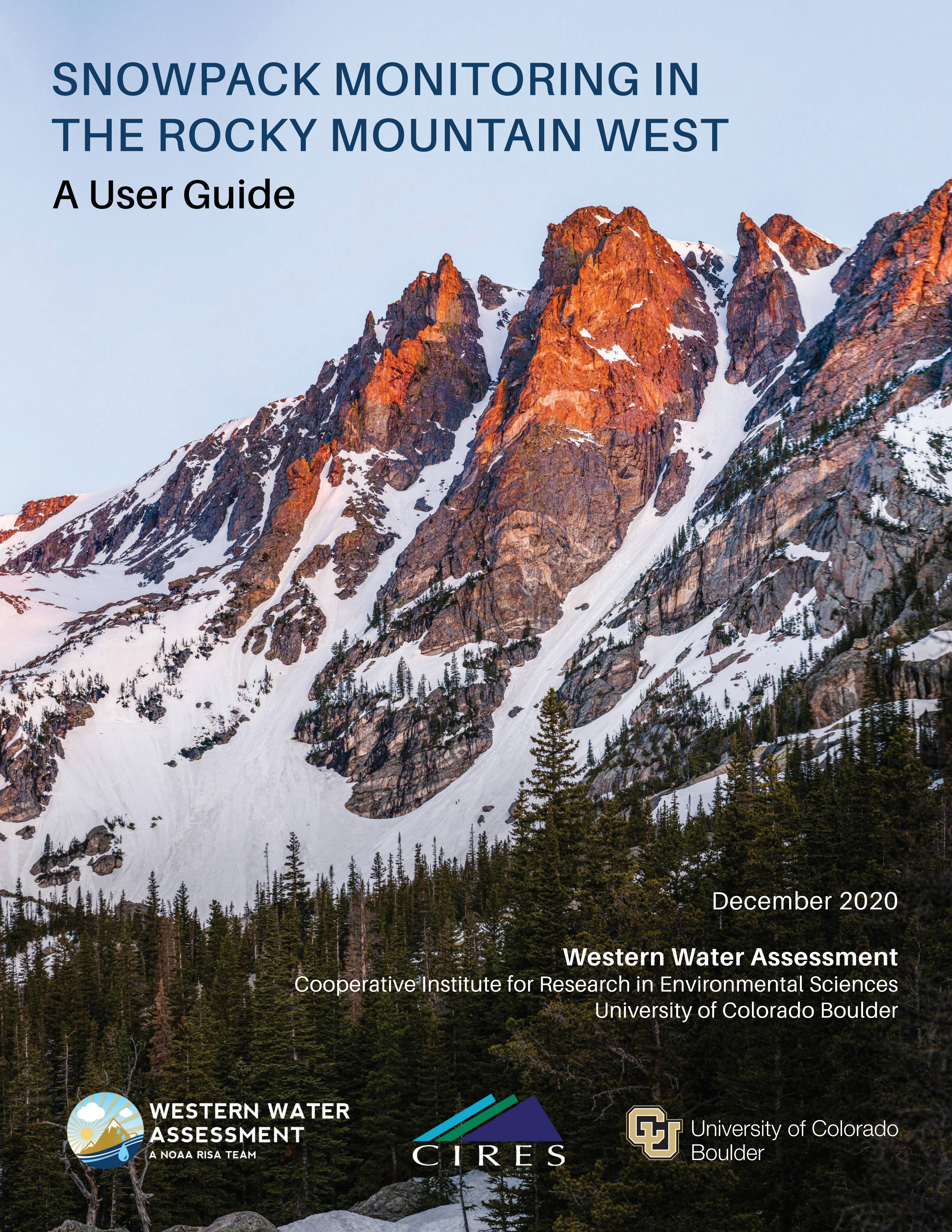


SNOWPACK MONITORING IN THE ROCKY MOUNTAIN WEST

A User Guide

December 2020

Western Water Assessment
Cooperative Institute for Research in Environmental Sciences
University of Colorado Boulder

WESTERN WATER ASSESSMENT
A NOAA RISA TEAM

CIRES

University of Colorado Boulder

SNOWPACK MONITORING IN THE ROCKY MOUNTAIN WEST: A USER GUIDE

Western Water Assessment
Cooperative Institute for Research in Environmental Sciences (CIRES)
University of Colorado Boulder

Lineke Woelders
Jeff Lukas *
Liz Payton
Benét Duncan

December 2020

Suggested citation: Woelders, L., J. Lukas, E. Payton, and B. Duncan, 2020. *Snowpack Monitoring in the Rocky Mountain West: A User Guide*. Western Water Assessment. Available online at http://wwa.colorado.edu/publications/reports.

Western Water Assessment (WWA) is a university-based applied research program that addresses societal vulnerabilities to climate variability and climate change in the Rocky Mountain West – Colorado, Utah, and Wyoming. We are part of the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado Boulder. Support for our program and this guide comes from NOAA's Regional Integrated Sciences and Assessments (RISA) Program.

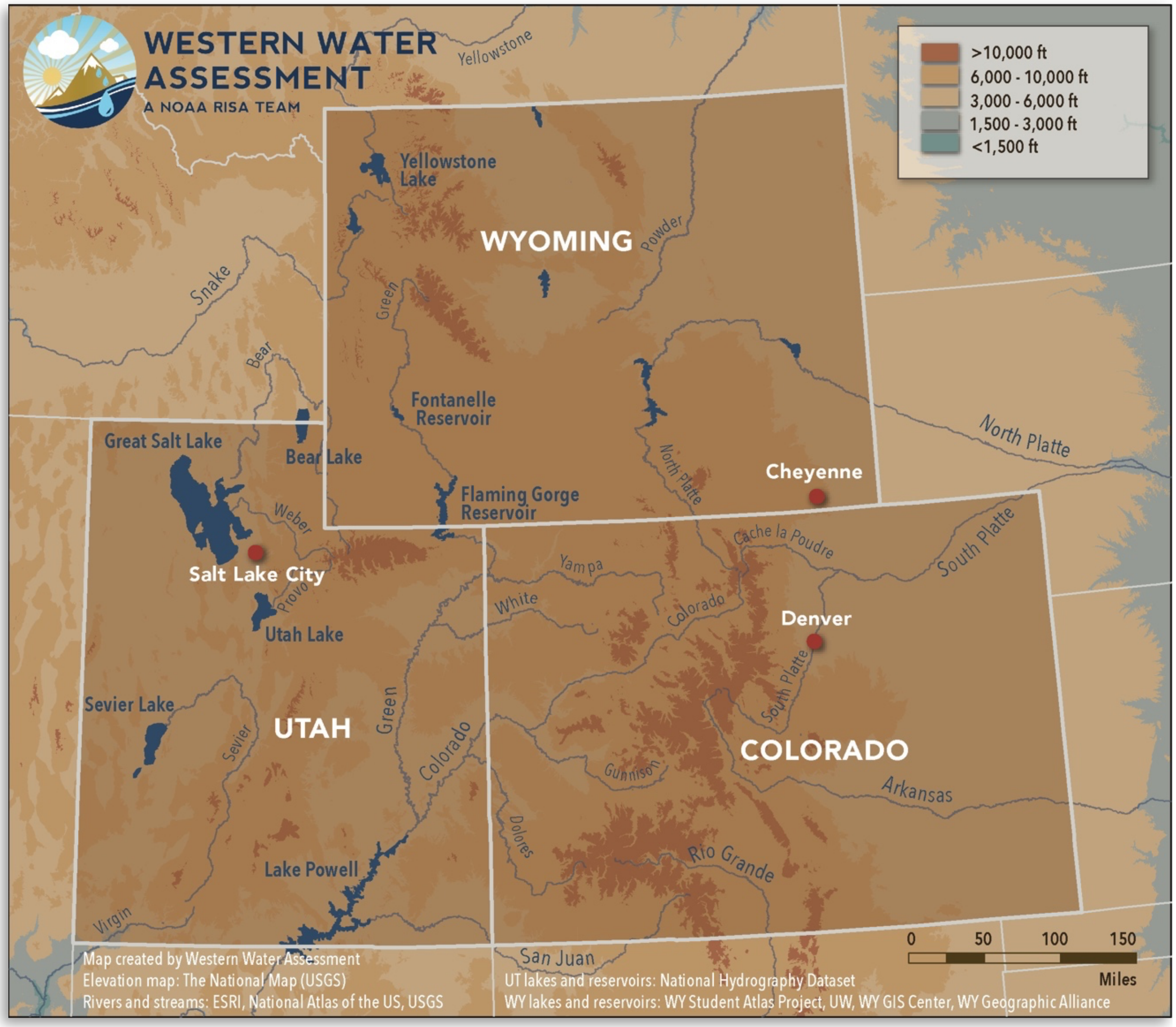
Cover Photo: Dream Lake, Colorado by Vincent Ledvina on Unsplash

* Current affiliation: Lukas Climate Consulting and Research, Louisville, CO

Contents

Section 1. Why a snowpack user guide?

In the Rocky Mountain West, snow is a dominant player in the hydrologic cycle. Across the states of Colorado, Utah, and Wyoming (where Western Water Assessment focuses its work, Figure 1), most of the region's annual streamflow—about 60-85%—originates as snowmelt [1]. The region's snowpack is effectively an enormous seasonal reservoir that fills and then empties every year. Schneider and Molotch (2016) show that across the states of Colorado, Utah, and Wyoming (where Western Water Assessment focuses its work, Figure 1) this snow reservoir has an average seasonal peak volume of about 40 million acre-feet, equivalent to 1.5 times the capacity of Lake Powell [2]. SWANN (Snow-Water Artificial Neural Network Modeling System) estimates of 1982-2019 median April 1st SWE volume, accessed via SnowView (https://climate.arizona.edu/snowview/) show a similar seasonal peak volume for this region.



Map created by Western Water Assessment
Elevation map: The National Map (USGS)
Rivers and streams: ESRI, National Atlas of the US, USGS
UT lakes and reservoirs: National Hydrography Dataset
WY lakes and reservoirs: WY Student Atlas Project, UW, WY GIS Center, WY Geographic Alliance

Figure 1. The Western Water Assessment's region comprises the states of Wyoming, Utah, and Colorado.

Since variation in the size of the snowpack from year to year strongly controls the magnitudes of seasonal, annual, and peak streamflows, monitoring the evolution of the snowpack over the course of the winter and spring is critical to forecasting streamflow and managing water supply. Snow monitoring is also vital to other river-based interests, such as fisheries management and guided rafting.

We assembled this guide for water managers, decision makers, forecasters, researchers, and others who use, collect, and produce snow information. The guide is organized around five objectives:

- Outline the fundamental characteristics of the snowpack, the processes that drive its variability over time and space, and the challenges of sampling such a dynamic resource.
- Highlight the key role of snowpack in seasonal water supply forecasting.
- Describe the SNOwpack TELemetry (SNOTEL), snow course, and other networks of point observations.
- Summarize the several products providing spatial estimates of snowpack derived from point observations, snow models, and remote sensing.
- Provide practical guidance on accessing, interpreting, and applying snow data.

Table 1 summarizes the data and products covered in this guide.

Table 1. Overview of the snow monitoring networks and products described in this guide [3].

Network or Product	Method and input data	Snow variables	Spatial resolution or # Stations	Spatial coverage	Temporal resolution
SNOTEL (NRCS)	In situ measurement	SWE, snow depth, precipitation, other weather obs.	336 stations in CO/UT/WY; ~900 stations West-wide	West-wide	Hourly
Snow course (NRCS)	In situ measurement	SWE, snow depth, snow density	178 courses in CO/UT/WY	West-wide	Monthly or semi-monthly
COOP (NOAA; volunteer observers)	In situ measurement	Snowfall, snow depth, daily precipitation	100s of sites, though few at high elevations	US-wide	Daily
CoCoRaHS (volunteer observers)	In situ measurement	Snowfall, snow depth, daily SWE accumulation	1000s of sites, though few at high elevations	US-wide	Daily

Network or Product	Method and input data	Snow variables	Spatial resolution or # Stations	Spatial coverage	Temporal resolution
ASO (NASA JPL)	Integrated airborne lidar and imaging spectrometer measures snow depth and albedo; fusion with measured/modeled snow density produces SWE	SWE, snow depth, snow albedo, snow grain size, dust radiative forcing	50 m	By watershed as flights are made on demand	As flights are made on demand; typically 1-6 per season
MODSCAG (NASA JPL)	MODIS satellite imagery used to derive snow extent and properties	Fractional snow-covered area, snow grain size	~500 m	US-wide	Daily, 2-4 day lag
MODDRFS (NASA JPL)	MODIS satellite imagery used to derive snow properties	Radiative melt forcing	~500 m	North and South America	Daily, 2-4 day lag
SNOW-17 snow model (NOAA CBRFC and other RFCs)	Snow model using area-averaged precipitation data derived from point observations, plus freezing-level data	SWE, snow covered area	~600 modeling units in the Colorado River Basin	CBRFC domain (Colo. Riv. Basin + E. Great Basin)	Daily
SNODAS (NOAA NOHRSC)	Snow model assimilates satellite, airborne, and in situ snow data and weather obs	SWE, snow depth, snowmelt, sublimation, snow temperature	1 km	US-wide	Daily
SWANN & SnowView (Univ. of Arizona)	Snow model and neural network algorithm, uses SNOTEL SWE and MODSCAG snow area	SWE, snow cover	1 km	US-wide	Daily
MODIS-based CU-SWE (Univ. of Colorado)	Statistical model blending SNOTEL, MODSCAG, physiography, analog historical SWE pattern	SWE	~500 m	Southern Rockies domain	Typically 4-8 per season, 3-7 day lag

Section 2. Understanding the snowpack

How do we know how much water is in the snowpack? The depth, density, and areal extent of the snowpack changes over time, making answering this question particularly challenging. One foot of densely packed snow will contain more water than one foot of newly fallen, loose snow. The metric most commonly used to integrate snow depth and density and thereby express the amount of water contained in the snowpack is snow water equivalent, or SWE. SWE can be thought of as the depth of water (e.g., in inches) that would result if you melted a column of the snowpack.

SWE expresses the depth of water contained in the snow at a particular site; point observations of SWE are often used as proxies or predictors for water volume in an area or basin. This simplification works well for most locations and basins most of the time, but a multi-dimensional perspective of the snowpack can track snow conditions more accurately than point observations can. Spatially explicit monitoring of the snowpack can represent the areal distribution of snow, but it takes more effort and additional data and tools, and may not always be achievable. That said, conceptualizing the snowpack in all dimensions can help us better understand and compensate for limitations of the network of point observations.

Broad aspects of the spatial distribution and temporal evolution of the snowpack are fairly consistent from one year to another. However, the details within these generalized patterns can vary greatly from year to year and from basin to basin. Many individual weather events shape the snowpack: storm dynamics that build snow accumulations, wind events that redistribute and help sublimate snow, and heat waves that drive rapid snowmelt. The aggregate of these events, and their complex interactions with the terrain and vegetation, give each snow season a unique form over space and time.

Overall spatial pattern

We start by describing the generalized spatial pattern of the snowpack. The most prominent and consistent aspect of that pattern is that snow depth and SWE generally increase with increasing elevation at least up to treeline. This gradient is a consequence of multiple factors:

- Higher precipitation, due to orographic lift of moist air masses.
- Larger fraction of precipitation falling as snow, due to lower temperatures at higher elevations.
- Lower sublimation and mid-season snowmelt, also due to lower temperatures.

Above treeline, snow depth and SWE may no longer increase with elevation in a given area, or may even decrease, depending on an area's exposure to high winds. Wind can prevent snow accumulation on windward slopes and can increase sublimation and cause scour in locations where snow does accumulate. There is also evidence that the elevational gradient in precipitation may flatten out at the very highest elevations.

In a given area, snow depth and SWE are also generally higher on north-facing slopes and lower on south-facing slopes, due to differential inputs of solar radiation and thus sublimation and snowmelt. The prevailing flow of moisture in the region is coming from the west throughout the cool season, which means that mountain areas on the *west* side of major drainage divides, such as the Continental Divide, tend to accumulate more snow at a given elevation than the slopes on the east side.

Figure 2 below shows a typical distribution of SWE across the Rocky Mountain West on April 1st, near the seasonal peak.

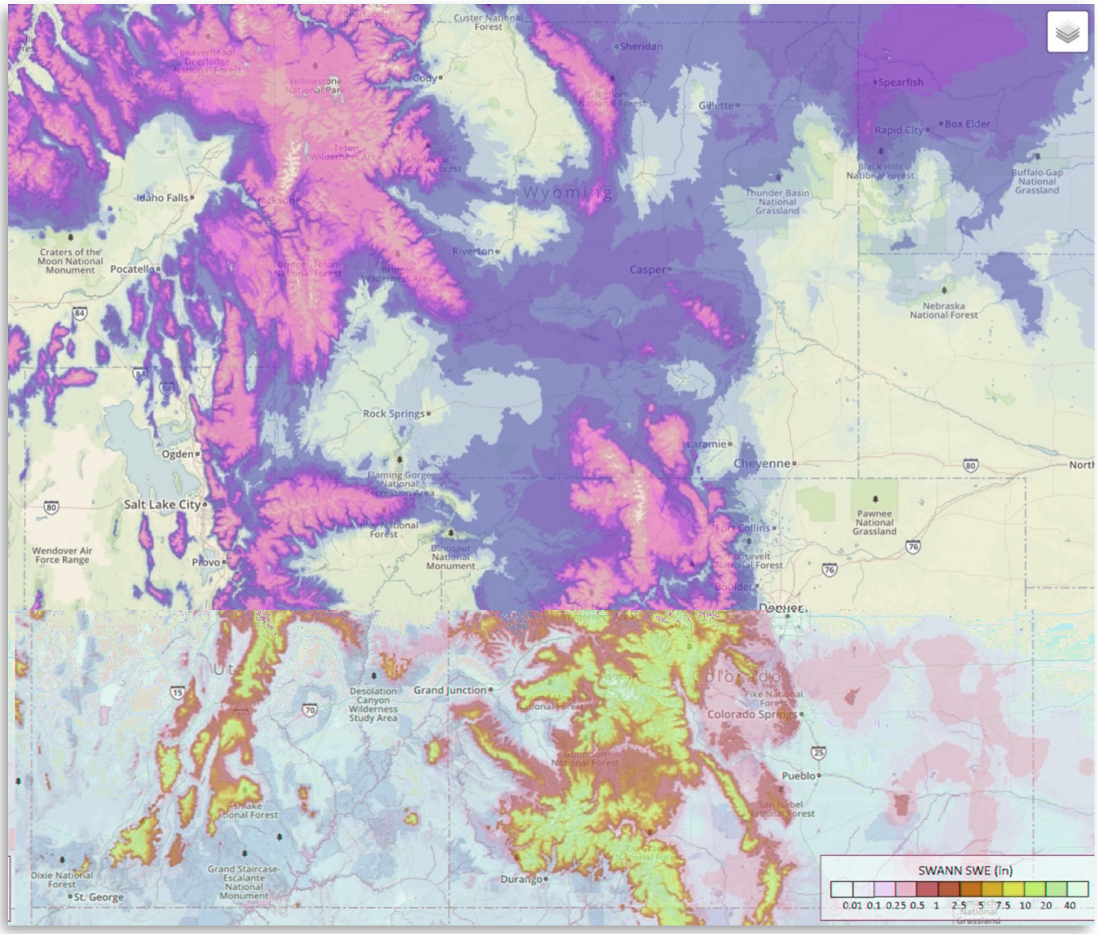


Figure 2. "Typical" pattern of April 1 SWE amounts across the Rocky Mountain West, with higher SWE at higher elevations and lower SWE at lower elevations. April 1, 2009, depicted here, had near-normal depths at most SNOTEL sites in the region. (Source: Map of SWE estimates from SnowView)

Snowpack accumulation and losses prior to spring snowmelt

The region's snowpack accumulates over a 4 to 7-month period, with accumulation typically beginning in October at higher elevations across most of the region, and later in the fall and early winter in locations that are further downslope or southward. The peak SWE value in wind-sheltered locations at high elevations, where SNOTEL stations are typically located, generally averages 15"–50" [4].

Field studies and modeling [5–7] suggest that the equivalent of 10–20% of peak SWE in the Rocky Mountain West is lost to sublimation—the transition of water from snow and ice directly to water vapor—during the course of the season. The highest losses occur during the spring months, March through May, when air temperatures and shortwave solar radiation are higher. Most of this sublimation loss is embedded in the overall downward trend of the snowpack during the spring melt. Sublimation losses from the snowpack are less than the evaporation losses that would occur if the same amount of precipitation fell as rain.

The overall winter climate (November–March) at high elevations in Colorado, Utah, and Wyoming is even colder than in the other mountain regions of the western U.S., such as the Sierra Nevada, Cascades, and northern Rockies [8]. This means that the snowpack itself is colder, and thus less prone to melt prior to the spring peak.

Spring snowmelt

The spring melt of the snowpack occurs over the span of 2 to 3 months. Snowmelt typically begins in earnest in April or May in a normal snow year. Snowmelt is driven primarily by greater shortwave radiation due to higher sun angles and longer days. However, higher air temperatures—especially when overnight low temperatures are above freezing—prime the snowpack for faster melt. Once the snowpack becomes isothermal, measuring 32°F (0°C) throughout its depth profile, rapid melt can occur.

The snowmelt rate is enhanced when the snow surface is dusty. In the past few decades, the dust-on-snow phenomenon has become more frequent in the region due to drier conditions, soil disturbance, and vegetation loss in the main dust source areas in the Colorado Plateau. Dust is deposited on the snowpack continuously, but it can be deposited in denser layers on the snowpack during distinct, usually dry, wind events. Typically, 3 to 10 dust-on-snow events affect parts of the region each spring, particularly in southwestern Colorado and southern Utah. The aggregate dust loading and thus impact on melt rates varies substantially from year to year [9–11].

Translation from snow to runoff

As noted above, the spring snowmelt drives most of the region's overall streamflow. But the translation from snowpack to runoff is not as straightforward as it might appear. Only a portion of each spring's snowmelt runs off directly to streams and rivers that same season. Instead, much of the snowmelt soaks into the soil, infiltrates deeper, and becomes new groundwater, which then displaces and pushes out a proportional volume of older, stored groundwater toward the stream channel. This process is illustrated in Figure 3.

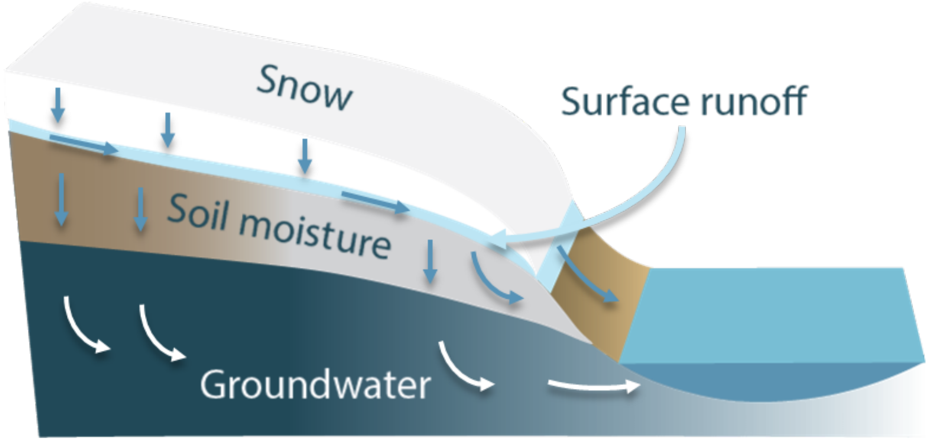


Figure 3. Schematic representation of the route of snowmelt from snowpack to streamflow. Only a portion of snowmelt runs off directly to streams and rivers, while much of the snowmelt becomes new groundwater, which then pushes older groundwater to the stream channel.

Critically, if the soil is abnormally dry, it will soak up a decent fraction of the snowmelt first, before any snowmelt infiltrates deeper. This phenomenon was evident in the 2020 Colorado River spring runoff, which was lower than would have been expected based on the precipitation and snowpack alone. Dry soils carried over from the very dry fall of 2019 absorbed much of the snowmelt, reducing the amount of water available for runoff.

Taken together, while the size of the snowpack is generally a good gage of the magnitude of the spring runoff, we shouldn't expect to see all of the water volume in a basin's snowpack at its peak to become runoff. Some will be lost to sublimation and evaporation, and some will be diverted to replenish soil moisture and ultimately lost to evapotranspiration. Importantly, this fraction will vary from year to year, typically being higher in wet years, and lower in dry years.

Recent trends in snow

The peak water volume of the region's snowpack (e.g., April 1 SWE) is mainly determined by the amount of cold season precipitation, but it can also reflect variation in other weather factors—temperature, humidity, wind, and solar radiation—that influence snow loss (sublimation and melt). Of these factors, temperature has an obvious and statistically significant recent trend. Temperatures in the three-state region increased in all seasons, and about 2°F overall, over the past 40 years. This warming trend, both regionally and globally, has been largely attributed to anthropogenic climate change. Cold season precipitation also appears to show a downward trend over the past 40 years, but given the high variability in precipitation, this could be due to natural variability [12].

A number of recent studies have noted substantial declining trends in April 1 SWE at locations across the western U.S. over the most recent 30 to 70 years. All of these studies indicate that rising temperatures have played a role in causing the observed declines in SWE. Generally, reduced cold season precipitation since 2000 has also contributed. These and other studies also show a pervasive shift toward earlier snowmelt and peak runoff across the West, typically occurring 1-4 weeks earlier than in the 20th century. Again, rising temperatures are believed to have played a role, along with reduced precipitation—smaller snowpacks peak and melt earlier—and increasing dust-on-snow impacts. When snowmelt initiates earlier in the spring, average melt rates are lower on average. Slower melt actually tends to lead to *less* efficient runoff, as snow is more prone to being sublimated away during an extended melt season.

Expected future changes in snow

All climate models project that the recent warming trend for the region will continue, if not accelerate, depending on the trajectory of greenhouse gas emissions and uncertain feedbacks in the climate system. Due to this continued warming, future hydrologic projections for the Rocky Mountain region show a strong tendency toward future declines in April 1 SWE [4] (and references therein), despite modest projected increases in winter and early spring precipitation. This strong tendency toward decreased April 1 SWE reflects multiple effects of the projected warming: a shift toward precipitation falling as rain instead of snow, greater sublimation and melt of the snowpack throughout the season, and a shift toward earlier snowmelt in the spring. These warming-related effects are strongly modulated by elevation, with snowpack at higher elevations seeing less impact from warming as a percentage of current snowpack than at lower elevations.

The general mid-range of the projected change in April 1 SWE by mid-century is a loss of roughly 10% to 20% [13]. These declines in SWE are expected to be greater by mid-century at lower elevations in the snowpack zone (roughly 8,000-10,000’ in Colorado) and in southern parts of the Colorado River Basin where the winter climate is not as cold, the snowpack is shallower, and the snow season is shorter. Even at higher elevations (above 11,000’ in Colorado), spring snowpacks are expected to decline [4].

Section 3. Monitoring the snowpack: SNOTEL and snow courses

For over 80 years, snowpack monitoring and water supply forecasting in the western U.S. has relied on a network of in situ, ground-based observations (point measurements) managed and maintained by the NRCS along with state and local cooperators. From the mid-1930s until the late 1970s, these observations came solely from snow courses that were manually measured monthly or semi-monthly, from January through May or June. Starting in the late 1970s, the snow courses have been increasingly augmented by, and at many sites replaced by, automated SNOTEL (SNOwpack TELemetry) stations. Currently, the SNOTEL stations carry the vast majority of the load for operational monitoring, but snow courses are still critical for validation purposes and for the continuation of long-term records, which extend back as far as 85 years in some locations. SNOTEL data are used to construct, calibrate, and validate other snow data products, including those described in Section 4.

In addition to the foundational SNOTEL and snow course point observations, the COOP (Cooperative Observer Program) and CoCoRaHS (Community Collaborative Rain, Hail, and Snow) programs provide useful supplemental snow data collected by volunteer observers. These monitoring programs are also described below.

SNOTEL stations

The key element of the SNOTEL station is the *snow pillow*: large (1.5-3.0 m wide) bladders of stainless steel or synthetic rubber containing an antifreeze solution that are buried so that their upper surface is at ground level. As snow accumulates on the pillow, it exerts pressure on the bladder, and this pressure caused by the weight of the snow is measured and converted into snow water equivalent (SWE).

SNOTEL stations also collect data on snow depth, all-season precipitation (frozen and liquid), and air temperature with daily maximums, minimums, and averages. Many enhanced SNOTEL sites also have sensors for collecting soil moisture and soil temperature measurements at various depths, as well as solar radiation, wind speed, and relative humidity (Figure 4). The data collected at SNOTEL sites are generally reported hourly.

Real-time data collected at SNOTEL sites are transmitted to the NRCS Water and Climate Information System using one of three telemetry systems, depending on the location of the station: meteor burst (most stations), satellite, or cellular.

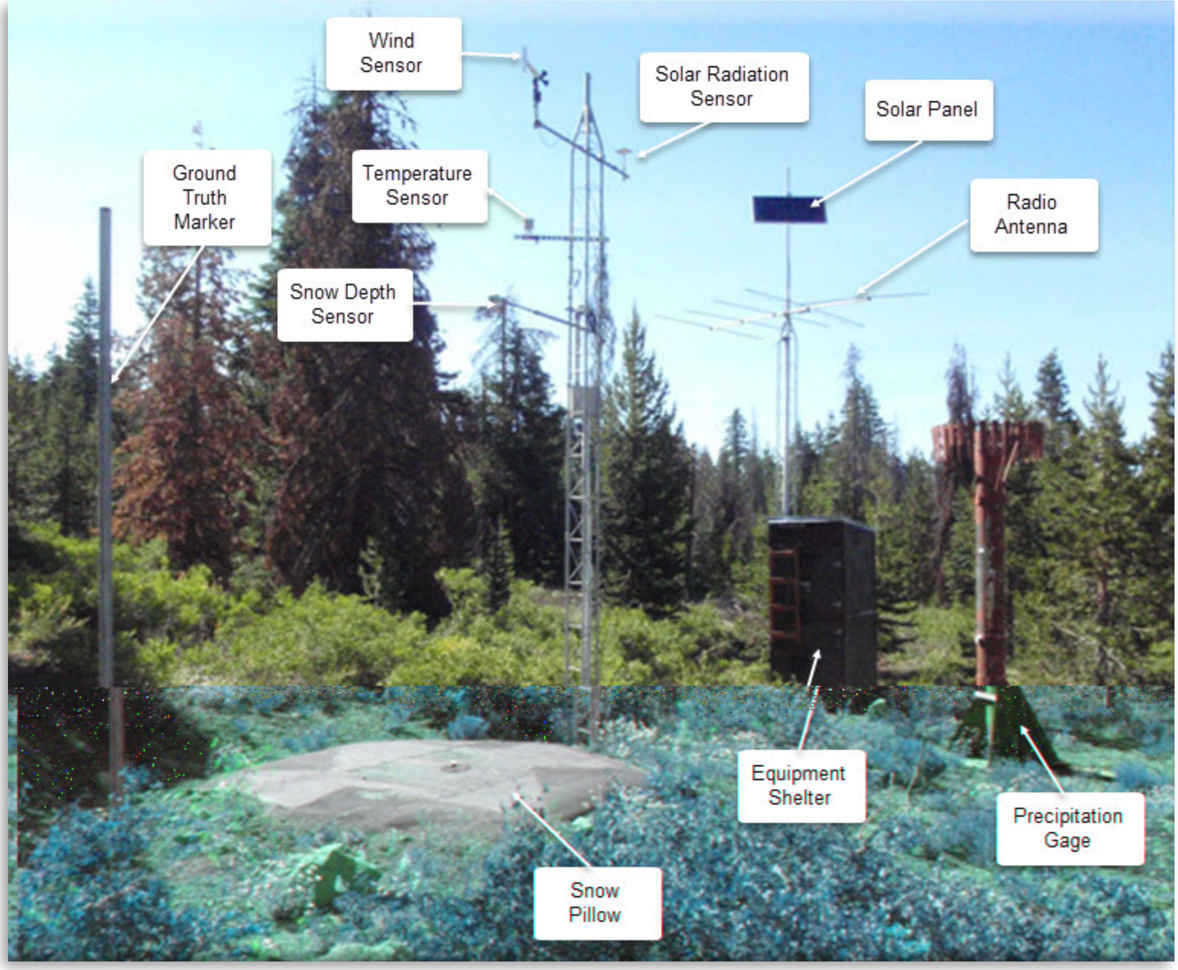


Figure 4. SNOTEL automated collection site. Source: NRCS (https://www.wcc.nrcs.usda.gov/about/mon_automate.html).

Currently, there are 336 SNOTEL sites within the region: 115 in Colorado, 132 in Utah, and 89 in Wyoming (Figure 5). Each site receives preventative maintenance and sensor adjustment annually. The reliability of each SNOTEL site is verified by ground truth measurements taken during regularly scheduled manual surveys. These readings are compared with the telemetered data to check that values are consistent and compatible. For more information about SNOTEL, visit https://www.wcc.nrcs.usda.gov/about/mon_automate.html.

Snow courses

Snow courses are typically about 1,000 feet (300 meters) long and located in small meadows protected from the wind. They consist of a variable number, typically 5 to 10, of equally spaced individual sample points. Snow surveyors use tubular aluminum snow samplers at each sample point to weigh the snow to determine the snow-water equivalent, and also measure the snow depth (Figure 6). The SWE measurements from each sample point are averaged to determine the site value.

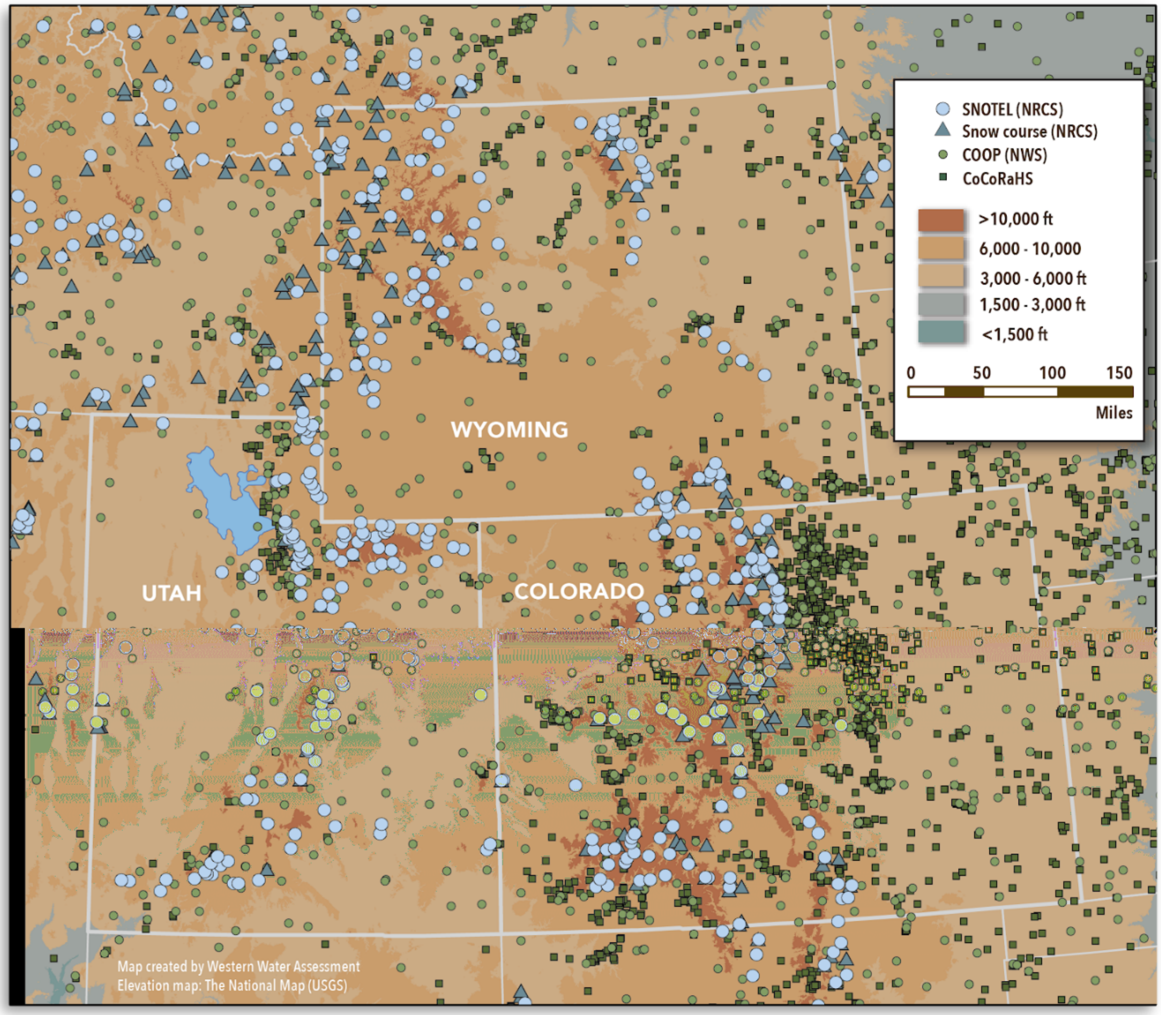


Figure 5. Locations of in-situ snow observing sites in the Rocky Mountain West (CO, UT, WY). The NRCS SNOTEL and snow course sites are focused on snow observations at higher elevations, and under normal operations, SWE measurements are available from all of the sites shown. The COOP and CoCoRaHS (see 'Other in situ snow observations', p. 18) networks have broader purposes but typically report snow observations (e.g., daily snowfall and daily SWE accumulation) from many, though not all, of the sites shown. The vast majority of COOP and CoCoRaHS sites are at elevations below the SNOTEL/snow course network.

Since snow courses have a larger measurement "footprint" than SNOTEL snow pillows, snow-course SWE measurements are somewhat more spatially representative than SNOTEL SWE observations. But snow-course measurements are carried out only monthly or semi-monthly, compared to hourly for SNOTEL. Monthly manual SWE measurements are still taken at 178 snow courses in the region: 92 within Colorado, 23 within Utah, and 63 within Wyoming (Figure 5). For more information about snow courses, visit https://www.wcc.nrcs.usda.gov/about/mon_manual.html.

Figure 6. After clearing out any soil from the tube, the surveyor determines the amount of water in the snowpack by weighing the tube with its snow core and subtracting the weight of the empty tube. Source: NRCS (www.wcc.nrcs.usda.gov/factpub/sect_4a.html)

Limitations of the SNOTEL/snow course networks

SNOTEL sites and snow courses provide very accurate *point* measurements. These point measurements, when aggregated across multiple sites, also do a decent job of representing the relative snow conditions in the vast majority of a watershed that is not measured directly. However, there are general limitations related to the coverage of these networks. Due to siting constraints and cost considerations, SNOTEL sites and snow courses are not located on slopes, above treeline, or at lower elevations where snowpack is generally low or intermittent. In Colorado, for example, the vast majority of SNOTEL sites and snow courses are located in the elevation band between 9,000' and 11,000' (Figure 5).

Thus, in seasons with unusual spatial patterns—for example, a spring with abnormally low sublimation loss above treeline, or unusually high mid-winter melt on south-facing slopes, or unusually high accumulation at lower elevations relative to higher elevations—the SNOTEL and snow course measurements may not collectively capture the actual basin-wide SWE conditions.

Also, SNOTEL and snow course sites are not evenly distributed through the mountain headwaters. Some headwaters catchments have relatively fewer sites, or lack in situ sites completely. Monitoring for those catchments relies on sites in neighboring watersheds—where snow conditions will be comparable in most years, but not all years. According to the Colorado Basin River Forecast Center (CBRFC), it is likely that there is greater streamflow forecast error related to snowpack conditions in these data-sparse areas, though no quantitative analysis has been done to confirm this.

In situ snow data are also subject to non-climatic influences that may decrease the spatial representativeness of the information from a given station. In particular, changes in the vegetation surrounding a SNOTEL site or snow course, such as from beetle infestation or wildfire, can impact snow accumulation and melt. This can affect the site's suitability for real-time monitoring as well as its use for assessing long-term trends. For example, the Trapper Lake SNOTEL in the White River Basin in northwestern Colorado was impacted by wildfire and now shows much lower SWE values than nearby sites due to wind scour. Because of this, NRCS no longer uses Trapper Lake in calculating basin-wide SWE conditions. Vail Mountain SNOTEL in the Eagle River Basin in central Colorado was impacted by the mountain pine beetle infestation and subsequent tree removal. This SNOTEL site now appears to accumulate less SWE, and to melt out faster, than it did prior to the beetle infestation.

Interpreting SNOTEL/snow course SWE information

A number of considerations factor into interpretation of SNOTEL and snow course SWE information:

- The percent of normal values are less helpful, and potentially misleading, in the early season or the late season, when even a very small observed value may appear to be a huge percentage of a near-zero normal.
- In late spring, there is always some snow remaining in a watershed, sometimes a lot--even after all of the SNOTEL observed values have dwindled to zero.
- Because of local microclimates and other conditions, observations from SNOTEL sites just a short distance apart may show surprisingly large differences in percent of median values.
- When using percent of normal data, ask "What is the normal?" Is it the median (usually) or the mean? Because SWE observations cannot drop below zero, but can occasionally be extremely high, historical SWE values are not symmetrically distributed on either side of the mean, and the median is usually lower than the mean.
- Check the time period over which the normal is calculated (usually 1981-2010, but not always).
- Be attentive to systematic differences in both SWE and % of normal SWE within a watershed, either with elevation, or with north-south and east-west orientations.

Other in-situ snow observations (CoCoRaHS, COOP, CODOS)

Additional in situ snow observations from networks of volunteer observers can help fill out the picture of the snowpack, particularly at lower elevations. Note that these observations are principally for snowfall and snow depth.

CoCoRaHS (Community Collaborative Rain Hail and Snow) observations

Since its initiation in 1997, the CoCoRaHS network (Figure 5) has become an important supplemental source of precipitation data for weather and climate monitoring and other purposes. The volunteer observers who make up the CoCoRaHS network are encouraged to record snow measurements along with their daily precipitation observations, including snowfall, daily SWE accumulation, snow depth, and total SWE on the ground. Most CoCoRaHS observers do record snowfall and the daily SWE accumulation, and most of those also record snow depth, though far fewer of them measure and record total SWE on the ground. For example, on a typical day in March 2019, roughly 100 CoCoRaHS observers in western Colorado reported snowfall, snow depth, and the daily SWE accumulation, and roughly 20 of them also reported total SWE on the ground. For more information about CoCoRaHS, visit https://www.cocorahs.org/.

COOP snow observations

The Cooperative Observer Program (COOP) of the National Weather Service (NWS) has more than 10,000 volunteers who take daily weather observations in urban and suburban areas, at National Parks, seashores, and farms (Figure 5). Most stations in the COOP weather observer network in the Rocky Mountain region report daily snowfall and snow depth on the ground, in addition to temperature and precipitation. For example, on a typical day in March 2019, 40 of 56 COOP observers in western Colorado reported snowfall and snow depth. For more information about COOP, visit https://www.weather.gov/rah/coop.

CODOS dust-on-snow observations

As described above, the dust load on snow can influence the melt rate of the snowpack, and therefore affect the accuracy of streamflow forecasts. The Colorado Dust-on-Snow (CODOS) program is part of the Center for Snow and Avalanche Studies (CSAS). CSAS monitors the presence/absence of dust layers at 11 mountain pass locations throughout Colorado. The CODOS program uses those observations, data from nearby SNOTEL sites, and weather forecasts to issue a series of analyses of how dust-on-snow is likely to influence snowmelt timing and rates during the runoff season. For more information about CODOS, visit http://www.codos.org/. Based on the work of CSAS researchers and others, CBRFC now uses satellite data (described in the next section) showing the dust loading to adjust melt rates in their forecast model.

Section 4. Monitoring the snowpack: Remote sensing and spatial modeling

Remote sensing of snow (ASO, MODIS)

Remote sensing from satellite or airborne platforms provides spatially continuous data that can usefully complement the point SWE data from SNOTEL or other in situ observations. In the Colorado River Basin, remotely sensed snow data are being increasingly deployed and integrated into snowpack monitoring and runoff forecasting systems. It is important to note that remote sensing products generally have inherent uncertainties not shared by in situ measurements. For example, snow coverage itself is not directly sensed, but instead is derived from reflected radiation from the surface, and the algorithms have trouble distinguishing the signature of clean snow from that of clouds. In general, airborne products are more reliable and have higher spatial resolution than satellite products, mainly due to the sensor being roughly 100-1000 times closer to the land surface. However, satellite observations have much broader spatial coverage.

Airborne Snow Observatory (ASO) observations

The Airborne Snow Observatory (ASO) is an airborne sensing, modeling, and processing system developed by NASA Jet Propulsion Laboratory (NASA JPL) in 2013 and is now operated as a private enterprise led by former NASA researchers. It carries a very high-resolution scanning LiDAR (Light Detection and Ranging) sensor that can accurately measure snow depth as the difference between the current snow surface height and the land surface height as measured during a previous flight under snow-free conditions. Observed or modeled snow density, or both, is then used to translate the snow depth data into SWE, resulting in a spatial SWE product with a 50-m resolution. A second sensor, an imaging spectrometer, also measures snow albedo and thus the radiative melt forcing from dust-on-snow. Of the remote sensing systems, ASO produces the most accurate estimates of spatial variability in SWE across large areas (tens of km), with errors on the order of 1-2 cm of SWE, and typically provides direct estimates of snow-water volume with full watershed coverage.

ASO has been primarily deployed operationally in several basins in California's Sierra Nevada, but its use has been increasing in the Rocky Mountains. In western Colorado, ASO has been flown as part of pilot projects in the Uncompahgre Basin (2013–2017), Rio Grande and Conejos Basins (2015-2017), Gunnison Basin (2016, 2018–19), over Grand Mesa (2013–2017), and in the Blue River watershed (2019). Typically, 1–6 flights are carried out per basin per season. For the spring of 2021, flights are planned in the Blue River watershed, and in the Conejos, Animas, Dolores, and Upper Gunnison basins. For more information about ASO, visit https://www.airbornesnowobservatories.com.

MODIS satellite products

MODIS (Moderate Resolution Imaging Spectroradiometer) is a moderate-resolution (500 m for most products) multi-spectral sensor that is currently on two different satellites, Aqua and Terra, with daily near-global coverage and data availability back to 2000. NASA JPL developed and continues to refine two snow-specific data products from MODIS that are made available in near real-time: one that depicts fractional snow-covered-area and snow-grain size (MODIS Snow Covered Area and Grain-size, or MODSCAG) and one that depicts the radiative melt forcing from dust-on-snow (MODIS Dust Radiative Forcing in Snow, or MODDRFS). While MODSCAG does not capture SWE, it can be integrated with in situ observations to better represent the distribution of SWE across a landscape. The MODSCAG product is a key input to the CU-SWE spatial snow product described below. For more information about MODIS, visit https://modis.gsfc.nasa.gov and read Painter et al (2009) [14].

Spatially distributed snow modeling (SNOW-17, SNODAS, SWANN, CU-SWE)

Spatially distributed snow modeling integrates observed meteorological and snow conditions with modeled physical processes, including the effects of topography, to produce snowpack estimates specific to each location or grid cell across a basin. For water supply purposes, the key output of such modeling is an estimate of SWE for each pixel or other modeling unit, such that the total volume of basin-wide SWE can be calculated directly from the smaller units. In principle, spatially distributed snow modeling compensates for the key limitations (spatial density, representativeness, and elevational coverage) of the SNOTEL network. Perhaps just as critically, spatially distributed modeling also generates insights into processes, sensitivities, and patterns in time and space that are difficult or impossible to glean from point observations alone.

However, it is important to note that the different modeled snow products are not independent of SNOTEL. All of the products described below calibrate and/or validate their respective models on SNOTEL data, and a few also directly assimilate SNOTEL data to inform the SWE estimates. In general, they use modeled spatial SWE estimates and remotely sensed snow data to effectively spread the SNOTEL observations across the landscape, generating a snowpack that is consistent with the SNOTEL observations but that fills in the spatial gaps and detail missed because of topography and other factors. Accordingly, the SWE estimates from these products—with the exception of ASO—will have lower uncertainty within the elevation band where the SNOTEL network is predominantly located, and higher uncertainty at elevations above and below that band.

It is also difficult to independently validate the accuracy of these spatial SWE products because of their incorporation of SNOTEL data. Comparing them to each other can identify systematic differences, but not which product is “right.” ASO SWE data, however, can serve as a viable reference for those basins on specific dates for which ASO flights have been carried out.

CBRFC modeled SWE (SNOW-17)

For operational streamflow forecasting, the CBRFC pairs a snow model (SNOW-17) with a hydrology model (Sac-SMA). SNOW-17 is run in a spatially “lumped” or partially distributed framework, meaning that area averages are calculated for each modeling unit, with each unit typically representing an elevation zone, of which there are usually three in each watershed. The mean area precipitation for a modeling unit is calculated from the precipitation observations at one or more SNOTEL or COOP stations using weightings determined by model calibration and the PRISM precipitation climatology.

SNOW-17 then builds a simulated snowpack, using the temperatures observed at the SNOTEL sites and local freezing levels, to determine whether precipitation is falling as snow or rain and whether the snowpack is accumulating or ablating. Historical precipitation observations are used to calibrate the snow model. The model effectively estimates a snow-water volume for each modeling unit, and thus for each watershed, sub-basin, and basin, which is then used to model the forecasted spring-summer streamflow volume. The model allows snow to persist at the highest elevations even after most or all SNOTEL sites have melted out, consistent with the real-world behavior of the snowpack. For more information on SNOW-17, visit https://www.wcc.nrcs.usda.gov/ftpref/wntsc/H&H/snow/AndersonSnow17.pdf.

Snow Data Assimilation System (SNODAS)

The Snow Data Assimilation System (SNODAS) is a physically based energy and mass-balance snow model, driven by near real-time weather variables that can assimilate available snow data from remote sensing and in situ measurements. SNODAS was developed by NOAA's National Operational Hydrologic Remote Sensing Center (NOHRSC) and has been produced operationally for the U.S. since 2004. SNODAS estimates multiple snow characteristics on a daily basis by merging satellite, airborne, and in situ snow data with modeled depictions of snow cover. The snow variables that are modeled and made available include SWE, snow depth, snowmelt, sublimation, and snowpack average temperature. Model calibration and validation are focused primarily on SWE because of its importance to water management. Both COOP and CoCoRaHS snow observations are now being incorporated into the NOAA SNODAS products. For more information on SNODAS, visit https://nsidc.org/sites/nsidc.org/files/files/nsidc_special_report_11.pdf.

Snow Water Artificial Neural Network Modeling System (SWANN)

The SWANN modeling system is a research product developed at the University of Arizona that uses snow models, assimilated in situ SWE data, and artificial neural networks (ANNs; a type of machine learning) to generate gridded estimates of SWE and snow cover. SWANN was prototyped for the Salt River Basin in Arizona, in collaboration with the Salt River Project (SRP) but is available for the whole U.S. The SWANN SWE estimates, which are available back to the early 1980s, use ANNs to account for local variations in topography, forest cover, and solar radiation, while the snow cover estimates (generated on a limited basis) use ANNs that are applied to Landsat and MODIS satellite reflectance data. The models are trained with in situ SWE observations and aerial LiDAR SWE estimates from across the southwestern U.S. The SWANN SWE data are produced in near real-time and delivered to SRP via a prototype decision support tool that provides daily-to-annual operational monitoring of spatial and temporal changes in SWE and snow cover conditions. The product now covers the conterminous U.S. and includes 35+ years of daily SWE estimates, allowing it to be used in modeling applications that require long-term SWE records. More information may be found at this link: https://nsidc.org/data/nsidc-0719.

MODIS-based spatial SWE estimates (CU-SWE)

CU-SWE, a research product developed at the University of Colorado, blends observed SWE from SNOTEL and CoCoRaHS, concurrent MODSCAG snow-covered data, physiographic variables that affect snow (elevation, latitude, upwind barriers, and slope), and an analogous historical daily SWE pattern (from 2000–2012) that had been generated using historical MODSCAG data and an energy-balance snow model. This results in near real-time (3-7-day lag) spatial estimates of SWE at a 500-m resolution. This product has been generated over a Sierra Nevada domain roughly biweekly during February to June for California water managers since 2012. The methodology has been refined and extended to a Southern Rockies domain that includes the snow accumulating areas in Colorado, eastern Utah, and all but far northern Wyoming. The SWE data are distributed in a multi-page report that includes maps, a summary of current conditions, and summary statistics. From 2018-2020, the Southern Rockies SWE estimates were produced and distributed 4-5 times per season with the support of Western Water Assessment. The developers hope to produce them again for winter-spring 2021.

The Mountain Hydrology Group at CU Boulder provides reports that contain an experimental research product that provides near-real-time estimates of SWE for the Sierra Nevada mountain range in California and the Intermountain West region (Colorado, Utah and Wyoming) from mid-winter through the melt season. These reports can be found at this link: https://instaar.colorado.edu/research/labs-groups/mountain-hydrology-group/services-detail/.

Section 5. Applying snowpack data: Seasonal streamflow forecasting

Water users and providers in the Colorado-Wyoming-Utah region rely on forecasts of runoff timing and amounts made by the Natural Resource Conservation Service (NRCS) and the NOAA River Forecast Centers (RFCs). Other entities produce streamflow forecasts, but the forecast guidance from these two agencies is the most commonly consulted in our region. These forecasts, which are critical to water operations and management in the region, are briefly described in this section of the guide and summarized in Table 2. More in-depth descriptions of methods are linked in the discussion below.

NRCS forecast methods

The snow-course and SNOTEL networks in the western U.S. were specifically developed by NRCS to support their seasonal water supply forecasts, as well as for general snow monitoring. Thus, the characteristics of these networks have influenced the NRCS water supply forecasting approach, and vice versa. In this forecast approach, statistical regression modeling is used to relate several predictors—typically water-year-to-date precipitation and current SWE from SNOTEL sites—to the target predicted value: spring-summer streamflow at a given forecast point. NRCS models are calibrated on historical data at particular sites and are applied to real-time predictor data to produce runoff forecasts at individual stream gages. Point-based measurements are well suited for this statistical approach—it requires a limited number of predictors to represent the basin snowpack above the stream gage being forecasted. More information can be found at: https://www.nrcs.usda.gov/wps/portal/wcc/home/aboutUs/waterSupplyForecasting/.

NOAA RFC forecast methods

Seasonal water supply forecasts for the Great Basin and the Colorado River Basin are provided by NOAA's Colorado Basin River Forecast Center, or CBRFC. Streamflow forecasts for Wyoming's North Platte River and Colorado's Front Range are provided by the Missouri Basin River Forecast Center (MBRFC) and Arkansas-Red Basin River Forecast Center (ABRFC), while the Snake River headwaters in western Wyoming are covered by the Northwest River Forecast Center (NWRFC). The Rio Grande headwaters in southwestern Colorado are covered by the West Gulf River Forecast Center.

All of these RFCs use the same forecast tools for seasonal water supply, but they produce and distribute their operational forecasts differently. The two tools are (1) a statistical forecast method very similar to that used by the NRCS, and (2) a more physically based conceptual hydrologic modeling system that produces an ensemble of equally likely streamflow sequences (Ensemble Streamflow Prediction, or ESP). More information can be found in Chapter 8 of the Colorado River Basin Climate and Hydrology State of the Science Report [15] and https://www.cbrfc.noaa.gov/wsup/doc.php. All of these RFCs (and the California Nevada RFC) produce a Western Water Supply Forecast Page, which takes forecasts from the

Western RFCs and puts them all on a single page (https://www.cbrfc.noaa.gov/wsup/graph/west/map/esp_map.html).

Table 2. Key characteristics of the NRCS and NOAA RFC seasonal water supply forecasting approaches.

	NRCS	NOAA RFC
Primary forecast tool/model	Statistical modeling (principal components regression equations)	Conceptual spatially lumped process modeling system (snow model + soil-moisture/runoff model)
How it works	Several variables that in combination best explain the historic runoff outcomes at each forecast point are used as predictors of the current year's runoff.	The watershed above each forecast point is divided into multiple modeling units based on topography and elevation; within each unit, the current year's hydrology is simulated up to the forecast date and then projected forward given the initial hydrologic conditions and the range of historical weather.
How current state of snowpack is incorporated into the forecast	Current SWE and water-year-to-date precipitation at SNOTEL sites are the typical predictors in the forecast equations.	Snowpack is "built up" in the snow model for each modeling unit using SNOTEL and COOP observations of precipitation and temperature (but not SWE); weather model output is used to distinguish snow from rain.
How antecedent (previous fall) soil moisture is incorporated in the forecast	Only partially and indirectly. For example, anomalously low October and/or November precipitation will nudge the year-to-date precipitation predictors down, which will push the forecasted streamflow volumes downward as well.	Directly. SNOTEL and COOP precipitation and temperature are used to explicitly model antecedent fall soil moisture; anomalous soil conditions directly affects the modeled runoff efficiency and thus forecasted streamflows.
How the effects of future weather (i.e., between the forecast date and the end of the spring-summer runoff period) are incorporated in the forecast	The forecast equations are calibrated on historical observed SWE, precipitation, and streamflows for each year in the 1981-2010 period. These observed streamflows were generated, in part, by the spring weather sequences during those years, so the spring weather is implicitly incorporated in the forecast equations.	*Short term:* 5-day forecast of precipitation and 10-day forecast of temperature are used to adjust the modeled snowpack. *Longer term:* The 35 historical weather sequences from the 1981-2015 period are used to separately evolve the modeled snowpack to the end of the forecast period.

Section 6. Accessing snowpack data: Data tools and resources

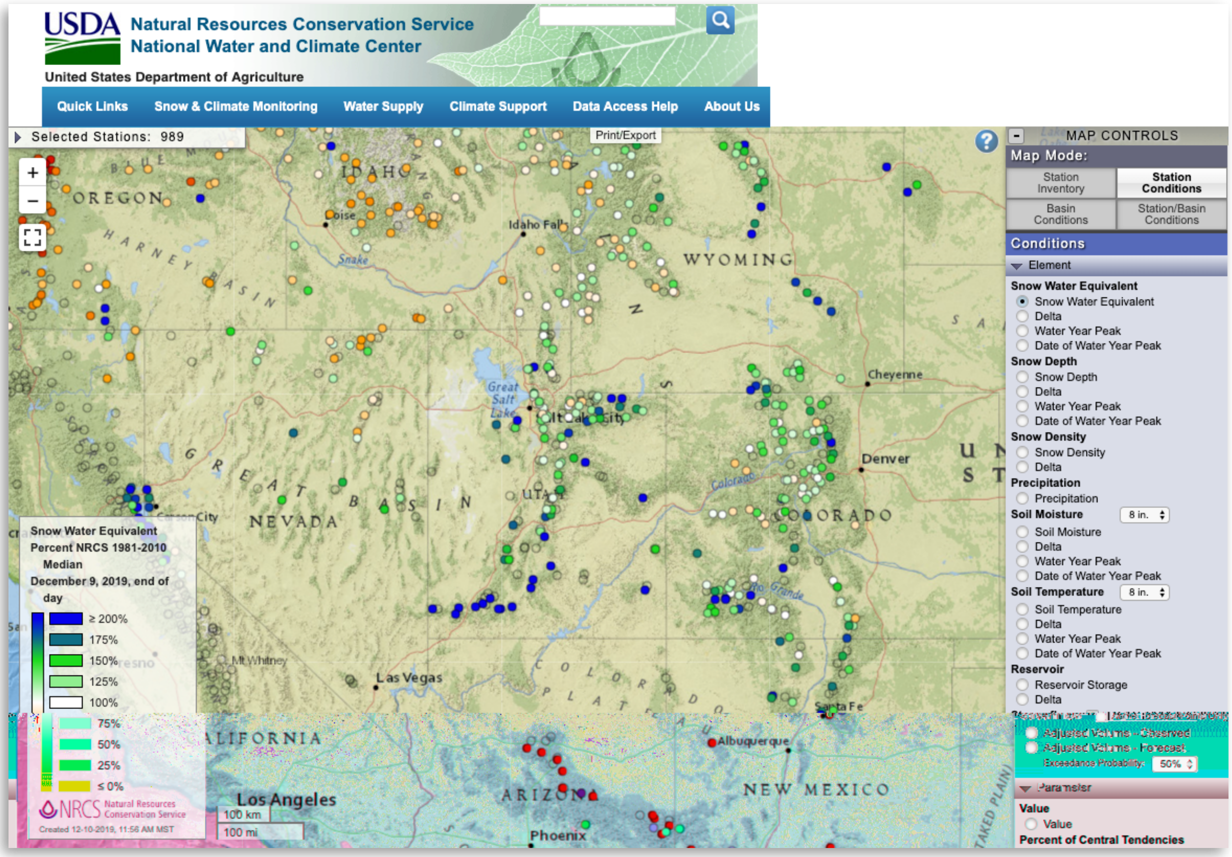
This section of the guide provides practical information to help users find and retrieve the snow data they need. Consult the simple matrix (Table 3) below to find the tool or resource that offers the variables of interest.

In addition, as may have been evident from the snow product descriptions above, there can be differences among data retrieved from product to product. We recommend that you consult multiple snow products and networks, including SNOTEL, and compare them over time for the watershed(s) of interest. Historical comparisons between snow data and other observed variables such as streamflow may lead you to choose one product over another.

Table 3. Schematic overview of variables provided by the tools and resources presented in this guide.

Tool or resource	**Variable**								**Snow products / networks displayed in tool**
	SWE	Snowfall	Snow depth	Snow density	Snow temperature	Air temperature	Precipitation	Precipitation as snow	
NRCS Interactive Map	Yes		Yes	Yes		Yes	Yes		SNOTEL Snow course
NRCS Snow Survey Interactive Charts	Yes (CO, UT only)					Yes (UT only)	Yes (CO, UT only)		SNOTEL Snow course
CBRFC snow groups	Yes (CBRFC domain only)								SNOTEL
NOAA snowfall and snow depth map		Yes	Yes						COOP CoCoRaHS
CoCoRaHS maps	Yes	Yes	Yes				Yes		CoCoRaHS
NOAA SNODAS map	Yes		Yes	Yes	Yes		Yes	Yes	SNODAS SNOTEL COOP CoCoRaHS
CWCB CDSS SNODAS tools	Yes (CO only)								SNODAS
U. Arizona SnowView map	Yes						Yes		SWANN SNODAS SNOTEL
CBRFC modeled snowpack map	Yes								SNOW-17

NRCS Interactive Map



Quick facts

- Provides a clear spatial overview of snowpack (SNOTEL) and other hydroclimate conditions across the western U.S., while allowing users to easily drill down into site-level data
- Tool Access: https://www.nrcs.usda.gov/wps/portal/wcc/home/quicklinks/imap
- Instructions/Help: https://www.nrcs.usda.gov/wps/portal/wcc/home/dataAccessHelp/helpCenters/imapHelpCenter/

Data from snow monitoring networks discussed in this user guide displayed by this tool

- SNOTEL data
- Snow course data

The Interactive Map was debuted by NRCS in 2015 and has quickly become the go-to tool for displaying real-time and historical data from multiple hydroclimate sensor and data networks, most notably SNOTEL and snow courses.

Data from other networks/sources NOT discussed in this user guide displayed by this tool

- SNOLITE data
- Cooperator Snow Sensors (California only)
- Many other non-snow networks/sources

Variables available

SWE, snow depth, snow density, precipitation, air temperature, soil moisture, soil temperature, observed streamflow, forecasted streamflow, reservoir storage (NRCS).

Historical snow data available

Full record for each site; extends back to the late 1970s for the oldest SNOTEL sites, and the mid-1920s for the oldest snow courses, in the region.

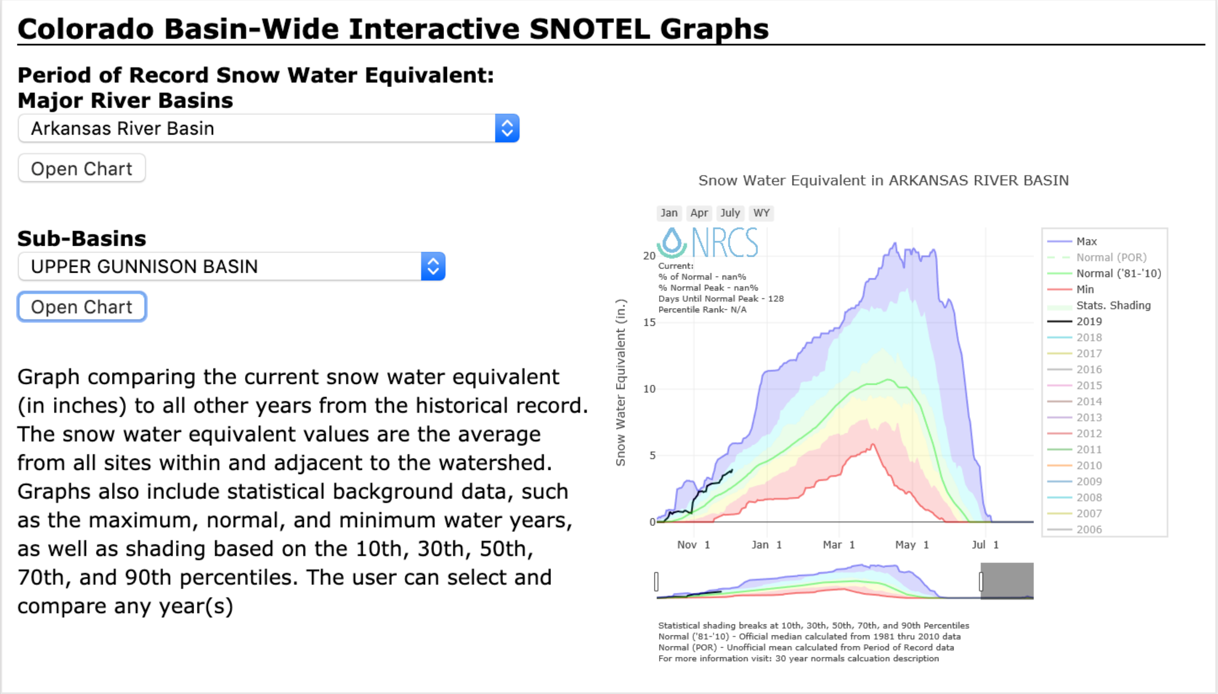
Viewing data

- The Help Center/About the Interactive Map has a fairly comprehensive overview and instructions. Make sure you click on all of the links within that page for a tour of all of the map controls.
- NRCS also has a set of Predefined Map Links to quickly bring up a map showing the variable and parameters of interest (e.g., current SWE percentile relative to the period-of-record).

Downloading data

- From any map view, at the upper left, open the Selected Stations dropdown and click 'Export [Site/Basin] Data as CSV' to download that day's data for all available stations.
- Click on an individual station on the map; a pop-up window has options to download a **7-day Hourly Table** or a **30-day Daily Table**. Clicking on the **Site Page** option provides access to additional download options.

NRCS Snow Survey tools and products



Colorado Basin-Wide Interactive SNOTEL Graphs

Period of Record Snow Water Equivalent: Major River Basins

Arkansas River Basin

Sub-Basins

UPPER GUNNISON BASIN

Graph comparing the current snow water equivalent (in inches) to all other years from the historical record. The snow water equivalent values are the average from all sites within and adjacent to the watershed. Graphs also include statistical background data, such as the maximum, normal, and minimum water years, as well as shading based on the 10th, 30th, 50th, 70th, and 90th percentiles. The user can select and compare any year(s)

Snow Water Equivalent in ARKANSAS RIVER BASIN

Current:
% of Normal - nan%
% Normal Peak - nan%
Days Until Normal Peak - 128
Percentile Rank- N/A

Statistical shading breaks at 10th, 30th, 50th, 70th, and 90th Percentiles
Normal ('81-'10) - Official median calculated from 1981 thru 2010 data
Normal (POR) - Unofficial mean calculated from Period of Record data
For more information visit: 30 year normals calcuation description

Quick facts

- All three CO/WY/UT state snow survey sites provide many different options for plotting and viewing SNOTEL and snow course data over different spatial scales and time scales.
- Tool Access:
    - Colorado: https://www.nrcs.usda.gov/wps/portal/nrcs/main/co/snow/products/
    - Utah: https://www.nrcs.usda.gov/wps/portal/nrcs/main/ut/snow/
    - Wyoming: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/wy/snow/products/data/?cid=nrcs142p2_027344/
- Interactive SNOTEL graphs plot seasonal/annual time series of SWE and other variables. **They are currently only available for Utah and Colorado.**

Data from snow monitoring networks discussed in this user guide displayed by this tool

- SNOTEL data
- Snow course data

Colorado graphs can be found on the 'CO Snow Survey snow products' page under the link 'CO Basin and Sub-Basin SWE-Projections and Time Series Charts'. This will lead the user to the 'Interactive SNOTEL Graphs'. For Utah, they can be found under 'Individual site time-series graphs' and 'Basin-averaged time-series graphs' on the UT Snow Survey snow product page.

Variables available

SWE, precipitation, projected SWE, projected precipitation, temperature (UT only), soil moisture (UT only).

Historical data available:

Period of record for each SNOTEL site.

Viewing data

- Choose the variable of interest from the several available, then select the site or basin of interest from the drop down, then click Open Chart. The chart will open in a pop-up window.
- In the chart window, click on any year or parameter to add or remove lines in the chart. Double clicking on any year or parameter will show only that line; double-clicking again will make all lines appear.
- Hovering the mouse over the chart will make additional controls (e.g., zoom, pan, select, show data on hover, download plot) appear in the upper right of the chart window.

Downloading data

- Data along each plotted line can be viewed using the ‘show closest data on hover’ and ‘compare data on hover’ controls on the graphs. Colorado data can be downloaded in CSV or JSON formats as indicated at the top of the charts, or use the NRCS Interactive Map to view data tables and site pages for individual SNOTEL sites in Colorado, Utah and Wyoming.

CBRFC Snow Groups

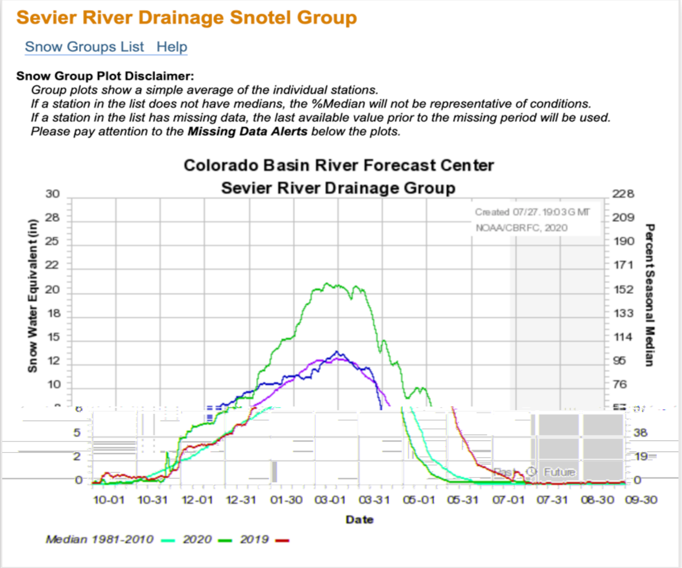
Snow Groups

Raw SNOTEL data from NRCS.

CBRFC Groups
Groups listed by basin below have been created by CBRFC staff.

Great Basin
Bear River Drainage (bulu1 fbni1 hfku1 kllw4 llku1 lbnu1 ltbu1 mcru1 tglu1
Bear River Headwaters (hfku1 llku1 chcu1)
Bear River below Woodruff (dbpu1 mcru1 bulu1 kllw4 givi1 fbni1)
Beaver Minersville (bgfu1 mvyu1)
Chalk Ck Index (ccku1 chcu1)
Clear Creek Sevier (kmnu1)
Cottonwood Canyons (mldu1 briu1 sbdu1)
Logan BlacksFork Little Bear Basins (bulu1 tglu1 fbni1)
Ogden River Drainage (blpu1 bltu1 dbpu1 hrgu1 ltbu1 mcru1)
Provo River Basin (trlu1 dstu1 nwyu1 stdu1 timu1)
Sevier River Basin Blo Piute (mcdu1 rpru1 seeu1 bvdu1 pklu1)
Sevier River Basin Headwaters (wflu1 mdvu1 cvyu1 lvju1 hrsu1)
Sevier River Drainage (mdvu1 frlu1 pklu1 cvyu1 kmnu1 pcku1 mcdu1 bvdu
Six Creeks Headwaters (lopu1 psuu1 mldu1 briu1 sbdu1)
Smith Fork Bear Basin (cllw4 sltw4 kllw4 incw4)
Spanish Fork Drainage (clcu1 crku1 pysu1 wrvu1 stdu1)
Utah Lake Drainage (clcu1 crku1 dstu1 nwyu1 pysu1 timu1 trlu1 stdu1)
Weber Basin Headwaters (smmu1 trlu1 ccku1 chcu1)
Weber River Drainage (blpu1 bltu1 ccku1 chcu1 dbpu1 hrgu1 fmnu1 mcru1

Lower Colorado
Central Mogollon Rim (proa3 bkba3)
Gila River (cnda3 frdn5 scdn5 lktn5 sgnn5 hnma3)
LC Southern Headwaters (bbsa3 blda3 hbea3 mvfa3)
Little Colorado River (bkba3 blda3 mvfa3 mbea3 proa3)
Lower Colorado (whla3 frya3 mrma3 bkba3 proa3 wkma3 blda3 mvfa3 wct
Salt (mvfa3 cnda3 wcta3 xbha3)
Salt River (blda3 cnda3 hnma3 mvfa3 wcta3)
San Francisco (frdn5 cnda3 xbha3)
Upper Gila (scdn5 lktn5 sgnn5)
Upper Salt (mvfa3 cnda3 wcta3 xbha3)
Verde (whla3 bkba3 frya3 mrma3)
Verde River (bkba3 frya3 mrma3 whla3)
virgin (hrsu1 lgfu1 mdvu1 klbu1 wflu1 lvju1)



Sevier River Drainage Snotel Group

Snow Groups List   Help

Snow Group Plot Disclaimer:
Group plots show a simple average of the individual stations.
If a station in the list does not have medians, the %Median will not be representative of conditions.
If a station in the list has missing data, the last available value prior to the missing period will be used.
*Please pay attention to the **Missing Data Alerts** below the plots.*

Quick facts

- Provides current annual time-series plots of SNOTEL SWE averaged across multiple SNOTEL sites ("snow groups") selected to represent a particular catchment or area.
- CBRFC Groups were created by CBRFC staff to represent ~100 key catchments in their forecast region; User groups were created by other users to represent >200 additional catchments.
- Tool Access: https://www.cbrfc.noaa.gov/station/sweplot/sweplot2.cgi???open

Data from snow monitoring networks discussed in this user guide displayed by this tool

- SNOTEL data

Variables available

SWE

Years available

All years in the period of record for the oldest SNOTEL site in that group; note that younger SNOTELs will drop out of the calculated group average as you go back in time.

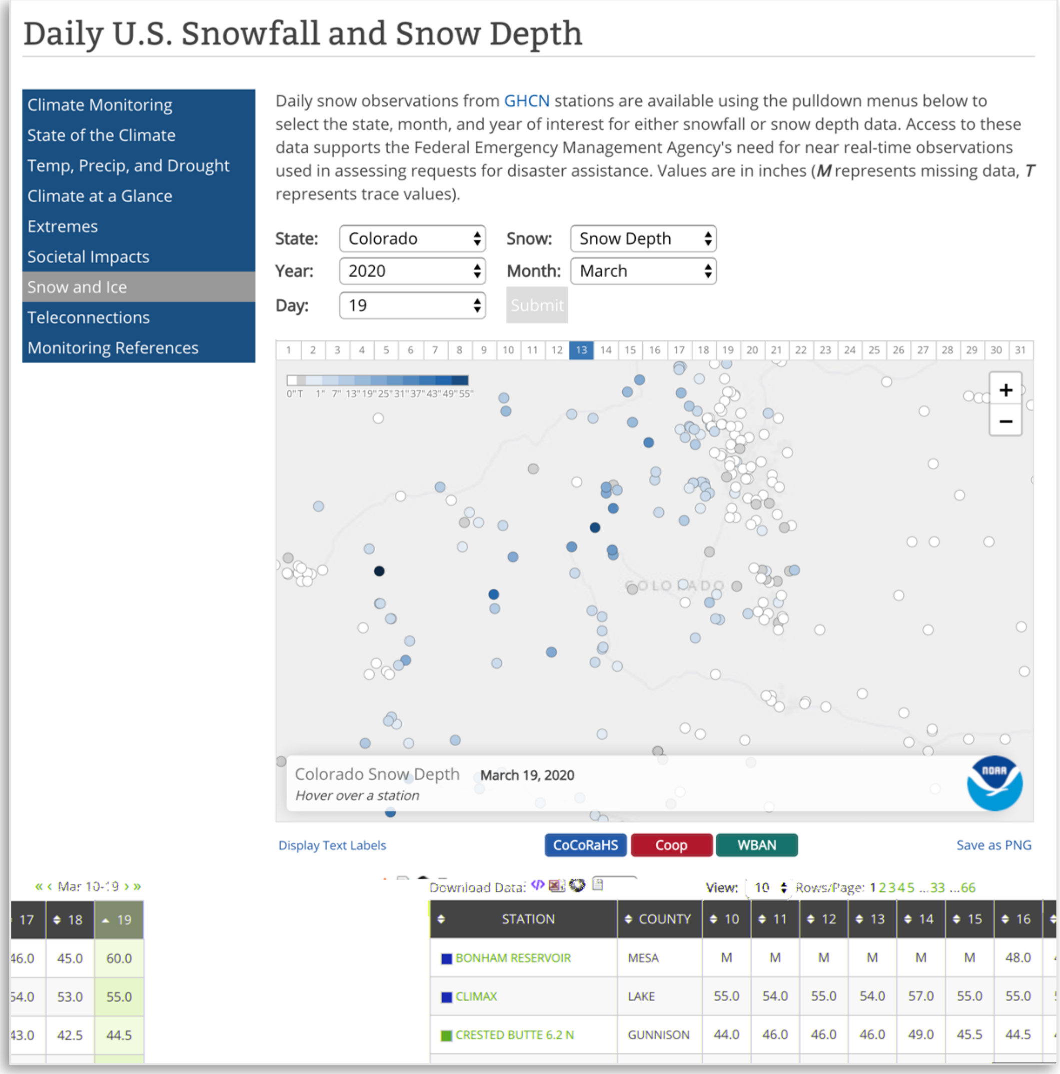
Viewing data

- Clicking on a snow group opens an interactive chart page that allows different years to be plotted, and for the SNOTEL sites making up that snow group to be removed, and additional sites to be added. Click "Apply" to re-plot the chart after making new selections.

Downloading data

Check the "Show Tabular Data" option to show the daily data for each year/line that is plotted in chart.

COOP–NOAA NCEI Daily Snowfall & Snow Depth maps and data table



Daily U.S. Snowfall and Snow Depth

Daily snow observations from GHCN stations are available using the pulldown menus below to select the state, month, and year of interest for either snowfall or snow depth data. Access to these data supports the Federal Emergency Management Agency's need for near real-time observations used in assessing requests for disaster assistance. Values are in inches (*M* represents missing data, *T* represents trace values).

State: Colorado
Snow: Snow Depth
Year: 2020
Month: March
Day: 19

Colorado Snow Depth March 19, 2020
Hover over a station

Download Data:
View: 10 Rows/Page: 1 2 3 4 5 ...33 ...66

STATION	COUNTY	10	11	12	13	14	15	16	17	18	19
🟦 BONHAM RESERVOIR	MESA	M	M	M	M	M	M	48.0	46.0	45.0	60.0
🟦 CLIMAX	LAKE	55.0	54.0	55.0	54.0	57.0	55.0	55.0	54.0	53.0	55.0
🟩 CRESTED BUTTE 6.2 N	GUNNISON	44.0	46.0	46.0	46.0	49.0	45.5	44.5	43.0	42.5	44.5

Quick facts

- Provides snowfall (daily, 2-day, 3-day and 7-day) and snow depth data (daily) per station
- Tool Access: https://www.ncdc.noaa.gov/snow-and-ice/daily-snow/

Data from snow monitoring networks discussed in this user guide displayed by this tool

- COOP data
- CoCoRaHS data

Data from other networks/sources NOT discussed in this user guide displayed by this tool

- WBAN (airport weather stations)

Variables available

Daily snowfall, 2-day snowfall, 3-day snowfall, 7-day snowfall, daily snow depth

Historical data available

2015 to present.

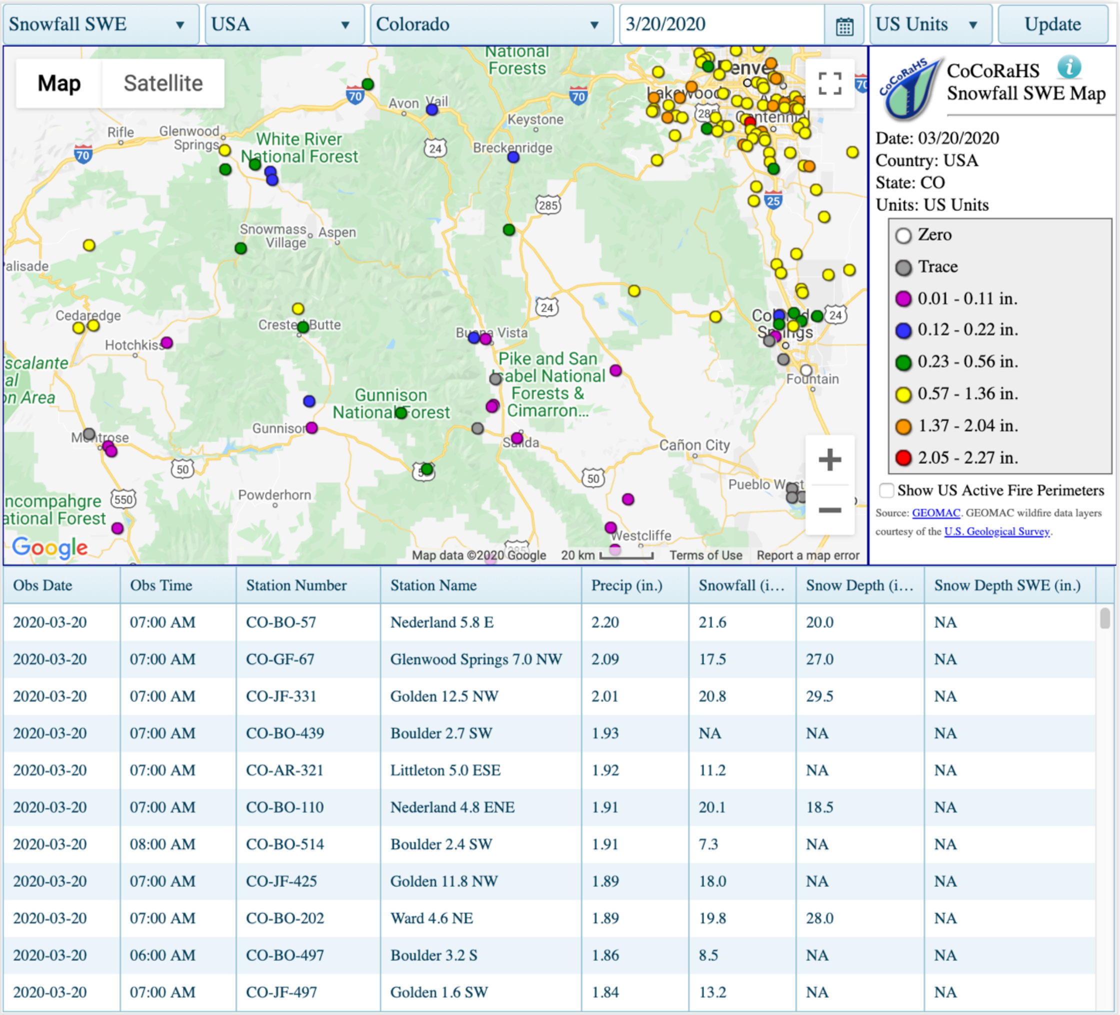
Viewing data

- Select the State, Year, Month, Day, and Snow variable of interest, and click Submit. Underneath the map, the CoCoRaHS, Coop, and WBAN buttons can be used to stop and start displaying those networks in the map and the table below.
- The map shows a single day's value, while the table shows 10 days of data leading up to and including the selected day. The numbers 1-31 at the top of the map can be used to quickly select display data for other days in the same month.
- While the base map lacks detail in the initial statewide view, there is high local detail when zoomed in.

Downloading data

- At the upper left of the table, the Download Data options allow the daily data for the month and the state that is being viewed in the table to be downloaded as XML, CSV, JSON, or ASCII format.
- To download COOP daily and monthly snow (and other) data for years prior to 2015 for a selected COOP site, use the SC ACIS tool.

CoCoRaHS Maps



Snowfall SWE ▾ | USA ▾ | Colorado ▾ | 3/20/2020 | US Units ▾ | Update

CoCoRaHS Snowfall SWE Map

Date: 03/20/2020
Country: USA
State: CO
Units: US Units

- ○ Zero
- ● Trace
- ● 0.01 - 0.11 in.
- ● 0.12 - 0.22 in.
- ● 0.23 - 0.56 in.
- ● 0.57 - 1.36 in.
- ● 1.37 - 2.04 in.
- ● 2.05 - 2.27 in.

☐ Show US Active Fire Perimeters

Source: GEOMAC. GEOMAC wildfire data layers courtesy of the U.S. Geological Survey.

Obs Date	Obs Time	Station Number	Station Name	Precip (in.)	Snowfall (i…	Snow Depth (i…	Snow Depth SWE (in.)
2020-03-20	07:00 AM	CO-BO-57	Nederland 5.8 E	2.20	21.6	20.0	NA
2020-03-20	07:00 AM	CO-GF-67	Glenwood Springs 7.0 NW	2.09	17.5	27.0	NA
2020-03-20	07:00 AM	CO-JF-331	Golden 12.5 NW	2.01	20.8	29.5	NA
2020-03-20	07:00 AM	CO-BO-439	Boulder 2.7 SW	1.93	NA	NA	NA
2020-03-20	07:00 AM	CO-AR-321	Littleton 5.0 ESE	1.92	11.2	NA	NA
2020-03-20	07:00 AM	CO-BO-110	Nederland 4.8 ENE	1.91	20.1	18.5	NA
2020-03-20	08:00 AM	CO-BO-514	Boulder 2.4 SW	1.91	7.3	NA	NA
2020-03-20	07:00 AM	CO-JF-425	Golden 11.8 NW	1.89	18.0	NA	NA
2020-03-20	07:00 AM	CO-BO-202	Ward 4.6 NE	1.89	19.8	28.0	NA
2020-03-20	06:00 AM	CO-BO-497	Boulder 3.2 S	1.86	8.5	NA	NA
2020-03-20	07:00 AM	CO-JF-497	Golden 1.6 SW	1.84	13.2	NA	NA

Quick facts

- Provides an overview of daily snowfall, daily SWE accumulation and snow depth from the hundreds of volunteer CoCoRaHS observers in the region.
- Tool Access:
  - Static maps: https://www.cocorahs.org/Maps/ViewMap.aspx?state=usa
  - Interactive maps: https://data.cocorahs.org/cocorahs/maps/ [shown and described below]

Data from snow monitoring networks discussed in this user guide displayed by this tool

- CoCoRaHS data

Variables available

Static map: Precipitation, new snow (snowfall), total snow depth, and hail.

Interactive map: Precipitation, snowfall, snow depth, and snow depth SWE.

Historical data available

Maps can be generated for any day back to fall 1997; good station coverage for CO, UT, WY extends back to the mid-2000s.

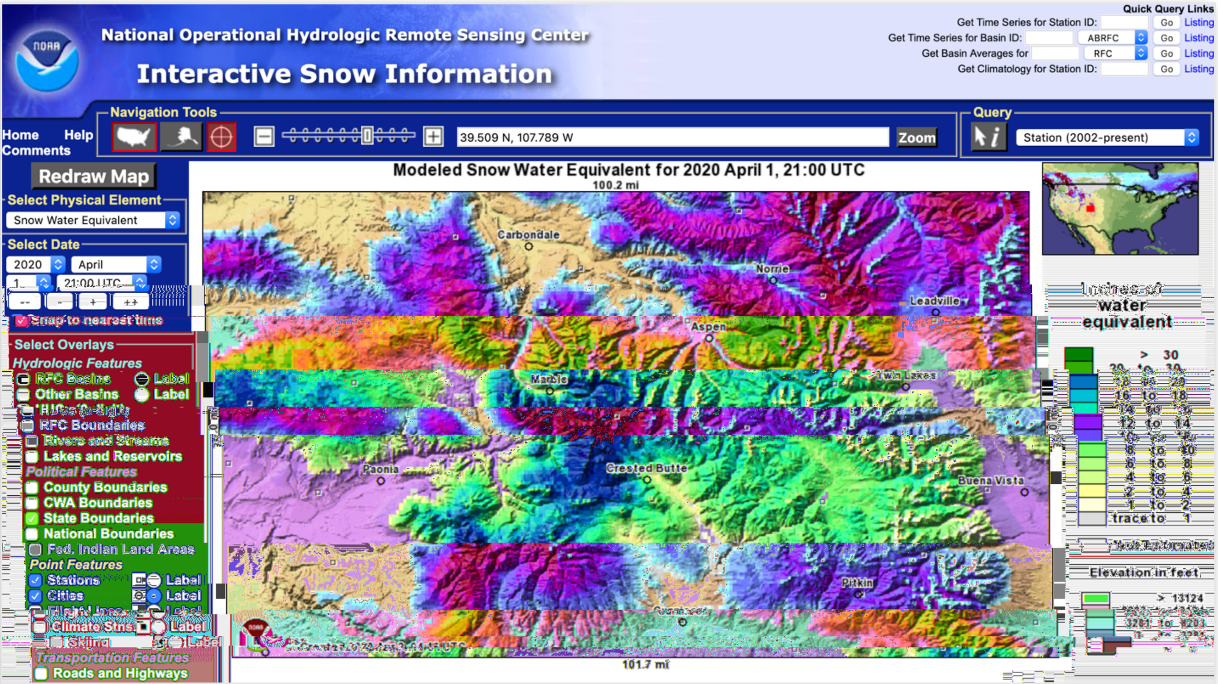
Viewing data

- From the drop-downs across the top of the window, select the variable, the state, and the date of interest, and click Update.

Downloading data

- Under the interactive map, a table with Precipitation (in.), Snowfall (in.), Snow Depth (in.) and Snow Depth SWE (in.) for every station in the selected state. The data in this table can be copied and pasted in, for example, Excel.
- To obtain daily data for a time period of interest for individual stations in the map, click on a station and note its site code (e.g., CO-LR-273). Then go to https://www.cocorahs.org/ViewData/StationSnowSummary.aspx, enter the site code and select the start end dates, and click Get Summary.

NOAA NOHRSC - SNODAS Interactive Map



Modeled Snow Water Equivalent for 2020 April 1, 21:00 UTC

39.509 N, 107.789 W

Query: Station (2002-present)

Select Physical Element: Snow Water Equivalent

Select Date: 2020 April 1 21:00 UTC

☑ Snap to nearest time

Quick facts

- Provides map-based access to the SNODAS modeled snow variables.
- Tool Access: https://www.nohrsc.noaa.gov/interactive/html/map.html

Snow data discussed in this user guide displayed by this tool

- SNODAS modeled snow variables
- SNOTEL, COOP and CoCoRaHS data can be displayed if stations are selected

Variables available

SWE, snow depth, snow temperature, air temperature, snow density, snowmelt, snow precipitation, non-snow precipitation, and more.

Historical data available

2002 to the current date. Note that the SNODAS modeling methodology has changed over time; more recent data shows more topographic detail than older data.

Viewing data

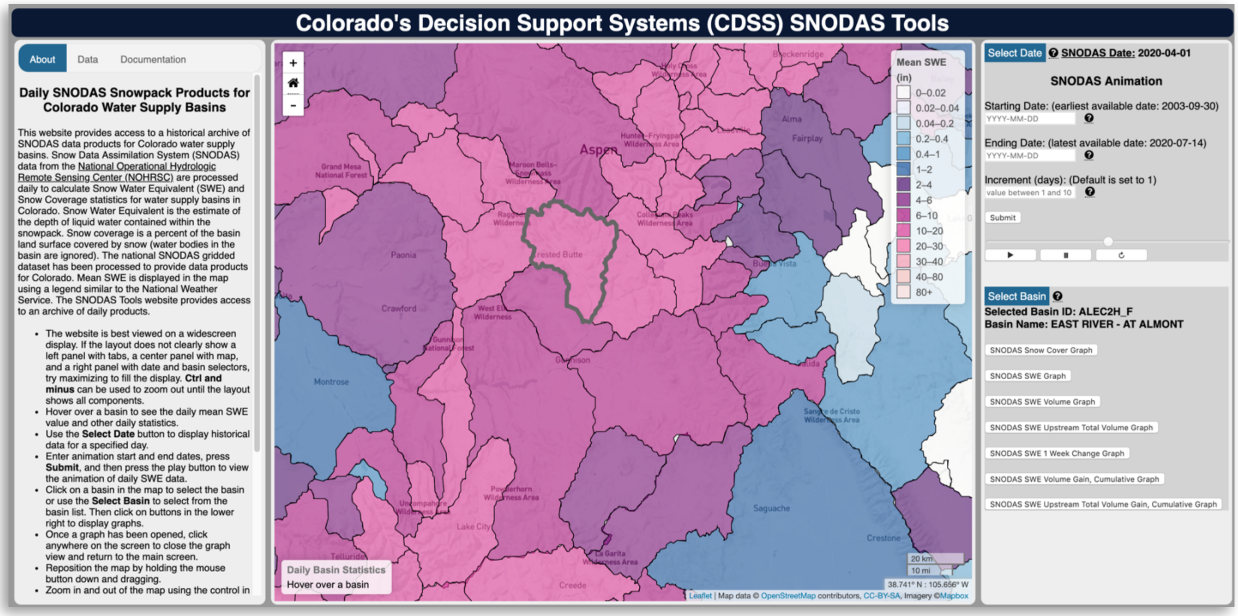
- Basic directions are provided just below the map window.
- Users *cannot pan* the map using the mouse; instead, click on a spot to re-center the map and use the zoom slider to zoom in, or click-drag to select a rectangle that will be zoomed in on.
- In the default view, Stations (SNOTEL, COOP, CoCoRaHS, etc.) are displayed as open squares. Zooming in will allow more of them to appear.

- Basin outlines (e.g., for RFC Basins) can also be displayed by checking the boxes at left under Hydrologic Features.
- To display interactive time-series charts for any station or basin, click on the Query button in the upper right, select Station or Basin from the drop down, and then select that station or basin with the cursor (hand).
- The Query tool drop down can also be used to view basin average SWE and total SWE volume for a selected date, in acre-feet and billion gallons.

Downloading data

- For any data or chart viewed using the 'Query' tool (see the 'Viewing data' section on how to use the 'Query' tool. A new screen opens when the Query tool is used), find the drop down at the upper left of the newly opened screen, under the start date selection box. In this drop down, the options can be Graph, Data, CSV file, HTML and/or Text, depending on what was queried. Selecting CSV file and then clicking Refresh Screen will download a CSV file of those data.
- Mapped data is downloadable as vector or raster GIS datasets:
    - Vector: https://www.nohrsc.noaa.gov/gisdatasets/
    - Raster: https://www.nohrsc.noaa.gov/archived_data/

CWCB CDSS SNODAS Tools (Colorado-only SNODAS map)



Colorado's Decision Support Systems (CDSS) SNODAS Tools

Daily SNODAS Snowpack Products for Colorado Water Supply Basins

This website provides access to a historical archive of SNODAS data products for Colorado water supply basins. Snow Data Assimilation System (SNODAS) data from the National Operational Hydrologic Remote Sensing Center (NOHRSC) are processed daily to calculate Snow Water Equivalent (SWE) and Snow Coverage statistics for water supply basins in Colorado. Snow Water Equivalent is the estimate of the depth of liquid water contained within the snowpack. Snow coverage is a percent of the basin land surface covered by snow (water bodies in the basin are ignored). The national SNODAS gridded dataset has been processed to provide data products for Colorado. Mean SWE is displayed in the map using a legend similar to the National Weather Service. The SNODAS Tools website provides access to an archive of daily products.

- The website is best viewed on a widescreen display. If the layout does not clearly show a left panel with tabs, a center panel with map, and a right panel with date and basin selectors, try maximizing to fill the display. **Ctrl and minus** can be used to zoom out until the layout shows all components.
- Hover over a basin to see the daily mean SWE value and other daily statistics.
- Use the **Select Date** button to display historical data for a specified day.
- Enter animation start and end dates, press **Submit**, and then press the play button to view the animation of daily SWE data.
- Click on a basin in the map to select the basin or use the **Select Basin** to select from the basin list. Then click on buttons in the lower right to display graphs.
- Once a graph has been opened, click anywhere on the screen to close the graph view and return to the main screen.
- Reposition the map by holding the mouse button down and dragging.
- Zoom in and out of the map using the control in

SNODAS Date: 2020-04-01

SNODAS Animation

Starting Date: (earliest available date: 2003-09-30) YYYY-MM-DD

Ending Date: (latest available date: 2020-07-14) YYYY-MM-DD

Increment (days): (Default is set to 1) value between 1 and 10

Selected Basin ID: ALEC2H_F
Basin Name: EAST RIVER - AT ALMONT

Quick facts

- The CWCB Colorado's Decision Support Systems (CDSS) Tools displays SNODAS SWE data, including average SWE and total snow-water volume, for hundreds of basins covering the state of Colorado.
- Shows the same SNODAS gridded SWE data as on the NOAA NOHRSC main portal and interactive map, but the interface is focused on basin (catchment)-level data.
- Tool Access: http://snodas.cdss.state.co.us/app/index.html

Snow data discussed in this user guide displayed by this tool

- SNODAS SWE data

Variables available

SWE (basin average depth and total volume)

Historical data available

2003 to present, any day within that period.

Viewing data

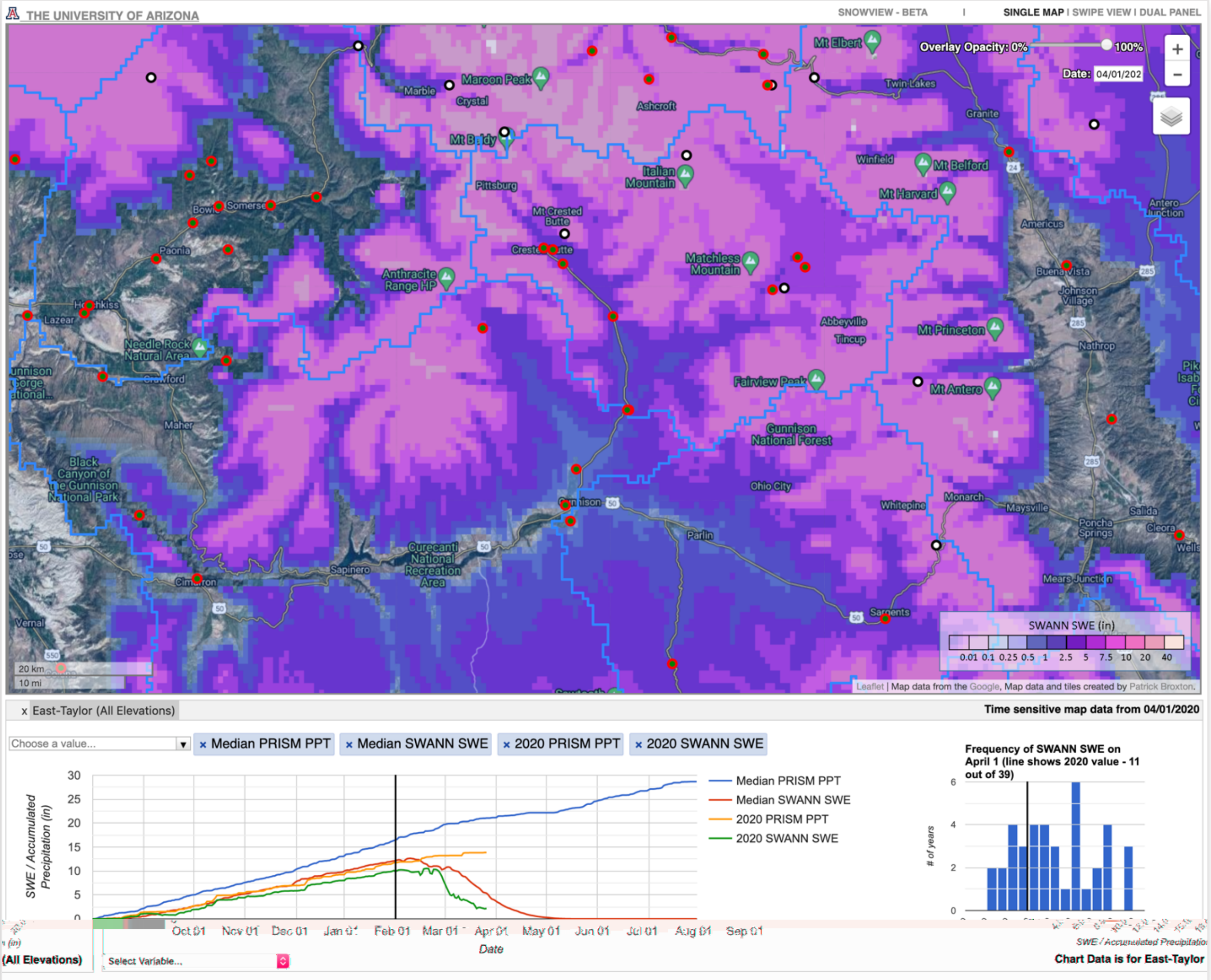
- Step-by-step instructions are provided in the "About" tab in the left panel of the main screen.
- Briefly: Select the analysis date in the upper right; default is the current date. Mouse-over a basin of interest to bring up its name and daily SWE statistics. Click to select that basin, which makes available the seven options for viewing time-series plots (lower right).

- This resource does not provide % of normal statistics, but all of the time-series plots compare the current year with all past years, allowing for assessment of the current snowpack relative to past years with known runoff outcomes.
- Not all of the basin SWE volume (in acre-feet) will be seen in the stream as runoff. As a rough rule of thumb, about 50-70% of the seasonal peak SWE volume will become runoff.

Downloading data (CSV files)

- All archived daily data (2003-present) for a single basin **(in the URL, replace "LOCAL_ID" with the Local ID of that basin)**: http://projects.openwaterfoundation.org/owf-proj-co-cwcb-2016-snodas/prototype/SnowpackStatisticsByBasin/SnowpackStatisticsByBasin_LOCAL_ID.csv
- Data for all CO basins for a single date (**in the URL, replace "YYYYMMDD" with the date of interest)**: http://projects.openwaterfoundation.org/owf-proj-co-cwcb-2016-snodas/prototype/SnowpackStatisticsByDate/SnowpackStatisticsByDate_YYYYMMDD.csv
- Data for all CO basins for the latest date: http://snodas.cdss.state.co.us/app/SnowpackStatisticsByDate/SnowpackStatisticsByDate_LatestDate.csv

SnowView – Snow Water Artificial Neural Network Modeling System (SWANN)



Quick facts

- Interactive map that displays the SWANN gridded estimates of SWE and snow depth and allows comparison with SNODAS data.
- Tool Access: https://climate.arizona.edu/snowview/

Snow data discussed in this user guide displayed by this tool

- SWANN data
- SNODAS data

Snow data NOT discussed in this user guide displayed by this tool

- PRISM data

Variables available

SWE (SWANN); SWE (SNODAS), precipitation (PRISM)

Years available

1981-present for SWANN SWE.

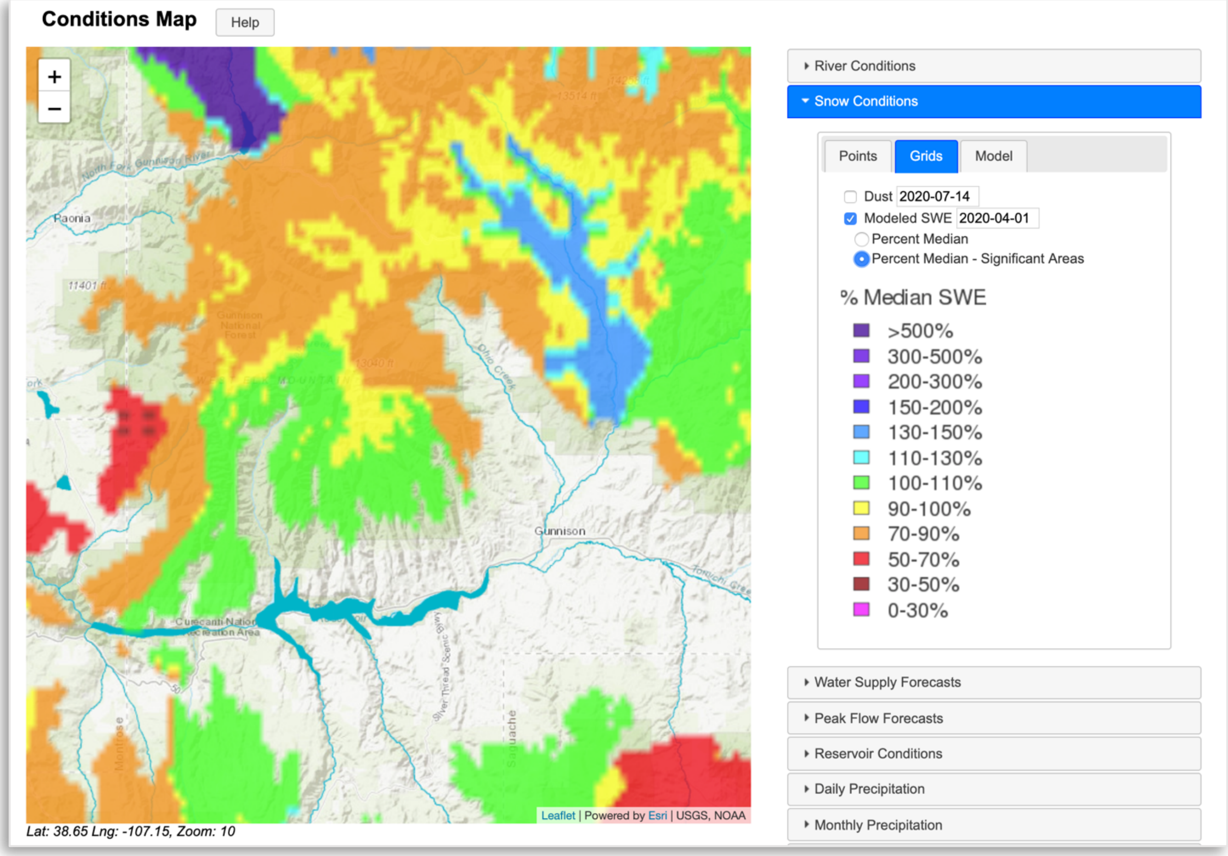
Viewing data

- The map's default display is gridded SWANN SWE data for the selected date, overlain by basin boundaries. Clicking the icon showing 3 stacked layers will open dropdowns to select the Basemap, the Vector Data (SNOTEL sites and stream gages, watersheds, and borders and roads), and the Raster Data (gridded SWANN SWE or PRISM precipitation).
- Select the **Date** of interest in the upper right. Note that the dropdown for year may not show all available years; select the year nearest to the year of interest, then open the dropdown again to see additional years.
- Pan and zoom into the map to the region or basin of interest. As you zoom in further, sub-basins within the basins will become visible, as will individual stations.
- Clicking on any basin in the map will open a pop up window which identifies that basin. Clicking **All Elevations** in that pop up will open up a panel across the lower part of the screen. By default, this lower panel shows a time-series plot which displays median PRISM PPT, median SWANN SWE, current year PRISM PPT and current year SWANN SWE for that (sub)basin.
- Clicking on any SNOTEL site in the map will display that site's SNOTEL SWE/Accumulated precipitation as a time-series plot in the lower panel.
- Similarly, clicking on any stream gage in the map will display that gage's Accumulated Streamflow (af) as a time-series plot.
- The dropdown box in the upper left corner of the time-series panel allows selection of other years or other variables to be displayed in the plot. In the lower left corner of the panel, the user can choose to display SWE and precipitation in either inches or in acre feet.
- The histogram at the right side of the time-series panel shows the historical distribution of values for the variable and date selected for the time-series plot. This allows the user to compare the selected year with all other years in the record.

Downloading data

SWANN SWE data cannot be downloaded from the tool. When a SNOTEL site is selected in the map, SNOTEL SWE and precipitation can be downloaded by clicking the link at the bottom right of the histogram.

CBRFC Modeled Snowpack – Interactive Conditions Map



☐ Dust 2020-07-14
☑ Modeled SWE 2020-04-01
○ Percent Median
● Percent Median - Significant Areas

Lat: 38.65 Lng: -107.15, Zoom: 10

Quick facts

- Interactive map that provides daily-updated SNOW-17 modeled SWE covering the Colorado River Basin and eastern Great Basin (including the Wasatch Front).
- The interactive map shows the same data as in the CBRFC's static maps of modeled snowpack, but allows the user to zoom into local watersheds.
- Tool Access: https://www.cbrfc.noaa.gov/lmap/lmap.php?interface=snow

Snow data discussed in this user guide displayed by this tool

- SNOW-17 modeled data

Variables available

SWE (% of median)

Years available

2015-present (Model Grids); 1981-present (Modeled SWE by forecast point)

Viewing data

Map of gridded SWE for forecast zones: In the right-hand navigation, select the *Grids* tab under *Snow Conditions*. Click the check box for *Modeled SWE* and select a year and date in the box. The modeled SWE % of Median for all CBRFC forecast zones will be shown. Selecting *Percent Median – Significant Areas* will show only those higher-elevation forecast zones that contribute significant runoff to the basin.

Time-series of SWE for each forecast point: In the right-hand navigation, select the *Model* tab under *Snow Conditions,* and click the *Show* check box. This will make all of the forecast points appear as gray dots. Click on a forecast point to identify it, and click *View Graph* to open a time-series plot of modeled SWE for the watershed above that forecast point.

Downloading data

Modeled SWE data cannot be downloaded directly from the CBRFC website. Contact CBRFC for access to the data.

Glossary

Ablation: The loss of snow from the snowpack due to melting, evaporation, or wind.

Albedo: The percentage of incoming light that is reflected off of a surface.

Calibration: The process of comparing a model with the real system, followed by multiple revisions and comparisons so that the model outputs more closely resemble outcomes in the real system.

Catchment: River basin, watershed

Climatology: In forecasting and modeling, refers to the historical average climate used as a baseline (e.g., "compared to climatology"). Synonymous with climate normal.

Evapotranspiration: A combination of evaporation from the land surface and water bodies, and transpiration of water from plant surfaces to the atmosphere. Generally includes sublimation from the snow surface as well.

In situ: A ground-based measurement site that is fixed in place.

Isothermal: A dynamic in which temperature remains constant while other aspects of the system change.

LiDAR (or lidar): Light detection and ranging; a remote sensing method which uses pulsed lasers of light to measure the variable distances from the sensor to the land surface.

Neural network: A series of algorithms or computing systems that endeavors to recognize underlying relationships in a set of data through a process that is inspired by the way the human brain operates.

Physiography: The subfield of geography that studies the patterns and processes of the natural environment such as the atmosphere, geosphere, hydrosphere and biosphere. Also known as physical geography.

Probabilistic method: A method based on the theory of probability or the fact that randomness plays a role in predicting future events. The opposite is deterministic, which tells us something can be predicted exactly, without the added complication of randomness.

Radiative forcing: The difference between solar irradiance (sunlight) absorbed by the Earth and energy radiated back to space.

Regression: A statistical technique used for modeling the linear relationship between two or more variables, e.g., snowpack and seasonal streamflow.

Relative humidity: The amount of moisture in the atmosphere relative to the amount that would be present if the air were saturated. RH is expressed in percent and is a function of both moisture content and air temperature.

Remote sensing: The science and techniques for obtaining information from sensors placed on satellites, aircraft, or other platforms distant from the object(s) being sensed.

Runoff: Precipitation that flows toward streams on the surface of the ground or within the ground. Runoff as it is routed and measured within channels is *streamflow*.

Snow-water equivalent (SWE): The depth, often expressed in inches, of liquid water contained within the snowpack that would theoretically result if you melted the snowpack instantaneously.

Snow course: A linear site used from which manual measurements are taken periodically, to represent snowpack conditions for larger area. Courses are typically about 1,000’ long and are situated in areas protected from wind in order to get the most accurate snowpack measurements.

Snow pillow: A device (e.g., at SNOTEL sites) that provides a value of the average water equivalent of snow that has accumulated on it; typically the pillow contains antifreeze and has a pressure sensor that measures the weight pressing down on the pillow.

Spectrometer: A scientific instrument used for measuring wavelengths of light spectra.

Streamflow: Water flow within a river channel, typically expressed in cubic feet per second for flow rate, or in acre-feet for flow volume. Synonymous with discharge.

Sublimation: When water (i.e., snow and ice) or another substance transitions from the solid phase to the vapor phase without going through the intermediate liquid phase; a major source of snowpack loss over the course of the season.

Telemetry: The process of collecting in situ measurements or other data and automatically transmitting these to receiving equipment.

Undercatch: When less precipitation is captured by a precipitation gage than actually falls; more likely to occur with snow, especially under windy conditions.

Validation: The process of comparing a model and its behavior and outputs to the real system, after calibration.

Watershed: River basin, catchment

Acronyms and abbreviations

ACIS: Applied Climate Information System

ANN: artificial neural network

ASO: NASA Airborn Snow Observatory

CBRFC: Colorado Basin River Forecast Center

CDSS: Colorado Decision support system

CoCoRaHS: Community Collaborative Rain, Hail and Snow Network

CODOS: Colorado Dust-on-Snow Program

COOP: Cooperative Observer Program

CSAS: Center for Snow and Avalanche Studies

ESP: ensemble stream flow prediction

Landsat: Land Remote-Sensing Satellite (System)

Lidar: Light detection and ranging

MODDRFS: MODIS Dust Radiative Forcing in Snow

MODIS: Moderate Resolution Imaging Spectroradiometer

MODSCAG: MODIS Snow Covered Area and Grain-size

NASA JPL: NASA Jet Propulsion Laboratory

NOAA: National Oceanic and Atmospheric Administration

NOHRSC: National Operational Hydrologic Remote Sensing Center

NRCS: Natural Resource Conservation Service

PRISM: Parameter-elevation Relationships on Independent Slopes Model

RFC: River Forecast Center

Sac-SMA: Sacramento Soil Moisture Accounting Model

SCAN: Soil Climate Analysis Network

SNODAS: Snow Data Assimilation System

SNOTEL: Snow Telemetry

SRP: Salt River Project

SWANN: Snow-Water Artificial Neural Network Modeling System

SWE: Snow Water Equivalent

Reference

1. Li, D., Wrzesien, M. L., Durand, M., Adam, J. & Lettenmaier, D. P. How much runoff originates as snow in the western United States, and how will that change in the future? *Geophysical Research Letters* **44**, 6163–6172 (2017).

2. Schneider, D. & Molotch, N. Real-Time Estimation of Snow Water Equivalent in the Upper Colorado River Basin Using MODIS-Based SWE Reconstructions and SNOTEL Data. *Water Resources Research* **52**, 7892–7910 (2016).

3. Lukas, J., Payton, E., Deems, J., Rangwala, I. & Duncan, B. Observations-Hydrology. in *Colorado River Basin Climate and Hydrology: State of the Science* (eds. Lukas, J. & Payton, E.) 154–219 (Western Water Assessment, University of Colorado, 2020).

4. Lukas, J. & Harding, B. Current Understanding of Colorado River Basin Climate and Hydrology. in *Colorado River Basin Climate and Hydrology: State of the Science* (eds. Lukas, J. & Payton, E.) 42–81 (Western Water Assessment, University of Colorado, 2020).

5. Hood, E., Williams, M. & Cline, D. Sublimation from a seasonal snowpack at a continental, mid-latitude alpine site. *Hydrological Processes* **13**, 1781–1797 (1999).

6. Phillips, M. Estimates of sublimation in the Upper Colorado River Basin. (Colorado State University, 2013).

7. Hultstrand, D. M. & Fassnacht, S. R. The sensitivity of snowpack sublimation estimates to instrument and measurement uncertainty perturbed in a Monte Carlo framework. *Frontiers of Earth Science* **12**, 728–738 (2018).

8. Lute, A. C., Abatzoglou, J. T. & Hegewisch, K. C. Projected Changes in Snowfall Extremes and Interannual Variability of Snowfall in the Western United States. *Water Resources Research* **51**, 960–972 (2015).

9. Deems, J. S., Painter, T. H., Barsugli, J. J., Belnap, J. & Udall, B. Combined impacts of current and future dust deposition and regional warming on Colorado River Basin snow dynamics and hydrology. *Hydrology and Earth System Sciences* **17**, 4401–4413 (2013).

10. Clow, D. W., Williams, M. W. & Schuster, P. F. Increasing aeolian dust deposition to snowpacks in the Rocky Mountains inferred from snowpack, wet deposition, and aerosol chemistry. *Atmospheric Environment* **146**, 183–194 (2016).

11. Painter, T. H., Skiles, S. M., Deems, J. S., Brandt, W. T. & Dozier, J. Variation in Rising Limb of Colorado River Snowmelt Runoff Hydrograph Controlled by Dust Radiative Forcing in Snow. *Geophysical Research Letters* **45**, 797–808 (2018).

12. Lukas, J. J., Barsugli, J. J., Doesken, N. J., Rangwala, I. & Wolter, K. *Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation*. 114 https://wwa.colorado.edu/climate/co2014report/Climate_Change_CO_Report_2014_FINAL.pdf (2014).

13. Lukas, J., Gutmann, E., Harding, B. & Lehner, F. Climate Change-Informed Hydrology. in *Colorado River Basin Climate and Hydrology: State of the Science* (eds. Lukas, J. & Payton, E.) 384–449 (Western Water Assessment, University of Colorado, 2020).

14. Painter, T. H. *et al.* Retrieval of Subpixel Snow Covered Area, Grain Size, and Albedo from MODIS. *Remote Sensing of Environment* **113**, 868–879 (2009).

15. Wood, A., Woelders, L. & Lukas, J. Streamflow Forecasting. in *Colorado River Basin Climate and Hydrology: State of the Science* (eds. Lukas, J. & Payton, E.) 287–333 (Western Water Assessment, University of Colorado, 2020).