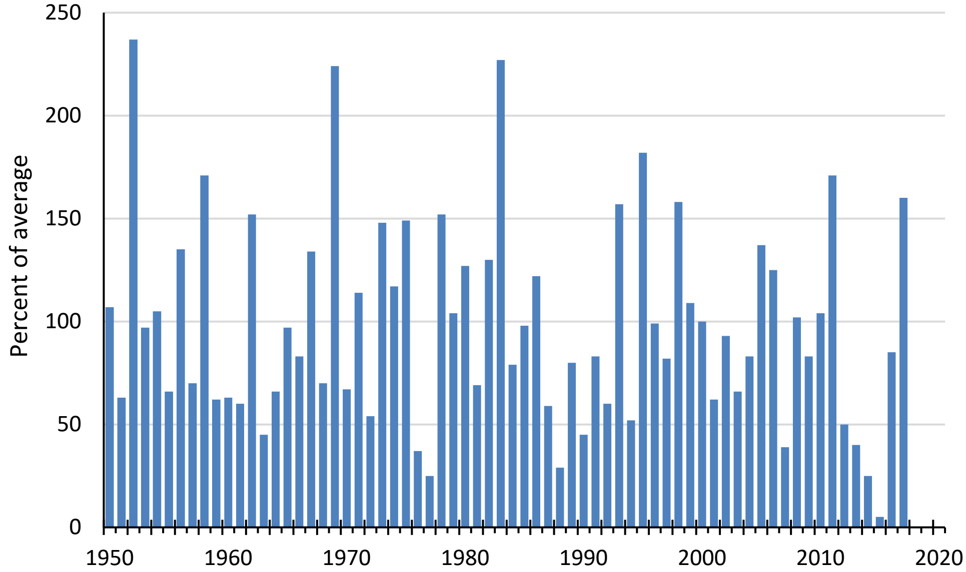
SNOW-WATER CONTENT

The amount of water stored in the state's snowpack has been highly variable from year to year, ranging from a high of about 240 percent of average in 1952 to a record low of 5 percent in 2015.

Figure 1. Statewide April 1 snow-water content (Percent of average)



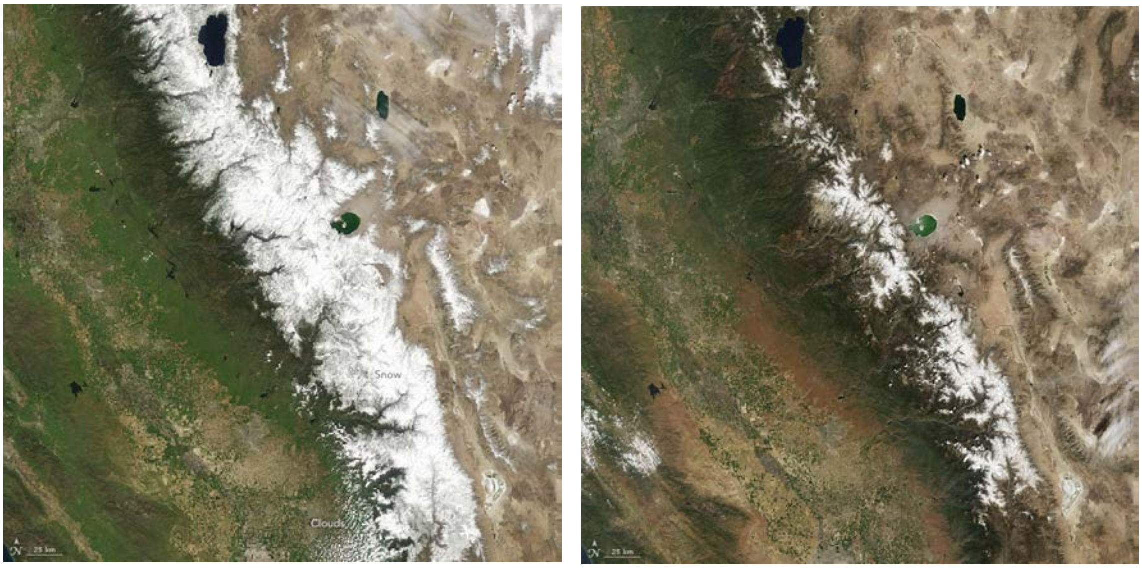
Source: DWR, 2017a

What does the indicator show?

The amount of water contained in California's snowpack — expressed as "snow water content" — is highly variable from year to year. Snow-water content is the depth of water, usually expressed in inches, 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; more recently, sensing devices take measurements of the mass of snow laying on top of a large scale, called a snow pillow. In either case, 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, when the snowpack has historically been deepest; these measurements are used by water managers for water supply forecasting and operations. The historical average snow-water content on April 1 is about 28 inches.

As shown in Figure 1, since 1950, statewide snow-water content has ranged from more than 200 percent of average in 1952, 1969 and 1983, to the lowest value on record, 5 percent, during the drought in 2015 (see satellite images comparing the 2015 snowpack with average conditions, Figure 2). In 2017, snowpack was at 160 percent of average. These statewide values reflect measurements taken at about 250 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.

Figure 2. Satellite images showing average conditions of the Sierra Nevada snowpack in 2010 (left) and the record-low snowpack in 2015

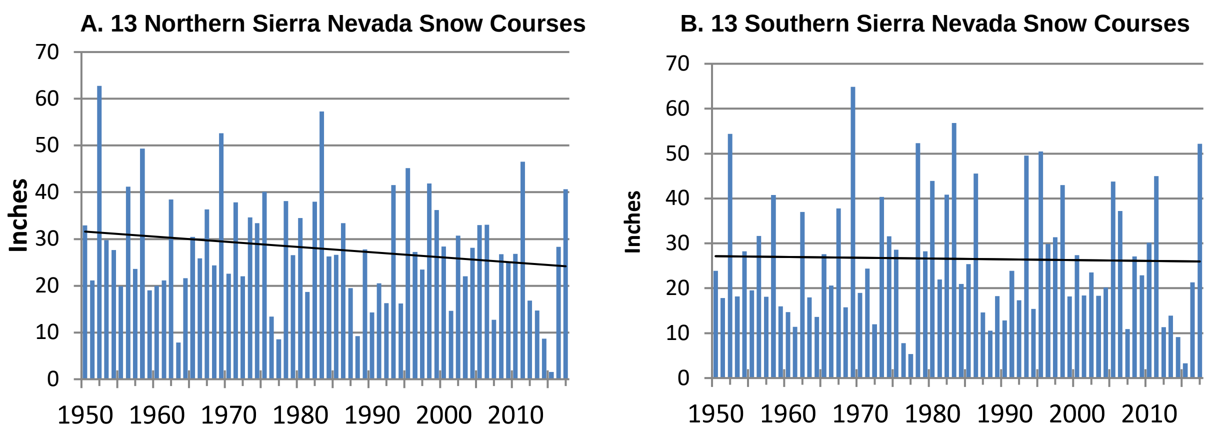


March 26, 2010 March 31, 2015

Source: NASA, 2017

Over the time period from 1950 to present, snow-water content in both the northern and southern Sierra Nevada long-term snow courses have been declining (Figure 3A and B), part of a broader pattern of declining snowpack across the West. Snow courses are permanent locations that represent snowpack conditions at a given elevation in a given area; further details are provided in *Technical Considerations.*

Figure 3. April 1 Snow-Water Content*



Source: DWR, 2017a

** Snow–water content is measured in inches, equivalent to amount of water that would be obtained by meling snow over a given area.*

When snowpack trends were examined in 2009 and 2012, the northern Sierra Nevada showed a decline, but courses in the southern Sierra Nevada showed a small increase. Factors which may account for this difference in trends are discussed in *What factors* *influence this indicator?* A more recent reevaluation of snowpack trends showed that the southern Sierra group is now declining although the slope is flatter than in the northern Sierra group of snow courses (DWR, 2017a; Roos and Fabbiani-Leon, 2017). In 2017, the snowpack trend for the southern Sierra group showed an overall decline of about 1.2 inches since 1950, compared to 7.4 inches for the northern Sierra group of snow courses (DWR, 2017a).

Why is this indicator important?

Snow-water content is a measure of how much water is locked up in the snowpack at a given location. Although some of this water will be lost to direct evaporation, most will be available to run off into streams and rivers or percolate into soils once the snow melts in spring and summer.

The Sierra Nevada snowpacks are an integral part of the state's water-supply. They serve as natural water storage, adding about 35 percent to the reservoir capacity available in the state. Information on the amount of water stored in the snowpack is used by water managers to forecast the availability of water to meet the state's water needs for domestic and agricultural uses, hydroelectric power production, and recreation. The water stored in the snowpack also plays a role in the ecosystem, providing cold water habitat for salmonid fishes (Roos, 2000), and water for forests.

Traditionally, California's snowpacks are thickest and contain the most water by about April 1 of each year — at which time they have historically stored about 15 million acre-feet of water. 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. Although the timing of maximum snowpack is predicted to come earlier in the year as the climate warms, continued monitoring of the April 1 snowpack should provide the data needed to determine changes in total warm-season water supplies from snowmelt.

California receives its largest and most dangerous storms during the wintertime. Likewise, its most devastating floods have occurred during the same season. In order to balance flood-risk management and water-supply considerations, California's water managers have developed a strategy of maintaining empty space in the major reservoirs during winter, so that flood flows can be captured or at least reduced when necessary. By about April 1, when most of the winter storms stop reaching California, flood risks generally decline considerably. At this time, reservoir managers change strategies and instead capture as much streamflow as possible to fill flood-control spaces to store water in the 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 to reservoirs after about April 1. In a big snowpack year like 2017, some of the early portion of the snowmelt will be 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. The forecasted volume becomes a tool to guide reservoir operations.

To the extent that climate change depletes the state's snowpacks in the future (Knowles and Cayan, 2004), this historical flood- and water-management strategy will be severely challenged. Thus, it is important to monitor whether the state's snowpacks are declining, increasing, or staying the same.

What factors influence this indicator?

April 1 snow-water content is determined by winter and spring precipitation totals and by air temperatures, which affect whether precipitation falls as rain or as snow. Elevation matters. Cooler air temperatures at higher elevations generally mean higher snow accumulations compared to lower elevations. The average elevation of the northern Sierra group of 13 courses is 6,900 feet, whereas the average is 8,900 feet for the southern group.

The record low snowpack in 2015 was accompanied by the warmest winter temperatures since 1950. The average minimum winter temperature in 2015 was 37.1^{o}F, about 5 ^{o}F higher than the long-term average (WRCC, 2017). 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. 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). Over the past decade, the average snow level (altitude where precipitation changes from snowfall to rain) along the western slope of the northern Sierra Nevada has risen over 1,200 feet — a change hypothesized to be related to atmospheric rivers that are predominantly associated with low snow-fraction storms and anomalously warm coastal sea surface temperatures (Hatchett et al., 2017). A decade of available data is not sufficient to connect this change to longer term snow-rain trends in recent decades (Knowles et al., 2006). However, the change is large enough and important enough so that following the altitudes of snowlines offers a metric to assess hydrologic impacts of climate change in the mountains.

The declines in snow-water content are part of a much broader pattern of declining snowpacks across the western United States — a pattern that has been associated with springtime warming trends and earlier snowmelt seasons in recent years by several different scientific studies (e.g., Mote, 2003; Barnett et al., 2008). Prior to the 2012-2016 drought, increases in the southern Sierra Nevada were part of a more localized pattern associated with El Niño climate conditions since about the mid-1970s (e.g., McCabe and Dettinger, 2002). During El Niño winters, the southwestern United States, including the southern Sierra Nevada, is typically wetter (Cayan and Webb, 1992), so that snowpacks are consequently thicker and store more water by April. The southern Sierra Nevada snowpack may also be influenced by weather modification programs that generate snow through cloud seeding programs.

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.

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 snowpacks and on snowmelt timing. Recent field measurements and modeling have provided potentially important indications that the presence or absence of dust in the atmosphere, including dust carried to California by high-altitude winds from Asia, may help to determine amounts of snowfall over the Sierra Nevada, which in turn could contribute to variations and trends in April 1 snowpack (Ault et al., 2011). 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 has been measured in the Sierra Nevada snowpack at concentrations sufficient to affect snowmelt and surface temperatures (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.

In its *Climate Change Indicators Report*, the US Environmental Protection Agency presents an indicator showing declining trends in April snowpack for the Western United States from 1955 to 2016 (US EPA, 2016); an interactive map can be accessed from the US EPA's website. Of the 233 sites in California, all except for 24 showed declining trends.

Technical Considerations

Data Characteristics

Snow-water content has traditionally been 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 permanent snow courses — 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; 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 300 snow courses in California.

To examine trends for the Northern and Southern Sierra Nevada, snow courses that have fairly complete records from 1950 (that is, sites with the fewest missing years of data), and that provide a good representation of the region were selected (by DWR, see Roos and Sahota, 2012). The thirteen snow courses selected for each region are as follows:

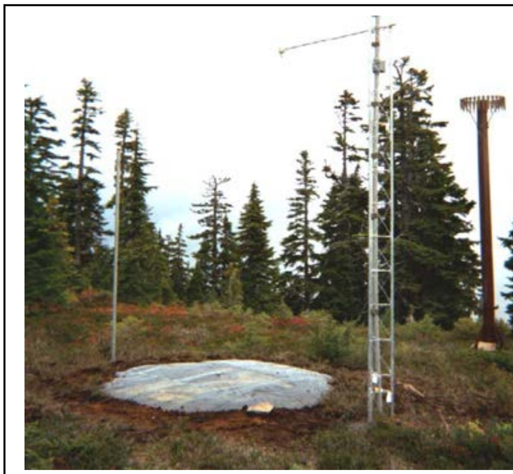
Northern Sierra Nevada	River Basin	Elevation, in feet
North Fork Sacramento	Upper Sacramento	6900
Cedar Pass	Upper Sacramento	7100
Adin Mountain	Upper Sacramento	6800
Mount Dyer	Feather	7100
Harkness Flat	Feather	6600
Feather River Meadow	Feather	5400
Webber Peak	Yuba	7800
Meadow Lake	Yuba	7200
Cisco	Yuba	5900
Lake Spaulding	Yuba	5200
Upper Carson Pass	American	8500
Silver Lake	American	7100
Blue Lakes	Mokelumne	8000
Southern Sierra Nevada	River Basin	Elevation, in feet
Piute Pass	San Joaquin	11300
Agnew Pass	San Joaquin	10300
Kaiser Pass	San Joaquin	9100
Florence Lake	San Joaquin	7200
Blackcap Basin	Kings	10300
Beard Meadow	Kings	9800
Upper Burnt Corral	Kings	9700
Long Meadow	Kings	8500
Helms Meadow	Kings	8250
Panther Meadow	Kaweah	8600
Giant Forest	Kaweah	6400
Ramshaw Meadows	Kern	8700
Little Whitney Meadows	Kern	8500

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. 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 now 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 website (DWR, 2017b).

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. During the past three decades, continuous snow-measurement instrumentation has been established at many of the snow courses. These sensors provide snow-water content information at more frequent time intervals, and serve as a valuable check on the representativeness and accuracy of the snow-course measurements.

The sensors measure the weight of snow on the ground (along with several meteorological variables) with a snow pillow (see photograph, right). Snow pillows are large (10 foot (') diameter), flat, flexible tanks or a group of four interconnected 4' x 5' sheet metal tanks filled with denatured alcohol or other liquids that do not freeze at winter temperatures, buried just below the ground surface. As snow piles up on the pillows, it squeezes the tanks and liquids they contain, raising the pressure in the tanks, and that pressure change is used to determine the weight of snow on the tank and ground. The sensor network provides important data for assessing changes in snowpack and the effect of storms, supplementing data from monthly snow course measurements.



A typical snowpack telemetry site includes a snow pillow, an antenna with solar panels and a temperature sensor, and a precipitation gauge (brown structure in background, right)

Source: NRCS, 2018

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