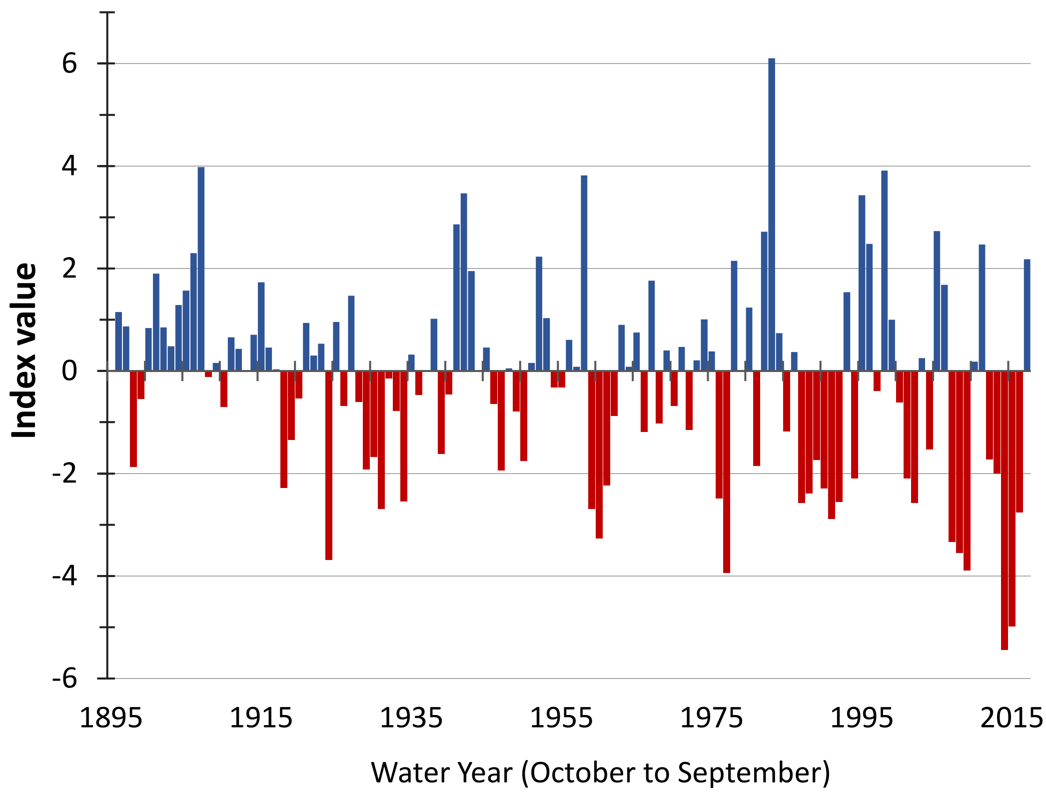
DROUGHT

Over the past 120 years, California has become increasingly dry. The most recent drought from 2012 to 2016 was the most extreme since instrumental records began. Extraordinarily high precipitation in 2017 ended the drought.

Figure 1. California Palmer Drought Severity Index (PDSI)



Source: NOAA, 2017a

What does the indicator show?

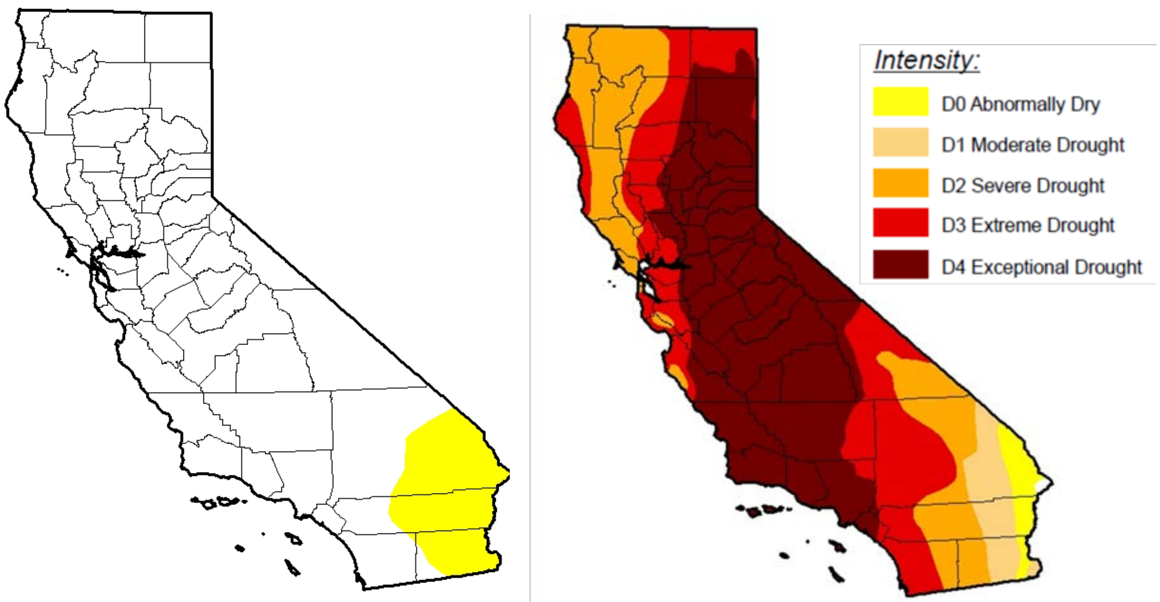
Droughts are generally thought of as periods of unusually dry weather that last long enough to cause a shortage of water (IPCC, 2014). Figure 1 shows values for the Palmer Drought Severity Index (PDSI) over the past 120 years: positive values (blue bars) indicate “wet” years; negative values (red bars) are “dry” years. Although drought can be defined in multiple ways and tracked using different metrics, the PDSI is a universally used indicator of drought; it measures relative dryness of a region using readily available temperature and precipitation data and local available water content of the soil (NDMC, 2017a). Values below -3 represent severe to extreme drought. Five of the eight years when PDSI values fell below -3 were between 2007 and 2016, with unprecedented dry years in 2014 and 2015.

As noted above, from 2012 to 2016, California experienced the most extreme drought since instrumental records began in 1895 (AghaKouchak et al., 2014; Diffenbaugh et al., 2015; Griffin and Anchukaitis, 2014; Robeson, 2015; Swain et al., 2014; Williams et al., 2015). It was possibly the most extreme for a millennium or more (Griffin and

Anchukaitis, 2014; Robeson, 2015). This drought occurred at a time of record warmth — 2014 is the warmest year on record, followed by 2015 — accompanied by record low snowpack, less than 5 percent of average in 2015. In response to the drought, a State of Emergency was declared in 2014 (https://www.gov.ca.gov/news.php?id=18368). Other periods of major droughts in California include 1929-1934, 1976-1977, and 1987-1992 (DWR, 2015). The drought ended with unusually high precipitation in 2017; however, because precipitation is only one component of PDSI (temperature and soil moisture are two others), an unusually high precipitation value does not necessarily result in an equally high PDSI value, particularly given the unusually hot temperatures in 2016 and 2017.

The maps in Figure 2 compare the intensity of the drought in 2015 to conditions in 2011 (NDMC, 2017b). Drought conditions fall under one of five drought categories, from least intense ("D0, abnormally dry") to most intense ("D4, exceptional drought"). These categories are based on five key indicators, including PDSI and measures of soil moisture, streamflow and precipitation; they also incorporate numerous supplementary indicators including drought impacts (such as on crops, pastures and water supply) and local reports from expert observers. In 2015, the entire state was under one of the five drought categories, with almost half of the state's area (46 percent) in the "exceptional drought" category. By comparison, in 2011 only 11 percent of the state was considered "abnormally dry."

Figure 2. Drought intensity in California: 2011 vs. 2015



September 27, 2011 | September 29, 2015

Source: NDMC, 2017b

Why is this indicator important?

Droughts have major environmental, social, and economic repercussions, affecting the availability of water both for human use — such as urban uses (including drinking), agriculture, hydroelectricity generation — and for ecosystems. People most reliant on annual rainfall are generally the first to feel the impacts of drought. A single dry year can impair activities like dryland farming or livestock grazing that depend on unmanaged water supplies (DWR, 2015).

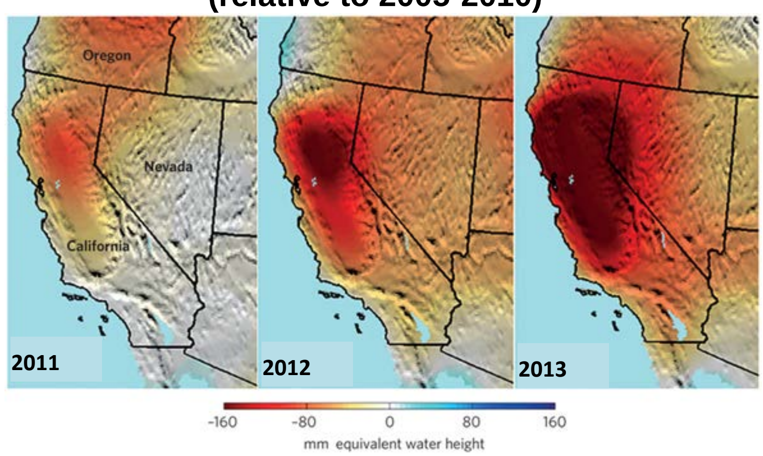
Drinking water shortages primarily occur among small drinking water systems. By late 2015, more than 100 small water systems lacked enough water and more than 2,000 domestic wells went dry, particularly in the Central Valley and Sierra Nevada foothills (PPIC, 2016). Drinking water shortages place a disproportionate burden on lower income households, as financial costs of water services tend to rise during droughts (Famiglietti, 2014; Feinstein et al., 2017).

Drought also impacts the generation of hydroelectricity, a major source of power in California. Hydroelectricity, which is dependent on snowmelt runoff and rainfall, costs less than most other forms of electricity, produces no greenhouse gases, and helps satisfy peak energy demands (Gleick, 2016). In 2014, the state's driest year, hydroelectric power generation provided 6 percent of the in-state electricity generation, down from 12 percent in 2013 (CEC, 2017). The total reductions in hydroelectricity generation during the recent drought may have increased state electricity costs by about $2.0 billion (Gleick, 2016).

Negative economic impacts on California's agricultural sector as a whole from the recent drought were significant (Howitt et al., 2014 and 2015). Impacts included abandoned orchards and vineyards, fallowed land (more than 500,000 acres, or 6 percent of irrigated acreage, were fallowed in 2015), and lost jobs (DWR, 2015; PPIC, 2016). The livelihoods of many farmworkers disappeared (Swain, 2015).

Approximately 30 to 46 percent of the state's total water supply comes from groundwater (DWR, 2017a). Reliance on groundwater increases during droughts. Between 2011 and 2016, groundwater levels decreased by at least 10 feet in over 40 percent of monitored wells in the state (DWR, 2017b). Figure 3 illustrates how groundwater levels in California significantly dropped between 2011 and 2013 (Famiglietti, 2014).

Figure 3. Groundwater storage anomalies (relative to 2005-2010)



Maps of dry season (September-November) total water storage anomalies (mm equivalent water height, anomalies with respect to 2005-2010), constructed using data from NASA's Gravity Recovery and Climate Experiment satellite mission.

Source: Famiglietti, 2014

Over pumping of groundwater results in aquifer compaction, reducing its water-holding capacity, and land subsidence (i.e., the land surface sinks). Land subsidence can impact infrastructure — including water conveyance systems, roads, railways, bridges — aquifer storage capacity, and land topography (USGS, 2017a and 2017b).

Source: USGS, 2017c

The San Joaquin Valley, one of the most productive agricultural regions in the nation, has been impacted by the over pumping of groundwater. Starting in the early 1900s, farmers relied on groundwater for water supply. By 1970, about half of San Joaquin Valley experienced land subsidence. Some areas had dropped by as much as 28 feet. Reduced surface water availability during 1976-77, 1986-92, 2007-09, and 2012-2015 caused even more groundwater pumping. The photograph on the right from the San Joaquin Valley shows the approximate height of the land surface in 1925 compared to much lower levels in 1955 and 1977 as a result of excessive groundwater pumping.

Droughts can harm aquatic ecosystems. During the latest drought, rivers in California experienced record-low flows and poor water quality. Various coastal and mountain streams that are home to native fish like salmon and steelhead dried up. Rivers below Central Valley dams deteriorated. As many as 18 native fish species may face extinction with continued drought, which could put other species at risk of extinction. In addition, water shortages in wildlife refuges in the Central Valley and Klamath Basin during the recent drought forced birds to gather in smaller areas, making them more vulnerable to disease outbreaks and predation (PPIC, 2016).

Droughts produce drier-than-normal conditions that can increase the intensity and severity of wildfires (USGS, 2017a). Droughts and wildfires, in combination with altered land cover, disease, and human activity, can contribute to expanding or contracting vegetation ranges. Forests may convert to shrubland and grassland. Die-offs in whitebark pine in the Sierra Nevada and conifers in southern California have been related to drought. A rapid redistribution of coniferous and broadleaf species occurred in the mountains of southern California during droughts in the early 2000s (Clark et al., 2016). Droughts can contribute to bark beetle outbreaks, which cause tree mortality. Between 2010 and late 2015, aerial surveys conducted by the US Forest Service found that around 40 million trees had died in California. Nearly three quarters of this total died from drought and insect infestation from September 2014 to October 2015 alone (Tree

Mortality Task Force, 2017). Droughts also affect most ecosystem services provided by forests, including carbon storage (Clark et al., 2016).

Finally, drought may affect human health by altering patterns of certain diseases like West Nile (see *Vector-borne diseases* indicator), and by increasing air pollution from wildfires and dust storms, (DWR, 2015; see *Wildfires* indicator). These drought-related changes potentially can impact respiratory health (CDC, 2016). Interestingly, however, a study by Berman et al. (2017) found a lowered incidence of hospital admissions for respiratory illness among older people in the western US during drought periods compared to non-drought periods. The reduced incidence of respiratory admissions may be due to less exposure to pollen and allergenic spores during dry spells. In the same study, California had an overall decreased risk of mortality among the elderly during drought. Counties in the western US that have less frequent droughts showed significantly greater risks for cardiovascular admissions and mortality when droughts occurred. Another study found that the stress caused by drought may induce anxiety, depression, or other adverse mental health outcomes for some people (Vins et al., 2015).

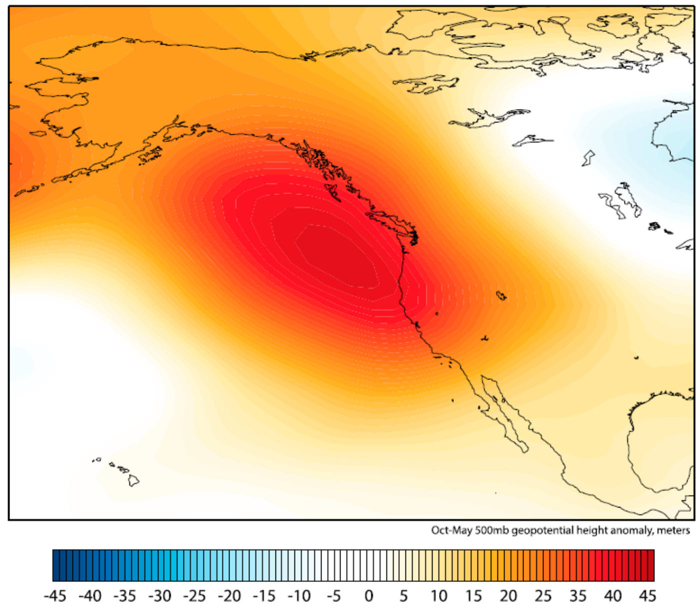
What factors influence this indicator?

Droughts in California are influenced by the El Niño-Southern Oscillation, regional atmospheric pressure anomalies, and “drought-busting” atmospheric rivers (Griffin and Achukaitis, 2014; Dettinger, 2013). Historically dry winters in California have been associated with a ridge of high atmospheric pressure off the west coast, and wet winters have been associated with a trough off the west coast and an El Niño event. A study using climate change models and observational data found the precipitation deficit during the most recent drought to be dominated by natural variability, although sea surface temperatures were found to also play a role (Seager et al., 2015).

While precipitation is a main driver of drought variability, a growing body of evidence suggests that anthropogenic warming has increased the likelihood of extreme droughts in the state (AghaKouchak et al., 2014; Williams et al., 2015; Diffenbaugh et al., 2015; Shukla et al., 2015; Swain et al., 2014). Climate change has increased the chances of co-occurring temperature and precipitation conditions that have historically led to drought in California (Diffenbaugh et al., 2015). In fact, a combination of record high temperatures and low (but not unprecedented) precipitation contributed to the severity of the recent drought (Griffin and Achukaitis, 2014). Anthropogenic warming has been linked to the unusually intense atmospheric pattern that initiated the dry 2013-2014 winter in California (Wang et al., 2014). Mao et al. (2015) determined that the effect of anthropogenic warming in the winter of 2013-2014, although modest, likely exacerbated drought conditions. In the future, climate change is expected to continue to make dry and warm years happen more often (Diffenbaugh et al., 2015). More heat from climate change will likely increase the rate of drying, which will further exacerbate drought (Trenberth et al., 2014).

Atmospheric circulation patterns like those observed during California’s most extreme dry and hot years have increased during recent decades (Swain et al., 2016). In particular, patterns characterized by a persistent ridge near the West Coast of North America — similar to those during the latter half of the most recent drought — have occurred more frequently; these patterns lead to both extremely low precipitation and extremely warm temperatures.

Figure 5. The "ridiculously resilient ridge"



Colors represent the mean cool season 500mbar geopotential height anomaly (meters) over four consecutive years (i.e., October–May 2012, 2013, 2014, and 2015).

Source: Swain, 2015

In 2012-2015, a region of atmospheric high pressure, nicknamed the "ridiculously resilient ridge" (see Figure 5) resulted in a northward shift in the Pacific storm track during the rainy season, preventing storms from reaching California. Studies (such as Swain et al., 2014 and Wang et al., 2014) suggest that climate change may be increasing the likelihood of the type of rare atmospheric event associated with the recent and unusually severe drought California.

Technical Considerations

Data Characteristics

PDSI identifies droughts by incorporating data on temperature, precipitation, and the water-holding capacity of soil. The index takes into consideration moisture received as precipitation and moisture stored in the soil, accounting for potential loss of water due to temperature. It originally functioned to identify drought affecting agriculture but has since been used to identify drought associated with other types of impacts (WMO and GWP, 2016). PDSI is used to assess long-term drought patterns (NOAA, 2017b).

Strengths and Limitations of the Data

Considered a robust index of drought, PDSI is universally used and has been employed since the 1960s. However, PDSI assumes all precipitation comes as rain (Williams et al., 2015) and does not account for frozen precipitation or frozen soils very well (WMO and GWP, 2016). PDSI also does not provide information on human water demand, streamflow and reservoir storage, or groundwater accessibility (Williams et al., 2015).

Another metric for drought, the Palmer Hydrological Drought Index (PHDI), accounts for longer-lasting dryness that can perturb water storage, streamflow, and groundwater (WMO and GWP, 2016). It measures hydrological impacts, including reservoir levels and groundwater data, and responds more slowly to changing conditions than the PDSI (NOAA, 2017b). It does not account for human influences like irrigation or management practices (WMO and GWP, 2016).

For more information, contact:

Michael L. Anderson, Ph.D., P.E.
State Climatologist
California Department of Water Resources
Division of Flood Management
3310 El Camino Ave Rm 200
Sacramento, CA 95821
(916) 574-2830
Michael.L.Anderson@water.ca.gov

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