observed in five out of eight regions extending 10-20 years into the future, (2) drought analysis at the HUC-8 sub-basin level for impact evaluation of individual plants, (3) effects of longer drought duration (1-5 years), and (4) potential drought impacts under climate change scenarios for the near future (20 years). Methodologies should be developed to include the buffering effect from the drawdown of water storage from lakes and reservoirs and to incorporate mitigation strategies. Efforts should also be made to estimate the impact of lost generation capacity on electricity prices and the resulting economic impacts.

While it is recommended that future studies initially focus on basins with the highest risk, it may also be important to study other areas not normally associated with drought or water-related stress, as generators in these areas may be more dependent upon surface water sources and may be less likely to have adequate contingency plans in place.

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Appendix A List of Ongoing and Current Drought Studies

A.1 Drought Analysis

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
1	Three Recent Flavors of Drought in the Pacific Northwest	2010	KARIN A. BUMBACO Office of the Washington State Climatologist, University of Washington, Seattle, Washington	http://journals.ametsoc.org/doi/pdf/10.1175/2010JAMC2423.1	Pacific Northwest	The paper describes three droughts in terms of the precipitation, temperature, and soil moisture anomalies, and discusses different drought impacts experienced in the Pacific Northwest (PNW) in the past decade. For the first drought, in 2001, low winter precipitation in the PNW produced very low streamflow that primarily affected farmers and hydropower generation. For the second, in 2003, low summer precipitation in Washington (WA) and low summer precipitation and a warm winter in Oregon (OR) primarily affected streamflow and forests. For the last, in 2005, a lack of snowpack due to warm temperatures during significant winter precipitation events in WA and low winter precipitation in OR had a variety of different agricultural and hydrologic impacts.	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
2	Water, climate change, and sustainability in the Southwest	2010	Glen M. MacDonald Institute of the Environment and Department of Geography, University of California, Los Angeles E-mail: macdonal@geog.ucla.edu	http://www.pnas.org/content/107/50/21256.full.pdf+html	Southwest	Study addressed the recent frequent water shortages and droughtss in the Southwest, which posed sustainability challenges for the people in the region. Since 2001, large portions of the arid Southwest have experienced prolonged drought. Particularly widespread drought occurred in 2002, 2003, 2007, and 2009. During these years, the region's precipitation averaged as much as 22–25% below the 20th century mean, with local deficits being greater. In 2002 and 2009, annual precipitation in Arizona was ~40% below normal. The effects of low precipitation have been exacerbated by high temperatures, increased evapotranspiration, and decreased runoff. The average annual temperature for 2001–2009 was 0.8°C warmer than the 20th century mean. To meet these 21st century sustainability challenges, the authors recommended technical innovations, policy measures, and market-based solutions that increase supply and decrease water demand.	Journal Article
3	Increasing Drought in the American Southwest? A Continental Perspective Using a Spatial Analytical Evaluation of Recent Trends	2010	Balling, Robert C., Jr. Arizona State Univ., School of Geographical Sciences and Urban Planning, Tempe, AZ 85287, U.S.A	http://bellwether.metapress.com/content/n2v0078xj3316u16/	Southwest U.S.	The authors investigated drought trends in the U.S. Southwest with respect to trends throughout the rest of the conterminous United States by using a variety of spatial analytical methods and showed a highly statistically significant trend toward increased drought in the Southwest, with a particularly strong trend over the Colorado River Basin.	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
4	The Columbia Basin Climate Change Scenarios Project (CBCCSP)	2009	Alan F. Hamlet et al. University of Washington Climate Impacts Group/The Bonneville Power Administration/The Northwest Power and Conservation Council/Oregon Water Resources Department/British Columbia Ministry of the Environment	http://www.hydro.washington.edu/2860/report/	Columbia River Basin	The study incorporates a number of important improvements in the hydrologic models and the scenario generation process. The most important changes are (1) the increased spatial resolution of the macro-scale hydrologic model (VIC) (Chapter 5), and (2) improvements in the downscaling procedures used to translate GCM simulations to driving data for the hydrologic models, especially to support daily time step analysis at the finer spatial scales (Chapter 6).The primary final products of this project are a set of hydrologic databases encompassing 297 streamflow locations, GIS layers for key hydrological and meteorological variables (Chapter 8), and a web site (Chapter 9) for providing these data resources to a diverse user community (Chapter 2). An analysis of future hydrologic extreme events was performed (Chapter 7).	Report
5	The Transboundary Setting of California's Water and Hydropower Systems: Linkages between the Sierra Nevada, Columbia, and Colorado Hydroclimates	2009	Daniel R. Cayan Climate Research Division, Scripps Institute of Oceanography, University of California, San Diego, La Jolla, California E-mail: dcayan@ucsd.edu	http://tenaya.ucsd.edu/~dettinge/transboundary.pdf	Sierra Nevada, Columbia River, and Colorado River Basins	To characterize the transboundary hydroclimatic influences on California's hydropower and water supplies, water-year river discharge totals from the west slope of the Sierra Nevada were compared to concurrent flows of the Columbia River (in the Pacific Northwest) and the Colorado River (in the southwestern United States). In general, the winter climatic conditions have particularly strong impacts on hydropower production in the region. The study also showed that years that are anomalously dry (or anomalously wet) in two or more of the watersheds occur with greater frequency than expected by chance. Dry/dry	Book Chapter

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
						occurrences that pair the Sierra/Columbia watersheds or that pair the Sierra/Colorado watersheds are common. However, there is a modest tendency for opposing extremes to sometimes occur for the Columbia and Colorado Rivers, perhaps in response to Pacific Decadal Oscillation (PDO) or El Niño-Southern Oscillation (ENSO) episodes.	
6	Drought Resilience of the California Central Valley Surface-Ground-Water-Conveyance System(1)	2009	Miller, Norman L. Univ. Calif. Berkeley, Lawrence Berkeley Lab, Climate Science Dept, Berkeley, CA 94720 U.S.A E-mail: nlmiller@lbl.gov	http://onlinelibrary.wiley.com/doi/10.1111/j.1752-1688.2009.00329.x/pdf	California	The article presents drought simulations for the California Central Valley's four subbasins: the Sacramento Basin, the San Joaquin Basin, the Tulare Basin, and the Eastside Drainage. Results suggest (1) greatest impacts in the San Joaquin and Tulare Basins, regions that are heavily irrigated and are presently overdrafted in most years; (2) a decrease of regional surface water diversions by as much as 70%; (3) a decline of stream-to-aquifer flows and aquifer storage proportional to drought severity; and (4) most significantly, a decline in groundwater head for severe drought cases, where results suggest that under these scenarios the water table is unlikely to recover within the 30-year model-simulated future.	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
7	Predicting Drought in the Green River Basin	2008	Glenn Tootle Department of Civil and Architectural Engineering, University of Wyoming Email: tootleg@uwyo.edu	http://wwweng.uwyo.edu/economic/owp/finalreports/pdfs/FinalReportP17.pdf	Northwest	The main research results are as follows: (1) The development of six new tree-ring chronologies for the Upper Green River Basin. (2) Streamflow reconstructions in the Upper Green River Basin, including at major nodes used by the Bureau of Reclamation (BOR). BOR uses both instrumental and reconstructed streamflow in its Colorado River System Simulation System (CRSS) model. Also, headwater gauges that were reconstructed allowed for observing spatial variation in drought. (3) The streamflow reconstructions revealed that significant “megadroughts” have occurred. These megadroughts far exceeded (in both length and magnitude) those droughts observed in the instrumental record. (4) The magnitude, severity, and risk of drought in the Upper Green River Basin were quantified, and the recent (2000 to 2004) five-year drought was examined. 5. A distinct ENSO was observed in streamflow and snowpack in the Wind River Range, including the Upper Green River Basin. A previous-year summer La Niña (El Niño) resulted in increased (decreased) streamflow (or snowfall).	Report
8	Drought analysis of monthly hydrological sequences: a case study of Canadian river	2008	T. C. Sharma Department of Civil Engineering, Lakehead University, Ontario, Canada	http://pdfserve.informaworld.com/208976__918666044.pdf	Canada	The authors analyzed monthly flow sequences of Canadian rivers over two parameters of importance in hydrological droughts (the longest duration and the largest severity), standardized over a desired return period.	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
9	Management Strategies for the Colorado River Reservoir System under Major Drought Scenarios	2008	Donald K. Frevert Bureau of Reclamation, Lakewood, CO	World Environmental and Water Resources Congress 2008	Colorado River Basin	The authors emphasize the importance of drought in the management strategies of water resources in the Colorado River Basin. They describe the process, findings, and conclusions reached to date and future steps toward implementation of shortage criteria for the basin.	Confer-ence Paper
10	Southern California and the perfect drought: Simultaneous prolonged drought in southern California and the Sacramento and Colorado River systems	2007	Glen M. MacDonald Department of Geography, UCLA, Los Angeles, CA	Quaternary International, Volume 188, Issue 1, September 2008, Pages 11-23	Southern California, Sacramento River and Colorado River	In this paper, a "perfect drought" is defined as a prolonged drought that affects southern California, the Sacramento River basin, and the upper Colorado River basin simultaneously. According to the study, perfect droughts, which generally persist for less than five years, occurred in the regions over the past century. Perfect droughts that extended across all three areas were associated with anomalous upper-level high pressure off the West Coast and over western North America and were in turn associated with anomalously cool eastern Pacific SSTs. Exploratory dendrochronological reconstructions of winter Palmer Drought Severity Index (PDSI) in southern California, annual discharge of the Sacramento River, and annual discharge of the Colorado River demonstrate that prolonged perfect droughts (~30–60 years), which produced arid conditions in all three regions simultaneously, developed in the mid-11th century and the mid-12th century, during the period of the so-called "Medieval Climate Anomaly." Prolonged aridity in western North America during this period appears to have been associated with cooling of the eastern equatorial and northern Pacific related to	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
						the differential thermal response of the western and eastern Pacific to increased tropical radiative forcing at that time.	
11	Colorado River Basin Water Management: Evaluating and Adjusting to HydroclimaticVariability	2007	Jeffrey W. Jacobs National Research Council, Washington, D.C.	http://www.nap.edu/catalog/11857.html	Colorado River Basin	The report reviews hydrologic and climatic sciences of the Colorado River region by assessing the extent of scientific studies regarding both Colorado River hydrology and hydroclimatic trends that might affect river flows. The authors conisder related topics, including hydrologic models, data, and methods; organizations for evaluating hydroclimatic data; and systems operations and water management practices. The report also highlights the many factors that are likely to heighten future water management challenges and might eventually prompt substantial changes in policies for managing and using water. As this report notes, future events may necessitate a new level of federal and interstate collaboration on Colorado River water management. The challenges of managing limited water supplies in a region with growing population and demands are not unique to the Colorado River basin, and Colorado River water managers are encouraged to explore further the potential benefits that might accrue from scientific exchanges with other regions of the nation and the world. This report points to several important scientific findings as they relate to Colorado River hydrology and climate. It also includes findings related to cooperation among the basin states and between scientists and water managers. The report recommends a comprehensive	Report

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
						assessment of contemporary urban water management practices and other relevant water supply-and-demand issues, including consideration of both the full implications of agriculture-to-urban water transfers and future development of regional water demand forecasting. As the Colorado River basin enters a new phase of coping with aridity and drought, future challenges promise to be more exacting than those faced in the past, and the cooperation that such a study would entail will be of great value. In the 21st century, good scientific information regarding Colorado River flows and variability, along with close cooperation and communication at all levels, will prove more important than ever.	
12	Major Environmental Threats to the Great Basin in the 21st Century	2006	Mark Salvo Sagebrush Sea Campaign	http://www.sagebrushsea.org/pdf/SSC_Statement_Senate_Subcomm_Hearing_Las_Vegas.pdf	Great Basin	This report to the Subcommittee on Public Lands and Forests, Energy and Natural Resources Committee, United States Senate, identifies drought as one of the 21st century's enviromental threats to the Great Basin.	Report
13	Occurrence of Sustained Droughts in the Interior Pacific Northwest (A.D. 1733–1980) Inferred from Tree-Ring Data	2004	Paul A. Knapp Department of Anthropology and Geography, Georgia State University, Atlanta, Georgia	http://journals.ametsoc.org/doi/pdf/10.1175/1520-0442%282004%29017%3C0140%3AOOSDIT%3E2.0.CO%3B2	Pacific Northwest	The authors examine the spatial patterns of moderate and severe sustained droughts in the interior PNW by using tree-ring data over the period 1733–1980. The main objective is to demonstrate that drought frequency, particularly of severe droughts, can be substantially impacted by spatial variability of climatic transition-zone boundaries. The spatial patterns of drought frequency and duration results suggest the presence of a core region for drought (i.e., a drought zone) in the interior PNW. As	Journal Article

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						for core regions in the Great Plains, understanding the locations of these drought zones is important because they may be the first areas to experience the effects of a sustained drought that can affect a much larger region.	
14	Climatic Fluctuations, Drought, and Flow in the Colorado River	2004	Robert H. Webb United States Geological Survey	http://www.publiclandsranching.org/htmlres/PDF/U.S.GS%20Drought%20Factsheet.pdf	Colorado River basin	The purpose of this Fact Sheet is to discuss the causes of drought in the Colorado River basin and the predictability of river flows by using global climate indices. The fact sheet also describes the sources of moisture to the Colorado River basin, relevant drought indices, Colorado River flow, and multidecadal climate variability.	Fact Sheet
15	West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections	2011	Subhrendu Gangopadhyay and Tom Pruitt Water and Environmental Resources Division, Bureau of Reclamation, Denver Colorado	Technical Memorandum No. 86-68210-2011-01	West-wide	This technical assessment report provides: (1) an analysis of changes in hydroclimate variables including precipitation, temperature, snow water equivalent, and streamflow across the major Reclamation river basins and the technical foundation for the SECURE report and (2) documentation for this new hydrologic-projections dataset, which will be made publicly available over the western United States. The analysis involves developing hydrologic projections associated with World Climate Research Programme Coupled Model Intercomparison Project3 (WCRP CMIP3) climate projections that have been bias-corrected and spatially downscaled and served at the following Web site: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections. In total, 112 hydrologic projections were developed, relying on watershed applications of the Variable Infiltration	Report

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						Capacity (VIC) macroscale hydrology model. From these time-series climate and hydrologic projections, changes in hydroclimate variables were computed from the reference 1990s decade (water years 1990–1999) for three future decades: 2020s (water years 2020–2029), 2050s (water years 2050–2059) and 2070s (water years 2070–2079). The reference 1990s are from the ensemble of simulated historical hydroclimates, not from the observed 1990s.	
16	Drought duration and frequency in the U.S. Corn Belt during the last millennium (AD 992-2004)	2011	Michael C. Stambaugh Missouri Tree-Ring Laboratory, Department of Forestry, 203 ABNR Building, University of Missouri, Columbia, MO 65211 Email: stambaughm@missouri.edu	http://web.missouri.edu/~stambaughm/2011_Stambaugh_drought.pdf	U.S. midwestern corn belt	A new reconstruction of drought was developed from preconstructed tree-ring chronology to characterize the historic occurrence, duration, and frequency of drought events for the U.S. corn belt region. The authors claim that their reconstruction is the first paleoclimate reconstruction achieved with subfossil oak wood in the United States and that it increases the current dendroclimatic record in the central U.S. agricultural region by more than 500 years.	Journal Article
17	Future dryness in the southwest U.S. and the hydrology of the early 21st century drought	2010	Daniel R. Cayan Division of Climate, Atmospheric Sciences, and Physical Oceanography, Scripps Institution of Oceanography,	http://www.pnas.org/content/early/2010/12/06/0912391107.full.pdf	West Wide	The authors provide in-depth analysis of drought in the Southwest region. Results from a small but representative selection of climate simulations, downscaled to 1⁄8° × 1⁄8° and applied to a hydrological model, suggest a future where drought becomes more extreme by the mid to late 21st century. Inevitably, there will be precipitation shortages, and during these	Journal Article

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			University of California, San Diego, La Jolla, California E-mail: dcayan@ucsd.edu			times, the resulting hydrological drought will be aggravated by a trend toward much less snowpack, warmer temperatures (especially in summer), and diminished runoff and soil moisture.	
18	A copula-based joint deficit index for droughts	2010	Shih-Chieh Kao Computational Sciences and Engineering Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, U.S.A email: kaos@ornl.gov	http://drinet.hubzero.org/resources/35/download/Kao-Govindaraju_JHydrol_Copula_paper.pdf	Indiana	The paper argues that current indices-based drought information is limited because it does not capture the joint behavior of hydrologic variables. The authors explore the potential of copulas in characterizing droughts from multiple variables to address this limitation. They propose a modified index that accounts for seasonality in precipitation and streamflow marginals. The authors claim that the proposed index is able to reflect both emerging and prolonged droughts in a timely manner and allows a month-by-month drought assessment, such that the required amount of precipitation to achieve normal conditions in the future can be computed.	Journal Article
19	Statistical Modeling of the Monthly Palmer Drought Severity Index	2010	Debbie J. Dupuis Dept. of Management Sciences, Chemin de la Côte-Sainte-Catherine, Montréal, PQ, Canada E-mail: debbie.dupuis@hec.ca	Journal of Hydrologic Engineering, Vol. 15, No. 10, October 2010, pp. 796-807 [DOI 10.1061/(ASCE)HE.1943-5584.0000249] http://ascelibrary.org/heo/resource/1/jhyeff/v15/i10/p796_s1?isAuthorized=no	Nebraska, Nevada, Arizona, and Florida	This article presents a new approach for the modeling of dry period interarrival times. The method targets dry period interarrival times directly and uses a combination of an empirical model and results from extreme-value theory. Existing approaches initially model dry period duration and successive wet period duration, then develop a model for dry period interarrival times as a by-product. In this study, the authors performed a statistical study and analyzed various	Journal Article

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						duration characteristics of dry and wet periods based on monthly PDSI values for climate divisions in the United States. Data from the states of Nebraska, Nevada, Arizona, and Florida were used to show that previous models are often inadequate. The authors also argue that their proposed approach for modeling dry period interarrival times is necessary and that designs and actuarial calculations based on the results produced by fitting previously published models would be severely flawed.	
20	Tree ring record of streamflow and drought in the upper Snake River	2010	Erika K. Wise Univ. of North Carolina, Department of Geography, Chapel Hill, NC 27599, U.S.A E-mail: ekwise@email.unc.edu	http://www.agu.org/pubs/crossref/2010/2010WR009282.shtml	Snake River Basin	This work used tree ring samples collected near the Snake River headwaters, augmented with pre-existing tree ring chronologies, to create a 415-year reconstruction of upper Snake River streamflow. The authors claim that their results provide the first description of multicentury water supply variability in this river, indicating that the region's early 21st century drought was severe, even in the context of long-term climatic variability.	Journal Article
21	Rapid hydrologic shifts and prolonged droughts in Rocky Mountain headwaters during the Holocene	2010	Bryan Shuman Univ. of Wyoming, Dept. of Geology and Geophysics, Laramie, WY 82071, U.S.A E-mail: bshuman@uwyo.edu	http://www.agu.org/pubs/crossref/2010/2009GL042196.shtml	Rocky Mountain headwaters	The authors examined the history of water supplies at the convergence of three major North American watersheds (the Snake-Columbia, Bighorn-Missouri-Mississippi, and Green-Colorado River basins) by reconstructing water-level changes at the Lake of the Woods, assuming past changes in lake volume to be equal to changes in the balance of watershed inputs and outflow. The result is a quantified hydroclimatic history.	Journal Article

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22	Economic consequences of optimized water management for a prolonged, severe drought in California	2010	Julien J. Harou University College London, Environment Institute, London WC1E 6BT, England E-mail: j.harou@ucl.ac.uk	http://www.agu.org/pubs/crossref/2010/2008WR007681.shtml	California	The article synthesizes a 72-year drought condition with half of the mean historical inflows by using random sampling of historical drought years. The authors also explored economic effects and potential adaptation of California's water supply system in 2020 to this drought by using a hydroeconomic optimization model, illustrating the ability of extensive and flexible water systems with heterogeneous water demands to respond to severe water stress.	Journal Article
23	Meta-elliptical copulas for drought frequency analysis of periodic hydrologic data	2010	Songbai Song NW A&F University, College of Water Resources & Architecture Engineering, Yangling 712100, Shaanxi, PRC E-mail: ssb6533@nwsuaf.edu.cn, vsingh@tamu.edu	http://www.springerlink.com/content/t4k06705758v3w63/fulltext.pdf	Texas	Meta-elliptical copulas were used to model the joint probability distribution of periodic hydrologic data using monthly precipitation data from a gauging station in Texas, U.S., to illustrate parameter estimation and goodness-of-fit for univariate drought distributions with various statistical tests.	Journal Article
24	A 1,200-year perspective of 21st century drought in southwestern North America	2009	Connie A. Woodhouse School of Geography and Development, University of Arizona, Tucson, AZ	http://www.pnas.org/content/107/50/21283.full.pdf+html	Southwest	Since the 21st century droughts in southwestern North America saw a concurrence of elevated temperatures and increased aridity, the paper argues that the instrumental records and paleoclimatic evidence for past prolonged droughts in the Southwest that coincide with elevated temperatures can be assessed to provide insights on temperature-drought relations and to develop worst-case scenarios for the	Journal Article

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						future.	
25	Developing Objective Operational Definitions for Monitoring Drought	2009	Steven M. Quiring Texas A&M University, Dept. of Geography, College Station, TX 77843, U.S.A E-mail: squiring@tamu.edu	http://journals.ametsoc.org/doi/pdf/10.1175/2009JAMC2088.1	Texas	This paper argues that many state drought plans utilize operational drought definitions that are derived subjectively and therefore may not be appropriate for triggering drought responses. The authors claim that they have developed an objective methodology for establishing operational drought definitions. This paper shows the advantages of this methodology, as demonstrated by calculating meteorological drought thresholds for the PDSI, the standardized precipitation index, and percent of normal precipitation for both station and climate division data from Texas. Results indicate that using subjectively derived operational drought definitions may lead to over- or underestimation of true drought severity. The authors suggest an objective location-specific method for defining operational drought thresholds.	Journal Article
26	United States drought of 2007: historical perspectives	2009	Justin T. Maxwell Appalachian State Univ., Dept. of Geography and Planning, Boone, NC 28608, U.S.A E-mail: jtmaxwel@uncg.edu	http://www.int-res.com/articles/cr2009/38/c038p095.pdf	U.S.	The paper investigates the 2007 drought in historical perspective, based on climate records for 1895-2007, to increase understanding of this hazard and contribute to improvements in drought mitigation plans. The authors compare the 2007 drought historically against the climatic record (1895-2007) by using the PDSI, then examine the temporal progression of the 2007 drought and place the peak month of drought severity (November) in historical perspective by using rankings of severity and statistical recurrence intervals. Results show that	Journal Article

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						while some regions experienced the worst drought on record, both annually and in November during the calendar year 2007, this year was not as severe as other notable drought years. The article argues that November 2007 ties (with five other years) for the 12th worst on record in terms of the number of climatic divisions experiencing the worst November drought.	
27	Towards a Global Drought Monitoring and Forecasting Capability	2008	Lifeng Luo Environmental Engineering and Water Resources, Department of Civil and Environmental Engineering, Princeton University E-mail: lluo@Princeton.EDU	http://www.nws.noaa.gov/ost/climate/STIP/33CDPW/Luo_33cdpw.pdf	U.S.	This report presents a Drought Monitoring and Prediction System (DMAPS) for monitoring and forecasting drought in near real time for the United States and globally. Part of the system is currently in transition to EMC/NCEP for operational testing, including implementation for the United States and a pilot extension to Africa. The study also demonstrates the feasibility of doing drought prediction by using seasonal forecasts from dynamic climate models.	Report
28	Climate Warming and 21st-Century Drought in Southwestern North America	2008	Glen M. MacDonald Institute of the Environment and Department of Geography, University of California, Los Angeles E-mail: macdonal@geog.ucla.edu	http://www.cec.yamanashi.ac.jp/~tetsu/englishpaper/2009/1st/2008EO090003.pdf	Southwest	Using the Medieval Climate Anomaly, the study relates drought conditions to volcanic activity and solar radiation. The peak radiative forcing associated with multidecadal persistence of La Niña-like conditions and a negative PDO lead to cool surface temperatures in the eastern tropical Pacific and eastern North Pacific that promote arid conditions and sustained droughts in southwestern North America. PDSI reconstructions from northwestern Mexico to the prairies of Canada demonstrate a persistent state of aridity during the 12th century. River discharge reconstructions for the North	EOS Article

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						Saskatchewan, Colorado, and Sacramento rivers also show a consistent response of decreased flow. Mapped PDSI for the central period of the drought (1130–1180 A.D.) displays a spatial pattern broadly similar to the 21st century drought.	
29	Five Hundred Years of Hydrological Drought in the Upper Colorado River Basin	2007	Janak Timilsena Department of Civil and Environmental Engineering, University of Nevada, Las Vegas, Nevada, U.S.A E-Mail: piechota@unlv.nevada.edu.	http://www.egr.unlv.edu/~piechota/LinkFiles/timilsena-et-al-jawra-2007.pdf	Upper Colorado River basin	This article evaluates drought scenarios of the upper Colorado River basin, considering multiple drought variables for the past 500 years, and positions the current drought in terms of magnitude and frequency. Drought characteristics were developed by considering water-year data of the basin's streamflow, along with basin-wide averages of the Palmer Hydrological Drought Index (PHDI) and the Palmer Z Index. Streamflow and drought indices were reconstructed for the last 500 years by using a principal-component regression model based on tree-ring data. The reconstructed streamflow showed higher variability than the reconstructed PHDI and reconstructed Palmer Z Index. The magnitude and severity of all droughts were obtained for the last 500 years for historical and reconstructed drought variables and ranked accordingly. The frequency of the current drought was obtained by considering two different drought-frequency statistical approaches and three different methods of determining the beginning and end of the drought period (annual, 5-year moving average, and 10-year moving average). The authors concluded that the current drought is the worst in the observed record	Journal Article

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						period (1923-2004), but 6th to 14th largest in terms of magnitude and 1st to 12th considering severity in the past 500 years. Similarly, the current drought has a return period ranging from 37 to 103 years, depending on how the drought period was determined.	
30	Warming may create substantial water supply shortages in the Colorado River basin	2007	Gregory J. McCabe U.S. Geological Survey, Denver, Colorado, U.S.A	http://water.usgs.gov/nrp/proj.bib/Publications/2007/mccabe_wolock_2007.pdf	Colorado River Basin	The authors studied the potential effects of specific levels of atmospheric warming on water-year streamflow in the Colorado River basin by using a water-balance model and analyzed the results in the context of a multi-century tree-ring reconstruction (1490– 1998) of streamflow for the basin. The results indicate that if future warming in the basin is not accompanied by increased precipitation, then the basin is likely to experience periods of water supply shortages more severe than those inferred from the long-term historical tree-ring reconstruction. Furthermore, the modeling results suggest that future warming would increase the likelihood of failure to meet the water allocation requirements of the Colorado River Compact.	Journal Article
31	Trend Analysis of Streamflow Drought Events in Nebraska	2007	Hong Wu	http://www.springerlink.com/content/j58370m6	Nebraska	The authors evaluated statistical characteristics of streamflow drought	Journal Article

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			Texas Institute for Applied Environmental Research, Tarleton State University, Stephenville, TX e-mail: hwu@tiaer.tarleton.edu	8rl144t5/fulltext.pdf		event parameters and spatial and temporal trends in streamflow drought in terms of frequency, duration, and severity in Nebraska during three time periods: 1970–2001 (60 stations), 1950–2001 (43 stations), and 1932–2001 (9 stations). The statistical tests performed for the drought event parameters included correlation between event parameters tests, Hurst coefficients and lag-one coefficients, and trend-free pre-whitening Mann–Kendall tests. The analysis showed no uniform trend in the streamflow drought over the whole state. However, some trends were evident for specific regions. Specifically, droughts in the Republican watershed have most likely become more intense, whereas the drought has been slightly alleviated in the Missouri and nearby watersheds.	
32	Updated Streamflow Reconstructions for theUpper Colorado River Basin	2006	Connie A. Woodhouse National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center, Boulder CO	http://www.onthecolorado.org/resources/ClimateDocs/WoodhouseGrayMeko2006.pdf	Upper Colorado River basin	The authors reconstructed streamflow for four key gauges in the upper Colorado River basin by using an expanded tree-ring network and calibration. The reconstructions explain 72-81% of the variance in the gauge records, and results were robust across several reconstruction approaches. Time-series plots, as well as results of cross-spectral analysis, indicate strong spatial coherence in runoff variations across the sub-basins.	Journal Article
33	Multi century tree-ring reconstructions of Colorado streamflow for water resource planning	2006	Connie A. Woodhouse NOAA Paleoclimatology Branch, National	http://wwa.colorado.edu/treeflow/docs/woodhouse&lukas_climaticchange_2006.pdf	Upper Colorado and South Platte River basins	This article presents a network of 14 annual streamflow reconstructions, 300–600 years long, for gauges in the Upper Colorado and South Platte River basins in Colorado, generated from new and existing tree-ring chronologies. The	Journal Article

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			Climatic Data Center, Boulder, CO			reconstruction models explain 63–76% of the variance in the gauge records and capture low flows particularly well. Analyses of the reconstructions indicate that the 20th century gauge record does not fully represent the range of streamflow characteristics in the prior two to five centuries. Multi-year drought events more severe than the 1950s drought have occurred, notably in the 19th century, and the distribution of years with extremely low flow is markedly uneven over the past three centuries. When the 14 reconstructions are grouped into Upper Colorado, northern South Platte, and southern South Platte regional flow reconstructions, the three time series show a high degree of coherence, but also time-varying divergences that may reflect the differential influence of climatic features in the western United States.	
34	20th century drought in the conterminous United States	2005	Dennis P. Lettenmaier Department of Civil and Environmental Engineering, University of Washington, Seattle, WA Email: dennisl@u.washington.edu	http://journals.ametsoc.org/doi/pdf/10.1175/JHM450.1	U.S.	The authors developed severity-area-duration (SAD) curves to evaluate drought severity. The method is derived by replacing storm depth with an appropriate measure of drought severity in the depth-area-duration analysis, which is widely used to characterize precipitation extremes. The authors used gridded precipitation and temperature data to force a physically based macroscale hydrologic model at 1/20 spatial resolution over the continental United States, then constructed a drought history from 1920 to 2003 based on the model-simulated soil moisture and runoff. A clustering algorithm was used to identify individual drought events and	Journal Article

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						their spatial extent from monthly summaries of the simulated data. A series of SAD curves was constructed to relate the area of each drought to its severity.	
35	Drought 2002 in Colorado – An Unprecedented Drought or a Routine Drought?	2005	Roger A. Pielke Department of Atmospheric Science, Colorado State University, Fort Collins, CO Email: pielke@atmos.colostate.edu	http://www.springerlink.com/content/t728040qx7pv1363/fulltext.pdf	Colorado	The 2002 drought in Colorado was considered an exceptionally severe drought. However, this study showed that despite the observed exceptional water shortages, the observed precipitation deficit was less than extreme over a good fraction of the state. A likely explanation of this discrepancy is the imbalance between water supply and water demand over time. For a given level of water supply, water shortages become intensified as water demands increase over time. This observation shows that Colorado is more vulnerable to drought today than under similar precipitation deficits in the past.	Journal Article
36	Drought Indicators and Triggers	2005	Anne Steinemann City and Regional Planning Program, Georgia Institute of Technology, Atlanta, Georgia E-Mail: anne.steinemann@ar	http://water.washington.edu/research/Reports/droughtindicatorsandtriggerschapter.pdf		The objectives of the study were to (1) review common indicators and triggers, their functions, and their strengths and limitations; (2) examine typical problems with indicators and triggers in drought plans and offer a solution that transforms all indicators, triggers, and drought levels to percentiles; and (3) provide criteria for developing and evaluating indicators and triggers, with recommendations for using	Book Chapter

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			ch.gatech.edu			them in a drought plan.	
37	Columbia River Flow and Drought Since 1750	2004	Ze'ev Gedalof Department of Geography, University of Guelph, Guelph, Ontario, Canada E-Mail: zgedalof@uoguelph.ca	http://www.uoguelph.ca/cedar/Pubs/GPM_JAWRA2004.pdf	Columbia River Basin	The authors used a network of 32 drought-sensitive tree-ring chronologies to reconstruct mean water year flow on the Columbia River at the Dalles, Oregon, since 1750. Their findings suggest that the relationship between drought and streamflow has changed over time, supporting results from hydrologic models suggesting that changes in land cover over the 20th century have had measurable impacts on runoff production.	Journal Article
38	Long-Term Aridity Changes in the Western United States	2004	Edward R. Cook et al. Lamont-Doherty Earth Observatory, Palisades, NY E-mail: drdendro@ldeo.columbia.edu	http://www.sciencemag.org/content/306/5698/1015.full.pdf	Western U.S.	The western United States is experiencing a severe multi-year drought that is unprecedented in some hydroclimatic records (e.g., 4-yr duration is unusual over the past 104 years). Using gridded drought reconstruction areas that cover most of the western United States over the past 1200 years, the authors showed that current drought since the 20th century does not stand out as extreme in comparison to an earlier period of elevated aridity and epic drought in AD 900 to 1300, an interval broadly consistent with the Medieval Warm Period. If elevated aridity in the western United States is a natural response to climate warming, then any trend toward warmer temperatures in the future could lead to a serious long-term increase in aridity over western North America.	Journal Article

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39	Tree-ring footprint of joint hydrologic drought in Sacramento and Upper Colorado river basins, western U.S.A	2004	David M. Mekoa Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ, U.S.A	http://www.u.arizona.edu/~conniew1/papers/meko.woodhouse2005a.pdf	Western U.S.	The authors applied tree-ring-based annual streamflow reconstructions for the Sacramento River in California and the Blue River in western Colorado to analyze the temporal and spatial variability of widespread drought simultaneously affecting both basins over the past five centuries. The results show that although flow in the two rivers is only very weakly correlated over the 538-yr reconstruction period, more years of joint drought occurred than would be expected by chance alone.	Journal Article
40	An aggregate drought index: Assessing drought severity based on fluctuations in the hydrologic cycle and surface water storage	2004	John A. Keyantash Department of Earth Sciences, California State University, Dominguez Hills, Carson, CA	http://www.geo.oregonstate.edu/classes/ecosys_info/readings/2003WR002610.pdf	California	The authors developed an aggregate drought index (ADI) and evaluated it within three diverse climate divisions in California. The ADI comprehensively considers all physical forms of drought (meteorological, hydrological, and agricultural) through selection of variables that are related to each drought type. The ADI time series were compared with the PDSI to describe the 1976–1977 and 1987–1992 droughts in California. The results show that the ADI methodology provides a clear, objective approach for describing the intensity of drought and can be readily adapted to characterize drought on an operational basis.	Journal Article

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41	Drought Conditions in Utah During 1999-2002: A Historical Perspective	2003	Chris D. Wilkowske, David V. Allen, and Jeff V. Phillips U.S. Geological Survey, 2329 West Orton Circle, Salt Lake City, UT 84119 801.908.5000 http://ut.water.usgs.gov	http://pubs.usgs.gov/fs/fs-037-03/resources/drought.pdf	Utah	Precipitation: On the basis of the PDSI classification scale, the droughts of 1988-1993 and 1999-2002 were severe to extreme, but conditions were not as dry as those during 1896-1905. Streamflow: Data from eight long-term streamflow-gauging stations suggest that major droughts occurred during 1896-1905, 1930-1936, 1953-1965, and 1974-1978. The average length of these droughts was about 5 years, and they occurred about every 10-20 years. The fact sheet evaluated effects on water levels in selected reservoirs and lakes and groundwater levels in selected wells.	USGS Fact Sheet
42	Investigation of the 2006 drought and 2007 flood extremes at the Southern Great Plains through an integrative analysis of observations	2011	Xiquan Dong Department of Atmospheric Sciences, University of North Dakota, Grand Forks, North Dakota, U.S.A	http://www.agu.org/journals/jd/jd1103/2010JD014776/2010JD014776.pdf	Southern Great Plains	Hydrological years 2006 (HY06; October 2005 to September 2006) and 2007 (HY07; October 2006 to September 2007) provide a unique opportunity to examine hydrological extremes in the central United States because of the two highly contrasting precipitation extremes occurring in consecutive years at the Southern Great Plains (SGP) observation site in recorded history. The HY06 annual precipitation in the state of Oklahoma is around 61% of the normal (92.84 cm, based on the 1921–2008 climatology), making HY06 the second-driest year on record. In particular, the total precipitation during the winter of 2005–2006 was only 27% of the normal, and this winter ranks as the driest season. On the other hand, the HY07 annual precipitation amount was 121% of the normal, and HY07 ranks as	Journal Article

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						the seventh wettest year for the entire state and the wettest year for the central region of the state. Summer 2007 was the second wettest season for the state. Large-scale dynamics were assumed to play a key role in these extreme events.	
43	Drought variability in the Pacific Northwest from a 6,000-yr lake sediment record	2011	Daniel B. Nelson Dept. of Geology and Planetary Science, University of Pittsburgh, Space Research Coordination Center, Pittsburgh, PA	http://www.pnas.org/content/early/2011/02/16/1009194108.full.pdf	Pacific Northwest	This article presents a 6,000-yr record of changing water balance in the Pacific Northwest, inferred from measurements of carbonate $\delta^{18}O$ and grayscale on a sediment core collected from Castor Lake, Washington. This subdecadally resolved drought record tracks the 1,500-yr tree-ring-based PDSI reconstructions of Cook et al. (2004) in the Pacific Northwest and extends knowledge (from this study) back to 6,000 yr B.P. The results demonstrate that low-frequency drought/pluvial cycles, with occasional long-duration, multidecadal events, are a persistent feature of regional climate. Furthermore, increased average duration of multidecadal wet/dry cycles since the middle Holocene has increased the amplitude and impact of these events. This is especially apparent during the last 1,000 yr. The results suggest that these transitions were driven by changes in the tropical and extratropical Pacific and are related to apparent intensification of the ENSO over this interval and its related effects on the PDO. The Castor Lake record also corroborates the notion that the 20th century, prior to recent aridity, was a relatively wet period compared to the last 6,000 yr. The findings suggest that the hydroclimate response in the Pacific Northwest to future warming	Journal Article

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						will be intimately tied to the impact of warming on the ENSO.	
44	Drought in the United States: Causes and Issues for Congress	2010	Peter Folger Congressional Research Service	http://www.nationalaglawcenter.org/assets/crs/RL34580.pdf	U.S.	The report discusses the physical causes of drought, its history in the United States, and what may be expected in the near future. The study indicates that the physical conditions causing drought in the United States are increasingly understood to be linked to SSTs in the tropical Pacific Ocean. Studies indicate that cooler-than-average SSTs have been connected to the recent severe western drought, severe droughts of the late 19th century, and precolonial North American "megadroughts." Some climate model projections suggest that warming temperatures resulting from increased greenhouse gases in the atmosphere could return the western United States within decades to more arid baseline conditions similar to those during earlier times.	Report
45	Identification of Pacific Ocean sea surface temperature influences of Upper Colorado River Basin snowpack	2010	A. Aziz Oubeidillah Department of Civil and Environmental Engineering, University of Tennessee, Knoxville, Tennessee, U.S.A	http://faculty.unlv.edu/piechota/LinkFiles/Aziz_et_al_wrr_2010.pdf	Upper Colorado River basin	Snowpack in the upper Colorado River basin is considered as the primary driver of streamflow (water supply) for the southwestern United States. Using the Singular Value Decomposition, the authors showed the importance of the Pacific Ocean SST as a valuable variable in long-lead-time forecasting of snowpack in Utah and Colorado.	Journal Article
46	Long-Term Relationships Between Ocean Variability and Water Resources in Northeastern Utah	2010	Abbie H. Tingstad Department of Geography, UCLA, Los Angeles, California 90095	http://onlinelibrary.wiley.com/doi/10.1111/j.1752-1688.2010.00471.x/pdf	North-eastern Utah	This paper uses reconstructed records to show (1) how 20th century hydrology compares with preinstrumental variations in streamflow and snowpack in northeastern Utah, (2) if Pacific and Atlantic Ocean SST variability impacts	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
			Email: abbie1@ucla.edu			streamflow and snowpack in northeastern Utah, and (3) the mean magnitude of ENSO, PDO, and Atlantic multidecadal oscillation (AMO) influence on northeastern Utah hydrology.	
47	The seasonality of precipitation signals embedded within the North American Drought Atlas	2010	Scott St. George Geological Survey of Canada, Canada E,ail: sstgeorg@nrcan.gc.ca	http://hol.sagepub.com/content/20/6/983.short	North America	The paper examines how the seasonality of precipitation signals embedded within the North American Drought Atlas varies across the continent and suggests that seasonal biases must be taken into account when comparing drought reconstructions across North America.	Journal Article
48	Evaluating the utility of the Vegetation Condition Index (VCI) for monitoring meteorological drought in Texas	2010	Steven M Quiring Texas A&M Univ., Dept. of Geography, College Station, TX 77843, U.S.A E-mail: squiring@tamu.edu	http://www.sciencedirect.com/science/article/B6V8W-4Y0K9HJ-2/2/850039311ef25f4d20a3db0453450b21	Texas	This article evaluates the relationship between the satellite-based Vegetation Condition Index (VCI) and a number of frequently used meteorological drought indices [the PDSI, Moisture Anomaly Index (Z-index), Standard Precipitation Index (SPI), percent normal, and deciles] by using data from all 254 Texas counties during 18 growing seasons (March to August, 1982–1999). Results show (1) strong correlation of the VCI with the 6-month SPI and the 9-month SPI and PDSI; (2) significant spatial variability in the strength of the relationship between the VCI and the meteorological drought indices; and (3) generally much higher correlations for the counties in northwestern and southwestern Texas ($R2 > 0.6$) than for counties in eastern Texas and along the Gulf Coast ($R2 < 0.1$). The author argues that the climate region is the most important determinant of the nature	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
						of the relationship between the VCI and PDSI. The results demonstrate that care must be taken when using the VCI for monitoring drought, because it is not highly correlated with station-based meteorological drought indices and it is strongly influenced by spatially varying environmental factors.	
49	Assessing spatiotemporal variability of drought in the U.S. central plains	2010	K.E. Logan Univ. of Kansas, Dept. of Geography, Lawrence, KS 66045, U.S.A E-mail: brunsell@ku.edu	http://www.sciencedirect.com/science/article/B6WH9-4X4G2P1-1/2/501e0bfe3f2320978842779772d66253	Central U.S. Kansas River Basin	The authors examined the change in precipitation from 1900 to 2006 by using monthly precipitation data kriged over the Kansas River basin region. They calculated a linear trend of the SPI, showing many areas of increasing wetness throughout the area, with drying in isolated regions of the West and North. The authors argue that the isolated regions of drying overlap regions of heavy water use and irrigation, suggesting possible detrimental effects on agricultural production and aquifer levels if the trend continues.	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
50	Assessment of Drought Due to Historic Climate Variability and Projected Future Climate Change in the Midwestern United States	2010	Vimal Mishra Purdue Univ, W Lafayette, IN 47907, U.S.A E-mail: vmishra@purdue.edu	https://engineering.purdue.edu/ABE/People/Papers/keith.a.cherkauer.1/MidwesternU.S.	Midwestern U.S.: Illinois and Indiana	This paper estimates changes and trends associated with climate variables in historic climate variability (1916–2007) and in projected future climate change (2009–2099) and identifies regional-scale droughts and associated severity, areal extent, and temporal extent under historic and projected future climate conditions by using reconstructed soil moisture data and gridded climatology for the period 1916–2007 using the Variable Infiltration Capacity (VIC) model. Results indicate that precipitation, minimum air temperature, total column soil moisture, and runoff have experienced upward trends, whereas maximum air temperature, frozen soil moisture, and snow water equivalent experienced downward trends.	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
51	A hydroclimatic index for examining patterns of drought in the Colorado River Basin	2009	Andrew W. Ellis School of Geographical Sciences, Arizona State University, Tempe, Arizona, U.S.A	http://www.u.arizona.edu/~gmgarfin/2009.ellis.ijoc.pdf	Colorado River Basin	The authors used a hydroclimatic drought coverage index and analyzed its linear trend and relationships with key climate teleconnections. The results showed that the past century was characterized by an increase in drought coverage, during the warm portions of the years almost exclusively, as a result of climatic warming. In recent decades, a significant increase in the drought coverage occurred earlier in the year, during the spring season, primarily as a function of warming, but in combination with a decline in precipitation for a significant portion of the basin. The El Niño (La Niña) phase of the ENSO phenomenon is associated with drought during fall and winter, and the ENSO phase during the preceding six months is a significant predictor. The area of drought within the Colorado River basin is larger (smaller) during the warm (cold) phases of the AMO and the PDO, although the relationship with the PDO is weak. Monthly AMO values for the two years preceding drought provide minor predictability. Decadal averages of drought coverage closely follow those of both the AMO and PDO index. However, the nature of the PDO-drought relationship is reversed over the two halves of the historical record, possibly indicating dominance of the AMO over the PDO in influencing drought in the region. Teleconnection-drought relationships are stronger for the southern portion of the basin.	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
52	A Spatio-Temporal Drought Analysis for the Midwestern U.S.	2009	Shih-Chieh Kao Computational Sciences and Engineering Division, Oak Ridge National Laboratory, Oak Ridge, TN, U.S.A Email: kaos@ornl.gov	http://drinet.hubzero.org/resources/8/download/EWRI-Kansas_conference_paper.pdf	Midwestern U.S.	The authors investigated the spatio-temporal dependence relationships between various drought variables and constructed a joint probability distribution by combining drought marginals with the dependence structure. They adopted a copula based joint deficit index for objective description of the overall drought status and compared this to the PDSI results to show that the copula provided information for drought identification and further allowed a month-by-month assessment of the future drought recovery.	Confer-ence Paper
53	Early 21st-Century Drought in Mexico	2009	David W. Stahle Department of Geosciences, University of Arkansas, Fayetteville, AR 72701 Email: dstahle@uark.edu	http://www.ldeo.columbia.edu/res/div/ocp/pub/seager/Stahle_etal_2009-Eos.pdf	Mexico	This article compares early 21st century droughts in Mexico with droughts in the 1950s and argues that the persistent widespread drought over western North America that began in 1994 in Mexico has been the most severe and sustained. It has been influenced by anthropogenic activities that resulted in intense warming. The authors relate the intense warming to changes in land cover in Mexico.	EOS Article
54	Spatial and temporal soil moisture and drought variability in the Upper Colorado River Basin	2009	Thomas C. Piechota Dept of Civil & Environmental Engineering, University of Nevada, Las Vegas, NV 89154, U.S.A E-mail: thomas.piechota@unl	http://www.sciencedirect.com/science/article/B6V6C-4XDD0B9-3/2/2129ff43c798e6b83c845ccaebaa34fa	Colorado River Basin	This article investigates the interannual variability of soil moisture as related to large-scale climate variability and also evaluates the spatial and temporal variability of modeled deep-layer (40–140 cm) soil moisture in the upper Colorado River basin. The authors compare deep-layer 50-year soil moisture to the PDSI, precipitation, and streamflow to determine whether deep soil moisture is an indicator of climate variability. Results show a	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
			v.edu			strong relationship between the PDSI, climate variability, and deep soil moisture and indicate distinct regions with higher vulnerability to drought and wet conditions.	
55	Late Pleistocene California droughts during deglaciation and Arctic warming	2009	Jessica L. Oster Dept. of Geology, Univ. of California-Davis, Davis, CA 95616, U.S.A E-mail: joster@ucdavis.edu	http://www.sciencedirect.com/science/article/B6V61-4XMC064-2/2/bf8f629c8ec5cfa8ad7beb8805c8b072	California	This article presents a U-series calibrated stable isotopic and trace element time series for a speleothem from Moaning Cave on the western slope of the central Sierra Nevada, California, that documents changes in precipitation that are approximately coeval with Greenland temperature changes to investigate historical droughts. Results suggest that linkages between northern high-latitude climate and precipitation in the Sierra Nevada could indicate that, under conditions of continued global warming, this drought-prone region might experience a reduction in Pacific-sourced moisture.	Journal Article
56	Influence of ENSO and the Atlantic Multidecadal Oscillation on Drought over the United States	2009	Kingtse C. Mo NOAA, Climate Prediction Center, NCEP NWS, Camp Springs, MD 20746, U.S.A E-mail: kingtse.mo@noaa.gov	http://journals.ametsoc.org/doi/pdf/10.1175/2009JCLI2966.1	U.S.: the Great Plains and Lower Colorado River Basin	Uses drought experiments to examine the impact of ENSO and the Atlantic multidecadal oscillation (AMO) on drought over the United States. The authors investigated the impact of ENSO on drought over the Great Plains and the lower Colorado River Basin. Cold (warm) ENSO events favor drought (wet spells). Results show (1) small impact of ENSO over the East Coast and the Southeast, because the precipitation responses to ENSO are opposite in sign for winter and summer, and for these areas a prolonged ENSO does not always favor either drought or wet spells; (2) major influence	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
						of the AMO in modulating the impact of ENSO on drought, with large influence when the SSTAs in the tropical Pacific and in the North Atlantic are opposite in phase; and (3) a cold (warm) event in a positive (negative) AMO phase amplifying the impact of the cold (warm) ENSO on drought, with much weaker influence of the ENSO on drought when the SSTAs in the tropical Pacific and in the North Atlantic are in phase.	
57	Low frequency drought variability associated with climate indices	2009	Mehmet Ozger Texas A&M Univ., Dept. of Biol & Agricultural Engineering, College Station, TX 77843, U.S.A E-mailogical: mehmetozger@tamu.edu, amishra@tamu.edu, vsingh@tamu.edu	http://www.sciencedirect.com/science/article/B6V6C-4TVJ3RT-3/2/09fb2efb98a57f42cabde42f2122f104	Texas	This article investigates the spatial structure of teleconnections of both ENSO and the PDO to droughts during the 20th century, with particular reference to the state of Texas, by using wavelet transforms and cross-correlations and kriging. Results show (1) different responses for each region in Texas, with stronger correlations of arid regions to climate anomalies than sub-tropic humid regions; (2) lag times and correlation coefficients detected between droughts and climate indices; and (3) maps indicating the spatial variations of lag times and correlation coefficients for annual and decadal scales. The authors claim that the proposed investigation will permit determination of lag times between drought characteristics and climate indices, along with significant correlations. These features are different from those of existing methods, and decision makers in the field of water resources management and agriculture can benefit from them.	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
58	The Tree-Ring Record of Drought on the Canadian Prairies	2009	Scott St. George Geological Survey Canada, Natural Resources Canada, Ottawa, ON K1A 0E8. Canada E-mail: sstgeorg@nrcan.gc.ca	http://journals.ametsoc.org/doi/pdf/10.1175/2008JCLI2441.1	Canada	This paper uses data from 138 sites in the Canadian Prairie Provinces and adjacent regions to estimate summer drought severity during the past several hundred years by dividing the network into five regional groups based on geography, tree species, and length of record: the eastern Rockies, northern Saskatchewan, central Manitoba, southern Manitoba, and northwestern Ontario. Results show that (1) the data are not linearly related to major modes of climate variability, including ENSO and the PDO, which primarily affect the climate of western Canada during winter; (2) the extended drought records inferred from tree rings indicate that drought on the Canadian Prairies has exhibited considerable spatial heterogeneity over the last several centuries; (3) for northern Saskatchewan and northwestern Ontario, intervals of persistently low tree growth during the 20th century were just as long as or longer than low-growth intervals in the 18th or 19th centuries; (4) longer records from southern Alberta suggest that the most intense dry spell in that area during the last 500 yr occurred during the 1720s; (5) at the eastern side of the prairies, the longest dry event was centered around 1700 and might coincide with low lake stands in Manitoba, Minnesota, and North Dakota; and (6) although the Canadian Prairies were dry at times during the 1500s, there is no regional analog to the 16th century "megadroughts" that affected much of the western United States and northern	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
						Mexico.	
59	When will Lake Mead go dry?	2008	Tim P. Barnett and David W. Pierce Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California Email: tbarnett-ul@ucsd.edu	http://www.agu.org/journals/wr/wr0803/2007WR006704/2007WR006704.pdf	Lakes Mead and Powell	The authors estimated impacts of climate change associated with global warming, the effects of natural climate variability, and the effects of current operating status of the reservoir system on storage in Lakes Mead and Powell.	Journal Article
60	Global and Continental Drought in the Second Half of the Twentieth Century: Severity–Area–Duration Analysis and Temporal Variability of Large-Scale Events	2008	Justin Sheffield Department of Civil Engineering, Princeton University, Princeton,New Jersey, U.S.A.	http://water.washington.edu/research/Articles/2008.global.continental.drought.pdf	Global	By using observation-driven simulations of global terrestrial hydrology and a cluster algorithm that searches for spatially connected regions of soil moisture, the authors identified 296 large-scale drought events (greater than 500,000 km^2 and longer than 3 months) globally for 1950–2000. They analyzed the drought events by using the SAD method to identify and characterize the most severe events for each continent and globally at various durations and spatial extents.	
61	Use of a standardized runoff index for characterizing hydrologic drought	2008	Shraddhanand Shukla and Andrew W. Wood Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington	http://www.agu.org/journals/gl/gl0802/2007GL032487/2007GL032487.pdf	U.S.	This article compares the behavior of a standardized runoff index (SRI) with that of the well-known standardized precipitation index (SPI) during drought events in a snowmelt region. Although the SRI and SPI are similar when evaluated for long accumulation periods, the SRI incorporates hydrologic processes that determine seasonal lags in the influence of climate on streamflow. As a result, on	Journal Article

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			Email: aww@u.washington.edu			monthly to seasonal time scales, the SRI is a useful complement to the SPI for depicting hydrologic aspects of drought.	
62	Extended drought in the Great Basin of western North America in the last two millennia reconstructed from pollen records	2008	Scott Mensing Department of Geography, University of Nevada, Reno, NV	http://www4.nau.edu/direnet/publications/publications_m/files/Mensing_S_Smith_J_Norman_KB_Allan_M_Extended_drought_Great_Basin.pdf	Great Basin	The authors reviewed the pollen record from four sites that record evidence of drought within the Great Basin. They used pollen ratios between taxonomic indicators of wet and dry climate to interpret droughts and compared these records with submerged stumps, tree-ring chronologies, packrat middens, and $\delta^{18}O$ data from sediments. Studies in the Great Basin have identified four periods of low lake levels that have been interpreted as century long droughts, with drought termination dates at approximately 1800, 1200, 800, and 550 cal yr BP. The pollen records indicate that the period between 2000 and 1800 cal yr BP was dry, with the driest sites being in the western Great Basin. The century ending at 1200 cal yr BP might have been dry, but the pollen record does not support severe drought.	Journal Article
63	Analysis of drought determinants for the Colorado River Basin	2007	Robert C. Balling Department of Geography, Arizona State University, Tempe, AZ, U.S.A e-mail: robert.balling@asu.edu	http://www.springerlink.com/content/9157122130k0g572/fulltext.pdf	Colorado River Basin	This article applies principal components analysis (PCA) to independently assess the influence of various teleconnections on basin-wide and sub-regional winter season PHDI and precipitation variations in the basin. The results show that the PDO explains more variance in PHDI than do ENSO, the AMO, and the planetary temperature combined for the basin as a whole. When rotated, PCA is used to separate the basin into two regions. The lower portion of the basin is similar to the	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
						basin as a whole, while the upper portion, which contains the high-elevation locations important to hydrologic yield for the watershed, demonstrates poorly defined relationships with the teleconnections. The PHDIs for the two portions of the basin are shown to have been out of synch for much of the 20th century. In general, teleconnection indices account for 19% of the variance in PHDI, leaving large uncertainties in drought forecasting.	
64	North American Droughts of the Last Millennium from a Gridded Network of Tree-ring Data	2007	Celine Herweijer Lamont Doherty Earth Observatory, Columbia University, Palisades, New York Email: celineh@ldeo.columbia.edu	http://www.ldeo.columbia.edu/res/div/ocp/pub/herweijer/Herweijer_etal_2007.pdf	North America	The objectives of this study were to (1) identify a set of criteria to systematically define episodes of widespread and persistent drought over the last 1000 yr and determine how the severity of drought has changed with time; (2) examine the spatial distribution of drought and its persistence by using a PCA and identify causal mechanisms; (3) use both the multitaper method of spectral analysis and wavelet analysis to investigate the dominant frequencies of North American drought and how these vary with time; and (4) examine the global context of the North American megadroughts of the MCA in the paleoclimate record for comparison with modern-day analogs.	Journal Article
65	Data mining and spatiotemporal analysis of extreme precipitation and Northern Great Plains drought	2007	Josiah D. Smith 46607 Carriage Ct., Sterling, VA 20164 Email: josiahdsmith@yahoo.	2007 Geological Society of America Denver Annual Meeting, October 28-31, 2007: Geological Society of America Abstracts with	Northern Great Plains	The authors applied data mining to available weather station observations to extract significant information and gain insight into drought behavior in the Prairie Pothole Region or the Northern Great Plains. The results show that large fluctuations in monthly drought conditions	Confer-ence Paper

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
			com	Programs, 39(6): 16		were controlled by changes in both the frequency and intensity of precipitation events. Extreme drought took a minimum of two to three months both to develop and dissipate from a semi-arid state. However, the biggest shifts in month-to-month conditions were observed when both precipitation intensity and frequency were well above or below normal over the same area; hence, the onset or end of an extreme drought took place more rapidly when the intensity and frequency of changes were great and harmonized. The methods applied in this research could be adapted to a study of any other U.S. climate region.	
66	Recent and Multicentennial Precipitation Variability and Drought Occurrence in the Uinta Mountains Region, Utah	2007	Glen M. MacDonald Department of Geography, UCLA, Los Angeles, CA E-mail: macdonal@geog.ucla.edu	http://instaar.metapress.com/content/h7414wg675637047/	Utah	The authors examined instrumental meteorological records to compare recent precipitation regimes in the eastern and western Uinta Mountains region of Utah. The comparison demonstrated that, although the summer monsoon contributes a higher proportion of annual precipitation in the east, the two regions are significantly correlated in terms of precipitation variations, including summer precipitation. Major droughts, such as the 1930s Dustbowl event, the 1976-1977 event, and the 1987-1989 event, are largely typified by strong decreases in winter precipitation, although deficits can extend into summer. Droughts generally impact the entire region when they occur. Unlike the Southwest and the Pacific Northwest, year-to-year precipitation variability in the Uinta Mountains region does not appear correlated with the ENSO or the PDO. However, severe prolonged	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
						droughts such as the 1976-1977 and 1986-1987 events are related to decreases in eastern Pacific Ocean SSTs.	
67	Effects of temperature and precipitation trends on U.S. drought	2007	David R. Easterling NOAA National Climatic Data Center, Asheville, NC	http://www.agu.org/journals/gl/gl0720/2007GL031541/2007GL031541.pdf	U.S.	The authors examined the influence of the multidecadal warming trend on drought coverage and the possibility that the general increase in regional and contiguous U.S. precipitation since about 1980 has masked a tendency for increasing drought driven largely by increasing temperature. Results indicate that without the increase in precipitation, severe to extreme drought would have affected as much as 50% more of the United States during some months in the most recent drought period.	Journal Article
68	Monitoring and predicting the 2007 U.S. drought	2007	Lifeng Luo Environmental Engineering and Water Resources, Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ	http://www.agu.org/journals/gl/gl0722/2007GL031673/2007GL031673.pdf	U.S.	This work applied the Drought Monitoring and Prediction System (DMAPS) to estimate droughts developed in the U.S. West and Southeast, starting early in 2007. The authors used the North America Land Data Assimilation System (NLDAS) real-time meteorological forcing and the Variable Infiltration Capacity (VIC) land surface model as input to DMAPS to provide a quantitative assessment of drought in near-real time. Using seasonal climate forecasts from the NCEP's Climate Forecast System (CFS) as one	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
						input, they successfully predicted the evolution of the droughts several months in advance.	
69	Characteristics of global and regional drought, 1950–2000: Analysis of soil moisture data from off-line simulation of the terrestrial hydrologic cycle	2007	Justin Sheffield Department of Civil Engineering, Princeton University, Princeton, NJ, U.S.A.	http://www.agu.org/journals/jd/jd0717/2006JD008288/2006JD008288.pdf	Global	The authors analyzed drought occurrence over global land areas for 1950-2000 by using soil moisture data from a simulation of the terrestrial water cycle with the Variable Infiltration Capacity (VIC) land surface model, which is forced by an observation-based meteorological data set. A monthly drought index based on percentile soil moisture values relative to the 50-year climatology was analyzed in terms of duration, intensity, and severity at global and regional scales. The results show that short-term droughts (< 6 months) are prevalent in the tropics and mid-latitudes, where inter-annual climate variability is highest. Medium-term droughts (7–12 months) are more frequent in mid to high latitudes. Long-term (12+ months) droughts are generally restricted to sub-Saharan Africa and higher northern latitudes.	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
70	Annual and Warm Season Drought Intensity – Duration – Frequency Analysis for Sonora, Mexico	2007	Michelle Hallack-Alegria Department of Civil and Environmental Engineering, Michigan Technological University, Houghton, MI	http://journals.ametsoc.org/doi/pdf/10.1175/JCLI4101.1	Mexico	The objectives of this work were to characterize the spatial and temporal variabilities of precipitation in Sonora and to conduct a meteorological drought intensity–duration–frequency analysis based on annual and warm-season precipitation records.	Journal Article
71	North American Drought: Reconstructions, Causes, and Consequences	2007	Edward R. Cook Lamont-Doherty Earth Observatory, Palisades, NY E-mail: drdendro@ldeo.columbia.edu	http://www.ldeo.columbia.edu/res/div/ocp/pub/cook/Cook_Seager_Cane_Stahle.pdf	North America	This resource presents the current status of research regarding North American droughts and their consequences. It includes discussions of drought indices and their use, the tree ring network often used for drought reconstruction, the statistical methods employed, and drought variability since 800 A.D., together with evidence for widespread medieval megadroughts, social impacts of droughts, and climate modeling conducted to study causes of drought.	Journal Article
72	Multidecadal drought and Holocene climate instability in the Rocky Mountains	2006	Jeffery R. Stone and Sherilyn C. Fritz Department of Geosciences, University of Nebraska–Lincoln, 214 Bessey Hall, Lincoln, Nebraska	http://geology.gsapubs.org/content/34/5/409.full.pdf+html	Rocky Mountains	This time-series analysis of a diatom-inferred drought record suggests that the Holocene hydroclimate of the northern Rocky Mountains is characterized by oscillation between two mean climate states.	Journal Article
73	Late-Holocene flooding and drought in the Northern Great Plains, U.S.A, reconstructed from tree rings, lake sediments and ancient shorelines	2005	M.D. Shapley Limnological Research Center, University of	http://www.neglwatersheds.org/Natural_History/NESDLakesShapley_Johnson_et_al.pdf	Northern Great Plains	This article develops a 1000-year hydroclimate reconstruction from local burr oak (*Quercus macrocarpa*) tree-ring records and lake-sediment cores. Analysis of lake shoreline and drainage features	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
			Minnesota, Minneapolis,MN			provides a late-Quaternary geomorphic context for this high-resolution record. Tree-ring width and shell geochemistry of the ostracode *Candona rawsoni* show marked coherence, indicating synchronous responses to moisture balance in vegetation and lake salinity; geomorphic evidence suggests buffering of lake-system expansion during pluvial periods by evaporative dynamics. Pluvial periods display a recurrence frequency of approximately 140-160 years over the past millennium. Prior to AD 1800, both lake highstands and droughts tended toward greater persistence than during the past two centuries.	
74	Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States	2004	Gregory J. McCabe U.S. Geological Survey, Denver Federal Center, Denver, CO	http://wwwpaztcn.wr.usgs.gov/julio_pdf/McCabe_ea.pdf	U.S.	More than half (52%) of the spatial and temporal variance in multidecadal drought frequency over the conterminous United States is attributable to the PDO and the AMO. An additional 22% of the variance in drought frequency is possibly related to increasing Northern Hemisphere temperatures or some other unidirectional climate trend.	Journal Article
75	Climate precursors of multidecadal drought variability in the western United States	2004	Hugo G. Hidalgo Climate Research Division, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA	http://www.agu.org/journals/wr/wr0412/2004WR003350/2004WR003350.pdf	U.S.	The authors examined low-frequency (periodicities < 20 years) hydrologic variability in the western United States over the past 500 years by using available tree-ring reconstructions of PDSI, streamflow, and climate indices. The rotated principal component (RPC) scores of a gridded tree-ring reconstruction of the PDSI from 1525 to 1975 are significantly correlated with indices representing large-scale climate variations from the Pacific	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
						and Atlantic Oceans. RPC1 (31%) is related to the influence of North Pacific SST variations, RPC2 (24%) is apparently related to North Atlantic SST variations, and RPC3 (19%) is moderately correlated with a smoothed version of the Southern Oscillation Index.	
76	Persistent drought in North America: a climate modeling and paleoclimate perspective		Richard Seager Lamont-Doherty Earth Observatory of Columbia University	http://www.ldeo.columbia.edu/res/div/ocp/drought/#physical	North America	The author demonstrated that persistent droughts and pluvials over North America are associated with subtle changes in SSTs of the tropical oceans, especially the tropical Pacific Ocean.	Website
77	The Public Part of the Final Report for the Drought Research Initiative (DRI)	2011	Ronald Stewart and John Pomeroy Email: dri.drought@gmail.com	http://www.drinetwork.ca/dri_final_report.pdf	Canada	This report from the Drought Research Initiative in Canada summarizes drought characterization, processes, prediction, history and responses. It evaluates the impact of the research initiative on the scientific understanding of drought.	Report
78	Forced and unforced variability of twentieth century North American droughts and pluvials	2010	Benjamin I. Cook Lamont-Doherty Earth Observatory, 61 Route 9W, Palisades, NY 10964, U.S.A Email: bc9z@ldeo.columbia.edu	http://www.ldeo.columbia.edu/res/div/ocp/pub/seager/Cook_etal_20thC_2010.pdf	North America	Statistically based modeling was used to investigate SST forcing of the 20th century pluvial and drought events. The results show that the three principal components of the American PDSI from the North American Drought Atlas correlate with the SSTs in the equatorial Pacific, North Pacific, and North Atlantic. The correlation is consistent with the current understanding of North American drought responses to SST forcing. By using ensemble statistical modeling, the authors claim that they can reproduce these drought and pluvial events successfully, though the severity of the drought was underestimated. This suggests that drought intensity can only be reproduced through internal variability or other processes. The	Journal Article

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						findings highlight the importance of internal noise and non-SST processes for hydroclimatic variability over North America, complementing existing research using general circulation models (GCMs).	
79	The Convective Instability Pathway to Warm Season Drought in Texas. Part I: The Role of Convective Inhibition and Its Modulation by Soil Moisture	2010	Boksoon Myoung Dept. of Atmospheric Science, Texas A&M University, College Station, TX 77843, U.S.A Email: n-g@tamu.edu	http://journals.ametsoc.org/doi/pdf/10.1175/2010JCLI2946.1	Texas	This article investigates how convective instability influences monthly mean precipitation in Texas in the summertime and examines the modulation of convective instability and precipitation by local and regional forcings by using NCEP–NCAR reanalysis data and observed precipitation data, correlation analysis, multiple linear regression analysis, and back-trajectory analysis to reveal the underlying dynamics of linkage and causality. Results show that (1) monthly mean precipitation is modified mainly by convective inhibition (CIN) rather than by convective available potential energy (CAPE) or by precipitable water; (2) excessive CIN is caused by surface dryness and warming at 700 hPa, leading to precipitation deficits on a monthly time scale; and (3) while the dewpoint temperature and thermodynamics at the surface are greatly affected by the soil moisture, the temperature at 700 hPa is statistically independent of the surface dewpoint temperature, since the 700-hPa temperature represents a free-atmospheric	Journal Article

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						process. The paper concludes that the strong correlations among precipitation, soil moisture, and CIN, as well as their underlying physical processes, suggest that the tight linkage between precipitation and soil moisture is due not only to the impacts of precipitation on soil moisture but also to the feedbacks of soil moisture on precipitation through control of CIN.	
80	The Convective Instability Pathway to Warm Season Drought in Texas. Part II: Free-Tropospheric Modulation of Convective Inhibition	2010	Boksoon Myoung T Dept. of Atmospheric Science, Texas A&M University, College Station, TX 77843, U.S.A Email: n-g@tamu.edu	http://journals.ametsoc.org/doi/pdf/10.1175/2010JCLI2947.1	Texas	This paper examines the dynamic and physical processes controlling the temperature at 700 hPa and elucidates the large-scale influences on convective instability and precipitation, integrating the principal processes found in the author's previous and current studies. Results indicate that (1) upper-level anticyclonic circulations in the southern United States strongly affect Texas summertime precipitation by modulating the thermodynamic structure of the atmosphere and thus convective instability; (2) stationary anticyclonic anomalies increase CIN not only by enhancing warm-air transport from the high terrain but also by suppressing the occurrence of traveling disturbances; and (3) the resulting reduced precipitation and dry soil significantly modulate surface conditions, elevating CIN and decreasing precipitation. The author concludes that	Journal Article

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						the aforementioned chain reaction of upper-level anticyclone influences that is expected to play an important role in initiating and maintaining Texas summer droughts can be understood within the context of CIN.	
81	On glacier retreat and drought cycles in the Rocky Mountains of Montana and Canada	2010	W.H. Berger Univ. of California, San Diego, Scripps Institute of Oceanography, La Jolla, CA 92093, U.S.A. Email: wberger@ucsd.edu	http://www.sciencedirect.com/science/article/B6VGS-4VFK7X4-1/2/174e84e058563f768e17acdd0eca8a7f	Rocky Mountains: Montana and Canada	The paper argues that the direct cause of mountain glacier retreat appears to be the onset of drought in the 1830s and concludes that the presence of tidal lines in the spectrum of the PDO, together with the presence of lines that could be interpreted as beat periods between solar and tidal forcing in the drought series, suggests that the energy of solar variation is preempted for interference with tidal forcing, within the system of oscillations informing precipitation patterns in the region.	Journal Article
82	Vertical moisture profile characteristics of severe surface drought and surface wetness in the western United States: 1973-2002	2010	Colleen M. Garrity Dept. of Geography, SUNY College at Geneseo, Geneseo, NY 14454, U.S.A. Email: garrity@geneseo.edu	http://onlinelibrary.wiley.com/doi/10.1002/joc.1944/pdf	Western U.S.	The authors characterize drought across the western United States from 1973 to 2002 in a three-dimensional context by examining its vertical moisture extent through use of NCEP/NCAR Reanalysis data derived from rawinsonde moisture profiles. They apply a discriminant analysis to establish the degree of difference between the vertical moisture profiles of extreme drought and extreme wetness conditions. Results show that the discriminant analysis of the 9254 cases	Journal Article

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						indicates that moisture in the lowest (850 hPa) level of the profile is most important in identifying dry versus wet regions, and, consequently, implies a strong influence of convective precipitation in defining surface drought and wet conditions in the study region.	
83	Megadroughts in North America: Placing IPCC Projections of Hydroclimatic Change in a Long-Term Paleoclimate Context	2009	Edward R. Cook Lamont-Doherty Earth Observatory, Palisades, NY	http://www.ldeo.columbia.edu/res/div/ocp/pub/cook/2009_Cook_IPCC_paleo-drought.pdf	North America	The article discusses possible causes of the megadroughts in the West and in the agriculturally and commercially important Mississippi Valley that are indicated in the Living Blended Drought Atlas (LBDA) and their implications for the future.	Journal Article
84	Drought in the Southeastern United States: Causes, variabilty over the last millennium and the potential for future hydroclimatic change	2009	Richard Seager Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY.	http://www.ldeo.columbia.edu/res/div/ocp/pub/seager/Seager_etal_SE_2009.pdf	South-eastern U.S.	The authors assessed the nature and causes of drought in the southeastern United States and modeled projected anthropogenically forced hydroclimate change in the region by using observations of precipitation, model simulations forced by historical SSTs, tree-ring records of moisture availability over the last millennium, and climate change projections conducted for the fourth assessment report of the IPCC.	Journal Article
85	Reservoir Operation and Water Allocation to Mitigate Drought Effects in Crops: A Multilevel Optimization Using the Drought Frequency Index	2009	Julio Canon Dept. of Hydrology & Water Resources, University of Arizona, Tucson, AZ 85721, U.S.A. Email: jecanonb@email.arizona.edu	http://ascelibrary.org/wro/resource/1/jwrmd5/v135/i6/p458_s1?isAuthorized=no	U.S. and Mexico Rio Grande Basin/Bravo Basin	The authors employed drought frequency index (DFI) as a drought indicator and a trigger mechanism for multireservoir system operations during drought. They evaluated performance with and without the DFI by using reliability and resilience indices, for the Conchos River basin (a tributary of the Rio Grande/Bravo basin between United States and Mexico), through a multilevel nonlinear optimization procedure oriented to reduce water deficits to the United States and	Journal Article

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						maximize net benefits for farmers in Mexican irrigation districts. Results show that the inclusion of the DFI improves the reliability of both reservoirs and water deliveries to users during periods of drought, reflecting an overall improvement of net benefits associated with crop production in Mexican irrigation districts.	
86	Relict nebkhas (pimple mounds) record prolonged late Holocene drought in the forested region of south-central United States	2009	Christopher L. Seifert Dept. of Earth Sciences, Univ. of Memphis, Memphis, TN 38152, U.S.A. Email: randycox@memphis.edu	http://www.sciencedirect.com/science/article/B6WPN-4VP5XGS-1/2/60ca3e32d4342e68bcd9539c49f58c5f	South central U.S.	The authors used pimple mounds sampled at four sites spanning the Ozark Plateau, Arkansas River Valley, and Gulf of Mexico Coastal Plain and found that the Mounds have a regionally consistent textural asymmetry, with a significant excess of coarse-grained sediment within their northwest flanks. The authors concluded that the Mounds are relict nebkhas deposited during protracted middle to late Holocene droughts, showing that vegetation loss during extended droughts led to local eolian deflation and pimple-mound deposition.	Journal Article
87	Analysis of annual hydrological droughts: the case of northwest Ontario, Canada	2009	U.S. Panu Dept. of Civil Engineering, Lakehead Univ., Thunder Bay, ON P7B 5E1, Canada Email: uspanu@lakeheadu.ca, tcsage@yahoo.com	http://www.informaworld.com/smpp/content~db=all~content=a917987749	Ontario Canada	The paper compares two approaches (time series simulation and a probability theory-based approach) to estimate drought parameters and tests their applicability for deducing drought parameters across Canada, with emphasis on northwest Ontario, a region bordering Lake Superior. The authors argue that the results of the probabilistic approach yielded marginally better results than the simulation approach. The regional variation of droughts in northwest Ontario was portrayed by a map plotting the values of drought potential index (DPI), which indicated proneness to	Journal Article

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						drought, along the Ontario-Manitoba border in the northwest Ontario region.	
88	Amplification of the North American "Dust Bowl" drought through human-induced land degradation	2009	Benjamin I. Cook Lamont Doherty Earth Observatory, Palisades, NY 10964, U.S.A. Email: bc9z@ldeo.columbia.edu	http://www.pnas.org/content/106/13/4997.full.pdf+html	North America	The authors argue that the inclusion of forcing from human land degradation in GCMs, in addition to SST anomalies, is necessary to reproduce the anomalous features of the Dust Bowl drought. They represent the degradation over the Great Plains in the GCM as a reduction in vegetation cover and the addition of a soil dust aerosol source, both consequences of crop failure. They argue that, as a result of land-surface feedbacks, the simulation of the drought is much improved when the new dust aerosol and vegetation boundary conditions are included. The authors conclude that human-induced land degradation is likely to have not only contributed to the dust storms of the 1930s but also amplified the drought, and these together turned a modest SST-forced drought into one of the worst environmental disasters the United States has experienced.	Journal Article
89	An analysis of the relationship of U.S. droughts with SST and soil moisture: Distinguishing the time scale of droughts	2008	Renguang Wu Center for Ocean-Land-Atmosphere Studies, Calverton, Maryland	ftp://grads.iges.org/pub/ctr/CTR268_ms.pdf	U.S.	The study distinguishes the time scale of droughts on the basis of the standardized precipitation index and analyzes the relationship between SST and soil moisture and boreal summer U.S. droughts. The relative roles of remote SST forcing and local soil moisture differed significantly for long-term and short-term droughts in the U.S. Great Plains and Southwest. For short-term droughts (< 3 months), simultaneous remote SST forcing plays an important role. For medium-term	Report

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						and long-term droughts (> 6 months), the antecedent remote SST forcing contributes to droughts through soil moisture and evaporation changes. The tropical Pacific SST is the dominant remote forcing for U.S. droughts. The most notable impacts of the tropical Pacific SST are found in the Southwest, with extension to the Great Plains. Tropical Indian Ocean SST forcing has a notable influence on medium-term and long-term U.S. droughts. The relationships between tropical Indian and Pacific Ocean SST and boreal summer U.S. droughts have undergone obvious long-term changes, especially for the Great Plains droughts.	
90	Drought Index Mapping at Different Spatial Units	2008	Jinyoung Rhee Department of Geography, University of South Carolina, Columbia, SC	http://journals.ametsoc.org/doi/pdf/10.1175/2008JHM983.1	North and South Carolina	The authors investigated the influence of spatial interpolation and aggregation of data to depict drought at different spatial units relevant to and often required for drought management. Four different methods of drought index mapping were explored, and comparisons were made between two spatial operation methods (simple unweighted average versus spatial interpolation plus aggregation) and two calculation procedures (whether spatial operations are performed before or after the calculations of drought index values). Deterministic interpolation methods including Thiessen polygons, inverse distance weighting, and thin-plate splines as well as a stochastic and geostatistical interpolation method of ordinary kriging were compared for the two methods that use interpolation. The interpolation and aggregation introduced fewer errors in	Journal Article

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						cross validation than the two simple unweighted average methods. Whereas the method performing spatial interpolation and aggregation before calculating drought index values generally provided consistent drought information between various spatial units, performing spatial interpolation and aggregation after calculating drought index values reduced errors related to the calculations of precipitation data.	
91	Potential Predictability of Long-Term Drought and Pluvial Conditions in the U.S. Great Plains	2007	Siegfried D. Schubert Global Modeling and Assimilation Office, Earth Sun Exploration Division, NASA GSFC, Greenbelt, MD	http://journals.ametsoc.org/doi/pdf/10.1175/2007JCLI1741.1	U.S. Great Plains	This study examines the predictability of seasonal mean Great Plains precipitation using an ensemble of century-long atmospheric general circulation model (AGCM) simulations forced with observed SSTs. The results show that the predictability (intraensemble spread) of the precipitation response to SST forcing varies on interannual and longer time scales. In particular, this study finds that pluvial conditions are more predictable (have less intraensemble spread) than drought conditions. This might be because the changes in predictability are primarily driven by changes in the strength of the land–atmosphere coupling, such that under dry conditions a given change in soil moisture produces a larger change in evaporation and hence precipitation than the same change in soil moisture would produce under wet soil conditions.	Journal Article

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92	Recent methods and techniques for managing hydrological droughts	2007	G. Rossi Department of Civil and Environmental Engineering, University of Catania, Italy	http://www.iamz.ciheam.org/medroplan/a-80_OPTIONS/Sesion%203/%28251-266%29%2036%20Rossi%20GS3.pdf	Global	This paper discusses characterization, monitoring, and forecasting of hydrological droughts using new indices, the potential improvements in early drought detection that could be derived from the use of aggregated drought indices, and the role of global climatic indices for increasing the reliability of drought forecasting.	Journal Article
93	Assessing Vulnerability to Natural Hazards: An Impact-Based Method and Application to Drought in Washington State	2007	Matthew M. Fontaine Department of Civil & Environmental Engineering, Univ. of Washington, Seattle, WA 98195, U.S.A.	http://water.washington.edu/Theses/Fontaine.pdf	Washington State	MSc thesis which developed a Vulnerability Assessment Method (VAM) to assess not only the hazard, but also the causes of vulnerability, potential for adaptation, previous impacts, and ways to mitigate future impacts. The VAM is applied to a case study of Washington State, assessing drought vulnerability across 34 sub-sectors including power, agriculture and M&I.	Thesis
94	Severe and sustained drought in southern California and the West: Present conditions and insights from the past on causes and impacts	2007	Glen M. MacDonald Department of Geography, UCLA, Los Angeles, CA	http://cat.inist.fr/?aModele=afficheN&cpsidt=19107825	Western U.S.	Paleoclimatological and paleooceanographic data indicate that the arid conditions in western North America during the medieval climate anomaly were produced by the prolonged occurrence of cool surface waters in the eastern Pacific. Recent climate model experiments suggest that relatively small increases in insolation and decreases in atmospheric volcanic emission concentrations can trigger such depressions of eastern Pacific temperatures. It is thus possible that a similar event, due to natural or anthropogenic causes, could occur in the future.	Journal Article

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95	Droughts and Persistent Wet Spells over the United States and Mexico	2007	Kingtse C. Mo NOAA/NWS/NCEP/ Climate Prediction Center, Camp Springs, MD	http://journals.ametsoc.org/doi/pdf/10.1175/2007JCLI1616.1	U.S. and Mexico	The purposes of this paper are (1) to identify regions where droughts and wet spells are most likely to occur and persist using different indices and methods, and (2) to understand the impact of low-frequency SSTAs and ENSO on persistent wet and dry conditions. Results show that the long persistent drought and wet spells are often modulated by low-frequency SST anomalies (SSTAs). The persistent dry or wet conditions over northwest Mexico and the Southwest are associated with decadal variability of SSTAs over the North Pacific. Persistent events over the northwestern mountains are associated with two decadal SSTA modes. One mode has loadings over three southern oceans and another one is an El Niño–Southern Oscillation (ENSO) like decadal mode. Wet and dry conditions over the Pacific Northwest and the Great Plains are often associated with ENSO. The seasonal cycle of precipitation over the central-eastern United States, the East Coast, and the Ohio Valley is weak. Drought and wet spells over these regions are less persistent because the ENSO events have opposite impacts on precipitation for summer and winter.	Journal Article

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96	The Turn of the Century North American Drought: Global Context, Dynamics, and Past Analogs	2007	Richard Seager Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY	http://journals.ametsoc.org/doi/pdf/10.1175/2007JCLI1529.1	North America	Examined the causes and global context of the North American drought between 1998 and 2004 using atmospheric reanalyses and ensembles of atmosphere model simulations variously forced by global SSTs or tropical Pacific SSTs alone. The global context of the most recent turn-of-the-century drought is compared to the five prior persistent North American droughts in the instrumental record from the mid-nineteenth century on. A classic La Niña pattern of ocean temperature in the Pacific is common to all. A cold Indian Ocean, also typical of La Niña, is common to all five prior droughts, but not the most recent one.	Journal Article
97	Climatic Influences on Midwest Drought during the Twentieth Century	2007	Warren B. White Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA	http://horizon.ucsd.edu/maltmn/sasha/White%20et%20al%20JCLIM2008.pdf	Midwestern U.S.	Applied the optimized canonical correlation analysis (CCA) to forecast April–August and September –December Midwest rainfall variability in cross-validated fashion from antecedent December-February and June-August SST variability in the surrounding oceans. The CCA models simulate the Dustbowl Era drought of the 1930s, four of seven secondary April–August droughts (>= 3-yr duration) during the twentieth century, the principal Midwest drought of the 1950s, and one of three secondary September–December droughts.	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
98	Widespread drought episodes in the western Great Lakes region during the past 2000 years: Geographic extent and potential mechanisms	2006	Robert K. Booth Center for Climatic Research, University of Wisconsin, Madison, WI, U.S.A.	http://www.uwyo.edu/terra/pdf/Booth_et_al_2006.pdf	Great Lakes	Objectives of the study are: (1) determine whether large, decadal to multidecadal droughts of the past 2000 yrs were spatially and temporally coherent across the region, and (2) assess the underlying mechanisms of widespread droughts in the region. The study reveals that most of the historical extreme drought events in the region were contemporaneous with large droughts already documented at sites far to the west in the Great Plains and Rocky Mountains. Using the empirical orthogonal function (EOF) analysis, the authors showed the correlation of drought to regional precipitation and SSTs in both the Atlantic and Pacific basins.	Journal Article
99	Trends in 20th century drought over the continental United States	2006	Konstantinos M. Andreadis Dept. of Civil and Environmental Engineering, University of Washington, Seattle, Washington	http://www.agu.org/journals/gl/gl0610/2006GL025711/2006GL025711.pdf	U.S.	Evaluated a simulated data set of hydro-climatological variables for 20th century trends in soil moisture, runoff, and drought characteristics over the conterminous United States (U.S.). The result shows an increasing trend in both model soil moisture and runoff over much of the U.S., with a few decreasing trends in parts of the Southwest.	Journal Article

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100	New drought frequency index: Definition and comparative performance analysis	2006	Javier González Department of Civil Engineering, University of Castilla–La Mancha, Ciudad Real, Spain	http://www.agu.org/journals/wr/wr0611/2005WR004308/2005WR004308.pdf	Global	Presents a new index for drought characterization called the drought frequency index (DFI). The index focuses on this common aspect of drought origins, with a purely probabilistic treatment. Because droughts are persistent phenomena, the index is based on the stochastic characterization of extreme persistent deviation sequences using a novel probabilistic criterion. In this way, the DFI is related to the mean frequency of recurrence of extreme persistent events. The mean frequency of recurrence is adopted as the scale for drought significance evaluation. The index performance is analyzed and compared with respect to the different issues that result from applying other methodologies: magnitude selection, univariate versus multivariate, threshold selection (related to run theory), and timescale issues [related to the standard precipitation index (SPI) application]. Results reveal the ability of the DFI to reduce the sensitivity to practical issues. The DFI provides a consistent index for spatial comparisons and for application to general drought characterization goals.	Journal Article

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101	Megadroughts in the Indian Monsoon Region and Southwest North America and a Mechanism for Associated Multidecadal Pacific Sea Surface Temperature Anomalies	2006	Gerald A. Meehl and Aixue Hu National Center for Atmospheric Research, Boulder, CO	http://journals.ametsoc.org/doi/pdf/10.1175/JCLI3675.1	Southwest North America	Analyzed a 1360-yr control run from a global coupled climate model (the Parallel Climate Model). The model simulation shows "megadroughts" in the southwestern United States and Indian monsoon regions. Analysis of the model variability shows that the mechanism involves atmosphere–ocean and tropical–midlatitude interactions, with a crucial element being wind-forced ocean Rossby waves near 20°N and 25°S in the Pacific whose transit times set the decadal time scale. At the western boundary, the Rossby waves reflect into the equatorial Pacific to affect thermocline depth. The resulting feedbacks, involving surface temperature, winds, and the strength of the subtropical cells, produce SST anomalies and associated precipitation and convective heating anomalies.	Journal Article
102	Modeling of Tropical Forcing of Persistent Droughts and Pluvials over Western North America: 1856–2000	2005	Richard Seager Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY	http://journals.ametsoc.org/doi/pdf/10.1175/JCLI3522.1	Western U.S.	Examined the causes of persistent droughts and wet periods, or pluvials, over western North America using model simulations of the period from 1856 to 2000. The simulations used either (1) global SST data as a lower boundary condition or (2) observed data in just the tropical Pacific and computed the surface ocean temperature elsewhere with a simple ocean model. With both arrangements, the model was able to simulate many aspects of the low-frequency (periods greater than 6 yr) variations of precipitation over the Great Plains and in the American Southwest including much of the nineteenth-century variability, the droughts of the 1930s (the "Dust Bowl")	Journal Article

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						and 1950s, and the very wet period in the 1990s. Results indicate that the persistent droughts and pluvials were ultimately forced by persistent variations of tropical Pacific surface ocean temperatures.	
103	Summer Drought Patterns in Canada and the Relationship to Global Sea Surface Temperatures	2004	Amir Shabbar Meteorological Service of Canada, Environment Canada, Toronto, Ontario, Canada	http://journals.ametsoc.org/doi/pdf/10.1175/1520-0442%282004%29017%3C2866%3ASDPICA%3E2.0.CO%3B2	Canada	Examined the Canadian summer (June–August) Palmer Drought Severity Index (PDSI) variations and winter(December – February) global SST variations from 1940 to 2002. The authors related the extreme wet and dry Canadian summers to anomalies in the global SST pattern in the preceding winter season. Using singular value decomposition (SVD) analysis, large-scale relationships between summer PDSI patterns in Canada and previous winter global SST patterns are analyzed. Results show that the three leading SVD-coupled modes [trend in global SSTs and multi-decadal variation of the Atlantic SST, El Nino–Southern Oscillation (ENSO), and the Pacific decadal oscillation(PDO)] explain greater than 80% of the squared covariance between the two fields. In addition, the 6-month lag relationship between the PDSI and large-scale SSTs provides a basis for developing long-range forecasting schemes for drought in Canada.	Journal Article

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104	SECURE Water Act Section 9503(c) – Reclamation Climate Change and Water 2011	2011	Patty Alexander et al. U.S. Department of the Interior, Bureau of Reclamation	http://www.usbr.gov/climate/SECURE/docs/SECUREWaterReport.pdf	Western U.S.	Section 9503 of the SECURE Water Act identifies the "Reclamation Climate Change and Water Program." In this report, the Bureau of Reclamation is addressing the authorities within the SECURE Water Act through a broad set of activities in conjunction with Secretarial Order 3289 establishing the U.S. Department of the Interior's integrated approach to addressing climate change and Secretarial Order 3297 establishing the WaterSMART Program and Research and Development activities. This report is the Bureau of Reclamation's first report under the authorities of the SECURE Water Act and presents the current information available.The report includes (1) effects of and risks resulting from global climate change with respect to the quantity of water resources located in each major Bureau of Reclamation river basin, (2) the impact of global climate change with respect to the operations of the Secretary of the Interior in each major Bureau of Reclamation river basin, (3) mitigation and adaptation strategy considered and implemented by the Secretary to address each effect of global climate change, and (4) coordination activities conducted by the Secretary with the USGS, NOAA, USDA, and others.	Report to Congress

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
105	Strengthening the Scientific Understanding of Climate Change Impacts on Freshwater Resources of the United States	2011	Advisory Commettee on Water Information (ACWI)?	http://acwi.gov/Rpt.Congress3.18.11.pdf	U.S.	The report provides a general overview of the challenges that a changing climate poses for water resources managers in the context of other water-resource stressors. In particular, the report considers water resources measurement and modeling systems that are relevant to climate change adaption, as required by Section 9506. Recommendation are focused on strengthening these systems to inform water management decisions at the Federal, State, and local levels. This report draws from and builds on a number of recent climate and water documents that have been produced across the Federal, State, local, Tribal, and private water sectors.	Report to Congress

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
106	Regional Climate and Hydrologic Change in the Northern U.S. Rockies and Pacific Northwest: Internally Consistent Projections of Future Climate for Resource Management	2011	Littell et al. University of Washington College of the Environment, Climate Impacts Group, Seattle, Washington	http://cses.washington.edu/picea/USFS/pub/Littell_etal_2010/	Columbia, Upper Missouri, Upper Colorado, and Great Basins	This project was designed to (1) develop consistent historical and future downscaled climate and hydrologic data and projections using the same methodology for several major river basins in the western United States (Columbia, upper Missouri, upper Colorado, and Great Basins) and (2) summarize that information in forms consistent with the needs of the funding agencies. This report describes where to get the information developed as well as the methods, results obtained, uses of and uncertainties associated with the data and projections.It provides an internally consistent set of historical (1916-2006) and future (2040s, 2080s) downscaled climate and hydrologic data and projections that can be tailored to management units in the Columbia , upper Missouri, Colorado, and Great Basins. Summary products developed for the project include the following: Historical trend maps (graphics) and station tables for Historical Climate Network climate trends for maximum/minimum temperature and precipitation; data, graphics, and future projections summarized by Bailey ecosections, 8 digit HUCs, and Omernik ecoregions. Maps showing results for the historical period and the 2040s over the whole project domain can be accessed.	Report
107	Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lakes Powell and Mead	2007	Bureau of Reclamation	http://www.usbr.gov/lc/region/programs/strategies/FEIS/index.html	Colorado River Basin	The report provides guidelines and coordinated management strategies for Lakes Mead and Powell, particularly under low reservoir conditions. The guidelines will be used for determinations regarding	EIS Report

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
						water supply and reservoir operating decisions through 2026 and for guidance each year in development of the Annual Operating Plan for Colorado River Reservoirs (AOP)	
108	Medieval drought in the upper Colorado River Basin	2007	D.M. Meko (reprint author) Tree Ring Research Lab, Univ. of Arizona, Tucson, AZ 85721, U.S.A. Email: dmeko@ltrr.arizona.edu	http://www.agu.org/journals/gl/gl0710/2007GL029988/2007GL029988.pdf	Colorado River Basin	This draft report identifies key actions to improve the nation's capacity to detect and predict changes in freshwater resources that are likely to result from a chnaging climate. In addition, a series of next steps for federal agencies is provided. The ultimate goal is to help decision-makers and water resource managers by facilitating improvements in observational, data acquisition, and modeling capacilities.	Journal Article
109	A 545-year drought reconstruction for central Oregon	2002	K.A. Pohl (reprint author) Dept. of Geography, Portland State Univ, POB 751, Portland, OR 97207, U.S.A.	http://www.willamette.edu/~karabas/research/Pohletal2002.pdf	Central Oregon	Using a 545-year Ponderosa pine (Pinus ponderosa) tree-ring chronology, the authors examined the drought history of central Oregon to (1) determine the relationship amongdrought, the ENSO (El Niño/Southern Oscillation), and the PDO (Pacific Decadal Oscillation) and (2) compare the climatic sensitivity of Ponderosa pine and western juniper (Juniperusoccidentalis) to determine their suitability as interchangeable climate proxies. The climatic reconstruction explained 35% of the variance in historical Palmer Drought Severity Index(PDSI) values and revealed severe drought periods during the 1480s, 1630s, 1700s, and1930s.	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
110	Mitigating Impacts of a Severe Sustained Drought on Colorado-River Water-Resources	1995	T.B. Sangoyomi (reprint author) Hydrosphere Resource Consultants, 1002 Walnut St, Suite 200, Boulder, CO 80302, U.S.A.	http://www.hydrosphere.com/publications/ssd/MitigatingImpactsSevereSustainedDrought.pdf	Colorado River Basin	Old but important document, with information on impacts of drought on energy production at the Colorado River.	Journal Article
111	Drought Analysis with Reservoirs Using Tree-Ring Reconstructed Flows	1995	H.W. Shen (reprint author) Univ. of California, Berkeley, 412 O'Brien Hall, Berkeley, CA 94720, U.S.A.	http://scitation.aip.org/getpdf/servlet/GetPDFServlet?filetype=pdf&id=JHEND8000121000005000413000001&idtype=cvips&doi=10.1061/%28ASCE%290733-9429%281995%29121:5%28413%29&prog=normal	Sacramento River Basin	Important drought analysis at the Sacramento river basin.	Journal Article
112	Drought frequency in central California since 101 BC recorded in giant sequoia tree rings	1991	M.K. Hughes (reprint author) Tree Ring Research Lab, Univ. of Arizona, Tucson, AZ 85721, U.S.A.	http://www.springerlink.com/content/r012218005026183/fulltext.pdf	Sierra Nevada, California	Old document with important drought analysis at Jan sequoia drainage.	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
113	West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections	2011a	Bureau of Reclamation, Technical Services Center, Denver, Colorado	http://www.usbr.gov/WaterSMART/docs/west-wide-climate-risk-assessments.pdf	Colorado River Basin, Columbia River Basin, Klamath River Basin, Missouri River Basin, Rio Grande River Basin, Sacramento and San Joaquin River Basins, Truckee and Carson River Basins	This technical assessment report provides: an analysis of changes in hydroclimate variables—namely, precipitation, temperature, snow water equivalent, and streamflow across the major Bureau of Reclamation river basins.	Report
114	Literature Synthesis on Climate Change Implications for Water and Environmental Resources	2011	Bureau of Reclamation, Technical Services Center, Denver, Colorado	http://www.usbr.gov/research/docs/climatechangelitsynthesis.pdf	Pacific Northwest Region, Mid-Pacific Region, Lower Colorado Region, Upper Colorado Region, Great Plains Region	This docoument offers a summary of recent literature on the past and projected effects of climate change on hydrology and water resources and then summarizes implications for key resource areas featured in Bureau of Reclamation planning processes. The literature review considered documents pertaining to general climate change science; climate change as it relates to hydrology, water resources, and environmental resources; and application of climate change science in western United States and region-specific planning assessments. Most of the documents reviewed consist of anonymously peer-reviewed scientific articles. Certain other documents, such as national and regional assessments, were included because of their comprehensive	Report

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
						nature and/or for management-related perspectives.	

A.2 Drought Monitoring

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description
1	State of the Climate Drought	1999-present	NOAA National Climatic Data Center	http://www.ncdc.noaa.gov/sotc/drought/	U.S.	Provides monthly drought (climate, hydrologic, and agriculture) and moisture conditions for all contiguous U.S. states, the nine standard regions, and the nation (contiguous U.S.).
2	U.S. Drought Portal	Since 2006	National Integrated Drought Information System (NIDIS)	http://www.drought.gov/portal/server.pt/community/drought_gov/202;jsessionid=37737AC6DA18CE106C45FE6B2C89A549	U.S.	Provides early warning about emerging and anticipated droughts; assimilates and performs quality control on data about droughts and models; provides information about risk and impact of droughts to different agencies and stakeholders; provides information about past droughts for comparison and to understand current conditions; explains how to plan for and manage the impacts of droughts; provides a forum for different stakeholders to discuss drought-related issues.
3	U.S. Department of the Interior Bureau of Reclamation, Reclamation Managing Water in the West	Last up-dated 3/28/2011	Reclamation Drought Coordinator, Bureau of Reclamation, 84-50000 PO Box 25007, Denver, CO 80225-0007 Phone: 303-445-2727	http://www.usbr.gov/drought/	U.S.	The Bureau of Reclamation has a Drought Program and this website is used to post its program services, including drought directives and standards, assistance during drought, and drought contingency planning.
4	North American Drought Monitor, National Oceanic and Atmospheric Administration National Climatic Data Center	Last up-dated 10/21/2010	Climate Services and Monitoring Division, NOAA/National Climatic Data Center, 151 Patton Avenue ,Asheville, NC 28801-5001 ncdc.info@noaa.gov	http://www.ncdc.noaa.gov/temp-and-precip/drought/nadm/	North America	The North America Drought Monitor (NADM) is a cooperative effort between drought experts in Canada, Mexico and the United States to monitor drought across the continent on an ongoing basis. This website is used to assess and communicate the state of drought in North America and provide data related to drought.

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description
			phone: +1-828-271-4800			
5	Drought Monitor	Last up-dated 01/11/2011	The Drought Monitor, National Drought Mitigation Center, P.O. Box 830988, Lincoln, NE 68583-0988 (402) 472-6707 Email: DroughtMonitor@unl.edu	http://drought.unl.edu/dm/	U.S.	This website is an outlet to communicate U.S. Drought Monitoring maps managed by the National Drought Mitigation Center.
6	U.S. Environmental Protection Agency Natural Disasters and Weather Emergencies	Last up-dated 4/19/2011	U.S. Environmental Protection Agency	http://www.epa.gov/naturalevents/drought.html	U.S.	This website is used as an outlet to communicate drought information that helps the public to take steps to reduce impacts before and during a drought.
7	New York Drought Information	Last up-dated 3/1/2010	New York Water Science Center, 425 Jordan Road, Troy, NY 12180-8349 (518) 285-5695	http://ny.water.usgs.gov/projects/duration/	New York	The website is used to communicate the State's drought information resources.
8	Agriculture and Agri-Food Canada Drought Watch	Last up-dated 09/20/2010	Agriculture and Agri-Food Canada, 1341 Baseline Road, Ottawa, Ontario K1A 0C5 (613) 773-1000	http://www4.agr.gc.ca/AAFC-AAC/display-afficher.do?id=1256658312655&lang=eng	Canada	The website is an outlet to communicate current drought conditions, climate profiles and drought management information in Canada.
9	Drought Research Initiative (DRI)	2011	dri.drought@gmail.com	http://www.drinetwork.ca/index.php	Canada	The website is used by the Drought Research Initiative to coordinate and integrate drought research in Canada. Drought Research Initiative is a research network that brings together many

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description
						university and federal/provincial government researchers to address drought issues with expertise encompassing the atmospheric, hydrologic, land surface, and predictive aspects of droughts at a variety of spatial and temporal scales.
10	British Columbia Drought Information	2011	livingwatersmart@gov.bc.ca	http://www.livingwatersmart.ca/drought/	British Columbia	The British Columbia government drought information website used to communicate current levels of drought and help the public to respond accordingly.
11	Lamont-Doherty Earth Observatory, The Earth Institute At Columbia University, Drought Research	2011	Dr. Richard Seager (845) 365-8736 Email: seager@ldeo.columbia.edu	http://www.ldeo.columbia.edu/res/div/ocp/drought/	North America	The website is used to communicate various publications on historical and current drought in North America.
12	Drought for Kids	2010	National Drought Mitigation Center	http://www.drought.unl.edu/kids/	U.S.	This website was developed by the National Drought Mitigation Center especially for children to help them develop awareness about drought.
13	Canadian Drought Alert and Monitoring Program (CDAMP)	Last up-dated 12/02/2010	Adaptation and Impacts Research Division (AIRD), Environment Canada, 4905 Dufferin Street, Dounsview, Ontario, Canada M3H 5T4 (416) 739-4436	http://www.cdamp.ca/contact-e.html	Canada	This website was developed by the Canadian Drought Alert and Monitoring Program (CDAMP) to raise public awareness of the importance of drought to Canadians. In the current climate and with the knowledge that climate change is expected to potentially increase both drought severity and frequency, the CDAMP program helps analyze the level of current rainfall deficiencies compared to critical thresholds. CDAMP helps individuals, farms, communities and municipalities analyze the level of their current rainfall deficiencies and take action.

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description
14	California Drought Preparedness		Dustin Hardwick Director of Resource Development (760) 920-0842 Email: dhardwick@calruralwater.org	http://www.cadroughtprep.net/index.htm	California	This website provides resources to help water systems with respect to water shortages, water conservation and Emergency/Disaster response planning.
15	DECISION SUPPORT: A Regional-Scale Drought Monitoring Tool for the Carolinas	2008	Gregory J. Carbone Department of Geography, University of South Carolina, Columbia, SC	http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-89-1-20	North and South Carolina	A web-based drought-monitoring tool that addresses the scale, flexibility, and stakeholders' demands. The 1998–2002 drought in North and South Carolina, followed by multiyear dam relicensing negotiations, spurred development of a regional drought monitoring tool.

A.3 Federal Efforts and State Plans

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description
1	Method for Determining Long-term Drought Status	2010	Arizona Department of Water Resources	http://www.azwater.gov/AzDWR/StatewidePlanning/Drought/documents/long-termmapmethods-updated3-2011.pdf	Arizona	Arizona's long-term drought status map, updated quarterly, incorporates 24-, 36- and 48-month precipitation and streamflow percentiles from multiple gages in each of Arizona's major watersheds: • Abnormally Dry (21st-30th percentile) • Moderate Drought (11th-20th), reduced streamflows and lower than average reservoir levels • Severe Drought (6th-10th), reduction in reservoir levels and reduced stream- and spring-flows • Extreme Drought (2nd-5th), near-record low streamflows, noticeable reduction in reservoir levels, and measurable reduction in groundwater levels
2	Arizona Drought Preparedness Plan - Operational Drought Plan	2004	Governor's Drought Task Force	http://www.azwater.gov/AzDWR/StatewidePlanning/Drought/documents/operational_drought_plan.pdf	Arizona	Identifies impacts of drought on various water uses, defines sources of drought vulnerability for water use sectors, outlines monitoring programs, and provides drought response options and drought mitigation strategies.
3	Austin Drought Contingency Plan	2009	City of Austin, TX	http://www.ci.austin.tx.us/water/downloads/2009austindroughtcontingencyplan.pdf	Austin, TX	Contains Demand, Supply and Emergency Triggers, and for each trigger, provides actions, goals, and end conditions, but does not address power generation
4	California's Drought: Water Conditions and Strategies to Reduce Impacts Report to the Governor, March 30, 2009	2009	Department of Water Resources, California Department of Food and Agriculture, California	http://www.water.ca.gov/news/newsreleases/2009/040209droughtrpt-gov.pdf	California	Examines current hydrologic conditions including changes that have occurred since the Governor's proclamation was issued. Snowpack, runoff, groundwater, and surface reservoir levels are evaluated, as well as Colorado River supplies, and current social, economic, and environmental impacts caused by drought. The report also

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description
						outlines steps that have been taken in response to the drought including progress on the Governor's statewide water conservation outreach campaign and the status of the Drought Water Bank.
5	California Drought Contingency Plan	2010	California Department of Water Resources	http://www.water.ca.gov/drought/docs/Final_CA_Drought_Contingency_Plan-11-18-2010a.pdf	California	Recommends a general framework for agency planning and coordination to facilitate drought response and management; identifies activities and strategies that may be implemented to minimize drought impacts on vulnerable regions and sectors. These activities include actions that may be implemented before, during, and after a drought with respect to planning and coordination, monitoring, local assistance, and conservation programs. Includes qualitative discussion of impacts of drought on power production.
6	Drought Contingency Plan for Guadalupe-Blanco River Authority	2009	Guadalupe-Blanco River Authority (GBRA)	http://www.gbra.org/documents/conservation/GBRADroughtContingencyPlan.pdf	Canyon Reservoir, South Central Texas	Applies to Canyon Reservoir stored water, GBRA's hydroelectric lakes, but not to run-of-river water. Provides triggering criteria for various types of drought and associated response strategies, but does not address power generation per se.
7	The Colorado Drought Mitigation and Response Plan	2010	Colorado Department of Natural Resources, Colorado Water Conservation Board	http://cwcb.state.co.us/water-management/drought/Pages/StateDroughtPlanning.aspx	Colorado	The Plan outlines a mechanism for coordinated drought monitoring, impact assessment, response to emergency drought problems, and mitigation of long-term drought impacts. The Plan has three major components: mitigation, response and vulnerability assessment.
8	Southern Nevada Water Authority Drought Plan	2007	Southern Nevada Water Authority (SNWA)	http://www.snwa.com/assets/pdf/drought_plan07.pdf	Colorado River Basin	Lays out a comprehensive plan for how the SNWA and its member agencies will work together to implement proactive drought response measures to ensure that appropriate demand reductions occur during periods of drought, but does not address power generation per se.
9	Avista Electric Integrated Resource Plan	2009	Avista Power	http://www.avistautilities.com/inside/resources/irp/electric/Documents/Avista%202009%20IR	Eastern Washing-ton,	Guides the utility's resource acquisition strategy over the next two years and the overall direction of resource procurements for the remainder of the

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description
				P.pdf	northern Idaho and parts of southern and eastern Oregon	20-year planning horizon. Provides a snapshot of the company's resources and loads, and provides guidance regarding resource needs and acquisitions. The company has implemented estimates of the impacts of climate change in its retail load forecast. Discusses reserve margins needed for weather events and impacts of weather on load planning.
10	Idaho Drought Plan	2001	Idaho Department of Water Resources	http://www.idwr.idaho.gov/News/drought/PDFs/Drought%20Plan.pdf	Idaho	Provides current and historic information, guidance and a framework for managing water shortage situations in Idaho; does not specifically address power generation.
11	Idaho Power Integrated Resource Plan	2009	Idaho Power	http://www.idahopower.com/pdfs/AboutUs/PlanningForFuture/irp/2009/2009IntegratedResourcePlan.pdf	Idaho, Oregon, and Nevada	Provides a comprehensive look at present and future demands for electricity, and a plan for meeting those demands; describes the company's projected need for additional electricity and the resources necessary to meet that need while balancing reliability. Four load forecasts reflect a range of load uncertainty resulting from differing economic and weather-related assumptions.
12	Big Hole River Drought Management Plan		Big Hole River Foundation	http://www.bhrf.org/drought_mngt.htm	Montana	Provides threshold triggers and response conditions, but does not address power generation per se.
13	New Mexico Drought Plan	2006	New Mexico's Governor's Drought Task Force	http://www.ose.state.nm.us/DroughtTaskForce/2006-NM-Drought-Plan.pdf	New Mexico	Provides drought indicators and triggers, but does not address power generation per se
14	Water Conservation and Drought Contingency Plan	2009	Sabine River Authority of Texas	http://www.sra.dst.tx.us/basin/water_conservation/Conservation_and_Drought_Contingency_Plan/SRA-WCDCP_Adopted20091008.pdf	Sabine River Area, East Texas	Includes trigger criteria for initiation and termination of drought conditions and drought water-use measures associated with each trigger condition, but does not address power generation per se.
15	Seattle Public Utilities Water Shortage Contingency Plan	2006	Seattle Public Utilities (SPU)	http://www.seattle.gov/util/groups/public/@spu/@rmb/@resplan/@plancip/documents/webcontent/watershor_200312021018	Seattle, WA	Provides guidelines for SPU to manage water supply and demand in the event of a supply problem such as a drought. Contains triggers and operating actions, but does not address power

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description
				123.pdf		generation per se.
16	National Integrated Drought Information System (NIDIS) Workshop: Status of Drought Early Warning Systems in the United States, June 17-19, 2008, Kansas City, Missouri	2008	National Integrated Drought Information System	http://www.drought.gov/imageserver/NIDIS/workshops/kc/NIDIS_KCWorkshop_Final.pdf	U.S.	Key workshop findings on the status of Drought Early Warning Systems in the U.S. and implications are summarized.
17	Soil Moisture and Soil Temperature Observations and Applications: A Joint U.S. Climate Reference Network (USCRN) – National Integrated Drought Information System (NIDIS) Workshop, Oak Ridge, TN, March 3-5, 2009	2009	National Integrated Drought Information System	http://www.drought.gov/imageserver/NIDIS/workshops/crn/USCRN_SMST_workshop_summary.pdf	U.S.	Issues related to installation of soil moisture, soil temperature and relative humidity instruments for the U.S. Climate Reference Network stations are summarized.
18	Creating a Drought Early Warning System for the 21st Century: The National Integrated Drought Information System	2004	Western Governors' Association (WGA)	http://www.westgov.org/wga/publicat/nidis.pdf	Western U.S.	This is the first report resulting from the partnership between WGA and NOAA. The report presents vision and recommendations on developing NIDIS, a proactive approach to drought. Two key components of NIDIS are (1) improve and expand the compilation of reliable data on the various indicators of droughts, from both the physical/hydrological data (such as a national surface observing network) to the socio-economic and environmental impacts data (such as agriculture losses and wildfire impacts); and (2) integrate and interpret those data with easily accessible and understandable tools, which provide timely and useful information to decision-makers and the general public.
19	Water Needs and Strategies for a Sustainable Future: Next Steps	2008	Western Governors' Association	http://www.westgov.org/reports?view=reports&start=4	Western U.S.	Identifies the findings and "next steps." Discusses action items that represent the most important next steps to further WGA's recommendations regarding the West's most vital natural resource.

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description
20	Climate Change, Drought and Early Warning on Western Native Lands, 9-11 June, 2009, Jackson Lodge, Grand Teton National Park, WY	2010	National Integrated Drought Information System	http://www.drought.gov/imageserver/NIDIS/workshops/tribal/NIDIS_Jackson_Hole_Report.pdf	Western U.S.	This workshop report summarizes findings from the workshop, highlighting (1) data collection and monitoring gaps, (2) interdisciplinary research needs, and (3) financial capital and institutional framework recommendations. The workshop discussion and this report highlight definitive projects and research needs that possess clear capabilities for implementation into a current institutional framework or contain specific decisive recommendations for achieving project goals.
21	Wyoming Drought Plan prepared for Governor Jim Geringer	2003	Jon Etchepare, Director (co-chair) Department of Agriculture, Univ. of Wyoming, 2219 Carey Avenue, Cheyenne, WY 82002-0100 (P) (307) 777-6569 (F) (307) 777-6593 Email: jetche@state.wy.us	http://www.wrds.uwyo.edu/sco/drought/droughtplan.pdf	Wyoming	This document lays out a drought plan for the Wyoming State to help the governor make decisions pertaining to assessment and responses.
22	Wyoming Drought Plan	2003	Wyoming Drought Task Force	http://www.wrds.uwyo.edu/sco/drought/droughtplan.pdf	Wyoming	Provides a framework for an integrated approach to minimize the impacts of drought; identifies triggers for determining drought; and outlines long- and short-term measures to mitigate the effects of drought, but does not address power generation per se.

A.4 Effects on Power Plants

No	Title	Year	Contact Information	Source (URL, etc.)	Study Area	Brief Description
1	Department of Energy/National Energy Technology Laboratory's Water-Energy Interface Research Program: December 2010 Update	2010	Jared Ciferno U.S. Department of Energy/National Energy Technology Laboratory	http://www.netl.doe.gov/technologies/coalpower/ewr/water/pdfs/Water_Program_Overview.pdf	U.S.	Provides background information on the relationship between water and thermoelectric power generation and describes the R&D activities currently being sponsored by DOE/NETL's EPEC Program to address current and future water-energy issues.
2	Impact of Drought on U.S. Steam Electric Power Plant Cooling Water Intakes and Related Water Resource Management Issues	2009	Barbara Carney National Energy Technology Laboratory Prepared by Todd A. Kimmell and John A. Veil, Argonne National Laboratory	http://www.netl.doe.gov/technologies/coalpower/ewr/water/pdfs/final-drought%20impacts.pdf	Nationwide steam electric power plant fleet	Estimates the impact of water level drops on generation capacity of U.S. steam electric power plants due to climatic or other conditions. The impact was evaluated against a number of different power plant characteristics, such as the nature of the water source (river vs. lake or reservoir) and type of plant (nuclear vs. fossil fuel).
3	An Analysis of the Effects of Drought Conditions on Electric Power Generation in the Western United States	2009	Barbara Carney National Energy Technology Laboratory Prepared by Leslie Poch, Guenter Conzelmann, and Tom Veselka, Argonne National Laboratory	http://www.netl.doe.gov/technologies/coalpower/ewr/water/pdfs/final%20-%20WECC%20drought%20analysis.pdf	Western U.S.	Evaluates the availability of water at power plants under drought scenarios and quantifies the impacts of water level decreases on the generation mix, future electricity prices, and carbon dioxide (CO_2) emissions that would occur if the utility and system operators were forced to take any of those steam-electric plants out of service, or reduce their outputs, for extended periods of time. Plausible drought scenarios for electric power system simulation: (1) the year with lowest hydroelectric power production and (2) power plants that were undergoing a moderate or more severe drought based on U.S. drought monitor map (week of Jan 27, 2009) are chosen for shutdown or curtailment.

No	Title	Year	Contact Information	Source (URL, etc.)	Study Area	Brief Description
4	Running on Empty: The Electricity-Water Nexus and the U.S. Electric Utility Sector	2009	Benjamin K. Sovacool Lee Kuan Yew School of Public Policy, part of the National University of Singapore	http://www.felj.org/docs/elj301/11_-_sovacool.pdf ENERGY LAW JOURNAL Vol. 30:11	20 metro-politan areas	The article discusses how the water needs of the electricity industry may engender a series of water and power crises in eight future metropolitan areas—Atlanta, Charlotte, Chicago, Denver, Houston, Las Vegas, New York, and San Francisco—where water resources will be scarce or declining, especially if electricity demand grows as expected.
5	Water, Energy, and Drought: Water Use for Energy Production in the U.S.	2009	Seth D. Sheldon Seth.Sheldon001@umb.edu	http://www.umass.edu/tei/wrrc/WRRC2004/Conference2009/PDF/Sheldon.pdf	U.S.	The article analyzes the water use rates for thermoelectric power generation with respect to cooling system, plant type, plant age, geographic location, and regional drought condition between 2001 and 2005.
6	The Impact of Drought on Electricity Supply in North Carolina	2009	Dominic B.K. Milazi Master's Thesis Duke University	http://dukespace.lib.duke.edu/dspace/bitstream/handle/10161/1042/The%20Impact%20of%20Drought%20on%20Electricity%20Supply%20in%20North%20Carolina.pdf?sequence=1	North Carolina	The study covers various issues en-route to quantifying the impact of drought, including: identifying areas in the state historically prone to drought, locations of major power plants in relation to these drier areas, electricity generation costs of different powers plants within the state, and changes in aggregate generation costs under different scenarios when countering the adverse effects of drought.
7	Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements: 2009 Update	2009	Erik Shuster Office of Systems, Analyses and Planning, National Energy Technology Laboratory	http://www.netl.doe.gov/energy-analyses/pubs/2009%20Water%20Needs%20Analysis%20-%20Final%20%289-30-2009%29.pdf	U.S.	The report characterizes the significance of regional impacts on water use and identifies regions where water issues could become acute by comparing the regional electricity demand and capacity forecasts with representative water withdrawal and consumption estimates.
8	Effects of Climate Change on Energy Production and Use in the United States	2008	Thomas J. Wilbanks Oak Ridge National Laboratory	http://www.climatescience.gov/Library/sap/sap4-5/final-report/sap4-5-final-all.pd	U.S.	This report summarizes the current knowledge about possible direct and indirect effects of climate change on energy production, supply, and use in the United States.
9	Physical Impacts of Climate Change on the Western U.S. Electricity System: A Scoping Study	2008	Katie Coughlin Energy Analysis Department, Ernest	http://eetd.lbl.gov/ea/ems/reports/lbnl-1249e.pdf	U.S.	Study of the possible physical impacts of climate change on the electric power system, and how these impacts could be incorporated into resource planning in the western United

No	Title	Year	Contact Information	Source (URL, etc.)	Study Area	Brief Description
			Orlando Lawrence Berkeley National Laboratory			States.
10	The Electric Power Industry and Climate Change: Issues and Research Possibilities	2007	Judith Cardell Smith College, Northampton, MA, 01063 (413) 585-7000 Email: jcardell@smith.edu).	http://www.science.smith.edu/~jcardell/Courses/EGR325/Readings/CC.pdf	U.S.	Summarizes issues and research opportunities related to global climate change for the electric power industry in terms of infrastructure response to extreme weather events; operating strategies, configuration, and expansion plans; expansion of renewable and alternative energy technologies; and impacts of market rules and policy mandates on power system operation.
11	Northwest Power Supply Outlook	2005	John Harrison Northwest Power and Conservation Council Officer (503) 222-5161 Email: jharrison@nwcouncil.org	http://www.nwcouncil.org/energy/powersupply/outlook/2005outlook.pdf	Northwest	Presentation showing high correlation between power generated and stream runoff volume from January to July. It also compares impacts on hydropower of the 2005 and future water shortages with that of the 2001 shortage.
12	Guide to Tools and Principles for a Dry Year Strategy	2002	Bonneville Power Administration (BPA) Bonneville is the federal agency that sells nearly half of the electricity consumed in the Northwest.	http://www.bpa.gov/power/pgp/dryyear/08-2002_Draft_Guide.pdf	Pacific Northwest	Describes BPA's Dry Year Strategy to deal with longer duration load/resource imbalances that might last an entire year, or even a couple of years.

No	Title	Year	Contact Information	Source (URL, etc.)	Study Area	Brief Description
13	Impact of Extreme Weather on Power System Blackouts and Forced Outages: New Challenges	2008	Mladen Kezunovic Department of Electrical & Computer Engineering, Texas A&M University, College Station, TX Email: kezunov@ece.tamu.edu	http://www.ece.wisc.edu/~dobson/PAPERS/kezunovicBPC08.pdf	U.S.	Studies the direct (surface temperature and precipitation) and indirect (stream runoff and drought) impact of extreme weather on power system outages and component failure.
14	An Electric Power Industry Perspective on Water Use Efficiency	2009	John R.Wolfe Limno Tech, Inc., Ann Arbor, MI	http://onlinelibrary.wiley.com/doi/10.1111/j.1936-704X.2009.00062.x/pdf	U.S.	Provides review of growing electric power and water demand and their potential consequences for sustainability. Highlights the importance of increasing water conservation and water use efficiency and of integrated assessment of energy and water to have sustainable development of the resources.
15	The Last Straw: Water Use by Power Plants in the Arid West	2003	Ellen Baum Hewlett Foundation Energy Series	http://www.catf.us/resources/publications/files/The_Last_Straw.pdf	Western U.S.	Studies the relationship between power generation and water, including water use effects on competing uses, water quality and power system reliability. The report emphasizes the severity of the impact of drought conditions in the region, and provides recommendations to minimize the impacts from water used for power generation and to help ensure power system reliability and conserve scarce resources.
16	Identifying future electricity–water tradeoffs in the United States	2009	Benjamin K.Sovacool Energy Governance Program, Centre on Asia and Globalisation, Lee Kuan Yew School of Public Policy, National University of Singapore, Singapore	Energy Policy, 37: 2763–2773	U.S.	Study of water shortages resulting from the addition of thermoelectric power plants. Authors used county-level data on (1) rates of population growth collected from the U.S. Census Bureau; (2) increases in future power-plant capacity in the contiguous United States from the U.S. Energy Information Administration; and (2) expected water shortages from the U.S. Geological Survey and National Oceanic and Atmospheric

No	Title	Year	Contact Information	Source (URL, etc.)	Study Area	Brief Description
						Administration, to identify the most likely locations of severe water shortages caused by increased thermoelectric capacity.
17	Preventing National Electricity-Water Crisis Areas in the United States		Benjamin K.Sovacool Energy Governance Program, Centre on Asia and Globalisation, Lee Kuan Yew School of Public Policy, National University of Singapore, Singapore	http://aquadoc.typepad.com/files/sovacool-and-sovacool-water-columbia.pdf	U.S.	The article is similar to reference 16; it deals with population growth, rising electricity demand, and drought.
18	Consumptive Water Use for U.S. Power Production	2003	Torcellini, P. National Renewable Energy Laboratory	http://www.nrel.gov/docs/fy04osti/33905.pdf	U.S.	Studies water consumption by thermoelectric and hydroelectric power plants through evaporation during cooling and reservoir storage, respectively.
19	Energy Down the Drain: The Hidden Costs of California's Water Supply	2004	Ronnie Cohen, Gary WolffNatural Resources Defense Council;Pacific Institute, Oakland, California	http://www.nrdc.org/water/conservation/edrain/edrain.pdf	Western U.S.	Demonstrates the importance of integrating energy use into water planning to avoid high costs for consumers and wasteful water-supply decisions. Authors included analysis of drought impact on hydropower in the region. In the Colorado River's lower basin, a 10 percent decrease in runoff reduces hydropower production by 36 percent.
20	Energy and Water Sector Policy Strategies for Drought Mitigation	2009	Andjelka Kelic Sandia National Laboratories, Albuquerque, New Mexico	http://prod.sandia.gov/techlib/access-control.cgi/2009/091360.pdf	U.S.	This report discusses prior work on the interdependencies between energy and water. It identifies the types of power plants that are most likely to be susceptible to water shortages, the regions of the country where this is most likely to occur, and policy options that can be applied in both the energy and water sectors to address the issue.

No	Title	Year	Contact Information	Source (URL, etc.)	Study Area	Brief Description
21	Program on Technology Innovation: Water Resources for Thermoelectric Power Generation. Produced Water Resources, Wet-Surface Air Cooling, and WARMF Decision Support Framework		C. McGowin Electric Power Research Institute, Hillview Avenue, Palo Alto, CA	http://my.epri.com/portal/server.pt?Abstract_id=000000000001014487	Southwest	Assesses the use of produced water (in terms of volume and quality), a byproduct of oil and gas production, as a supplemental supply for the San Juan Generating Station (SJGS). Evaluates the infrastructure that would be needed to deliver it to SJGS and to treat it for plant use, the economics of delivery and treatment, and alternative drought management plans. The authors have adapted a deterministic watershed model to forecast the impact of climate change on river hydrology in the San Juan Basin.
22	Framework to Evaluate Water Demands and Availability for Electrical Power Production Within Watersheds Across the United States: Development and Applications	2005	R. Goldstein Electric Power Research Institute, Palo Alto, CA	http://my.epri.com/portal/server.pt?Abstract_id=000000000001010116	U.S.	The authors developed a framework to evaluate the water resources available to sustain present and projected electrical power production and applied it to four case studies around the United States, which vary in climatic conditions, water availability, and the mixture of thermoelectric and hydroelectric power plants. Those case studies are the Lower Coosa River Basin (AL), the Muskingum River Basin (OH), the San Juan River Basin (CO, UT, AZ, NM), and the Platte River Basin (NE, CO, WY).
23	The Electric Power Industry and Climate Change: Issues and Research Possibilities	2007	Judith Cardell Smith College, Northampton, MA (p) (413) 585-7000 (f) (413) 585-7001 Email: jcardell@smith.edu.	http://www.science.smith.edu/~jcardell/Courses/EGR325/Readings/CC.pdf	U.S.	Summarizes issues and research opportunities related to global climate change for the electric power industry. The authors have considered the following issues: (1) power infrastructure response to extreme weather events; (2) impact on system operating strategies, configuration, and expansion plans; (3) effects of an expanded use of renewable and alternative energy technologies; and (4) impacts of market rules and policy mandates on power system operation.

No	Title	Year	Contact Information	Source (URL, etc.)	Study Area	Brief Description
24	Water Dependency of Energy Production and Power Generation Systems	2009	Tamim Younos Virginia Polytechnic Institute and State University, Blacksburg, VA	http://www.nirs.org/reactorwatch/water/sr46waterdependency.pdf	U.S.	Shows dependency of energy production technologies (such as coal, natural gas, petroleum oil, ethanol, diesel, coal gasification, and tar sands) and power generation systems on water availability. Power generation technologies considered include hydroelectric, fossil-fueled thermoelectric, nuclear, geothermal, solar thermoelectric and hydrogen.
25	The Energy-Water Nexus in Texas	2011	Ashlynn S. Stillwell Department of Civil, Architectural, and Environmental Engineering, The University of Texas at Austin	http://www.ecologyandsociety.org/vol16/iss1/art2/	Texas	Examines the water requirements for various types of electricity generating facilities, for typical systems both nationwide and in Texas. The authors compared national average energy requirements of water supply and wastewater treatment systems with Texas-specific values. They recommend site-specific data for a full understanding of the nature of the energy-water nexus and the sustainability of economic growth in Texas. Texas should increase efforts to collect accurate data on the withdrawal and consumption of cooling and process water at power plants, as well as data on electricity consumption for public water supply and wastewater treatment plants and distribution systems.
26	Evaluation of the Sustainability of Water Withdrawals in the United States, 1995 to 2025	2005	Sujoy B. Roy Tetra Tech, Inc., Lafayette, CA	http://onlinelibrary.wiley.com/doi/10.1111/j.1752-1688.2005.tb03787.x/pdf	U.S.	Uses estimates of growth in population and electricity generation to estimate the change in water withdrawals, assuming that the rates of water use either remain at their current levels (the business-as-usual scenario) or exhibit improvements in efficiency at the same rate as observed over 1975 to 1995 (the improved-efficiency scenario). The estimates show several areas, notably the Southwest and major metropolitan areas throughout the United States, as being likely to have significant new storage requirements with the business-as-usual scenario, under the condition of average water

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						availability. These new requirements could be substantially eliminated under the improved-efficiency scenario, thus indicating the importance of water use efficiency in meeting future requirements. The national assessment identified regions of potential water sustainability concern; these regions can be the subject of more targeted data collection and analyses in the future.
27	A Survey of Water Use and Sustainability in the United States with a Focus on Power Generation	2003	S. Roy Electric Power Research Institute, Palo Alto, CA	http://my.epri.com/portal/server.pt?Abstract_id=000000000001005474	U.S.	The report takes a first step toward development of a comprehensive framework for evaluating possible impacts of water supply limitations on electric power generation and management approaches to limiting these impacts. Information provided will be of particular value to power generation and delivery managers and planners, as well as government energy and water resource managers and regulators.
28	Water Vulnerabilities for Existing Coal-fired Power Plants	2010	Barbara Carney National Energy Technology Laboratory	http://www.ipd.anl.gov/anlpubs/2010/08/67687.pdf	U.S.	This study identified coal-fired power plants that are considered vulnerable to water demand and supply issues by using 18 indicators of water demand and supply simultaneously in a geographical information system (GIS) for more than 500 plants in the NETL's Coal Power Plant Database (CPPDB). Two types of demand indicators were evaluated. The first type consisted of geographical areas where specific conditions can generate demand vulnerabilities. These conditions include high projected future water consumption by thermoelectric power plants, high projected future water consumption by all users, high rates of water withdrawal per square mile, high projected population increases, and areas projected to be in a water crisis or conflict by

No	Title	Year	Contact Information	Source (URL, etc.)	Study Area	Brief Description
						2025. The second type of demand indicator was plant-specific. These indicators were developed for each plant and include annual water consumption and withdrawal rates and intensities, net annual power generation, and carbon dioxide emissions. The supply indicators, which are also area-based, include areas with low precipitation, high temperatures, low streamflow, and drought.
29	Cooling Water Issues and Opportunities at U.S. Nuclear Power Plants		Gary Vine Idaho National Laboratory, Idaho Falls, ID	http://www.inl.gov/technicalpublications/Documents/4731807.pdf	U.S.	Provides a status report on the challenges and opportunities facing the U.S. commercial nuclear energy industry in the area of plant-cooling water supply. Also provides a number of policy recommendations.
30	Incorporating Parameter and Data Uncertainties in the Analysis of Energy Drought	2008	Bertuğ Akintuğ Department of Civil Engineering, Middle East Technical University, Turkey Email: bertug@metu.edu.tr	ASCE Conf. Proc. DOI:10.1061/40976(316)565	Canada	Integrates and quantifies uncertainty associated with parameters and extended data in the frequency analysis of energy drought for Manitoba Hydro, Manitoba, Canada. In the frequency analysis, a multivariate Markov-Switching model is employed in the modeling of annual streamflow data. Parameter uncertainty is then incorporated in the Markov-Switching model through Bayesian inference.
31	Estimates of the Long-Term U.S. Economic Impacts of Global Climate Change-Induced Drought	2010	Drake Warren Sandia National Laboratories	http://www.osti.gov/bridge/product.biblio.jsp?query_id=0&page=0&osti_id=984152&Row=0	U.S.	This study examines the economic impact of estimated changes to precipitation in the U.S. between 2010 and 2050 due to climate change. It includes impacts on both thermoelectric and hydroelectric generation. For thermoelectric, economic impacts are based upon cost of conversion to dry cooling systems and associated efficiency losses. Hydroelectric impacts are related to replacement of lost power production

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32	Electricity Impacts of the Drought	2005	State of Washington Department of Community, Trade, and Economic Development, Energy Policy Division	http://www.commerce.wa.gov/_cted/documents/ID_2015_Publications.pdf	Washington State	The document is a memo that describes the impact of drought in 2005 on electricity production and associated economic impacts. The report mentions congested transmission as a challenge for matching load with demand. Hydro power was significantly impacted, but not outside of normal planning parameters. A 5% increase in electricity costs was anticipated
33	Ex Post Power Economic Analysis of Record of Decision Operational Restrictions at Glen Canyon Dam	2010	T.D. Veselka Argonne National Laboratory	http://www.ipd.anl.gov/anlpubs/2010/04/66655.pdf	Arizona	The study evaluates the economic impact of operating criteria defined in 1996 and compares it to the estimates made at the time of the decision. The report provides significant details of the power plant characteristics and operating history.
34	Effects of the Drought on California Electricity Supply and Demand	1977	Peter Benenson Lawrence Berkeley National Laboratory	http://escholarship.org/uc/item/3646z72g	California	The study looks at the drought that took place in the west and California in particular over 1976 and 1977. This drought was the most severe on record at the time. The report looks at the actual impacts on electricity supply and demand and evaluates remedial actions. While the paper is over 30 years old, it represents a direct account of a major drought and its impact on electricity production. The drought was not found to have a significant impact on peak electricity demand. There was significant impact on hydropower, which impacted supply margin and was a risk to reliability. At the time of the study, air conditioning wasn't as prevalent. Most California thermoelectric plants were along the coast and used once-through cooling, so there was minimal impact on generation availability.

No	Title	Year	Contact Information	Source (URL, etc.)	Study Area	Brief Description
35	Potential Eelectricity Impacts from a 1978 California Drought	1978	Jayant Scathaye Lawrence Berkeley National Laboratory	http://escholarship.org/uc/item/2x0723gs	California	Expands on the work from the previous year in the report "Effects of the Drought on California Electricity Supply and Demand." It includes data for the rest of 1977 and considers the impacts if the drought were to continue into 1978. Electricity demand in 1977 actually declined in some areas, contrary to previous estimates. Summer temperatures were relatively mild in 1977, helping to keep demand lower than anticipated. Electricity supply for 1978 was anticipated to be sufficient, but prices would rise due to increased oil consumption for thermoelectric production and there would be potential reliability risk. The appendix contains graphs and tables showing changes in precipitation in different areas of the state.
36	Project/Program Briefing Paper: Improving the Coordination of Federal Climate and Water Resource Science Efforts (with a Focus on the Colorado River)	2009	Hoyt Battey U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy Email: hoyt.battey@ee.doe.gov	http://wwa.colorado.edu/climate_change/docs/DOE_hydropower.doc	Colorado River	The briefing described the Statement of Work, leading agency partners, end-products, and end users for the project "Climate Change Effects on Federal Hydropower Projects" under Section 9505. A report to congress was expected in April 2011 and the project was to be completed in June 2011.
37	DOE Study of Hydropower Impacts under Section 9505: Report to Congress	2011	Mike Sale Oak Ridge National Laboratory Email: mike@frozenhead.net	Link not found yet		

A.5 Effects on Electricity Demand

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
1	High Temperatures & Electricity Demand: An Assessment of Supply Adequacy in California, Trends & Outlook.	1999	California Energy Commission Staff	http://www.energy.ca.gov/reports/1999-07-23_HEAT_RPT.PDF	California and WECC	When hot temperatures prevailed across California, in 1998, two of the three regions of the Western Systems Coordinating Council (WSCC), the Pacific Northwest and the Desert Southwest, also experienced high temperatures. There is also a strong correlation between the timing of peak demand in California and the peak demand for the entire WSCC. Using historical temperature and demand data for 67 utility service areas within the WSCC, two high-temperature forecasts of electricity demand in the WSCC for the summer of 1999 were derived. One forecast assumed temperature conditions corresponding to a 1-in-40 year probability, (i.e., similar to the temperature conditions that occurred in 1998). The other forecast assumed temperature conditions corresponding to a 1-in-5 year probability. The paper provides estimates for increase in peak demand (MW) for each of 17 transmission areas.	Report
2	Relating residential and commercial sector electricity loads to climate – evaluating state level sensitivities and vulnerabilities.	2001	David J. Sailor Department of Mechanical Engineering, 400 Lindy Boggs Center, Tulane University, New Orleans, LA 70118,	http://www.sciencedirect.com/science/article/pii/S0360544201000238	California, Florida, Illinois, Texas, Louisiana, New York, Ohio, Washington	• Developed predictive models for monthly residential and commercial per capita electricity consumption, looking at climate variables • Applied model to eight states (including TX, CA, WA). • Model input includes CDD, HDD, wind speed and enthalpy latent days	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
			U.S.A.			(ELD), which relate to humidity and reflect the effect of humidity on summer AC demand. • The coefficients for CDD for the states included in the present study (CA, TX and WA) are quite different; the coefficients for the residential sector monthly per capita electricity consumption are 0.287 for CA, 0.591 for WA, and 1.057 for TX (the range for all eight states is 0.270 to 1.177). • Reports percent change in monthly per capita electricity consumption from 1, 2 and 3°C increases in temperature. • Note: the study included two neighboring states, TX and LA. The author provides this comment: "The results indicate significantly different sensitivities for neighboring states, suggesting the inability to generalize results." • The results of this 2001 study could potentially be used for the WGA drought study. We would need mean daily temperatures for each state in order to utilize these authors' electricity consumption model. We would then need to assume that the coefficients for WA also applied to neighboring Pacific NW areas, and that the coefficients for CA applied to most of the WECC transmission areas (although that contradicts one of the key conclusions of Sailor 2001).	

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
3	Weather Effects on Electricity Loads: Modeling and Forecasting	2005	Christian Crowley and Frederick L. Joutz Research Program on Forecasting, Department of Economics, The George Washington University	http://www.ce.jhu.edu/epastar2000/epawebsrc/joutz/Final%20Report%20EPA%20Weather%20Effects%20on%20Electricity%20Loads.pdf	Pennsylvania-New Jersey-Maryland (PJM) Independent System Operating (ISO); PJM ISO is the mid-Atlantic council region of the North American Electric Reliability Council	• Estimated impact of higher temperatures on electricity consumption, using hourly and annual data from PJM ISO and additional data from ECAR and SERC. • Scenarios: impact of a uniform 2°F increase in temp. Short-run and long-run models were used. Long-run model was NEMS. Looked at two seasons: summer and winter. • Short-run: a 2°F increase in temperature for July and August 2000 resulted in a 4.6% increase in electricity demand for the region. Hourly models range from 2% to 6.9% above baseline (neural network) or a 2.1% - 6.3% increase for the OLS forecast. • Long-run: NEMS, using a scenario comprised of five warmest summers, which equaled a 2.09°F increase in CDDs. Average load demand was 2.7% higher in summer months and peak demand was 5.4% higher. • "A fairly standard set of thresholds are temperatures above 72 degrees Fahrenheit and below 65 degrees Fahrenheit" for degree-days.	Report
4	Sensitivity of electricity and natural gas consumption to climate	1997	David J. Sailor and J. Ricardo Muñoz Department of Mechanical Engineering, Tulane University, New Orleans, LA 70118, U.S.A.	http://www.sciencedirect.com/science/article/pii/S0360544297000340	California, Florida, Illinois, Texas, Louisiana, New York, Ohio, Washington	• Used primitive weather variables (temperature) versus derived variables (degree-days): "The degree-day approach is best for electricity and the primitive variable is best for natural gas." • One limitation of any "national or large-scale regional analysis of climate influences on the energy sector" is that	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
						there can be substantial differences between neighboring states; this was shown in the model coefficients for LA and TX in this study. • "The hottest (southern) states have a higher temperature sensitivity than the cooler (northern) states…in a relatively cool climate, a slight increase in temperature will not significantly impact summertime electricity consumption."	
5	Energy and Water Use in Irrigated Agriculture During Drought Conditions	1978	Ronald L. Ritschard and Karen Tsao Energy Analysis Program, Energy and Environment Division, Lawrence Berkeley Laboratory	http://escholarship.org/uc/item/3fb876g0	California	During the 1976-1977 drought, PG&E's summer electricity sales to agriculture increased 15% from 1975 to 1976, then another 15% from 1976 to 1977. But water conservation activities (typically applied during a drought) can reduce electricity demand by as much as 25%.	Report
6	Electricity Use in California: Past Trends and Present Usage Patterns	2002	Richard E. Brown and Jonathan G. Koomey Energy Analysis Department, Environmental Energy Technologies Division, Ernest Orlando Lawrence Berkeley National Laboratory, University of California	http://enduse.lbl.gov/info/LBNL-47992.pdf	California	Extreme summer weather can cause up to a 5–8% increase in peak load compared to a typical year.	Journal Article
7	Electricity load and temperature: Issues in dynamic specification	1994	John Peirson and Andrew Henley Kent Energy Economics Research Group and Department of	http://www.sciencedirect.com/science/article/pii/0140988394900213	UK	Paper discusses the dynamic specification of the relationship between temperature and load; it shows that the relationship has a dynamic component, and ignoring the dynamic component can lead to bias.	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
			Economics, University of Kent at Canterbury, Canterbury, Kent CT2 7NP, UK.				
8	Analyzing the Impact of Weather Variables on Monthly Electricity Demand	2005	C.-L. Hor, S.J. Watson, and S. Majithia Centre for Renewable Energy Systems Technology, Loughborough Univ., UK	http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1525139&tag=1	UK	• Proposed a multiple-regression forecasting model that includes climate and socio-economic factors for assessing long-term monthly electricity patterns by using long-term estimates of climate parameters. • Found that degree-day parameterization of temperature performed better than a model using a simple temperature variable.	Conference Paper
9	Regional Energy Demand Responses to Climate Change: Methodology and Application to the Commonwealth of Massachusetts	2005	Anthony D. Amato[1], Matthias Ruth[1], Paul Kirshen[2] and James Horwitz[3] [1]Environmental Policy Program, School of Public Policy, University of Maryland E-mail: mruth1@umd.edu [2] Department of Civil and Environmental Engineering, Tufts University [3]Climatological Database Consultant, Binary Systems Software, Newton, MA	http://www.springerlink.com/content/h4u856n1107nk834/fulltext.pdf	Massachusetts	Evaluated historic temperature sensitivity of residential and commercial energy demand for Massachusetts; found that degree-day variables have "significant explanatory power in describing historic changes in residential and commercial energy demands." Authors argue that for policy analyses, energy demand sensitivities to climate and climate change should be performed at the regional scale.	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
10	Effects of Climate Change on Energy Production and Use in the U.S.	2008	Thomas J. Wilbanks, Oak Ridge National Laboratory, Coordinator Vatsal Bhatt, Brookhaven National Laboratory Daniel E. Bilello, National Renewable Energy Laboratory Stanley R. Bull, National Renewable Energy Laboratory James Ekmann, National Energy Technology Laboratory William C. Horak, Brookhaven National Laboratory Y. Joe Huang, Lawrence Berkeley National Laboratory Mark D. Levine, Lawrence Berkeley National Laboratory Michael J. Sale, Oak Ridge National Laboratory	http://www.climatescience.gov/Library/sap/sap4-5/final-report/sap4-5-final-all.pdf	U.S.	Authors reviewed existing studies.• Electricity demand for cooling was projected to increase by roughly 5% to 10% per 1°C temperature increase in the national studies surveyed. • One cited study projected annual cooling-energy consumption to increase by roughly 12% to 20% per 1°C. • Commercial-sector studies show that the percentage increases in space-cooling energy consumption tend to be less sensitive to temperature than are the corresponding energy increases in the residential sector. • Analyses performed with building energy models generally indicate a 10% to 15% electric energy increase for cooling per 1°C.	Report

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
			David K. Schmalzer, Argonne National Laboratory Michael J. Scott, Pacific Northwest National Laboratory				
11	Climate Change Impacts on Residential and Commercial Loads in the Western U.S. Grid.	2008	N. Lu, L.R. Leung, P.C. Wong, M. Paget, Z.T. Taylor, J. Correia, Jr., P.S. Mackey, W. Jiang, Y. Xi, Pacific Northwest National Laboratory	http://www.pnl.gov/main/publications/external/technical_reports/PNNL-17826.pdf	Western U.S.	"Using the IPCC A1B climate change scenarios and the DOE-2 energy building simulation program, this study shows that by mid-century, building yearly energy consumption and the peak load will increase in the Southwest (Phoenix, Salt Lake City, and Boulder). Moreover, the peak load months will spread out to not only the summer months but also spring and autumn months. The Pacific Northwest (Portland, Vancouver, Calgary, and Billings) will be hotter in the summer months. As a result, the penetration and use of a/c systems in the Pacific Northwest is likely to increase significantly over the years. Consequently, some locations that traditionally supply only a small fraction of cooling load in summer months may shift from winter peaking to summer peaking because of the reduction of heating load and increase in cooling load. Overall, the Western U.S. grid may see more simultaneous peaks across the North and South in the summer months." • The dominant weather-sensitive building loads are heating and cooling.	Report

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
						• Cooling load increases significantly when temperatures rise above 85°F. • Cooling loads are well correlated with temperature changes. • Peak hourly electricity usage correlates well with temperature. • For the coastal cities in California, because of the marine influence (cloudiness), the temperature-building energy consumption correlations are not well established. • Portland will experience more load increase in summer months. • Average building energy consumption will increase based on IPCC-predicted temperature profiles for 2050.	
12	A Discrete-Continuous Choice Model of Climate Change Impacts on Energy	2005	Erin T. Mansur ,Yale University School of Management and School of Forestry and Environmental Studies, New Haven, CT Robert Mendelsohn Edwin Weyerhaeuser, Yale University School of Forestry and Environmental Studies, New Haven, CT Wendy Morrison, Texas A&M University El Paso Agricultural Research Center	http://environment.yale.edu/files/biblio/YaleFES-00000219.pdf	U.S.	• When July temperatures are increased by 1°C (relative to a mean of 24°C), electricity consumption increases substantially for all pipeable customers: electricity-only customers increase their consumption by 5%. • Authors define the marginal impact of climate change to be a 1°C increase in temperature, which is approximately an 8% increase in average temperature, and a 7% increase in precipitation.	Report

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
13	Air conditioning market saturation and long-term response of residential cooling energy demand to climate change.	2003	David J. Sailor and A. A. Pavlova Department of Mechanical Engineering, Tulane University, New Orleans, LA 70118, U.S.A.	http://www.sciencedirect.com/science/article/pii/S0360544203000331	Ohio, Texas, California, New York	Abstract: "Existing state-level models relating climate parameters to residential electricity consumption indicate a nominal sensitivity of 2–4% for each degree Celsius increase in ambient temperatures. Long-term climate change will also impact electricity consumption through corresponding increases in the market saturation of air conditioning. In this paper we use air conditioning market saturation data for 39 U.S. cities to develop a generalized functional relationship between market saturation and cooling degree days. The slope of this saturation curve is particularly high for cities that currently have low to moderate saturation. As a result, the total response of per capita electricity consumption to long-term warming may be much higher than previously thought. A detailed analysis of 12 cities in four states shows that for some cities changes in market saturation may be two to three times more important than the role of weather sensitivity of current loads."	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
14	Future U.S. Energy Use for 2000–2025 as Computed with Temperatures from a Global Climate Prediction Model and Energy Demand Model	Un-known	Stanton W. Hadley, David J. Erickson III and Jose Luis Hernandez, Oak Ridge National Laboratory S. L. Thompson, Lawrence Livermore National Laboratory	http://www.csm.ornl.gov/~fj7/USAEE_paper.pdf	U.S.	"While cooling needs increase energy use, heating needs reduce the amount. Since cooling (using electricity) is more inefficient than heating, the increase in primary energy use is amplified. Over time, the increase in cooling outweighs the decrease in heating leading to an overall increase. The variety of energy sources used for these services, the regional variation in energy requirements, and the market impacts on other energy consumption all combine to complicate the calculation of the net impact on the U.S. A trend of increased net energy use, cost, and carbon emissions are observed. Other economic changes such as prices may mitigate the increase, but with concomitant change to economic growth. Regional analysis shows a much larger impact in the southern regions of the U.S., while some northern regions have energy and cost savings."	Report
16	Impacts of Climate Change on Global Electricity Production and Consumption: Recent Literature and a Useful Case Study from California.		Jayant Sathaye Lawrence Berkeley National Laboratory	http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0566-121.pdf/$file/EE-0566-121.pdf	Global	Abstract: "The study finds that higher temperatures will decrease the capacity of existing natural gas fired power plants to generate electricity during particularly hot periods in the future. The estimated decrease in capacity varies by region, emission scenario, climate model, and plant type. During the hottest periods in August (at the end of the century) and under the high emission scenario (A2), our models estimate a decrease in simple cycle natural gas power plants generating	Report

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
						capacity of3%-6% in California and 3%-4% in the San Francisco region. Under similar conditions, our models suggest diminished transformer and substation capability—between 2 and 4% across California and between 2 and 3% in the San Francisco region with a small increase in transmission line carrying capacity."	
17	Impacts of Climate Change on Residential Electricity Consumption: Evidence from Billing Data	2009	Anin Aroonruengsawat and Maximilian Auffhammer California Climate Change Center	http://www.energy.ca.gov/2009publications/CEC-500-2009-018/CEC-500-2009-018-D.PDF	California	Provides estimates of California's residential electricity demand under climate change based on a large set of panel micro-data. Results suggest much larger effects of climate change on electricity demand than previous studies, largely due to the highly non-linear response of demand at higher temperatures. Temperature response varies greatly across the climate zones in California—from flat to U-shaped to hockey stick shaped, suggesting that aggregating data over the entire state may ignore important nonlinearities, which combined with heterogeneous climate changes across the state may lead to underestimates of future electricity demand. Notably, population uncertainty leads to larger uncertainty over demand than uncertainty over climate change.	Report

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
18	Climate Change and Electricity Demand in California	2006	Guido Franco and Alan H. Sansta California Climate Change Center	http://www.energy.ca.gov/2005publications/CEC-500-2005-201/CEC-500-2005-201-SF.PDF	California	"This paper aims only to obtain simple, first-order estimates to illustrate the potential implications for electricity consumption and demand of the new regional climate projections described above. For this purpose, we apply these projections to data on the historical and current configuration and operation of the regional electric power system, and, implicitly, current demographics. In other words, we imagine the newly projected temperature increases in the coming century imposed on our current system, assuming the underlying relationships between temperature and consumption and maximum temperature and peak demand remain invariant."	Report
19	Climate, Extreme Heat, and Electricity Demand in California.	2008	Norman L. Miller, Earth Sciences Division, Lawrence Berkeley National Laboratory, University of California Katharine Hayhoe, Department of Geosciences, Texas Tech University, Lubbock, Texas Jiming Jin, Earth Sciences Division, Lawrence Berkeley National Laboratory, University of California	http://journals.ametsoc.org/doi/pdf/10.1175/2007JAMC1480.1	California	When the projected extreme heat and observed relationships between high temperature and electricity demand for California are mapped onto current availability, maintaining technology and population constant for demand-side calculations, a potential for electricity deficits as high as 17% during T90 peak electricity demand periods is found. Similar increases in extreme-heat days are likely for other southwestern U.S. areas. All indicators point to increases in summer electricity demand in California, even when confounding factors such as increased population and market saturation of air conditioning are disregarded.	Journal Article

No	Title	Year	Contact Information	Source (URL, etc.)	Geographic Area	Brief Description	Document Type
			Maximilian Auffhammer Agricultural and Resource Economics Department, University of California - Berkeley				

Appendix B Regional Drought Information: Areal Extents of Severe Droughts using PDSI and Annual Stream Flow Records

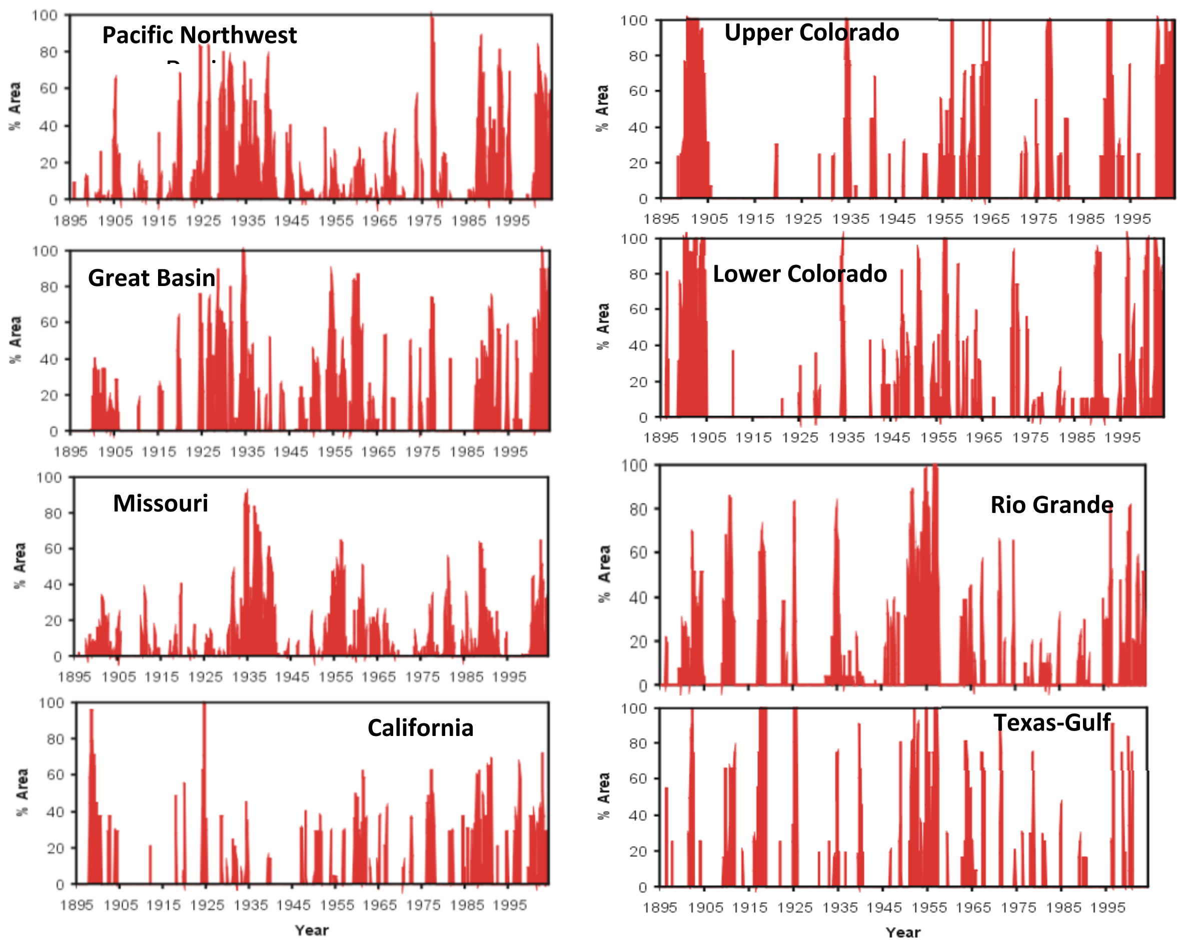

Figure B.1 Regional drought patterns (severity, duration, and frequency) over the period of 1895-2004. Drought aerial percentage of the region is calculated using area of PDSI < -3 in each region. Source: National Drought Mitigation Center.

Table B.1 Regional streamflow data in 1901-2009 (annual million acre feet [MAF]).

	HUC-2 Basin							
Year	Texas (MAF)	Rio Grande (MAF)	Upper Colorado (MAF)	Lower Colorado (MAF)	Great Basin (MAF)	Pacific Northwest (MAF)	California (MAF)	Missouri (MAF)
1901	7.29	5.12	34.42	2.00	10.57	205.26	139.91	79.84
1902	9.32	2.48	22.22	1.21	5.72	184.29	149.72	74.91
1903	8.67	7.32	34.90	6.56	8.43	216.80	150.98	83.17
1904	10.19	1.31	36.92	1.06	14.32	232.76	252.57	86.50
1905	37.84	19.30	23.86	21.12	6.10	131.32	137.03	69.97
1906	25.89	6.52	24.19	11.44	15.25	153.99	193.29	69.22
1907	13.82	7.55	26.36	18.36	27.78	238.18	244.14	116.44
1908	27.95	4.87	14.68	9.74	10.63	199.14	103.15	114.19
1909	4.58	32.47	27.46	17.06	21.29	198.09	222.37	103.78
1910	5.61	10.56	15.85	9.41	47.79	232.94	141.67	77.16
1911	6.03	14.51	21.38	10.36	27.45	189.18	184.59	92.29
1912	6.34	17.66	32.75	10.27	13.04	202.35	108.87	106.78
1913	6.61	7.44	21.86	6.09	8.84	208.00	107.58	122.56
1914	32.00	11.59	35.75	7.06	19.06	164.07	194.81	88.97
1915	21.73	9.97	20.14	15.36	9.95	121.54	153.85	85.32
1916	11.68	13.76	28.53	16.45	12.95	211.79	169.39	99.91
1917	3.21	7.52	37.35	10.97	17.36	186.44	121.83	108.28
1918	4.05	3.40	26.79	6.88	8.25	185.86	77.69	55.27
1919	27.72	8.63	18.45	8.24	8.81	150.78	103.04	43.14
1920	30.97	12.67	32.11	13.83	9.08	134.94	63.23	50.22
1921	14.32	9.27	33.30	10.06	14.74	203.69	149.35	49.26
1922	27.26	5.82	17.11	7.53	17.57	165.12	118.38	48.72
1923	15.62	3.40	17.07	7.59	17.93	165.29	87.54	64.28
1924	32.34	5.01	13.11	6.74	9.17	129.75	33.55	65.36
1925	6.68	2.92	11.89	4.85	9.65	205.96	99.29	57.74
1926	28.94	7.27	14.71	7.03	8.13	119.09	66.25	43.36
1927	22.30	8.94	17.40	7.65	12.89	199.43	133.44	76.09
1928	14.01	7.13	16.09	5.12	14.62	218.60	87.84	57.09
1929	23.98	7.94	20.19	6.33	12.80	132.08	49.80	83.92
1930	19.40	6.46	13.73	3.88	10.06	131.21	58.77	40.67
1931	20.01	4.71	6.70	3.06	4.85	120.37	30.26	27.15
1932	36.20	9.89	16.04	6.41	11.70	185.57	76.71	51.73
1933	16.69	5.32	10.23	3.09	10.12	194.60	53.93	37.99
1934	14.05	2.95	4.60	1.56	6.82	197.51	45.77	21.79
1935	35.85	6.46	10.42	3.38	10.93	169.37	89.33	58.70
1936	21.92	5.93	12.56	3.24	11.61	162.90	95.39	30.16
1937	19.32	10.00	12.49	4.68	10.87	134.53	84.02	43.25
1938	30.66	6.07	16.21	3.38	14.53	195.59	173.45	41.53

Table B.1 (Cont.)

	HUC-2 Basin							
Year	Texas (MAF)	Rio Grande (MAF)	Upper Colorado (MAF)	Lower Colorado (MAF)	Great Basin (MAF)	Pacific Northwest (MAF)	California (MAF)	Missouri (MAF)
1939	10.35	3.93	9.84	3.35	9.86	153.58	48.68	38.96
1940	14.32	2.01	7.41	3.18	9.62	149.62	110.15	22.75
1941	51.09	9.55	16.85	7.80	11.43	127.65	139.40	34.77
1942	33.83	10.61	17.90	5.24	24.59	176.89	121.05	76.95
1943	14.74	3.37	11.82	3.32	22.24	233.75	109.41	70.72
1944	26.69	5.01	13.90	3.65	10.51	128.53	50.57	70.51
1945	38.33	4.15	12.13	3.44	11.73	163.89	77.05	80.38
1946	31.27	2.06	9.18	2.50	10.72	212.60	90.72	45.40
1947	26.65	2.92	14.18	2.62	9.29	212.02	51.22	78.88
1948	14.78	4.79	14.37	3.03	9.74	247.79	72.37	58.70
1949	15.92	4.82	15.09	4.09	9.62	207.01	62.42	67.93
1950	25.16	2.73	11.61	2.82	12.09	249.54	68.14	67.61
1951	7.06	1.64	10.32	2.00	12.36	255.31	118.48	102.17
1952	9.13	4.48	18.90	4.77	19.59	220.41	153.52	75.77
1953	17.41	1.92	9.25	3.00	11.43	203.11	103.75	40.57
1954	7.98	1.53	6.41	2.59	7.27	236.37	96.21	29.94
1955	9.81	2.06	7.68	2.44	6.04	195.18	57.51	34.56
1956	6.83	1.48	9.20	1.59	10.75	272.21	151.45	25.76
1957	40.05	4.34	18.21	2.24	9.23	207.36	78.10	34.45
1958	36.73	5.60	14.95	4.12	10.99	201.18	168.14	53.87
1959	14.93	1.95	7.08	2.41	6.64	212.89	67.33	41.85
1960	22.91	2.98	9.65	2.88	6.40	197.51	60.53	58.17
1961	34.25	2.48	6.98	1.62	4.47	197.05	62.52	58.06
1962	15.77	3.45	15.54	2.53	8.81	180.32	68.72	62.24
1963	8.63	1.92	2.62	2.03	8.37	180.67	107.58	32.95
1964	6.41	1.31	2.55	1.74	7.98	199.55	61.07	34.88
1965	20.96	4.07	11.37	2.35	12.12	241.97	122.54	58.70
1966	22.79	3.45	8.27	3.50	9.17	165.35	76.50	43.89
1967	7.52	2.17	8.20	2.03	12.03	193.14	127.96	48.72
1968	31.46	3.15	8.77	3.12	9.68	178.63	70.58	48.62
1969	24.40	3.56	9.27	2.29	18.07	219.88	149.05	78.77
1970	16.76	3.18	9.13	1.79	13.58	180.32	114.76	61.71
1971	7.03	2.03	9.03	1.68	18.25	252.75	113.94	56.77
1972	15.73	1.84	9.80	2.12	15.84	278.91	71.76	52.48
1973	27.07	4.65	10.63	5.41	15.36	153.06	100.78	103.03
1974	24.59	2.23	8.70	1.74	17.42	288.40	162.69	84.03
1975	37.04	3.98	9.73	2.18	15.63	222.74	100.17	64.61
1976	14.39	2.92	8.91	1.74	13.34	256.82	55.21	50.65

Table B.1 (Cont.)

Year	Texas (MAF)	Rio Grande (MAF)	Upper Colorado (MAF)	Lower Colorado (MAF)	Great Basin (MAF)	Pacific Northwest (MAF)	California (MAF)	Missouri (MAF)
	HUC-2 Basin							
1977	22.83	1.36	8.68	1.41	6.73	127.19	27.56	41.53
1978	7.67	2.31	8.80	2.97	10.21	201.94	113.20	71.26
1979	25.47	5.60	8.72	5.71	10.27	170.48	66.45	66.97
1980	14.09	4.73	11.47	6.47	15.36	175.72	122.78	46.25
1981	13.90	1.84	8.75	2.35	10.42	196.64	56.02	48.19
1982	25.81	3.82	8.75	2.09	18.94	251.35	165.26	73.62
1983	16.91	4.76	18.43	6.30	38.11	238.30	222.81	88.22
1984	8.48	4.26	21.57	7.38	38.71	238.41	123.83	93.37
1985	17.33	6.07	20.09	7.12	23.55	183.24	73.97	77.59
1986	21.27	6.43	17.73	4.53	31.00	205.09	119.16	82.21
1987	31.61	7.35	14.13	3.53	16.76	158.71	51.25	93.37
1988	10.16	3.31	8.58	2.77	8.10	145.19	48.34	48.51
1989	22.79	3.04	8.39	1.85	9.47	173.92	62.73	38.10
1990	28.10	2.23	8.70	1.59	7.77	183.99	44.62	57.74
1991	21.99	4.29	8.49	2.62	8.34	211.44	38.69	40.89
1992	60.40	4.60	8.39	3.47	6.55	147.23	39.13	49.37
1993	25.16	5.35	8.56	11.36	13.19	172.17	101.55	133.29
1994	16.57	4.90	8.63	2.09	8.34	138.96	42.18	80.60
1995	36.27	6.24	9.73	4.30	17.75	186.38	148.27	90.58
1996	6.15	2.95	12.04	1.77	18.76	276.23	103.18	72.98
1997	37.57	4.37	14.35	2.24	25.55	294.75	122.85	89.07
1998	23.67	4.15	13.99	3.15	25.43	204.97	155.89	85.75
1999	25.16	3.98	11.75	2.15	21.47	237.01	99.46	99.48
2000	6.61	2.67	9.84	1.74	11.49	194.48	79.89	42.50
2001	29.51	2.79	8.70	2.32	8.10	121.13	44.01	62.46
2002	24.32	1.81	8.77	1.62	8.04	192.79	59.34	46.79
2003	21.27	1.62	8.80	1.88	8.37	170.07	79.72	33.05
2004	22.91	2.37	8.77	1.62	7.89	167.86	70.65	50.33
2005	27.38	4.32	8.82	4.82	15.27	158.59	83.78	53.87
2006	5.96	2.40	8.94	1.91	21.89	214.35	146.68	30.59
2007	39.21	3.09	8.84	1.85	9.95	192.62	51.05	57.95
2008	14.13	3.82	9.65	2.56	9.35	198.44	53.45	84.24
2009	9.28	3.26	8.84	1.77	11.79	182.89	48.51	69.11

Source: USGS WaterWatch website (http://waterwatch.usgs.gov/).

Table B.2 Stream flow correlation among the eight regions over the 109-year period (1901-2009).

Basins	Texas	Rio Grande	U. colorado	L. colorado	Missouri	GreatBasin	California	Pacific
Texas	1	0.216	-0.060	0.094	-0.016	-0.085	-0.187	-0.362
Rio Grande	0.216	1	0.659	0.815	0.398	0.311	0.272	-0.287
U. colorado	-0.060	0.659	1	0.605	0.508	0.404	0.508	0.061
L. colorado	0.094	0.815	0.605	1	0.354	0.289	0.305	-0.281
Missouri	-0.016	0.398	0.508	0.354	1	0.503	0.386	0.226
Great Basin	-0.085	0.311	0.404	0.289	0.503	1	0.605	0.386
California	-0.187	0.272	0.508	0.305	0.386	0.605	1	0.377
Pacific	-0.362	-0.287	0.061	-0.281	0.226	0.386	0.377	1

Table B.3 Stream flow correlation among the eight regions during drought years.

Basins	Texas	Rio Grande	U. colorado	L. colorado	Missouri	GreatBasin	California	Pacific
Texas	1	0.159	-0.101	0.076	-0.210	-0.502	-0.456	-0.568
Rio Grande	0.159	1	0.649	0.870	0.480	0.275	0.183	-0.375
U. colorado	-0.101	0.649	1	0.593	0.657	0.469	0.548	0.009
L. colorado	0.076	0.870	0.593	1	0.399	0.237	0.247	-0.343
Missouri	-0.210	0.480	0.657	0.399	1	0.414	0.326	0.084
Great Basin	-0.502	0.275	0.469	0.237	0.414	1	0.577	0.408
California	-0.456	0.183	0.548	0.247	0.326	0.577	1	0.382
Pacific	-0.568	-0.375	0.009	-0.343	0.084	0.408	0.382	1

Appendix C Power Generation Capacity and Distribution in Eight Major Basins in the Western U.S.

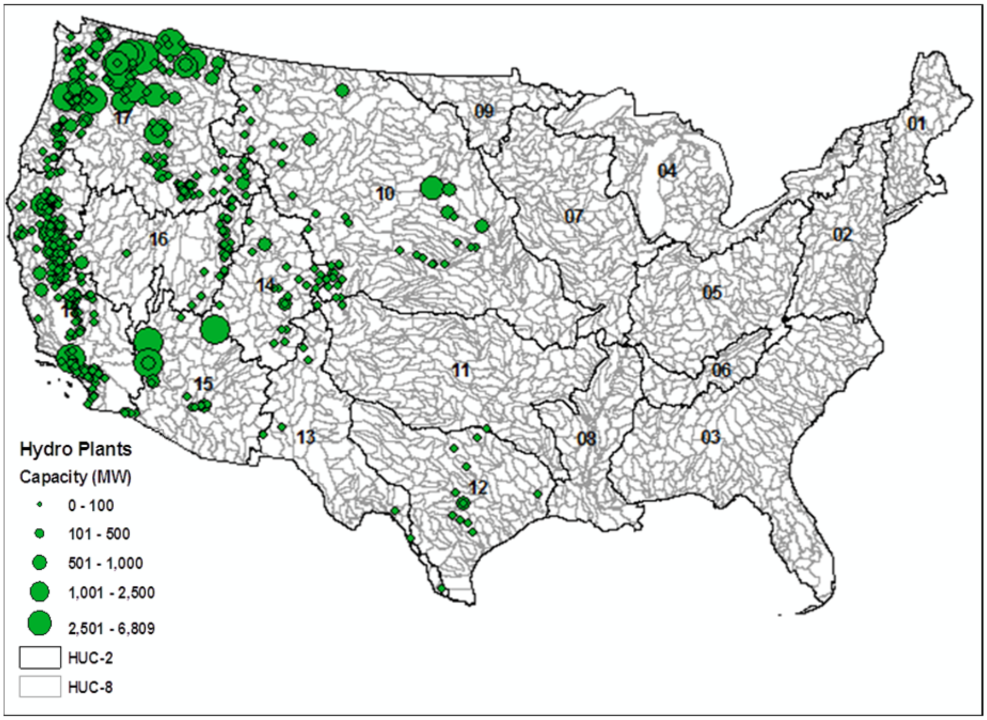

Figure C.1 Distribution of hydroelectric plants and their generation capacities in the western U.S.

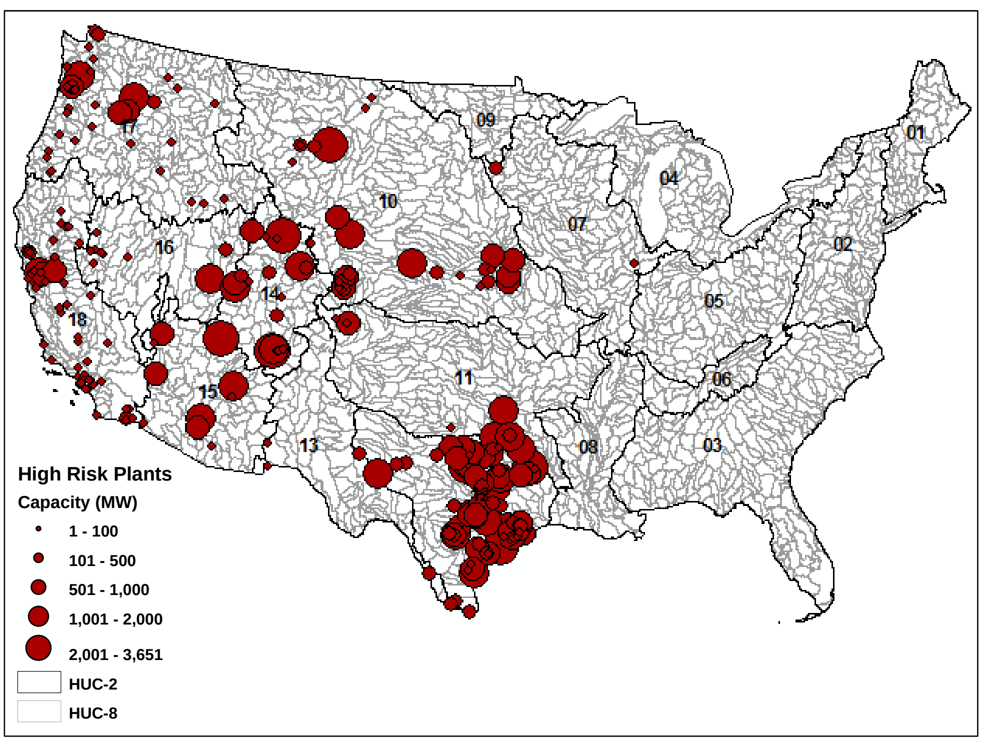

Figure C.2 Distribution of "at-risk" thermoelectric plants and their generation capacities in the western U.S.

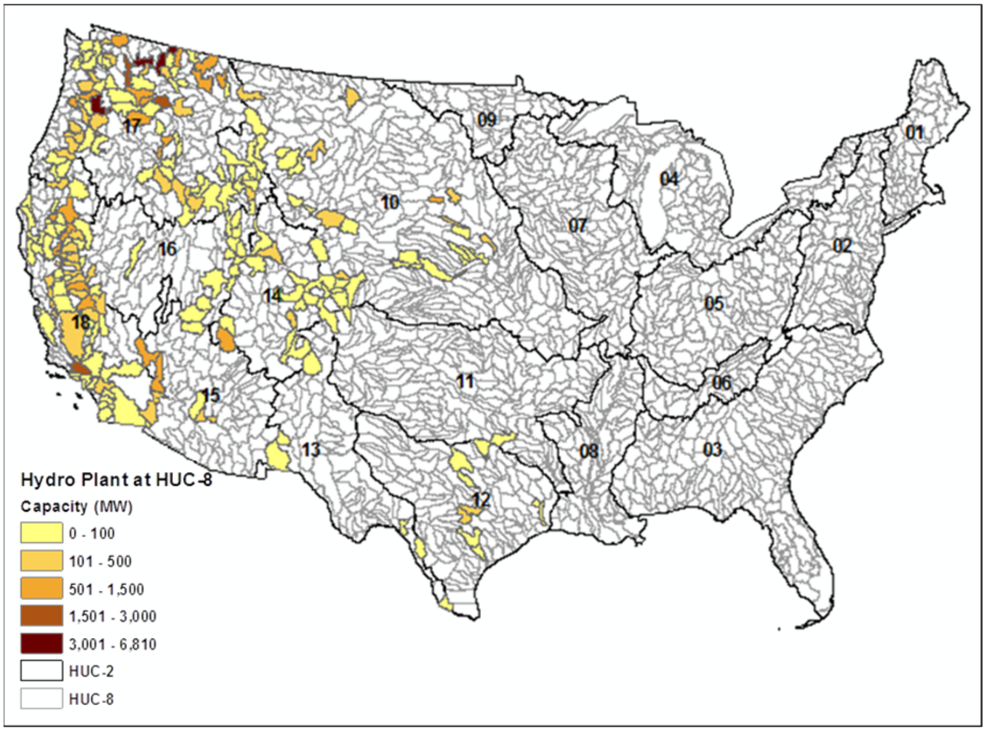

Figure C.3. Distribution and generation capacity of HUC-8 basins with hydroelectric plants in the western U.S.

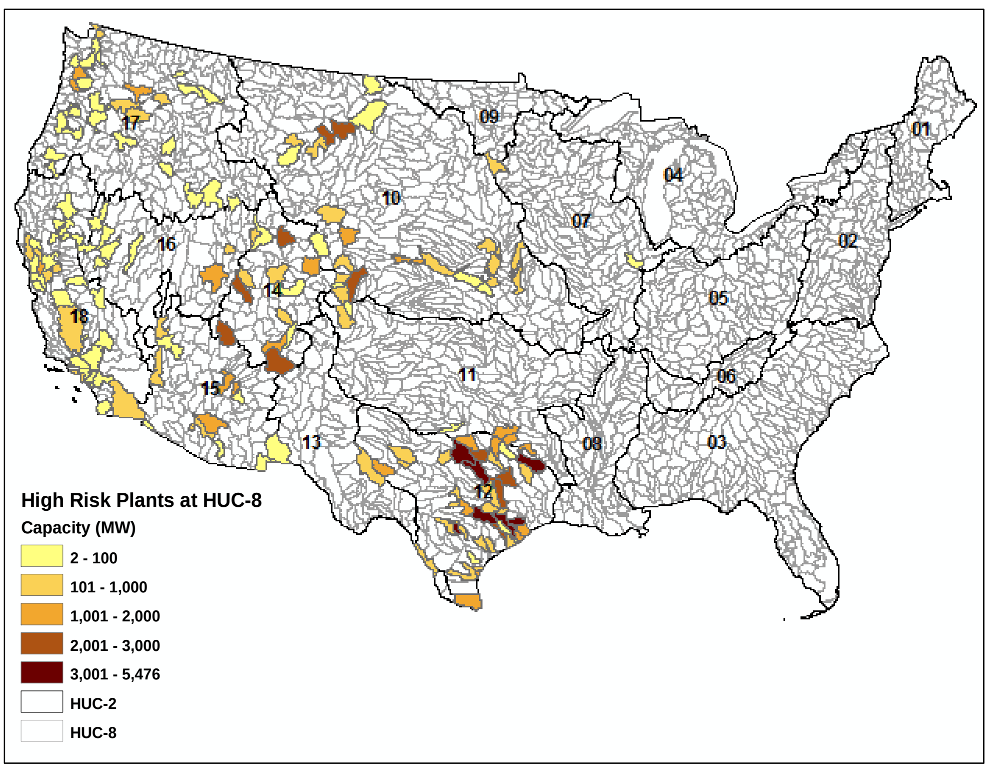

Figure C.4. Distribution and generation capacity of HUC-8 basins with "at risk" thermoelectric plants in the western U.S.