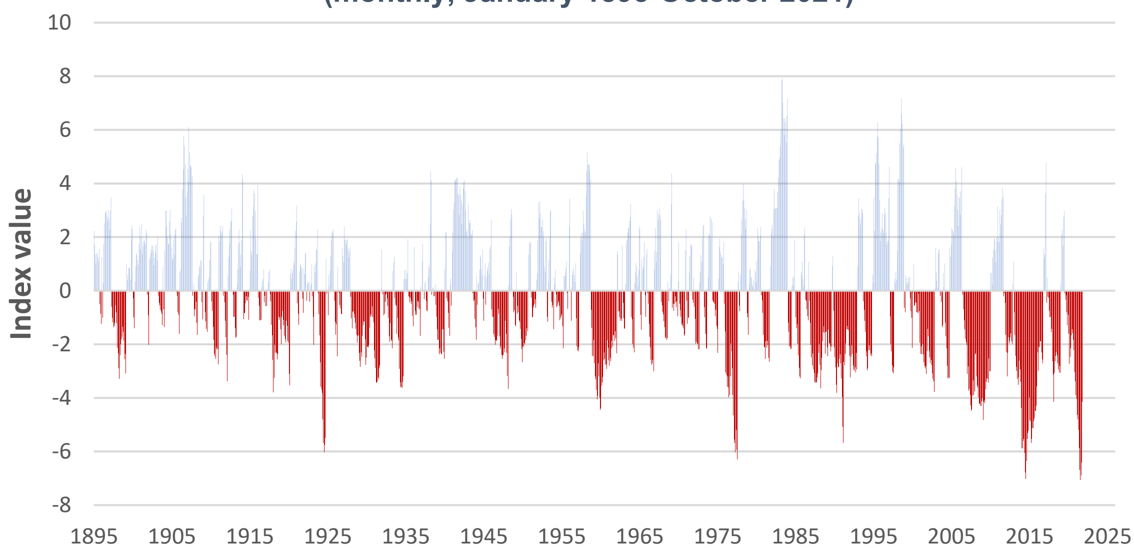
DROUGHT

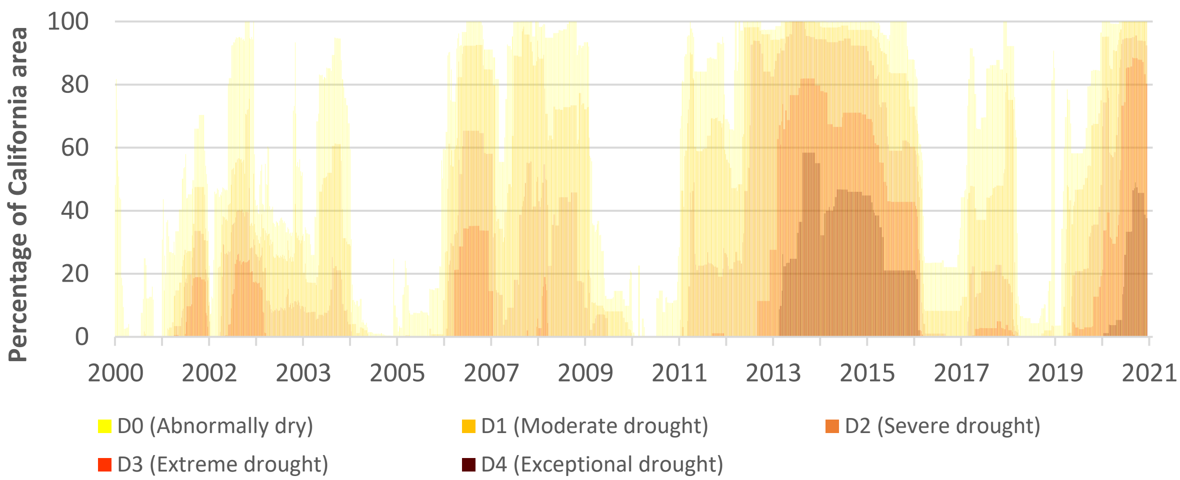
California has become increasingly dry since 1895. Statewide drought conditions by the end of the 2021 water year were comparable to those experienced during 2012 to 2016, the most severe drought since instrumental records began. The area of California land affected by extreme drought during the 2021 water year was larger compared to 2012 to 2016.

Figure 1 California Palmer Drought Severity Index (monthly, January 1895-October 2021)



Source: NOAA, 2021

Figure 2. Percentage of California land area in drought (2000 to 2021)*



Source: National Drought Mitigation Center (NDMC), 2021a

**Based on weekly assessments of drought intensity published as the U.S. Drought Monitor.*
Note: Category D0 designates abnormally dry conditions, not actual drought.

What does the indicator show?

Droughts refer to periods of unusually dry weather that last long enough to cause a shortage of water (IPCC, 2014). Figures 1 and 2 show values for two metrics of drought: the Palmer Drought Severity Index (PDSI) and the percentage of the land area designated by the U.S. Drought Monitor (USDM) in different drought categories. Developed in the 1960s, the PDSI is universally used and measures the relative dryness of a region by incorporating readily available temperature, precipitation, and soil moisture data (NDMC, 2021b; WMO and GWP, 2016). The newer USDM is a more comprehensive percentile-based drought metric that incorporates soil moisture, streamflow, and precipitation indicators, along with PDSI and local observations and experts' best judgment (NDMC, 2021a). Both the PDSI and the USDM track drought conditions in natural (unmanaged) water systems, and thus directly reflect patterns related to a changing climate. In addition, these indices have direct applicability to activities that rely on unmanaged water supplies, such as dryland farming and livestock grazing.

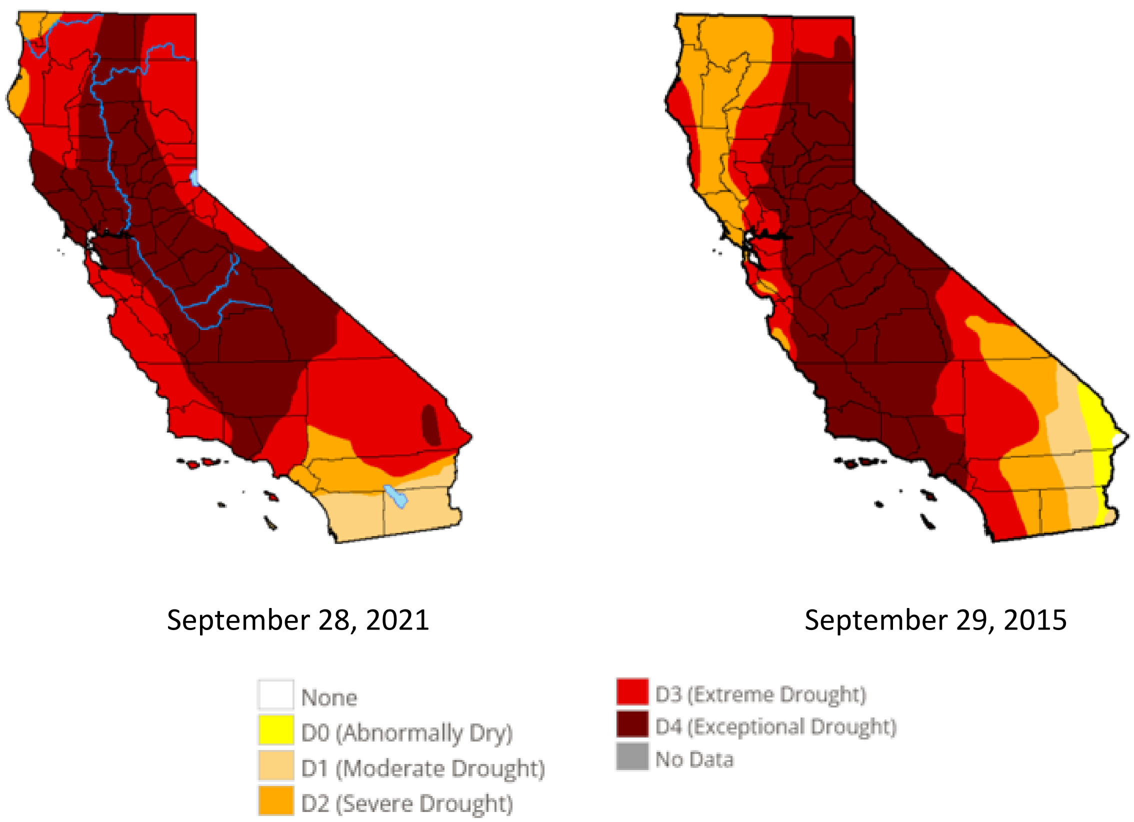
Figure 1 shows PDSI values since 1895: positive values (blue bars) indicate "wet" years; negative values (red bars) are "dry" years. Values at or below -3 represent severe drought. Values below -6 represent very extreme drought. From 2012 to 2016, California experienced the most severe drought since instrumental records began in 1895 (AghaKouchak et al., 2014; Diffenbaugh et al., 2015; DWR, 2021a; Harootunian, 2018; Griffin and Anchukaitis, 2014; Robeson, 2015; Swain et al., 2014; Williams et al., 2015). It was possibly the most severe for a millennium or more (Griffin and Anchukaitis, 2014; Robeson, 2015). The 2012-2016 drought in California ended with unusually high precipitation in 2017. Drought conditions began developing again in early 2020 and remained through the 2021 water year (October 2020 to September 2021); drought conditions have continued into the 2022 water year. This coincided with a period of anomalously warm temperatures and low precipitation. California's other major droughts occurred from 1929-1934, 1976-1977, and 1987-1992 (DWR, 2015).

Figure 2 shows the percentage of land area in California impacted by different levels of drought severity since 2000 according to the USDM. The index uses five "dryness" categories, from least intense ("D0, abnormally dry" but not considered drought) to most intense ("D4, exceptional drought"). Geographically, the 2012-2016 drought affected the entire state, with more than two-thirds of California experiencing extreme or exceptional drought conditions during that time. During the 2021 water year, at least 90 percent of the state was under severe drought for 22 weeks, during which at least 85 percent was under extreme drought (for 17 consecutive weeks), and at least 45 percent under exceptional drought (for 10 weeks).

The maps in Figure 3 compare the intensity of the drought at the end of the 2021 and the 2015 water years (NDMC, 2021a). In September 2021, the entire state was in drought, with 88 percent experiencing extreme to exceptional drought. In September

2015, 97 percent of the state was experiencing drought, with 71 percent in the "extreme" to "exceptional drought" categories.

Figure 3. Drought intensity in California: Comparison of conditions at the end of the Water Year, 2021 vs. 2015



Source: NDMC, 2021a

Why is this indicator important?

Droughts have major environmental, social, and economic repercussions, affecting water availability for human use, such as urban uses (including drinking water supply and industrial uses), agriculture, hydroelectricity generation, and ecosystems (DWR, 2015). The unprecedented drought of 2012-2016 led to significant and widespread impacts across the state, underscoring the need to prepare for drought's broad and devastating effects. These impacts include widespread tree mortality, greater wildfire activity, threatened fish populations, and harmful algal blooms in freshwater bodies. In addition, drought challenges water management systems by exacerbating drinking water shortages, further reducing water deliveries to farmers, and increasing groundwater pumping (CNRA, 2021). The impacts of drought on natural systems, managed water systems, and human health are discussed below.

<u>Natural systems</u>

Forests and aquatic ecosystems are especially vulnerable to the impacts of drought. The record warmth and low stream flows during the 2012-2016 drought put threatened, endangered, and culturally and economically important salmon and steelhead populations, already in decline due to other stressors, at risk (CNRA, 2021; Hanak et al., 2020). Widespread tree mortality, conversion of forests to shrubland and grassland, and changes in habitat range are some ways in which drought has impacted vegetation in California (see the *Changes in forest and woodlands* and *Forest tree mortality* indicators). Dead or dying vegetation increases the risk of wildfires: for example, the unusually high tree mortality seen during the 2012-2016 drought, which was caused by water stress, created a massive fuel load (see *Wildfires* indicator).

Figure 4. Southwestern willow flycatcher

Photo: USGS.
Source: Pala Tribe, 2022

The drying of riparian habitats threatens species dependent on these habitats, including birds such as the southwestern willow flycatcher (*Empidonax trailii extimus;* Figure 4). These songbirds were once abundant in nearly all shrubby riparian areas throughout California but have sharply declined statewide over the past several decades. In the Sierras, for instance, the number and density of willow flycatcher territories declined between 1997 and 2019 at a local watershed (Loffland et al., 2022). In addition, the Pala Band of Mission Indians in Southern California reports that these songbirds have not been seen on their land since 2013, citing drought stress and riparian habitat loss as likely factors of this local extirpation (Pala, 2019), with the latter a primary factor for the decline of this species statewide. Dams, water diversion for agriculture, and groundwater pumping all have altered streamflow, affecting riparian vegetation. Aside from drought, other factors that have impacted riparian habitats include livestock grazing, off-road vehicle use, increased fires, and urban development (NPS, 2016).

Many of the impacts of drought on California's ecosystems disproportionately affect people who depend on these diverse natural resources. People most reliant on annual rainfall usually feel the impacts of drought first. A single dry year can impair activities like dryland farming or livestock grazing that depend on unmanaged water supplies (DWR, 2015). Drought impacts on local habitats place additional burdens on rural populations that depend on them for food, firewood, or their livelihood (Roos, 2018; SWRCB, 2021a). Furthermore, the loss of culturally significant animals and plants can have profound impacts on Tribes who rely on them for traditional foods, medicine, and cultural practices.

Drought impacts on plant and animal species important to California Tribes include:

- Reduced deer and Bighorn sheep on Tribal lands, hunted for food (Big Pine Paiute and Pala, 2022)
- Loss of Clear Lake hitch, a ceremonial food source (Big Valley Pomo, 2022)
- Declines in shrubs and reeds like tules, used in traditional ceremonies, for weaving and boat building, and as food (Big Valley Pomo, 2022)
- Declining numbers of trees like sugar pines (provide pitch for medicine, and roots for basketry) and coast live oak (source of acorns for food) (Karuk and Pala, 2022)

Managed water systems

Domestic water supply

Although drinking water shortages affected many local and regional water suppliers during the 2012-2016 drought, many large urban water districts with diversified water sources and stored supplies did not suffer major disruptions (Lund et al., 2018). Communities that were highly dependent on supply from a single source and had no connections with other water utilities experienced severe shortages. These included more than 100 small water systems and more than 2,000 domestic wells in some small, poor, rural communities, particularly in the Central Valley and the Sierra Nevada foothills (PPIC, 2016). These small communities – often communities of color – remain vulnerable (PPIC, 2021a).

In addition to water supply, droughts also compromise drinking water quality (Bell et al., 2018). Saltwater intrusion, for instance, can happen because of drought, sea-level rise, and changing water demands (US EPA, 2021). As discussed further below (see “Human health impacts”), pathogens in drinking water are another concern. Compounding this issue, low-income communities and people of color are disproportionately impacted by water quality even during normal (non-drought) years. An analysis of drinking water quality, accessibility, and affordability in California found that water quality is worse in low-income communities and that small drinking water systems face greater affordability challenges compared to larger systems (OEHHA, 2021a). In the San Joaquin Valley, for example, tens of thousands of people living in low-income unincorporated communities often lack access to safe drinking water. Most of the Central Valley’s residents who live in low-income unincorporated communities are Hispanic (London et al., 2018).

The rising cost of water services during droughts places an even greater burden on low-income households (Famiglietti, 2014; Feinstein et al., 2017; PPIC, 2021b). Issues of water affordability were exacerbated by the COVID-19 economic recession, when low-income families, women, African Americans, and Latinos were especially impacted by unemployment and underemployment (Bohn et al., 2020). A survey by the California Water Boards (December 2020) found that approximately 1.6 million households in California had water debt at an average amount of $500 per household. A state moratorium on water service shutoffs helped to ensure that homes and small businesses unable to pay their bills continued to have access to water (SWRCB, 2021b).

California's water utilities face fiscal challenges during major droughts and recessions when revenues decline (PPIC, 2021b). Exacerbating this issue, wildfires worsened by droughts can damage water utilities, as seen when the 2018 Camp Fire destroyed the water distribution system at Paradise in northern California (Chow et al., 2021).

Hydroelectric power generation
Drought also impacts the generation of hydroelectricity, a major source of power in California that depends on snowmelt runoff and rainfall. Reductions in hydroelectricity generation during the 2012-2016 drought increased state electricity costs and raised California's carbon footprint until a shift towards different renewable energy sources helped to offset the increased emissions (Gleick, 2016; Hardin et al., 2017; Herrera-Estrada et al., 2018; Szinai et al., 2020; Zohrabian and Sanders, 2018).

Agricultural water supply
As the 2012-2016 drought reduced water deliveries for agricultural use, farmers compensated by fallowing cropland (leaving cropland idle). More than 500,000 acres, or 6 percent of irrigated acreage, were fallowed in 2015. Additional economic impacts on California's agricultural sector from the 2012-2016 drought included abandoned orchards and vineyards and lost jobs; the livelihoods of many people dependent on seasonal farm jobs and agricultural goods and services disappeared (DWR, 2015; Howitt et al., 2014 and 2015; Lund et al., 2018; PPIC, 2016; Roos, 2018).

Along with fallowed land, farmers compensate for water shortages from droughts by pumping groundwater (Lund et al., 2018). Most groundwater in California gets used for agriculture, and to a lesser degree for urban and domestic supply (some communities rely solely on groundwater) and managed wetlands. From 1998 through 2018, groundwater levels decreased in approximately 65 percent of wells statewide (DWR, 2021b).

Overpumping of groundwater in the San Joaquin Valley has depleted the region's groundwater supply. Farmers first started pumping groundwater in the early 1900s. By 1970, about half of San Joaquin Valley experienced land subsidence (i.e., the land surface sinks). 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. Worsening droughts will make it hard to achieve sustainable levels of groundwater by the early 2040s as required by the Sustainable Groundwater

Management Act passed in 2014. People in the San Joaquin Valley may need to permanently fallow 500,000 acres of land (Hanak et al., 2019).

Overpumping of groundwater also results in aquifer compaction, reducing its water-holding capacity, and land subsidence. Some of the most severe recorded land subsidence in history occurred in the western San Joaquin Valley near Mendota, where the land surface has subsided about 30 feet (NASA, 2016; Sneed et al., 2018). The photograph in Figure 5 shows the approximate height of the land surface in 1925 compared to much lower levels in 1955 and 1977 because of excessive groundwater pumping in the San Joaquin Valley. Surface water deliveries from the California Aqueduct replaced reliance on groundwater for irrigation, slowing subsidence showed over a large part of the affected area (Galloway et al., 1999) Land subsidence impacts infrastructure — including water conveyance systems, roads, railways, bridges — aquifer storage capacity, and land topography (USGS, 2017a and 2017b). Moreover, many rivers and wetlands that rely on groundwater for some or most of their flow suffer from groundwater overdraft that worsens during droughts (Hanak et al., 2020; Klausmeyer et al., 2018). Additional impacts of groundwater overuse, exacerbated by droughts, include dying crops, habitat loss, and species extinction (The Nature Conservancy, 2020).

Figure 5. Land subsidence in the San Joaquin Valley

Photo: USGS, 2017c

Land surface in the San Joaquin Valley subsided ~9 m from 1925 to 1977 due to aquifer-system compaction. Signs on the telephone pole indicate the former elevations of the land surface in 1925 and 1955 (Faletti RC, 2022).

Human health

Droughts adversely impact human health in a myriad of ways other than through impacts on drinking water (Bell et al., 2018). For instance, reduced water quantity during periods of drought decreases water flow and promotes the production of pathogens that favor warm, stagnant environments (Paz, 2015; see the *Vector-borne diseases* indicator). Consumption or contact with water containing pathogens, such as *Vibrio* species, may result in ear, eye, wound infections, diarrheal illness, and death (Trtanj et al., 2016). Reduced hand and food washing in response to the drought increased the risk of communicable diseases, such as enteric disease and influenza, and exposure to pesticide residues (CDC, 2016a and 2016b, 2017).

Drought also increases air pollution from wildfires and dust storms (DWR, 2015). Under dry conditions, winds tend to transport inhalable soil particles, leading to air quality concerns. In the Owens Valley, for example, where the soil is alkaline (Big Pine Paiute, 2022), and there has been a rise in the level of PM10 (Bishop Paiute, 2022) the Big Pine Paiute Tribe has reported eye, throat, and lung irritation during dust storms. The Tribe is concerned over the impacts of wind-blown dust on Paiute Tribal elders with lung issues and the growing number of cases of children with asthma and other breathing issues. Drought also stresses peoples' mental and emotional well-being (Barreau et al., 2017; CDC, 2016a and 2016b, 2017; Vins et al., 2015).

A visible surface water quality impact during the 2012-2016 drought came in the form of more frequent harmful algal blooms. These blooms appeared in freshwater bodies throughout the state, from the Klamath River in the north to Lake Elsinore and the Salton Sea in the south (CNRA, 2021). Certain bloom-forming organisms such as cyanobacteria, produce toxins that adversely impact people and their pets. In humans, exposure to these toxins can lead to a wide array of symptoms including skin rashes, blisters, vomiting, and abdominal pain (CWQMC, 2021; OEHHA, 2021b). In pets, exposure can be lethal (CNRA, 2021).

Exposures to the toxins can occur through consuming contaminated water and foods and by direct contact with water. Communities that rely on recreational water use to generate revenue from tourism and those who use freshwater bodies as drinking water sources are disproportionately affected. During periods of bloom, certain Tribes are unable to carry out cultural traditions or practices that involve immersion in, or other contacts with, water bodies. The Karuk's World Renewal Ceremonies in which the medicine man traditionally bathes and drinks Klamath River water overlaps annually with the highest levels of toxin in river water (Karuk, 2022). At Clear Lake, members of the Big Valley Band of Pomo Indians are prevented from spiritual activities, water immersion for ceremonies, using plants for ceremonies and basketry, and the collection and consumption of fish and other aquatic organisms when toxin levels are high (Big Valley, 2022). In addition, the Tribe has reported that clogged drinking water intakes in Clear Lake due to sludge induced by blooms, and that detection of toxins in raw water have led to additional operational and water treatment costs.

What factors influence this indicator?

Droughts are a naturally occurring feature of California's climate (DWR, 2021c). They are naturally influenced by modes of global climate variability such as the El Niño-Southern Oscillation, regional atmospheric pressure anomalies, and the frequency of landfalling "drought-busting" atmospheric rivers (Dettinger, 2013; Griffin and Achukaitis, 2014). Singular wet years composed of frequent landfalling atmospheric rivers can terminate persistent droughts (e.g., Dettinger, 2013; Hatchett et al. 2016). 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 (Seager et al., 2015).

Droughts of the 21[st] century are hotter, longer lasting, and spatially larger than previous droughts (Crausbay et al., 2017). 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; Griffin and Achukaitis, 2014; Luo et al., 2017; Hatchett et al. 2016; Harootunian, 2018) and worldwide (Chiang et al., 2021). Atmospheric circulation patterns like those observed during California's most extreme dry and hot years have increased during recent decades (Swain et al., 2016). Climate change may be increasing the likelihood of the type of rare atmospheric events associated with the 2012-2016 drought (Swain et al., 2017; Cvijanovic et al., 2017). Notably, this was part of a larger drought across the southwestern United States that has been described as a "megadrought." Using a tree-ring reconstruction to extend summer soil moisture records back to 800 CE, investigators determined 2000-2021 to be the driest 22-year period in the region over this period. About 19 percent and 42 percent of the dryness in 2021 and in 2000-2021, respectively, were attributable to anthropogenic climate change (Williams et al., 2022). Climate change will continue to make dry and warm years happen more often (Diffenbaugh et al., 2015) and drought conditions will worsen (Underwood et al., 2018; Ullrich et al., 2018). Other ways climate change directly contributes to drought conditions include more variable but less frequent precipitation (Gershunov et al., 2019) and widespread snowpack decline (Siirla-Woodburn et al., 2021; see the *Snow-water content* indicator).

As temperatures warm, the atmosphere takes up more water from land through evapotranspiration (McEvoy et al. 2020; Pottinger, 2020). "Evaporative demand," often referred to as the "thirst" of the atmosphere, reflects maximum evapotranspiration assuming unlimited moisture supply and ambient atmospheric conditions. Almost all the western U.S. has seen a rise in the atmosphere's thirstiness since the 1980s when temperatures began to noticeably warm (Pottinger, 2020). During the 2021 summer and water year, the evaporative demand over much of California was higher than it had been over the last 40 years (NIDIS, 2021). A thirstier atmosphere also means California's big storms will get even bigger because more water will go into the atmosphere (see the *Precipitation* indicator for a discussion on atmospheric rivers, which also affect heavy precipitation). Altogether, projections of climate change suggest that California will experience a perennial drought for most of the year, interrupted periodically by large storms that produce heavy to extreme precipitation (Pottinger, 2020).

Regional variations such as geography and local climate patterns also determine the extent and severity of droughts. The 2012-2016 drought was more severe in southern California, which has displayed greater drying trends over the past century than in northern California (Dong et al., 2019).

Technical considerations

Data characteristics

PDSI identifies droughts by incorporating data on temperature, precipitation, and the soil's water-holding capacity. The metric takes into consideration moisture received as precipitation and moisture stored in the soil, while also 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, 2017).

The U.S. Drought Monitor provides a big-picture look at drought conditions in the United States. As previously mentioned, along with PDSI, metrics used in the U.S. Drought Monitor include soil moisture data, streamflow conditions, the standardized precipitation index, and blends of various drought indicators.

Strengths and limitations of the data

The PDSI and USDM as used in this report are not intended to gather information about water availability or delivery in California.

PDSI is considered a robust index of drought, 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). It represents drought conditions in natural (unmanaged) systems only.

The USDM is based on many types of data, including observations from local experts across the country, as well as information about reservoir storage. It can be used to identify likely areas of drought impacts but should not be used to infer specifics about local conditions.

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