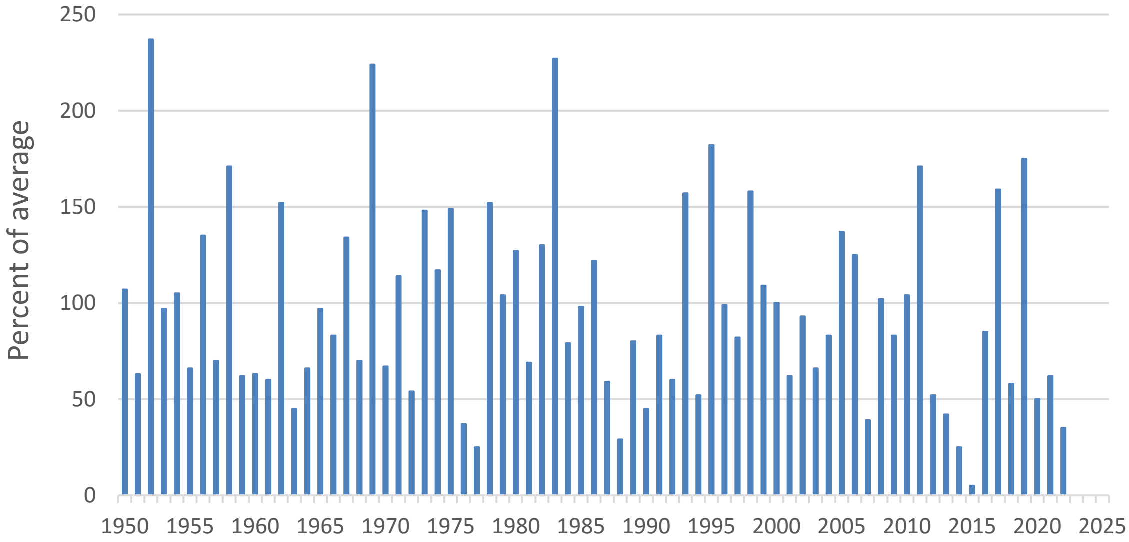
SNOW-WATER CONTENT

The amount of water stored in the state's snowpack varies greatly from year to year, reflecting the variability in the amount and form of precipitation over California's mountain areas. Average statewide snow-water content—a measure of the amount of liquid water contained in the snowpack—is about 28 inches. It has ranged from a high of about 240 percent of average in 1952 to a record low of 5 percent in 2015. In 2022, snow-water content was 35 percent of average.

Figure 1. Statewide April 1 snow-water content based on snow courses*
(Percent of average)



Source: DWR, 2022a

*Snow courses are permanent locations where snow-water content is measured by weighing cores of snow pulled from the entire depth of the snowpack at a given location. The measurements represent snowpack conditions at a given elevation in a given area.

What does the indicator show?

Since 1950, statewide snow-water content has been highly variable, ranging from more than 200 percent of average in 1952, 1969 and 1983, to 5 percent in 2015 during the multi-year drought (2012 to 2016) (Figure 1). The past decade included years that were among the lowest (2013, 2014, 2015 and 2022) and the highest (2011, 2017, 2019) on record. In 2022, snow-water content was 35 percent of average. The historical average snow-water content on April 1, based on the water years 1991-2020, is about 28 inches.

Snow-water content – also referred to as snow water equivalent – is the amount of water contained in snowpack. It represents the depth of water that would cover the ground if the snow cover was in a liquid state (NWS, 2018). It is traditionally measured by weighing the mass of a core of snow — from snow surface to soil — collected by an observer (snow gauger) in the field. The weight of snow is a measure of how much liquid water would be obtained by melting the snow over a given area. Manual measurements are taken near the first of the month starting about January 1 and ending in May. The most important one is taken around April 1, near the time when the snowpack has historically been deepest on a monthly scale. The statewide values are based on measurements taken at about 260 snow course stations from the Trinity Alps and Mount Shasta in northern California, and throughout the Sierra Nevada down to the Kern River basin in the south (see map in *Technical Considerations*).

Why is this indicator important?

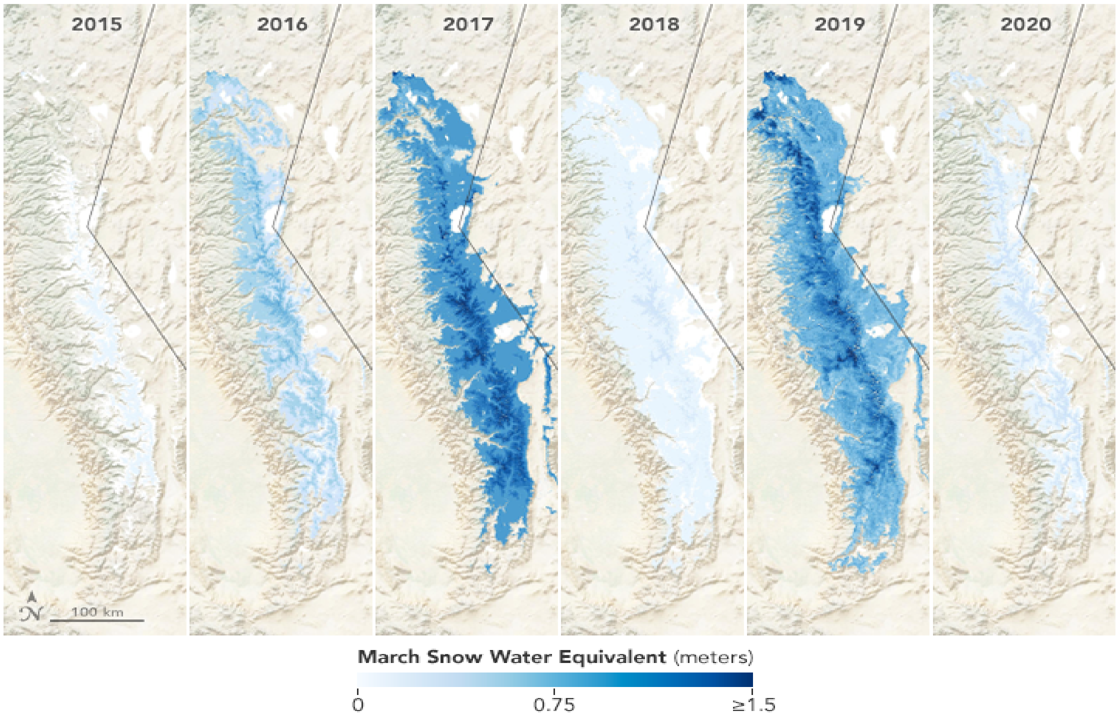
This indicator tracks how much water is locked up in the state's snowpack, which accumulates from October through March in the Sierra Nevada and southern Cascade Mountains. Although some of this water will be lost to direct evaporation and transpiration, most will be available to percolate into soils or run off into streams and rivers as temperatures rise. Sierra Nevada snowpack provides the primary source of streamflow in the Central Valley. The snowpack supplies water to meet human needs such as domestic and agricultural uses and hydroelectric production. It also supports ecosystems, for example by providing suitable aquatic habitat and moisture for forest vegetation. Snowpack is also vital for winter recreation and tourism (Hatchett and Eisen, 2018).

Historically, California's snowpacks contained the most water (about 15 million acre-feet) between mid-March and mid-April of each year, and the Sierra Nevada snowpack added about 35 percent to the reservoir capacity available in the state. While the date of maximum snow-water content may vary from year to year and place to place, measurements taken on April 1 have been used to estimate how much water stored in the state's snowpacks will be released as snowmelt later in the year.

Monitoring snowpack is key to managing both the state's water supplies and flood risks. California's water managers have developed a strategy of maintaining empty space in major reservoirs during winter, so that flows can be captured or at least reduced during large storms to prevent floods. By about April 1, flood risks generally decline considerably as large winter storms stop impacting California. At this time, reservoir managers change strategies and instead capture and store as much streamflow as possible in reservoirs for the summer when water demands are highest. This strategy works primarily because, during winter, the state's snowpacks are holding copious amounts of the winter's precipitation in the mountain watersheds, only releasing most of it as runoff after about April 1. In big snowpack years like 2017 and 2019, some of the early portion of the snowmelt is released in March and April prior to the normal peak snowmelt. The gradual release of snowmelt during the spring precludes the need for overly high-volume reservoir releases later in the runoff season. Forecasts of runoff volume and timing based on snow-water content data are a critical tool to guide reservoir operations. (Forecasts are published by the Department of Water Resources in Bulletin 120)

The series of maps in Figure 2 showing early March snowpack clearly illustrate the variability over the last six years in the Sierra Nevada: record low snowpack in 2015, an average year in 2016, two of the highest snowpack years in 2017 and 2019, and two years at about 60 and 50 percent of average – 2018 and 2020, respectively.

Figure 2. Snow-water equivalents across the Sierra Nevada in early March, 2015 to 2020



Source: NASA 2020

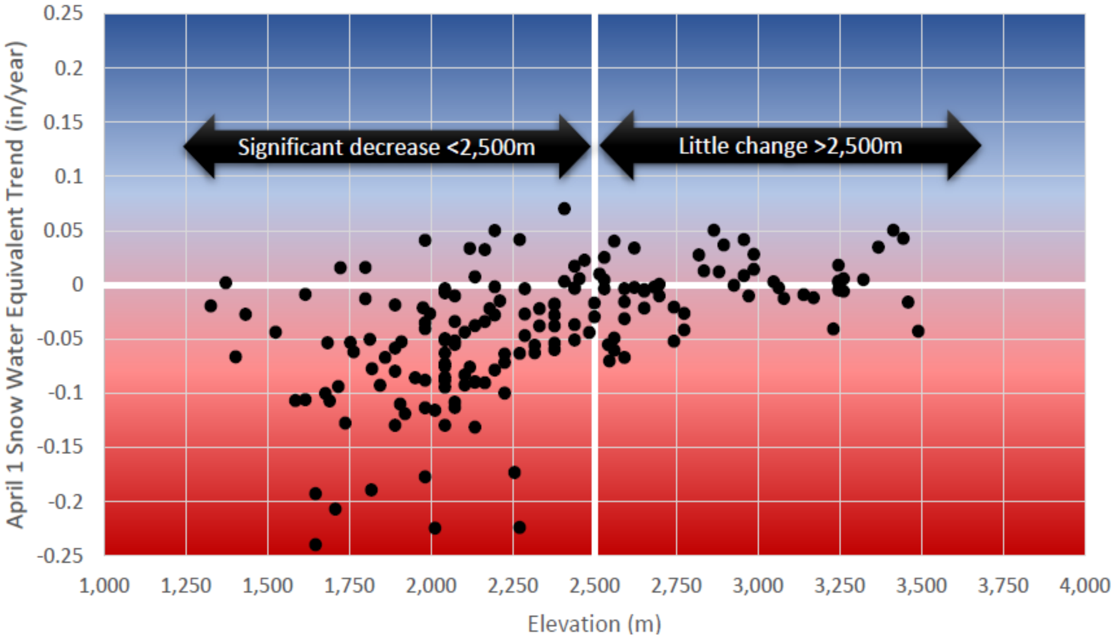
Maps developed by the University of Colorado's Center for Water, Earth Science, and Technology. Data are derived from ground-based data, computer models, and satellite imagery. They incorporate a data set from the [Jet Propulsion Laboratory] called the MODIS Snow Covered Area and Grain-size (MODSCAG), which uses data from NASA's Terra satellite to determine properties of the snow—things like the area covered, grain size, and albedo—that are useful for deriving accurate estimates of snow-water equivalent.

Adaptive strategies employing advanced observations, forecasts, and system management perspective are needed to maintain the functionality of the existing water management infrastructure in the face of climate change. Current management practices for water supply and flood management in California will need to be revised for a changing climate (Siirila-Woodburn et al., 2021). This is in part because such practices were designed for historical climatic conditions, which will continue to change as the climate warms. Adapting to a warming climate will bring numerous challenges to both supply and demand sides (Sterle et al., 2019), however planning for a future characterized by less water availability is prudent based on the state of climate science.

What factors influence this indicator?

Factors that affect snow-water content include winter and spring precipitation, air temperature, and elevation. Colder air temperatures at higher elevations generally mean higher snow accumulations compared to lower elevations. The influence of elevation is evident in an analysis of snowpack trends in the Sacramento River, San Joaquin River, and Tulare Lake Basins (see Figure 3; Riddlebarger et al., 2021).

Figure 3. 60-year trends in April 1 snow water equivalent at Sierra Nevada and Cascade Mountain snow courses, by elevation



Source: Riddlebarger et al., 2021

The 60-year trend at each snow course is represented by each dot. Over this period, snowpack has declined at 78 percent (129 of 166) of the snow courses: snow courses at elevations below 2,500 meters showed negative trends at an overall average of --0.07 inch/year; at higher elevations, the trends clustered between -0.05 and +0.05 inch/year.

The snow courses that make up the northern Sierra group in Figure 2 are at lower elevations (average 6,900 feet) compared to the southern group (average 8,900 feet). In the past 70 years, the proportion of precipitation as snow has decreased at the rate of 4 percent per decade over lower and middle elevation regions of the northern Sierra Nevada, while the highest elevations of the southern Sierra Nevada, where temperatures remain at or below 0°C during winter and spring, showed no declines (Lynn et al., 2020). In an analysis of data on April snow-water content and temperature from 1985 to 2016, the northern Sierra Nevada was found to be more vulnerable to warming than the southern region (Huning and AghaKouchak, 2018). Over the past decade, the average snow level (the altitude where precipitation changes from snowfall to rain) along the western slope of the northern Sierra Nevada has risen over 1,200 feet (Hatchett et al., 2017).

A study of trends in the Sierra Nevada snowpack found warm daily maximum temperatures in March and April to be associated with a shift toward earlier timing of peak snow mass by 0.6 day per decade since 1930; this earlier trend is associated with snow melting earlier, which also results in trends toward lower snow-water equivalent (Kapnick and Hall, 2010). Under climate change, warming is likely to lead to less snowpack if precipitation does not increase too markedly (Knowles and Cayan, 2004). If precipitation increases, snow-water content could increase in those areas above the retreating snowlines that are still cold enough to receive snowfall; if precipitation decreases, snow-water content may be expected to decline even faster than due to warming alone.

The term “snow drought” refers to anomalously low snow-water content (Cooper et al. 2016). Snow drought occurs under conditions that reflect either a lack of winter precipitation (“dry” snow drought) or near-normal winter precipitation when temperatures prevent accumulation of snowpack (“warm” snow drought) (Harpold et al., 2017). During water years 1951 to 2017 in the northern Sierra Nevada, snow droughts have originated and evolved in various ways, including from extreme early season precipitation, frequent rain-on-snow events, low precipitation years, lower fractions of precipitation falling as snow, and midwinter peak runoff events (Hatchett and McEvoy, 2018). Consecutive snow drought years, which currently occur in the western United States at about 7 percent of the time, are projected to become more frequent in the mid-21st century, occurring at about 42 percent of the time under a high greenhouse gas emissions scenario (Marshall et al., 2019).

The record low snowpack in 2015 was accompanied by the warmest winter temperatures as well as the fifth lowest precipitation volume since 1950 (see *Air Temperature* and *Precipitation* indicators). In addition to enhancing the likelihood of rain instead of snow, warm temperatures increase the frequency of melt events, leading to a reduction of snow-water content. Across western North America, early snowmelt has increased at over one-third of the long-term snow stations studied; at these locations, snowmelt occurred before peak snow accumulation (Musselman et al., 2021). The same study found decreased snow-water content at about 11 percent of snow stations. Snowmelt trends were found to be highly sensitive to temperature, while trends in snow water equivalent were more sensitive to variability in precipitation.

Across the western United States, a broad pattern of declining snowpack has been reported (e.g., Siirila-Woodburn et al. 2021; Musselman et al., 2021; Mote et al., 2018; Mote, 2003; Barnett et al., 2008). Declining trends have been observed across all months, states, and climates, but are largest in spring, in the Pacific states, and in locations with mild winter climate (Mote et al., 2018). By removing the influence of natural variability, investigators showed a robust anthropogenic decline in western U.S. snowpack since the 1980s, particularly during the early months of the accumulation season (October–November) (Siler et al., 2019).

To a lesser extent, snow-water content may be influenced by the amount of solar radiation that falls on the snowpack in each season, which, in turn, depends on cloudiness and timing of the beginning of the snowmelt season (Lundquist and Flint, 2006). Cloudiness decreases solar radiation on the snowfields, and would tend to result in less wintertime snowmelt and thus more snow-water content left by April 1 (the opposite would occur if cloudiness declines in the future).

A potential confounding factor in the variation and trends in snowpack is the effect of dust and air pollutants (including black carbon, a component of soot) on both the initial formation of mountain snowpack and on snowmelt timing. Field measurements and modeling have shown that the presence of dust in the atmosphere, including dust from Asia and the Sahara carried to California by high-altitude winds, may increase snowfall over the Sierra Nevada by serving as ice nuclei, which in turn could contribute to increased snowpack (Ault et al., 2011; Cremean et al., 2013). Recent studies in the Colorado River Basin have helped to quantify important influences on snowmelt timing and, ultimately, amounts that are due to springtime snow albedo (reflectivity) changes associated with dust (mostly from within the region) falling onto snow surfaces across the Western US (e.g., Painter et al., 2010). Black carbon, which in burned forests is deposited onto the snow surface, has been measured in the Sierra Nevada snowpack at concentrations sufficient to increase surface temperatures and increase snowmelt (Hadley et al., 2010). These factors likely play roles in past and future variations of April 1 snowpack amounts, but the long-term past and future trends in these additional factors in California remain largely unknown at present.

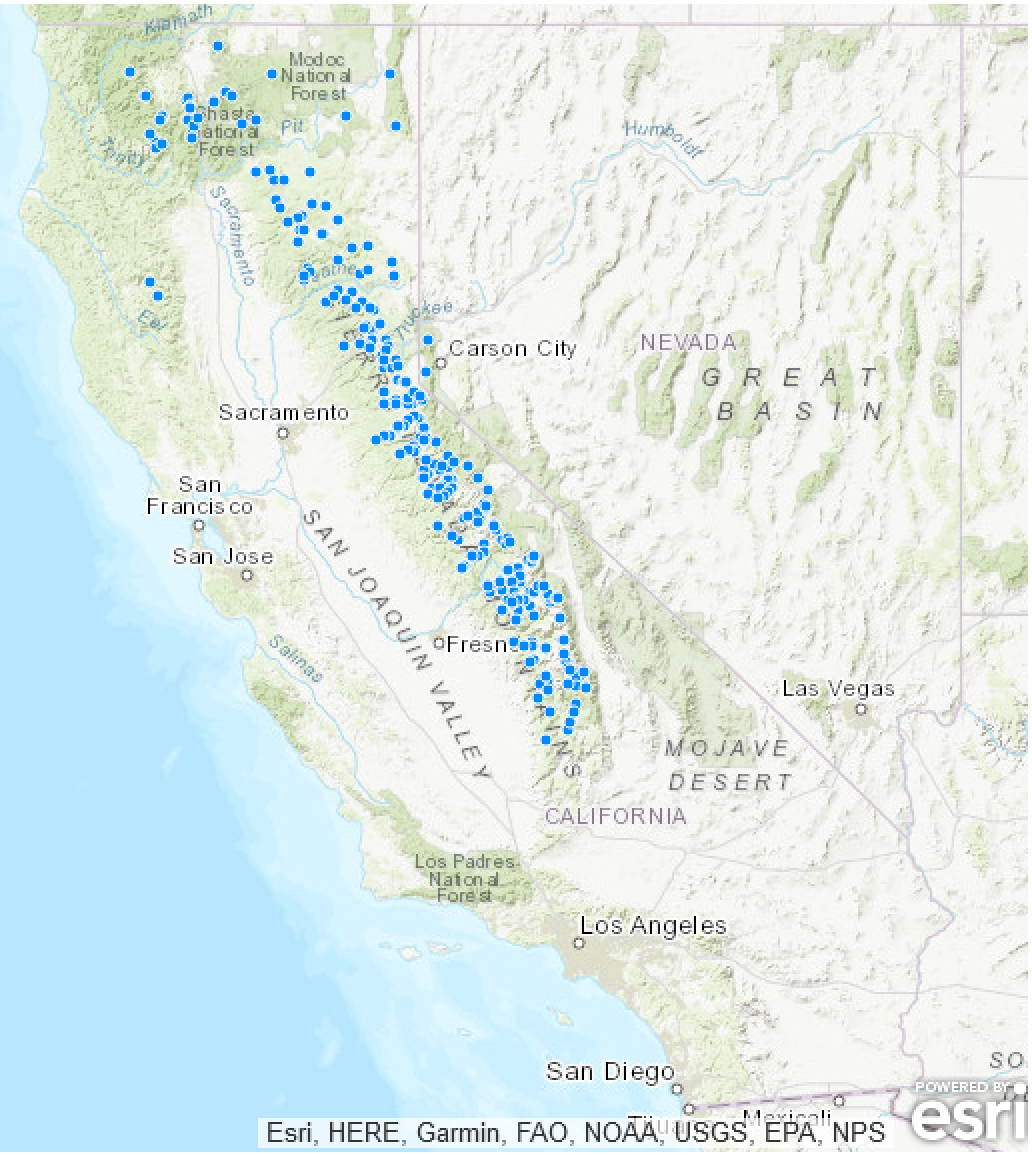
Technical Considerations

Data characteristics

Statewide snow-water content is based on observations from permanent snow courses. At these locations, snow-water content is measured by weighing cores of snow pulled from the whole depth of the snowpack at a given location. Since the 1930s, within a few days of the beginning of each winter and spring month, measurements have been taken along snow course locations that represent snowpack conditions at a given elevation in a given area.

Measurements are taken by skiing or flying to remote locations and extracting 10 or more cores of snow along ¼ mile-long pre-marked “snow course” lines on the ground. The depth of snow and the weight of snow in the cores are measured. The weights are converted to a depth of liquid water that would be released by melting that weight of snow, and the results from all the measurements at the snow course are averaged to arrive at estimates of the snow-water content at that site (Osterhuber, 2014). More than 50 state, federal and private entities pool their efforts in collecting snow data from over 250 snow courses in California (see Figure 4 for locations).

Figure 4. Location of snow courses



Source: DWR, 2022b

The map shows permanent snow courses where snow-water content is measured during regular snow surveys (more details in text).

Data from monthly snow surveys are supplemented by daily information from an automatic snow sensor network (often called snow pillows), developed and deployed over the last 30 years. They serve as a valuable check on the representativeness and accuracy of the snow-course measurements. The snow sensors measure the accumulation and melting cycles in the snowpack, providing data on the effect of individual storms or hot spells. In addition to tracking changes during the snow accumulation season, snow sensor data help greatly in forecasting water volumes involved in the late-season filling of reservoirs. There are approximately 130 snow sensor sites from the Trinity Alps to the Kern River, with 36 sites included from the Trinity area south to the Feather and Truckee basins, 57 sites from the Yuba and Tahoe basins to the Merced and Walker basins, and 36 sites from the San Joaquin and Mono basins south to the Kern basin.

Snow-water content data for snow courses and snow sensors can be downloaded from the Department of Water Resources' California Data Exchange Center.

Strengths and limitations of the data

The measurements are relatively simple, and the methods have not changed since monitoring started. Averaging of the 10 or more measurements at each course yields relatively accurate and representative results for each survey.

OEHHA acknowledges the expert contribution of the following to this report:

Sean de Guzman, P.E.
California Department of Water Resources
sean.deguzman@water.ca.gov

Michael L. Anderson, Ph.D., P.E.
Michael.L.Anderson@water.ca.gov

Elissa Lynn
elissa.lynn@water.ca.gov

Peter Coombe
peter.coombe@water.ca.gov

Benjamin Hatchett, Ph.D.
Western Regional Climate Center
Benjamin.Hatchett@dri.edu

References:

Ault AP, Williams CR, White AB, Neiman PJ, Creamean JM, et al. (2011). Detection of Asian dust in California orographic precipitation. *Journal Geophysical Research* **116**(D16).

Barnett TP, Pierce DW, Hidalgo HG, Bonfils C, Santer BD, et al. (2008). Human-Induced Changes in the Hydrology of the Western United States. *Science* **319**(5866): 1080-1083.

Cayan DR and Webb R (1992). El Niño/Southern Oscillation and streamflow in the western United States. In: *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation*. Diaz HF and Markgraf V (Eds.). New York: Cambridge University Press, 29-68.

Cooper MG, Nolin AW and Safeeq M (2016). Testing the recent snow drought as an analog for climate warming sensitivity of Cascades snowpacks. *Environmental Research Letters* **11**: 084009.

Creamean J, Suski K, Rosenfeld D, Cazorla A, DeMott P, et al. (2013). Dust and biological aerosols from the Sahara and Asia influence precipitation in the Western U.S. Science **339**: 1572–1578.

DWR (2022a). California Department of Water Resources. Snow Course Data provided by Peter Coombe and Sean de Guzman, also California Statewide April 1 Snow Water Equivalent. Retrieved January 9, 2022. Individual snow course data available from California Data Exchange Center.

DWR (2022b). California Department of Water Resources. Snow Courses in California. California Data Exchange Center: CDEC Station Locator. Retrieved January 9, 2022.

Hadley OL, Corrigan CE, Kirchstetter TW, Cliff SS and Ramanathan V (2010). Measured black carbon deposition on the Sierra Nevada snow pack and implication for snow pack retreat. *Atmospheric Chemistry and Physics* **10**: 7505-7513.

Hatchett BJ, Daudert B, Garner CB, Oakley NS, Putnam AE et al. (2017). Winter Snow Level Rise in the Northern Sierra Nevada from 2008 to 2017. *Water* **9**(11): 899.

Kapnick S and Hall A (2010). Observed Climate–Snowpack Relationships in California and their Implications for the Future. *Journal of Climate* **23**: 3446–3456.

Knowles N and Cayan DR (2004). Elevational dependence of projected hydrologic changes in the San Francisco estuary and watershed. *Climatic Change* **62**(1-3): 319-336.

Knowles N, Dettinger MD and Cayan DR (2006). Trends in Snowfall versus Rainfall in the Western United States. *Journal of Climate* **19**: 4545–4559.

Lundquist JD and Flint AL (2006). Onset of snowmelt and streamflow in 2004 in the western United States: How shading may affect spring streamflow timing in a warmer world. *Journal of Hydrometeorology* **7**(6): 1199-1217.

McCabe GJ and Dettinger MD (2002). Primary modes and predictability of year-to-year snowpack variations in the western United States from teleconnections with Pacific Ocean climate. *Journal of Hydrometeorology* **3**(1): 13-25.

Mote PW (2003). Trends in snow water equivalent in the Pacific Northwest and their climatic causes. *Geophysical Research Letters* **30**(12): 1601.

Mote, PW, Hamlet AF, Clark MP and Lettenmaier DP (2005). Declining mountain snowpack in western North America. *American Meteorological Society* **86**(1): 39–49.

NASA (2021). National Aeronautics and Space Administration: Thin Snow Cover in the Sierra Nevada Snowpack in the Sierra Nevada. Retrieved July 29, 2021.

NRCS (2018). Natural Resources Conservation Service. Snow Surveys and Water Supply Forecasting. Retrieved February 21, 2018.

NWS (2018). National Weather Service. Snow water equivalent and depth information. Retrieved February 21, 2018.

Osterhuber R (2014). Snow Survey Procedure Manual. Prepared for the California Department of Water Resources, California Cooperative Snow Surveys.

Painter TH, Deems JS, Belnap J, Hamlet AF, Landry CC et al. (2010). Response of Colorado River runoff to dust radiative forcing in snow. *Proceedings of the National Academy of Sciences* **107**(40): 17125-17130.

Riddlebarger M, Curtis DC and Cunha L (2021). *Sierra Nevada Mountain Snowpack Trends*. White Paper. WEST Consultants, Inc. April 8, 2021.

Roos M (2000). Possible Effects of Global Warming on California Water or More Worries for the Water Engineer. *W.E.F. Water Law and Policy Briefing*. San Diego, CA, Department of Water Resources.

Roos M and Fabbiani-Leon A (2017). Recent Changes in the Sierra Snowpack in California. Presented at the 2017 Western Snow Conference.

Roos M and Sahota S (2012). Contrasting Snowpack Trends in the Sierra Nevada of California. Presented at the 2012 Western Snow Conference.

Siirila-Woodburn ER, Rhoades AM, Hatchett BJ. Huning LS, Szinai J, et al. (2021). A low-to-no snow future and its impacts on water resources in the western United States. *Nature Reviews Earth Environment* **2**: 800–819.

Sterle K, Hatchett BJ, Singletary L and Pohll G (2019). Hydroclimate variability in snow-fed river systems: Local water managers' perspectives on adapting to the new normal. *Bulletin of the American Metrological Society* **100**(6): 1031-1048.

USEPA (2016). US Environmental Protection Agency. Climate Change Indicators: Snowpack. Retrieved December 1, 2017.