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ScienceDirect
Quaternary International 173–174 (2007) 87–100

Severe and sustained drought in southern California and the West: Present conditions and insights from the past on causes and impacts

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Available online 27 March 2007

Abstract

Southern California and much of the western United States face a chronic challenge of limited water supply due to high potential evaporation and low precipitation coupled with frequent droughts. Mitigation approaches include the use of ground water, reliance on water from river systems fed by mountainous regions that have relatively high precipitation, and the construction of extensive aqueduct and water storage systems. In southern California the present infrastructure is capable of insulating large water districts against the typical annual and multi-annual droughts experienced over the past 100 years. However, paleoclimatic records indicate that the region is also prone to much longer droughts, including a prolonged episode of generally arid conditions and severe droughts extending from the 9th through 14th centuries. This period is sometimes referred to as the medieval climate anomaly. Archaeological evidence suggests that prehistoric populations such as the Anasazi in the Southwest and the Chumash in southern California were impacted by mega-drought conditions during the medieval climate anomaly. These groups appear to have displayed a variety of responses—ranging from increased violence and the abandonment of some regions, to the development of greater cultural complexity and material infrastructure. 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 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 could occur in the future due to natural or anthropogenic causes.

1. Introduction

In 1999 large sections of western North America began to experience a severe and sustained drought. During subsequent years drought conditions extended from northern Mexico, through the Colorado River Basin, and into the western interior of Canada (Fig. 1). In Los Angeles, four of the six water-years from 1998–1999 through 2003–2004 experienced below average rainfall. Rainfall during ‘wet’ years was barely above average. In 2002 annual precipitation in states such as Colorado and Utah had fallen by 40% from 20th century means. The severity of the drought caused decreased flow in major river systems from Canada to the US-Mexico Border. The Colorado River, a major source of water for many regions including southern California, was particularly impacted by the drought. At the Lees Ferry gauging station in Arizona, which lies at the boundary of the upper and lower Colorado basins, flow declined by more than 50% from its 20th century average (Fig. 1). The water levels in critical reservoirs along the Colorado dropped drastically as a result of decreased flow and high rates of evaporation. By 2003 Lake Mead had experienced a drop in reservoir levels of over 18 m and was at about two-thirds capacity. Even more strikingly, Lake Powell, had dropped by approximately 40 m (Fig. 1). Hydrologists, water managers and politicians waited to see if the drought would continue or be broken. Talk of litigation for river water rights had already flared between jurisdictions along the Colorado and in California.

Fortunately, 2005 saw improved conditions over most of the drought area and near record precipitation in southern California. Despite the severity of the drought, mitigation

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doi:10.1016/j.quaint.2007.03.012

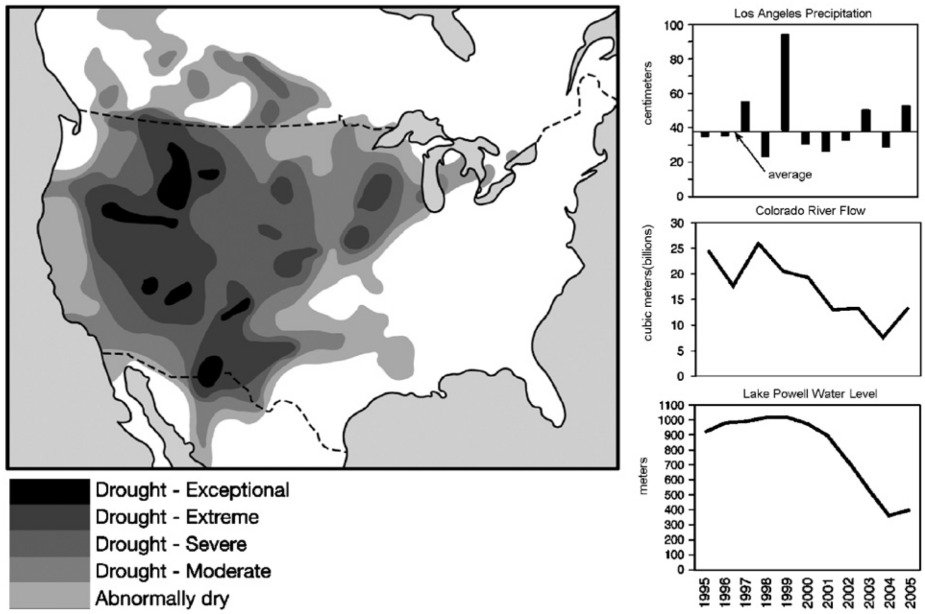

Fig. 1. Map of the extent of North American drought in 2003 (based upon NOAA North American Drought Monitor), Los Angeles water-year precipitation (June–July—data from NOAA), naturalized flow of the Colorado River at Lees Ferry, Arizona and water level of Lake Powell Reservoir (data from the US Bureau of Reclamation).

infrastructures such as the reservoir system on the Colorado River allowed most large water districts to weather the drought relatively well. However, reservoirs such as Lake Mead and Lake Powell remained significantly below full storage capacity (Fig. 2). Astute hydrologists and water managers might consider if this recent drought is really over, or if we are simply experiencing a brief respite in the midst of a longer-term dry spell? Answering that question depends upon understanding the full range of natural variability in drought severity and duration. The answer also hinges upon understanding the climatic forcing factors that produce severe and sustained droughts in western North America. Finally, we might consider what lessons can be gleaned from the past impacts of exceptional droughts on human society in California and the West.

Instrumental records of climate and hydrology in western North America only span the last 100 years or so. They are too short to capture the full range of natural climate variability, drought behavior and drought impact. The instrumental records are also too short to provide evidence on the full range of potential forcing factors that could produce severe and prolonged droughts. The paleoenvironmental archives provided by tree-rings, sedimentary records and other sources allow the extension of hydroclimatic records back in time through centuries and millennia (e.g. Woodhouse and Overpeck, 1998; Cook et al., 2004). These proxy-records of climate can provide both baseline data to help anticipate the most severe and sustained droughts that might occur, and can also help to identify potential forcing mechanisms that produce prolonged droughts. Finally, comparison of the paleohydrological records with historical and archaeological records allows us to consider how previous severe droughts may have impacted people in the past, and perhaps, at some basic level, provide insights into our own potential responses.

Fig. 2. Low water levels at Lake Mead, Nevada in August, 2005 (© Glen M. MacDonald used by permission).

In this paper I briefly outline the general drought vulnerability of western North America and southern California in particular, and summarize some of the mechanisms in place that mitigate chronic water scarcity and droughts. I then use a new tree-ring reconstruction of drought in conjunction with previously published paleoclimatic data and climate model results to explore the occurrence and causes of general aridity and severe and sustained drought during the medieval period (~9th through 14th centuries). I will briefly consider the potential impacts of medieval drought conditions on prehistoric

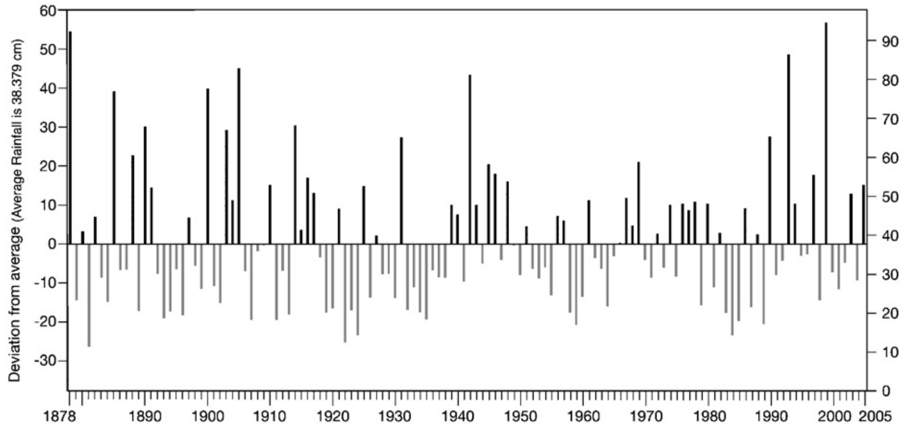

Fig. 3. Los Angeles precipitation (July–June) deviations from the long-term mean from AD 1877 to 2005 (data from NOAA).

peoples in southern California and adjacent Southwest. Finally, I will make a few observations regarding what the past tells us about the future in terms of droughts in southern California and the West.

2. The threat and mitigation of chronic water shortage and drought in southern California and the West

Aside from mountains and northwestern coastal regions, much of western North America is typified by a chronic deficit in terms of the ratio of precipitation to potential evaporation. In addition to chronic water deficits, the region is also prone to episodes of severe drought.

Annual precipitation over much of the West is less than 50 cm and in large areas it is less than 25 cm, while potential evaporation rates are often much greater (Vörösmarty et al., 1998). In addition, annual precipitation is generally highly variable and prone to multi-year periods of below average precipitation. These facets of hydrology are well expressed in the annual water-year precipitation deviations for Los Angeles (Fig. 3). Over the period AD 1877–2005 mean annual precipitation was only about 38 cm, while potential evaporation in the region was over 90 cm (Vörösmarty et al., 1998). In addition, there have been a number of prolonged periods of below average precipitation that extended up to seven years in duration. The Los Angeles precipitation record shows another interesting feature. The distribution about the mean is asymmetrical, with a high proportion of below average years punctuated by a lesser number of years above the mean. This situation exists because the magnitude of positive precipitation anomalies is greater than for negative anomalies. Total precipitation during some of these positive anomaly years can be as much as 2.5 times higher than the mean. Unfortunately, much of the water during such high precipitation years is lost in run-off from the surface of saturated soils and is not available for human use or terrestrial ecological functioning. The net result of the low annual precipitation, the high variability and the presence of asymmetric distributions of positive and negative precipitation anomalies is that southern California and much of the western United States experiences a high proportion of years (>10–>15%) of severe to extreme drought (Fig. 4) as measured by the Palmer Drought Severity Index (PDSI). The challenges of low water supply and drought, particularly in the Southwest and California, has been confronted by native cultures, European colonizers and recent society in a number of ways.

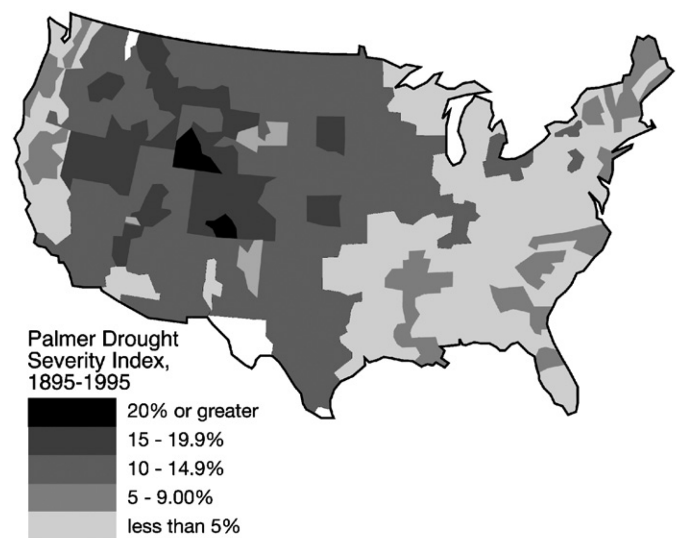

Fig. 4. The percentage of years from AD 1895–1995 during which US Climate Divisions experienced severe to extreme drought typified by PDSI of <-3 (after National Drought Mitigation Center).

The pumping of groundwater from aquifers has long been used to supplement precipitation in the arid West. California, for example, obtains about 30–40% of its average annual water supply from groundwater (Carle, 2004). However, prolonged high rates of ground water withdrawal have exceeded rates of recharge in a number of aquifers in the West. This had led to drops in local and regional water tables of 10 to >30 m in areas of southern California and adjacent states (Leake et al., 2000). Deeper water is more expensive to pump to the surface, but this is not the only problem. About one-third of the water supply in the greater Los Angeles region is derived from groundwater, but since the 1920s the extraction of freshwater has led to hydrologic reversals and incursions of saltwater from the Pacific Ocean into coastal aquifers. Salt water incursions have curtailed coastal aquifer withdrawals and required the pumping of freshwater back into the ground to produce hydraulic barriers (Edwards and Evans, 2002). The withdrawal of large amounts of groundwater and the lowering of water tables have produced considerable subsidence in many regions. The arid Antelope Valley of southern California has experienced 2 m of water-related subsidence in some areas since the 1940s (Bawden et al., 2003). Due to the high cost of pumping water from increasingly greater depths, problems of seawater incursion along the coast and widespread subsidence, water mining at the rates of the 20th century is not a sustainable strategy for many aquifers.

A large component of water resource management in California and the West involves the transference of water from areas with higher precipitation, such as mountainous regions and the northwestern coastal zone, to more arid sites. Large river systems, such as the Colorado River (Fig. 5), which extends from the mountainous regions of Wyoming, Colorado and Utah to the low elevation desert regions of Nevada, Arizona, California and Mexico, are a prime example of such a natural water transference route. In recent years southern California has used some 6400–5400 million m^{-3} of Colorado River water per-year, largely for agriculture in the arid Imperial Valley, but also with a significant portion allocated to the urban megalopolis centered on Los Angeles and extending from Ventura County in the north to the Mexican border in the south. In all, since AD 1922 some 16.5 million acre-feet of water have been apportioned from the Colorado River to the states along its course and to Mexico (an acre-foot is a basic unit for water management in the United States and equals 1233 m^{-3}). The full text of the legislation and treaties pertaining to the Colorado River water allocations and the so called 'Law of the River' can be found at http://www.usbr.gov/lc/region/pao/lawofrvr.html.

The use of southwestern river systems to support agricultural societies dates to pre-Columbian times. Native Americans, most notably the Hopi, Zuni, Rio Grande Pueblo and Pecos Pueblo tribes built large villages and practiced intensive irrigation-based agriculture, along rivers such as the Little Colorado, the Rio Grande and the Pecos in arid portions of Arizona and New Mexico. Some of the pueblos they built contained over 1000 rooms, and the Rio Grande and upper Pecos valleys in New Mexico may have supported up to 50,000 people during the 13th through 15th centuries (Riley, 1995, 2005; Stuart, 2000). The Chumash Indians of the southern California coastal region did not practice agriculture, but also located their villages along river courses and where permanently flowing streams entered the ocean (Johnson, 2000). Similarly, early Spanish missions and settlements in California were typically established near rivers and perennial stream systems. The location of Los Angeles was dictated by the presence of reliable water in the Rio de

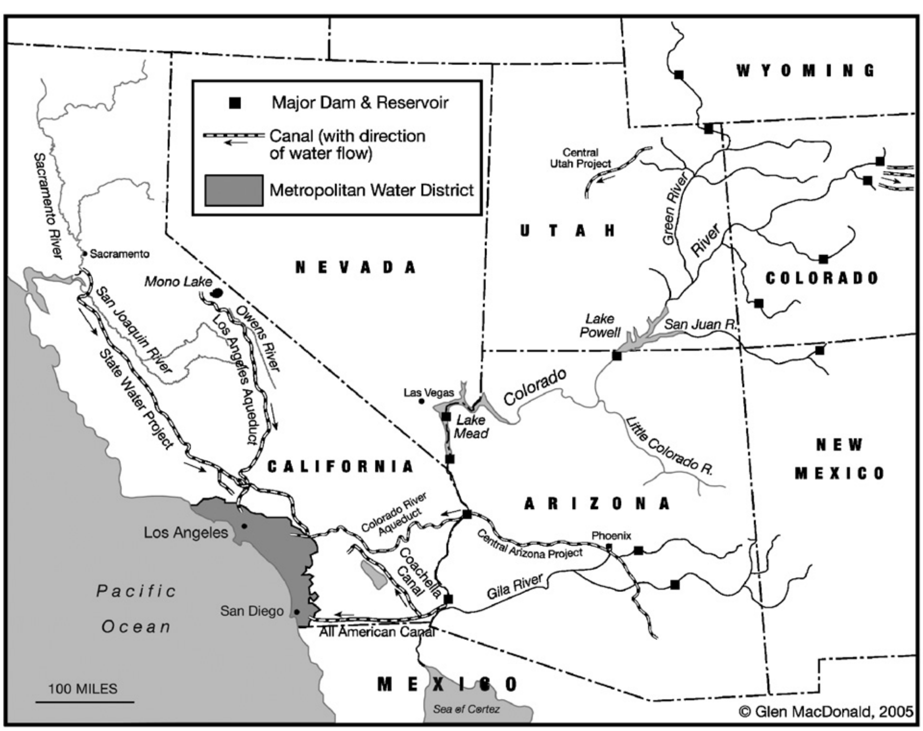

Fig. 5. The Colorado River system with major dams and aqueducts and the major California aqueducts serving southern California (from various sources).

Porciúncula (Los Angeles River) which is fed from the surrounding hills and mountains (Baugh, 1942; Torres-Rouff, 2006).

The natural means of water storage and transference afforded by the mountains and river systems was augmented by native peoples in the Southwest through the use of small check dams and irrigation canals beginning 2000 years ago (Riley, 2005). The remnants of some of the abandoned systems were exploited by later European settlers (Reed, 2004). The Spanish also built impressive irrigation projects in the vicinity of missions and other settlements. As Gentilcore (1961, p. 54) states about California "The problem of supplying water was met at many missions by the construction of imposing water systems which place the Franciscans in the forefront of irrigation history in the state". In California, the Spanish water transfer infrastructures included masonry dams over 3 m thick and stone aqueducts over 10 km in length (Gentilcore, 1961). In AD 1781 some of the first structures that Spanish governor, Felipe de Neve, ordered to be built in Los Angeles were a dam and the *Zanja Madre* (mother ditch) to bring water to the pueblo. Remnants of this open system remained in use until 1904 (DeMarco, 1988; Torres-Rouff, 2006). The infrastructure for the transference and storage of water expanded greatly during the late 19th and 20th centuries through the development of large aqueducts and reservoir systems. The process of developing such infrastructure was so critical and so pervasive that it has been cited as a defining factor in the shaping of modern society in the West (Worster, 1985).

Southern California's urban areas are home to over 18 million people today and are dependent upon a huge water transference and storage infrastructure. The development of this hydraulic infrastructure was strongly influenced by the highly seasonal precipitation regime in which almost all precipitation in southern California occurs in the winter, and by droughts experienced in the mid to late 19th century. More generally, there was a pervasive interest in large-scale hydrological engineering projects during the 19th century that transcended the Unites States and was expressed in similar projects in places such as India and Australia (Worster, 1985). In Los Angeles, a relatively short period of drought in AD 1862–1864 caused the loss of 70% of the county's cattle (DeMarco, 1988). At that time cattle ranching was a preeminent economic activity and supported the large ranchos and other vestiges of the previous Mexican social structure in southern California. The drought of the 1860s was responsible for not only shifting the economic basis of the region, but also for stripping many of the Californianos (Hispanic Californians) of their land, power and overall standing in California society (Fogelson, 1967; DeMarco, 1988). In 1868 the city issued a franchise to the Los Angeles Water Company to supply drinking water, and the company began a program of developing water sources, constructing reservoirs and installing water pipes to replace the open *zanja* system (Fogelson, 1967; Torres-Rouff, 2006).

Droughts continued to plague the region in the 1870s and 1880s and accelerated the process of replacing *zanjas* with pipes for domestic use and irrigation (Torres-Rouff, 2006). By the end of the 19th century the population of Los Angeles had reached 100,000 and local water resources were insufficient to meet growth needs. During the early 1900s the city acquired land and water rights throughout the Owens Valley, at the foot of the eastern Sierra Nevada. Under the leadership of William Mulholland, a former *zanajero* or ditch tender, the city built an aqueduct stretching over 370 km to bring Sierra snowmelt to Los Angeles. This first large aqueduct was dedicated at a public ceremony on November 13, 1913. As the water flowed, Mulholland issued his famous, and uniquely concise, dedication speech "There it is, take it!" (DeMarco, 1988).

Today, although some 75% of California's precipitation falls north of Sacramento, 75% of the consumption occurs south of there (Carle, 2004) thanks to aqueduct projects. The four major aqueducts supplying water to Los Angeles and vicinity (Fig. 5) might be compared in terms of importance to those supplying another great city—classical Rome. If not in number, then certainly in length and volume of water transfer, the four aqueducts that bring Colorado River and northern California water to southern California more than rival the 9–11 aqueducts that served ancient Rome (Smith, 1978; Aicher, 1995; Hodge, 2002). The longest of the classical aqueducts entering Rome ran for some 90 km. The longest aqueduct system serving southern California is the California Aqueduct of the State Water Project which runs 714 km from the Sacramento River Delta to southern California. The entire Roman aqueduct system likely carried some 500,000–1,000,000 m^{-3} of water daily. Whereas, the southern California aqueducts can carry some 12,000,000 m^{-3} of water to the southern California urban region daily.

The California aqueducts are not unique. Important systems to divert Colorado River water exist in Utah, Colorado and Arizona (Fig. 5). However, the observed flow of the Colorado over the past 100 years indicates that there are potential problems in reliance on the river for water needs in Southern California and other states. First, the water apportioning made under the 1922 and 1944 pacts that allocated 16.5 million acre-feet to various states and Mexico may have been based on an overly short record and optimistic estimate of average river discharge. Based on AD 1905–1922 data the average flow of the Colorado was estimated at around 17 million acre-feet. However, the longer-term mean for the 20th century suggests that the average may be closer to 15 million acre-feet (Fig. 6). Thus, due to the reliance on the short AD 1905–1922 discharge record, more water was apportioned than the average flow actually provides. In contrast to the declining estimates of average discharge, the population of the states and urban areas that utilize Colorado water has grown explosively (Fig. 6). Second, despite its immense basin of approximately 583,000 km^2, observations over the past century have shown that the flow of the Colorado is highly

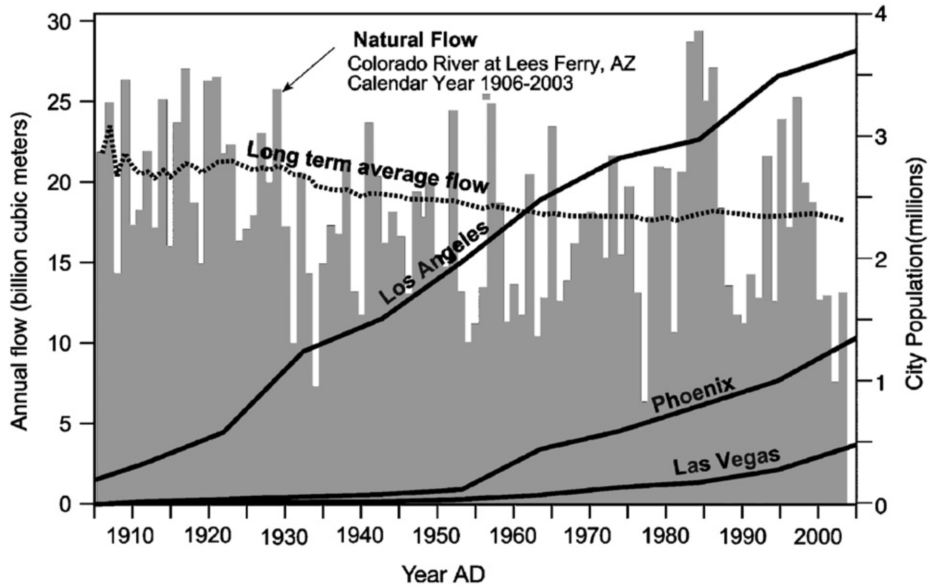

Fig. 6. Year to year variability and long-term mean of the naturalized flow of the Colorado River at Lees Ferry, Arizona and the population growth of the cities of Los Angeles, Las Vegas and Phoenix (does not include the large metropolitan regions beyond city limits—data from the US Bureau of Reclamation and the US Census Bureau after MacDonald, 2005).

susceptible to significant variability due to drought (Fig. 6). River flow measured at the boundary between the upper and lower basins at Lees Ferry can fall to as low as almost one-third of the long-term mean in particularly bad individual years. In addition, multi-year periods of low flow are not uncommon. During the drought of the Dust Bowl years (AD 1930–1937) the annual flow at Lees Ferry averaged only about 10.2 million acre-feet. To alleviate the impact of such events, and to generate hydroelectricity, the Colorado supports an extensive reservoir system that can store some 60 million acre-feet of water (Fig. 5). However, as the AD 1999–2004 drought highlighted, the reservoir system remains vulnerable to severe droughts that persist for more than 5–6 years.

Today, the State of California has an admirable comprehensive water management strategy. Every five years the large water districts in California must produce revised plans to deal with typical historical droughts. The present infrastructure or reservoirs, aquifer storage and water transfer provides most of such capability. In addition, there have been remarkable decreases in per-capita water consumption in jurisdictions such as the Metropolitan Water District of Southern California. In that district, water distribution dropped some 35% between the early 1990s and today. Small districts that rely on their own surface reservoirs and limited groundwater remain vulnerable to short droughts. In addition, if a severe and widespread drought impacting the California and the Colorado were to persist for decades, the current infrastructure would likely not be capable of complete mitigation. Policy changes to lessen water usage or shift water from agricultural to urban uses would need to be considered. Increasing the costs for water would likely be used to decrease demand and provide funding for deeper groundwater pumping, desalinization facilities and increased tertiary wastewater treatment and recycling.

So, after more than 100 years of modern drought mitigation planning and projects there is in California and the West a remarkable multi-faceted infrastructure capable of coping with chronic water shortage and most anticipated droughts. However, it can be argued that large areas of the West, including Southern California, remain vulnerable to the impacts of severe and sustained (decadal-plus) drought at least in economic, legal and political terms—and potentially in terms of significant social change in rural areas if a very prolonged drought required a large-scale shift of water away from agriculture to urban water users. Could such a mega-drought occur?

3. A paleo-perspective on drought in southern California

What are the possibilities of droughts that last decades or longer occurring in southern California and the West? Although an instrumental meteorological station was established in San Francisco as early as AD 1827 (Bradley, 1976), little useful climate data exist for the West prior to the 1850s. Most meteorological stations in the western United States and Canada possess instrumental records which extend back 100 years or less. This span is too short to capture the full potential variability in drought severity or duration. It is also too short to confidently identify any multi-decadal or longer periodicities that might exist in droughts or ascribe such variations to potential causal mechanisms. Historical documents which provide evidence of drought can be used to extend the instrumental records in limited instances. For example, Mock (1991) used diaries and other sources to reconstruct cold and dry conditions on the northern and central Great Plains during AD 1849.

Rowntree (1985) used Mission records and other sources of information on agricultural productivity to reconstruct California precipitation in the late 18th and 19th centuries. Finally, paleoenvironmental records for precipitation and drought are available from a number sources and are particularly plentiful for the past 500–2000 years (Woodhouse and Overpeck, 1998). One of the most widely applied paleoenvironmental data sources is dendroclimatology (the analysis of tree-rings to reconstruct climate).

The oldest known living trees in the mountains of southern California are limber pines (*Pinus flexilis* James) which live in open stands on dry rocky slopes at high elevation. On the slopes of Mount San Gorgonio (3506 m asl) there are living limber pines older than 1300 years in age and deadwood that is over 2000 years old. To produce a locally based reconstruction of drought variability cores were taken from these trees in 1998 and combined with tree-ring counts from San Gorgonio from collections made in 1970 by R. Tosh and archived in the International Tree-ring Data Bank (http://www.ncdc.noaa.gov/paleo/treering.html). Standard field sampling, cross-dating and chronology construction techniques were applied (Stokes and Smiley, 1968; Fritts, 1976; Cook and Kairiukstis, 1990). Visual cross-dating of the cores was further verified using the COFECHA Program and a standard chronology was produced using the ARTSAN Program (software by Cook, E.R. and Holmes, R.L. available at http://www.ltrr.arizona.edu/software.html). To maintain the low-frequency variations in the record, only a single detrending was done of the individual tree-ring chronologies using a negative-exponential curve or linear line as appropriate to remove any biological growth trend in the trees. The standard

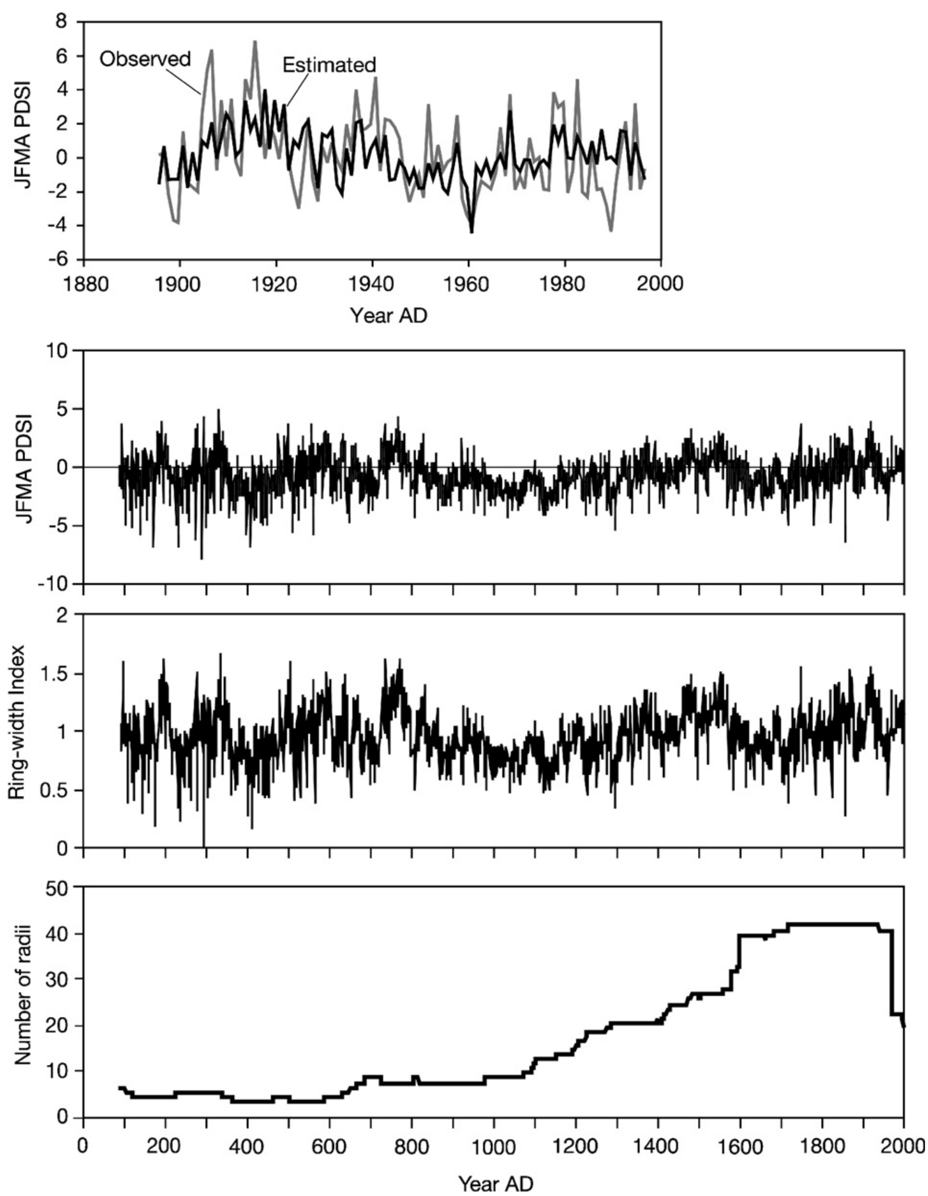

Fig. 7. Reconstruction of winter Palmer Drought Severity Index for winter (DJFMA) for California Climate Division 6, *Pinus flexilis* standard tree-ring chronology and sample depth from Mount San Gorgonio collections. Top inset shows comparison of estimated PDSI (black) with observed PDSI (gray).

chronology (Fig. 7; Table 1) is significantly correlated with winter monthly precipitation and with PDSI values for California Climate Division 6, which represents Los Angeles and the southern California coastal region (Table 2). Using the average PDSI values for the winter precipitation period of January, February, March and April for calibration and verification purposes and applying standard dendroclimatological methods (Cook and Kairiukstis, 1990; Fritts, 1976), a linear, multiple regression-based model was developed to estimate winter PDSI back to AD 90 (Fig. 7) when the number of trees present (seven) is sufficient to obtain a minimal subsample signal strength of .75 (Wigley et al., 1984). Although the number of trees or radii never drop below 4, there is not a consistent number of seven or greater until AD 651 and the early part of the record is presented for information, but should be viewed with caution. Focus should be on the past 1000–1400 years. The reconstruction captures about 35% of the total variation in the observed PDSI values (Table 3) and is clearly best at representing lower-frequency variability. As is typical in many dendrohydrological reconstructions, the reconstruction underestimates peaks in wet years and some of the troughs in PDSI during individual dry years (Fig. 7). The record should be viewed as a very general picture of long-term PDSI patterns in the region.

The two most striking features of the PDSI reconstruction is the presence of several periods of extended multi-annual to multi-decadal drought (mid 17th, early 18th and late 19th century dry periods, for example) and a general trough in PDSI values (and thus persistent drought) between the 9th and 14th centuries (Fig. 7). The reconstruction indicates that extended multi-year droughts of decadal length or greater can be anticipated as natural features of the southern California climate system. The prolonged dry periods during the 17th and 18th centuries extend beyond anything experienced in the historical period. During the medieval period PDSI values are depressed below 0 for very long stretches of time, indicating even longer persistent dry conditions, particularly in the 11th and 12th centuries when PDSI values are typically below −2 to −3, suggesting prolonged moderate to severe droughts. Particularly dry periods extend from ~AD 975–1075 and ~1120–1160 and ~1282–1342. At no

Table 1
Tree-ring chronology statistics for *Pinus flexilis* trees from Mount San Gorgonio including new samples taken from living trees in 1998 and cores and samples of deadwood obtained in 1970 by R. Tosh

Chronology type	STANDARD	RESID	ARSTAN
Mean	0.9530	0.9910	0.9558
Median	0.9389	0.9925	0.9565
Mean sensitivity	0.1796	0.1821	0.1691
Standard deviation	0.2378	0.1633	0.2182
Skewness	−0.1251	−0.4257	−0.3277
Kurtosis	0.8264	1.3406	1.3997

The total chronology time span is 42 BC–1998 AD (2041 years) and includes 53 radii from 39 trees.

Table 2
Correlations (r) between the standard tree-ring chronology from Mount San Gorgonio and monthly PDSI for California Climate Division 7 (southwestern region of the state) during the period 1896–1997

Month	January	February	March	April	May	June	July	August	September	October	November	December
r	0.520	0.581	0.563	0.514	0.513	0.510	0.505	0.422	0.393	0.344	0.271	0.287

All values are significant at $p \leqslant 0.01$.

Table 3
Calibration and verification statistics* for JFMA PDSI reconstruction model

Model and calibration period	R[d]	R^2_{adj}[e]	Verification period	R[f]	RE[g]	CE[h]
FULL[a]	0.604	0.352				
EARLY[b]	0.511	0.246	LATE	0.575	0.498	0.247
LATE[c]	0.671	0.427	EARLY	0.496	0.291	0.046

[a]FULL Model (PDSI = −6.653 + ((8.378 × SanG)−2.098 × SanGPriorYrRing)) calibration period extends 1896–1997.
[b]EARLY Model (PDSI = −6.346 + (6.259 × SanG)) calibration period extends 1896–1946; verification period extends 1947–1997.
[c]LATE Model (PDSI = −5.611 + (10.272 × SanG)−5.316 × SanGPriorYrRing)) calibration period extends 1947–1997; verification period extends 1996–1946.
[d]R: multiple correlation coefficient.
[e]R^2_{adj}: multiple correlation coefficient adjusted for degrees of freedom.
[f]R: correlation coefficient between model and observational data not used to construct model.
[g]RE: Reduction of error (values > 0 considered acceptable).
[h]CE: Coefficient of efficiency (values > 0 considered acceptable).
*All testable statistics significant at $p \leqslant 0.05$.

time over the past 200 years of historical and instrumental climate records has anything approaching such prolonged dry conditions been observed. In terms of current water resource management planning such a prolonged drought would present great challenges. Can prolonged aridity during the medieval period be verified with other supporting evidence?

The presence of prolonged droughts in southern California during the 9th–14th centuries is consistent with a number of other paleoclimatic records. In the Sierra Nevada Mountains of California evidence of prolonged drought conditions comes from the presence of rooted tree stumps beneath the present natural water levels of lakes such as Mono and Tenaya, and in the currently active channel of the Walker River. Many of these stumps have been shown to have been growing between approximately AD 890–1110 and AD 1210–1350 and mark the timing of extreme prolonged droughts that caused water levels to fall significantly (Stine, 1994). There are also several long periods of persistently low-flow conditions on the Sacramento River, which derives water from Northern California and in part the northwestern Sierra, during the medieval period (Meko et al., 2001). The two prolonged droughts in the 11th and 10th centuries observed in the southern California PDSI record are closely contemporaneous with prolonged periods of sharp declines in flow of the Sacramento River (Meko et al., 2001). Evidence of dry conditions in southern California at this time is also available from sediment records taken from a small lagoon near San Diego where inflows of freshwater were depressed following AD 1 to about AD 1400 (Davis, 1992). A previously developed tree-ring reconstruction of precipitation for southern California also presents evidence of severe declines in precipitation during the 9th through 14th centuries (Kennett and Kennett, 2000). In California and other parts of the West the development of severe prolonged droughts during the medieval period (broadly taken as AD 800–1350) is widely recognized and has been referred to as the ‘‘medieval climate anomaly’’ (Jones, 2002; Jones et al., 1999; Stine, 1994).

Evidence for a severe and prolonged droughts during the medieval period comes from many other sites in western North America and from many different proxy climate indicators. Tree-ring evidence from as far north as southwestern Canada shows that the flow of the Saskatchewan River, the major system on the western prairies, also suffered extremely low flows between roughly AD 900 and 1300 (Case and MacDonald, 2003). As reviewed by Cook et al. (2004) evidence from tree-rings, charcoal and diatoms from lake sediments, the dating of sand dune deposits and the submerged stumps reported by Stine (1994) all point to a period typified by episodes of extended severe aridity in western North America that resulted in increased forest fires, reductions in lake depths and increases in salinity, and activation of sand dune systems during the 9th–14th centuries. However, the specific timing of particularly severe aridity events within this time period displays regional variability. The southern California PDSI record is different from some regions in so far as it suggests that in addition to episodic prolonged droughts, almost the entire period of the 9th–14th centuries was somewhat arid.

4. Cause of medieval mega-droughts

What could cause such an extensive pattern of sustained and severe droughts, and could such events be anticipated in the future? The most likely control for periods of prolonged aridity in southern California and the adjacent West are sustained deviations in sea surface temperatures (SSTs) in the Pacific Ocean. In particular, cold temperatures in the northeastern Pacific are associated with the development of a blocking high-pressure system which directs the winter storm-track northward and deprives California of precipitation. Such conditions often occur during cooling of the tropical eastern Pacific and the development La Niñas, which generally persist for only a year or a little more, but more prolonged aridity can also be prompted by longer-term SST anomalies (Dettinger et al., 1998; Costello and Shelton, 2004; MacDonald and Case, 2005; Herweijer et al., 2006). One important longer-term mode of SST variability in the northeastern Pacific is the Pacific Decadal Oscillation (PDO), which in its negative phase is associated with cool temperatures in the northeastern Pacific and the development of dry conditions in southern California and adjacent portions of the southwestern United States and Mexico (Nigam et al., 1999; Mantua and Hare, 2002). Northern Mexico and adjacent southern California is a particularly strong center of action for the impact of the PDO on precipitation. A dominant periodicity of approximately 60 years in PDO phases has been present over the past 150 to 200 years, but seems to vary in strength during earlier periods (MacDonald and Case, 2005).

A tree-ring based reconstruction of the PDO over the past 1000 years (Fig. 8) suggests the development of a prolonged negative state of the PDO during the 10th through 12th centuries which is consistent with the establishment of a prolonged drought in California and the propensity for prolonged droughts over much of the West (MacDonald and Case, 2005). Beside the tree-ring based reconstruction of the PDO, there are other lines of evidence for cool temperatures in the northeastern Pacific at this time (Case and MacDonald, 2005). A high-resolution reconstruction of SSTs in the Santa Barbara Channel immediately adjacent to southern California has been developed from oxygen isotope ($\delta^{18}O$) analysis of the foraminifera species *Globigerina bulloides* (Kennett and Kennett, 2000). The reconstruction shows that SSTs were generally depressed from AD 500 to 1500 with prolonged low values between approximately AD 800–1400 (Fig. 8).

What could have caused depression of northeastern Pacific SSTs and generated episodes of prolonged and severe drought in the medieval period? Recent experiments using climate models confirm the potential for prolonged

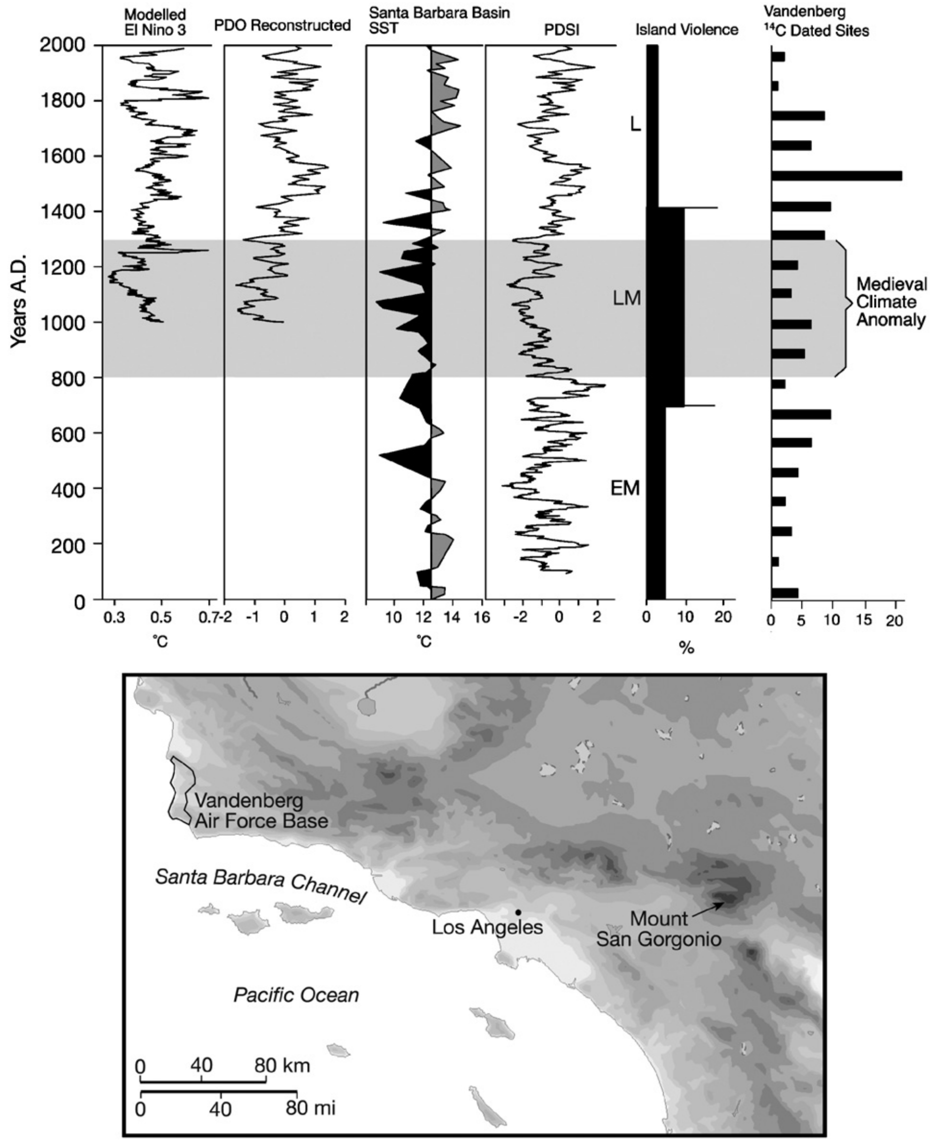

Fig. 8. Comparison of modeled SSTs for El Nino cell 3 (Mann et al., 2005), reconstructed PDO (MacDonald and Case, 2005), Santa Barbara Channel SSTs (Kennett and Kennett, 2000), the southern California PDSI record. Chumash violence reconstruction based on skeletal remains (data from Lambert after Kennett and Kennett, 2000) and frequency distribution of calibrated radiocarbon dates from Chumash sites in the Vandenberg region (Glassow, 2002). The PDO and PDSI records have been smoothed using an 11-year moving average.

depression of eastern Pacific SSTs between sometime prior to AD 1000 until around 1300 (Fig. 8) and the development of mega-drought conditions over California and much of the West during this time (Mann et al., 2005; Herweijer et al., 2006). The model experiments indicate that a combination of increased optical clarity in the atmosphere due to decreased volcanic activity, coupled with slightly increased insolation due to natural solar variability, led to generally warmer climatic conditions in many parts of the globe and a differential heating of the western equatorial Pacific relative to the eastern Pacific (Mann et al., 2005). The enhanced heating of the western Pacific promoted La Niña-like conditions and the resulting development of extensive droughts in the West (Mann et al., 2005; Herweijer et al., 2006). The persistent nature of arid conditions in southern California throughout this time may reflect its proximity to the cool eastern Pacific and its sensitivity as a center of action in the linkage of long-term Pacific Ocean variability such as the PDO to precipitation variability.

The combination of empirical evidence for prolonged drought in California and the West, empirical evidence supporting the role of prolonged cooling of the north-eastern Pacific in creating drought, and the model experiments showing how such a pronounced cooling could develop due to natural variations in solar output coupled with volcanic quiescence leaves no doubt about the veracity of the medieval mega-drought. The fact that relatively small, and potentially repeatable, coincidental natural changes in solar output and volcanic activity may have triggered this mega-drought period argues that a similar situation could develop again in the future due to natural or anthropogenic increases in radiative forcing.

5. Human impacts of medieval mega-droughts

The impacts of severe medieval droughts upon native peoples in the West have long been the object of interest and speculation. An excellent recent synthesis of the broad scale impacts of the medieval droughts on people throughout much of the arid West has been produced by Jones et al. (1999). As is often the case, much speculation has been made regarding the negative impacts of such environmental events, and Jones et al. (1999) indeed chronicle evidence for increased violence, abandonment of certain areas and some declines in trade during this period. Much interest in the West has focused upon the ancestral Pueblo peoples—the Anasazi. Perhaps the most well-known account of the relationship between drought and the Anasazi revolves around the decline of the Chaco Canyon Anasazi and the abandonment of the greater San Juan Basin of New Mexico and adjacent portions of Colorado (the account below draws from Jones et al., 1999; Stuart, 2000; Vivian and Hilpert, 2002; Reed, 2004; Diamond, 2005; Riley, 2005). During the height of the 'Chaco Canyon Phenomenon' between ~AD 1000 and 1050 there were nine massive 'great houses' in the Chaco valley core. The most impressive of these, Pueblo Bonito, contained nearly 700 rooms. It has been argued that if Pueblo Bonito was an apartment house, no similar residence in North America exceeded its capacity until the dawn of the modern period in the 1880s (Stuart, 2000). In addition to these large communal sites there were hundreds of smaller pit houses. Beside the impressive great house structures the Chaco Anasazi developed at least 640 km of roads that were 4 to almost 10 m in width and large irrigation works. A number of authors contend that series of droughts during the medieval period, including the 'great droughts' of AD 1090 and 1130, dealt a critical blow to Chacoan society. The Southwest droughts are evident in local tree-ring records (e.g. Dean, 1988; Grissino-Mayer, 1996) as well as being coincidental with the medieval mega-drought period (Fig. 8). By AD 1100, following the AD 1090 drought, the last great house in the southern region was abandoned and after AD 1150 the Chacoan phenomenon wound down to eventual complete abandonment of the San Juan basin by the Anasazi. It is widely recognized that drought alone did not cause the decline of Chacoan society, but probably a combination of environmental pressure caused by great drought coupled with subsequent climatic cooling, overpopulation, over-hunting, deforestation, accelerated soil erosion and increasing strife. However, as Diamond states many researchers believe "The *proximate* cause, the proverbial straw that broke the camel's back was the drought" (Diamond, 2005, p. 156).

In south coastal California and adjacent islands, researchers such as Kennett and Kennett (2000) and others have thoughtfully explored the linkages between medieval mega-drought and the prehistoric Chumash culture. During the same period as the medieval mega-droughts evidence from Chumash burials provides a record of increasing lethal violence (Fig. 8) (Kennett and Kennett, 2000). The evidence suggests levels of violence greater than what is normally expected of band societies (Jones, 2002). It has been speculated that increased violence was a direct result of resource competition caused by medieval mega-droughts (Johnson, 2000; Kennett and Kennett, 2000; Jones, 2002; Kennett and Conlee, 2002). The period of AD 1150–1300 appears to have been one of "severe settlement disruption" (Kennett and Conlee, 2002, p. 163) during which time drier interior sites were abandoned and settlements were moved to coastal sites and areas along permanent rivers (Kennett and Conlee, 2002; Johnson, 2000). Jones and Ferneau (2002) argue that drought conditions during the late medieval period negatively impacted population growth, diet breadth and interregional trade patterns in the central coast region of California.

If we stop here, with these accounts of the negative impacts of the medieval mega-droughts, we have only a partial story, however. In the case of Chacoan society it is instructive to examine the full history of its rise in addition to the desertion of the San Juan Basin. The construction of the first really massive great houses such as Pueblo Bonito, Pernasco Blanco and Uni Vida and associated huge storage rooms commenced in the late 800s, and the Chacoan Society reached its zenith in terms of buildings, roads and irrigation between AD 1020 and 1130 (Stuart, 2000). This was a period of time directly within the medieval climate anomaly and one which experienced numerous droughts. In fact, one of the longest tree-ring based reconstructions for the region indicates that much of the period of AD 800 to just after AD 1000 experienced below average precipitation (Grissino-Mayer, 1996). Although there was regional and temporal variability in drought during this time, it can be argued that the development of large communities and storage structures, irrigation works, the expansion of the road networks, indeed many of the features that appear to us the hallmarks of an advancing material culture with significant social complexity were developed, at least in part, as responses to the pressures created by general water scarcity and recurrent drought. The northward spread of Chacoan road systems and great house construction after AD 1090 have been specifically linked to drought. As Stuart (2000, p. 85) states "The third wave of construction seems to have been born by crisis—the drought of 1090s". Although Chacoan society may have succumbed to the impacts of drought, it can also be argued that it was also partially a product of drought.

Finally, it should be remembered that the evacuation of Chaco Canyon and the San Juan Basin does not correspond with the extinction of the Pueblo peoples. Rather there was resettlement to other regions. In particular, populations increased at sites along larger rivers which furnished reliable water—the Chaco River itself is largely seasonal. By AD 1275 this pattern of Pueblo settlement was playing out in the Southwest and in AD 1400 for example the Rio Grande region was relatively densely settled while the western settlements of the Pueblo people in Arizona were being depopulated (Adams and Duff, 2004). When the Spanish arrived there were large agricultural villages and communal structures along rivers such as the Rio Grande. Average village size ranged from 600 to 800 people. Trade routes extended southward to Sonora in Mexico and ultimately to the Aztec Empire (Riley, 2005). Indeed, the post-Chaco stage between AD 1300 and the arrival of the Spanish has been called the Golden Age for the Rio Grande Pueblo and a period of "expansion and vigor" (Riley, 2005, p. 9). Although, we do not know how the history of the Pueblo people would have progressed in the absence of the Spanish conquest, it is possible that the geographic shift in settlement to areas such as the Rio Grande may have produced a more sustainable setting than the San Juan Basin and Chaco Canyon.

There has been vigorous discussion of the role that the medieval mega-droughts may have played in promoting increasing cultural complexity, resource diversification and trade linkages for the Chumash in southern California (see for example Erlandson and Jones, 2002). There is evidence that drought promoted increased development of permanent settlements along coastal regions and a greater dependence upon marine resources (Johnson, 2000; Kennett and Kennett, 2000). Cool temperatures in the ocean would have promoted increased marine productivity (Kennett and Kennett, 2000). The resource base that was both diverse in terms of land components and heavy on marine resources allowed for sedentary settlement patterns and the development of the highest pre-European population densities in the state of California, reaching perhaps 56 people per km^{-2} (Jones, 2002). Compilations and analysis of radiocarbon dates from Chumash archaeological sites in several regions including off-shore islands suggest that this remarkable population density was developed during and after the medieval mega-drought period (Fig. 8) and may reflect the ability of the marine resource base coupled with increased social organization and trade to support permanent settlements of higher population densities. The co-dependence upon reliable water supplies and marine resources prompted the establishment of relatively large and permanent villages which may have numbered up to 880–1000 residents in the core area of Santa Barbara County (Erlandson and Rick, 2002). There is also evidence of an increase in the production of shell beads as commodities to be traded for food and other goods with interior groups at around AD 1150 (Arnold, 1992). Trade between island and mainland Chumash also appears to intensify and these trade linkages are taken as evidence of increasing cultural complexity (Munns and Arnold, 2002). The material record and ethnographic accounts from the Spanish contact period suggest that in addition to high population densities, permanent settlements, craft-specialization, dedicated trade-goods and intensive trade networks, the Chumash exhibited other traits of advancing cultural complexity including hierarchical political organization. Thus, it can be argued that the high population densities and relatively complex culture of the Chumash may have, in part, advanced due to responses to the medieval mega-droughts. However, there is also evidence that this pattern is not universal and the drought conditions in the late medieval period may have also led to decreased population growth, declining resource breadth and curtailed trade linkages in some regions (Jones and Ferneau, 2002).

Taken together, the Anasazi–Pueblo and Chumash experiences during the medieval mega-droughts suggest a common set of responses to prolonged severe drought that are likely not so different in kind to what we might invoke if faced with a similar situation. Increased dependence on larger rivers, and in the Southwest irrigated farming practices, would have counterparts in development of more extensive water transfer infrastructure, groundwater extraction, desalinization and recycling. Geographic shifts such as abandonment of the San Juan Basin or concentration of populations along coastal areas and rivers in California might have counterparts in zoning restrictions on development in areas that do not have adequate water, or the decrease in irrigated agriculture in some regions. Shifting water resources from agriculture to support urban areas engaged in the production of high-value goods and services is perhaps not so different from the Chumash's increased exploitation of marine resources and increased development of trade networks to exchange products such as shell beads. The increased strife and warfare evident in prehistoric history of the Anasazi and Chumash would play out today as political and legal battles over water resources. The potential for such actions is ever present in much of the West. As a typical example, in late 2005 the Los Angeles Times (Nov. 7) reported that the board of the Imperial Irrigation District of southern California responded to the federal government that they would provide "not a drop" of water to other districts in the event of prolonged drought. We might also consider, that as recently as 1927 Owens Valley residents angry at the loss of water to Los Angeles began to dynamite portions of the Los Angeles Aqueduct, resulting in the city sending a trainload of army veterans to patrol and protect the system (DeMarco, 1988). On a more positive note, the drought of the late 1980s and early 1990s stimulated innovative water management and conservation programs in California that have led to significant declines in per-capita water use, greater ground-water storage capability and other measures. Future droughts are also likely to spur further innovation in policy and technology.

6. Conclusions

Southern California and much of the West experience chronic shortages of water and are susceptible to periodic droughts. Long-term droughts of several years or more are typically linked to cool conditions in the northeastern

Pacific Ocean. The paleoclimatological record coupled with climate model studies indicates that relatively small natural changes in factors such as insolation and global volcanic activity can trigger changes in Pacific SSTs that can produce arid conditions lasting for decades or more. The most recent such mega-drought generating event occurred during the period of roughly AD 800–1300 and produced the widely experienced medieval mega-droughts. The severe drought episodes during this period had adverse impacts upon prehistoric peoples such as the Anasazi in the Southwest and the Chumash in California, but also arguably may have served to advance cultural complexity in those societies. The recurrence of such extended droughts is possible due to natural or anthropogenic changes to radiative forcing and would test current drought mitigation infrastructure and policy to the extreme. In terms of anthropogenic forcing through increased greenhouse gases, it is notable that the most recent Intergovernmental Panel on Climate Change (IPCC, 2007) assessment projects a 20% decrease in precipitation for southern California by AD 2100 based on a multi-model estimate of future climate conditions.

As was the case with earlier peoples, prolonged severe drought periods such as those of the past would necessitate technological, economic, policy and land use responses. Unlike the Anasazi and Chumash, through our understanding of past and present climates we have the gift of foresight and anticipation of such mega-droughts and we should use that advantage to its fullest. Although it is clear that multi-decadal to longer droughts can develop in California and the West, it can be argued that the uncertainty of when such event might occur again makes the provision of physical infrastructure for such an event economically unfeasible. However, it might also be argued that one hallmark of past responses to mega-drought has been societal conflict. Today we might consider at least developing planning and policy options, and associated agreements between Canada, the United States and Mexico, federal government organizations, state governments, water districts and other stake-holders so that when such an event occurs we at least do not waste time and resources in political and legal bickering.

Acknowledgments

I thank the organizers of the September 2005 Dark Nature Meeting in Lake Como, Italy (most notably Alessandro M. Michetti, Lucia Gamba and Suzanne Leroy) for the opportunity to present this paper and for several days of stimulating discussion on the lessons we might learn from past environmental events and their impacts on humans. I also thank Roslyn Case, Christine Farris, Hugo Hidalgo, Judy King and Sigrid Rian for assistance in the field and lab, and much interesting discussion on southern California drought. Portions of the research presented here were supported by NSF Grants (BCS-9905350, BCS-0135748 and SBR-9630999) to the author and an EPA Grant to the UCLA Institute of the Environment.

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