COLORADO
Colorado Water
Conservation Board
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TO: Colorado Water Conservation Board Members

FROM: Erik Skeie, Interstate, Federal & Water Information
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DATE: July 20-21, 2022

AGENDA ITEM: 9: Colorado Airborne Snow Measurement Group Update

This is informational only.

Background:
CWCB Staff has been using Airborne Snow Observatories (ASO) since 2014 to provide high resolution, spatial snowpack data to stakeholders. Data collection is conducted using airplane mounted LiDAR and Spectrometer units, then processed and modeled by ASO staff to provide stakeholders a highly accurate picture of the snowpack in their basins. When combined with modeling efforts such as WRF-Hydro, this data can strengthen decision making through refining streamflow forecasts. This data has always been fairly spotty, as funding would allow one or two basins to be flown each winter. It has always been the goal of CWCB to make this powerful data more available throughout the state. Water Year 2021/2022 was the first season that a broader scale program could be examined, developed, and implemented, thanks especially to the vision of Denver Water's Laurna Kaatz.

Denver Water and Northern Colorado Water Conservancy District began forming a leadership group to apply for funds to study what a statewide program might look like (Attachment 1), and were awarded a $45,000 Water Supply Reserve Fund Grant in March of 2021. Through this effort, the Colorado Airborne Snow Measurements Group (CASM) was formed. This stakeholder driven group held outreach meetings throughout the summer of 2021 to develop a plan for the 2021/2022 Water Year. In December 2021, CASM applied for and received a large Water Plan Grant to fully implement a 2022 winter season plan.

The CASM group will be sharing their findings from the WSRF Study, and some results from the Water Year 21/22 flights.

CWCB Staff is incredibly excited to continue working with the CASM Group to implement and refine this program to provide stakeholders statewide with this powerful tool.

CASM Website: https://coloradosnow.org/

Attachments:

1) CASM WSRF Final Report
2) ASO 2022 Results

Attachment 1:

WSRF Final Report

Colorado Airborne Snow Observatory Expansion Plan: Executive Summary

> *"ASO provides detailed information into the snowpack like we have never seen before. The information gained from ASO flights allows for a finer level of water management and provides more opportunity to benefit more users and get the maximum benefit out of every drop."*
>
> *Nathan Elder*
> *Raw Water Operations Manager*
> *Denver Water*

Primary Program Goal

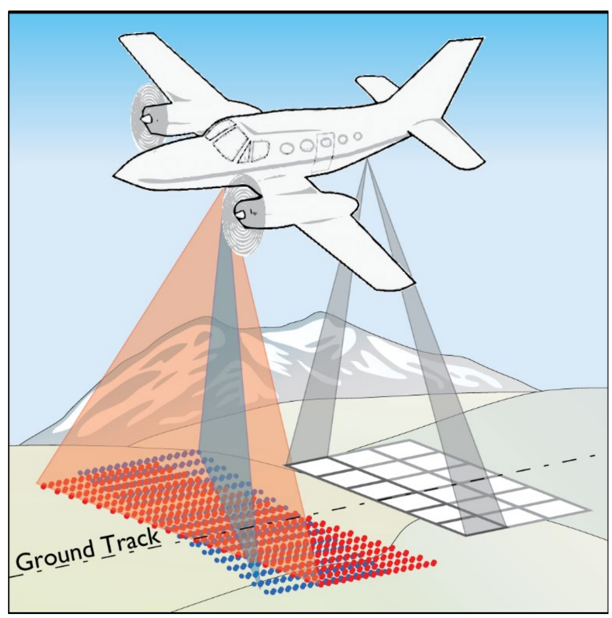
Every year, Colorado water managers and water users depend on seasonal runoff forecasts to make multi-million dollar planning decisions that have impacts across all water stakeholder communities. These seasonal runoff forecasts are heavily dependent on snowpack estimates, as roughly 75% of Colorado's annual total streamflow comes from melting snow between April and July. Historically, however, the tools have not existed to accurately measure snowpack at the watershed scale, which has led to inaccuracies in runoff forecasting. To increase the accuracy of seasonal runoff forecasts in Colorado, it is imperative that the snowpack is accurately measured at the scale of entire watersheds.

Fortunately, high-accuracy snowpack measurements are now possible with the technology of the Airborne Snow Observatories, Inc. (ASO, Inc.). The Colorado Airborne Snow Measurements (CASM) workgroup has formed to develop a statewide, long-term program that increases ASO survey coverage in Colorado and actively integrates the resulting ASO snowpack measurements into streamflow forecasting methods. The plan laid out in this document outlines how airborne lidar snowpack measurements from ASO will be deployed across Colorado and will be used to inform and improve water management for all water stakeholders in Colorado and beyond.

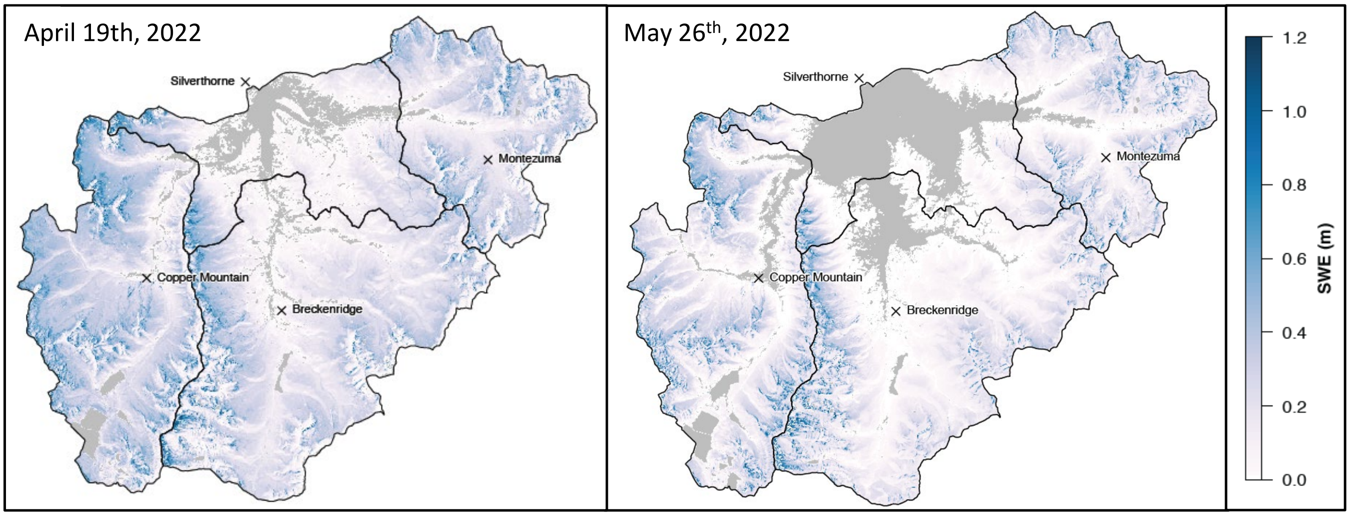
What does ASO Inc. provide?

ASO, Inc. offers an operational snowpack measurement product that allows for the most accurate measurement of snow water equivalent (SWE) and snow albedo for entire watersheds of any available products. Airborne Snow Observatories Inc. uses airborne laser altimetry (lidar) measurements, both with and without snow, to develop 3m gridded measurements of snow depth throughout a river basin. These lidar measurements are paired with the iSnobal energy balance model which models snowpack density over time to produce 50m gridded estimates of snow water equivalent (SWE).

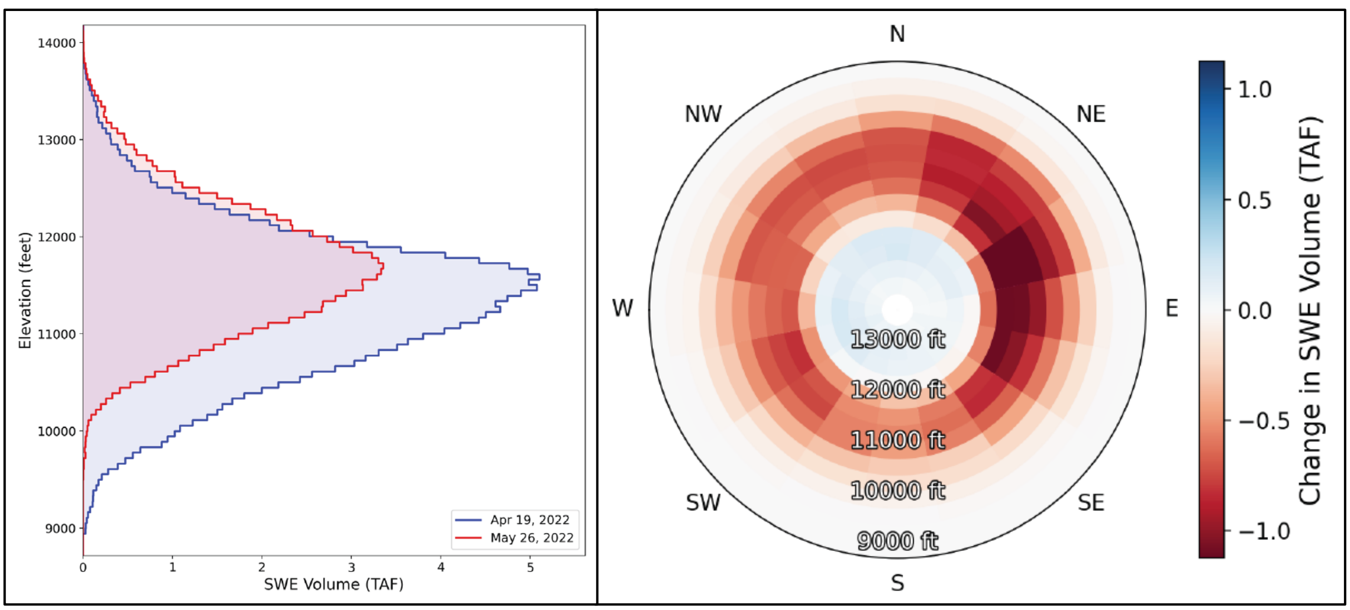
Historical data review shows that these ASO measurements are within 5-10% of the actual water contained in the snowpack at the time of the survey, though total runoff varies due to uncertainty in seasonal precipitation following the final ASO surveys of the season. Using ASO's current equipment, a single survey can cover a river basin approximately 3,500 sqkm, equivalent to the entire watershed of the Roaring Fork River.



ASO Lidar Technology



High resolution ASO snow depth grids from the Blue River Basin, 2022



(left) Change in Snow Water Equivalent by elevation band between two ASO flights in the Blue River Basin. (right) Change in SWE volume by elevation and aspect between the same two ASO flights.

What do we propose?

The Colorado Airborne Snow Measurement Working Group (CASM) was formed to develop a statewide program to provide significantly improved streamflow forecasting throughout Colorado through widespread deployment of ASO surveys and the supporting hydrologic science. The mission of CASM is to encourage adoption of ASO technology as a core component of the water resources management toolkit for stakeholders across Colorado. CASM currently engages with a stakeholder group of nearly 100 agencies that serve millions of Colorado residents, hundreds of thousands of irrigated acres, and represent all major river basins. The CASM workgroup projects a fully functional ASO flight and forecasting program to cost up to $26 Million per year, though this is dependent on how quickly the program grows.

> *"[Reservoir operators in California] indicate that [ASO] has improved decision making and the ability to balance competing water demands, including power supply and environmental flows, as well as minimizing flood risks*
>
> *US Bureau of Reclamation Emerging Technologies in Snow Monitoring Report to Congress, 2022*

If multiple ASO snow surveys per year can be conducted in the headwaters of every major river basin in Colorado, water stakeholders can use this information to make better water management decisions and respond in real time to the impacts of a changing climate. When snow depth estimates are improved substantially and those depth estimates are used to inform runoff forecasts, water managers have the potential to benefit directly through:

- Optimized reservoir use
- Better-informed drought planning
- More appropriate purchasing of agricultural supplies (e.g., seeds, fertilizer, etc.)
- More accurate streamflow forecasts for determining water allocations and for planning stream-based recreation and tourism
- Improved understanding of water availability for stream health
- Better understanding of natural yields for water contracts and leases
- Provide antecedent information to fire season forecasting
- Monitoring pre and post land management changes and impacts on runoff efficiency

Widespread ASO surveys include other benefits that can only come at the scale and accuracy of ASO data products:

- A better understanding of the uncertainty in current snowpack measurement networks
- Improved estimates of runoff efficiency and basin productivity for calibrating forecast models
- Quantitative understanding of the impacts of climate change on Colorado's water supply
- Detailed pre- and post-wildfire impacts to snowpack and runoff
- Detailed surveys of changes in the forest canopy
- Measurements of avalanches and landslides

How did this project come together?

In 2021, the Colorado Airborne Snow Measurement (CASM) group formed organically because there was widespread stakeholder interest in expanding ASO flight coverage in Colorado. The CASM workgroup was funded under a Colorado Water Conservation Board (CWCB) Water Supply Reserve Fund (WSRF) grant to study how to develop a long-term, sustainable program focused on expanding ASO coverage in Colorado. The WSRF funds were used for:

- Engagement with local, state, and federal water resources managers
- Mapping and statistical analysis of historical ASO flights
- Monthly CASM workgroup meetings
- ASO flight planning and snowpack data analysis for the State of Colorado
- Planning and coordination of future activities

CASM Program FAQ

1.1. What is this program called?

CASM is the Colorado Airborne Snowpack Measurement workgroup. The CASM workgroup is working toward implementing a statewide program to conduct regular ASO flights and provide significantly improved streamflow forecasting throughout Colorado.

1.2. What is ASO?

The Airborne Snow Observatories, Inc. (ASO Inc.) uses paired airborne lidar and imaging spectrometer sensors coupled with a snow dynamics model to measure snow depth and albedo and retrieve Snow Water Equivalent (SWE, the liquid depth of water stored in the snowpack) across large river basins at a high spatial resolution. The resulting data provides high-elevation snowpack measurements with detail, accuracy, and decision-support value unprecedented in water management.

The added value of these measurements to the water community has been thoroughly demonstrated through a multitude of pilot flights in Colorado and California. For example, in a 2019 pilot flight series in the Blue River watershed with Denver Water—during a time when the SNOTEL stations in the watershed had melted out—ASO data provided an accurate volume estimate of 115,000AF of water remaining in the high elevations. This provided Denver Water's operations manager the information needed to accurately reduce Dillon Reservoir levels to account for the incoming runoff, which in turn allowed downstream reservoir operators and other Colorado River reservoir operators to retime outflows and cancel Coordinated Reservoir Operations (CROS) that could have otherwise led to downstream flooding and lost water supply.

ASO Inc. is a private company that was formed out of a project at the NASA Jet Propulsion Lab (JPL). ASO Inc. provides aircraft-based measurements of snow albedo and depth along a flight path. These physical measurements are combined with physically based snow density modeling to create a high resolution (3m) gridded measurement of snow water equivalent across a river basin. The fully processed snow water equivalent (SWE) measurements are colloquially referred to as "ASO Data".

1.3. How accurate is ASO compared to other products?

Traditional snowpack estimates using ground and satellite-based measurements can be off by as much as 40%, and sometimes more. ASO snowpack measurements have been shown to have bulk snowpack measurement uncertainty of 5-13% (Oeida 2019). Other recent studies have demonstrated the suitability and accuracy of airborne and terrestrial lidar data for differential mapping of snow depth in mountainous terrain (Hopkinson et al., 2004; Deems et al., 2006; Trujillo et al., 2007; Prokop, 2008; Mott et al., 2011; Deems et al., 2013a; Deems et al., 2015)

1.4. How are ASO snow surveys used to improve streamflow forecasts?

ASO, Inc. processes its flight data to generate a 3m resolution gridded snow depth product. This depth measurement, paired with the iSnobal energy balance model and ground-based density measurements, is used to generate a total snowpack water volume estimate at 50m resolution. Since most of the annual runoff from Colorado headwater basins comes from snowmelt, this ASO-derived snowpack volume can be assimilated into most existing runoff forecasting tools that rely on SWE estimates. There are several ongoing academic and government research projects exploring different techniques for ASO assimilation to provide the most forecast improvement and maximize the value of this program. In 2022, the Weather Research and Forecasting Model Hydrological modeling system (WRF-Hydro, Gochis 2020) run by the National Center for Atmospheric Research (NCAR) was used to develop experimental streamflow forecasts for any basin with ASO flights. The Colorado Basin River Forecast Center (CBRFC) also provided a similar ASO-integrated experimental forecast.

1.5. What does a successful program look like?

CASM directly supports the goals of the Colorado Water Plan. All aspects of water availability and security are driven by the ability to properly measure and forecast Colorado's water supply. All Basin Implementation Plans (BIPs) identify the need to manage risk around water supply availability, both for in-basin municipal and industrial (M&I), recreational, and environmental demands, Colorado River Compact administration, and other goals. The CASM program aims to directly address all of these high-level water management goals, ultimately allowing Colorado water stakeholders to do more with less. The widespread adoption of cutting edge ASO technology is in tradition with Colorado being a model of leadership in water sciences and water resource management throughout the US. A successful CASM program will have:

- Seasonal runoff forecasts in key headwater basins that show improved accuracy and uncertainty due to the integration of the ASO Inc. SWE measurements
- Continued integration of ASO data with the scientific research community to better understand changing snowpack characteristics and further develop runoff forecasts and water management decision support tools that are useful in a changing climate
- Improved understanding of the impacts on snowpack and water supply due to forest management, wildfire, and other major landscape changes.
- An engaged group of water management stakeholders that includes broad geographic diversity and water sector diversity throughout Colorado.
- Continued education and stakeholder feedback sessions around how to improve decision-making using this data
- Data that is openly accessible to any interested stakeholder
- State-led oversight of the program to ensure fairness and equity in survey coverage as well as program sustainability
- Sustainable funding that allows for multiple ASO surveys each year for the majority of high-elevation watersheds in Colorado. This should also include budget flexibility around where and when to conduct ASO surveys.

1.6. How many flights per year does Colorado need?

The current CASM vision for a fully developed ASO program would be funded to conduct 6-8 snow-on surveys per year across all snow-covered areas of Colorado. Peak SWE in Colorado typically occurs between April 1st and 15th, depending on the year type. During peak SWE, it would require around 25 surveys for a single snapshot statewide of snowpack across all key headwaters. As the snowpack recedes throughout the snow season, fewer flights are required to reach full coverage. At an upper limit, 215 flights per year would provide detailed measurements across all major headwaters of Colorado's river basins from winter through the spring melt season.

It is an active area of scientific research by the US Bureau of Reclamation, the California Department of Water Resources, the CWCB, and multiple academic research groups to balance data from ground-based networks with the high accuracy of ASO snow surveys throughout the accumulation and melt seasons, though 6-8 surveys per basin is the current best estimate. There have not been enough ASO flights yet in Colorado to truly answer this question of the optimum number of flights. The geography and snowpack dynamics of Colorado's headwater basins is highly variable and needs to be studied in more detail.

As CASM grows, ASO flights should be conducted multiple times in headwater basins from winter through spring runoff season, while delivering improved runoff forecasts. As this program grows, the total number of flights per year will grow as well, based on stakeholder engagement, funding, and advancement of snow science.

1.7. How much will this program cost?

A single ASO flight survey can measure a basin up to 3,500 sqkm (1,351 sqmi), equivalent to the entire watershed area of the Roaring Fork River. As flight coverage expands, so will the total program cost. Program costs include:

- Snowpack measurement flights and data processing at around \$120,000-\$150,000 per flight
- Snow-Free flight costs at around \$44/sqkm, with 66,000 sqkm remaining to achieve full coverage
- Additional support activities including streamflow forecasting and stakeholder coordination
- Staff Support for 2 FTEs at \$100,000 annual salary

Table 1 shows the estimated program cost during each phase of growth. These costs are approximate and are subject to changes due to program direction, fuel costs and other factors.

Table 1. Estimated CASM Program Costs (all values in millions of dollars)

Phase	Timeline	Flights Per Year	Snow Survey Flight Cost	Snow-Free Flight Cost	Support Activities	Staff Support (2 FTEs)	Total Annual Cost
Phase 1	2022	14	**1.3**	**1.0**	**0.3**	**N/A**	**2.6**
Case Study Building	2023	30 (2 flights per basin with available snow-free data)	**3.6**	**2.0**	**0.5**	**0.2**	**6.3**
Widespread Adoption	2024-2026	64 (3 flights per basin with available snow-free data)	**7.7**	**0.2**	**0.5**	**0.2**	**8.6**
Program Buildout	2026-2028	214 (6 Flights across all major headwaters)	**25.7**	**0.2**	**0.5**	**0.2**	**26.6**

The flight estimates in this table are based on assumed program growth. For comparison to California's ASO program, increased demand by California stakeholders for ASO flights has led the program to plan for around 6-8 flights per year in each basin at full program buildout.

1.8. How is ASO currently being used in Colorado?

Airborne lidar snowpack measurements have been conducted across Colorado since 2013, with numerous scientific, applied science, and operations support efforts. The following list details ASO activity in Colorado to-date, along with funding source and application:

- **Uncompahgre River above Ridgway Reservoir**; 1-4 surveys per year 2013-2017: NASA Terrestrial Hydrology Program, Science support
- **Grand Mesa;** NASA Terrestrial Hydrology Program, Science support
- **Rio Grande and Conejos Rivers**; 1-2 flights per year 2015-2016, 2 surveys planned in Conejos 2021: CWCB Rio Grande Forecast Improvement Project; Applied science support, 2 surveys, 2022 CWCB Water Plan Grant Funds
- **Upper Gunnison River (East and Taylor Rivers);** 1-2 surveys per year 2016, 2018-2019, 2022: Dept. of Energy East River Watershed Function Scientific Focus Area, Science support, CWCB Project funds and 2022 CWCB Water Plan Grant Funds
- **Blue River above Dillon Reservoir;** 2 surveys 2019, 2021, 2022: Denver Water, Operations support
- **Animas River above Durango**; 2 surveys 2021: CWCB Project funds, Operations support
- **Dolores River above McPhee Reservoir**; 2 surveys 2022 CWCB Water Plan Grant funds, Operations support
- **Willow Creek Reservoir, Granby Reservoir, Fraser River;** 2 surveys, 2022 CWCB Water Plan Grant Funds

1.9. What does ASO provide that other snowpack measurement techniques do not?

Ground-based snow-measurement stations are highly accurate but only at their specific point location and require statistical extrapolation models to make basin-scale snowpack estimates. Satellite-based products provide broad coverage, but are often at a coarse horizontal resolution (1km+ cells) and poor vertical resolution. Drone-based technologies are similar in resolution to ASO but cannot provide sufficient geographic coverage.

ASO is the only product that provides high accuracy, high resolution, complete measurements of snow depth and snow water equivalent at the basin scale. ASO snow depth data is natively 3m horizontal resolution and 1cm vertical resolution (8cm uncertainty).

1.10. Can ASO data be used as a climate adaptation strategy?

Yes. As the snowpack changes with climate change, the historical snowpack record is becoming less and less reliable as an indicator for current snowpack conditions. Being able to accurately measure the snowpack at the watershed scale multiple times each year with ASO technology is a proven strategy for adapting to changing snowpack conditions.

1.11. I am a water manager in Colorado… how can I use this data?

An ASO snow survey provides a highly accurate estimate of the total volume of water contained in a basin's snowpack at a single point in time. This measurement can be used to validate estimates of reservoir inflow, make predictions about total and peak runoff timing downstream, and provide a check on other snowpack estimates. If any of your planning efforts require a numeric estimate of total seasonal runoff, ASO can provide basin-scale estimates of SWE that provide a point in time estimate of the total water available in a basin. For each ASO survey conducted in Colorado, the team at ASO, Inc. produces a post-survey report that summarizes the flight data. This report, and the associated raw data products, are freely accessible to the public and can downloaded from ASO, Inc's website. If you have ideas for a use case of this data for your sector, please reach out to the CASM planning team.

1.12. Is this data available even though I didn't pay for it?

Results from ASO snow surveys are publicly available on the ASO Inc. website (https://data.airbornesnowobservatories.com/). These data are limited to locations where snow surveys have been flown, but include:

- Basin-wide estimate of SWE volume
- 3m resolution snow depth gridded data
- 50m resolution snow water equivalent gridded data
- Detailed survey reports outlining model and data assumptions

1.13. How long has ASO existed?

In 2010, Dr. Thomas Painter was recruited to the NASA Jet Propulsion Laboratory to lead the development of the program that would become the NASA Airborne Snow Observatory. He and his ASO team, along with partnership with the California Department of Water Resources, began in 2013 with breakthrough measurements and modeling of mountain snowpack that led to the first high-accuracy maps of distributed snow water equivalent across entire mountain basins. In 2019, Dr. Painter, Dr. Joe Boardman, Dr. Jeff Deems, and Pat Hayes founded Airborne Snow Observatories, Inc. to transfer the NASA technology to commercial operations available around the globe.

The Colorado Airborne Snow Monitoring (CASM) program was established and funded under a Water Supply Reserve Fund (WSRF) Grant in 2021. CASM's mission is to improve water management across Colorado through widespread deployment of ASO flights.

1.14. Does a statewide ASO program like this exist anywhere else?

In California, the Department of Water Resources manages the Airborne Remote Sensing of Snow (ARSS) program and deploys 30+ ASO flights per year across nine different basins in the Sierra Nevada mountains. Data from ARSS flights are used to improve runoff estimates, issued as part of the Bulletin 120 seasonal runoff forecast (https://cdec.water.ca.gov/snow/bulletin120/ CA DWR 2022). In the wake of the recent large wildfires in California, ASO data is also used to quantify the impact of fire damage on snowpack and runoff efficiency.

ARSS began in 2013 and has slowly scaled up over several years to provide 3-5 snow surveys per year across nine major basins in the Sierra Nevada. The CASM team has engaged closely with CA-DWR staff to understand some lessons learned and potential challenges of developing a program like ARSS. In 2022, ARSS is funding 31 flights and all the associated support activities at a cost of $9.5 Million.

1.15. ASO, Inc. is a private company… how are the issues around sole-sourced contracting being addressed?

As of 2022, ASO, Inc., the developer of this technology and application, is the only organization providing the combination of airborne lidar and spectrometer snow depth, SWE, and snow albedo data products along with rapid processing that meets the needs of the CASM program and other managers of snowmelt systems. Unless another company offers this service and can demonstrate a similar accuracy, timeliness, and product suite, ASO Inc. will be the sole provider of snow surveys for CASM for the foreseeable future. ASO Inc has been integrally involved in the development of CASM and has made good faith efforts to provide their services at a reasonable cost. ASO Inc has stated that snow survey data for these locations will be public for the foreseeable future – data availability policy is maintained by ASO, Inc. responsive to the mandates of the funding agencies. Any potential change in contractor will require careful thought on the part of CASM to ensure that all aspects of their program and costs as well as their capabilities are well understood.

2. ASO Case Studies

2.1. 2019 Dillon Reservoir ASO Success

ASO is Critical to Reservoir Operations

- Above average snowpack in 2019 in Dillon Reservoir watershed caused higher than average inflows
- A June ASO flight indicated more remaining snowpack above Dillon Reservoir than it had room for, prompting a ramp up of outflows. This ramp up of outflows occurred earlier than otherwise would have without ASO data, thus preventing potential downstream flooding impacts
- Accurate knowledge of snowpack from the ASO flight allowed managers to avoid significant downstream impacts and keep the reservoir full

Colorado had an unusual snow year in the spring of 2019. Several late-season storms brought peak snow water equivalent (SWE) well above average, resulting in higher-than-normal runoff in many of its river basins. 2019 was also the first year Denver Water piloted using ASO data to inform their operations.

Dillon Reservoir, located in Summit County, is Denver Water's largest reservoir. Snowpack that accumulates in the Blue River Basin flows into Dillon Reservoir and is the source of 30% of the water supply delivered to Denver and its surrounding suburbs.

ASO, Inc. conducted an airborne snow survey for Denver Water on April 19th, 2019 over the headwaters of the Blue River, aiming to capture peak SWE for the entire Dillon Reservoir watershed. Data from this flight confirmed unusually high snowpack and indicated a delayed melt. A second ASO flight on June 24th revealed that about 107,204 acre-feet of water remained in the snowpack above Dillon Reservoir. Several SNOTEL sites (Grizzly Peak, Hoosier Pass, Fremont Pass, and Copper Mountain), which sit around 11,000 feet, had already mostly melted out. The figure below shows that between the additional snowpack and Dillon Reservoir storage contents, there was more water stored as snow in the basin than the capacity of Dillon Reservoir, necessitating a significant release.

Too much outflow release or an overtopping of the reservoir spillway could result in flooding in the downstream town of Silverthorne. Conversely, had reservoir managers acted conservatively without the ASO information, they may have released more water than necessary to make space for the coming runoff, and Dillon Reservoir may not have filled. Because of the ASO flight, Denver Water managers knew that they needed to begin ramping up outflows earlier than normal and continue them for additional weeks to avoid a peak release that was higher than acceptable.

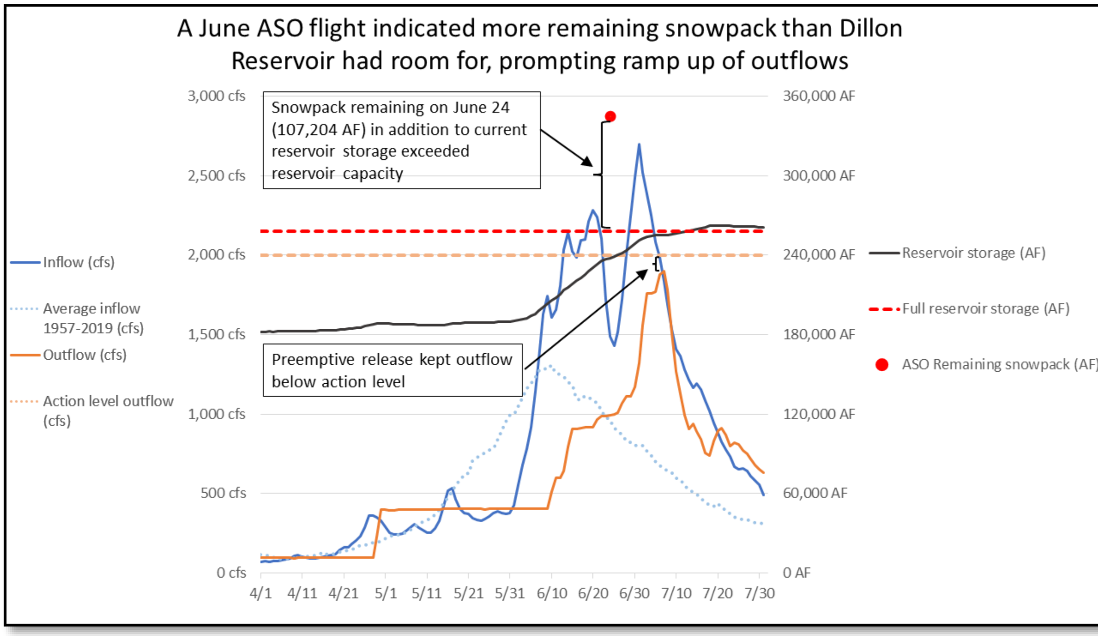


Figure* 1. *Dillon Reservoir operations in 2019.

2.2. 2020 McPhee Reservoir Over-Forecast

Dolores Water Conservancy District (DWCD) manages the operations of McPhee Reservoir which furnishes irrigation water for Montezuma and Dolores counties. Many irrigators in the region rely solely on water from McPhee to water their fields. Each spring, DWCD releases predictions of the coming runoff season so that Dolores Project water users can anticipate water allocations and make financial commitments for fertilizer, seed, and other purchases before the growing season.

The Dolores River basin began 2020 with soil moisture below 50% of average. Snowstorms in late March 2020 brought snowpack up to 100% of the long-term average based on SNOTEL sites. Given the 100% April 1st snowpack and above-average carryover from McPhee Reservoir, water managers expected to have a full supply even with lower-than-expected inflows from the dry soil. Communications went out to irrigators on April 20th indicating a year with full allocations.

ASO Is Critical to Reservoir Operations

- In 2020, dry soil moisture, historic warm temperatures, and inaccurate SNOTEL models contributed to an overestimation of snowmelt runoff
- Given the promising forecast, overallocations were made to irrigators reliant on McPhee Reservoir water
- An ASO flight would have provided a more precise measurement of remaining runoff, thus avoiding economic consequences for irrigators

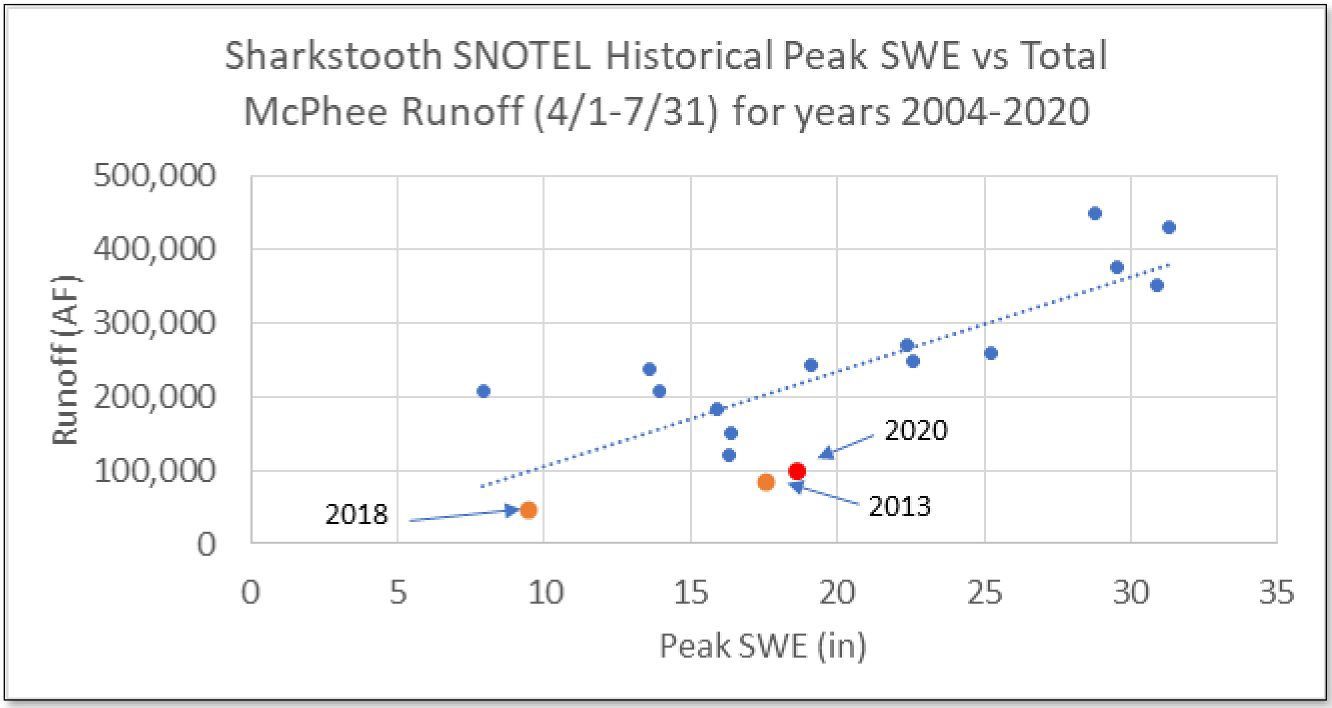


Figure 2. Historical peak SWE at Sharkstooth SNOTEL site vs total runoff into McPhee Reservoir (4/1-7/31) each year. Red dot is 2020. Historically dry years show SNOTEL peak SWE well below average total runoff.

April and May 2020 were windy and one of the driest and hottest springs on record. The combination of low soil moisture and historic warm weather meant that less snowpack was converted to runoff and made it into McPhee Reservoir. Factors contributing to this low runoff efficiency also included high elevation sublimation of the snowpack and increased evaporation and evapotranspiration from basin vegetation. DWCD managers also realized that SNOTEL measurements from the spring of 2020 did not accurately represent the lack of higher elevation snow, contributing to the early spring over-forecast.

Instead of the expected full supply, DWCD managers and irrigators ended up with 85% of the full supply. The early allocations from the April 1st forecast had both planning and financial consequences for Dolores Project water users. Wasted inputs, seed, fertilizer and application due to changed lower allocation from pre-season forecasts financially harmed project users that fund Project operations with less water sales. Dolores Project water users suffered economic damage when early models overestimated the amount of water based on SNOTEL sites and CBRFC forecasts.

As Southwest Colorado continues to face unprecedented drought conditions, a more accurate measurement of snowpack is necessary to optimize operations and minimize the financial impacts from situations like this. An ASO flight over the Dolores River Basin would have provided a more accurate picture of the snowpack above 11,000ft. A flight on April 1st around peak SWE would confirm the total water in the snowpack, allowing for managers to be more precise in their allocation estimations for the year. A second flight would have confirmed 2020 runoff efficiency given antecedent and current hydrologic conditions. More comprehensive data is critical to ensure accurate allocation forecasts are made so that the mistakes of 2020 are not repeated.

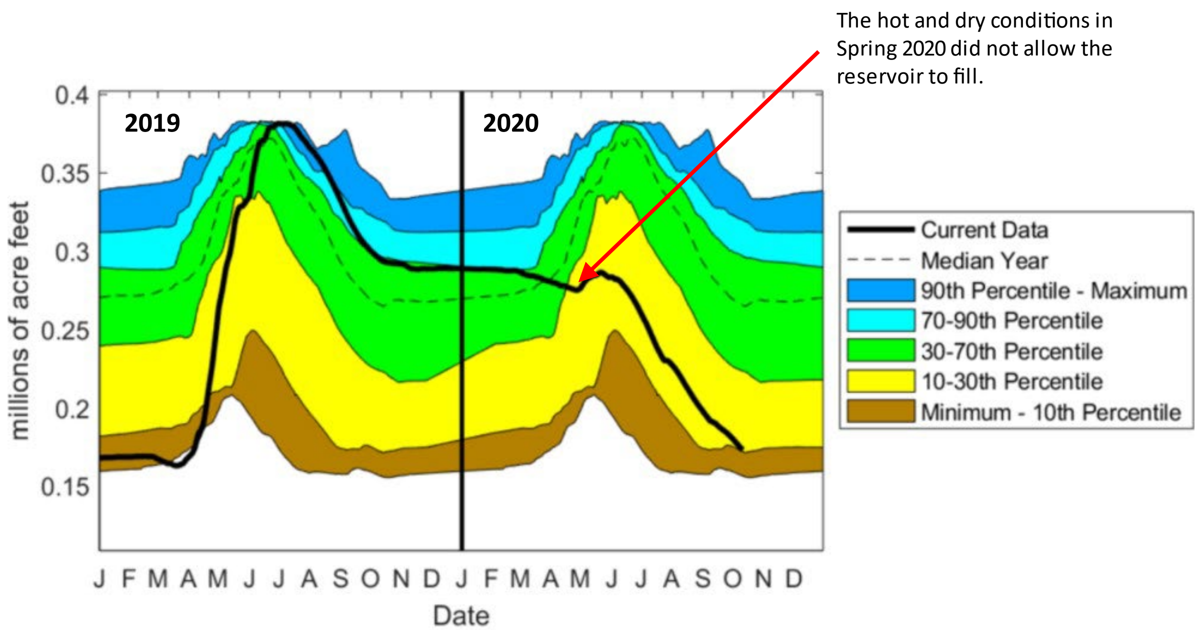


Figure 3. Reservoir storage (AF) in 2019 and 2020. The hot and dry conditions led to little reservoir filling in the spring and then a step drop in the summer.

2.3. 2017 McPhee Reservoir Boatable Days

Dolores Water Conservancy District (DWCD) manages the operations of McPhee Reservoir in Montezuma County. The reservoir, which dams the Dolores River, furnishes irrigation water for Montezuma and Dolores counties, plans releases for recreational rafting, and the tailwaters provide a popular destination for fishermen. Maximizing recreational potential, filling the reservoir, and fulfilling deliveries to irrigators are all important goals that DWCD attempts to meet each runoff season.

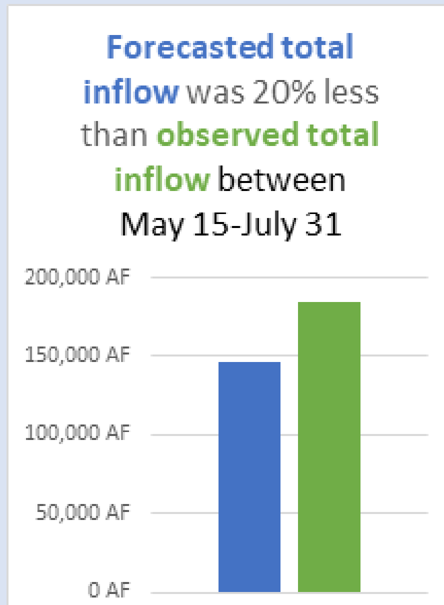
In the early spring of 2017, runoff forecasts from the Colorado Basin River Forecast Center (CBRFC) indicated an average or above average year, and DWCD expected to meet all operational goals. However, cold weather in late April reduced inflows more than what DWCD managers had anticipated, causing the reservoir elevation to drop quickly. By early May, SNOTEL sites had begun to melt out, leaving DWCD operators with no accurate measurement of the remaining snowpack.

Unable to measure changes in snowpack data by mid-May, managers were solely reliant on the CBRFC model, which suggested that the inflows had likely peaked for the runoff season. This meant that filling the reservoir became the primary priority, at the expense of boatable days. Managers began to ramp down releases below a key boatable threshold of 800cfs on May 21st. Between May 21st and May 29th (Memorial Day), releases were well below ideal rafting conditions, and were not forecasted to improve.

The end of May and beginning of June brought hot and dry conditions, as well as an unanticipated spike in inflows. The reservoir had almost filled, so DWCD managers were forced to increase releases above optimal boatable flows (>1,000cfs) in order to control reservoir elevation. In late June, yet another unanticipated spike in inflow forced additional releases to prevent the reservoir from spilling over.

ASO Is Critical to Reservoir Operations

- In 2017, SNOTEL sites around McPhee Reservoir melted out early, leaving only forecasts to estimate runoff
- With imperfect information, reservoir operators had to prioritize filling reservoir over recreational releases
- This led to inefficient operations for boaters and an early reservoir fill
- An ASO flight would have provided a more precise measurement of remaining runoff



An ASO flight in early May would have given DWCD more confidence in the total remaining snowpack that would run off. Had DWCD managers known the remaining snowpack volume after the initial peak in May, different operating decisions would have been made to better optimize recreational opportunities while still filling McPhee Reservoir. With more precise snowpack water content data, DWCD managers could have planned a release regime that would have benefitted rafters, such as in the Figure below. This new regime could have begun in mid-May and had only one ramp down as spring runoff began to recede. This would have allowed for more flows between 800-1,000cfs, the ideal range for rafters.

A review of historical McPhee Reservoir inflow data suggests that, with improved snowpack information, reservoir operations could have been changed to provide at least eight additional days of boatable conditions on the Dolores River around Memorial Day, one of the most popular weekends for rafting.

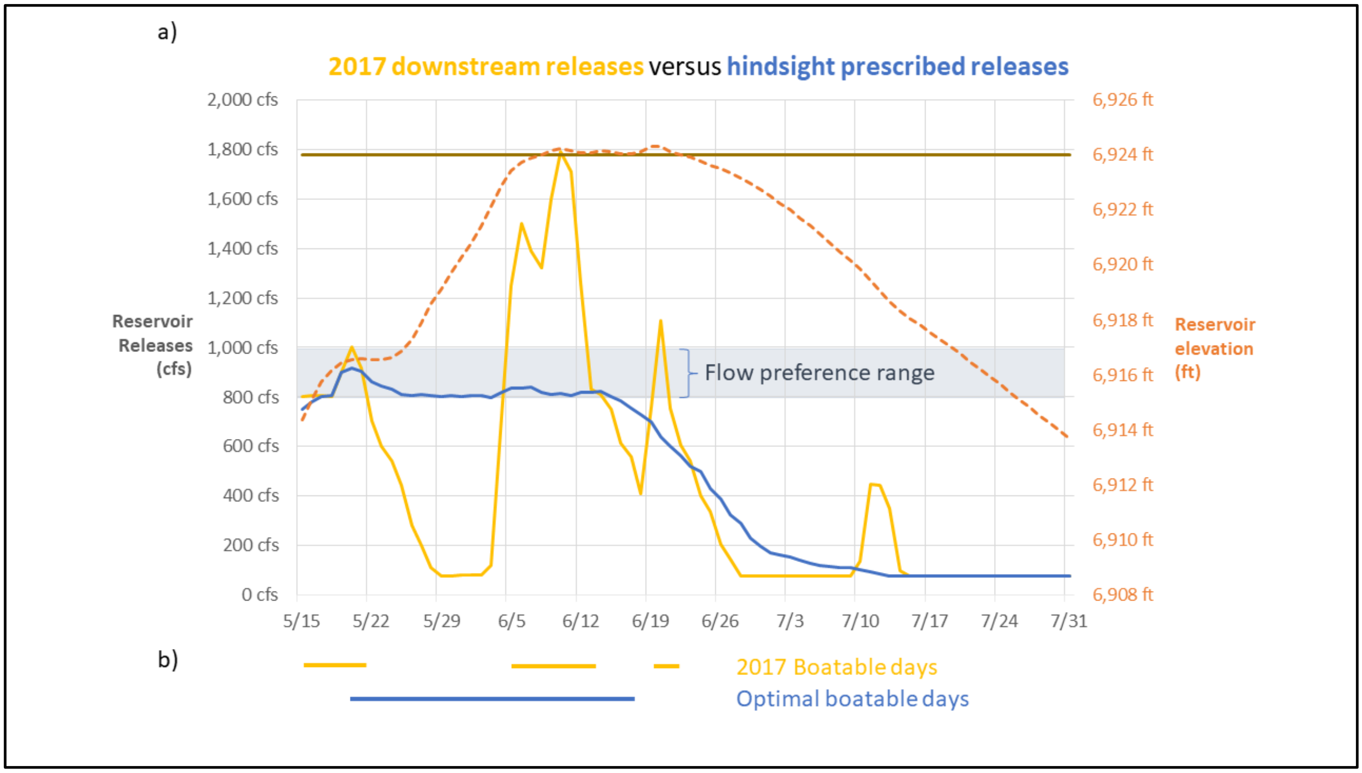


Figure 4. McPhee Reservoir downstream releases versus hindsight prescribed releases

Colorado Airborne Snow Observatory Expansion Plan: Project Report

Prepared on Behalf of Northern Colorado Water Conservation District

6/30/2022

Submitted To:

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Table of Contents

Figures

Tables

1. Executive Summary

Primary Program Goal

Every year, Colorado water managers and water users depend on seasonal runoff forecasts to make multi-million dollar planning decisions that have impacts across all water stakeholder communities. These seasonal runoff forecasts are heavily dependent on snowpack estimates, as roughly 75% of Colorado's annual total streamflow comes from melting snow between April and July. Historically, however, the tools have not existed to accurately measure snowpack at the watershed scale, which has led to inaccuracies in runoff forecasting. To increase the accuracy of seasonal runoff forecasts in Colorado, it is imperative that the snowpack is accurately measured at the scale of entire watersheds.

> *"ASO provides detailed information into the snowpack like we have never seen before. The information gained from ASO flights allows for a finer level of water management and provides more opportunity to benefit more users and get the maximum benefit out of every drop."*
>
> *Nathan Elder, Raw Water Operations Manager, Denver Water*

Fortunately, high-accuracy snowpack measurements are now possible with the technology of the Airborne Snow Observatories, Inc. (ASO, Inc.). The Colorado Airborne Snow Measurements (CASM) workgroup has formed to develop a statewide, long-term program that increases ASO survey coverage in Colorado and actively integrates the resulting ASO snowpack measurements into streamflow forecasting methods. The plan laid out in this document outlines how airborne lidar snowpack measurements from ASO will be deployed across Colorado and will be used to inform and improve water management for all water stakeholders in Colorado and beyond.

What does ASO Inc. provide?

ASO, Inc. offers an operational snowpack measurement product that allows for the most accurate measurement of snow water equivalent (SWE) and snow albedo for entire watersheds of any available products. Airborne Snow Observatories Inc. uses airborne laser altimetry (lidar) measurements, both with and without snow, to develop 3m gridded measurements of snow depth throughout a river basin. These lidar measurements are paired with the iSnobal energy balance model which models snowpack density over time to produce 50m gridded estimates of snow water equivalent (SWE).

Historical data review shows that these ASO measurements are within 5-10% of the actual water contained in the snowpack at the time of the survey, though total runoff varies due to uncertainty in seasonal precipitation following the final ASO surveys of the season. Using ASO's current equipment, a single survey can cover a river basin approximately 3,500 sqkm, equivalent to the entire watershed of the Roaring Fork River

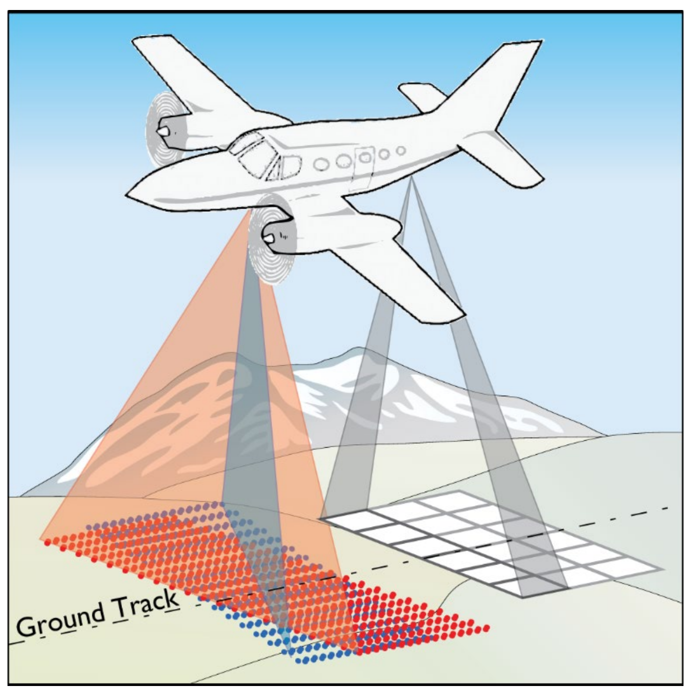

Figure 1. ASO Lidar Technology

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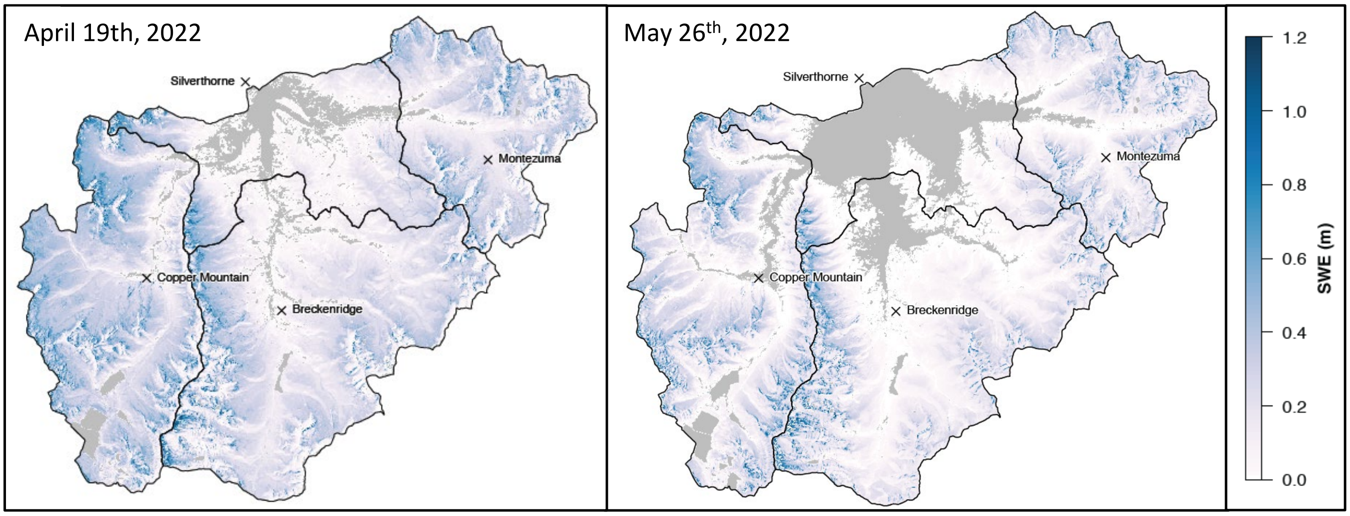

Figure 2.High resolution snow depth grids from the Blue River, 2022

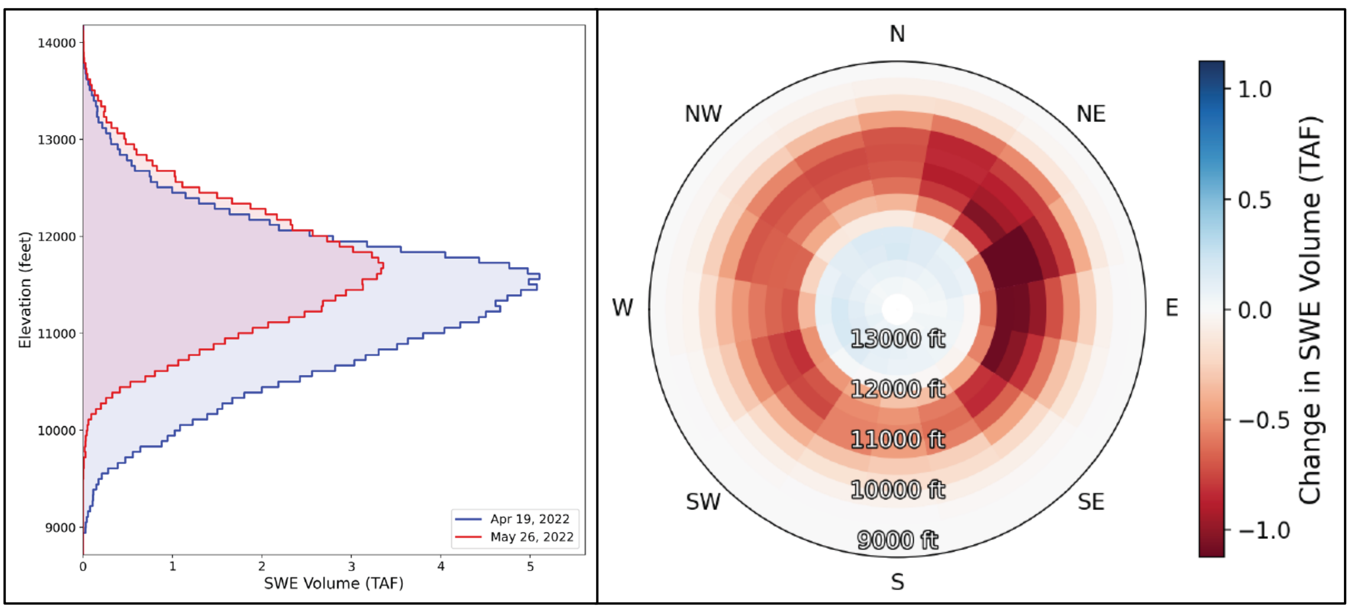

Figure 3. Change In Snow Water Equivalent by elevation band between the two flights. Change in SWE volume by elevation and aspect

What do we propose?

The Colorado Airborne Snow Measurement Working Group (CASM) was formed to develop a statewide program to provide significantly improved streamflow forecasting throughout Colorado through widespread deployment of ASO surveys and the supporting hydrologic science. The mission of CASM is to encourage adoption of ASO technology as a core component of the water resources management toolkit for stakeholders across Colorado. CASM currently engages with a stakeholder group of nearly 100 agencies that serve millions of Colorado residents, hundreds of thousands of irrigated acres, and represent all major river basins. CASM projects a fully functional ASO flight and forecasting program to cost around $26 Million per year, though this is dependent on how quickly the program grows.

> *"[Reservoir operators in California] indicate that [ASO] has improved decision making and the ability to balance competing water demands, including power supply and environmental flows, as well as minimizing flood risks*
>
> *US Bureau of Reclamation, Emerging Technologies in Snow Monitoring Report to Congress, 2022*

If regular ASO Snow Surveys can be conducted in the headwaters of every major river basin in Colorado, stakeholders can use this information to make better water management decisions and respond in real time to the impacts of a changing climate. When snow depth estimates are improved substantially and those depth estimates are used to improve runoff forecasts, water managers have the potential to benefit directly through:

- Optimized reservoir use
- Better-informed drought planning
- More appropriate purchasing of agricultural supplies (e.g., seeds, fertilizer, etc.)
- More accurate streamflow forecasts for planning stream-based recreation and tourism
- Water availability for stream health
- Better understanding of natural yields for water contracts and leases
- Provide antecedent information to fire season forecasting
- Monitoring pre and post land management and impacts on runoff efficiency

Widespread ASO surveys include other benefits that can only come at that scale and accuracy:

- A better understanding of the uncertainty in current snowpack measurement networks
- Improved estimates of runoff efficiency and basin productivity for calibrating forecast models
- Quantitative understanding of the impacts of climate change on Colorado's water supply
- Detailed pre- and post-wildfire impacts to snowpack.
- Measurements of avalanches and landslides

How did this project come together?

In 2021, the Colorado Airborne Snow Measurement (CASM) group was funded under a Colorado Water Conservation Board (CWCB) Water Supply Reserve Fund (WSRF) grant to study how to develop a long-term, sustainable program focused on expanding ASO coverage in Colorado. The WSRF funds were used for:

- Engagement with local, state, and federal water resources managers
- Mapping and statistical analysis of historical ASO flights
- Monthly CASM workgroup meetings
- ASO flight planning and snowpack data analysis for the State of Colorado
- Planning and coordination of future activities

1.1. CASM Program Mission and Vision:

The purpose of this document is to lay out a path to developing a sustainable CASM program that will enable improved water resources management through regular ASO snow surveys covering a wide range of Colorado watersheds into the future. This plan is organized around the benefits of ASO, the overall buildout goals of the program, and the CASM planning team's recommendations for how to get there.

> ***CASM Mission:***
>
> *"Improve water supply management and understanding of hydrology across Colorado through the widespread deployment of airborne lidar snowpack measurements"*

There are many emerging technologies in snow measurements, but currently none of these can provide operational coverage spatial accuracy comparable to the airborne lidar product of ASO, Inc. CASM focuses on deployment of airborne lidar as an integral component of the data streams required for improving water management and streamflow forecasting models.

> ***CASM Vision 1 - Water Management and Decision-Support Applications***
>
> *"Through the delivery of improved measurements and water supply forecasts water managers and water users will be empowered to make better short term (seasonal/annual) and long term (decadal) decisions. These improvements will be measurable."*

The end goal of CASM is to improve water resources decision-making for any agency and/or sector that relies on snowpack information. As more surveys are conducted and more stakeholders are educated around how to use ASO data and the associated runoff forecasts, the expectation is that those stakeholders will be able to make better water resource decisions. We expect that there will be a measurable economic benefit to stakeholders that use ASO data to optimize their use of water. We expect that, as CASM grows and key basins are surveyed regularly, this data will be used in novel and unanticipated ways not yet possible with current streamflow forecasts and monitoring tools.

> ***CASM Vision 2 - Hydroclimate Science***
>
> *"A fully developed ASO program will have accurate snowpack measurements and improved water supply forecasts across the high-elevation, snow-covered areas of Colorado, and will contribute to the advancement of hydrologic sciences."*

Water management around the state will be improved through widespread and regular ASO flights. Along with these flights will come improvements in the techniques used to determine snow water equivalent, as well as improved methods for integrating ASO data into streamflow forecasts. Additionally, the state of knowledge around Colorado's snowpack will be improved by a high-density program (5-6 surveys per year) in key headwater basins to understand runoff dynamics. The density of information will allow CASM to work with the academic community to improve our understanding of the relationship between measured snowpack and observed surface runoff.

> ***CASM Vision 3 - Program Administration and Structure***
>
> *"To be both effective and equitable, CASM should be managed by the CWCB and local stakeholders should be involved in the decision-making process on flight timing and location as well as leading CASM subcommittees."*

CASM should be an equitable program that improves water supply information for stakeholders of all types and in all river basins. To this end, CASM stakeholders believe? the program should be managed by the CWCB, both in terms of program guidance, as well as operational flight decision making. In 2022, CASM tested out a flight planning coordination committee, led by the CWCB, that considered weather, operational limits of ASO, Inc. and the needs of various stakeholders.

> ***CASM Vision 4 - Funding***
>
> *"While local stakeholders should demonstrate interest and engagement through match funding, especially as the program develops, ultimately a sustainable program will require consistent state and/or federal funding."*

In 2022, ASO surveys and other CASM activities were funded by a combination of local stakeholders and a significant Water Plan Grant from the CWCB. While it would be ideal for CASM to be funded from a single source, it is more realistic that some combination of local, state, and federal funds will be required to ensure that the program is sustainable, at least for the first few years of implementation. Additionally, since the improved water supply measurements from CASM could help the Upper Basin States meet their obligations under the Colorado River Compact, this program can potentially grow to include out-of-state interests as well.

1.2. CASM Program FAQ

1.2.1. What is this program called?

CASM is the Colorado Airborne Snowpack Measurement workgroup. The CASM workgroup is working toward implementing a statewide program to conduct regular ASO flights and provide significantly improved streamflow forecasting throughout Colorado.

1.2.2. What is ASO?

The Airborne Snow Observatories, Inc. (ASO Inc.) uses paired airborne lidar and imaging spectrometer sensors coupled with a snow dynamics model to measure snow depth and albedo and retrieve Snow Water Equivalent (SWE, the liquid depth of water stored in the snowpack) across large river basins at a high spatial resolution. The resulting data provides high-elevation snowpack measurements with detail, accuracy, and decision-support value unprecedented in water management.

The added value of these measurements to the water community has been thoroughly demonstrated through a multitude of pilot flights in Colorado and California. For example, in a 2019 pilot flight series in the Blue River watershed with Denver Water—during a time when the SNOTEL stations in the watershed had melted out—ASO data provided an accurate volume estimate of 115,000AF of water remaining in the high elevations. This provided Denver Water's operations manager the information needed to accurately reduce Dillon Reservoir levels to account for the incoming runoff, which in turn allowed downstream reservoir operators and other Colorado River reservoir operators to retime outflows and cancel Coordinated Reservoir Operations (CROS) that could have otherwise led to downstream flooding and lost water supply.

ASO Inc. is a private company that was formed out of a project at the NASA Jet Propulsion Lab (JPL). ASO Inc. provides aircraft-based measurements of snow albedo and depth along a flight path. These physical measurements are combined with physically based snow density modeling to create a high resolution (3m) gridded measurement of snow water equivalent across a river basin. The fully processed snow water equivalent (SWE) measurements are colloquially referred to as "ASO Data".

1.2.3. How accurate is ASO compared to other products?

Traditional snowpack estimates using ground and satellite-based measurements can be off by as much as 40%, and sometimes more. ASO snowpack measurements have been shown to have bulk snowpack measurement uncertainty of 5-13% (Oeida 2019). Other recent studies have demonstrated the suitability and accuracy of airborne and terrestrial lidar data for differential mapping of snow depth in mountainous terrain (Hopkinson et al., 2004; Deems et al., 2006; Trujillo et al., 2007; Prokop, 2008; Mott et al., 2011; Deems et al., 2013a; Deems et al., 2015)

1.2.4. How are ASO snow surveys used to improve streamflow forecasts?

ASO, Inc. processes its flight data to generate a 3m resolution gridded snow depth product. This depth measurement, paired with the iSnobal energy balance model and ground-based density measurements, is used to generate a total snowpack water volume estimate at 50m resolution. Since most of the annual runoff from Colorado headwater basins comes from snowmelt, this ASO-derived snowpack volume can be assimilated into most existing runoff forecasting tools that rely on SWE estimates. There are several ongoing academic and government research projects exploring different techniques for ASO assimilation to provide the most forecast improvement and maximize the value of this program. In 2022, the Weather Research and Forecasting Model Hydrological modeling system (WRF-Hydro, Gochis 2020) run by the National Center for Atmospheric Research (NCAR) was used to develop experimental streamflow forecasts for any basin with ASO flights. The Colorado Basin River Forecast Center (CBRFC) also provided a similar ASO-integrated experimental forecast.

1.2.5. What does a successful program look like?

CASM directly supports the goals of the Colorado Water Plan. All aspects of water availability and security are driven by the ability to properly measure and forecast Colorado's water supply. All Basin Implementation Plans (BIPs) identify the need to manage risk around water supply availability, both for in-basin municipal and industrial (M&I), recreational, and environmental demands, Colorado River Compact administration, and other goals. The CASM program aims to directly address all of these high-level water management goals, ultimately allowing Colorado water stakeholders to do more with less. The widespread adoption of cutting edge ASO technology is in tradition with Colorado being a model of leadership in water sciences and water resource management throughout the US. A successful CASM program will have:

- Seasonal runoff forecasts in key headwater basins that show improved accuracy and uncertainty due to the integration of the ASO Inc. SWE measurements
- Continued integration of ASO data with the scientific research community to better understand changing snowpack characteristics and further develop runoff forecasts and water management decision support tools that are useful in a changing climate
- Improved understanding of the impacts on snowpack and water supply due to forest management, wildfire, and other major landscape changes.
- An engaged group of water management stakeholders that includes broad geographic diversity and water sector diversity throughout Colorado.
- Continued education and stakeholder feedback sessions around how to improve decision-making using this data
- Data that is openly accessible to any interested stakeholder
- State-led oversight of the program to ensure fairness and equity in survey coverage as well as program sustainability
- Sustainable funding that allows for multiple ASO surveys each year for the majority of high-elevation watersheds in Colorado. This should also include budget flexibility around where and when to conduct ASO surveys.

1.2.6. How many flights per year does Colorado need?

The current CASM vision for a fully developed ASO program would be funded to conduct 6-8 snow-on surveys per year across all snow-covered areas of Colorado. Peak SWE in Colorado typically occurs between April 1st and 15th, depending on the year type. During peak SWE, it would require around 25 surveys for a single snapshot statewide of snowpack across all key headwaters. As the snowpack recedes throughout the snow season, fewer flights are required to reach full coverage. At an upper limit, 215 flights per year would provide detailed measurements across all major headwaters of Colorado's river basins from winter through the spring melt season.

It is an active area of scientific research by the US Bureau of Reclamation, the California Department of Water Resources, the CWCB, and multiple academic research groups to balance data from ground-based networks with the high accuracy of ASO snow surveys throughout the accumulation and melt seasons, though 6-8 surveys per basin is the current best estimate. There have not been enough ASO flights yet in Colorado to truly answer this question of the optimum number of flights. The geography and snowpack dynamics of Colorado's headwater basins is highly variable and needs to be studied in more detail.

As CASM grows, ASO flights should be conducted multiple times in headwater basins from winter through spring runoff season, while delivering improved runoff forecasts. As this program grows, the total number of flights per year will grow as well, based on stakeholder engagement, funding, and advancement of snow science.

1.2.7. How much will this program cost?

A single ASO flight survey can measure a basin up to 3,500 sqkm (1,351 sqmi), equivalent to the entire watershed area of the Roaring Fork River. As flight coverage expands, so will the total program cost. Program costs include:

- Snowpack measurement flights and data processing at around $120,000-$150,000 per flight
- Snow-Free flight costs at around $44/sqkm, with 66,000 sqkm remaining to achieve full coverage
- Additional support activities including streamflow forecasting and stakeholder coordination
- Staff Support for 2 FTEs at $100,000 annual salary

Table 1 shows the estimated program cost during each phase of growth. These costs are approximate and are subject to changes due to program direction, fuel costs and other factors.

Table 1. Estimated CASM Program Costs (all values in millions of dollars)

Phase	Timeline	Flights Per Year	Snow Survey Flight Cost	Snow-Free Flight Cost	Support Activities	Staff Support (2 FTEs)	Total Annual Cost
Phase 1	2022	14	**1.3**	**1.0**	**0.3**	**N/A**	**2.6**
Case Study Building	2023	30 (2 flights per basin with available snow-free data)	**3.6**	**2.0**	**0.5**	**0.2**	**6.3**
Widespread Adoption	2024-2026	64 (3 flights per basin with available snow-free data)	**7.7**	**0.2**	**0.5**	**0.2**	**8.6**
Program Buildout	2026-2028	214 (6 Flights across all major headwaters)	**25.7**	**0.2**	**0.5**	**0.2**	**26.6**

The flight estimates in this table are based on assumed program growth. For comparison to California's ASO program, increased demand by California stakeholders for ASO flights has led the program to plan for around 6-8 flights per year in each basin at full program buildout.

1.2.8. How is ASO currently being used in Colorado?

Airborne lidar snowpack measurements have been conducted across Colorado since 2013, with numerous scientific, applied science, and operations support efforts. The following list details ASO activity in Colorado to-date, along with funding source and application:

- **Uncompahgre River above Ridgway Reservoir**; 1-4 surveys per year 2013-2017: NASA Terrestrial Hydrology Program, Science support
- **Grand Mesa;** NASA Terrestrial Hydrology Program, Science support
- **Rio Grande and Conejos Rivers**; 1-2 flights per year 2015-2016, 2 surveys planned in Conejos 2021: CWCB Rio Grande Forecast Improvement Project; Applied science support, 2 surveys, 2022 CWCB Water Plan Grant Funds
- **Upper Gunnison River (East and Taylor Rivers);** 1-2 surveys per year 2016, 2018-2019, 2022: Dept. of Energy East River Watershed Function Scientific Focus Area, Science support, CWCB Project funds and 2022 CWCB Water Plan Grant Funds
- **Blue River above Dillon Reservoir;** 2 surveys 2019, 2021, 2022: Denver Water, Operations support
- **Animas River above Durango**; 2 surveys 2021: CWCB Project funds, Operations support
- **Dolores River above McPhee Reservoir**; 2 surveys 2022 CWCB Water Plan Grant funds, Operations support
- **Willow Creek Reservoir, Granby Reservoir, Fraser River;** 2 surveys, 2022 CWCB Water Plan Grant Funds

1.2.9. What does ASO provide that other snowpack measurement techniques do not?

Ground-based snow-measurement stations are highly accurate but only at their specific point location and require statistical extrapolation models to make basin-scale snowpack estimates. Satellite-based products provide broad coverage, but are often at a coarse horizontal resolution (1km+ cells) and poor vertical resolution. Drone-based technologies are similar in resolution to ASO but cannot provide sufficient geographic coverage.

ASO is the only product that provides high accuracy, high resolution, complete measurements of snow depth and snow water equivalent at the basin scale. ASO snow depth data is natively 3m horizontal resolution and 1cm vertical resolution (8cm uncertainty).

1.2.10. Can ASO data be used as a climate adaptation strategy?

Yes. As the snowpack changes with climate change, the historical snowpack record is becoming less and less reliable as an indicator for current snowpack conditions. Being able to accurately measure the snowpack at the watershed scale multiple times each year with ASO technology is a proven strategy for adapting to changing snowpack conditions.

1.2.11. I am a water manager in Colorado… how can I use this data?

An ASO snow survey provides a highly accurate estimate of the total volume of water contained in a basin's snowpack at a single point in time. This measurement can be used to validate estimates of reservoir inflow, make predictions about total and peak runoff timing downstream, and provide a check on other snowpack estimates. If any of your planning efforts require a numeric estimate of total seasonal runoff, ASO can provide basin-scale estimates of SWE that provide a point in time estimate of the total water available in a basin. For each ASO survey conducted in Colorado, the team at ASO, Inc. produces a post-survey report that summarizes the flight data. This report, and the associated raw data products, are freely accessible to the public and can downloaded from ASO, Inc's website. If you have ideas for a use case of this data for your sector, please reach out to the CASM planning team.

1.2.12. Is this data available even though I didn't pay for it?

Results from ASO snow surveys are publicly available on the ASO Inc. website (https://data.airbornesnowobservatories.com/). These data are limited to locations where snow surveys have been flown, but include:

- Basin-wide estimate of SWE volume
- 3m resolution snow depth gridded data
- 50m resolution snow water equivalent gridded data
- Detailed survey reports outlining model and data assumptions

1.2.13. How long has ASO existed?

In 2010, Dr. Thomas Painter was recruited to the NASA Jet Propulsion Laboratory to lead the development of the program that would become the NASA Airborne Snow Observatory. He and his ASO team, along with partnership with the California Department of Water Resources, began in 2013 with breakthrough measurements and modeling of mountain snowpack that led to the first high-accuracy maps of distributed snow water equivalent across entire mountain basins. In 2019, Dr. Painter, Dr. Joe Boardman, Dr. Jeff Deems, and Pat Hayes founded Airborne Snow Observatories, Inc. to transfer the NASA technology to commercial operations available around the globe.

The Colorado Airborne Snow Monitoring (CASM) program was established and funded under a Water Supply Reserve Fund (WSRF) Grant in 2021. CASM's mission is to improve water management across Colorado through widespread deployment of ASO flights.

1.2.14. Does a statewide ASO program like this exist anywhere else?

In California, the Department of Water Resources manages the Airborne Remote Sensing of Snow (ARSS) program and deploys 30+ ASO flights per year across nine different basins in the Sierra Nevada mountains. Data from ARSS flights are used to improve runoff estimates, issued as part of the Bulletin 120 seasonal runoff forecast (https://cdec.water.ca.gov/snow/bulletin120/ CA DWR 2022). In the wake of the recent large wildfires in California, ASO data is also used to quantify the impact of fire damage on snowpack and runoff efficiency.

ARSS began in 2013 and has slowly scaled up over several years to provide 3-5 snow surveys per year across nine major basins in the Sierra Nevada. The CASM team has engaged closely with CA-DWR staff to understand some lessons learned and potential challenges of developing a program like ARSS. In 2022, ARSS is funding 31 flights and all the associated support activities at a cost of $9.5 Million.

1.2.15. ASO, Inc. is a private company… how are the issues around sole-sourced contracting being addressed?

As of 2022, ASO, Inc., the developer of this technology and application, is the only organization providing the combination of airborne lidar and spectrometer snow depth, SWE, and snow albedo data products along with rapid processing that meets the needs of the CASM program and other managers of snowmelt systems. Unless another company offers this service and can demonstrate a similar accuracy, timeliness, and product suite, ASO Inc. will be the sole provider of snow surveys for CASM for the foreseeable future. ASO Inc has been integrally involved in the development of CASM and has made good faith efforts to provide their services at a reasonable cost. ASO Inc has stated that snow survey data for these locations will be public for the foreseeable future – data availability policy is maintained by ASO, Inc. responsive to the mandates of the funding agencies. Any potential change in contractor will require careful thought on the part of CASM to ensure that all aspects of their program and costs as well as their capabilities are well understood.

2. Background on ASO and Colorado Snowpack

2.1. Fundamentals of Colorado's Snowpack

Colorado is a headwater state supplying water to over 5 million Coloradans and millions of others downstream across several major river basins. Due to Colorado's semi-arid climate and high elevation, the regional hydrology is snow-dominated. Snowpack in Colorado acts as a water tower, storing winter precipitation and releasing it in the spring. Snowmelt-derived runoff makes up over 70% of total runoff in mountainous areas across the western United States (D. Li et al., 2017).

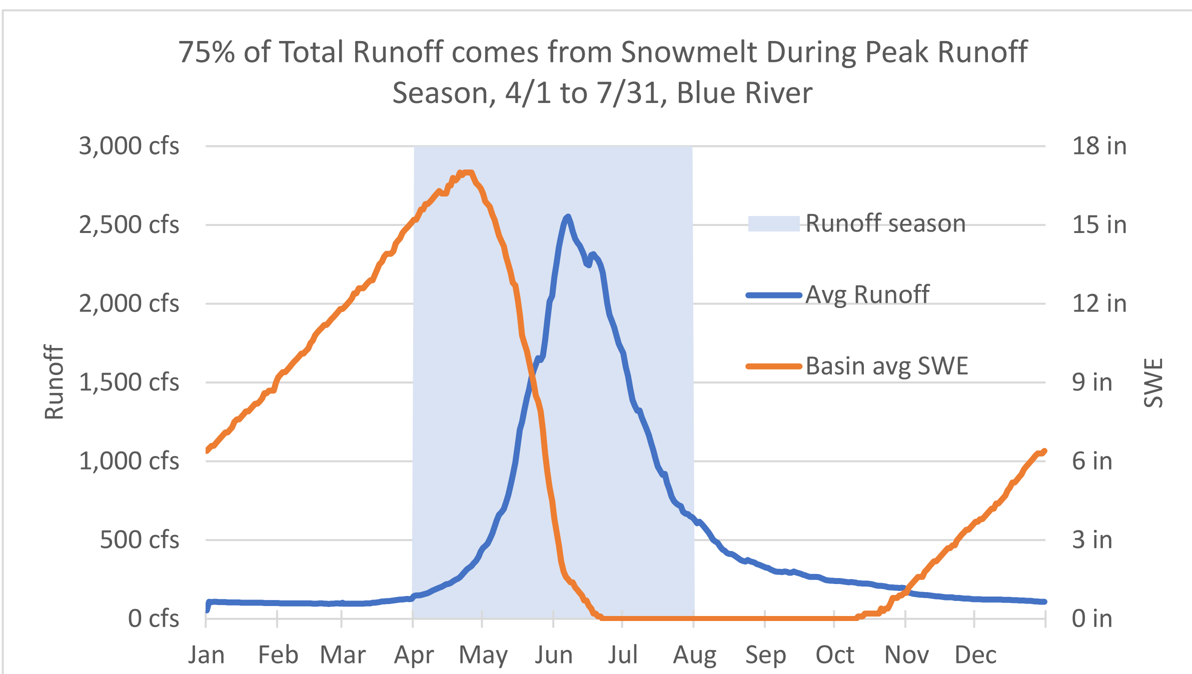

Figure 4. Blue River basin historical average daily runoff (blue) and SWE (orange) from 1991-2020.

Colorado averaged 66.7 inches of Snow Water Equivalent (SWE) measured at 106 SNOTEL sites from 1991-2020. The 30-year SWE ranges from as high as 222.4 inches at the Tower SNOTEL in the Medicine Bow-Routt National

Forest to as little as 14.1 inches at Cochetopa Pass SNOTEL in the Rio Grande headwaters. Peak SWE, or the day of the year with the maximum snowpack volume at the SNOTEL locations, is typically early April each year, though varies depending on location.

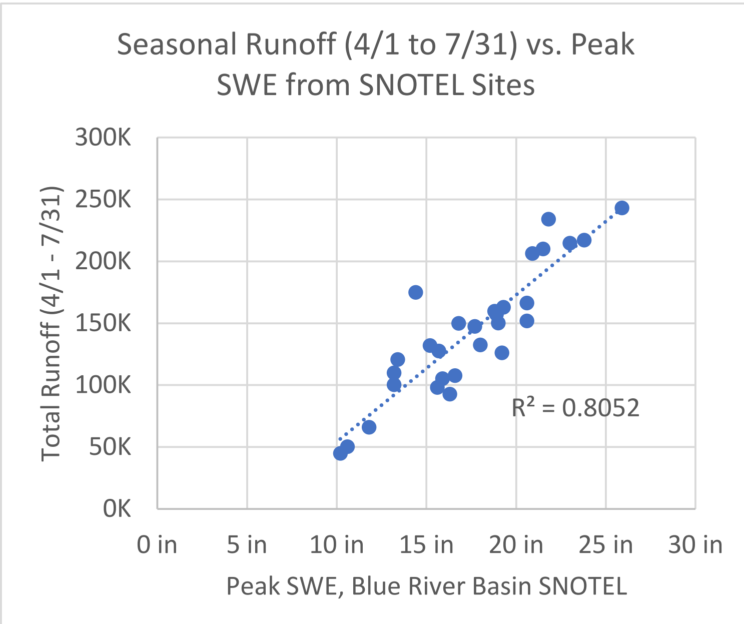

Figure 5. Blue River basin historical total runoff and peak SWE values

Snowmelt begins in earnest in April or May in a normal snow year. The bulk of the snowmelt then occurs over the span of two to three months from Peak SWE until late July. Some of the snowmelt is lost to evaporation or sublimation, and some soaks into the ground to satisfy soil moisture deficits or infiltrates and become groundwater. The remaining will eventually become runoff. In a typical snow-dominated Colorado basin, about 75% of the total runoff comes from snowpack (Figure 4). Runoff between April 1 and July 31 is highly correlated to the peak SWE value of that year (Figure 5).

It is important to note that the above characterizations, as well as our conventional understanding, of the seasonal dynamics of the mountain snowpack are based almost entirely on NRCS SNOTEL and Snow Course measurements. These measurement locations are confined to a relatively narrow elevation band and are sited in flat, forest clearings. Therefore, typical snow accumulation and melt patterns in most of the watershed, and deviations therein, are unmeasured and not accounted for in qualitative or quantitative assessments of snow water availability.

2.2. Existing snow products currently in use

Given the importance of snowpack in Colorado, there are multiple measurement networks that provide spatial estimates of snowpack derived from point observations, snow models, and remote sensing (WWA, 2021). A survey conducted by CASM in summer 2021 asked Colorado water stakeholders questions about the snow products they use and for what purposes. 72 responses were collected, and the percentage of respondents that use a specific snow product is listed in Table 2.

Table 2. Data and Products used by ASO survey respondents

Product or Network	Measurement Type	Percentage of survey respondents who use product/network
SNOwpack TELemetry (SNOTEL)	Ground-Based Stations	99%
NRCS runoff forecasts	Model Derived	76%
RFC forecasts	Model Derived	74%
NRCS basin estimates	Model Derived	69%
Reservoir inflow estimates	Model Derived	57%
Snow Course (NRCS)	Ground-Based Stations	56%
SNODAS	Remote Sensing	40%
In-house data	Ground-Based Stations	30%
Other manual measurements	Ground-Based	27%
ASO	Aerial Remote Sensing	26%
GOES/visible satellite	Remote Sensing	17%
Info from water agencies	Other	17%
CU-SWE/MODIS/MODSCAG	Remote Sensing	14%
NLDAS	Remote Sensing	3%
		Other products not mentioned by survey respondents
COOP (NOAA volunteer observers)	Ground-Based Stations	
CoCoRaHS	Ground-Based Stations	
MODDRFS	Remote Sensing	
SNOW-17 snow model	Model Derived	
SWANN & SnowView	Model Derived	

Survey respondents come from a wide variety of backgrounds, and represent many facets of government bodies, conservation districts, environmental groups, academic institutions, municipal water providers, recreational groups, and agricultural stakeholders. Most respondents regularly use NRCS snow products including SNOTEL, Snow Course, and NRCS river basin estimates. A thorough overview of the data and product characteristics, including spatial distribution and temporal availability, is in Additional Materials, Table 12.

Station-Based Measurements

SNOTEL sites are automated stations that record hourly SWE, snow depth, and air temperature data. Some can also collect soil moisture and soil temperature measurements, as well as solar radiation, wind speed, and relative humidity. There are 115 SNOTEL stations throughout Colorado, most of which sit within an elevation band of 9,000 to 11,000 feet. Beyond the network's designed use as index measurements for statistical runoff forecasts, SNOTEL data are used to construct and validate other snow data products, such as remote sensing and spatial modeling products. SNOTEL has the benefit of continuous and telemetered results for real-time monitoring of snow conditions.

Snow courses were the original precursor to SNOTEL stations; 92 still exist and operate in Colorado today. Snow courses have a wider footprint than manual survey transects, and therefore are typically more spatially representative than SNOTEL observations. Snow course manual measurements are taken monthly. Snow courses are in wide use but are limited in utility due to the poor temporal resolution of measurements and limited number of sites.

SNOTEL and snow course point measurements do not collectively capture the actual basin-wide SWE conditions. SNOTEL sites and snow courses are not located on slopes, above tree line, or at lower elevations, nor are they evenly distributed throughout the mountain headwaters. Additionally, these sites can also be subject to non-climatic influences that may decrease spatial representativeness of a given station. For instance, beetle infestation, wildfire, or forest growth near a SNOTEL site or snow course can impart spurious trends or step changes on measured snow accumulation and melt as the SNOTEL site becomes less representative of the surrounding basin. Lastly, because most SNOTEL and snow course sites sit within a particular elevation band, snowpack below or above that band is not measured. Once SNOTEL values dwindle to zero, reliance on basin-wide forecasts is necessary.

Remote Sensing and Modeled Snow Products

The second major category of snowpack monitoring products is remote sensing and spatial modeling techniques. Remote-sensing technology provides spatially continuous data that can usefully complement point SWE data from SNOTEL or snow course sites. Survey respondents listed ASO (described in detail in next section), GOES, and MODIS remote-sensing products that they have used. 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. Survey respondents listed SNODAS and CU-SWE as spatial-modeling products used. It is important to note that the different model snow products are not independent of SNOTEL. Thus, in addition to scale-related challenges, it is difficult to independently validate the accuracy of these spatial SWE products because of their incorporation of SNOTEL data.

A review of satellite-based products shown in the appendix in Table 13 lists all satellite-based snowpack measurement products and their challenges and opportunities. There are insurmountable technical barriers to all products that will prevent them from achieving the combined accuracy and spatial coverage of ASO anytime soon.

Model Derived Forecast Products

Lastly, seasonal runoff forecasts produced by the NRCS and CBRFC predict runoff timing and volume. These tools are popular and critical to water operations and management in Colorado. The NRCS forecasts use data from SNOTEL sites to inform a statistical regression model predicting April-July runoff. They are calibrated on historical data and produce runoff forecasts at individual stream gages. CBRFC forecasts also blends this statistical modeling with conceptual hydrological modeling system that produces an ensemble of equally likely streamflow sequences. These forecasts come with significant uncertainty and limitations since they rely on historical data to be calibrated. As climate change impacts increase, unprecedented precipitation, temperature, and soil moisture patterns could emerge that cause streamflow forecasts are not able to accurately predict. A review of existing remote-sensing technology and the technology that ASO can provide is described in Additional Materials, Table 13.dependent on historical datasets to become less accurate.

A report to Congress on emerging snow measurement technologies found ten technologies that have the potential to improve operational water supply forecasts (USBR, 2021). They are grouped into three categories – air and space-based technologies, ground-based technologies, and modeling technologies. Colorado groups are ahead of the curve when it comes to implementing promising technology that can enhance snow monitoring and subsequent water supply forecasts. The emerging technologies include:

Ground-based technologies:

- Net radiometers

- Snow temperature sensors

Air and Space-based technologies:

- ASO
- Snow Covered Area (SCA)/fractional Snow-Covered Area (fSCA)
- Satellite albedo methods
- Satellite stereo imagery

Modeling Technologies:

- Snow Data Assimilation System (SNODAS)
- Snow Water Artificial Neural Network (SWANN)
- University of Colorado real-time spatial estimates of SWE (CU-SWE)
- Advanced snow models (iSnobal)

Among dozens of existing and emerging snowpack measurement technologies that are ground, aerial, satellite and model based, ASO stands out. ASO data provides the most complete, most accurate, highest resolution, and watershed-scale snowpack measurement product of all technologies that are operationally viable. ASO produces the most accurate estimates of spatial variability in SWE across large areas (tens of square km), with errors on the order of 1-2cm of SWE (WWA, 2021). The key limitations of ASO are coordination, logistics, and cost, all of which are addressed by CASM. Figure 6 shows that ASO data has high measurement confidence across a broad scale at high resolution, when paired with the right combination of modeling and ground-based measurements.

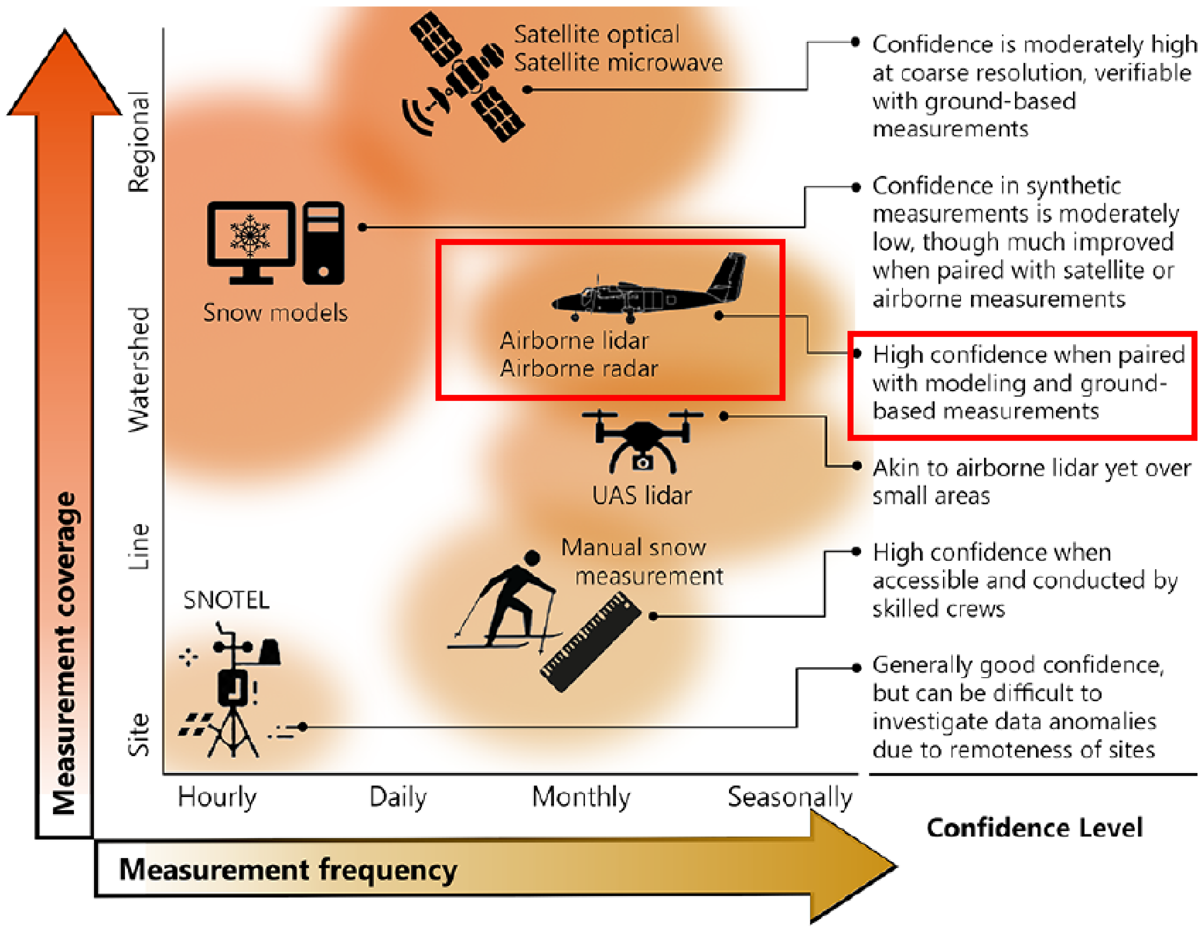

Figure 6. Comparison of Coverage, Frequency and Confidence in Emerging Technologies in Snow (USBR, 2021)

It is important to note that no single snow monitoring technology provides complete snow condition information throughout the entire snowpack season. Accordingly, USBR still recommends employing a "portfolio" approach to snow monitoring using a blend of complementary technologies.

2.3. Airborne Snow Observatory development

This ASO program began as the Airborne Snow Observatory project at the NASA Jet Propulsion Laboratory, emerging from the research legacies of its co-founders. The project began with a science and science applications focus, supporting basic research into mountain snow dynamics and hydrology. The operational implications of the data sets quickly became apparent, attracting attention of California water managers at state and local agencies. After eight years of development and refinement of the technology and applications, NASA leadership determined that the program had achieved an applications-readiness that exceeded the agency's science mission, and facilitated a technology transfer process resulting in the formation of Airborne Snow Observatories, Inc. ASO, Inc., a Public Benefit Corporation incorporated in Colorado and California, continues the original NASA program legacy, with exclusive license to the processing pipeline developed there.

2.4. ASO data and known value

> *"What you've done is created new reservoir space and water supply without any impacts to the current physical or environmental paradigms."*
>
> *Wes Monier, Chief Hydrologist, Turlock Irrigation District*

Airborne Snow Observatories, Inc. (ASO) uses an airplane mounted system consisting of an imaging spectrometer, scanning lidar, and inertial measurement unit to take high-resolution measurements of snow depth and albedo covering full watersheds. ASO is the first such system designed specifically for snow and water resources monitoring and research. The time-critical nature of the snow data coupled with the relatively large and complicated mountain areas being measured, drive the system to high-altitude flight, wide swaths, and optimized processing. The resulting ASO system is unique in two aspects: (a) the joint inversion of the active lidar and passive imaging spectrometer data coupled to an energy balance snow model for full SWE and snow albedo retrievals and (b) the low latency for full product generation and delivery (Painter 2016).

Key ASO Flight Details:

- A single flight can cover around 3,500 sqkm.
- 5-13% uncertainty in SWE measurement
- Larger basins may require multiple flights to develop a complete "snow survey"
- Ground based measurements of density augment flight data
- Results are available in 72 hours
- Flight plans are adjusted in real time to cover all snow-covered area

A single ASO snow measurement flight can develop a gridded snowpack measurement across an entire basin with an area up to 3,500 sqkm (1,351 sqmi) though this number is a planning-level estimate. Due to flight logistics and efficiencies, surveys are typically planned to cover a single watershed above an established stream gage or forecast point. For comparison here are a few basins with ASO measurements either in previous years or planned:

- Dillon Reservoir Watershed: 866 sqkm
- Eagle River below Gypsum (USGS Gage ID: 09070000): 2,447 sqkm
- Roaring Fork at Glenwood Springs (USGS Gage ID: 09085000): 3,763 sqkm
- Dolores River above McPhee Reservoir: 1,668 sqkm

ASO Data Products

ASO flights are conducted using a "mow the lawn" flight path over an identified basin. Each flight conducts coincident measurements using a scanning lidar (snow depth) and imaging spectrometer (snow albedo). These measurements are processed and combined to generate snow depth measurements at 3m horizontal resolution with an uncertainty of <8cm. Snow water equivalent measurements are generated at a 50m horizontal resolution. SWE measurements are typically further visualized by elevation and aspect, then aggregated to a basin scale. For each flight, ASO, Inc. prepares a data package that includes, a detailed summary report including total SWE estimate and uncertainties, as well as 3m gridded measurements of snow depth, and 50m depth, snow albedo, and SWE estimates throughout the basin. Figure 2and Figure 3 show some examples of these outputs from the Blue River above Dillon Reservoir during the 2022 flight season.

Snow Free Data Preparation

ASO snow surveys require that a basin has had a "snow free" lidar flight conducted for the area to provide a geodetic baseline to compare to the snow survey. Snow-free data preparation is centered around development of an error-corrected LiDAR dataset that has sufficient point density throughout the basin. Existing lidar data is typically not high enough quality, or with sufficient point density, to serve as an effective baseline, so individual summertime LiDAR flights must be conducted to collect this snow free data. Occasionally, this snow-free data can be prepared using data from existing LiDAR programs like the USGS 3DEP program, or the CWCB Risk Map program. Frequently, however, these programs were conducted for a different purpose and do not have sufficient point density in high-elevation areas critical for accurate snowpack measurement.

Once snow-free data is available, the cost of conducting a single measurement (one survey over a basin, one time, including all post-processing work) ranges from $100,000-$150,000 though there is significant operational and cost efficiency when more flights are flown in a single year. In 2022, the CASM Water Plan Grant application budgeted $1,325,000 for 14 snow-on flights across six different basins, amounting to ~$95,000 per flight.

Integration into Streamflow Forecasts

The resulting measurements can be used to inform or improve existing streamflow forecasts. Currently the National Center for Atmosphere Research (NCAR) uses their WRF-Hydro model to produce ASO-informed runoff forecasts after each ASO flight. The CASM workgroup recognizes that WRF-Hydro is currently set up to assimilate ASO data but is still in an experimental development phase. As part of the 2022 CASM activities, a model retrospective and forecast comparison will be conducted to assess the performance of other products. These results will be made available upon completion of the study. Additionally, it is part of the CASM vision to have ASO data integrated into official forecasts (CBRFC, NRCS) so agencies with a mandate to use those products will have improved decision-making support as well.

There are several components required to provide a complete ASO snowpack measurement, including snow-free data preparation, flight time and measurements, data post-processing, and streamflow forecast integration. These costs reflect the scalability and deployability of the WRF-Hydro system, leveraging NCAR computing resources and National Water Model infrastructure.

2.5. Benefits of ASO

There are many different snowpack measurement products available today for Colorado water managers, though many of these rely on point measurements or include significant uncertainties. Airborne lidar measurement using ASO technology fills a significant gap in these networks. Specifically, no other snowpack measurement product in Colorado provides measurements with:

- High accuracy: 5-13% uncertainty in total SWE volume (Oaida 2019), compared to >60% uncertainty by SNODAS, for example.
- Complete measurement of the snowpack at the watershed scale
- Distributed measurements showing variation by elevation and aspect
- Quantification of snow albedo, impacts due to dust-on-snow, and its influence on snowmelt

As an operational tool, ASO is limited to several surveys per year in a single river basin, depending on many logistical factors. However, this intermittent timeframe is balanced by the high accuracy of the data, which allows for insights not possible with other products:

- Accurate and precise total SWE volume
- Flexible and customizable data distillations (e.g. SWE by elevation and aspect)
- Validation of and local to regional context for ground-based sites

Section 7.1 contains a few simple case studies where ASO helped, or would have helped, inform decision-making around water resources operations. There are several uses of ASO data that are well-established by CA-DWR and users in Colorado.

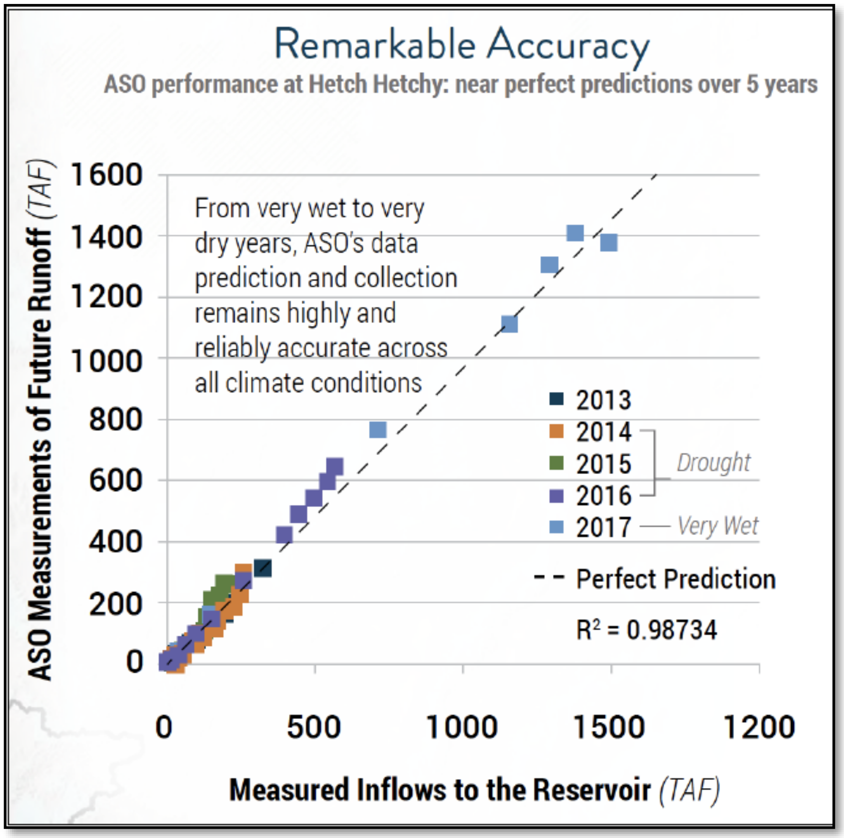

Figure 7. ASO Measurements compared to Hetch Hetchy Reservoir Inflows (CA-DWR 2018)

Forecast Improvement: Water resources managers throughout the West base many of their decisions on forecasted seasonal runoff. These forecasts can be improved through precise measurements of SWE. In Colorado and California, ASO data is used to inform WRF-Hydro and other streamflow forecasting models.

Dust-on-Snow Impacts: Research over the past decade (including much conducted by ASO, Inc.'s founders) has uncovered the importance of regional desert dust deposition on Colorado snowpacks, and the resulting acceleration of snowmelt and shortening of the snow season by up to two months compared to low-dust years. This phenomenon has the effect of substantially reducing the "snow reservoir" storage time, which reduces water availability later in the summer season and may reduce total basin runoff through a longer evapotranspiration season. ASO spectrometer data quantifies snow albedo (the fraction of reflected sunlight) and thereby quantifies the radiative impact of dust deposition at high resolution with complete basin coverage. This information can inform runoff forecast models to improve their simulation of melt rates and streamflow timing and magnitude.

Post-Fire Snowpack changes: In the wake of significant wildfires, canopy cover changes and albedo is reduced due to the presence of black carbon. Snow water equivalent and snow depth estimates are often based on statistical relationships using ground-based stations. ASO data can be used to correct these relationships and further inform total snowpack and melt rates in burned areas. ASO measurements of snow albedo quantify the impacts of soot on the snowpack and its impacts on snowmelt rate.

Runoff Efficiency and Basin Hydrology: A key aspect of any snowpack and runoff model is runoff efficiency. This factor informs what percent of the snowpack will end up as streamflow during melt season. While runoff efficiency is variable due to current and antecedent climate and soil moisture conditions and watershed characteristics, it is a highly uncertain factor with a large influence on runoff estimates. Conventional estimates of runoff efficiency are based on very poor knowledge of actual basin SWE content, which renders them unreliable from a water management standpoint. ASO data can be used to improve estimates of runoff efficiency by accurately quantifying the basin SWE. Additionally, any improvement in runoff efficiency calculations can be extended to geographically similar basins, where ASO flights may not yet be implemented.

Improve Estimates from Ground-Based Networks: Current snowpack monitoring networks do not measure the full basin water content, but rather are used as indices to inform statistical, seasonal runoff forecasts. As the climate continues to change, the relationship between these existing measurements and the basin water content will change relative to historical conditions – if indeed these relationships were ever stable to begin with. More precise, and regular, measurements are needed to add context and new value to these networks.

Changes in high and low elevation snowpack are not captured at all by these middle-elevation stations. Specifically, all but two SNOTEL sites in Colorado are found at elevations between 7,500 and 11,500 feet. A significant amount of Colorado's snowpack is stored at elevations above any ground-based observations (9% and 20% of typical April 1st and May 1st snow covered area is above 11,500 ft). Figure 8 shows the distribution of snowpack volume elevation in comparison to SNOTEL sites in the Blue River basin in 2019. In Appendix 7.1.2, we see an example case study of a ground-based station showing a "normal" snowpack but an observed seasonal runoff of 70% of normal.

One oft-expressed benefit to stakeholders from ASO data is a better knowledge of the representativeness of existing stations as well as an improved understanding of watershed snow and runoff behavior. (See Section 3.4 for details on Stakeholder Feedback). Factors such as where snow tends to persist later in the melt season, how forest character influences snow accumulation and melt in different parts of the basin, and which portions of the watershed are contributing to streamflow at different parts of the melt season all contribute to managers' fundamental understanding of their basins' unique hydrology, and to qualitative improvements in management operations.

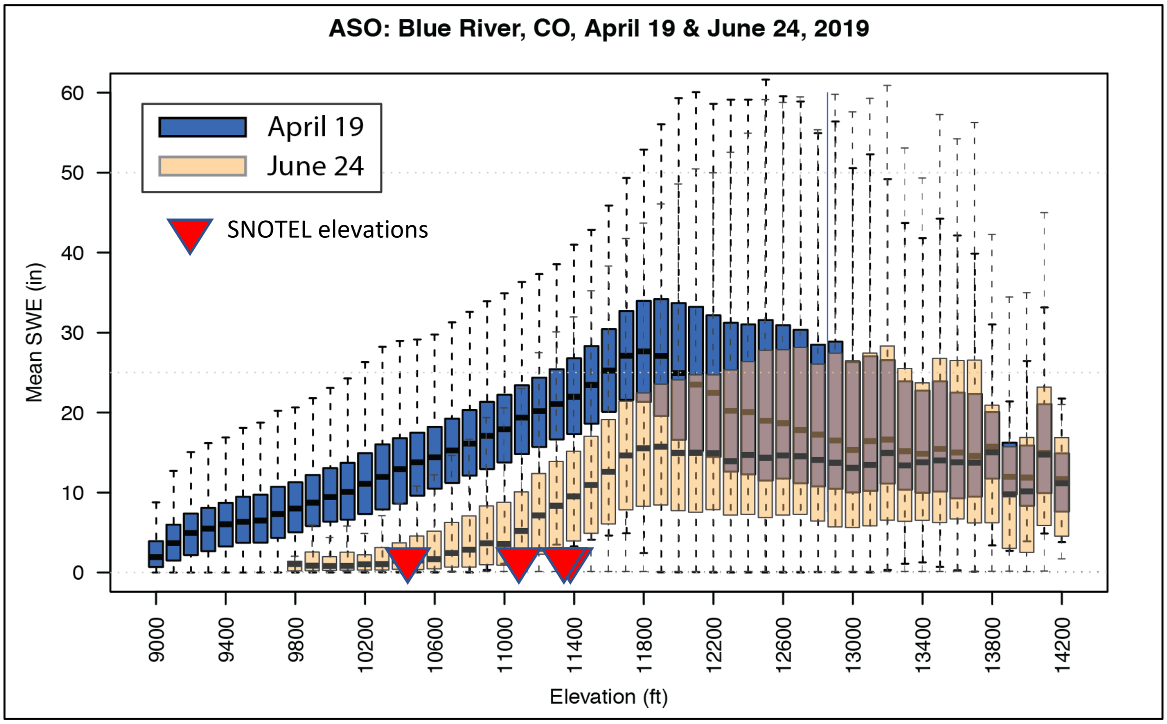

Figure 8. Distribution of Snowpack and SNOTEL Sites, Blue River, 2019

Climate Change Adaptation: The full build out of a CASM program will allow the state to track changing snowpack in a way that has not previously been possible. Non-stationarity is the concept that historical trends no longer apply to current and future conditions due to changes in the underlying physical processes driving a particular system. Climate non-stationarity has been observed throughout the Western US, manifesting in changing precipitation, temperature, and runoff conditions (Milly 2008).

Many of the snowpack measurement and streamflow forecast products in use throughout the West rely heavily on historical relationships between station observations and runoff amounts. ASO provides an accurate measure of SWE throughout the entire watershed, allowing a user to precisely validate the amount of water in the snowpack, rather than assuming that the historical relationships underpinning their predictions are still valid. This data source enables the use of runoff forecast systems that are not reliant on historic relationships and thus can be responsive to changing hydroclimate or land surface conditions.

Benefits to Complementary Management Challenges: The combination of high-resolution lidar, visible camera, and imaging spectrometer data represents a powerful observation and monitoring capacity that can benefit many complementary management needs. Ongoing ASO work with partner agencies and researchers in California is demonstrating the utility of these data for forest health initiatives, enabling responses to both forest and hydrologic changes induced by wildfire and forest mortality. ASO snow-free data collection can support forest health assessment, quantification of moisture stress and fire susceptibility, and fuel load assessments – in this way supporting partner agency activities across the land management spectrum.

Accurate and spatially-complete knowledge of the snowpack component of the water cycle offers subsequent improvements in modeling and forecasting of other, harder-to-measure components such as soil moisture and groundwater. Recent work constraining subsurface flow models with ASO snow data shows improvements and reduced error in soil and shallow groundwater simulations. A regular ASO snow monitoring program, in conjunction with assimilation of the data into operational hydrologic models (e.g. the WRF-Hydro system deployed in tandem with ASO flights recently) offers year-round improvements in water system knowledge and knock-on effects for seasonal forecasts influenced by antecedent moisture and baseflow states.

Colorado River Basin and Other Interstate Implications: The last several years have been abnormally dry for the Colorado River Basin. A large percentage of the streamflow in the Upper Colorado River basin originates in Colorado's snowpack. Use of precise snowpack measurements should be further explored for statewide decision making when it comes to interstate compacts.

2.6. Challenges of ASO

While ASO is a unique and powerful snow measurement tool, it comes with significant logistical and cost challenges. The CASM program is intended to address these challenges directly and place them in context with the value of the information and the implicit costs of poor snowpack knowledge.

Cost: In 2022, ASO Flights were typically $50,000-100,000 per snow survey. Due to rising fuel costs and the current inflationary economic environment, ASO, Inc. expects that $120,000-$150,000 per flight is a more realistic cost for long term planning. There are additional costs associated with supporting work like basin preparation, runoff forecasting, scientific inquiry, and stakeholder engagement. While these costs are high compared to existing snow monitoring programs, the data are of vastly greater accuracy, coverage, and resolution than existing products, and the level of support the CASM program has received indicates that this product is desired by water managers at the local, state, and federal level, and is worth the money. Valuation efforts by California Cooperative Snow Survey partners has estimated the return-on-investment (ROI) of ASO data at 40:1 for water supply alone, and at 600:1 when other factors such as hydropower production, flood mitigation, groundwater recharge, and operational flexibility are included (. A similar analysis has yet to be conducted in Colorado.

Field-Based Support: Accurate and geolocated field and in-situ measurements of snow depth, density, and SWE are extremely useful in the ASO data production process, to verify snow depths and to enable model density evaluation and bias adjustment. ASO Inc will often send staff to conduct field measurements of depth and density for flight validation, and regularly works with local stakeholders to coordinate additional field measurements. At CASM buildout, this activity will be aa regular topic to be paired with flight timing coordination discussions.

Intermittent measurements: ASO Flights are conducted only a handful of times each runoff season (2-4 times per season in Colorado to-date, with 6-10 flights being implemented as a full program build-out in California). In the gaps between measurements, snowpack modeling is necessary to provide a continuous picture of basin conditions. ASO, Inc. runs the iSnobal snowpack model to provide continuous estimates of snow depth, density, and water equivalent, in addition to providing the density fields used for SWE calculation. Streamflow forecasts are currently produced for all ASO flights using WRF-Hydro. Both models assimilate ASO flight data to provide maximum accuracy.

Coordination and planning: As of this report, ASO Inc. operates three aircraft to conduct snow surveys in California and Colorado. Weather is also a significant factor in flight timing. The aircraft availability and weather can lead to logistical challenges around when users want flights to happen and the feasibility of conducting measurements. Coordination issues are addressed through regular flight planning and coordination meetings.

Data Distribution and Use: Currently in Colorado, ASO flight data is primarily used by a handful of water managers. There is large interest in more widespread use of the data across different water sectors and different geographic regions, but there remain challenges in communicating the data products. The CASM workgroup will be actively working to facilitate more widespread use of ASO data products.

3. WSRF Project Activities

This report is the result of a CWCB grant from the Water Supply Reserve Fund (WSRF) in 2021. That grant allowed the project team to collect detailed stakeholder feedback on the use of existing snowpack measurements and to provide educational sessions on the value of the ASO technology. This report is intended to provide an overview of the recommendations from the WSRF-funded activities on how to expand the CASM program to improve water management throughout the state through regular, statewide coverage of ASO flights.

3.1. CASM Planning Team

In 2020, a group from several different public and private agencies set a to discuss benefits from some recent ASO flights funded by Denver Water. That group also discussed the potential to expand the program statewide and make the data available more broadly through cost sharing. Over 2020-2022, this group grew and, as of this writing includes representatives from:

- Denver Water
- Northern Water
- Dolores Water Conservation District
- Colorado River District
- Airborne Snow Observatories, Inc.
- Lynker Technologies

This group is referred to throughout as the CASM Planning team.

3.2. WSRF Funding

This project was funded with $45,000 from the CWCB Water Supply Reserve fund and $44,000 of in-kind matching funding, and was endorsed by five basin roundtables (BRT); the Yampa, North Platte and Southwest basin roundtables indicated their support but due to timing constraints they were not able to indicate formal BRT support. Table 3 shows the funding sources used in support of this project.

Table 3. WSRF Grant Funding Sources

Contributing Entity	Amount and Form of Match (note cash or in-kind):
Northern Water	$5,000 (in kind)
Denver Water	$10,000 (in kind)
Airborne Snow Observatories, Inc.	$5,000 (in kind)
Collaborative Workgroup (Colorado Springs Utilities, City of Aspen, City of Fort Collins, Colorado River District, City of Boulder, City of Greeley, Thornton Water, Pueblo Water, Eagle River Water & Sanitation District, Aurora Water, City of Westminster, and the Ruedi Water and Power Authority)	$24,000 (in kind)
WSRF - Arkansas Basin Account	$5,000 (cash)
WSRF - Colorado Basin Account	$5,000 (cash)
WSRF - South Platte Basin Account	$5,000 (cash)
WSRF - Metro Basin Account	$5,000 (cash)
WSRF – Gunnison Basin Account	$5,000 (cash)
WSRF – Statewide Account	$20,000 (cash)
Total Funding	$89,000

3.3. Subtask 1: Basin Flight Planning

This task was intended to create an approach and preliminary set of locations and timings for ASO flights. This involved review of existing snow measurement products, as well as considerations around how to equitably select basins that will get flights. The CASM group oversaw flight planning for 2022 and worked with stakeholders to come up with options for long range program buildout. The final range of recommended flight programs was informed by the stakeholder engagement process and available funding.

As part of this task, the project team reviewed flight coverage and available lidar data from previous years to develop maps of basins that were ready for snowpack measurement flights in spring 2022. Basins were reviewed and prioritized based on available funding, benefit to multiple stakeholders, availability and quality of snow-free data, flight timing and other logistical considerations.

This task also included mapping all areas of the state that would benefit from ASO snow surveys, and what it would take to make them "shovel ready" for future measurements. A "Shovel Ready" basin is one with a completed and validated set of snow-free data, an identified downstream gage where forecasts are or will be conducted, and plans to deploy a streamflow forecasting model and generate operational results.

3.4. Subtask 2: Stakeholder Engagement

The goal of this task was to collect information from stakeholders on the perceived value of ASO to their agency and specific benefits they saw. This involved educating them on the possible benefits of the program as well as understanding the operational benefit to each agency of ASO flights at various times of year. The actual process to collect this feedback included a large survey and a series of one-on-one interviews with key stakeholders. Additionally, we collected feedback on willingness of stakeholder agencies to commit funds to future ASO flights. There are a range of funding options, some of which may include some small amount of matching funds from different groups.

Stakeholder Workgroup Meetings

Throughout 2021, the CASM workgroup conducted several different types of engagement activities to understand how and why snowpack information was used to inform water resources decision-making. Table 4 below shows the meeting dates, and topics for all educational sessions:

Table 4. CASM Stakeholder Educational Sessions

Date	Topic	Presenter
April 27th, 2021	Everything you want to know about ASO!	Jeff Deems, ASO Inc.
May 5th, 2021	California's ASO Program CU-SWE: A Satellite Data Application	Dave Rizzardo, CA DWR Noah Molotch, CU
June 2nd, 2021	Panel Discussion: Using ASO in Practice	Denver Water, USBR in CO and CA, CBRFC, Kings River Water Association, CA DWR
July 14th, 2021	Forecasting and Data Assimilation Efforts using ASO Colorado's 2021 ASO Outcomes	Dave Gochis, NCAR Jeff Deems, ASO Inc.

On July 27th, 2022 CASM shared with the stakeholder group a detailed survey on the demographics, geography, use of snowpack data and perceptions of ASO as a product. We received 73 responses from a wide variety of local, state and federal agencies that represent stakeholders in all major river basins of Colorado. A few key findings from this survey are described in section 4.

Once these surveys were completed, the project team conducted focused interviews with a few key stakeholders to better understand their needs, ideas around program design and implementation, opportunities, and challenges. These interviews were conducted with representatives from each of these agencies:

- NRCS
- USACE
- CWCB
- CBRFC
- Colorado DWR

In addition to the focused engagement activities, the project team has held regular monthly meetings throughout 2021 to update stakeholders on project progress. These meetings are well attended, with typically 30-50 agencies in attendance. Figure 9 shows some example demographics from informal surveys conducted at each meeting (Data is from Mentimeter.com).

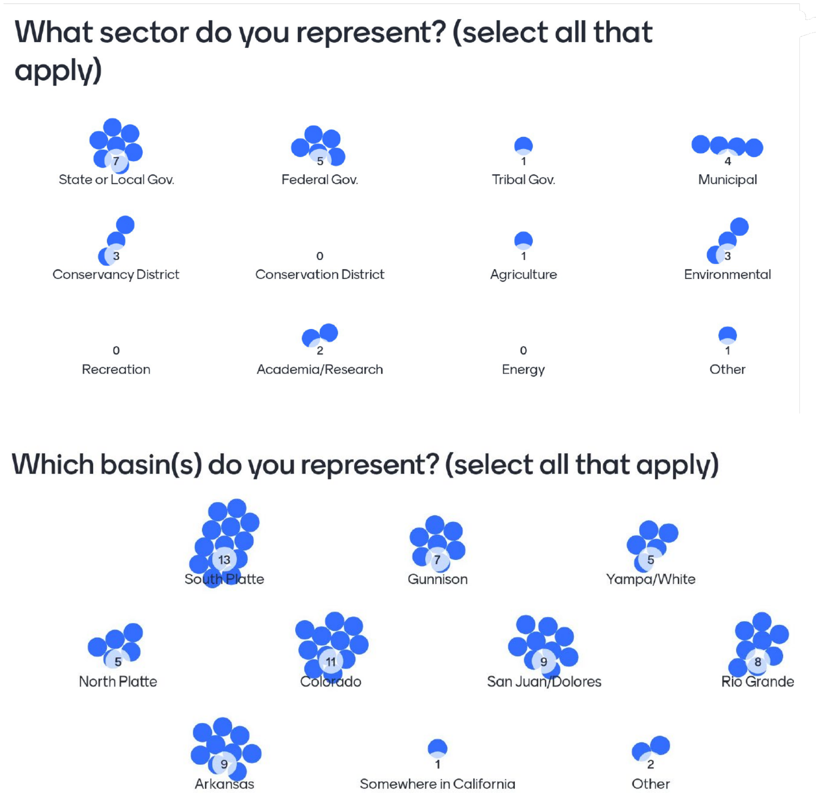

Figure 9. Example Meeting Demographics from Live Meeting Poll

3.5. Subtask 3: Program Administration and Funding Structure/Overall Plan Development

As a program, CASM will only function well if it has sustainable funding and equitable program oversight. This task was intended to help the project team identify necessary and desired aspects of a sustainable CASM program.

The CASM workgroup had several direct interviews with representatives from state governments of Colorado and California. In addition, survey results from the stakeholder engagement process were used to inform the conversation. The most similar program to CASM is the California Airborne Remote Sensing of Snow (ARSS) program. The project team met with CA-DWR representatives on numerous occasions to learn how to approach program funding, operations, and program administration.

As this activity drew to a close, the CASM program implemented a pilot of the flight planning and coordination committee (described below in section 5.6) to coordinate flight logistics and data needs across all stakeholders for 2022.

3.6. 2022 Activities

A key milestone of this project was to begin implementation of CASM activities in 2022. Northern Water, acting as fiscal agent on behalf of the CASM Program, submitted a Water Plan Grant application in December 2021 to fund foundational CASM activities including 14 operational flights, six basins of additional snow free data preparation, and several supporting activities including ongoing stakeholder engagement, forecast improvement and other things. In March 2022, this grant was approved for $1.88 million in funding from the Colorado water Conservation Board. This grant was made possible through matching funds provided by Northern Water, Denver Water, St. Vrain & Left-Hand Water Conservancy District, the USGS, and Lawrence Berkeley National Laboratory. The CASM program's 2022 grant application received 37 letters of support for this grant and the associated activities. The signatories on these letters included seven Basin Roundtables, the Colorado Division of Water Resources, the U.S. Bureau of Reclamation, environmental nonprofit agencies, and dozens of municipal water providers. Figure 10 shows the proposed flight activities as part of this grant.

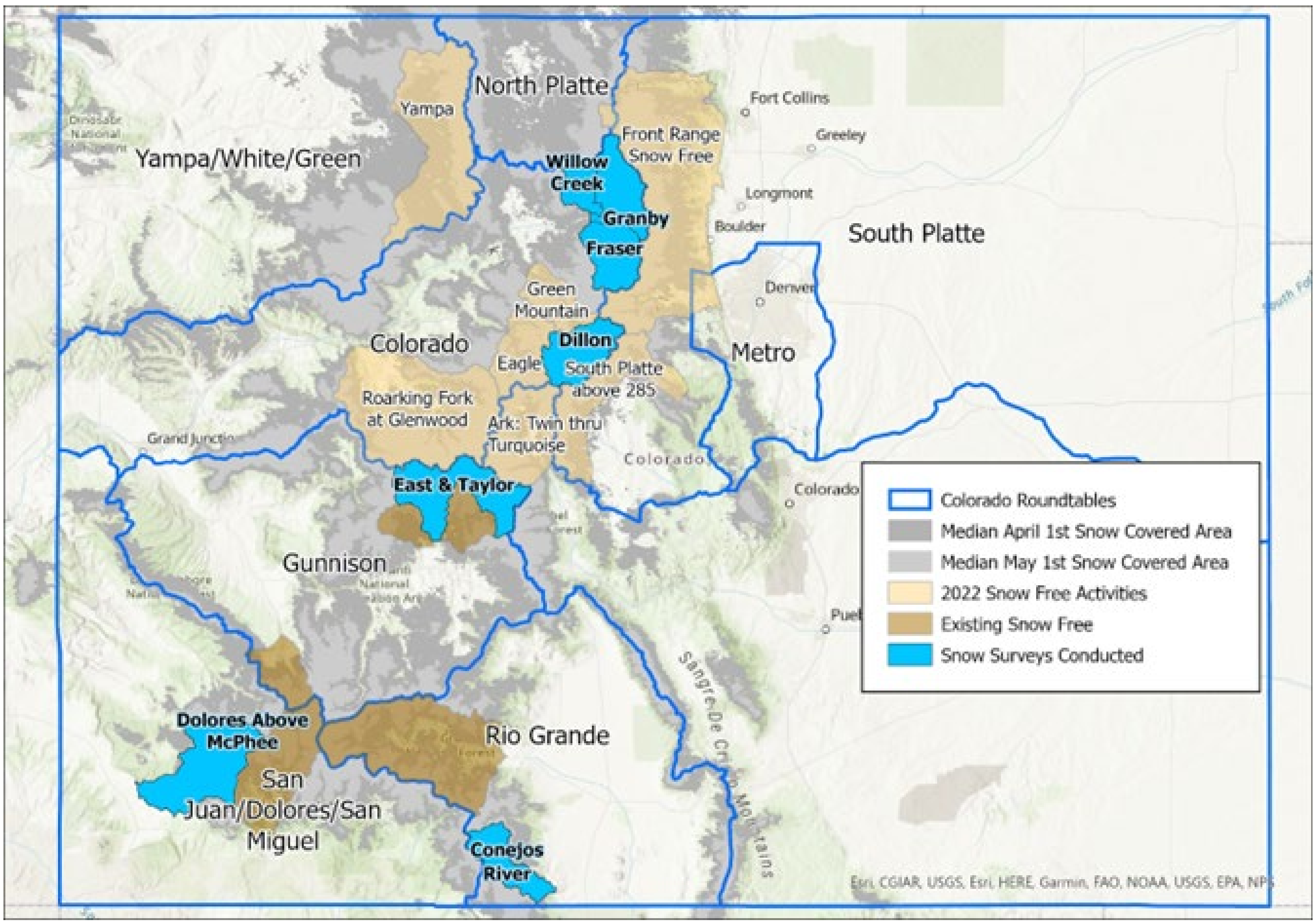

Figure 10. 2022 Water Plan Grant Activities

The basins that received snow measurements in 2022 were selected based on a combination of existing funding and overall program benefit. Willow Creek, Granby, Dillon, and East & Taylor basins were all partially funded by local stakeholder agencies. initially Dolores above McPhee and the Conejos basins were fully funded by the Water Plan Grant –initially - however after funding, the existing snow-free data for this domain was judged to not be in useable state, so the Conejos River was substituted. As CASM grows, it is anticipated that there will be more multi-stakeholder areas to measure and will require stakeholder education to maximize the utility of those snow surveys.

Snow-free activities include review of existing LiDAR datasets, and additional summertime flights as necessary to prepare as many basins as possible for snowpack measurements in coming years. The 2022 snow-free activities include expansion throughout most major river basins, and significant multi-stakeholder areas. At the end of all 2022 activities, up to 45,000 sqkm will be prepared for snowpack measurements in years to come.

In addition to the snowpack measurements and snow-free data development, several supporting activities were proposed to promote the CASM program. All basins with snowpack measurements in 2022 also had experimental WRF-Hydro streamflow forecasts generated within a week of the flight being conducted. These forecasts incorporated ASO data using the “direct insertion” technique. CASM will also conduct a detailed streamflow model hindcast to evaluate the performance of several different model frameworks and streamflow forecasting approaches. There are several additional stakeholder engagement activities planned for 2022 as well to provide continuity with the CASM program, help stakeholders improve their use of the CASM data, and demonstrate program value through additional case studies.

4. Lessons Learned from Stakeholders

Stakeholder engagement through webinars, conference presentations, surveys and direct interviews was a core part of the 2021 WSRF activities. At the outset of this project, many stakeholders were uninformed or under-informed about the use and benefits of ASO. The CASM team conducted several educational sessions between April and July (Table 4) to demonstrate to stakeholders the value of ASO as a data product, as well as continued monthly stakeholder check-in meetings from August 2021 to present. After these educational sessions, the CASM team shared with the stakeholder group a detailed survey on the demographics, geography, use of snowpack data and perceptions of ASO as a product.

Key Stakeholder Opinions

- CASM needs to show improved streamflow forecasts to add value to most groups
- 2-4 flights per year are desired, centered around peak SWE
- The CWCB should manage the program
- State-Federal partnership is ideal for funding

This section highlights a few of the key survey results. Stakeholders represent all major basins in Colorado: South Platte, Gunnison, Yampa/White, North Platte, Colorado, San Juan/Dolores, Rio Grande, and the Arkansas. Figure 11 shows the location of the CASM stakeholders who completed this survey.

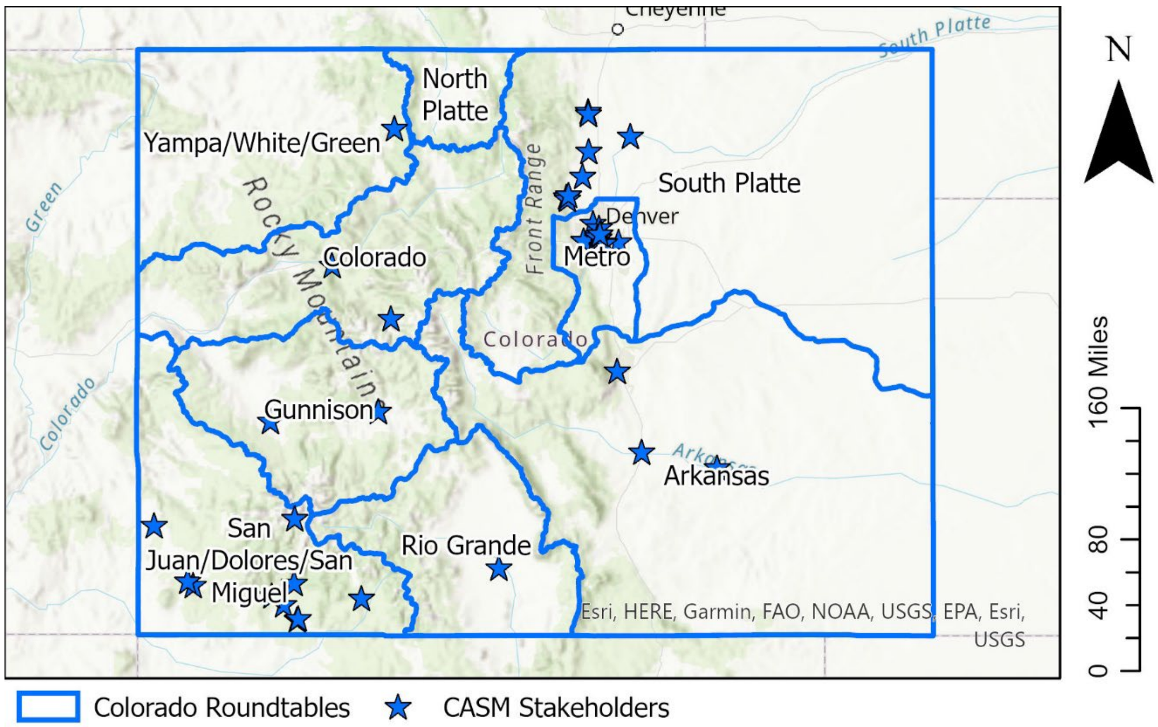

Figure 11. CASM Stakeholder Locations

4.1. Survey Results

The stakeholders come from a wide variety of fields within Colorado and represent the breadth of possible organizations and agencies that care about snowpack and can benefit from the results of ASO flights. Figure 12 shows the representation of the stakeholders in the group.

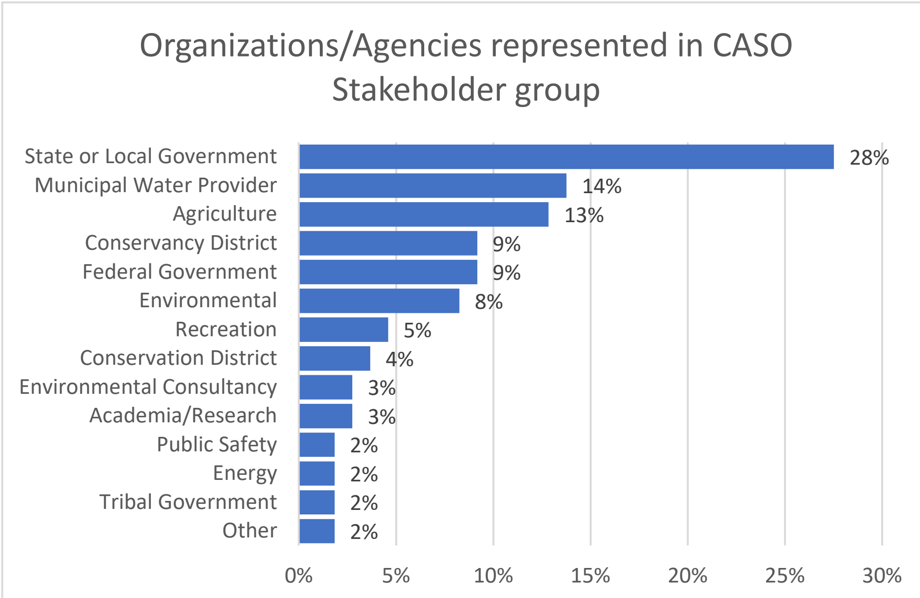

Figure 12. Stakeholder representation in survey

After detailed educational sessions, stakeholders generally had a favorable impression of ASO and its accuracy for seasonal runoff forecasting. Figure 14 shows that about half of the respondents felt that ASO would provide High/Extremely High value to their organization.

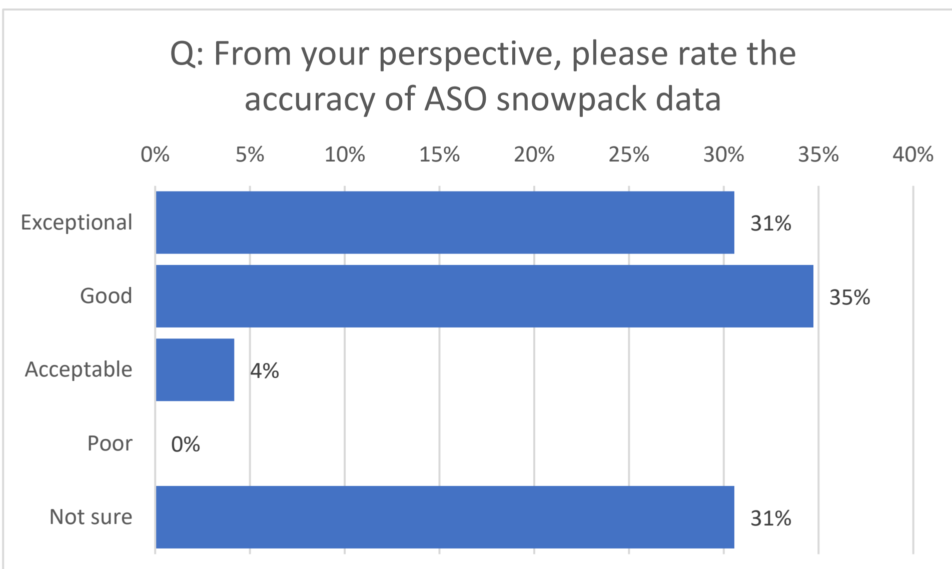

Figure 13. Survey response percentages of total for ASO accuracy

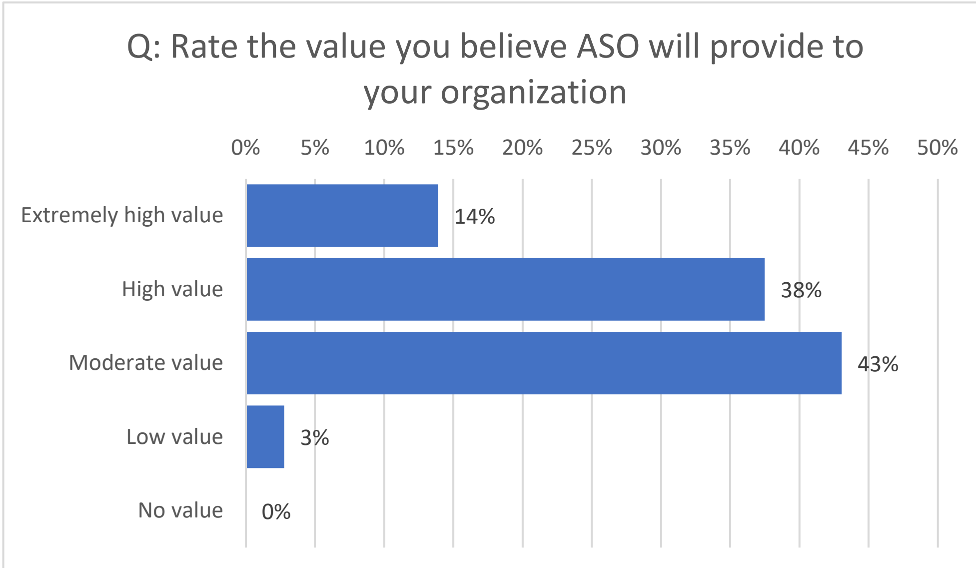

Figure 14. Stakeholder survey results: Rate the value ASO will provide to your organization

Stakeholders were asked how they would use ASO data and what specific applications they see from ASO data. Figure 15 shows that most respondents saw the utility of improved seasonal streamflow forecasts for their organizations. There were several other added benefits indicated including scientific research support, and optimization of operations. Table 5 lists the open-ended answers on how exactly organizations plan to use ASO data.

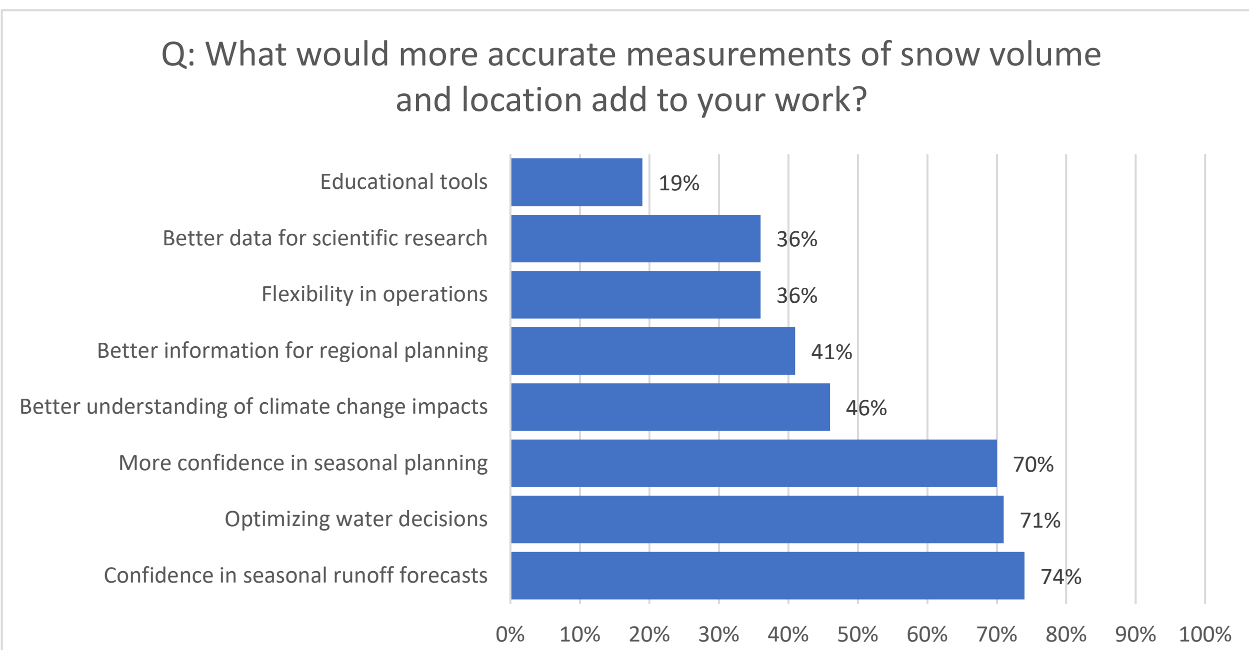

Figure 15. Stakeholder survey results: How would improved accuracy benefit you?

In Table 5Table 6 and Table 7, stakeholders expressed that improved runoff forecasts are the most desired aspect of a function CASM program. No matter how the flight program is coordinated, forecast improvement needs to be at the center of the CASM effort every year.

Table 5. Stakeholder Survey Results: Open Ended Responses on How ASO Would Add Value

Q: What are ways ASO data might add value to your organization?	
Improved Reservoir operations	Fill rate of reservoir
	Water storage predictions
	Reservoir level
	Flexibility for operations
Better understanding of snowpack distribution regionally	More accurate forecasts of SWE by basin
	Better understanding of snowpack above SNOTEL sites/areas without SNOTEL sites
Improve seasonal runoff forecast	Better understand changes in runoff efficiency
	Improve runoff volume and timing estimates
	Improve peak flow estimation
	Late season forecasting
Better data equals better decisions	Hydrologic model verification/validation
	Reduce forecast uncertainty
	More data to track snowpack over time (climate change)
Optimizing water decisions	Enhanced decision making for drought planning
	Climate change
	Annual water supply planning
Agricultural use water planning	Planting and season planning
Recreation benefits	Inform seasonal fish stocking or environmental water transactions
Water rights and obligations	Improved estimates of water rights yields
	Meet environmental flow targets that depend on runoff volume and timing

Table 6. Stakeholder survey results: Program design insights

Q: The following four things are most important to me in designing a CASO program (select up to four)	
Incorporating Colorado ASO data into Colorado River streamflow forecasts and operations planning	45
ASO results are easily accessible and interpretable	44
The ASO data is quickly integrated with streamflow runoff forecasts	38
Program is funded sustainably (3-5 years at least)	33
Multiple yearly flights over my basin of interest	30
Paying contributors to the program have a say in where and when flights happen	19
Being able to provide stakeholder feedback to the program on an annual basis	16
This should be primarily funded by a combination of state and federal funding	16
Fly the entire state above 10,000 feet at least once per year	12
The should be a primarily federally funded program	2
This should be a primarily state funded program	1
Governed by a state agency	1
Governed by a state-federal partnership	1
A stakeholder governing body defines annual flight program (when and where to fly) in partnership with governing agency	0
Governed by a federal agency	0
Governed by a non-profit	0
Other (please specify)	4

Each organization has varying data needs and operational uses for ASO data. Flight planning is one of the key logistical challenges of CASM, so it is important to understand the number and timing of flights desired across the stakeholder group. Figure 16 and Figure 17 show responses around when and how often flights would ideally be conducted to benefit operations.

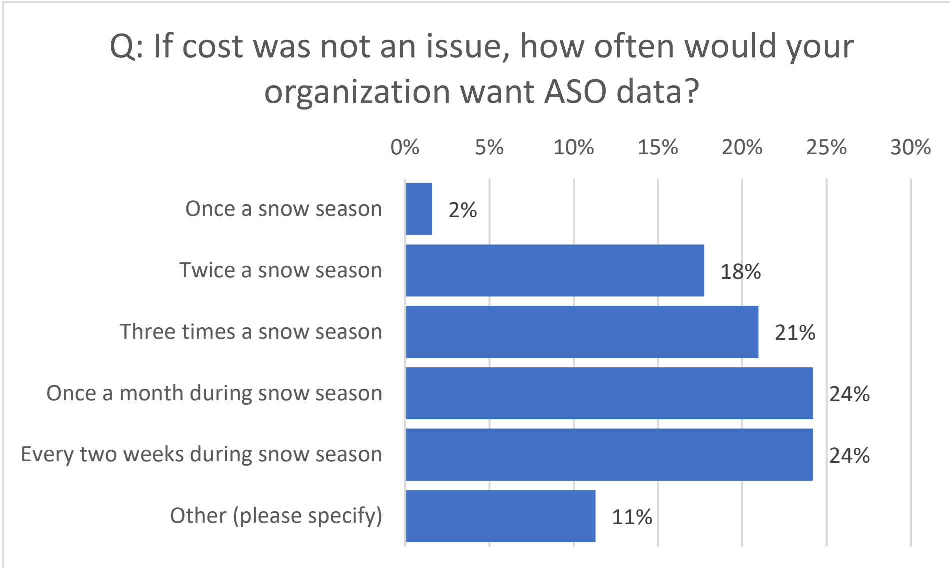

Figure 16. Stakeholder survey results: How often would you want ASO data?

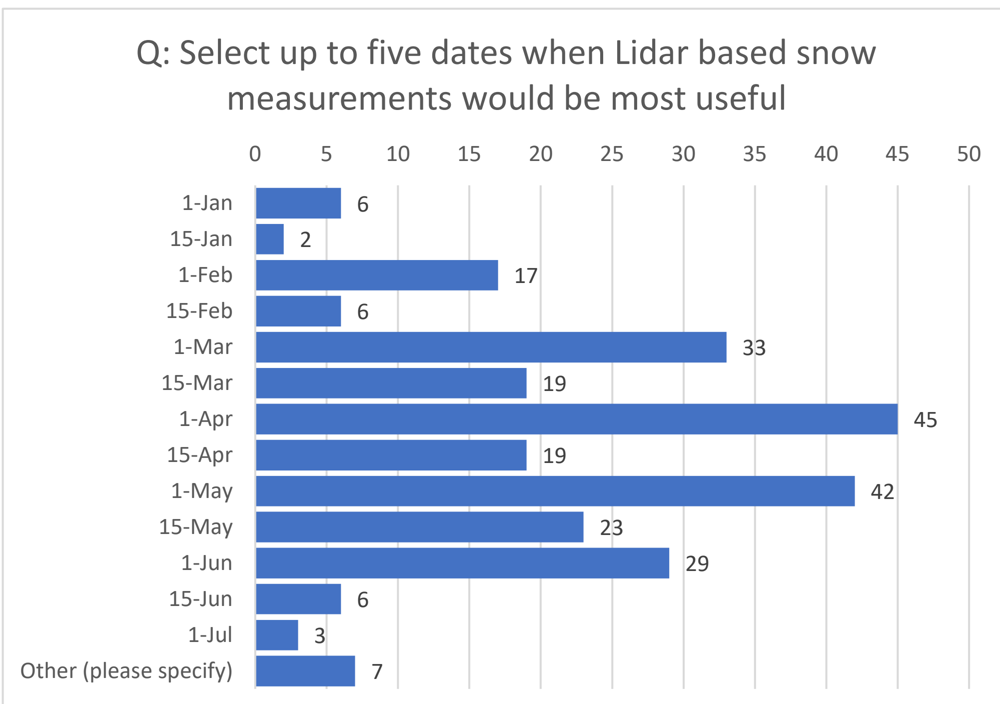

Figure 17. Stakeholder survey results: Ideal Dates for ASO Flights

Lastly stakeholders were asked for opinions on program funding and program oversight. Table 7 shows the perceived pitfalls of a CASM program. Table 7 lists the program design insights from these stakeholders, based on their experience managing a wide variety of agencies. Figure 18 and Figure 19 show some insights from the stakeholder survey on the amount individual agencies may be able to contribute, and where the program should be hosted to be most effective.

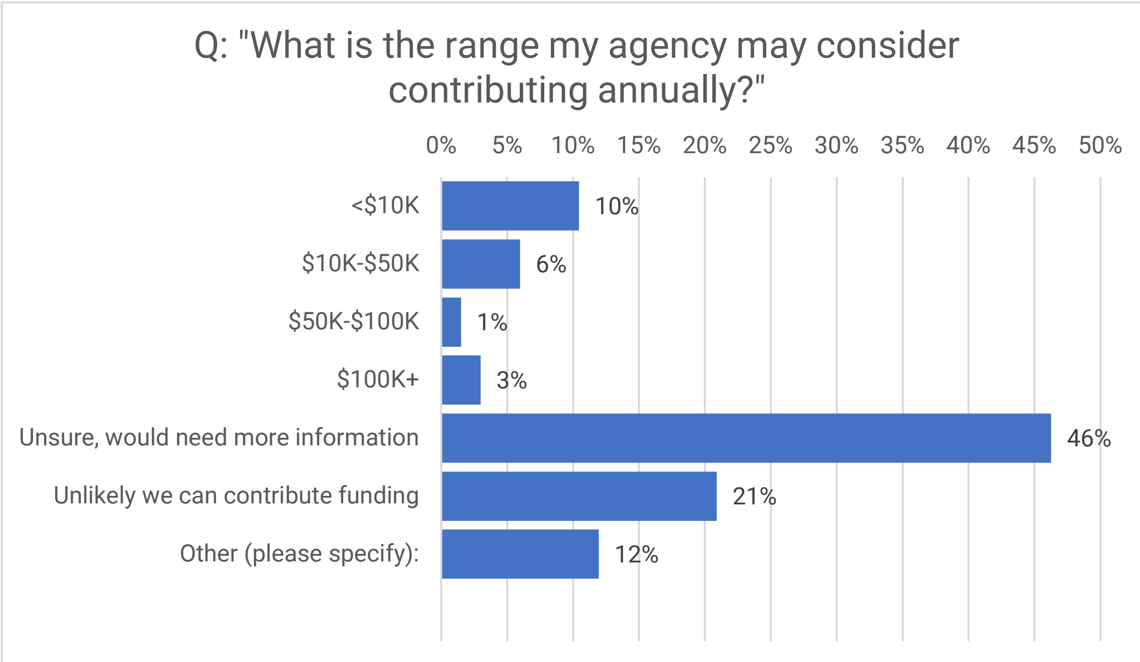

Figure 18. Stakeholder survey results: Willingness to Contribute Funding

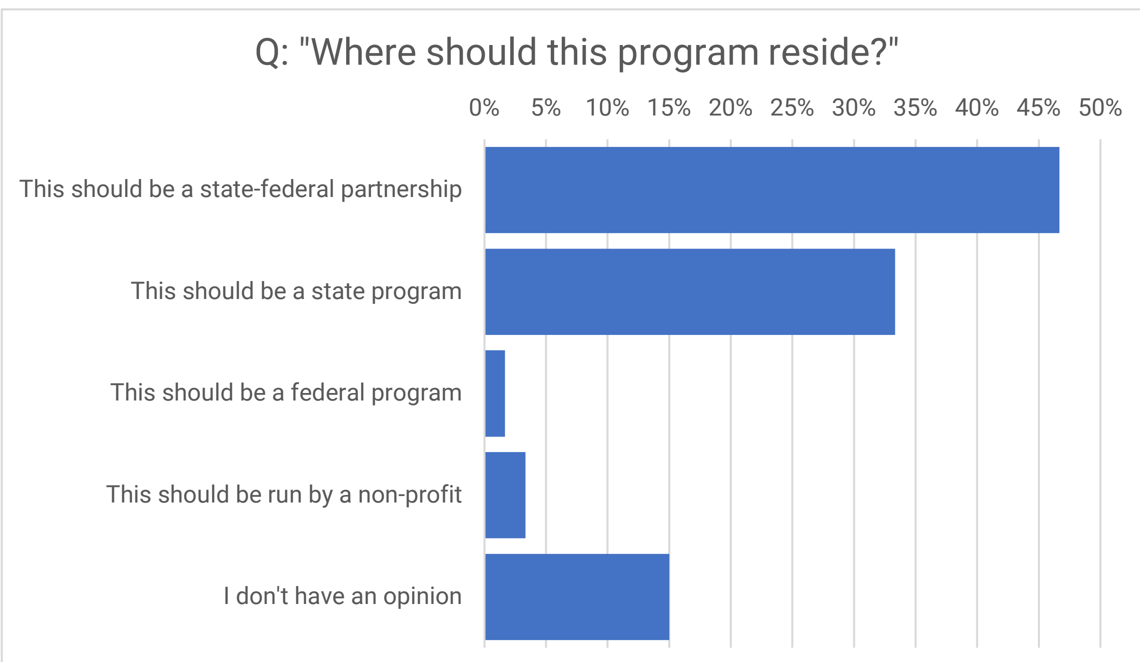

Figure 19. Stakeholder survey results: Ideal program location

Table 7. Stakeholder Survey: Anticipated Program Pitfalls

Q: What pitfalls come to mind when considering various aspects of this program?	
Flight Planning	Timing of snowpack and user need
	Timing of user needs for all sectors
	Performance of forecasting models
	Weather
	Make sure to "Bank" flights for wet years
	Having enough planes to cover simultaneous flights
	Will stakeholders be expected to pay without getting a flight?
Program Administration	Focus on compact compliance
	Capacity of CWCB Staff to manage program
	How is flight planning committee organized as program grows
	Make sure all sectors, basins and agency sizes have a voice
	Sole source contracting with ASO Inc.
Funding	How to ensure multi-year funding since state and federal appropriations are yearly
	Expensive
	How to balance stakeholder payment vs flight location
	Need multi-year funding flexibility
What do you support generally?	Multi-year flight concept
	Statewide flights are important
	Publicly available data is key
	CWCB is a good agency to lead CASM
	Start slowly and grow with funding and outreach

asdf

4.2. Additional Insights from 1:1 Interviews

The CASM team conducted six focused interviews with key stakeholders with questions on the details of how ASO would be used, and program design insights. The themes that emerged were similar to the results of the broader survey but included:

Applications of ASO Data: There were a wide range of expected uses of ASO data including delivering forecasts, improving existing models, validating hydrologic assumptions like soil moisture impacts and others. Several different direct benefits were discussed for reservoir operators, irrigators, environmental protections, compact compliance, and others.

Funding and Program Administration: Most interviewees supported a state-federal partnership for funding, recognizing that the cost burden would be too much for local stakeholders. As CASM takes off, it was stressed that this program needs to include a more formal structure to allow for continuity as CWCB staff change positions and political administrations turn over.

Incorporating ASO into Official Forecasts: The CO-DWR, NRCS, and CBRFC were all interested in both using ASO data directly in their streamflow forecasts and using it to improve calibration of their models. Most recognized that given the structure of their index-based forecast systems, it will take many years of data to develop significant empirical relationships to show improvements in their products.

4.3. California ARSS Program

CASM was formed to lay the groundwork for a statewide program that will deliver ASO flight data yearly and statewide. California DWR has a program called the Airborne Remote Sensing of Snow (ARSS) which coordinates 30+ ASO flights per year across many headwater basins in the Sierra Nevada and northern California mountains. The project team had several conversations with CA-DWR around program development, benefits, pitfalls, and lessons learned.

> *"Having used this technology, it is hard to imagine a future without it."*
>
> *Dave Rizzardo, Chief of Snow Surveys and Water Supply Forecasting, CA DWR*

ARSS began in 2013 and has slowly scaled up over several years to provide 3-5 snow surveys per year across nine major basins in the Sierra Nevada. The CASM team has engaged closely with CA-DWR staff to understand some lessons learned and potential challenges of developing a program like ARSS. Figure 20 shows the planned ARSS flight activities in WY2022; the colors in the flight planning table indicate the various funding sources used for flights in each flight and basin. In 2022, ARSS is funding 31 flights and all the associated support activities at a cost of $9.5 Million. ARSS buildout includes expansion to 6-10 flights annually covering 26 headwater basins in the Sierra Nevada mountains.

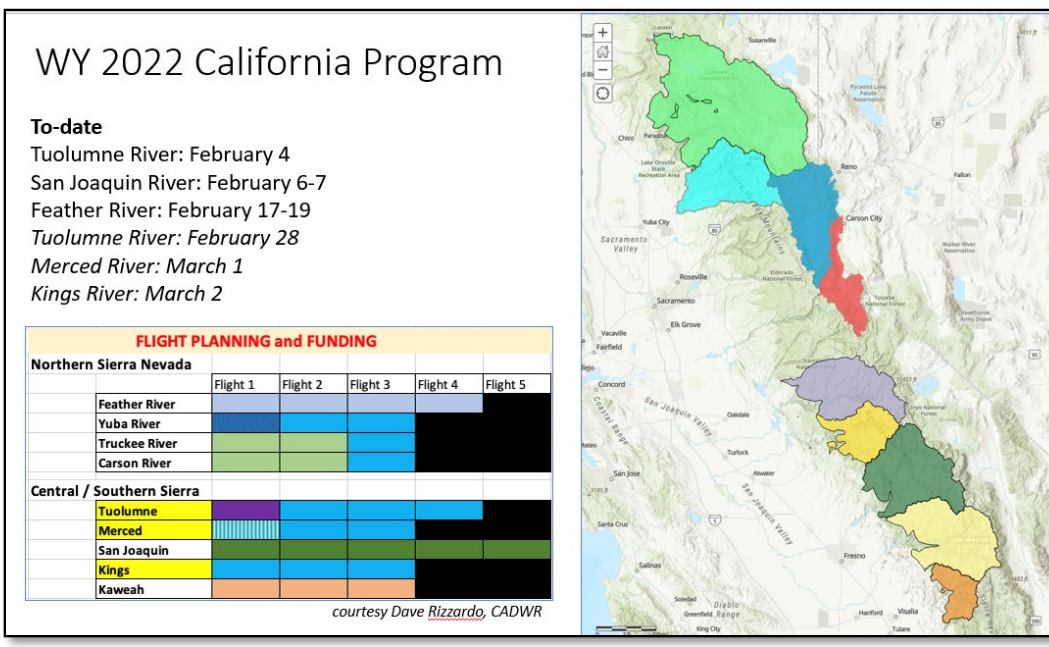

Figure 20. ARSS Implementation Overview, WY 2022

ARSS was developed partly in support of the CA DWR Bulletin 120, a water supply forecast product issued for 26 basins across California. Bulletin 120 is similar to the Streamflow Forecasts issued by NRCS basin forecasts in Colorado (NRCS 2022).

> "Bulletin 120 is a publication issued four times a year, in the second week of February, March, April, and May by the California Department of Water Resources. It contains forecasts of the volume of seasonal runoff from the state's major watersheds, and summaries of precipitation, snowpack, reservoir storage, and runoff in various regions of the State." (CA DWR 2022)

The ARSS program provides improved information in many of the basins that receive Bulletin 120 reports. ASO snow survey data are compared against other models and used as a check on California's snow pillow and snow course network. Snowpack models are run by ARSS continuously through the runoff season to track estimated remaining water supply. ASO flight data is used to correct those models and fine tune the seasonal runoff forecasts.

4.3.1. ARSS Committee Structure

ARSS activities are managed using a simple committee structure to oversee data and modeling, outreach and logistical activities. Figure 21 shows the organizational hierarchy.

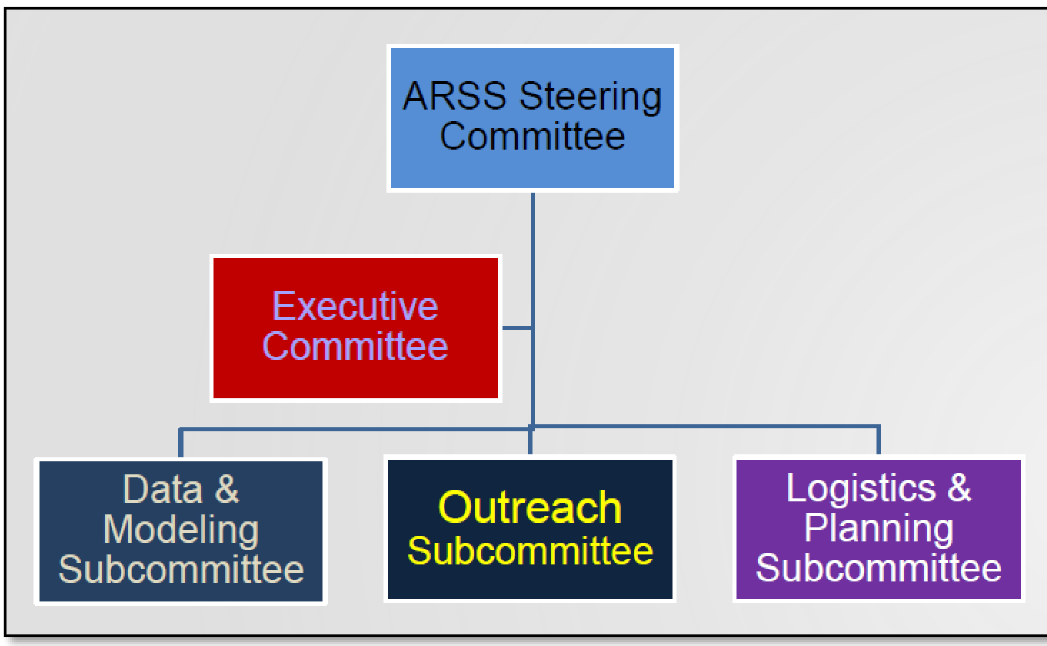

Figure 21. CA-DWR ARSS Committee Structure

In each committee, all active watersheds are represented. The roles and responsibilities of each subcommittee are shown below:

ARSS Steering Committee:

Similar to the CASM stakeholder group, this is a general forum for ARSS program discussion. Engagement with this group helps set the overall program direction based on benefits, program needs, ongoing issues, etc. This committee reports back with direction to individual Subcommittees and advises the Executive Committee as well.

Executive Committee

This committee oversees the individual subcommittees and implements ARSS program activities. This is the primary group responsible for direct interaction with ASO Inc around flight planning and program development.

Data and Modeling Subcommittee:

This committee's focus is on advancement of hydrologic modeling. Specifically, their role is to implement standards and strategies to bring in ASO snow surveys and use them to improve the Bulletin 120 forecasts. Their first task is to oversee data management and QA/QC and make sure ASO data is collected and disseminated in a timely manner. Their other task is to oversee how water supply forecasts are made using ASO data and several related activities:

- Integrate ASO data post-flight
- Conduct water supply modeling between flights using manual ground-based sensors
- Assimilate information into Bulletin 120 forecasts
- Conduct outreach and data sharing with cooperators

Outreach Subcommittee:

This committee's focus is on maintaining and expanding the scope of the ARSS program for maximum benefit. They work closely with lawmakers around various state and federal budgeting processes. This committee is also responsible for reaching out to other partners including other Western states, forecasting and monitoring networks, and remote sensing data providers to collaborate and improve the overall ARSS product. They are also responsible for presenting ARSS activities and findings to conferences and workshops.

Logistics and Planning Subcommittee:

This committee's focus is on program logistical planning to address month to month needs of stakeholders. They also manage the "Pecking Order" of where and when flights will happen, as well as coordinating summer and fall program needs like additional snow-free data acquisition. This committee gives the program flexibility to adjust flight schedules based on numerous factors including:

- Weather windows
- Rapidly changing snow cover
- Changing hydrologic year types, including adjusting the number and timing of flights in a given year

This committee is also responsible for all agreements and contracts to run the program, including the subcontract with ASO Inc.

An internal CA-DWR program assessment whitepaper (CA-DWR 2020) also outlines the various required DWR staff roles to operate ARSS. These roles are:

- Program Management and External Engagement (0.5 FTE)
- Flight Planning and Coordination (0.5 FTE)
- Deliverables and Products (1 FTE)
- Modeling and Data Management Support and Deliverables (2 FTEs)

4.3.2. ARSS Funding

ARSS resource requirements are designed around an ideal number of flights and basins, but actual program operations require that this funding be available across multiple years. Flexibility in funding allows for ARSS to conserve funding in drier years if fewer flights are required.

ARSS funding has grown over time, but it still comprises multiple funding sources. In Figure 20, there are eight colors in the flight planning table, indicating eight different sources of funding for one year of flights. While the largest source of funding is from the California Department of Water Resources, the others include the California Cooperative Snow Surveys (CCSS) program, FEMA, and others.

While the largest source of funding is from the California Department of Water Resources (CADWR), other funding sources include the United States Bureau of Reclamation (USBR), the State Water Project Contractors (SWC), and local agency partners that are part of the California Cooperative Snow Surveys (CCSS) program. The contributions from the USBR, SWC, and local agency partners allowed for important ASO data collection and modeling updates to occur at the minimum frequency needed to make the program effective. Beginning in the 2022-2023 season, CADWR has secured baseline funding for the first time in program history which will allow for continued operations in the watersheds in which ASO was operational in 2021-2022 and expand to additional watersheds in which CADWR produces a forecast for in the Bulletin 120 (CA-DWR, Personal Communication)

Similar to the program proposed in this document, the California ARSS program has funded flights in a staged approach. Table 8 shows the estimated annual costs for the ARSS program at different stages of rollout.

Table 8. CA-DWR Airborne Remote Sensing of Snow Program Costs

Phase	Roll Out Option	Operational Flights	Maintenance Flights	4 FTEs at CA-DWR	Total Annual Cost
1	**Current Program**	6.1	0.9	2.5	**9.5**
2	**Expand to Snow Free Ready**	13.8	2.1	2.5	**18.4**
3	**Expand to Shasta-Trinity plus Kern**	19.3	2.9	2.5	**24.7**
4	**"Statewide"**	17.1	2.6	2.5	**22.2**

All values in million dollars

5. CASM Recommended Plan

To maximize the benefits of ASO to Colorado water management stakeholders, it is recommended to phase in a fully operational, statewide CASM program. When operating at full capacity, the program will provide an extensive time series of detailed snowpack measurements and improved streamflow forecasting for all normally snow-covered areas of the Colorado. This fully operational program is estimated to cost between $6-$13M per year and could include up to 100 snowpack measurement flights. Following stakeholder guidance, we recommend that this program be implemented under and governed by the CWCB, with funding achieved through state/federal partnership.

From conversations with state representatives who manage similar programs (CA-DWR, CWCB), it is important to know how big CASM will be at full build-out, and how long it will take to achieve this vision. Below is a roadmap that lays out key activities associated with future years of program development.

5.1. CASM Program Development Roadmap

There are several different activities that are part of a growing CASM program that will happen in parallel and are related to different aspects of the overall program vision (Section 1.1). The graphic below outlines the different aspects of how we expect CASM to grow. There are different activities that correspond to the advancement of each aspect of the CASM vision while the program grows. In general, CASM will evolve over a series of milestone years:

- **Phase 1 (2022):**
    - Initial demonstration of forecast improvement and utility of ASO products

  - Local funding matched with grant funding, expand airborne lidar data access across CO, develop case studies to study and demonstrate value, work with State to coordinate
- **Case Study Building (2023):**
  - Continued improvement of forecast accuracy and more wide use among stakeholders
  - Pooled funding, formal State-led process, 2+ flights per year in key headwater basins
- **Widespread Adoption (Next 5 years):**
  - Robust streamflow forecast product and use of ASO data each year
  - Some federal funding, Lower Basin involvement, 2+ flights per year in all high elevation basins, adoption of airborne-lidar-improved forecasts statewide
- **Program Buildout (Within 10 years):**
  - Integral part of Colorado and west-wide water management decision-making processes.
  - Mostly federally funded, well-managed, integration into decision-making statewide

Logistically, it would be difficult for ASO Inc to scale up their operations within a single year to handle a fully developed program, in large part due to the risks incurred by scaling to support a program with annually- granted funding as opposed to a sustained program. As of this writing, ASO Inc. operates two aircraft across Colorado and California to conduct their snow surveys. The optimal time for most flights is late March to early April, on or around peak SWE, with late April/early May being of close secondary importance. In a fully built-out program, as many as 10 snow surveys could be requested within a few days of each other. ASO Inc. plans expansion to outfit more aircraft to respond to demand, but there are lead time considerations with hardware procurement as well as the risk considerations of operating without a sustained program pathway. To ensure program equity, we will share results, check in regularly with stakeholders and ensure stakeholder engagement before promoting growth in a particular area. Figure 22 shows a CASM program roadmap including activities over time corresponding to each component of the CASM vision.

5.2. Program Costs

Table 9 shows the estimated program cost during each phase of growth. These costs are approximate and are subject to changes due to program direction, fuel costs and other factors. Program costs include:

- Snowpack measurement flights at around $120,000-$150,000 per flight
- Snow-Free flight costs at around $44/sqkm, with 66,000 sqkm remaining to fly
- Regular annual support activities including streamflow forecasting and stakeholder coordination
- Staff Support for 2 FTEs at $100,000 annual salary

Table 9. Estimated CASM Program Costs (All values in million dollars)

Phase	Timeline	Flights Per Year	Snow Survey Flight Cost	Snow-Free Flight Cost	Support Activities	Staff Support (2 FTEs)	Total Annual Cost
"Phase 1"	2022	14; Basins Flown in 2022	**1.3**	**1.0**	**0.3**	**N/A**	**2.6**
Case Study Building	2023	30; 2 Flights in All Prepped Basins	**3.6**	**2.0**	**0.5**	**0.2**	**6.3**
Widespread Adoption	2024-2026	64; 3 Flights in All Prepped Basins	**7.7**	**0.2**	**0.5**	**0.2**	**8.6**
Program Buildout	2026-2028	214; 6 Flights Across All Major Headwaters	**25.7**	**0.2**	**0.5**	**0.2**	**26.6**

The flight estimates in this table are based on assumed program growth. Due to increased demand by California stakeholders, the CA-DWR ARSS program plans around 6-8 flights per year in each basin.

	Water Management	Snow Science	Funding	Governance	Ongoing Activities
2022 "Phase 1"	• Experimental streamflow forecasts integrating ASO data • Capture specific application case studies	• Forecast integration pilot development • High density flight pilot development • Further snow-free area prep	• Local agency match • Water Plan Grant • Understand local/state/federal interrelationship and funding sources	• Help the CWCB take over program management and coordination • Test of the flight planning coordination	• Continuous stakeholder engagement & state partners • Streamflow forecast improvements • Continuous incorporation of data into CBRFC/NRCS • Engage with Upper/Lower basin partners so ASO can be linked to CRB goals
2023 "Case Study Building"	• Forecast product improvement • Adoption by broader stakeholder group • Economic case studies	• Clearly establish pilot basins with multiple flights • 2 flights per year in all other basins unless better funded • Complete all snow-free prep	• Fund pooling from state and local partners • State-level exploratory funding	• Formal adoption of the program by CWCB • Formal state-led facilitation process for flight planning	
5 Years "Widespread Adoption"	• Regional forecasting efforts (NRCS/CBRFC) are improved using ASO data • Regular use by stakeholders	• Widespread snow surveys • Multiple years completed of high-density pilot basins • 2 flights per year in all high elevation basins • Well understood program to offset flight emissions	• State-level permanent funding • Identify and engage with a Federal partner (USBR) • Funding coordination and payment	• Multiple committees established (e.g. flight planning, data management) • CWCB well organized around managing program	
10 Years "Program Buildout"	• ASO data is integrated with regional forecasting efforts (NRCS/CBRFC) • Published article(s) demonstrating forecast improvement	• ASO Inc – expansion of number of planes • Determine truly "necessary frequency" of flights • Climate change tracking of snow characteristics	• Federal match for state funding • Lower basin states contributing • Sustainable funding established, local partners contributing in-kind not funding	• Widespread advocacy by the CWCB • Replication into other states throughout CRB	

Figure 22. CASM Program Development Roadmap

5.3. CASM Vision 1: Water Management Improvement

CASM Vision 1 - Water Management and Decision-Support Applications *"Through the delivery of highly accurate measurements and improved water supply forecast reliability, local and regional water managers will be empowered to make better short term (annual) and long term (decadal) decisions. These improvements will be measurable."*
CASM Recommendation: Advancement of applied snow science and streamflow forecasting to improve water management decisions should be the primary objective of this program, with operational flights providing data to support this goal.

While the overall mission of CASM is to improve water management across Colorado through delivery of high-resolution data from ASO, this program is driven by both applied research and operational goals. The full implementation of CASM will advance water resources decision making across the state through several key activities:

- Streamflow forecast improvement
- Scientific Pilot Basin Program
- Demonstration of economic benefits

5.3.1. Forecast Improvement

From the stakeholder survey conducted in this project, 74% (54 of 73 respondents) saw the benefit of ASO as improving their confidence in seasonal runoff forecasts. Through interviews and other engagement sessions, it is clear that improving runoff forecasts is the primary method by which CASM will improve water management decision making across Colorado. As of 2022, the WRF-Hydro system streamflow forecasting model run by NCAR is the only streamflow forecast product currently operationally assimilating ASO data and providing improved forecasts as a result. CASM will continue to assess the best tool and approach for delivering an improved streamflow forecast using ASO data. The 2022 Water Plan Grant activities also include a forecast retrospective effort to assess the performance of different assimilation and forecasting methods.

"ASO provides invaluable information that is not otherwise available, most importantly information about the rate of melt that provides a real opportunity to optimize reservoir operations for water supply, flood control, and instream requirements."

Steve Haugen, Watermaster, Kings River Water Association

Water providers are often required to use an official forecast from CBRFC, NRCS, Colorado DWR and other sources, even if more accurate tools exist. Due to these legal requirements, it is CASM's recommendation to work towards data assimilation efforts to improve these official forecasts using ASO data. ASO, Inc. participates in ongoing projects with these entities to improve their ability to use ASO data effectively.

In addition to the streamflow forecasts issued by various official agencies, CASM stakeholders also rely on station-based snow depth, snow covered area and other primary data sources to make informed decisions. The scientific mission of CASM should improve local understanding around the accuracy of these products (e.g. when a SNOTEL site reads 100% of historical average, what does that mean in terms of actual basin SWE content or expected runoff?).

One potential pitfall to avoid is the direct insertion of ASO data into official model forecasts without model recalibration or a more robust data assimilation method. It is relatively straightforward to add ASO data into these models, but these data do not always lead to immediate model performance gains as the historic calibrations compensate for the lack of accurate snowpack knowledge. Many of these models are calibrated on historical conditions from existing datasets like snow covered area and SNOTEL stations and implicitly contain biases from these sources. Any data assimilation effort will likely require model re-calibration or a bias quantification effort to maximize forecast improvement. It will likely take many years of ASO data throughout Colorado to properly calibrate many existing streamflow forecasting models, which emphasizes the importance of expanding flight coverage as soon as possible and as consistently as possible.

In California in Water Year 2022, 31 surveys were conducted across nine river basins. There is an ongoing drought in California and high uncertainty in conventional snowpack estimates throughout the state. ASO Flights in early February caused basin-level SWE estimates to be reduced by 30-50% after ASO flights were conducted (Deems 2022). Without the ASO measurements, water managers may have made dramatically different decisions around reservoir releases and water use planning.

5.3.2. Scientific Pilot Basin Program

The stakeholder engagement process has included conversations with California DWR and USBR who both participate in a regular airborne lidar snowpack measurement program (ARSS) in California. Through their experience, it was determined that there is significant added value by having a few basins with concentrated flights (multiple times per year, every year). The data from these flights will then be used to develop a more detailed understanding of Colorado basin-scale snowpack dynamics at various times during late winter, spring, and early summer. This scientific pilot will augment any widespread rollout of ASO flights across Colorado and will meet the following Goals and Objectives:

Goals:

- Collect sufficient data to guide the optimization of flight planning in Colorado, both now and in the future.
- Support stakeholder understanding and application of ASO and track how needs change (by year types) with experience.
- Improve body of knowledge around Colorado snowpack including runoff forecasting, seasonal variability and changing hydrologic conditions (land cover change, dust on snow, change in snowmelt timing)

Objectives:

- Build on past flights and already gathered data
- Gather data in geographically diverse regions for several consecutive years
- Provide watershed stakeholders with regular data for improved decision-making
- Improve forecast and hydrology models with accurate watershed-scale data
- Quantify additional water available annual based on increased amount of data
- Provide runoff forecasting groups (CBRFC/NRCS/Others) with high resolution data improve their snowpack and runoff models.

This Scientific Pilot Basin program will include several key tasks:

Task 1. Identify ideal basins for pilot: We propose the selection of at least 2 basins to have ASO measurements conducted on a regular basis. Any basin chosen for multi-year measurement should meet several criteria to ensure the data provides the most value to stakeholders as well as the proposed scientific inquiries:

- Highly Productive (High runoff and snowfall)
- Multi-stakeholder or above key reservoirs
- Existing Ground-Based Measurement Networks (SNOTEL, Snow Courses)

- Geographically Diverse (Basins in multiple parts of the state)

Task 2. Identify optimal flight timing for key scientific questions

Once pilot basins have been identified, we propose the following timing of flights. While we recommend 6 flights at the outset, we understand that wet or dry conditions in future years may justify more or fewer flights. These flights should include this timing at a minimum:

- 1 flight each month from Late Winter/Early Spring
- Flights ever 2 weeks from March through May during runoff season
- 1 flight each month Late Spring/Summer as necessary

Task 3. Conduct flights and produce data

Once this program is well-established within CASM, it should include flights in each year, as well as the necessary scientific support to approach the research questions.

5.3.3. Assessing the Economic Benefits of Improved Data

The effective use of ASO data includes an understanding on the part of stakeholders of the economic benefits of improved forecasts. Many Colorado water management stakeholders have developed their operational programs based on measurement and forecast products that include high uncertainty. It is often a case that "they don't know what they don't know" with regards to how systems can be improved through the high-resolution data from ASO flights.

CASM recommends a detailed economic analysis of the potential benefits to further justify the program and to educate stakeholders on the impacts of improved decision making. Economic assessments of the benefits of ASO can take place as more flights are conducted in Colorado and results are adopted for operational activities.

5.3.4. Annual Data Workshops

It will be important to continue an annual dialogue amongst all water stakeholder groups in Colorado on different ways that ASO data is being used and can potentially be used amongst different water sectors. Regular annual workshops that allow water stakeholders to share information and learn from each other will be vital to the success of CASM. CASM believes that ASO flight data should be available as broadly as possible to the water community, and it will take consistent and sustained communication to achieve that goal.

5.4. CASM Vision 2: Hydroclimate Science and Snow Measurements

CASM Vision 2 - Hydroclimate Science *"A fully developed ASO program will have accurate snowpack measurements and improved water supply forecasts across the high-elevation, snow-covered areas of Colorado."*
CASM Recommendation: Program buildout is around 230 flights per year across all the major headwaters of Colorado. at a cost of approximately $26M per year. This is an eventual goal that will take several years to achieve due to logistical constraints, so the program should grow over a 3-5 year period.

A fully funded CASM program will support snowpack measurement surveys, snow-free lidar flights and data preparation, streamflow forecast improvement, and additional research activities to improve the understanding of Colorado's snowpack on behalf of water managers throughout the state and interstate basins.

CASM recommends the growth of this program building to the goal of 6-8 ASO flights per year across all snow-covered of Colorado from mid-winter, capturing peak SWE, and through melt out. Depending on year type, this is around 100 flights per year. This program vision – drawing predominantly from the long program experience in California – is anticipated to be phased in over a 3-to-5-year period, allowing time for refinement of the ultimate program details with input and experience from Colorado stakeholders to tailor the program to individual basin and operator needs.

Due to the high expense of ASO flights, it is important to balance the number of flights with statistical and hydrologic modeling methods that may provide very similar snowpack estimates once enough flights have been conducted. There are multiple research efforts at the US Bureau of Reclamation and NASA to understand how many flights are required to inform statistical models that can produce a snowpack estimate that is within a few percent of an ASO measurement, using only lower cost, ground-based measurements. As more flights are conducted, these statistical relationships will be improved, and less flights may be necessary to attain a similar level of accuracy.

While the bulk of the expense of CASM is in the operational snowpack measurement flights conducted by ASO, Inc., this program has a diverse and well-informed stakeholder group that will require regular engagement. To maximize the value of this program, there should be an ongoing applied research component of CASM tasked with improving streamflow forecasts and engaging stakeholders on the use of ASO data and the continued refinement of the program.

5.4.1. Flight Plans and Basin Prioritization

Annual ASO flight planning requires several activities, identification of key headwater basins, snow-free data preparation (for new basins), and the operational snowpack measurement flights themselves.

In technical terms, ASO Inc. refers to a “snow survey” as a complete measurement of the snow water equivalent and snow albedo across a particular basin. For larger basins a single snow survey can require multiple flights. For costing purposes, we have based everything on flight costs. A single ASO flight can cover around 3,500 sqkm (1351 sqmi). The process to choose timing and geography of snow surveys each year is based on several factors:

- **Basin readiness;** whether snow-free coverage is completed and forecast models are prepared
- **Equity;** are there multiple stakeholders who will benefit from the data collected?
- **Funding;** is there a specific stakeholder willing to pay for a flight; is there budget in the program to cover the flights?
- **Coverage;** Does the proposed flight path cover a basin with a specific USGS gage, forecast point, or management point/diversion at its outlet?
- **Timing;** Is there a specific forecast timing or scientific goal that will be achieved by a flight at on or before a set date?

5.4.2. Snow-Free Data Preparation

Acquisition and processing of snow-free lidar data is essential for establishing a watershed baseline that is necessary to fly snow measurement flights in future years. Before aerial lidar snowpack measurements can be conducted for any basin, that basin must have a set of snow-free data that meets ASO’s quality standards. Lidar data from other mapping programs like USGS 3DEP may be sufficient, but ASO experience to-date suggests that in most cases a dedicated snow-free survey is required. These snow-free flights (or possibly 3DEP data processing) are an integral part of the overall program, and can be re-flown to capture impacts of watershed disturbance e.g. from wildfires.

Based on the CASM buildout plan outlined below, there is around 110,000 sqkm of total area statewide that will be developed for snow surveys. After the activities of the 2022 Water Plan Grant, approximately 50,000 sqkm will be completed, leaving 60,000 sqkm of additional snow-free activities for future years.

5.4.3. CASM Buildout

Full program buildout can be thought of as multiple snow surveys per year across all high elevation, snow-covered areas of Colorado. Under a built-out program, there are several activities that will happen each year:

- 6-8 snow surveys above every major headwater basin with a stream gage
- More regular flights in key "scientific pilot" basin each year
- ASO-informed streamflow forecasts for every flown basin.
- Regular improvement and updates in snow-free data as necessary
- Ongoing stakeholder engagement and use of this data by all stakeholders.

The CASM team has approached program planning as objectively as possible; we want to avoid proposing a massive program if extra flights will not add useful incremental information. However, the ASO data are novel and different than existing products or snowpack indices, and experience in California suggests that once operators and decision-makers have several years of experience using ASO data, they gain a greater facility with its use and impact. Thus a "learning-curve' of stakeholder adoption is anticipated. Stakeholder feedback will help fine tune the final set of proposed flights.

Figure 23 shows the extent of snow-free coverage and remaining areas that must be developed to reach buildout. The gray boundaries behind the basins show the April 1st and May 1st median snow-covered area. CASM buildout includes flights covering nearly all these areas, with areas left out when there is not a specific stream gage where an improved forecast can be conducted.

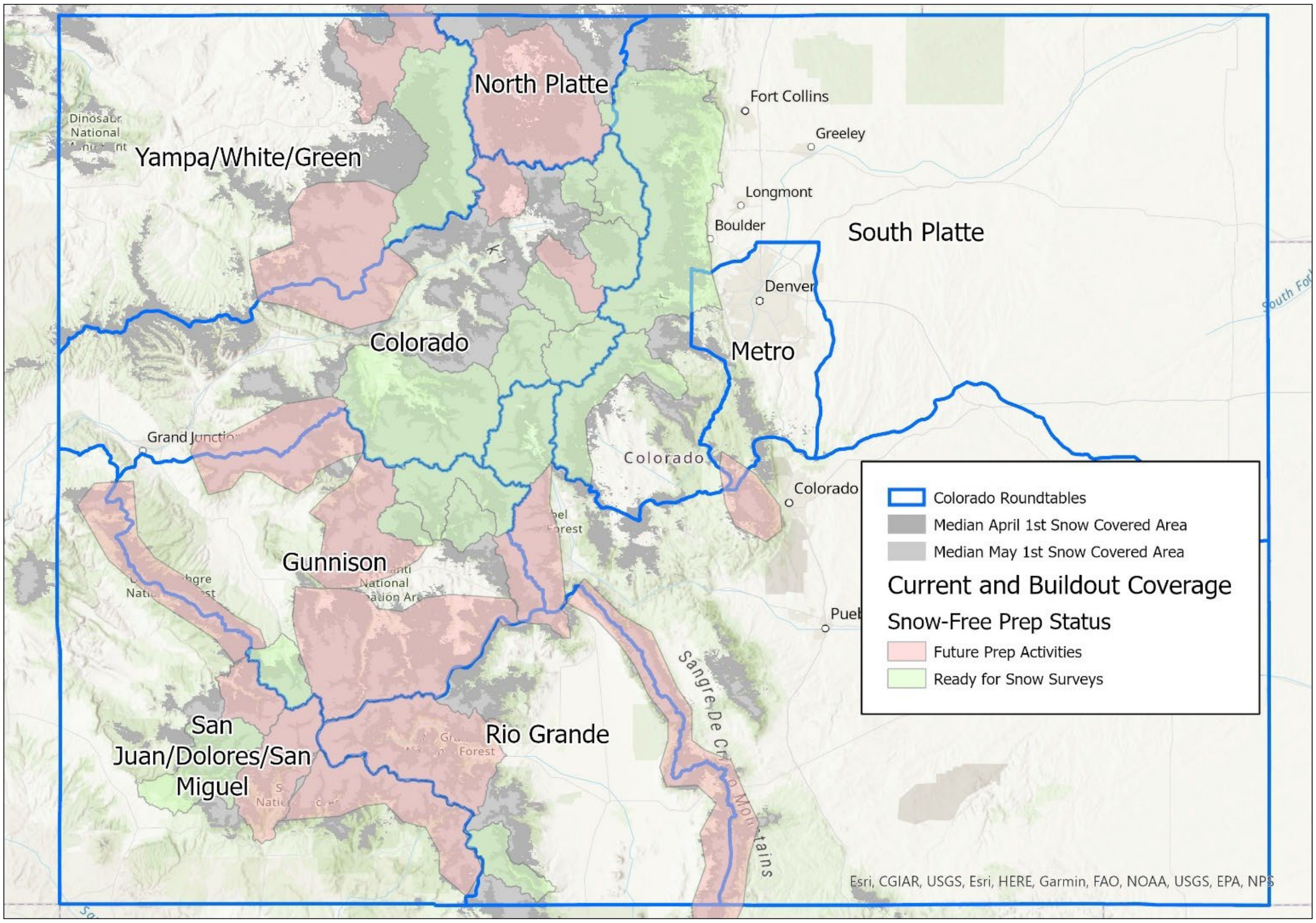

Figure 23. Potential CASM Buildout Coverage Map

There are several things that must happen to achieve program buildout including the development of snow-free data for the entire state, deployment of streamflow forecast models in all basins with flights, and the growth of ASO, Inc's fleet to allow for sufficient concurrent flights. As CASM expands each year, there will be regular assessment and stakeholder engagement to ensure that basins being flown have a specific forecast use case. The benefits of improved ASO data are widespread, but we want the program to grow in coordination with the development of stakeholder capacity.

5.5. CASM Vision 3: Funding Plan

CASM Vision 3 - Funding *"While local stakeholders should demonstrate interest and engagement through match funding, especially as the program develops, ultimately a sustainable program will require consistent state and/or federal funding."*
CASM Recommendation: Build on existing local partnerships, but work towards a larger percentage of the program coming from established state and federal funding sources. Funding should come from as few sources as possible and should be administered by the CWCB.

The financial goal of CASM is to have the entire program funded through a consistent state and/or federal appropriation. While funding cycles are highly variable, we recognize that cost can be prohibitive to local stakeholders if sustainable funding from a state or federal agency is not secured. Further, the maximum program value can be achieved only with a sustained program – individual, annual, "project-funded" implementations do not provide the dependable data resource required by forecasters and water managers.

We expect that the funding structure for CASM will change over time as more stakeholders use the data and as state and federal agencies become involved. In 2022, around 30% of CASM funding was from agencies local to Colorado who paid for one or more snow surveys for their own use. This local funding allowed for significant funding match enabling State Water Plan Grant funding.

It is necessary that any funding plan for CASM include flexibility to pay for an average number of flights across several years. It was strongly recommended by CA-DWR that an effective CASM program should have the flexibility to conduct as many or as few flights as they deem necessary each year and carry over any excess funding to future years.

As shown in the program development roadmap (Figure 22), multiple funding sources will likely be leveraged to promote CASM over the next several years as more secure funding is sought.

5.5.1. Program Cost

As CASM grows, there are several categories of activity that will need to be funded to support the program: basin preparation, operational flights, forecasting and scientific support. A critical aspect of this plan that needs to be considered carefully is the staff support time required by CWCB staff, and what tasks should be completed by contractors.

The next few years could require $6-10M in funding per year for this program to be effective with a projected program buildout of around $25M per year. Buildout will allow for 6 snow surveys per year (and supporting activities) as well as all supporting activities. This will include coverage for 110,000 sqkm representing more than 75% of all typically snow-covered area at peak SWE. For comparison, in 2022 the California ARSS program will conduct 31 snow surveys, at an annual cost of $9.5 M, in nine headwater basins. Figure 20 shows the flight coverage and timing for ARSS 2022 activities.

While the buildout of the CASM program could enable over 200 flights per year, there are several reasons it is necessary that this program grows deliberately. Over the next few years, we expect improvements in forecast products, data applications, and flight capacity of ASO Inc. A deliberate and planned phased approach over several years will allow CASM to work out any programmatic kinks and respond to stakeholder needs in each year.

5.5.1.1. Snow Surveys

Operational flights are the largest recurring cost in the CASM program. In the 2022 Water Plan Grant, $1,325,860 was budgeted for 14 snow surveys, for a unit cost of ~$95,000 per flight. At program buildout, we estimate the cost per survey to be between $100,000 and $150,000. This unit cost is affected by several competing factors:

- **More powerful aircraft;** high altitude, broader coverage
- **Fuel cost;** market increases
- **Aircraft upgrades;** may need to be rolled into the flight cost
- **Basin area**; variable based on snow coverage and basin size

5.5.1.2. Snow-Free Data Preparation

Pending the successful completion of all 2022 Water Plan Grant activities, around 30% of the typical peak SWE snow-covered area of Colorado will be prepared for future flights. Total coverage will continue to grow through future activities.

Table 10 shows the remaining cost of snow free data preparation statewide after 2022 activities have been completed. Based on the proposed buildout map, we estimate it will take $3 million to complete snow free coverage for all areas statewide that may get ASO snow surveys. Additionally, basin geography and land cover changes often enough that money should be allocated to re-survey snow-free basins. We expect that as the program grows, it will be necessary to conduct new snow free flights for about 1.5 basins per year on average.

Table 10. Estimated cost of Statewide Snow-Free Data Preparation

Snow Free Acquisition Method	Unit cost (2022 Estimate)	Estimate of Cost of Snow Free Acquisition Statewide
Summertime Snow-Free LiDAR Flights Conducted by ASO Inc.	$44/sqkm, (66,000 sqkm remaining after 2022)	$ 3,000,000
Annual "Maintenance" Flights	$44/sqkm (5,250 sqkm per year or about 1.5 basins per year)	$ 250,000

5.5.1.3. Support Activities

Streamflow forecasts produced as part of the 2022 Water Plan Grant will use the WRF-Hydro model, at a total cost $135,000 for multiple flights across 6 different basins. This cost includes setting up several basins for the first time. Whether WRF-Hydro remains the tool of choice or not, it is likely that the cost to produce forecasts at program buildout will benefit from economies of scale.

5.5.1.4. CWCB Staff

In addition to the operational activities, there are several administrative roles that must be included in any larger program budget. These roles include program administration at the State level, flight coordination and planning, data delivery, and model integration. The California ARSS Program includes funding for roles within DWR to promote the program. For the sake of rough budgeting, we estimate 2 Full-Time Employees at $100,000 per year for this support work. While much of this remains to be defined, we recommend CWCB staff to fill the following roles in managing a fully built-out CASM program:

- Program Management and Advocacy: 0.5 FTE
- Flight Planning and Coordination: 0.5 FTE
- Data Management and Hydrologic Science Improvement: 1 FTE

5.5.2. Roles of Partner Agencies

For funding, support will likely be required at several different levels. In the program review of ARSS, CA-DWR staff (Section 4.3) cautioned against using too many funding sources. In 2022, ARSS uses many different funding sources to pay for the program, which adds a huge amount of administrative inefficiency. While the ideal CASM funding structure would be from only a few sources, it may be necessary to fund the program on an interim basis from a combination of local, state, and federal sources.

Local Partners

For the 2022 grant application, several agencies independently funded flights that allowed for matching funding from the State of Colorado. These agencies were Northern Water Conservancy District, Denver Water, the US Geological Survey, Lawrence Berkeley National Laboratory, and the St. Vrain & Left Hand Water Conservancy District. Each of these local partners had specific identified uses for ASO data within their respective programs. This is a synergistic relationship since funding by these partners can be used to demonstrate to larger agencies the local value of ASO data. Additionally, a program with direct stakeholder involvement will be more successful since these agencies have an incentive to stay involved.

During the stakeholder engagement process, respondents were asked, without commitments, what level of funding their agency would be willing to contribute. Figure 18 shows the breakdown of these results. The estimated potential funding from the local CASM stakeholder entities was between $300,000-$500,000 with nearly 70% being unsure or unable to commit funding. Given that these survey respondents are some of the groups most interested in the growth of CASM, funding from local stakeholders alone will be insufficient to fund the fully built-out program. However, local funding is still useful and necessary to foster engagement and match funds from state and federal programs. In many cases, state or federal grant-funding sources require a demonstrated local match to provide operational funding.

There are different options for how to include local stakeholder funding in a growing CASM program. Groups with a specific use case for the data may pay for flights themselves and get priority in flight timing and location. Alternatively, the CWCB could administer a fund like the California Cooperative Snow Surveys Program where all interested agencies can contribute some small amount of funding that will go towards a larger pool for program execution.

State of Colorado

Since CASM is specific to Colorado, there is an obvious role for state agencies to participate. CASM aligns with the goals of the Colorado Water Plan, so the CWCB would naturally play a central role in securing and administering funding in addition to its role in overseeing program administration. Similarly, the California ARSS Program (Section 4.3) is primarily funded and managed by the California DWR.

A fully developed CASM program will help manage and optimize water supplies in Colorado and as a result, all downstream states. There are also several federal water projects within Colorado that would benefit from ASO data and improved forecasting. The NRCS and CBRFC have expressed interest in using ASO flight data to improve their forecast models. ASO measurements and associated forecasts will also be used to help Colorado and the Upper Colorado River Basin states comply with the Colorado River Compact. This relevance suggests both the importance of the CASM program to Colorado's interstate interests, and the potential for important funding contributions by neighboring state agencies.

At the state level, ASO has been funded before. Table 4 lists several previous spending bills passed by the Colorado legislature where the "Water Forecasting Partnership Project" for the CWCB has been funded with similar language (this is from SB 16-174)

> *"The Colorado water conservation board may use this appropriation to support the development of new ground and aerial remote sensing data and equipment and hydrologic modeling, to provide reliable volumetric water supply forecasting."*

Table 11. Previous Funding from the Colorado Legislature for Related Activities

State Fiscal Year	Bill ID	Funded Amount
FY 2016-17	Senate Bill 16-174	$300,000
FY 2017-18	House Bill 17-1248	$800,000
FY 2018-19	Senate Bill 18-218	$800,000
FY 2020-21	House Bill 20-1403	$350,000

This funding has been used for a range of activities including ASO flights, WRF-Hydro forecasting, and other forecast improvement activities. The program recommended as part of CASM aligns with these goals and we recommend further funding using this legislative approach.

Federal Funding

Given the current involvement of federal agencies and the broad impacts of this project, the CASM planning team agrees with the expressed stakeholder opinion that it is appropriate for CASM to be funded at least as a state/federal partnership, if not as a fully federally funded program. The federal budgeting process is complex and will require careful navigation for CASM to achieve its desired funding levels. It is beyond the scope of this report to describe the details of every available federal funding source except to say it is a CASM priority to find a large, consistent federal source of funds if CASM is to grow to a full-buildout condition.

For the 2022 Water Plan Grant activities, the USGS and US DOE (through Lawrence Berkeley National Lab) are both funding flights that were used to obtain funding match. The USDOE has paid for flights since 2016 in support of their East River Watershed Function Scientific Focus Area, for science support. Similarly, the USGS provided funding in 2022 toto support their Next Generation Water Observing System activities in the Fraser River basin. Also, NASA has previously funded flights via the Terrestrial Hydrology Program in the Uncompahgre River basin and over the Grand Mesa.

One potential funding source option is the Congressional Spending Bill that led to the development of the referenced "Emerging Technologies in Snow Monitoring" (USBR 2022). Specifically, that report is part of the recently authorized Snow Water Supply Forecasting Program (P.L. 260-116, Sec. 1111). Section 1111(g)

> *AUTHORIZATION OF APPROPRIATIONS.—There is authorized to be appropriated to the Secretary to carry out this Act $15,000,000, in the aggregate, for fiscal years 2022 through 2026.*

This program, aimed at supporting Reclamation and partner agency needs throughout the western US, is in its initial rollout stages, but offers an important cost-sharing opportunity for Colorado for the next 5 years.

Lower Colorado River Basin Funding Support

Conducting ASO flights throughout the Upper Colorado River Basin will have large benefit for the Lower Colorado River Basin as well, there is potential for a funding partnership whereby the Lower Basin States contribute annual funding to the CASM program. This would be similar to how weather modification flights are currently funded in the Upper Basin.

5.5.3. Other Funding Considerations

Beyond the funding sources themselves, there are several key funding issues that must be addressed for the CASM program to function effectively year to year:

Single Contractor: As of 2022, ASO, Inc., the developer of this technology and application, is the only organization providing the combination of airborne lidar and spectrometer snow depth, SWE, and snow albedo data products along with rapid processing that meets the needs of the CASM program and other managers of snowmelt systems. Unless another company offers this service and can demonstrate a similar accuracy, timeliness, and product suite, ASO Inc. will be the sole provider of snow surveys for CASM for the foreseeable future. ASO Inc has been integrally involved in the development of CASM and has made good faith efforts to provide their services at a reasonable cost. ASO Inc has stated that snow survey data for these locations will be public for the foreseeable future – data availability policy is maintained by ASO, Inc. responsive to the mandates of the funding agencies. Any potential change in contractor will require careful thought on the part of CASM to ensure that all aspects of their program and costs as well as their capabilities are well understood.

Flights by Individual Agencies: Water providers that manage reservoirs and other large facilities may want to contract directly with ASO, Inc. to fund flights for their areas of interest. These large stakeholders may want a more direct relationship with ASO, Inc. in terms of data delivery and customization. Stakeholders that pay for their own flights will likely have specific flight timing and frequency requirements though they should consider their requests in line with the overall CASM goals. This situation exists already in both California and Colorado and has been managed effectively through collaborative planning and communication.

CWCB Staff: From the review of the CA ARSS program, CASM will require significant staff support by the CWCB to oversee its various aspects. The CA-ARSS program is currently requires 2.5 FTE staff to manage program coordination, logistics, water resources modeling, and program advocacy.

Fiscal Agency: In 2022, Northern Water generously offered to apply for a Colorado Water Plan grant and administer contracts with ASO, Inc. and other supporting companies. In the long term, it makes more sense for the CWCB to take over financial management of this program, especially if this program is to remain equitable. The California ARSS Program accesses funding from many different sources including CA-DWR, the California Snow Survey Program, FEMA, and others. This has led to administrative challenges in running the program. A single fiscal agent with only a few sources of funding will help CASM be more efficient and effective.

5.6. CASM Vision 4: Program Administration Recommendations

CASM Vision 4 – Program Administration and Structure *"To be both effective and equitable, CASM should be managed by the CWCB and local stakeholders should be involved in the decision-making process on flight timing and location."*
CASM Recommendation: Implement several subcommittees to manage different aspects of this program.

For the CASM Program to be effective, all activities should be managed by appropriate subcommittees. There are several different independent components of a built-out CASM program that will require well-defined roles. Like CA-DWR's ARSS program, CASM proposes a series of subcommittees that will manage different activities including:

- Decision-Support and Forecasting Stakeholder Engagement
- Flight Planning and Logistics
- Program Funding, Advocacy, and Outreach
- Research Integrations

Each subcommittee is likely to require some level of paid CWCB staff involvement to manage properly. For a similar committee structure, CA-DWR required 2.5 Full-Time Employee (FTE) equivalent to oversee and run all aspects of the program. Some of the work can be managed through 3rd party contractors. This proposed organizational structure is shown in Figure 24. Figure 25 below outlines the roles and responsibilities of each subcommittee. In 2022, the Flight Planning and Coordination Committee was piloted and led by the CWCB to facilitate discussion and decisions on flight timing and location.

Regardless of the recommendations made here, there are aspects of program management that have not been considered. The CWCB should further investigate the correct governance and administrative approach.

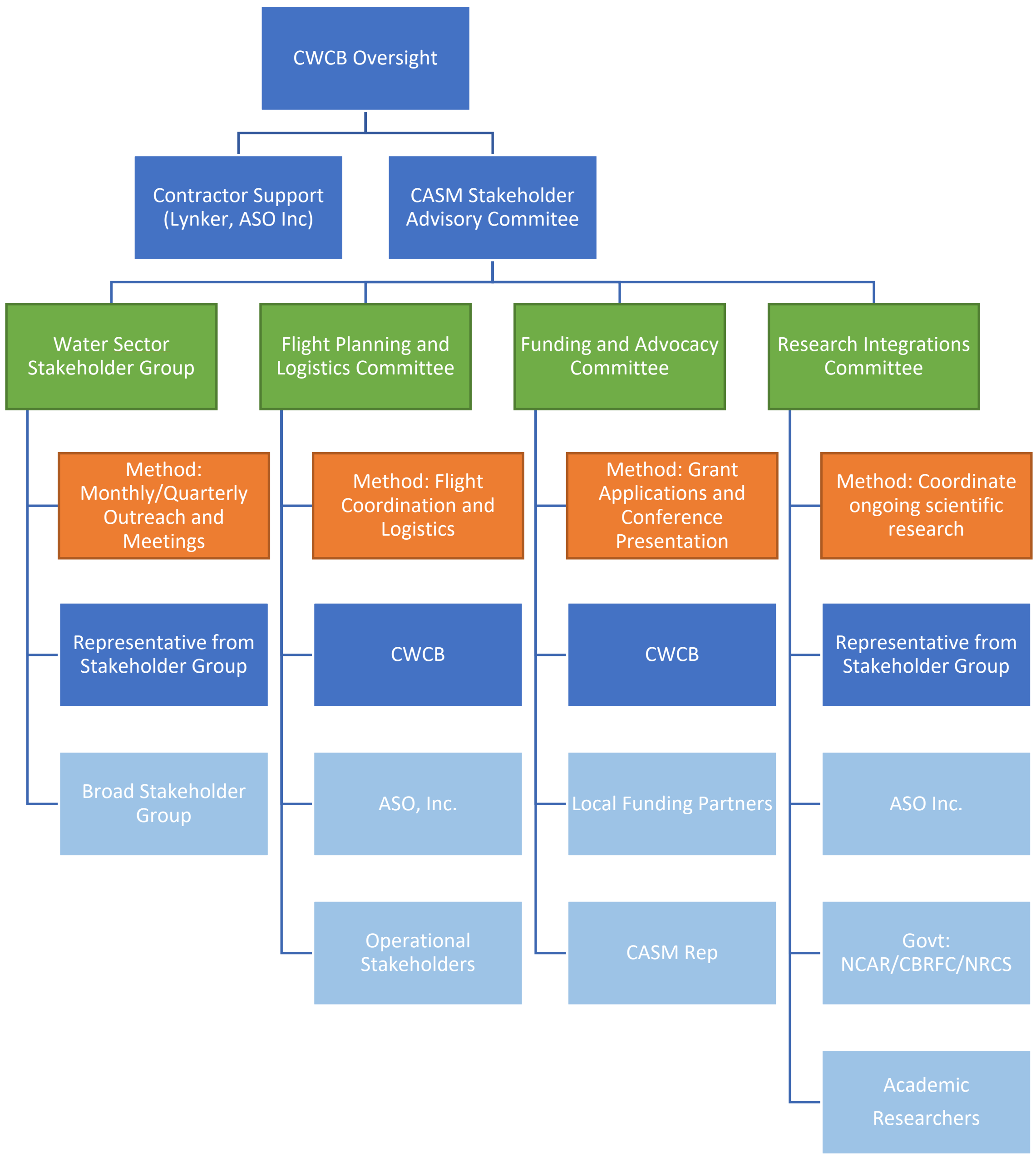

Figure 24. CASM Organizational Structure

Water Management Stakeholder Group — Chair: CASM Lead

- Responsibilities: Maintain engagement with the broad CASM stakeholder group
- Typical Activities: Monthly/Quarterly outreach and Meetings, Solicit feedback on how to improve program

Flight Planning and Logistics Committee — Chair: CWCB Representative

- Responsibilities: Coordinate flights year to year
- Typical Activities: Flight Planning Committee, Producing and sharing model results, Pre-planning flights for upcoming years

Funding and Advocacy Committee — Chair: CWCB Representative

- Responsibilities: Grant applications
- Typical Activities: Grant applications, Conference presentations

Research Integrations Committee — Chair: Stakeholder Representative

- Responsibilities: Coordinate ongoing scientific research
- Typical Activities: Select appropriate streamflow forecast models and locations, Coordinate CASM-related research efforts across agencies, academia and funding programs

Figure 25. CASM Committee Roles and Responsibilities

CASM data can help improve decision-making for stakeholders of all sizes, sectors and in all major river basins. For the CASM Program to be equitable, clear expectations need to be set around flight planning, stakeholder engagement and data availability. A few key tenets of an equitable program include:

- Publicly available data, including both snowpack measurements as well as streamflow forecasts
- Broad input on flight locations
- Proactively sharing and interpreting CASM program data and information will all water sectors and stakeholders
- Regular feedback on program performance
- Agreement on several key long-term study locations

5.6.1. Annual Activities

CASM is a program with a high degree of logistical complexity and will require planning, coordination, and secured funding up to a year in advance of snowpack measurements. Figure 26 below shows an example year, with a funding application requiring a 6-month lead time, and all the associated planning and operational activities.

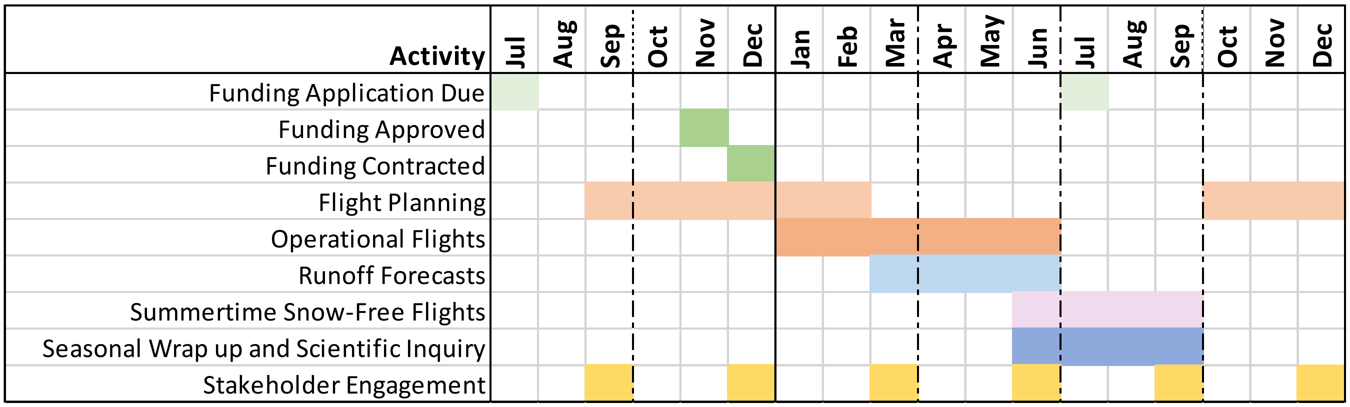

Figure 26. Example Schedule of Annual CASM Activities

Funding applications are highly variable and often require long lead times. For a multi-million-dollar funding request, a 6-12 month lead time from application to contracted funding is normal. Water Plan Grants from the CWCB, for example, require an application in July or December for eventual approval in October or March, with contracted funding in November or April, respectively. Further, for seasonal planning purposes, funding should be in place and contracted early in the Water Year (October/November) to allow for adequate program implementation and response to a variety of snow season evolutions.

Flight planning covers a range of activities including selection of target basins, review of basin readiness, preparation of forecast systems, stakeholder engagement, flight weather forecasting, and actual flight logistics. Basin readiness typically involves evaluating whether a basin has snow-free data of sufficient quality for airborne snow surveys. Forecast system preparation largely depends on the system in use, but this may take from a few days to a month depending on whether a basin to be flown has been forecasted before, or if the model needs calibration. Stakeholder engagement is critical since flights should be focused on areas with interested stakeholders downstream and timing to support decision-making. Final decisions on flight logistics are made by ASO, Inc. and typically includes flight timing, weather, aircraft, and instrument coordination.

Operational Flights to-date have taken place during melt season, beginning on or before peak SWE (April 1st or so) and ending a few weeks after all SNOTEL sites have melted out in a basin. At full program build-out, flights would begin at a monthly cadence in mid-winter, and continue at a bi-weekly interval from April 1st onwards. These operational flight are coordinated at the weekly flight coordination meeting where stakeholder needs are balanced with aircraft availability and weather.

Runoff Forecast Updates are produced as quickly as possible after each operational flight is completed. These continue through the operational flight season and provide direct value to stakeholders.

Seasonal Wrap Up and Scientific Inquiry: Once the operational flight season is complete, it is important to capture all lessons learned from both the flight planning logistics and the snow and forecast science aspects. This may include retrospective forecast comparisons, assessment of the impact of weather and soil moisture conditions on runoff efficiency, and other lines of inquiry. A formal program assessment should happen every year to maintain program effectiveness.

Stakeholder Engagement: The CASM team will engage regularly with the larger stakeholder group and will solicit input and feedback on all aspects of the process. Currently the CASM team conducts monthly meetings to describe the latest team activities, but at a minimum, quarterly webinars and updates are necessary to encourage involvement in all aspects of the CASM program, and to improve the breadth and depth of applications for the full community..

6. Conclusion

The CASM program came together in 2020 through a large collaborative effort across the public and private sectors. What began as a group of water managers interested in advancing the state of the science around snowpack measurement, grew into a program that is poised to be adopted by the State of Colorado. The grassroots approach we took involved careful data collection and interviews from a wide range of water interests.

The plan in this document outlines an approach to funding and implementing widespread aerial lidar snowpack surveys and improved streamflow forecasting that will benefit Colorado water managers statewide. A built-out CASM program has widespread water management and environmental benefits including:

- Improved streamflow forecasting and basin water balance
- Better-informed drought planning and reservoir operations
- Detailed understanding of Colorado's snowpack dynamics
- Quantitative understanding of the impacts of climate change on Colorado's water supply

There is great interest in programs like CASM at the federal level, since ASO snow surveys can help agencies like the USBR, USGS, NRCS, CBRFC and others manage their reservoirs and develop improved environmental management products. We expect CASM will grow organically as funding is available and more stakeholders understand the benefits and applications of the high-resolution snow surveys. The next few years will likely see CASM transition to state-led program management, widespread streamflow forecast improvement and measurable economic benefit for the water sector in Colorado.

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Additional Materials

7.1. ASO Case Studies

7.1.1. 2019 Dillon Reservoir ASO Success

Colorado had an unusual snow year in the spring of 2019. Several late- season storms brought peak snow water equivalent (SWE) well above average, resulting in higher-than-normal runoff in many of its river basins. 2019 was also the first year Denver Water piloted using ASO data to inform their operations.

Dillon Reservoir, located in Summit County, is Denver Water's largest reservoir. Snowpack that accumulates in the Blue River Basin flows into Dillon Reservoir and is the source of 30% of the water supply delivered to Denver and its surrounding suburbs.

ASO, Inc. conducted an airborne snow survey for Denver Water on April 19th, 2019 over the headwaters of the Blue River, aiming to capture peak SWE for the entire Dillon Reservoir watershed. Data from this flight confirmed unusually high snowpack and indicated a delayed melt. A second ASO flight on June 24th revealed that about 107,204 acre-feet of water remained in the snowpack above Dillon Reservoir. Several SNOTEL sites (Grizzly Peak, Hoosier Pass, Fremont Pass, and Copper Mountain), which sit around 11,000 feet, had already mostly melted out. The figure below shows that between the additional snowpack and Dillon Reservoir storage contents, there was more water stored as snow in the basin than the capacity of Dillon Reservoir, necessitating a significant release.

ASO is Critical to Reservoir Operations

- Above average snowpack in 2019 in Dillon Reservoir watershed caused higher than average inflows
- A June ASO flight indicated more remaining snowpack above Dillon Reservoir than it had room for, prompting a ramp up of outflows. This ramp up of outflows occurred earlier than otherwise would have without ASO data, thus preventing potential downstream flooding impacts
- Accurate knowledge of snowpack from the ASO flight allowed managers to avoid significant downstream impacts and keep the reservoir full

Too much outflow release or an overtopping of the reservoir spillway could result in flooding in the downstream town of Silverthorne. Conversely, had reservoir managers acted conservatively, they may have released more water than necessary to make space for the coming runoff, and Dillon Reservoir may not have filled. Because of the ASO flight, Denver Water managers knew that they needed to begin ramping up outflows earlier than normal and continue them for additional weeks to avoid a peak release that was higher than acceptable.

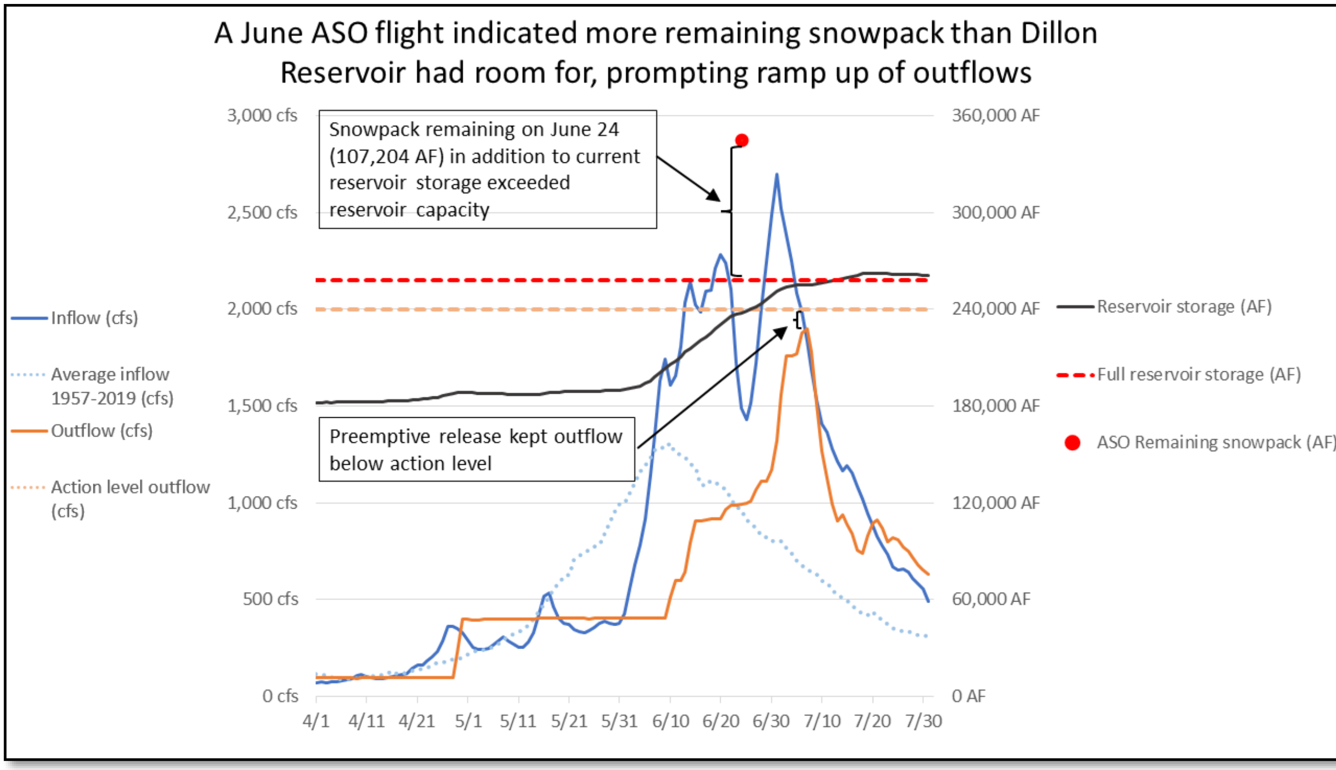


Figure 27. Dillon Reservoir operations in 2019.

If Denver Water had not conducted the June ASO flight and only relied on SNOTEL data, an unanticipated amount of snowmelt could have resulted in a large, unexpected reservoir release and significant negative impacts downstream. Alternatively, in the absence of ASO data, water managers may have chosen to be more conservative and draw down the reservoir farther than they would like to avoid this flooding issue. The ASO data allowed Denver Water to alter their operational plan, and thus optimize use of Dillon Reservoir, by continuing outflows longer than the forecast and hydrograph indicated to make room for the coming snowmelt and avoid downstream flooding. This also resulted in the runoff season ending continuing longer than the forecast and hydrograph indicated, thus ending with Dillon Reservoir as close to full as possible.

7.1.2. 2020 McPhee Reservoir Over-Forecast

Dolores Water Conservancy District (DWCD) manages the operations of McPhee Reservoir which furnishes irrigation water for Montezuma and Dolores counties. Many irrigators in the region rely solely on water from McPhee to water their fields. Each spring, DWCD releases predictions of the coming runoff season so that Dolores Project water users can anticipate water allocations and make financial commitments for fertilizer, seed, and other purchases before the growing season.

ASO Is Critical to Reservoir Operations

- In 2020, dry soil moisture, historic warm temperatures, and inaccurate SNOTEL models contributed to an overestimation of snowmelt runoff
- Given the promising forecast, overallocations were made to irrigators reliant on McPhee Reservoir water
- An ASO flight would have provided a more precise measurement of remaining runoff, thus avoiding economic consequences for irrigators

The Dolores River basin began 2020 with soil moisture below 50% of average. Snowstorms in late March 2020 brought snowpack up to 100% of the long-term average based on SNOTEL sites. Given the 100% April 1st snowpack and above-average carryover from McPhee Reservoir, water managers expected to have a full supply even with lower-than-expected inflows from the dry soil. Communications went out to irrigators on April 20th indicating a year with full allocations.

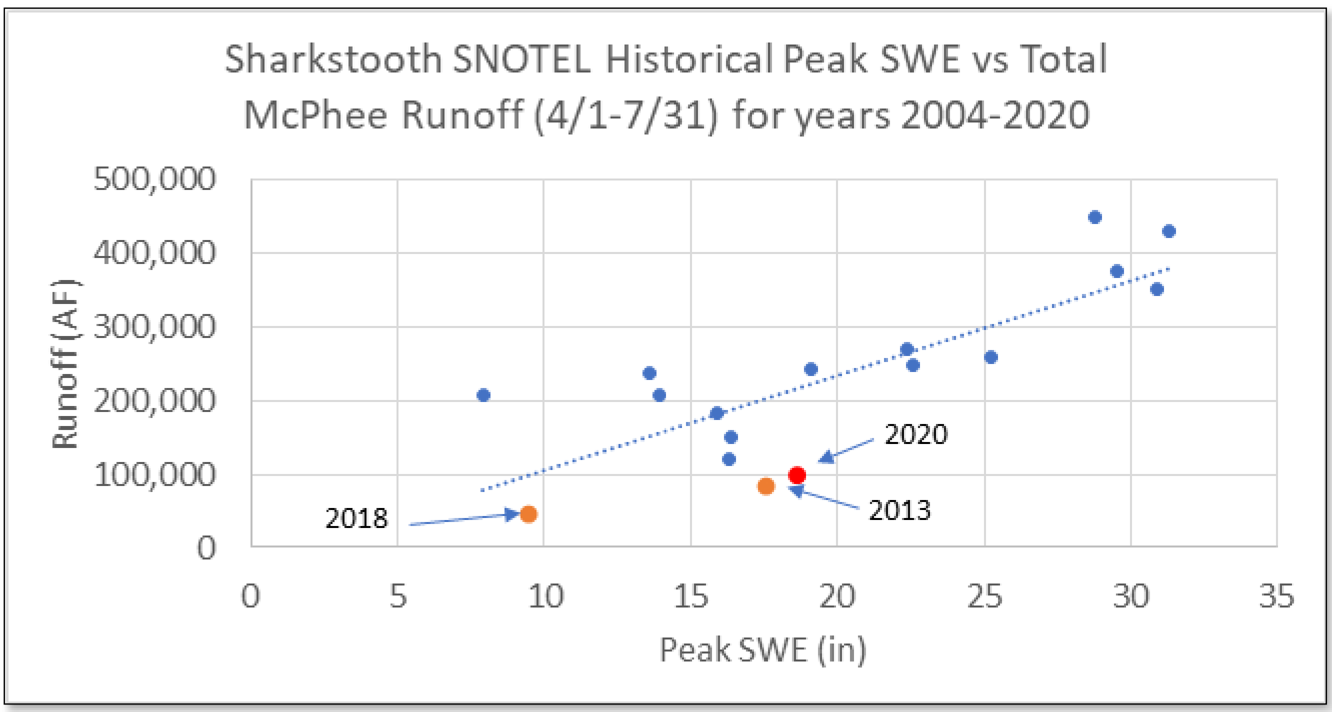


Figure 28. Historical peak SWE at Sharkstooth SNOTEL site vs total runoff into McPhee Reservoir (4/1-7/31) each year. Red dot is 2020. Historically dry years show SNOTEL peak SWE well below average total runoff.

April and May 2020 were windy and one of the driest and hottest springs on record. The combination of low soil moisture and historic warm weather meant that less snowpack was converted to runoff and made it into McPhee Reservoir. Factors contributing to this low runoff efficiency also included high elevation sublimation of the snowpack and increased evaporation and evapotranspiration from basin vegetation. DWCD managers also realized that SNOTEL measurements from the spring of 2020 did not accurately represent the lack of higher elevation snow, contributing to the early spring over-forecast.

Instead of the expected full supply, DWCD managers and irrigators ended up with 85% of the full supply. The early allocations from the April 1st forecast had both planning and financial consequences for Dolores Project water users. Wasted inputs, seed, fertilizer and application due to changed lower allocation from pre-season forecasts financially harmed project users that fund Project operations with less water sales. Dolores Project water users suffered economic damage when early models overestimated the amount of water based on SNOTEL sites and CBRFC forecasts.

As Southwest Colorado continues to face unprecedented drought conditions, a more accurate measurement of snowpack is necessary to optimize operations and minimize the financial impacts from situations like this. An ASO flight over the Dolores River Basin would have provided a more accurate picture of the snowpack above 11,000ft. A flight on April 1st around peak SWE would confirm the total water in the snowpack, allowing for managers to be more precise in their allocation estimations for the year. A second flight would have confirmed 2020 runoff efficiency given antecedent and current hydrologic conditions. More comprehensive data is critical to ensure accurate allocation forecasts are made so that the mistakes of 2020 are not repeated.

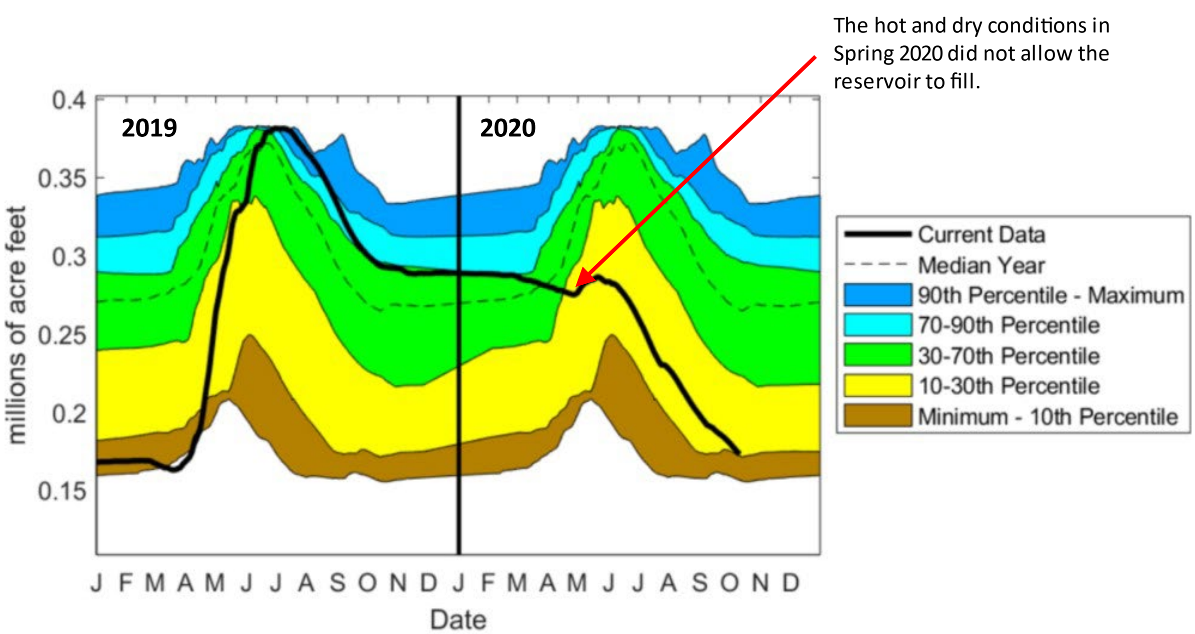
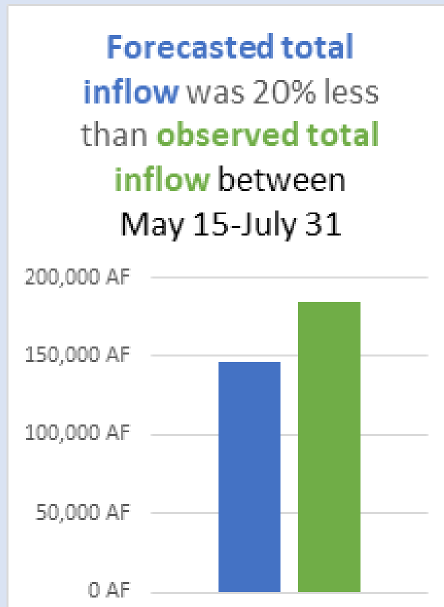


Figure 29. Reservoir storage (AF) in 2019 and 2020. The hot and dry conditions led to little reservoir filling in the spring and then a step drop in the summer.

7.1.3. 2017 McPhee Reservoir Boatable Days

ASO Is Critical to Reservoir Operations

- In 2017, SNOTEL sites around McPhee Reservoir melted out early, leaving only forecasts to estimate runoff
- With imperfect information, reservoir operators had to prioritize filling reservoir over recreational releases
- This led to inefficient operations for boaters and an early reservoir fill
- An ASO flight would have provided a more precise measurement of remaining runoff



Dolores Water Conservancy District (DWCD) manages the operations of McPhee Reservoir in Montezuma County. The reservoir, which dams the Dolores River, furnishes irrigation water for Montezuma and Dolores counties, plans releases for recreational rafting, and the tailwaters provide a popular destination for fishermen. Maximizing recreational potential, filling the reservoir, and fulfilling deliveries to irrigators are all important goals that DWCD attempts to meet each runoff season.

In the early spring of 2017, runoff forecasts from the Colorado Basin River Forecast Center (CBRFC) indicated an average or above average year, and DWCD expected to meet all operational goals. However, cold weather in late April reduced inflows more than what DWCD managers had anticipated, causing the reservoir elevation to drop quickly. By early May, SNOTEL sites had begun to melt out, leaving DWCD operators with no accurate measurement of the remaining snowpack.

Unable to measure changes in snowpack data by mid-May, managers were solely reliant on the CBRFC model, which suggested that the inflows had likely peaked for the runoff season. This meant that filling the reservoir became the primary priority, at the expense of boatable days. Managers began to ramp down releases below a key boatable threshold of 800cfs on May 21st. Between May 21st and May 29th (Memorial Day), releases were well below ideal rafting conditions, and were not forecasted to improve.

The end of May and beginning of June brought hot and dry conditions, as well as an unanticipated spike in inflows. The reservoir had almost filled, so DWCD managers were forced to increase releases above optimal boatable flows (>1,000cfs) in order to control reservoir elevation. In late June, yet another unanticipated spike in inflow forced additional releases to prevent the reservoir from spilling over.

An ASO flight in early May would have given DWCD more confidence in the total remaining snowpack that would run off. Had DWCD managers known the remaining snowpack volume after the initial peak in May, different operating decisions would have been made to better optimize recreational opportunities while still filling McPhee Reservoir. With more precise snowpack water content data, DWCD managers could have planned a release regime that would have benefitted rafters, such as in the Figure below. This new regime could have begun in mid-May and had only one ramp down as spring runoff began to recede. This would have allowed for more flows between 800-1,000cfs, the ideal range for rafters.

A review of historical McPhee Reservoir inflow data suggests that, with improved snowpack information, reservoir operations could have been changed to provide at least eight additional days of boatable conditions on the Dolores River around Memorial Day, one of the most popular weekends for rafting.

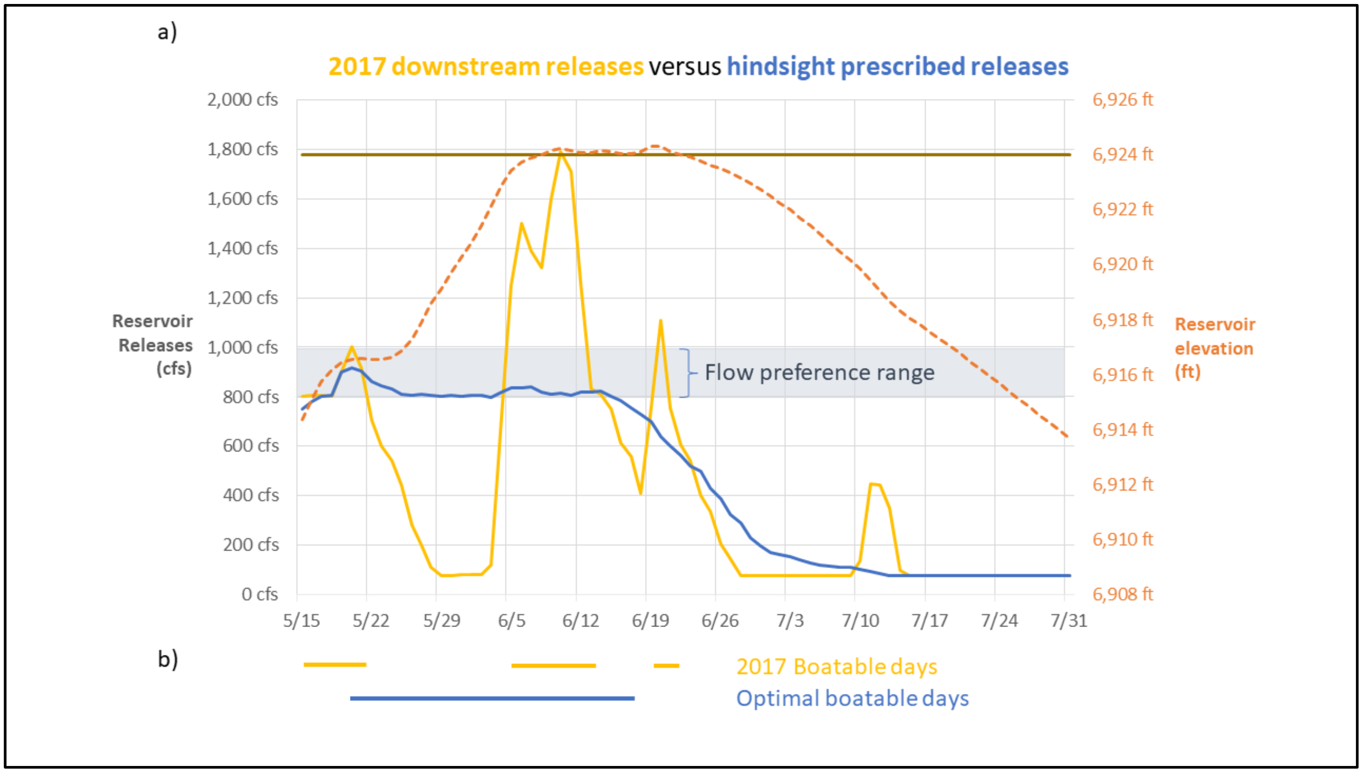


Figure 30. McPhee Reservoir downstream releases versus hindsight prescribed releases

7.2. Letters of Support

For the 2022 Water Plan Grant application, CASM received widespread interest in this study from stakeholders across many sectors and all major Colorado river basins. The evidence of this is the 37 letters of support we have received (including letters from 7 Basin Roundtables) to continue expanding the CASM program into the future. The following agencies have provided letters of support for the 2022 Water Plan Grant application project as well as matching funding:

- Northern Colorado Water Conservancy District
- Denver Water
- United States Geological Survey (USGS)
- Lawrence Berkeley National Laboratory
- St. Vrain and Left Hand Water Conservancy District

The following agencies have provided general letters of support:

- Southwest Basin Roundtable
- Metro Basin Roundtable
- Gunnison Basin Roundtable
- Colorado Basin Roundtable

- South Platte Basin Roundtable
- Yampa/White/Green Basin Roundtable
- Arkansas Basin Roundtable
- Colorado Division of Water Resources
- Colorado River Water Conservation District
- Colorado Springs Utilities
- Southwest Water Conservancy District
- Colorado Basin River Forecast Center (CBRFC)
- United States Bureau of Reclamation (USBR)
- United States Bureau of Reclamation Western Colorado Area Office
- Grand Valley Water Users Association
- Ute Water Conservancy District
- Colorado Water Trust
- Colorado State University
- City of Thornton
- City of Aspen
- Upper Yampa Water Conservancy District
- Colorado Snow and Avalanche Center
- City of Greeley
- Dolores Water Conservancy District
- City of Westminster
- City of Boulder
- Aurora Water
- Yampa Valley Sustainability Council
- City of Fort Collins
- Boulder County
- Pitkin County Healthy Rivers and Streams Board
- Town of Cedaredge

7.3. Snow data and products

Table 12 summarizes the data and products that were included in the Western Water Assessment Report on Snowpack Monitoring report (Woelders 2020) as well as products that are currently being used by Colorado water professionals. The last column shows the percentage of survey respondents that indicated they use this product in their regular operations and planning.

Table 12. Adapted from Western Water Assessment Snowpack Monitoring data overview

Product or Network	Method and input data	Snow variables	Spatial Resolution or # Stations	Spatial Coverage	Temporal Resolution	Survey Respondents percentage
SNOTEL	In situ measurement	SWE, snow depth, precipitation, other weather obs.	336 stations in CO/UT/WY; ~900 stations West-wide	West-wide	Hourly	99%
Snow Course (NRCS)	In situ measurement	SWE, snow depth, snow density	178 courses in CO/UT/WY	West-wide	Monthly or Semi-monthly	56%
COOP (NOAA volunteer observers)	In situ measurement	Snowfall, snow depth, daily precipitation	100s of sites, though few at high elevations	US-wide	Daily	-
CoCoRaHS	In situ measurement	Snowfall, snow depth, daily SWE accumulation	1000s of sites, though few at high elevations	US-wide	Daily	-
ASO	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	3 and 50m	By watershed as flights are made on demand	As flights are made on demand; typically 1-6 per basin per season	26%
MODSCAG	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	14%

Product or Network	Method and input data	Snow variables	Spatial Resolution or # Stations	Spatial Coverage	Temporal Resolution	Survey Respondents percentage
MODDRFS	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	Snow model using area-averaged precipitation data derived from point observations, plus freezing-level data	SWE, snow covered area	Lumped areas by elevation band; ~600 modeling units in CO River Basin	Nationwide; organized by River Forecast Center coverage areas	Daily	-
SNODAS	Snow model assimilates satellite, airborne, and in situ snow data and weather obs	SWE, snow depth, snowmelt, sublimation, snow temperature	1km	US-wide	Daily	40%
SWANN & SnowView	Snow model and neural network algorithm, uses SNOTEL SWE and MODSCAG snow area	SWE, snow cover	1km	US-wide	Daily	-
CU-SWE/MODIS	Statistical model blending SNOTEL, MODSCAG, physiography, analog historical SWE pattern	SWE	~500m	Southern Rockies domain	Typically 4-8 per season; 3-7 day lag	14%

Table 13. Snow remote future perspective considerations from Durand et al., NASA SnowEx Science program

	Snow Characteristic			Gap Capabilities							Space Potential		
Snow sensing/ estimation Technique	**Snow Depth**	**SWE**	**Melt**	**High-Res**	**Wet snow**	**Deep Snow**	**Forests**	**Complex Terrain**	**Shallow Snow**	**Clouds**	**Path to Space**	**Global coverage**	**Mature Algorithm**
Lidar (altimetry)	Green	Yellow	Gray	Green	Green	Green	Green	Green	Yellow	Red	Green	Yellow	Green
Ku-band SAR (volume scattering)	Yellow	Green	Green	Green	Red	Yellow	Red	Yellow	Yellow	Green	Yellow	Yellow	Yellow
Passive Microwave	Green	Green	Green	Red	Red	Red	Yellow	Yellow	Green	Green	Green	Green	Green
L-Band InSAR (Phase change)	Yellow	Green	Green	Green	Red	Yellow	Red	Yellow	Yellow	Green	Green	Yellow	Yellow
Gamma	Yellow	Green	Gray	Yellow	Green	Green	Yellow	Green	Green	Green	Red	Red	Green
Ka-band InSAR (altimetry)	Green	Yellow	Gray	Green	Green	Yellow	Red	Green	Yellow	Yellow	Yellow	Yellow	Yellow
FMCW Radar	Green	Green	Gray	Green	Yellow	Green	Yellow	Green	Green	Green	Red	Red	Yellow
Autocorrelation Radiometer	Yellow	Yellow	Gray	Red	Red	Yellow	Yellow	Yellow	Yellow	Green	Yellow	Yellow	Yellow
Stereo Photo-grammetry	Green	Yellow	Gray	Green	Green	Green	Red	Green	Yellow	Red	Green	Yellow	Green
Structure-from-Motion	Green	Yellow	Gray	Green	Green	Green	Red	Green	Yellow	Red	Yellow	Yellow	Green
Signals of Opporunity	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow
Modeling	Green	Green	Yellow	Green	Yellow	Green	Yellow	Green	Green	Green	Green	Green	Yellow

Green – Demonstrated capability
Yellow – Research Opportunity/Potential capability
Red – No Capability
Gray – Not Applicable

Attachment 2:

Winter 2022 Flight Results

1) Blue River
2) Conejos
3) Dolores
4) East & Taylor
5) Windy Gap

ASO Survey Report

Blue River Basin, CO
Survey date: May 26, 2022

Report delivered May 29, 2022

Airborne Snow Observatories, Inc. is a public benefit corporation with a mission to provide high-quality, timely, and accurate snow measurement, modeling, and runoff forecasts to empower the world's water managers to make the best possible use of our planet' precious water.

Historical data and reports can be found at:
data.airbornesnowobservatories.com

BLUE RIVER BASIN
MAY 26, 2022 SURVEY

Survey Date: May 26, 2022
Survey # of Water Year 2022: 2
Report Delivery Date: May 29, 2022
Version: 0

Full basin SWE: 92 TAF ±8
Change in SWE since Apr 19, 2022: -52
Estimated snowline: 10100 ft

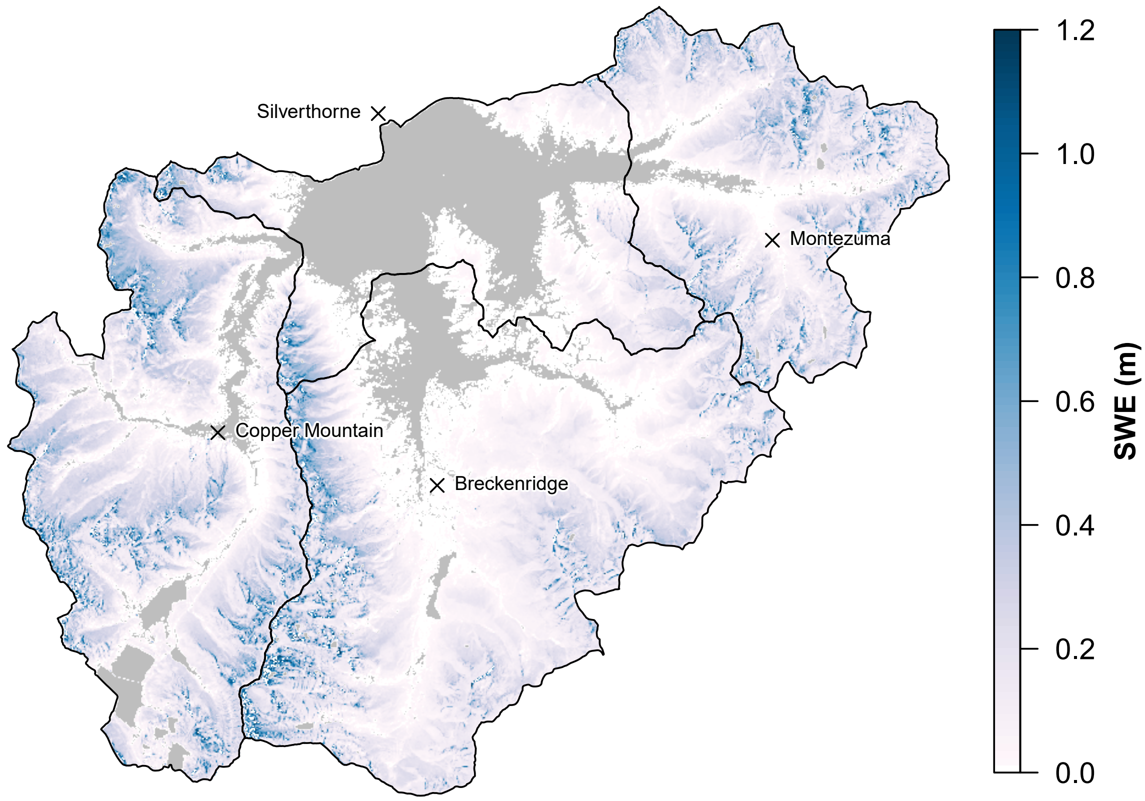


Figure 1. Spatial distribution of SWE depth (m).

	Estimated SWE (TAF)	
Basin	**April 19**	**May 26**
Full Basin	150	92
Uncertainty range	*146 - 154*	*84-100*
Main Stem	51	31
Snake River	27	20
Ten Mile Creek	57	34
Dillon	15	6

Table 1. Estimated SWE for the full Blue River basin and by subbasin.

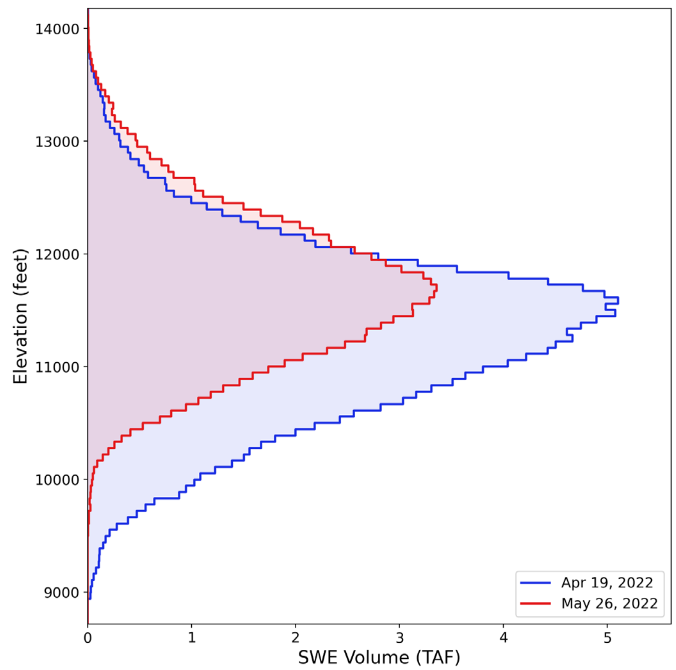
Summary of background conditions

Northern Colorado received a significant series of storms in mid-late December during which much of the water year's snowpack was deposited. January and the first half of February were exceptionally dry with very little precipitation – rain or snow. From late February there have been a series of smaller snowfall events to freshen up the snow surface, but nothing substantial. Substantial desert dust deposition had produced a dirty snowpack surface prior to the recent snowfall, and will emerge again as the recent snow melts off.

From the automated station information, peak SWE occurred in the first week of May above 10,500 ft (after our April 19 survey of the basin). The snowpack then underwent a period of rapid snowmelt with warming surface air temperatures until May 21 when a storm event brought 0.15-0.3 m (or 6-12") of fresh snow to the basin – based on three SNOTEL stations in the basin above 10,500 ft. The fresh snowfall not only paused snowmelt through freshening of the snow surface but increased the SWE (Figure 2) and likely also impacted bulk snow density.

Fresh snow typically has a much lower density than snow that has had time to settle. The fresh snow from the storm contributed contributed 17-86% of the snow depth at Fremont Pass and Hoosier Pass SNOTEL locations respectively. The bulk snow density on May 26 will therefore reflect these recent storm accumulations.

2.a.



2.b.

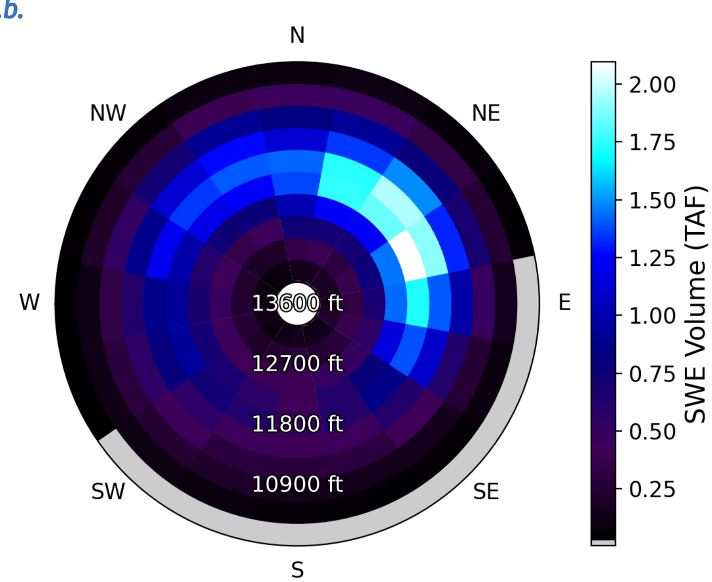


Figure 2.a. *Distribution of SWE depth (in) across elevations, dark blue line represents median SWE depth (in), lighter blue band represents the 25th to 75th percentile.* ***Figure 2.b.*** *Distribution of SWE volume (TAF) by aspect and elevation.*

Please see ***Figure 13 & 14*** *for more descriptive plots.*

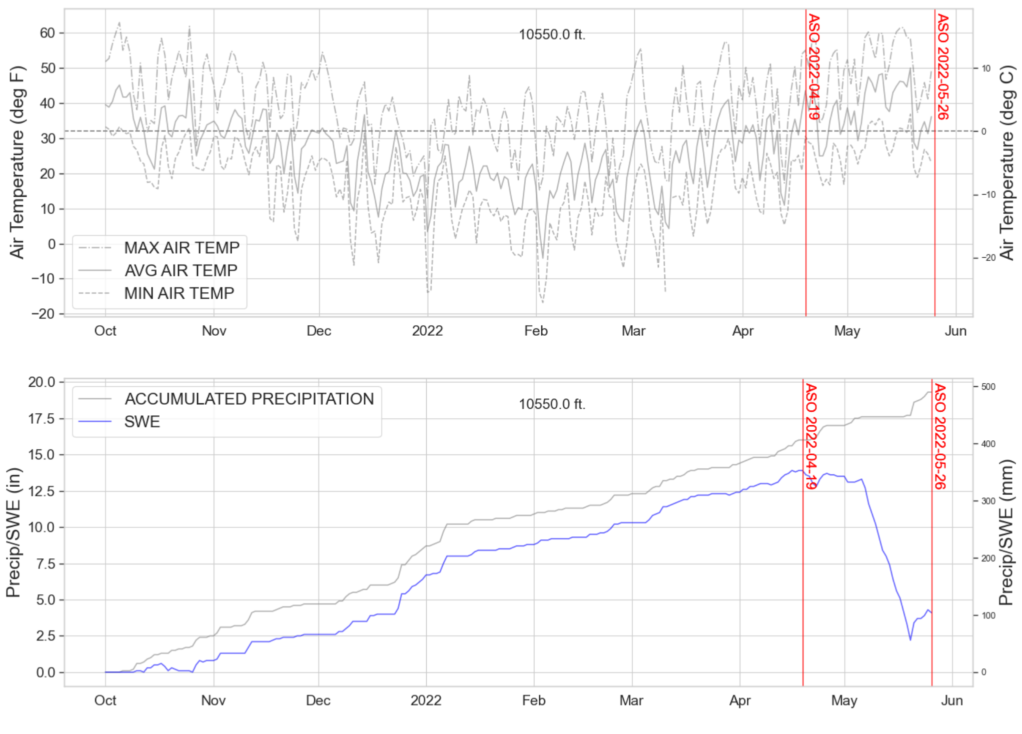


Figure 3. Daily meteorological conditions at Copper Mountain (Elevation 10550 ft) Note: the raw daily data shown has been downloaded directly from NRCS and has not been quality checked. There may be noise or incorrect data present. Precipitation data will only be shown if the featured station records it, and the air temperature plot shows daily max, mean, and min values. ASO surveys are marked with red vertical lines.

Table 2. Comparison of ASO with SNOTEL and manual snow depths. Note: ASO long-term depth uncertainty is ± 8 cm.

Site name	Elevation (ft)	Date	Site depth (cm)	ASO depth (cm)	Depth difference (cm)
Fremont Pass	11400	05/26/22	53	54	1
Hoosier Pass	11400	05/26/22	47	42	-5
Grizzly Peak	11100	05/26/22	104	103	-1
				Mean	-1.7

Evaluation of ASO Snow Depth Measurements

Snow-free, planar surfaces, common between the snow-on and snow-off datasets, are used to coregister the elevation datasets throughout the basin. This relative registration process ensures that in areas without snow, we measure a snow depth of 0, and forces snow depth accuracy throughout.

At 3 m resolution, the standard deviation of snow depth distribution was 0.01 m, unbiased. At 50 m resolution, the snow depth uncertainty based on a rigorous bare surface evaluation is less than 0.01 m.

Point-to-point comparison of ASO 3 m resolution snow depths and densities at in-situ sensor locations is shown in **Table 2**.

Table 3. Snow pit data from May 26

Site	Easting	Northing	Elevation (ft)	Depth (m)	Density (kg/m³)
Hoosier Pass	409749	4358133	11640	0.63	279
Mayflower Gulch	400675	4364094	11200	0.94	384
Berthoud Pass	433409	4406260	11315	0.36	259
Blue Ridge	416790	4422956	10668	0.88	447
Ranch Creek	435036	4418430	9531	0.06	162

Snow Density Constraint

ASO Field Collections

Two snow pits were excavated for snow density sampling on May 26 in the Blue River basin by the ASO Field Team. Pit 1 was in the Hoosier Pass vicinity and in 0.63m (or 25”) of snow a bulk snow density of 279 kg/m^3 was reported. Pit 2 was in the Mayflower Gulch area and a bulk snow density of 384 kg/m^3 was reported in snowpack that was 0.94 m (or 37”) deep (**Table 3**).

In addition, three snow pits were excavated for snow density sampling on May 26 in the nearby Fraser basin by the USGS (Table 1). The variability in the bulk density values reflect the impact of the fresh snowfall, where lower bulk snow densities were observed in shallow snowpack – where the contribution of fresh snow to the overall snowpack depth is higher (**Figure 4**).

Snow Course Measurements

There were 3 snow course locations that were monitored in the May 1 surveys in the Blue River, that were surveyed between April 27 - 29. These data are now 28 days old and the mean density during the survey window of 301 ± 11 kg/m³ has changed significantly – particularly in the past few weeks (**Figure 5**).
It is important to adjust for on-going densification as these measurements are now 28 days old and with the fresh snowfall it is difficult to make a robust adjustment to these measurements to account for densification and other changes.

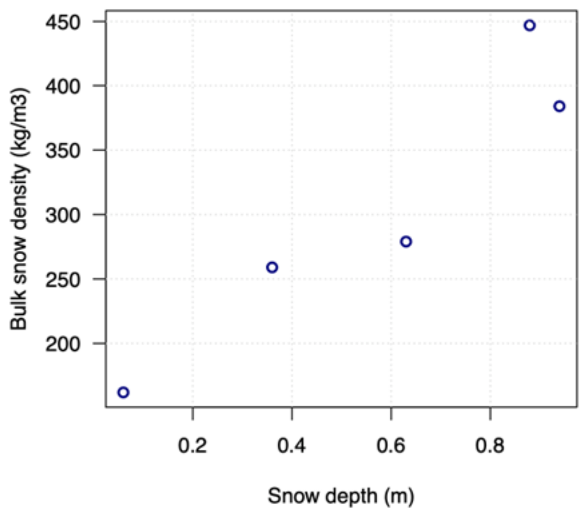


Figure 4. *Snow pit data*

With the relatively long interval between the snow course observations and the airborne survey date (28 days), the high temporal variability in the snowpack right now and challenge of fresh snow contributions - we cannot use these snow course measurements to constrain bulk snow density on May 26.

Sensor Measurements

Of the four automated stations operating in the Blue River, two locations are either showing unreasonable values or have stopped reporting daily SWE or snow depth – leaving two SNOTEL locations at which we can estimate bulk snow density (Fremont Pass and Grizzly Peak). The daily snow density timeseries at these locations are shown in **Figure 5** – the mean snow density from these locations on May 26 is 339 kg/m³ on May 26.

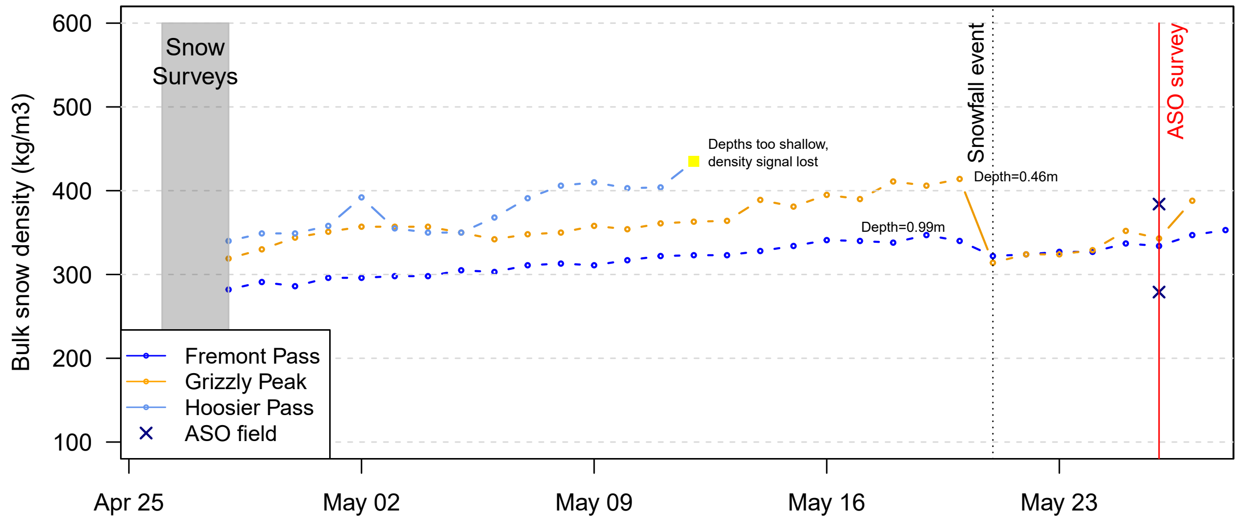


Figure 5. *Daily Snow Density Time Series*

Like the USGS field collections in Fraser, the bulk density estimates at the SNOTEL stations appears to be influenced by the fresh snowfall which is particularly notable in shallower snow (Grizzly Peak). We have high confidence in the SNOTEL network for constraining bulk snow density but recognize that the fresh snow impacts must be accounted for.

Physically-based model - iSnobal

This is the second survey of the season in the Blue River and the iSnobal model has been updated with maps from ASO this season on April 19. The mean bulk snow density from the model for May 26 is 434 ± 63 kg/m³, a value higher than the observations in the Blue River suggest.

It is important that the model captures the bulk density impacts of the recent storm events. An examination of the model prior to the storm (May 19), immediately after the storm (May 20) and on the day of the ASO survey (May 26) shows that the basin-median snow depth increased from during the storm from 0.30 m to 0.75 m (or 18" snow accumulation) – which was then reduced via compaction and perhaps snowmelt by May 26 (**Figure 6**). Correspondingly, the modeled snow density shows a significant reduction (564 to 273 kg/m³) with the deposition of fresh snow on May 20, which then settles by May 26 to a basin-mean of ~ 418 kg/m³ (**Figure 7**). The model dynamics are consistent with fresh snow accumulation, though without ASO data immediately prior to the storm it is difficult to evaluate model performance during the storm.

On May 26, ASO survey date, when plotted against elevation (**Figure 8**) the model is overestimating bulk snow density at all elevations of the basin, with the exception of areas > 13,000ft. At lower elevations, the fresh snow in the model has already densified from fresh snow values of ~ 170 kg/m³ (based on in-situ snow pit measurements from Windy Gap) to > 420 kg/m³ in many locations – after 5 days of settling. The densification rate to achieve this would need to be ~ 50 kg/m³/day which is very high and 2-5 times the expected densification rates after fresh snowfall. We saw similar dynamics in the Windy Gap model for the same time period, where the fresh snow appears to be densifying too fast in the model.

When plotted against snow depth (**Figure 9**) we observe that the overestimations are structured with snow depth – with the largest overestimations occurring in shallow snow. In addition, the model is displaying depth-density trends that are inconsistent with the in-situ data (**Figure 4**).

While the model captured the storm and generally displayed physically consistent dynamics of state variables (bulk snow density and snow depth), when examined in detail there are some issues with the fresh snow density dynamics that need to be constrained. Note: the model is tracking reasonably well with the in-situ measurements in deeper snow > 0.9 m, which is where we expect much of the SWE to be located – and the areas in the model where we see bulk density overestimation are occurring in shallow snow where much less of the basin SWE volumes are located.

At collocated pixels with the SNOTEL stations, we confirm the overestimation (bias of +127 kg/m³) in the model – **Figure 10.a**. At the manual snow pit locations (**Table 2**), a direct comparison confirms the relatively large overestimation by the model. There is insufficient information to make any further conclusions.

Snow density refinement

From the available information, the model is overestimating bulk snow density at all elevations and the overestimation is more pronounced in shallow snowpack, an adjustment is required to remove these biases. Leveraging the information in Figure 8, we rescaled snow densities at depths < 1.0 m to 85% of their original value, for example, modifying densities of 420 kg/m³ to 357 kg/m³. After density adjustment the biases at the SNOTEL stations were reduced from 127 kg/m³ to 57 kg/m³ (**Figure 10.b**). Note: we did not fully rescale the modeled snow densities to match the data at the two snow pillow locations (leaving some residual apparent bias) because we do not consider it prudent to make such large changes based on only two measurements. The resulting basin-wide mean bulk snow density was 374 kg/m³ (**Figure 9**).

To get a sense of the scale of impact of these density adjustments on basin SWE, additional sensitivity testing reveals that with a very low snow density (mean of 318 kg/m³), the basin SWE would be 82 TAF, and with a very high snow density (mean of 464 kg/m³), the basin SWE would be 110 TAF.

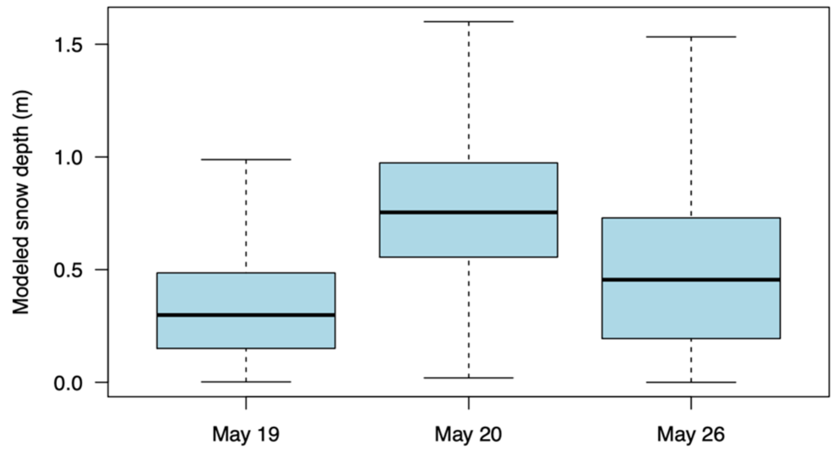


Figure 6. Modeled snow depths (m) during the May 20 storm.

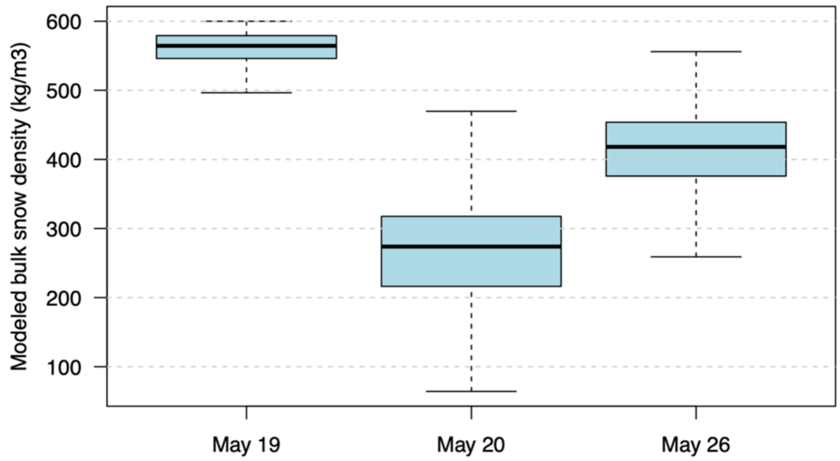


Figure 7. Modeled bulk snow densities (kg/m³) during the May 20 storm.

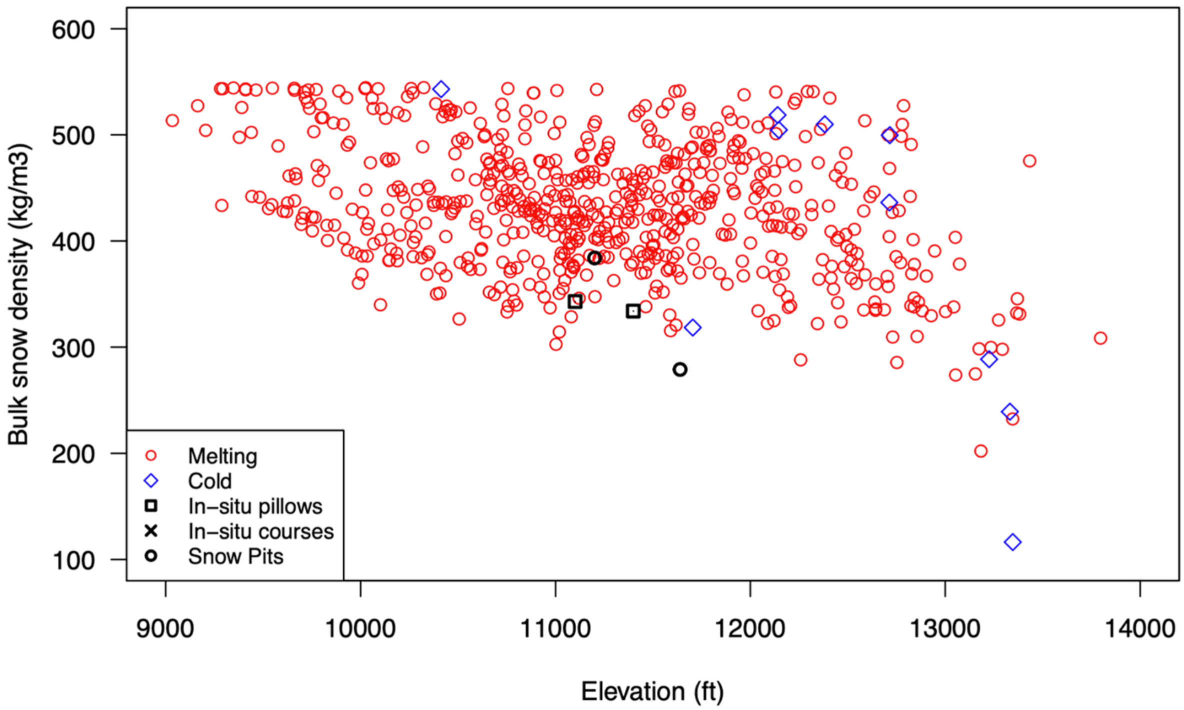


Figure 8. *Observed and unadjusted modeled bulk snow density (kg/m³) by snow depth (m) on May 26, 2022. Squares represent density observations at snow pillows, Xs represent density observations at snow courses. Red circles represent modeled densities of melting snow (cold content = 0), blue diamonds represent modeled densities of cold snow (cold content < 0).*

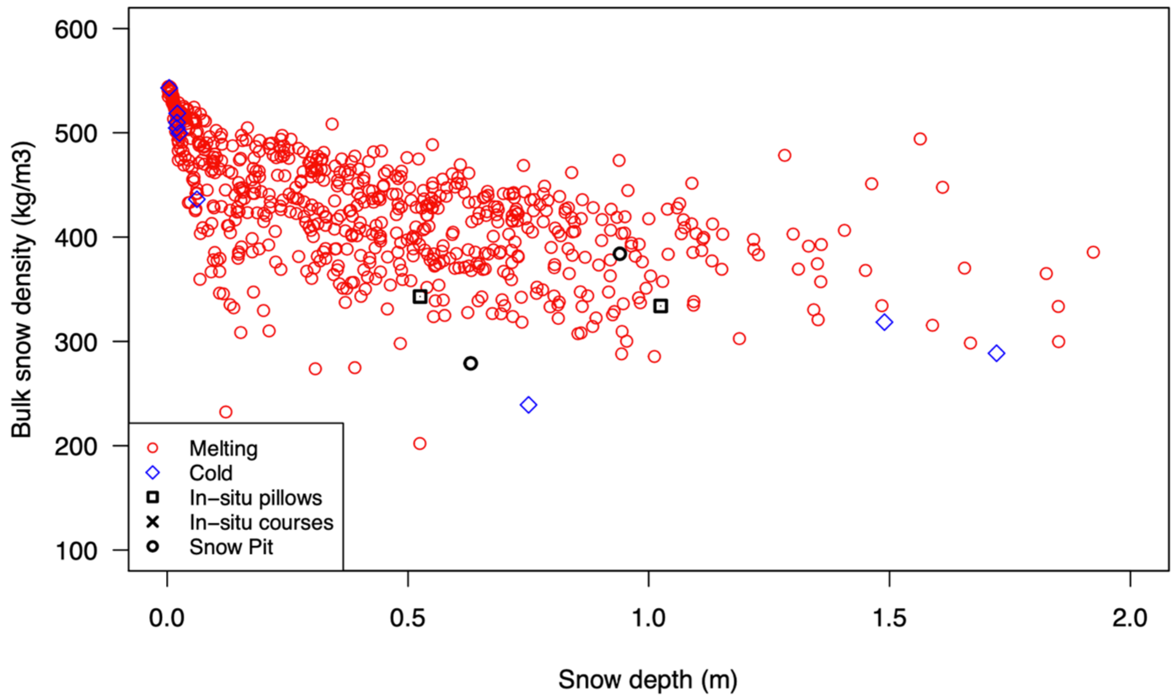
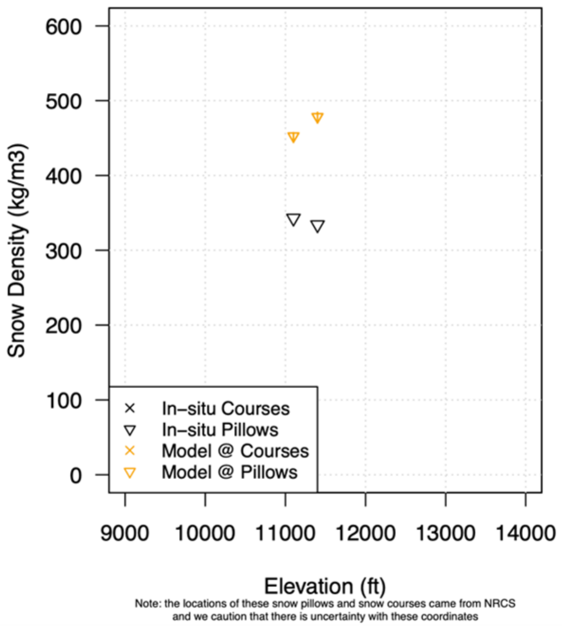


Figure 9. *Observed and adjusted modeled bulk snow density (kg/m³) by snow depth (m) on May 26, 2022. Squares represent density observations at snow pillows, Xs represent density observations at snow courses. Red circles represent modeled densities of melting snow (cold content = 0), blue diamonds represent modeled densities of cold snow (cold content < 0).*

10.a.



10.b.

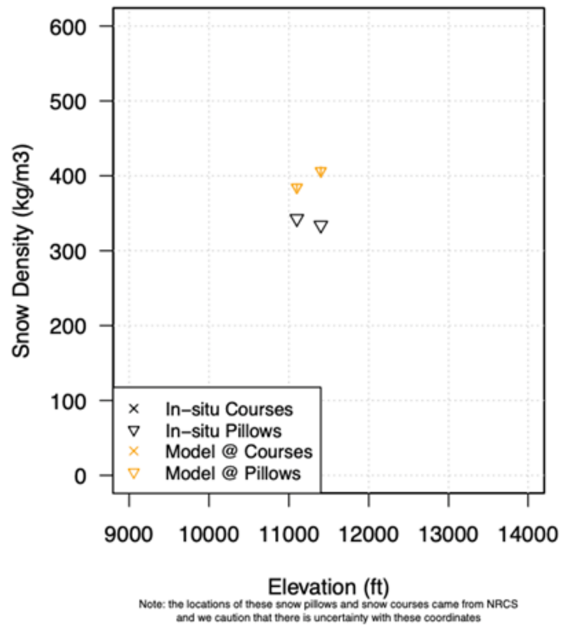


Figure 10 a & b. *Model comparison at collocated snow courses and snow pillows in the Blue River basin before (**a**) and after (**b**) the density adjustment. After adjustments, the modeled bulk snow densities are much more consistent with the in-situ measurements. (Note: the locations of these snow pillows and snow courses come from NRCS and we caution that there is uncertainty with these coordinates)*

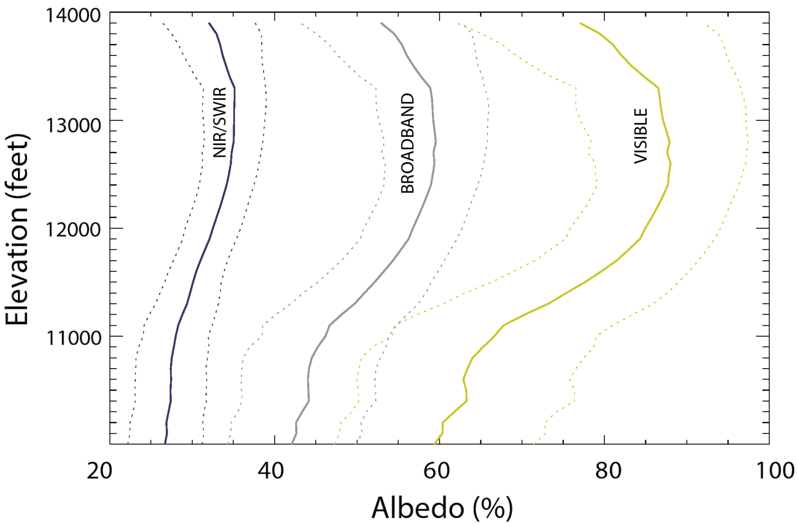
Snow Albedo

As described in Painter et al. (2016), in addition to the scanning lidar, ASO also carries a pair of visible to shortwave infrared imaging spectrometers from which we retrieve broadband albedo (400-2500 nm wavelength), visible albedo (400-700 nm), and near-infrared to shortwave-infrared (700-2500 nm). The latter two albedos are generated to ultimately constrain iSnobal and WRFHydro, as well as other physically-based models.

Solar radiation is the primary energy source for snowmelt. The snow albedo describes the fraction of incoming solar energy that is reflected by the snow surface.

The NIR/SWIR albedo values in the Blue River on May 26 (~25-30%) are consistent with the generation of large snow grains due to melt/freeze metamorphism (70-75% absorption), and the visible albedo values (>80%) reflect fresh snow deposition (Figure 10.a.). The broadband albedo, which is most critical for understanding the snow energy balance, ranges from 45 to 60%, which translates to 40-55% solar absorption. For this time of year, relatively clean snow typically has albedos of approximately 92% (visible), 74% (broadband), and 45% (NIR/SWIR), translating into associated absorption of 8%, 26%, and 55%

11.a.



11.b.

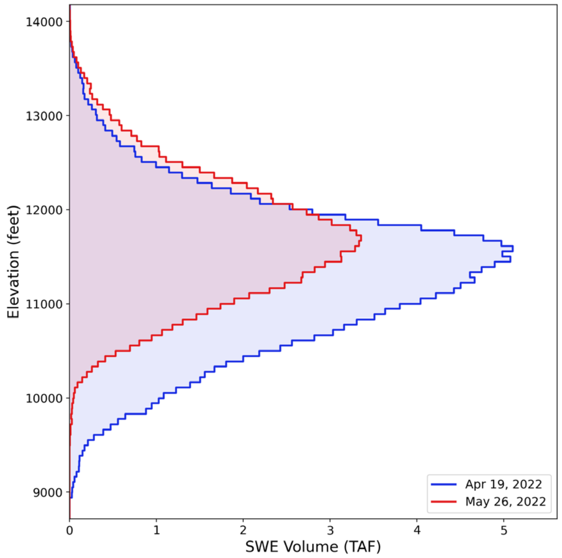


Figure 11.a. *Snow albedo (%) by elevation (ft) on May 26 with mean (solid lines) and ± 1 standard deviation (dotted lines) for near and shortwave infrared (dark blue), broadband (gray), and visible (green) wavelengths.* ***b.*** *Distribution of SWE volume (TAF) across elevations; red represents the May 26 survey, blue represents the April 19 survey.*

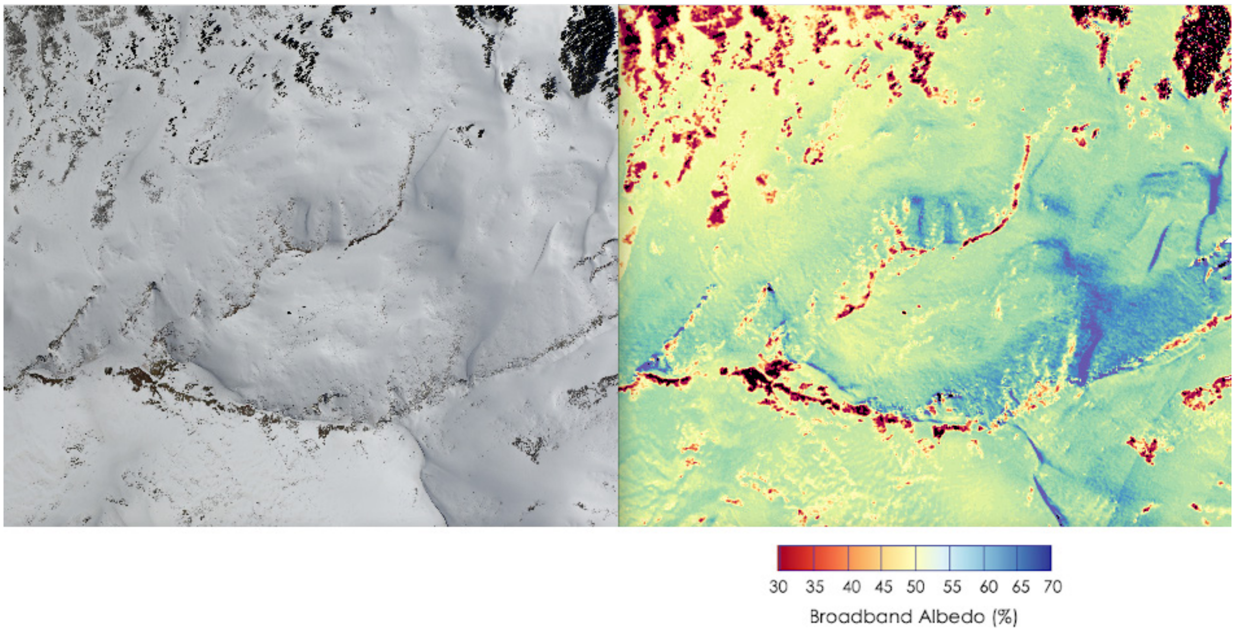


Figure 12. *ASO visible images (left panels) from three of the hundreds of ASO spectral bands over the Blue River high country. Corresponding snow albedo maps (right panels) showing the spatial variation of snow albedo/solar absorption due primarily to differential rates of warming and melt of new snow on different aspects.*

Additional data / remarks

Table 4. Snow density, depth, and SWE estimates from the snow course network (data source: NRCS)

Site	Site Code	Elevation (ft)	Date	Density (kg/m³)	Time adj. (day)	Adj. density (kg/m³)	Depth (m)	SWE (m)
Shrine Pass	06K09	10700	04/27/2022	312	-29	312.28	1.45	0.05
Blue River	06K21	10500	04/29/2022	290	-27	290	0.25	0.07
Snake River	05K16	10000	04/27/2022	300	-29	300	0.15	0.05

Table 5. Snow density, depth, and SWE estimates from the SNOTEL network (data source: NRCS).

Site	Site Code	Elevation (ft)	Date	Density (kg/m³)	Depth (m)	SWE (m)
Fremont Pass	485	11400	05/26/2022	337	1.04	0.35
Hoosier Pass	531	11400	05/26/2022	200	0.03	0.15
Grizzly Peak	505	11100	05/26/2022	340	0.53	0.18
Copper Mountain	415	10550	05/26/2022	NA	0.00	0.10

Table 6. Volume of SWE (AF) by subbasin and elevation range (ft).

Elevation range (ft)	Dillon	Main Stem	Snake River	Ten Mile Creek	Full basin
8000 - 8999	0	0	0	0	0
9000 - 9999	23	102	8	58	190
10000 - 10999	1505	4966	1327	4780	12578
11000 - 11999	4071	13713	10799	21062	49645
12000 - 12999	845	10223	7621	7703	26392
13000 - 13999	0	2054	570	532	3156

Additional data / remarks

Table 7. Change in volume of SWE (AF) since April 19 survey by subbasin and elevation range (ft).

Elevation range (ft)	Dillon	Main Stem	Snake River	Ten Mile Creek	Full basin
7000 - 7999	0	0	0	0	0
8000 - 8999	-25	0	0	0	-25
9000 - 9999	-1699	-2885	-369	-1084	-6037
10000 - 10999	-4330	-11434	-2978	-10058	-28799
11000 - 11999	-2220	-7598	-5643	-13016	-28476
12000 - 12999	7	1919	1500	802	4228
13000 - 13999	0	536	216	159	911

Table 8. Total area (mi²), snow-covered area (mi²), band coverage (%), SWE volume (AF), and mean SWE depth m) by elevation range (ft).

Elevation range (ft)	Total area (mi²)	Snow-covered area (mi²)	Band coverage (%)	SWE volume (AF)	Mean SWE depth (in)
8000 - 8999	6.7	0	0	0	0.0
9000 - 9999	64.8	27.4	42.4	190	.3
10000 - 10999	98.5	94.0	95.4	12578	2.5
11000 - 11999	114.5	111.4	97.3	19645	8.4
12000 - 12999	43.3	43.2	100	26392	11.5
13000 - 13999	6.0	6.0	100	3156	9.8

Additional data / remarks

*Table 9. Other SWE (TAF) and runoff forecasts (TAF) products for the Blue River basin around the time of the April 19 airborne survey (data sources: Colorado SNODAS Dashboard and CBRFC Blue River - Dillon Reservoir (DIRC2) Water Supply Forecast page). Mid-month NRCS forecast was not available at time of reporting. *Recent CU-SWE estimates have been adjusted using ASO data as guidance.*

SWE estimates	Date	SWE (TAF)
SNODAS	05/26/22	5
AJRO forecasts	**Date**	**10% / 50% / 90% exceedance (TAF)**
CBRFC	05/02/22	155/128/105
NRCS	05/01/22	147/120/96
AJRO forecast	**Date**	**SWE (TAF)**
CBRFC ESP	05/26/22	130

Additional data / remarks

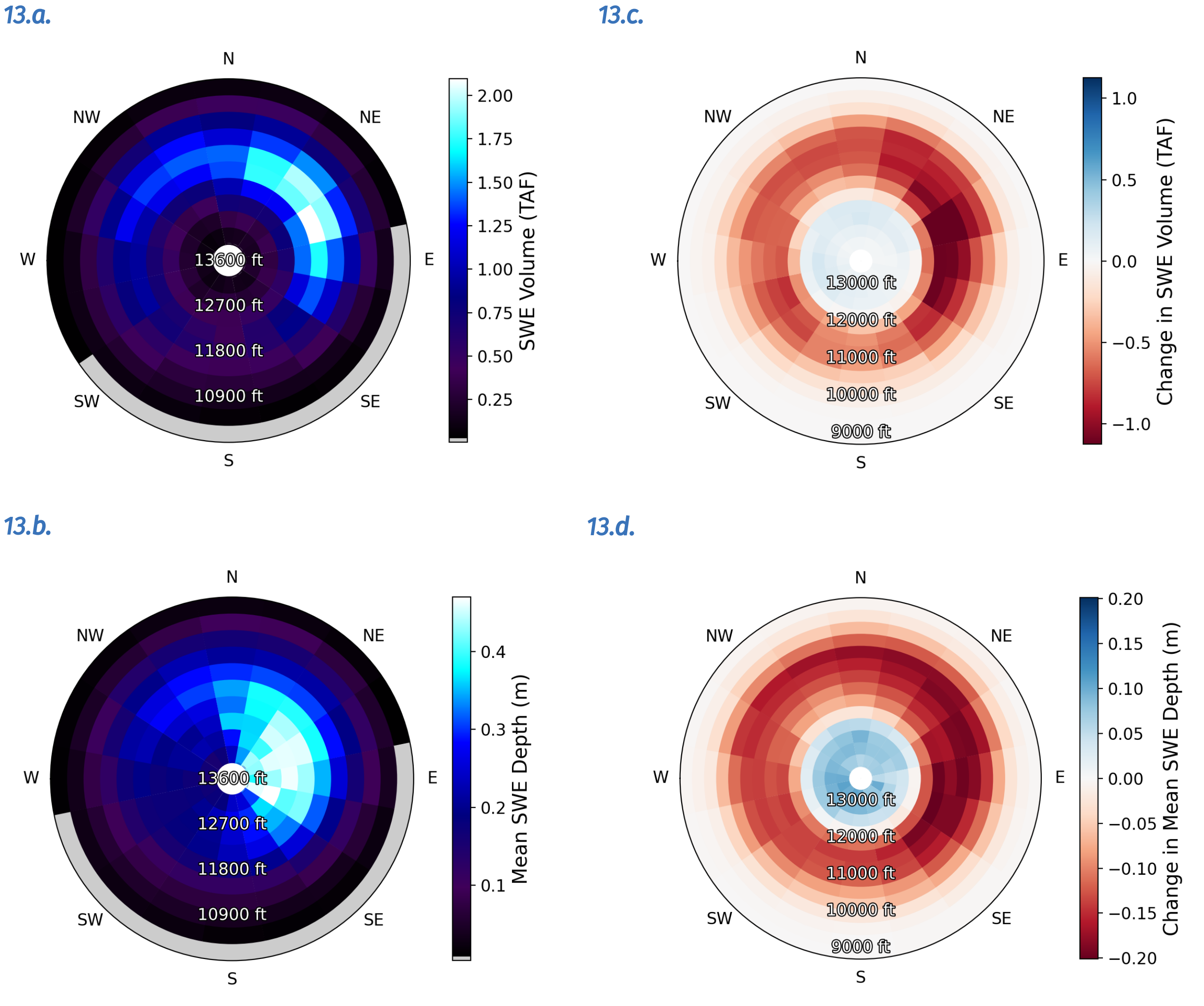
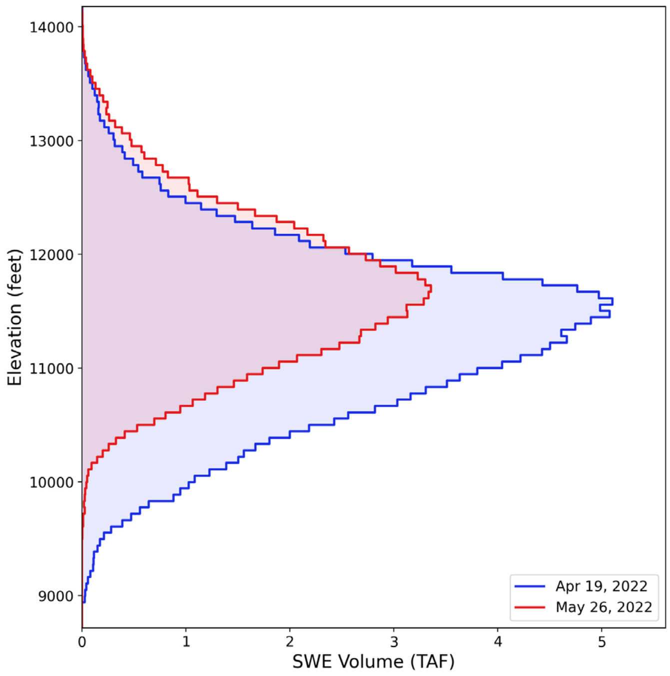


Figure 13. Aspect/elevation SWE and SWE difference plots. 13.a. & b. SWE volume (TAF) and depth (m) from May 26 survey; 13.c. & d. SWE volume (TAF) and depth (m) change from April 19 survey to May 26 survey

Additional data / remarks

14.a.



14.b.

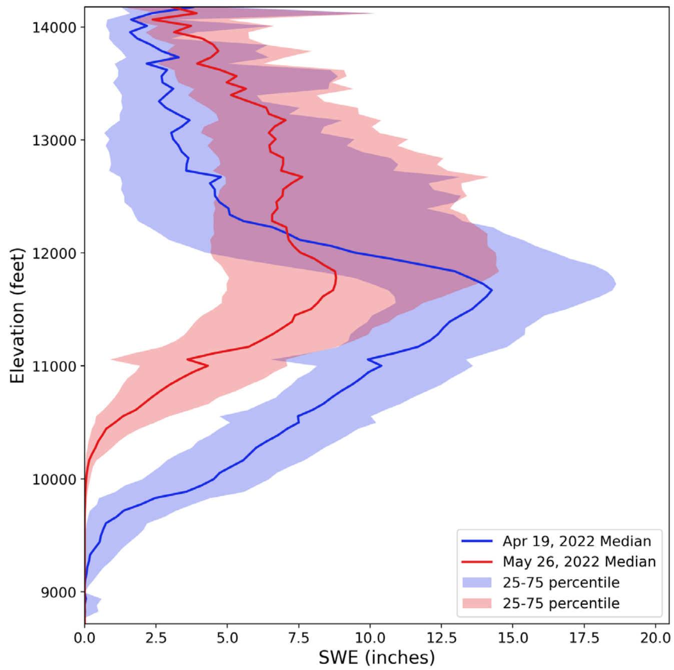


Figure 14. Difference plots of SWE volume (TAF) and depth (in) across elevations. 14.a. Distribution of SWE volume (TAF) across elevations; red represents the May 26 survey, blue represents the April 19 survey. 14.b. Distribution of SWE depth (in) across elevations; red represents the May 26 survey, blue represents the April 19 survey; solid lines represent median SWE depth (in), lighter color bands represent the 25th to 75th percentiles.

ASO Survey Report

Conejos River Basin, CO

Survey date: May 10, 2022

Report delivered May 13, 2022

Airborne Snow Observatories, Inc. is a public benefit corporation with a mission to provide high-quality, timely, and accurate snow measurement, modeling, and runoff forecasts to empower the world's water managers to make the best possible use of our planet's precious water.

Historical data and reports can be found at:
data.airbornesnowobservatories.com

CONEJOS RIVER BASIN
MAY 10, 2022 SURVEY

Survey Date: May 10, 2022
Survey # of Water Year 2022: 2
Report Delivery Date: May 13, 2022
Version: 0

Full basin SWE: 60 ± 4 TAF
Change in SWE since Apr 15, 2022: -109 TAF
Estimated snowline: 10700 ft

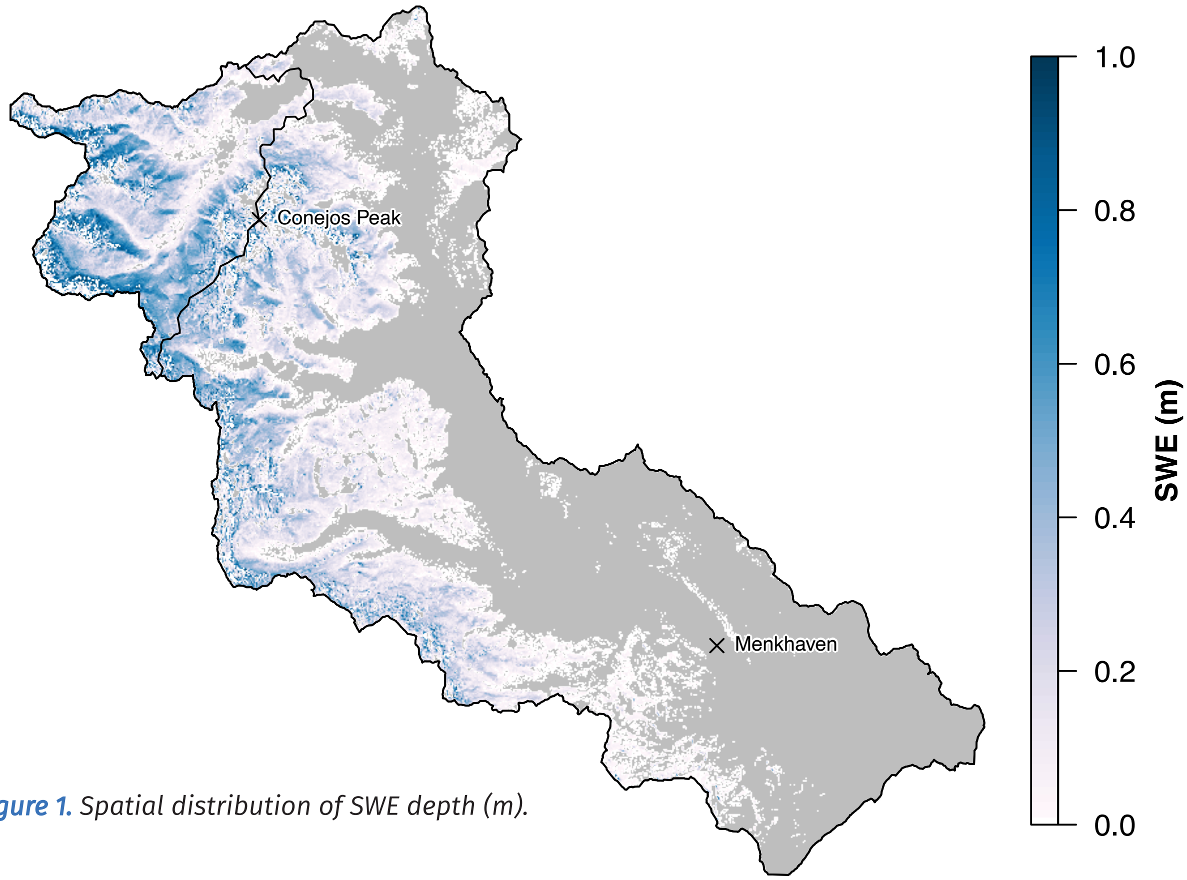


Figure 1. Spatial distribution of SWE depth (m).

Table 1. Estimated SWE volume (TAF) for the full Conejos River basin for the current and previous ASO survey (April 15).

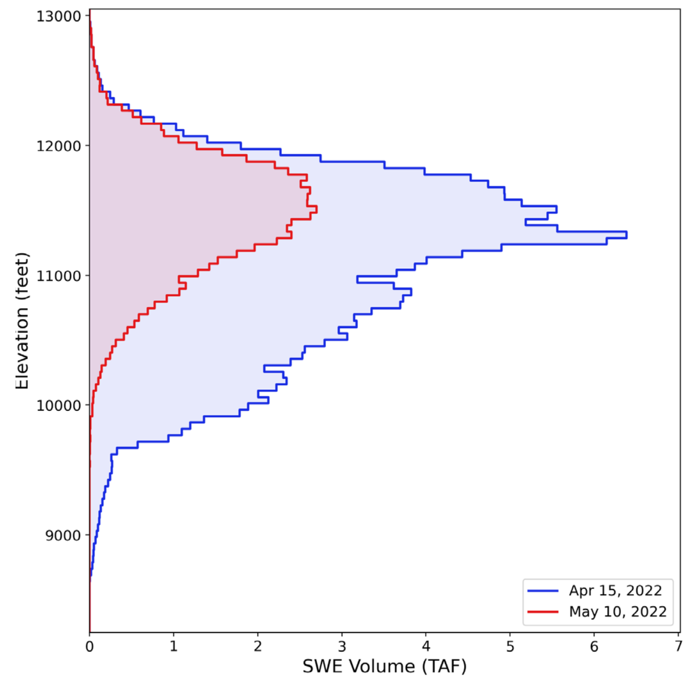
Basin	Estimated SWE volume (TAF) April 15	Estimated SWE volume (TAF) May 10
Full Basin	169	60
Uncertainty range	*161 - 177*	*56 - 64*
Platoro Reservoir Inflow	51	27
Lower Basin	118	33

Summary of background conditions

Southern Colorado received a significant series of storms in mid-late December during which much of the water year's snowpack was deposited. January and the first half of February were exceptionally dry with very little precipitation and plenty of wind. Since late February, there have been a series of snowfall events to freshen up the snow surface, but nothing substantial. The desert dust deposition that started earlier in the season has continued and even increased in frequency as of late, resulting in substantial dust accumulation at and near the snow surface and a very dirty snowpack surface.

The automated stations show that SWE has been in rapid decline since mid-March at elevations as high as 11069 ft (Figure 3). All the SNOTEL locations in and near the Conejos basin have melted out. The minimum surface air temperatures have risen above the melting point at all elevations in the past week, thus expanding melt to elevations above 11000 ft. The most recent snowfall event deposited 0.15 m (or 6") in two small storms at Cumbres Trestle SNOTEL on April 28, almost two weeks prior to the airborne survey – we do not expect this snowfall to impact bulk snow densities on May 10, nor do we expect this most recent snowfall to be currently "freshening" the snowpack surface. Figure 3 shows meteorological information from Lily Pond SNOTEL (580) at 11069 ft.

2.a.



2.b.

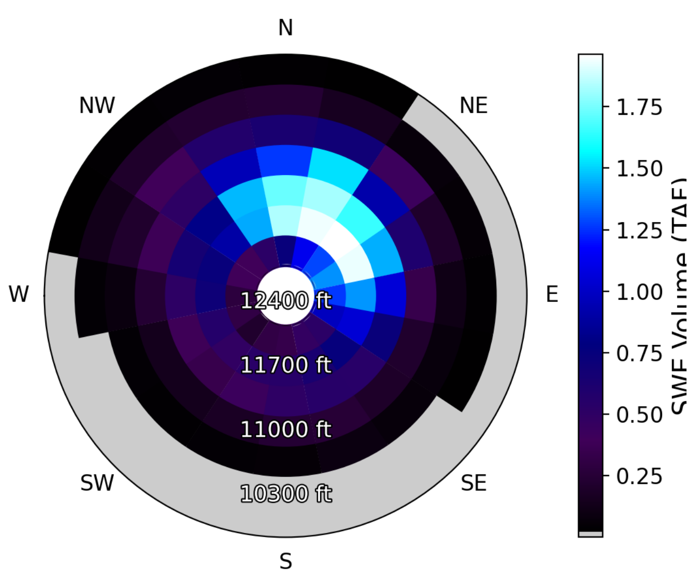


Figure 2.a. Distribution of SWE volume (TAF) across elevations; red represents the May 10 survey, blue represents the April 15 survey. Figure 2.b. Distribution of SWE volume (TAF) by aspect and elevation for the May 10 survey. See Figure 6 and Figure 7 for more descriptive plots.

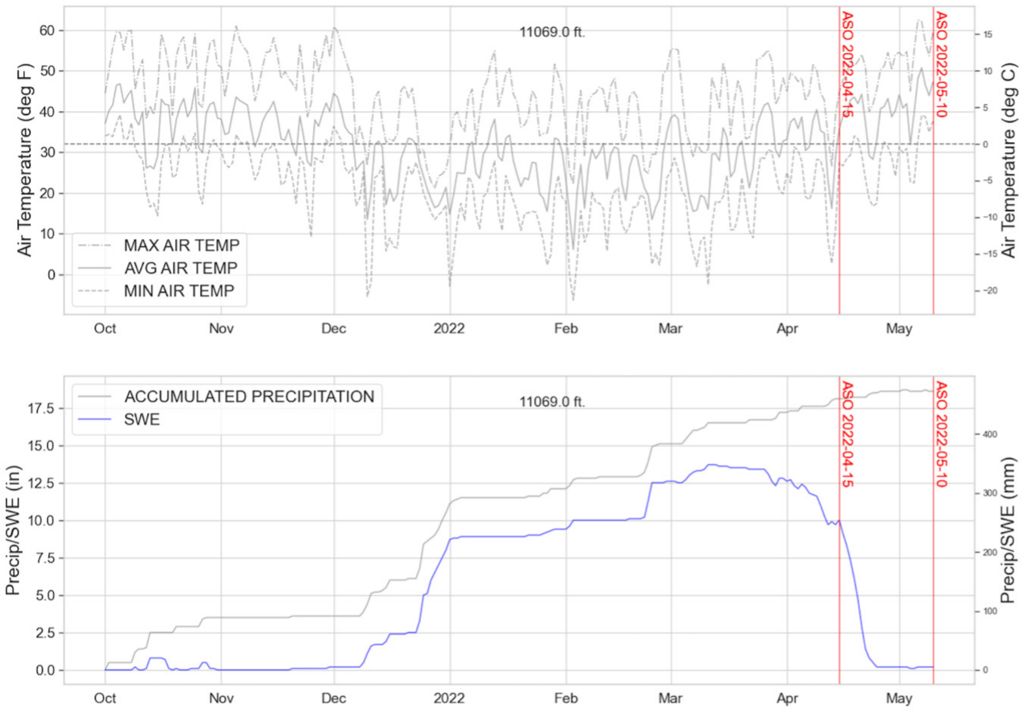


Figure 3. Daily meteorological conditions at Lily Pond (elevation 11069 ft). Note: the raw daily data shown has been downloaded directly from NRCS and has not been quality checked. There may be noise or incorrect data present. Precipitation data will only be shown if the featured station records it, and the air temperature plot shows daily max, mean, and min values. ASO surveys are marked with red vertical lines.

Evaluation of ASO snow depth measurements

Snow-free, planar surfaces, common between the snow-on and snow-off datasets, are used to co-register the elevation datasets throughout the basin. This relative registration process ensures that in areas without snow, we measure a snow depth of 0, and forces snow depth accuracy throughout. At 3 m resolution, the standard deviation of snow depth distribution was 0.02 m, unbiased. At 50 m resolution, the snow depth uncertainty based on a rigorous bare surface evaluation is less than 0.01 m.

Point-to-point comparison of ASO 3 m resolution snow depths and densities at in-situ sensor locations was not possible since all of the snow depth sensors in the basin with confirmed locations have melted out.

Snow density constraint

ASO field collections

The ASO Field Team did not conduct any field work in or near the Conejos River basin coincident with this airborne survey, however the Dolores Water Conservancy District (DWCD) made snow tube measurements in the Dolores River basin on May 9 and 10.

On May 9, the crew sampled a 10-hole transect with a Federal Sampler on north/northwest facing slopes in the vicinity of El Diente Peak SNOTEL location (elevation 10284 ft, UTM Zone 12 761861.7

E, 4185646.3 N). In snow ranging from 0.4 – 1.0 m (or 17-38”) deep, the bulk snow density ranged from 378 – 490 kg/m^3 with a transect mean of 472 ± 40kg/m^3. On May 10, the crew sampled a 9-hole transect on north/northwest facing slopes north of Black Mesa SNOTEL location (elevation 10652 ft, UTM Zone 12 747827.4 E, 4189085.1 N). In snow ranging from 0.7 – 1.0 m (or 28-38”) deep, the bulk snow density ranged from 392 – 514 kg/m^3 with a location mean of 445 ± 42 kg/m^3.

We recognize that these measurements are from a location much further to the west of the Conejos, and in a different region, and that their usefulness for constraining snow densities in the Conejos on May 10 should be applied qualitatively. However, these data are the only information in the region available to provide timely and high-quality insight into the snowpack on May 10 in a snowpack that is rapidly changing.

Snow course measurements

There were two snow course locations that were monitored in the May 1 surveys in the Conejos: Pinos Mill and Platoro, sampled on April 27-28, respectively (**Table 2**). At these locations, the mean bulk snow density was 439 kg/m^3 and the snow depths sampled were 0.4 – 0.7 m (or 15-26”).

It is important to adjust for ongoing densification given that this measurement is now 11-12 days old. After adjustment for densification between the measurement dates (at an estimated rate of 2 kg/m^3/day based on climatology in lieu of robust snow pillow measurements nearby) – the projected mean bulk snow density on May 10 is 464 kg/m^3, a value that is reasonably consistent with the guidance from the measurements in the Dolores on the same day.

Despite the relatively long interval between the snow course observations and the airborne survey date (12 days), the consistency with the DWCD in-situ measurements instills moderate confidence in the snow course network for constraining snow densities in the Conejos.

Sensor measurements

All automated stations operating in or near the Conejos River basin melted out by May 4, therefore we cannot use this network to constrain snow densities for the May 10 airborne survey (**Table 3**).

Regional measurements

In such a dynamic snow pack, and with very few robust measurements of snow density, we expand our assessment of the available in-situ data throughout the region to include snow course and SNOTEL locations as far north as the Elk Mountains (**Table 4**). The collated information shows a mean of 463 ± 52 kg/m^3 from the SNOTEL network and 412 ± 63 kg/m^3 from the snow course network. The regional statistics give us confidence in the adjusted snow course data from the Conejos basin.

Physically-based model - iSnobal

As this is the second ASO survey of the Conejos this season, the iSnobal model has been updated with information from our previous survey on April 15.

The mean bulk snow density from the model for May 10 is 570 ± 27 kg/m^3, a value much higher than any of the observations suggest. In shallow snowpack (< 0.6 m), the model tends to overestimate snow density – we have seen this behavior from the model before (**Figure 4**). In deeper snow, the model is still overestimating bulk snow density (by ~11%), but the distribution is much closer to the observations.

Snow density refinement

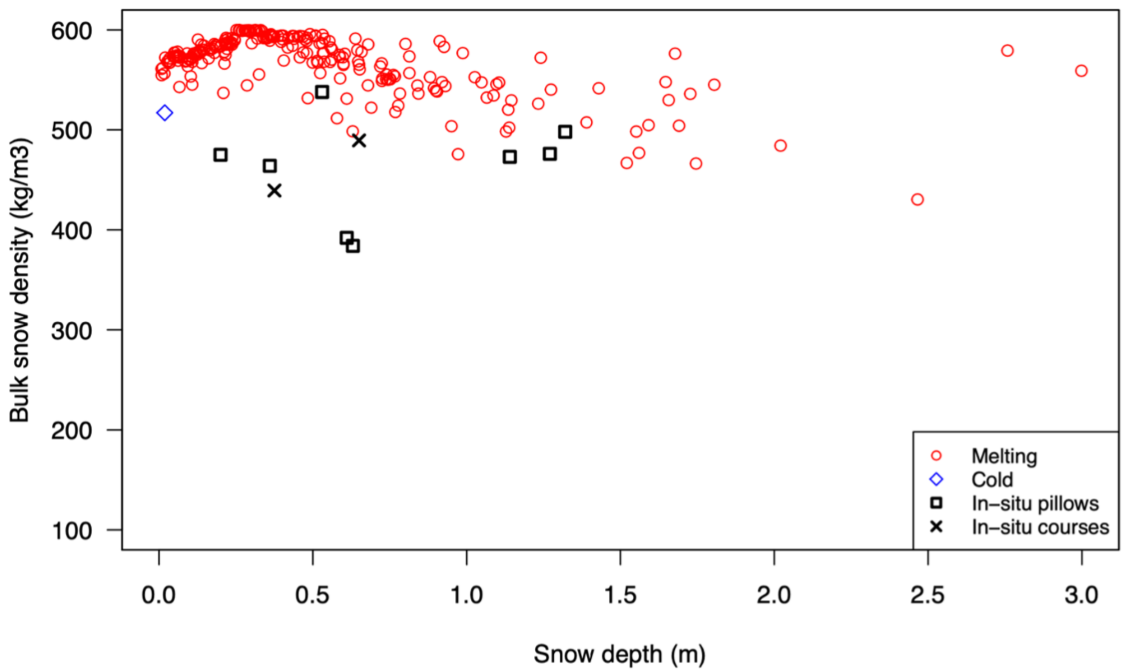


Figure 4. *Observed and unadjusted modeled bulk snow density (kg/m^3) by snow depth (m) on May 10, 2022. Squares represent density observations at snow pillows, Xs represent density observations at snow courses. Red circles represent modeled densities of melting snow (cold content = 0), blue diamonds represent modeled densities of cold snow (cold content < 0).*

From this information it is clear that the model is overestimating bulk snow density and an adjustment is required. We rescaled bulk snow density at depths < 0.6 m to 80% of their original value, and for deeper snow we rescaled the densities to 89% of their original value. We made a similar adjustment in the Dolores River basin.

After these density adjustments, the mean bulk density was 470 ± 21 kg/m^3 (**Figure 5**) and snow densities in shallow snow were reduced from 581 to 464 kg/m^3, which is much more consistent with the in-situ guidance.

Using the un-adjusted model (open-loop) densities, the basin SWE volume was 75 TAF. The model adjustments bring the basin SWE down to 60 TAF. To get a sense of the scale of impact of these density adjustments on basin SWE, additional sensitivity testing reveals that with a very low snow density (mean of 404 kg/m^3), the basin SWE would be 51 TAF, and with a very high snow density (mean of 546 kg/m^3), the basin SWE would be 69 TAF.

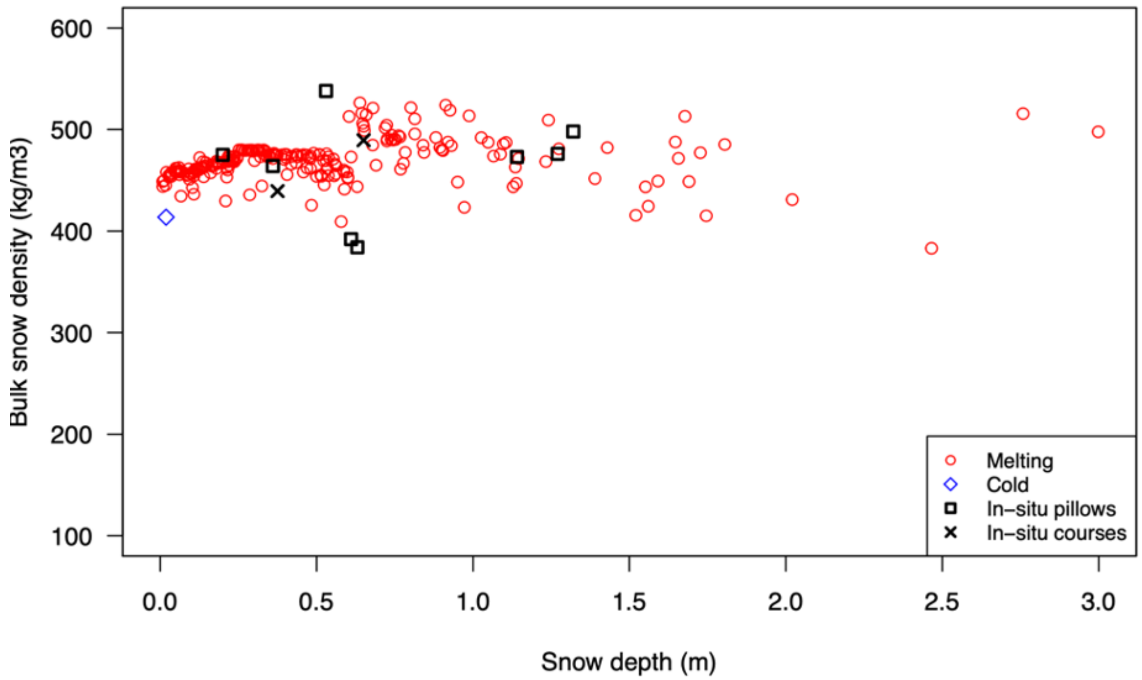


Figure 5. *Observed and adjusted modeled bulk snow density (kg/m^3) by snow depth (m) on May 10, 2022. Squares represent density observations at snow pillows, Xs represent density observations at snow courses. Red circles represent modeled densities of melting snow (cold content = 0), blue diamonds represent modeled densities of cold snow (cold content < 0).*

Additional data / remarks

Table 2. Snow density, depth, and SWE estimates from the snow course network (data source: NRCS).

Site name	Site code	Elevation (ft)	Date	Density (kg/m³)	Time adj. (day)	Adj. density (kg/m³)	Depth (m)	SWE (m)
Pinos Mill	06M24	10000	4/28/22	465	-12	489	0.7	0.3
Platoro	06M09	9880	4/27/22	413	-13	439	0.4	0.2

*Table 3. Snow density, depth, and SWE estimates from the SNOTEL network (data source: NRCS). *Excluded from snow density analysis.*

Station name	Station code	Elevation (ft)	Date	Density (kg/m³)	Depth (m)	SWE (m)
Lily Pond*	580	11000	5/10/22	NA	NA	< 0.1
Cumbres Trestle*	431	10040	5/10/22	NA	NA	< 0.1

*Table 4. SNOTEL and snow course data from neighboring watersheds around the time of the airborne survey on May 10 (data source: NRCS). *Excluded from snow density analysis.*

Site name	Network	Elevation (ft)	Date	Density (kg/m³)	Adj. density (kg/m³)	Depth (m)
Black Mesa	SNOTEL	11564	5/10/22	473	NA	1.1
Red Mountain Pass	SNOTEL	11080	5/10/22	384	NA	0.6
Wolf Creek Summit	SNOTEL	10957	5/10/22	538	NA	0.5
South Colony*	SNOTEL	10868	5/10/22	141	NA	1.2
Columbus Basin	SNOTEL	10781	5/10/22	392	NA	0.6
Porphyry Creek	Snow course	10760	4/27/22	352	417	0.8
Upper Taylor*	SNOTEL	10717	5/10/22	817	NA	0.2
Schofield Pass	SNOTEL	10653	5/10/22	498	NA	1.3
Lostman	Snow course	10626	4/29/22	308	363	1.0

Additional data / remarks

Table 4, continued.

Site name	Network	Elevation (ft)	Date	Density (kg/m³)	Adj. density (kg/m³)	Depth (m)
Independence Pass	Snow course	10600	4/27/22	308	373	0.7
Independence Pass	SNOTEL	10598	5/10/22	475	NA	0.2
Monarch Offshoot	Snow course	10500	4/27/22	391	456	0.9
Twin Lakes Tunnel	Snow course	10450	4/26/22	275	345	0.6
Saint Elmo	Snow course	10400	4/28/22	316	376	1.0
Mesa Lakes	SNOTEL	10168	5/10/22	464	NA	0.4
Lake City	Snow course	10160	4/27/22	257	322	0.2
Pinos Mill	Snow course	10000	4/28/22	465	525	0.7
Mesa Lakes	Snow course	10000	4/27/22	428	493	1.0
Park Reservoir	SNOTEL	9987	5/10/22	476	NA	1.3
Keystone	Snow course	9960	4/27/22	404	469	0.6
Platoro	Snow course	9880	4/27/22	413	478	0.4
Trout Lake	Snow course	9780	4/25/22	303	378	0.8
Cucharas Creek	Snow course	9700	4/26/22	285	355	0.3
Ironton Park	Snow course	9600	4/25/22	282	357	0.4
Park Cone	Snow course	9600	4/28/22	350	410	0.5
Crested Butte	Snow course	8920	4/27/22	414	479	0.4

Additional data / remarks

Table 5. Volume of SWE (AF) by subbasin and elevation range (ft) for May 10 survey.

Elevation range (ft)	Platoro Reservoir Inflow	Lower basin	Full basin
8000-8999	0	0	0
9000-9999	113	32	81
10000-10999	9646	5085	4560
11000-11999	43619	18186	25434
12000-12999	6160	3342	2818
13000-13999	1	0	1

Table 6. Change in volume of SWE (AF) since April 15 survey by subbasin and elevation range (ft)..

Elevation range (ft)	Platoro Reservoir Inflow	Lower basin	Full basin
8000-8999	-342	0	-342
9000-9999	-11116	-503	-10612
10000-10999	-48223	-9899	-38325
11000-11999	-48242	-12962	-35280
12000-12999	-1759	-985	-774
13000-13999	0	0	0

Additional data / remarks

Table 7. *Total area (mi²), snow-covered area (mi²), band coverage (%), SWE volume (AF), and mean SWE depth (m) by elevation range (ft).*

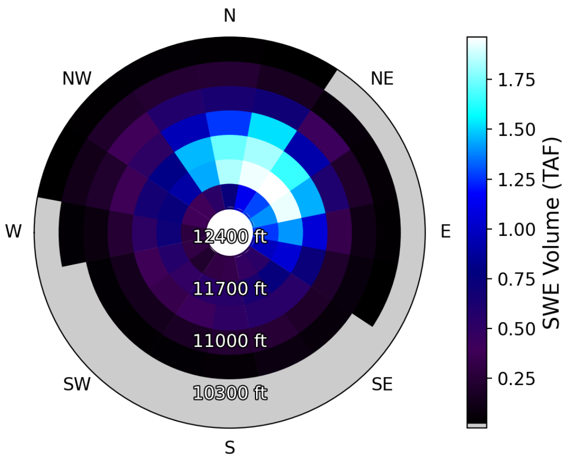
Elevation range (ft)	Total area (mi²)	Snow-covered area (mi²)	Band coverage (%)	SWE volume (AF)	Mean SWE depth (m)
8000 - 8999	27	0	0	0	NA
9000 - 9999	71	5	7	113	< 1
10000 - 10999	93	46	50	9646	4
11000 - 11999	83	75	91	43619	11
12000 - 12999	9	7	77	6160	17
13000 - 13999	0	0	71	1	2

Table 8. *Other SWE (TAF) and runoff forecasts (TAF) products for the Conejos River basin around the time of the May 10 airborne survey (data sources: Colorado SNODAS Dashboard and NRCS Interactive SWE Map).*

SWE estimate	Date	SWE (TAF)
SNODAS	5/10/22	27
Runoff forecasts	**Date**	**10% / 50% / 90% exceedance (TAF)**
NRCS April - Sept Runoff Conejos River at Mogote	5/1/22	183 / 145 / 113

Additional data / remarks

6.a.



6.b.

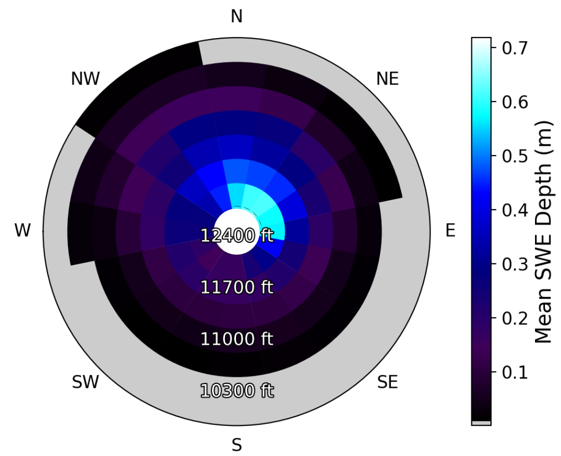
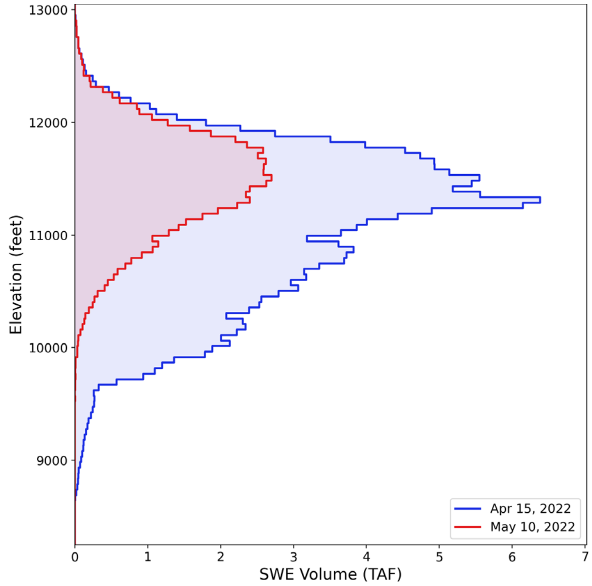


***Figure 6.** Distribution of SWE by aspect and elevation **6.a.** SWE volume (TAF) and **6.b.** SWE depth (m) for May 10 survey.*

7.a.



7.b.

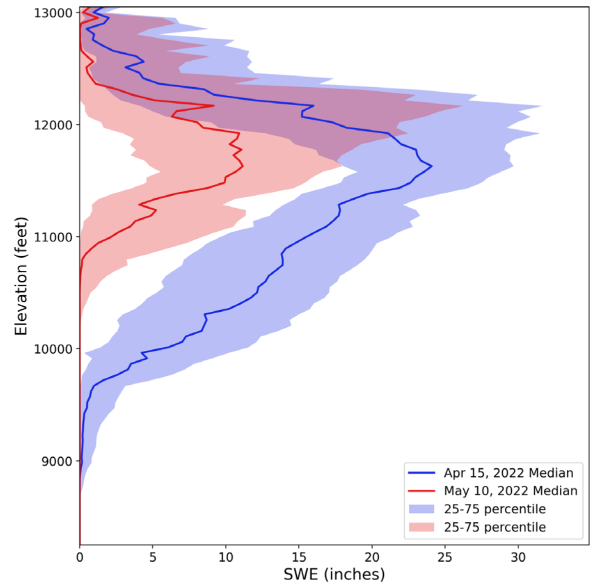


***Figure 7.** Difference plots of SWE volume (TAF) and depth (in) across elevations. **7.a.** Distribution of SWE volume (TAF) across elevations; red represents the May 10 survey, blue represents the April 15 survey. **7.b.** Distribution of SWE depth (in) across elevations; red represents the May 10 survey, blue represents the April 15 survey; solid lines represent median SWE depth (in), lighter color bands represent the 25th to 75th percentiles.*

ASO Survey Report

Dolores River Basin, CO

Survey date: May 10, 2022

Report delivered May 13, 2022

Airborne Snow Observatories, Inc. is a public benefit corporation with a mission to provide high-quality, timely, and accurate snow measurement, modeling, and runoff forecasts to empower the world's water managers to make the best possible use of our planet's precious water.

Historical data and reports can be found at:
data.airbornesnowobservatories.com

Survey Date: May 10, 2022
Survey # of Water Year 2022: 2
Report Delivery Date: May 13, 2022
Version: 0

Full basin SWE: 61 ± 5 TAF
Change in SWE since Apr 15, 2022: -127 TAF
Estimated snowline: 10000 ft

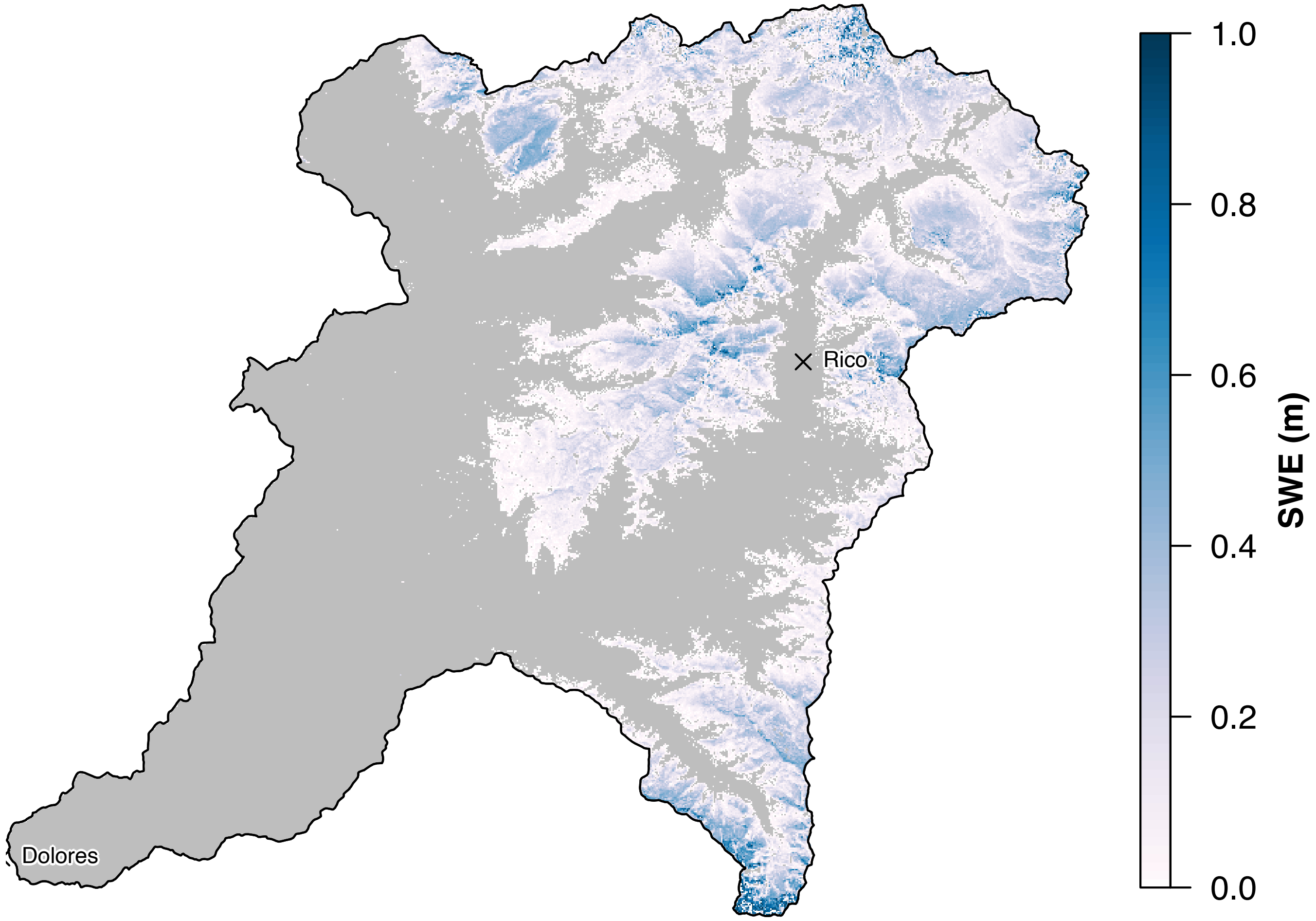


Figure 1. Spatial distribution of SWE depth (m).

Table 1. Estimated SWE volume (TAF) for the full Dolores River basin for the current and previous ASO survey (April 15).

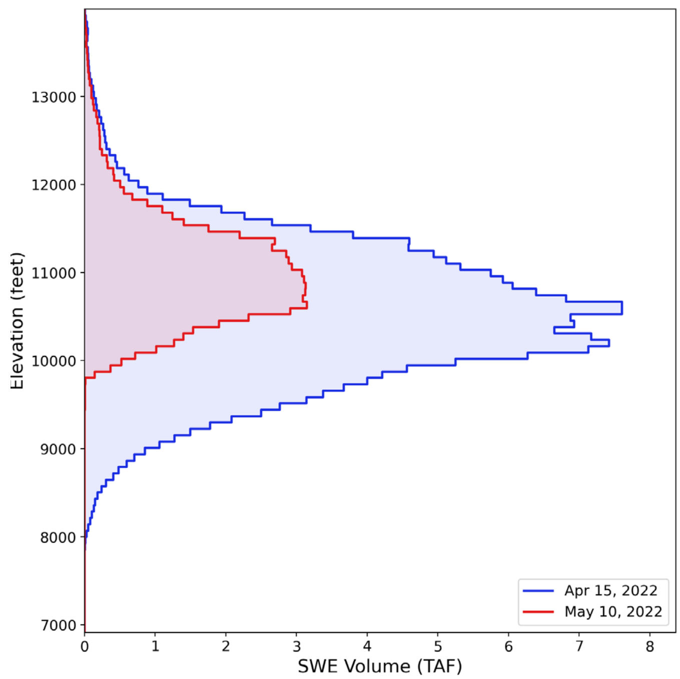
Basin	Estimated SWE volume (TAF) April 15	Estimated SWE volume (TAF) May 10
Full Basin	188	61
Uncertainty range	*182 - 194*	*56 - 66*

Summary of background conditions

Southwest Colorado received a significant series of storms in mid-late December during which much of the water year's snowpack was deposited. January and the first half of February were exceptionally dry with very little precipitation and plenty of wind. Since late February, there have been a series of snowfall events to freshen up the snow surface, but nothing substantial. The desert dust deposition that started earlier in the season has continued and even increased in frequency as of late, resulting in substantial dust accumulation at and near the snow surface and a very dirty snowpack surface.

The automated stations show that SWE has been in rapid decline since mid-March at elevations below 10720 ft (Figure 3), with complete melt out at stations below ~11000 ft. The only SNOTEL location with snow in the Dolores is at Black Mesa (1185) which sits at 11580 ft. The minimum surface air temperatures have risen above the melting point at all elevations in the past week, thus expanding melt to elevations above 11000 ft. The most recent snowfall event deposited 0.15 m (or 6”) in two small storms at Black Mesa SNOTEL on April 23-25. As this occurred over two weeks prior to the airborne survey, we do not expect this snowfall to impact bulk snow densities on May 10, nor do we expect this most recent snowfall to be currently “freshening” the snowpack surface. Figure 3 shows meteorological information from Sharkstooth SNOTEL (1060) at 10720 ft.

2.a.



2.b.

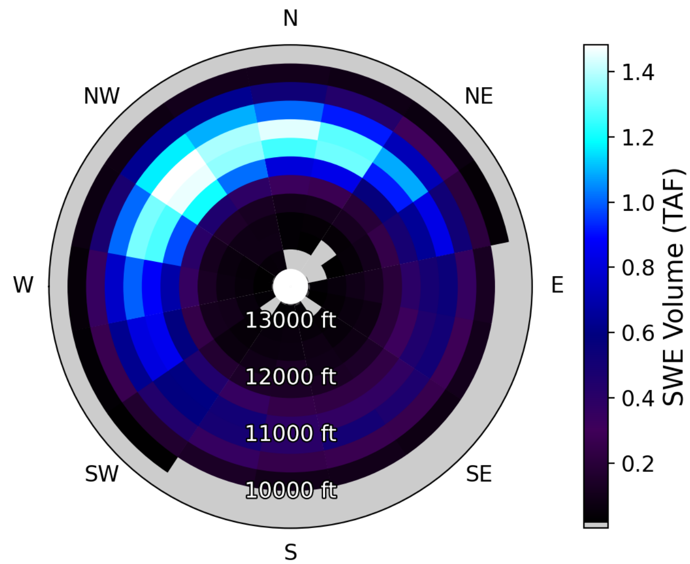
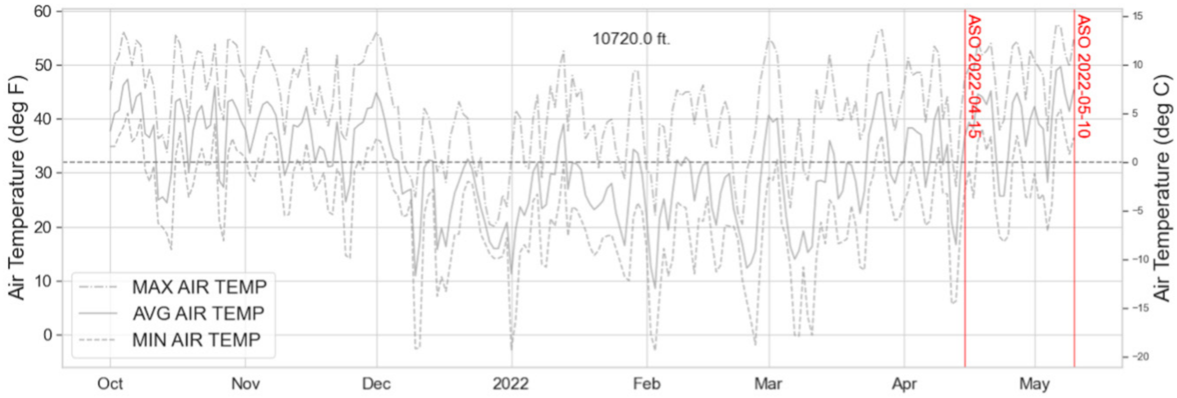


Figure 2.a. Distribution of SWE volume (TAF) across elevations; red represents the May 10 survey, blue represents the April 15 survey. Figure 2.b. Distribution of SWE volume (TAF) by aspect and elevation for the May 10 survey. See Figure 8 and Figure 9 for more descriptive plots.



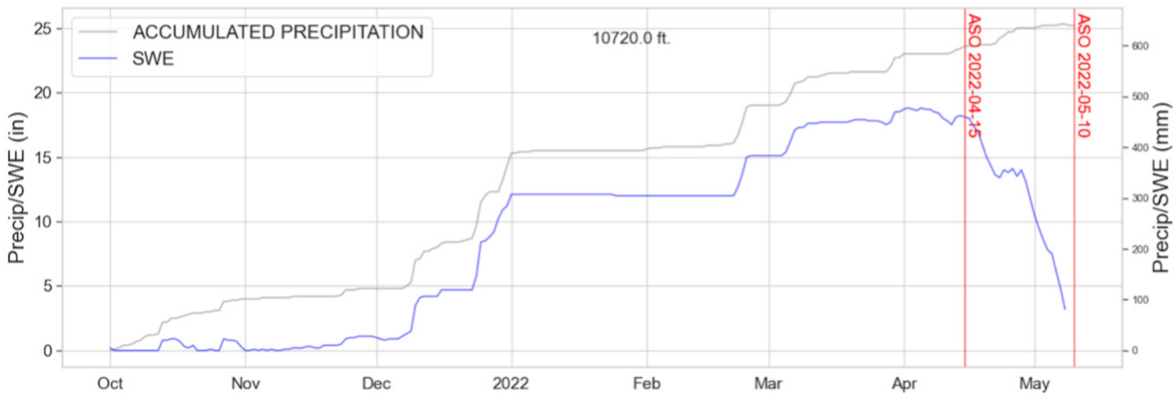


Figure 3. Daily meteorological conditions at Sharkstooth SNOTEL station (elevation 10720 ft). Note: the raw daily data shown has been downloaded directly from NRCS and has not been quality checked. There may be noise or incorrect data present. Precipitation data will only be shown if the featured station records it, and the air temperature plot shows daily max, mean, and min values. ASO surveys are marked with red vertical lines.

Table 2. Comparison of ASO and station snow depths (cm). Note: ASO long-term depth uncertainty is ± 8 cm.

Station name	Station code	Elevation (ft)	Date	Station depth (cm)	ASO depth (cm)	Depth difference (cm)
Lizard Head Pass	586	10200	5/10/22	0	0	0
El Diente Peak	465	10000	5/10/22	0	0	0
Black Mesa	1185	11580	5/10/22	122	118	-4
Sharkstooth	1060	10720	5/10/22	0	3	3
Scotch Creek	739	9100	5/10/22	0	3	3
					Mean	< 0.1

Evaluation of ASO snow depth measurements

Snow-free, planar surfaces, common between the snow-on and snow-off datasets, are used to co-register the elevation datasets throughout the basin. This relative registration process ensures that in areas without snow, we measure a snow depth of 0, and forces snow depth accuracy throughout. At 3 m resolution, the standard deviation of snow depth distribution was 0.01 m, unbiased. At 50 m resolution, the snow depth uncertainty based on a rigorous bare surface evaluation is less than 0.01 m.

Point-to-point comparison of ASO 3 m resolution snow depths and densities at in-situ sensor locations is shown in **Table 2**.

Snow density constraint

ASO field collections

The ASO Field Team did not conduct any field work in or near the Dolores River basin coincident with this airborne survey, however the Dolores Water Conservancy District (DWCD) made snow tube measurements on May 9 and 10.

On May 9, the crew sampled a 10-hole transect with a Federal Sampler on north/northwest facing slopes in the vicinity of El Diente Peak SNOTEL location (elevation 10284 ft, UTM Zone 12 761861.7 E, 4185646.3 N). In snow ranging from 0.4 – 1.0 m (or 17-38") deep, the adjusted bulk snow density* ranged from 378 – 490 kg/m^3 with a transect mean of 472 ± 40kg/m^3. On May 10, the crew sampled a 9-hole transect on north/northwest facing slopes north of Black Mesa SNOTEL location (elevation 10652 ft, UTM Zone 12 747827.4 E, 4189085.1 N). In snow ranging from 0.7 – 1.0 m (or 28-38") deep, the bulk snow density ranged from 392 – 514 kg/m^3 with a location mean of 445 ± 42 kg/m^3. Photos from this field campaign also confirm heavy dust loading on the snowpack surface (**Figure 4**).

**Note: looking closely at these data, we noticed that the Core Length measurement was several inches shorter than the Height of Snow (including several in the 6-13" range), indicating that the volume of the snow sample in the tube was smaller than reported, and given the nature of the snow*

Figure 4. Dust on snow near the intersection of Road 634 and Road 52 on the approach to Black Mesa SNOTEL (photo source: Dolores Water Conservancy District).

structure, likely missing mass. After adjustment of the calculation using the Core Length to calculate snow volume, we generated adjusted snow density estimates for each hole. Here we present the adjusted snow density estimates which were higher than the original reported density measurements and more consistent with snow pillow information in the region.

Snow course measurements

Trout Lake #2 was the only snow course location monitored in the May 1 survey window (on April 25) in the Dolores (**Table 3**). At this location, the reported snow density was 303 kg/m^3 in 0.8 m of snow depth.

It is important to adjust for ongoing densification given that this measurement is now 15 days old. After adjustment for densification between the measurement dates (at an estimated rate of 5 kg/m^3/day based on observed densification at Black Mesa SNOTEL) – the projected density at Trout Lake #2 on May 10 is 378 kg/m^3, a value that is lower than the guidance from the hole-by-hole information.

With the relatively long interval between the snow course observations and the airborne survey date (15 days), the high temporal variability in the snow pack right now, and the inconsistency with the DWCD in-situ measurements, we have relatively low confidence in the snow course network for constraining snow densities in the Dolores.

Sensor measurements

Of the five automated stations operating in the Dolores (**Table 4**), the only station with sufficient snow depth to extract a snow density signal is at Black Mesa SNOTEL. On May 10 in 1.2 m (48”) of snow, the snow density at this location is 456 ± 3 kg/m^3. Note: the variability listed in **Figure 5** represents the temporal change at Black Mesa in a 5-day window.

The guidance from the snow pillow information is consistent with that of the adjusted hole-by-hole measurements from the DWCD staff.

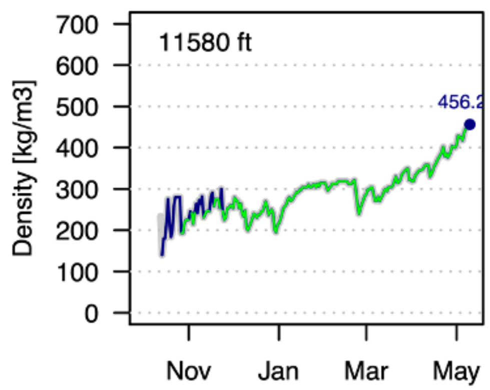


Figure 5. *Daily snow density timeseries at Black Mesa SNOTEL station in the Dolores River basin since October 2021. Gray represents all data, blue represents >10 cm snow depth, and green represents >30 cm snow depth (data source: NRCS).*

Regional measurements

In such a dynamic snow pack, and with very few robust measurements of snow density, we expand our assessment of the available in-situ data throughout the region to include snow course and SNOTEL locations as far north as the Elk Mountains (**Table 5**). The collated information shows a mean of 463 ± 52 kg/m^3 from the SNOTEL network and 412 ± 63 kg/m^3 from the snow course network. The regional statistics give us confidence in the adjusted hole-by-hole data.

Physically-based model - iSnobal

As this is the second ASO survey of the Dolores this season, the iSnobal model has been updated with information from our previous survey on April 15.

The mean bulk snow density from the model for May 10 is 565 ± 34 kg/m^3, a value much higher than any of the observations suggest. In shallow snowpack (<0.6 m), the model tends to overestimate snow density – a behavior we have seen previously from the model (**Figure 6**). In deeper snow, the model is still overestimating bulk snow density (by ~11%), but the distribution is much closer to the observations.

Snow density refinement

From this information it is clear that the model is overestimating bulk snow density and an adjustment is required. We rescaled bulk snow density at depths < 0.6 m to 80% of their original value, and for deeper snow we rescaled the densities to 83% of their original value. After these density adjustments, the mean bulk density was 455 ± 21 kg/m^3 and snow densities in shallow snow were reduced from 573 to 459 kg/m^3, which is much more consistent with the in-situ guidance.

Using the un-adjusted model (open-loop) densities, the basin SWE volume was 75 TAF. The model adjustments bring the basin SWE down to 61 TAF. To get a sense of the scale of impact of these density adjustments on basin SWE, additional sensitivity testing reveals that with a very low snow density (mean of 360 kg/m^3), the basin SWE would be 49 TAF, and with a very high snow density (mean of 540 kg/m^3), the basin SWE would be 73 TAF.

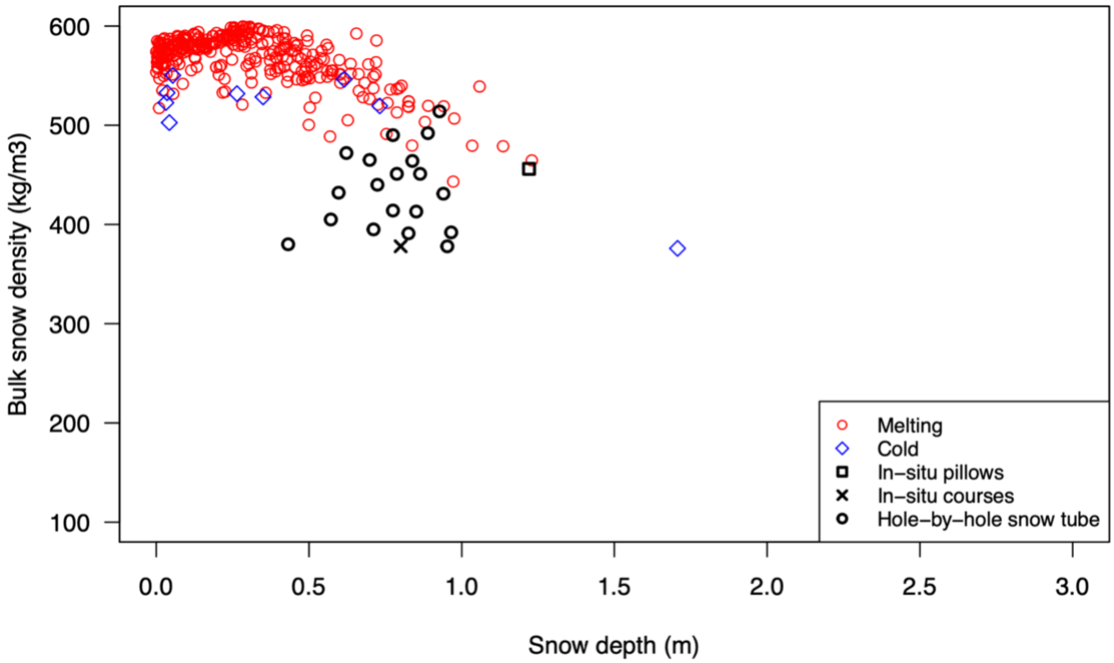


Figure 6. Observed and unadjusted modeled bulk snow density (kg/m³) by snow depth (m) on May 10, 2022. Squares represent density observations at snow pillows, Xs represent density observations at snow courses. Red circles represent modeled densities of melting snow (cold content = 0), blue diamonds represent modeled densities of cold snow (cold content < 0).

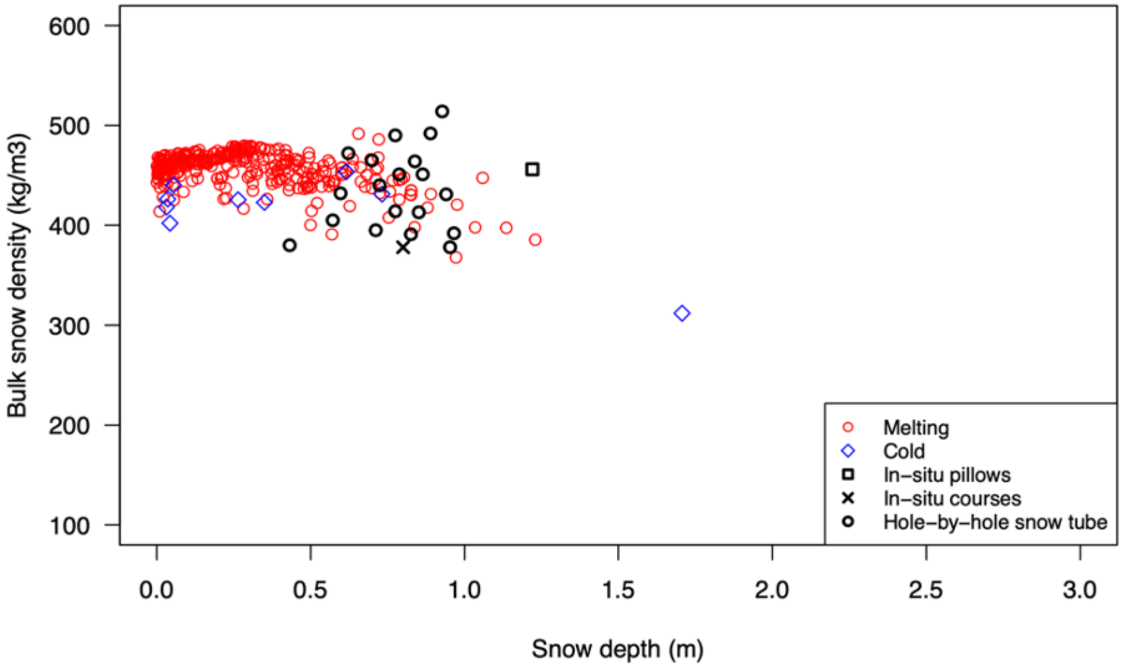


Figure 7. Observed and adjusted modeled bulk snow density (kg/m³) by snow depth (m) on May 10, 2022. Squares represent density observations at snow pillows, Xs represent density observations at snow courses. Red circles represent modeled densities of melting snow (cold content = 0), blue diamonds represent modeled densities of cold snow (cold content < 0).

Additional data / remarks

Table 3. Snow density, depth, and SWE estimates from the snow course network (data source: NRCS).

Site name	Site code	Elevation (ft)	Date	Density (kg/m³)	Time adj. (day)	Adj. density (kg/m³)	Depth (m)	SWE (m)
Trout Lake #2	07M28	9780	4/25/22	303	-15	378	0.8	0.2

*Table 4. Snow density, depth, and SWE estimates from the SNOTEL network (data source: NRCS). *Excluded from snow density analysis.*

Station name	Station code	Elevation (ft)	Date	Density (kg/m³)	Depth (m)	SWE (m)
Black Mesa	1185	11580	5/10/22	456	1.2	0.6
Sharkstooth*	1060	10720	5/10/22	NA	0.0	NA
Lizard Head Pass*	586	10200	5/10/22	NA	0.0	NA
El Diente Peak*	465	10000	5/10/22	NA	0.0	0.0
Scotch Creek*	739	9100	5/10/22	NA	0.0	0.0

*Table 5. SNOTEL and snow course data from neighboring watersheds around the time of the airborne survey on May 10 (data source: NRCS). *Excluded from snow density analysis.*

Site name	Network	Elevation (ft)	Date	Density (kg/m³)	Adj. density (kg/m³)	Depth (m)
Black Mesa	SNOTEL	11564	5/10/22	473	NA	1.1
Red Mountain Pass	SNOTEL	11080	5/10/22	384	NA	0.6
Wolf Creek Summit	SNOTEL	10957	5/10/22	538	NA	0.5
South Colony*	SNOTEL	10868	5/10/22	141	NA	1.2
Columbus Basin	SNOTEL	10781	5/10/22	392	NA	0.6
Porphyry Creek	Snow course	10760	4/27/22	352	417	0.8
Upper Taylor*	SNOTEL	10717	5/10/22	817	NA	0.2

Additional data / remarks

Table 5, continued.

Site name	Network	Elevation (ft)	Date	Density (kg/m³)	Adj. density (kg/m³)	Depth (m)
Schofield Pass	SNOTEL	10653	5/10/22	498	NA	1.3
Lostman	Snow course	10626	4/29/22	308	363	1.0
Independence Pass	Snow course	10600	4/27/22	308	373	0.7
Independence Pass	SNOTEL	10598	5/10/22	475	NA	0.2
Monarch Offshoot	Snow course	10500	4/27/22	391	456	0.9
Twin Lakes Tunnel	Snow course	10450	4/26/22	275	345	0.6
Saint Elmo	Snow course	10400	4/28/22	316	376	1.0
Mesa Lakes	SNOTEL	10168	5/10/22	464	NA	0.4
Lake City	Snow course	10160	4/27/22	257	322	0.2
Pinos Mill	Snow course	10000	4/28/22	465	525	0.7
Mesa Lakes	Snow course	10000	4/27/22	428	493	1.0
Park Reservoir	SNOTEL	9987	5/10/22	476	NA	1.3
Keystone	Snow course	9960	4/27/22	404	469	0.6
Platoro	Snow course	9880	4/27/22	413	478	0.4
Trout Lake	Snow course	9780	4/25/22	303	378	0.8
Cucharas Creek	Snow course	9700	4/26/22	285	355	0.3
Ironton Park	Snow course	9600	4/25/22	282	357	0.4
Park Cone	Snow course	9600	4/28/22	350	410	0.5
Crested Butte	Snow course	8920	4/27/22	414	479	0.4

Additional data / remarks

Table 6. *Volume of SWE (AF) by elevation range for the full Dolores River basin on April 15 and May 1.*

Elevation range (ft)	April 15 survey	May 10 survey	Difference
6000 - 6999	0	0	0
7000 - 7999	34	0	-34
8000 - 8999	4923	2	-4921
9000 - 9999	39728	1089	-38639
10000 - 10999	91490	29968	-61522
11000 - 11999	45774	25666	-20108
12000 - 12999	5158	3632	-1526
13000 - 13999	852	601	-251

Table 7. *Total area (mi^2), snow-covered area (mi^2), band coverage (%), SWE volume (AF), and mean SWE depth (m) by elevation range (ft).*

Elevation range (ft)	Total area (mi^2)	Snow-covered area (mi^2)	Band coverage (%)	SWE volume (AF)	Mean SWE depth (m)
6000 - 6999	1	0	0	0	NA
7000 - 7999	43	0	0	0	NA
8000 - 8999	113	0	0	2	1
9000 - 9999	147	22	15	1089	1
10000 - 10999	139	117	85	29968	5
11000 - 11999	52	50	96	25666	10
12000 - 12999	8	7	89	3632	10
13000 - 13999	2	1	91	601	8

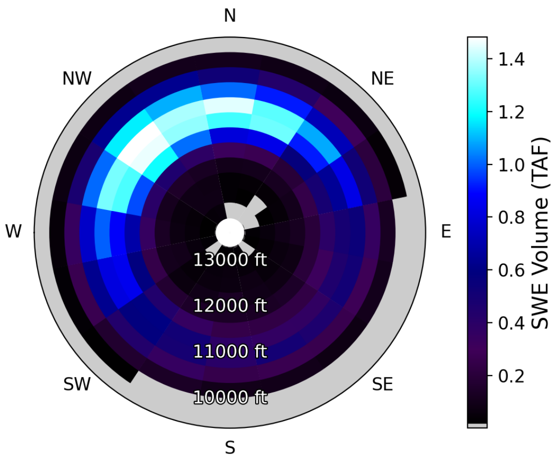
Additional data / remarks

Table 8. *Other SWE (TAF) and runoff forecasts (TAF) products for the Dolores River basin around the time of the May 10 airborne survey (data sources: Colorado SNODAS Dashboard, CBRFC Dolores (DOLC2) Water Supply Forecast page, and NRCS Interactive SWE Map).*

SWE estimate	Date	SWE (TAF)
SNODAS	5/10/22	82
Runoff forecasts	**Date**	**10% / 50% / 90% exceedance (TAF)**
NRCS April - July Runoff Dolores River at Dolores	5/1/22	169 / 128 / 94
CBRFC	5/1/22	169 / 130 / 100
Runoff forecasts	**Date**	**April - July volume (TAF)**
CBRFC ESP	5/10/22	137

Additional data / remarks

8.a.



8.b.

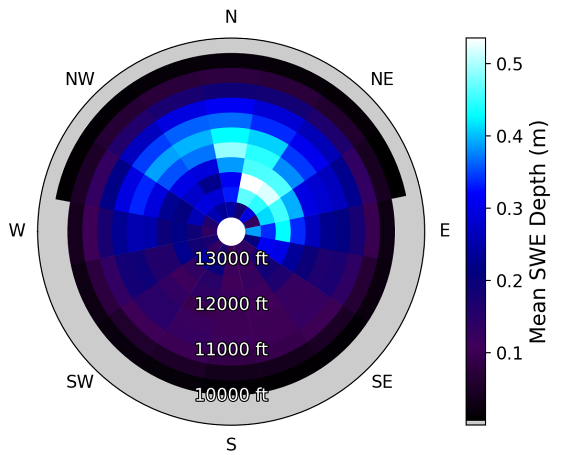
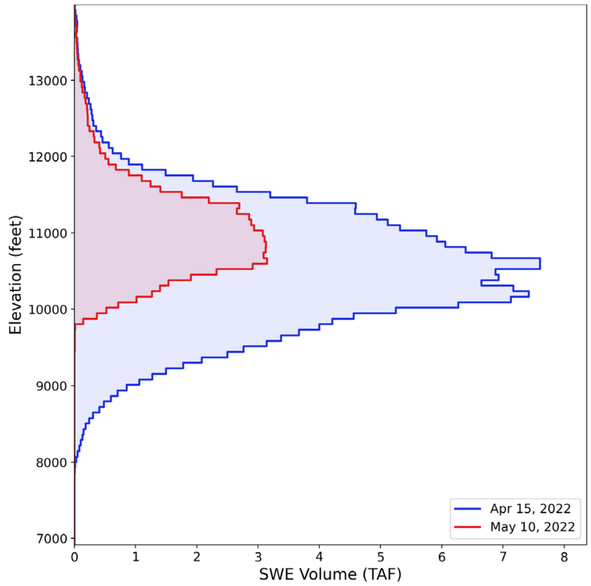


Figure 8. Distribution of SWE by aspect and elevation 8.a. SWE volume (TAF) and 8.b. SWE depth (m) for May 10 survey.

9.a.



9.b.

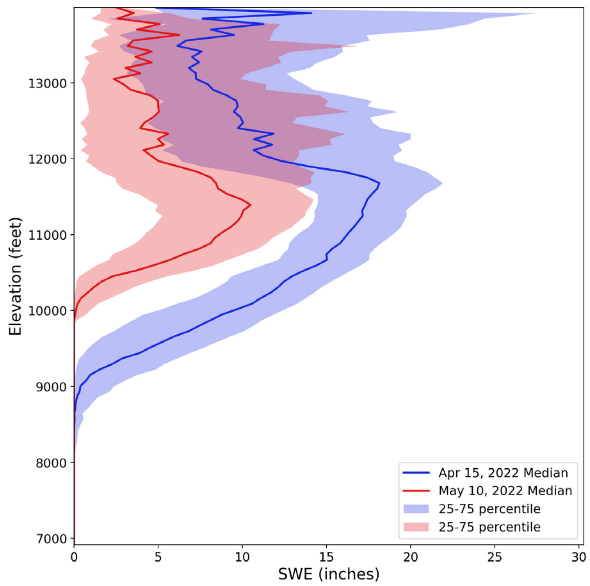


Figure 9. Difference plots of SWE volume (TAF) and depth (in) across elevations. 9.a. Distribution of SWE volume (TAF) across elevations; red represents the May 10 survey, blue represents the April 15 survey. 9.b. Distribution of SWE depth (in) across elevations; red represents the May 10 survey, blue represents the April 15 survey; solid lines represent median SWE depth (in), lighter color bands represent the 25th to 75th percentiles.

ASO Survey Report

East River basin, CO

Survey date: April 21, 2022

Report delivered April 24, 2022

Airborne Snow Observatories, Inc. is a public benefit corporation with a mission to provide high-quality, timely, and accurate snow measurement, modeling, and runoff forecasts to empower the world's water managers to make the best possible use of our planet's precious water.

Historical data and reports can be found at:
data.airbornesnowobservatories.com

Survey Date: April 21, 2022
Survey # of Water Year 2022: 1
Report Delivery Date: April 24, 2022
Version: 0

Full basin SWE: 177 ± 9 TAF
Estimated snowline: 8850 ft

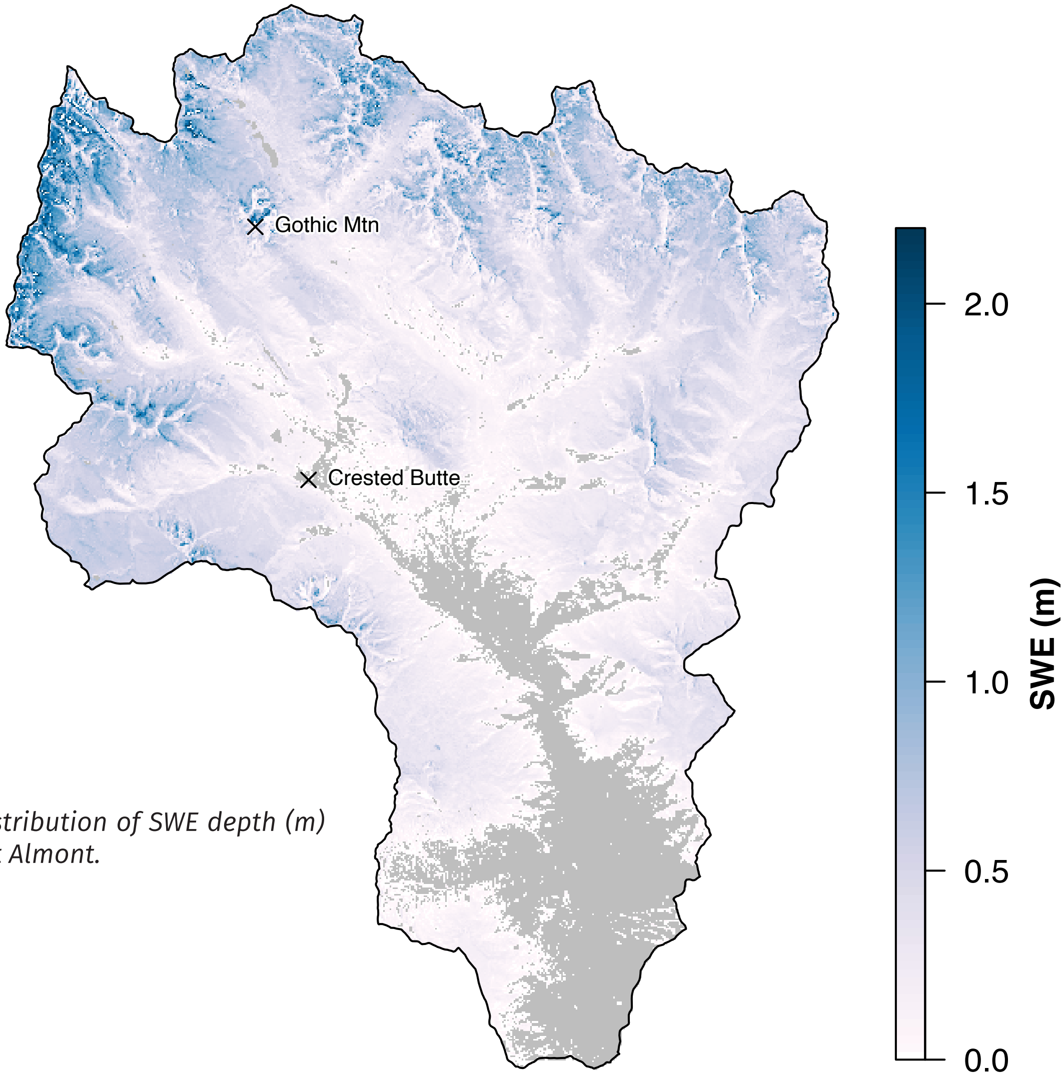


Figure 1. Spatial distribution of SWE depth (m) for the East River at Almont.

Table 1. Estimated SWE volume (TAF) and uncertainty range for the East River basin of the Gunnison.

Basin	Estimated SWE volume (TAF)
Full Basin	177
Uncertainty range	*168 - 186*

Summary of background conditions

Central Colorado received a significant series of storms in mid-late December during which about half of the current snowpack was deposited. January and the first half of February were exceptionally dry with very little precipitation and plenty of wind. Since late February, there have been a series of snowfall events, adding to the December accumulations at the station locations. Several of these spring storms have been accompanied by desert dust deposition, resulting in a number of dust layers at and near the snow surface.

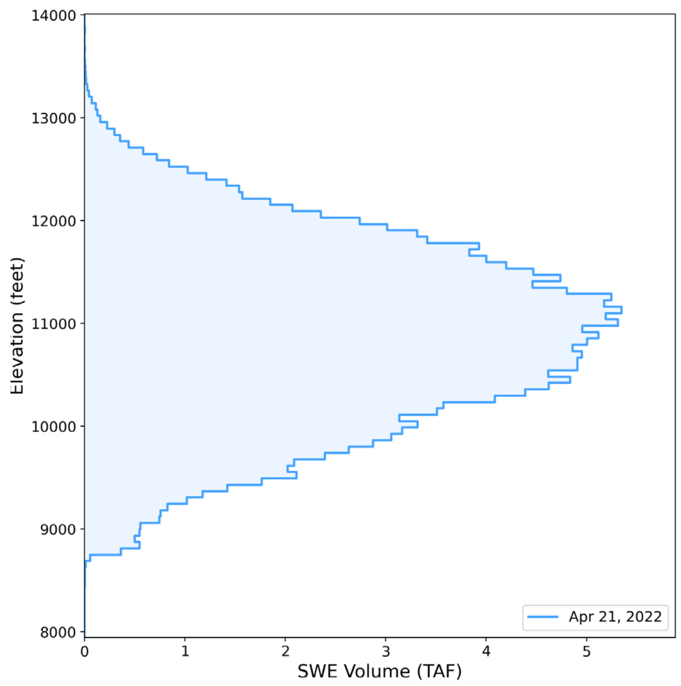
From the automated SNOTEL stations across the Upper Gunnison, within the last week SWE has started to rapidly decline at all monitored elevations (9629 - 10717 ft). Figure 3 shows meteorological information from Butte (SNOTEL 380) at 10200 ft.

The overnight surface air temperatures remain below the melting point, thus limiting the snowmelt to daytime at elevations above 9620 ft. The most recent snowfall event deposited < 2.5 cm (or < 1”) at the Butte SNOTEL on April 13, seven days prior to the airborne survey. We do not expect this snowfall to impact bulk snow densities on April 21 and there has not been any significant snowfall across the Upper Gunnison during April.

Evaluation of ASO snow depth measurements

Snow-free, planar surfaces, common between the snow-on and snow-off datasets, are used to co-register the elevation datasets throughout the basin. This relative registration process ensures that in areas without snow,

2.a.



2.b.

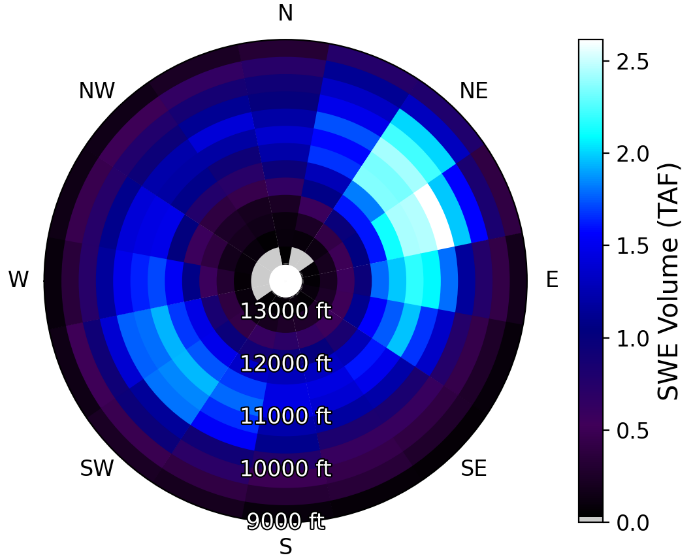


Figure 2.a. *Distribution of SWE volume (TAF) across elevations.* **Figure 2.b.** *Distribution of SWE volume (TAF) by aspect and elevation. See* **Figure 8** *and* **Figure 9** *for more descriptive plots.*

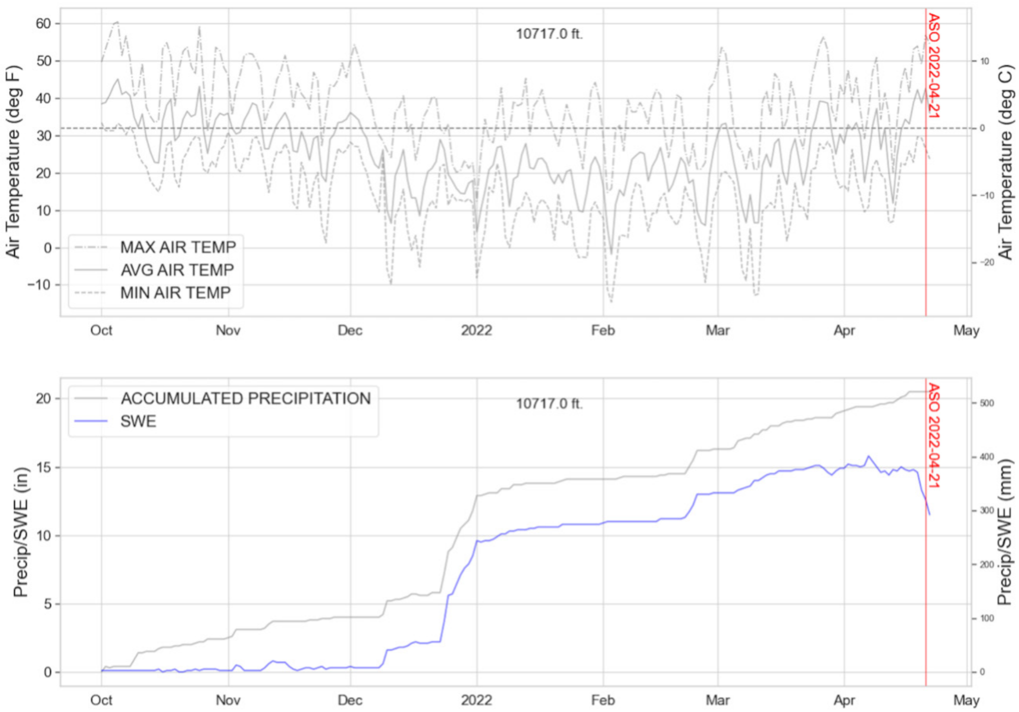


Figure 3. Daily meteorological conditions at Butte SNOTEL (elevation 10200 ft). Note: the raw daily data shown has been downloaded directly from NRCS and has not been quality checked. There may be noise or incorrect data present. Precipitation data will only be shown if the featured station records it, and the air temperature plot shows daily max, mean, and min values. ASO surveys are marked with red vertical lines.

we measure a snow depth of 0, and forces snow depth accuracy throughout. At 3 m resolution, the standard deviation of snow depth distribution was 0.01 m, unbiased. At 50 m resolution, the snow depth uncertainty based on a rigorous bare surface evaluation is less than 0.01 m.

Point-to-point comparison of ASO 3 m resolution snow depths and densities at in-situ sensor locations is shown in **Table 2**.

Snow density constraint

Field collections

The ASO Field Team dug a snow pit on Snodgrass Mountain at 10300 ft on April 17. The Lawrence Berkeley Lab team dug three snow pits in the East and Taylor River basins on April 16 and 17. These data were used for density and depth ground-checking and are listed in **Table 3**.

Snow course measurements

Three snow course locations were monitored during the April 1 survey window (March 29 - 30) in the East and Taylor River basins (**Table 4**). At these locations, the mean bulk snow density was 309 ± 39 kg/m^3.

It is important to note that these measurements are now 22 days old and snow density has changed during this time. There are two factors to consider: ongoing densification of the snowpack and the impact of the recent fresh snow. We can estimate the net impact of these two opposing processes

Table 2. Comparison of ASO with in-situ station (SNOTEL and other automated weather stations) snow depths. Note: ASO long-term depth uncertainty is ± 8 cm. +Outside the East and Taylor River basins.

Site name	Elevation (ft)	Date	Site depth (cm)	ASO depth (cm)	Depth difference (cm)
Schofield Pass SNOTEL+	10700	4/21/22	193	189	-4
Upper Taylor SNOTEL	10640	4/21/22	76	65	-11
Butte SNOTEL	10190	4/21/22	64	68	5
Park Cone SNOTEL	9600	4/21/22	69	76	7
USGS NGWOS Lake Irwin station	10453	4/21/22	138	146	8
Irwin Guides station	10423	4/21/22	144	144	0
Pumphouse EC Flux station	9060	4/21/22	37	38	1
				Mean	1

on snow density by looking at the 22-day change at the snow pillow locations. At all three SNOTEL locations, we observe a mean net change of 3.3 kg/m^3/day. This densification value is reasonably high for this time of year, however it does reflect the recent rapid SWE decline. As expected, the impact of the small fresh snowfall events on snow density has not offset any ongoing densification for the period between March 30 and April 21. After applying this adjustment rate, the time-and-fresh-snow-adjusted snow course estimate is 383 ± 37 kg/m^3.

Given the relatively long interval between the snow course observations and the airborne survey date (22 days) , we have low confidence in the snow course network for constraining snow densities in East Gunnison and Taylor River basins.

Sensor measurements

There is one SNOTEL stations operating in the East River basin and two operating in the Taylor River basin (**Table 5**). Additionally, the Schofield Pass SNOTEL sits just outside the East River basin to the north and is commonly used for SWE monitoring in this area. However, the Schofield Pass SNOTEL densities are anomalously high so we have excluded them from our

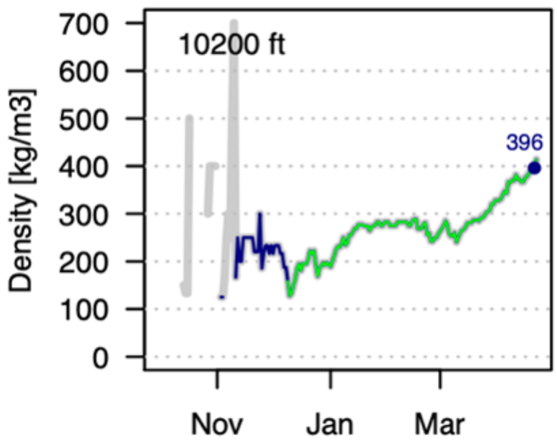


Figure 4. Daily snow density timeseries at Butte SNOTEL location (elevation 10200 ft) since October 2021. Gray represents all data, blue represents >10 cm snow depth, and green represents >30 cm snow depth. (data source: NRCS).

density evaluation. The mean bulk snow density from the other three locations is 399 ± 20 kg/m^3. These estimates are reasonably consistent with the time-adjusted snow course estimates. We have high confidence in these measurements for constraining the snow densities in East and Taylor River basins (**Figure 4**) and increased confidence in the snow course estimates from these values.

Physically-based model - iSnobal

As this is the first survey of the season in the East River basin, the iSnobal model is only now being updated with data from the April 21 airborne survey.

The mean bulk snow density from the model for April 21 is 462 ± 60 kg/m^3. A breakdown of bulk snow density with depth reveals that at depths > 1.1 m, the mean bulk snow density is 393 kg/m^3 and a little more consistent with the in-situ measurements. For snow depths < 1.1 m, the mean modeled snow density is 488 kg/m^3, much higher than the in-situ measurements (**Figure 5**). In general, the model is overestimating bulk snow density particularly when the snow is melting, a behavior we have seen perviously from the model. The majority of snow density overestimations appear to be at elevations below 12000 ft (**Figure 6**), which encompasses most of the basin. We do not have any in-situ measurements above 11000 ft, and as such the bulk snow densities in these areas of the basin remain somewhat unconstrained.

At collocated pixels, the modeled bulk snow densities have a mean absolute error of 111 kg/m^3, which is unusually large (**Figure 7**). The larger discrepancies occur at elevations below 10000 ft, as we saw in **Figure 6**.

Snow density refinement

The guidance from the in-situ measurements suggests that the model is overestimating snow density in general but more so in shallower snow pack (< 1.1 m). To address these biases, we rescaled bulk density for depths < 1.1 m to 75% of their original value (for example, reducing high densities of 480kg/m^3 to 360 kg/m^3).

After this density adjustment, the biases are reduced substantially to 21 kg/m^3 (**Figure 7**). This adjustment reduces the dynamic range in the spatial variability of bulk snow density in the model, better matching the in-situ observations and removing the bias observed in shallow snow. Using the un-adjusted model (open-loop) densities, the basin SWE volume was 214 TAF.

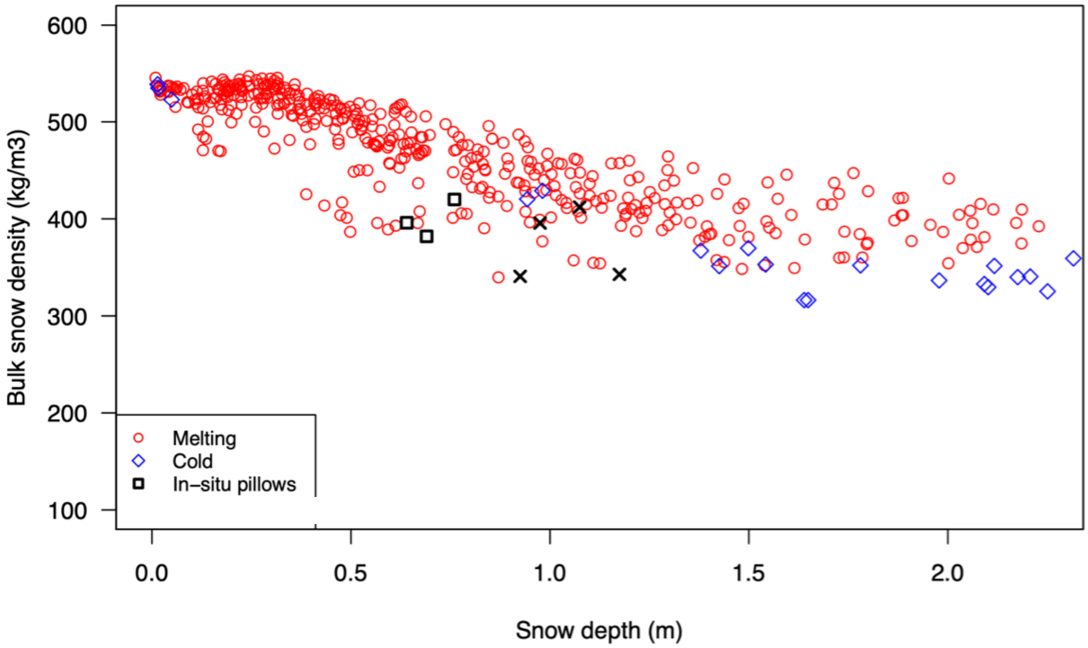


Figure 5. Observed and unadjusted modeled bulk snow density (kg/m³) by snow depth (m) on April 21, 2022. Squares represent density observations at snow pillows, Xs represent density observations at snow courses. Red circles represent modeled densities of melting snow (cold content = 0), blue diamonds represent modeled densities of cold snow (cold content < 0).

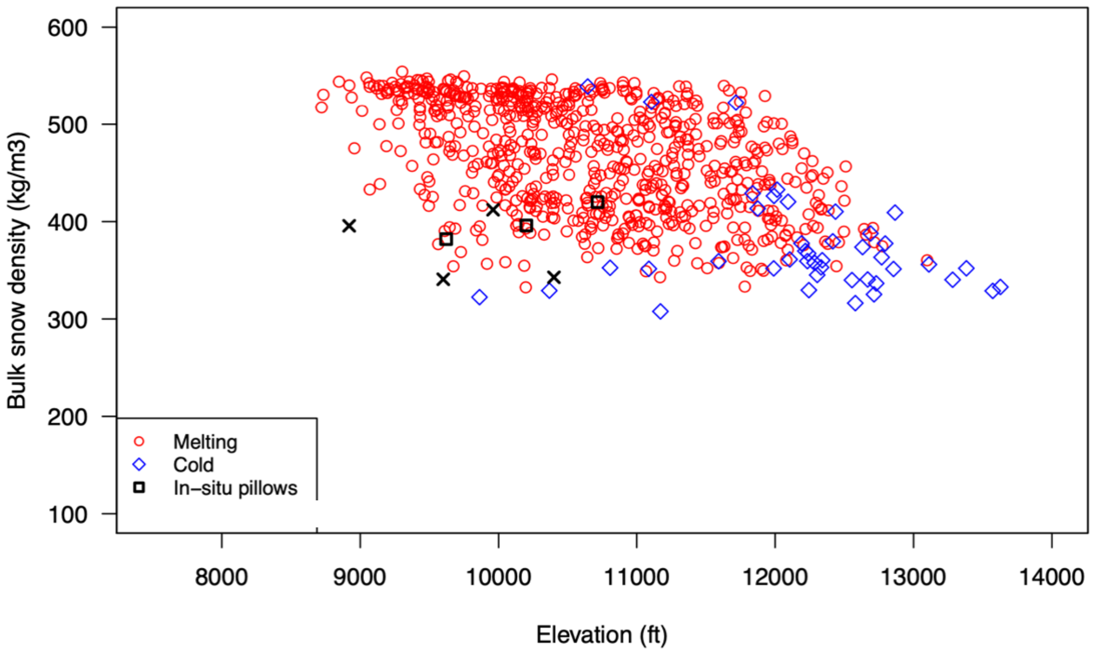


Figure 6. Observed and adjusted modeled bulk snow density (kg/m³) by snow depth (m) on April 21, 2022. Squares represent density observations at snow pillows, Xs represent density observations at snow courses. Red circles represent modeled densities of melting snow (cold content = 0), blue diamonds represent modeled densities of cold snow (cold content < 0).

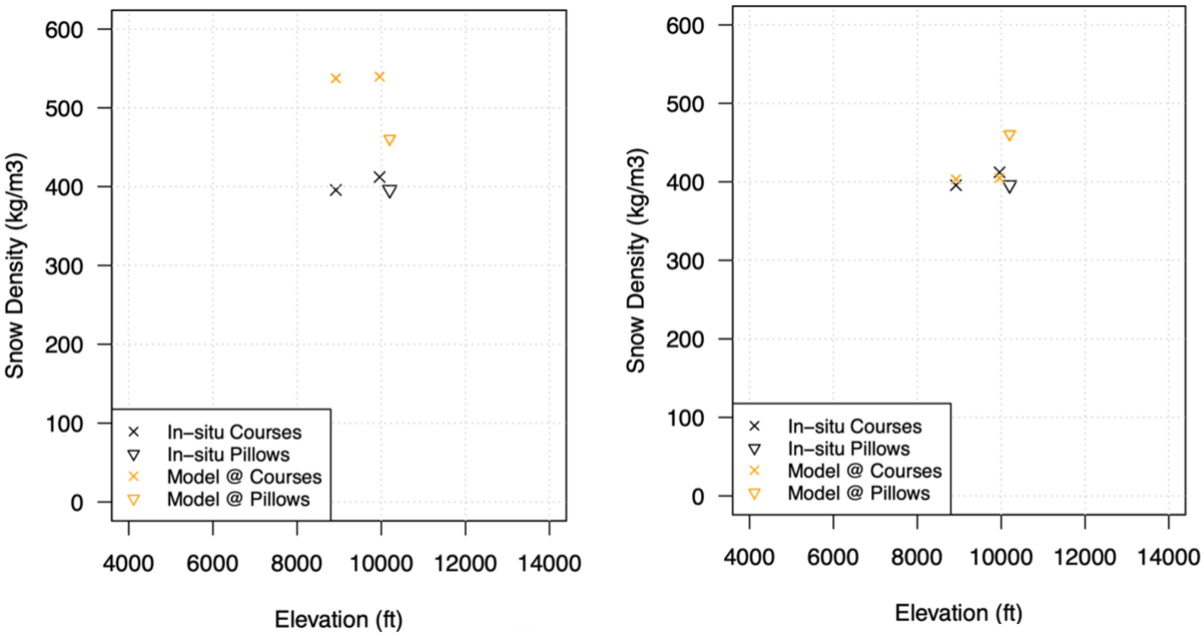


Figure 7. Model comparison at collocated snow courses and snow pillows in the East Gunnison basin before (left) and after (right) the density adjustment. The vertical bars show the variability in the model (±1σ) within the nine surrounding pixels. After adjustments, the modeled bulk snow densities are much more consistent with the in-situ measurements. (Note: the locations of these snow pillows and snow courses come from NRCS and we caution that there is uncertainty with these coordinates).

Additional data / remarks

Table 3. Comparison of ASO with manual snow pit densities adjusted for densification from measurement to airborne survey date.

Pit site	Elevation (ft)	Date	Pit depth (m)	Density (kg/m^3)	Adj. density (kg/m^3)	ASO density (kg/m^3)	Difference (kg/m^3)
Irwin	10451	4/16	186	350	358	345	13
Snodgrass	10328	4/17	138	401	409	389	20
Park Cone	9619	4/16	80	366	374	345	29
Brush Creek	9172	4/17	53	444	452	392	60
						Mean	31

Table 4. Snow density, depth, and SWE estimates from the snow course network (data source: NRCS).

Site name	Site code	Elevation (ft)	Date	Density (kg/m^3)	Time adj. (day)	Adj. density (kg/m^3)	Depth (m)	SWE (m)
Keystone	07L04	9960	3/30/22	340	-22	412	1.1	0.4
Park Cone	06L02	9600	3/29/22	265	-23	341	0.9	0.2
Crested Butte	07L01	8920	3/30/22	323	-22	396	1.0	0.3

*Table 5. Snow density, depth, and SWE estimates from the SNOTEL network (data source: NRCS). *Excluded from density analysis.*

Station name	Station code	Elevation (ft)	Date	Density (kg/m^3)	Depth (m)	SWE (m)
Upper Taylor	1141	10717	4/21/22	420	0.8	0.3
Schofield Pass*	737	10700	4/21/22	466	1.9	0.9
Butte	380	10200	4/21/22	396	0.6	0.3
Park Cone	680	9621	4/21/22	381	0.7	0.3

Additional data / remarks

Table 6. *Total area (mi^2), snow-covered area (mi^2), band coverage (%), SWE volume (AF), and mean SWE depth (m) by elevation range (ft).*

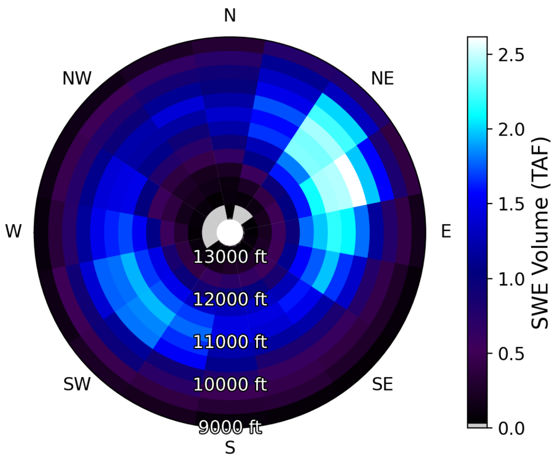
Elevation range (ft)	Total area (mi^2)	Snow-covered area (mi^2)	Band coverage (%)	SWE volume (AF)	Mean SWE depth (m)
8000 - 8999	46	16	36	1875	2
9000 - 9999	83	74	89	26675	7
10000 - 10999	87	87	99	65051	14
11000 - 11999	56	56	100	64600	22
12000 - 12999	16	16	100	17780	21
13000 - 13999	1	1	100	622	15

Table 7. *Other SWE (TAF) and runoff forecasts (TAF) products for the East River basin around the time of the April 21 airborne survey (data sources: Colorado SNODAS Dashboard and CBRFC East River - Almont (ALEC2) Water Supply Forecast page). Mid-month CBRFC and NRCS forecasts were not available at time of reporting.*

SWE estimates	Date	SWE (TAF)
SNODAS	4/21/22	194
AJRO forecasts	**Date**	**10% / 50% / 90% exceedance (TAF)**
CBRFC	4/1/22	220 / 176 / 140
NRCS	4/1/22	220 / 177 / 137
AJRO forecast	**Date**	**SWE (TAF)**
CBRFC ESP	4/21/22	165

Additional data / remarks

8.a.



8.b.

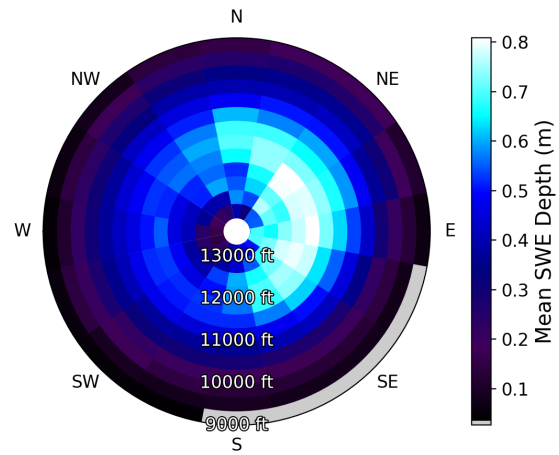
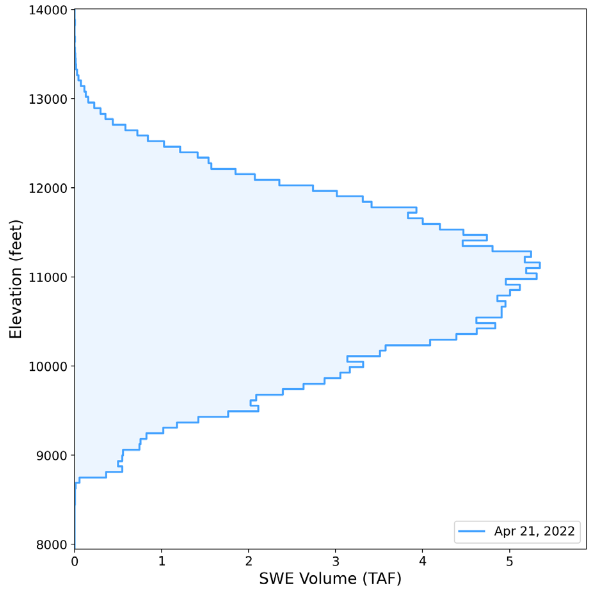


Figure 8. Distribution of SWE by aspect and elevation 8.a. SWE volume (TAF) and 8.b. SWE depth (m) on April 21.

9.a.



9.b.

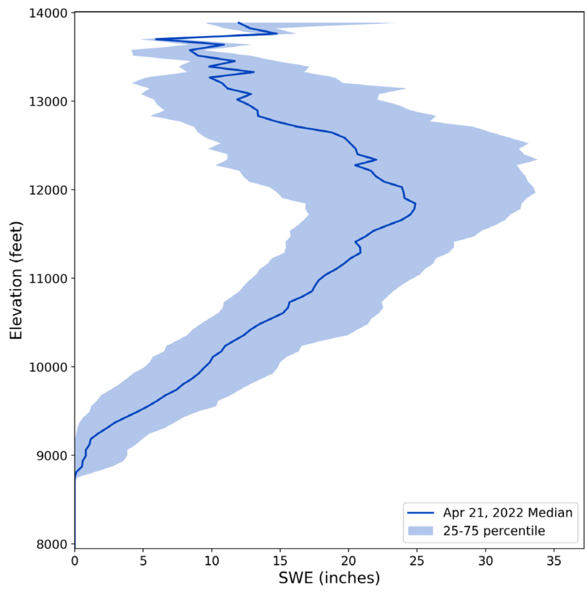


Figure 9. Distribution of SWE depth (in) and volume (TAF) across elevations. 9.a. SWE volume (TAF) and 9.b. SWE depth (n); dark blue line represents median SWE depth (in), lighter blue band represents the 25th to 75th percentile.

ASO Survey Report

Taylor River Basin, CO

Survey date: May 25, 2022

Report delivered May 27, 2022

Airborne Snow Observatories, Inc. is a public benefit corporation with a mission to provide high-quality, timely, and accurate snow measurement, modeling, and runoff forecasts to empower the world's water managers to make the best possible use of our planet's precious water.

Historical data and reports can be found at:
data.airbornesnowobservatories.com

TAYLOR RIVER BASIN
MAY 25, 2022 SURVEY

Survey Date: May 25, 2022
Survey # of Water Year 2022: 2
Report Delivered: May 27, 2022
Version: 0

Full basin SWE: 43 ± 3 TAF
Change in SWE since Apr 21, 2022: -76 TAF
Estimated snowline: 10800 ft

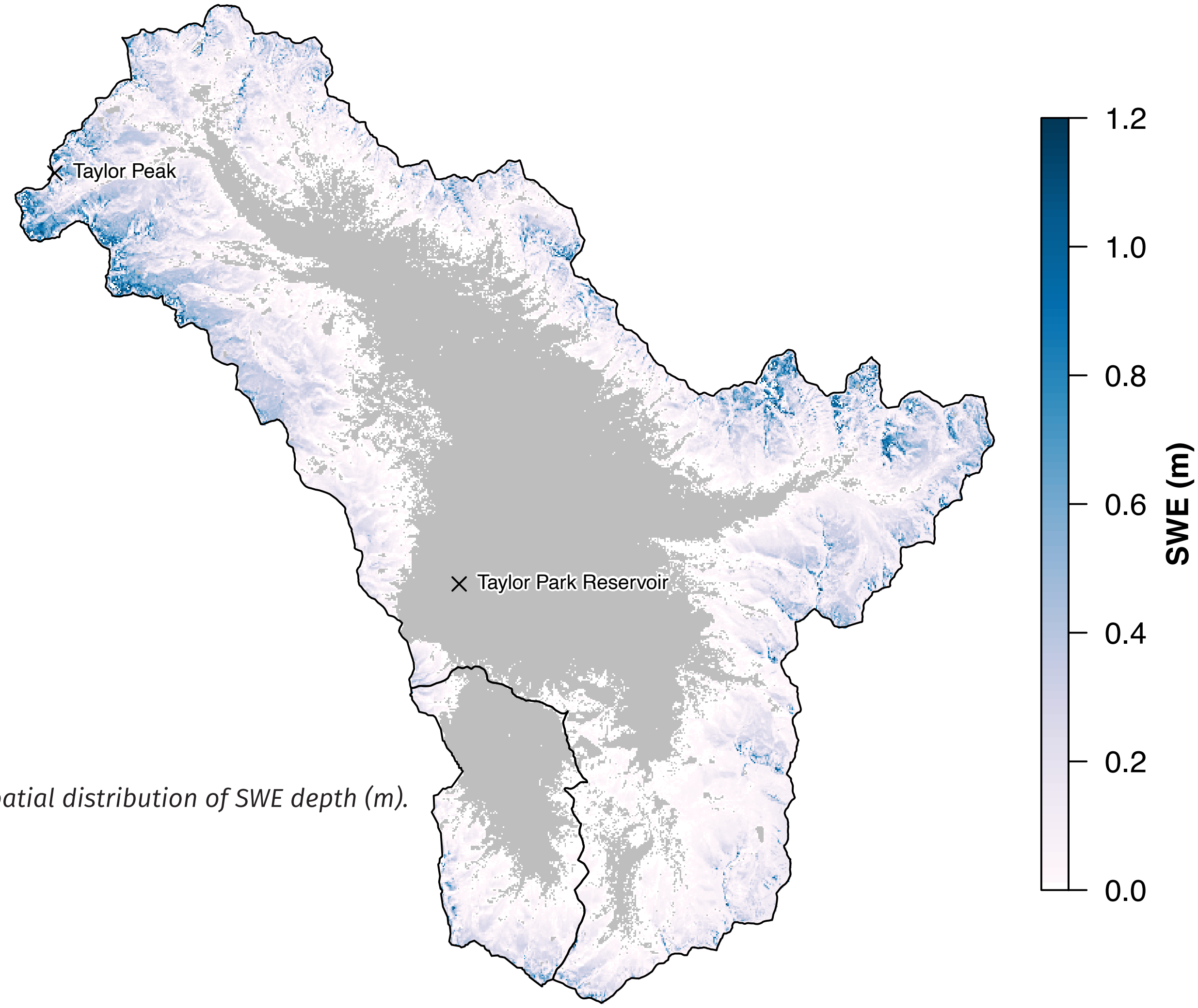


Figure 1. Spatial distribution of SWE depth (m).

Table 1. Estimated SWE volume (TAF) for the Taylor River basin and Lottis Creek for the current survey (May 25) and the previous ASO survey on April 21.

Basin	Estimated SWE volume (TAF) April 21	Estimated SWE volume (TAF) May 25
Full Basin	119	43
Uncertainty range	*113 - 125*	*40 - 46*
Lottis Creek	1	2

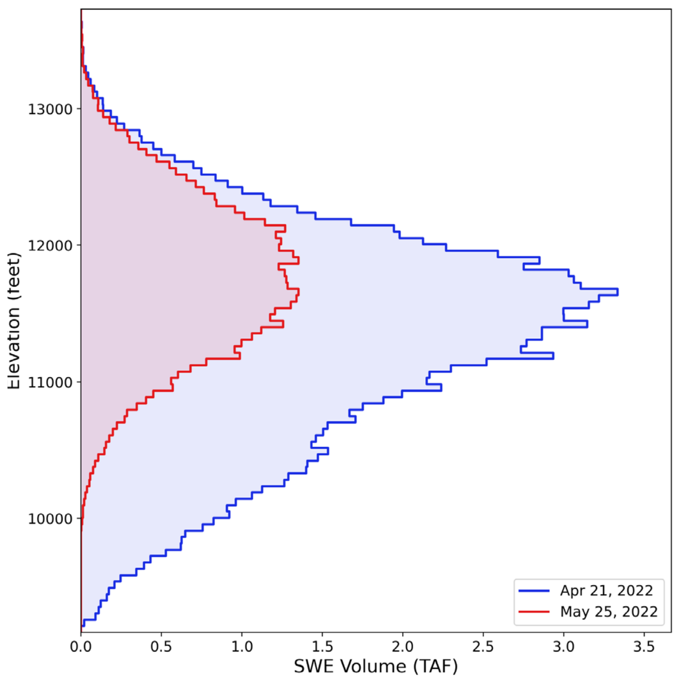
Summary of background conditions

Southwest Colorado received a significant series of storms in mid-late December during which much of the water year's snowpack was deposited. January and the first half of February were exceptionally dry with very little precipitation – rain or snow. Since late February there have been a series of smaller snowfall events to freshen up the snow surface, but nothing substantial. The desert dust deposition that started earlier in the season has continued and even increased in frequency as of late, resulting in substantial dust accumulation at and near the snow surface and a very dirty snowpack surface. Though snowfall in the in the Taylor basin over the past week was not as significant as in more northern basins, it added a little volume, reset albedos through much of the area, and substantially reduced the snowmelt rates.

From the automated station information, the SWE peaked (at 9600 – 10700 ft) in mid-April (just prior to our April 21 survey of the basin) and has been in rapid decline since at all monitored elevations (**Figure 3**) – with complete melt out at all stations by mid-May. The surface air temperatures have been steadily increasing since our previous survey on April 21, such that mean air temperatures have remained above the melting point in the past week, though we are still seeing overnight temperatures drop below the melting point above ~10000 ft, thus limiting snowmelt to daytime.

The most recent snowfall event deposited 0.1-0.15 m (or 4-6") in the upper elevations of the Taylor on May 21, as reported at both Saint Elmo and Upper Taylor SNOTEL locations. The fresh snow

2.a.



2.b.

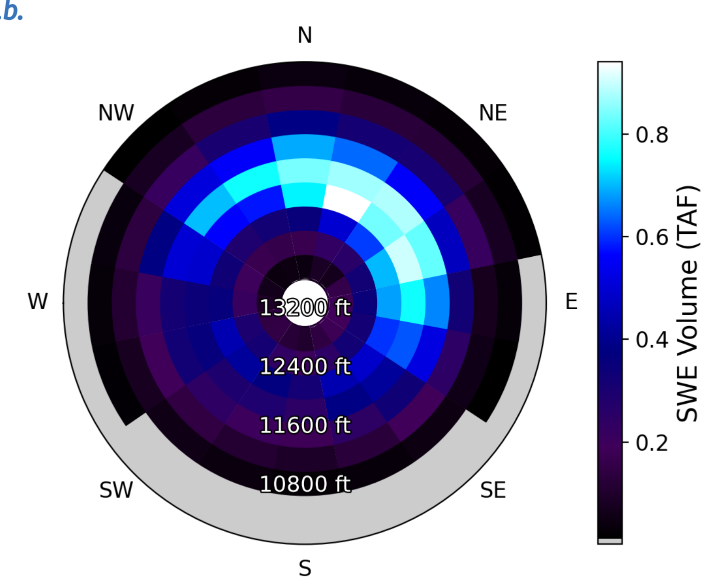


Figure 2.a. *Distribution of SWE volume (TAF) across elevations; red represents the May 25 survey, blue represents the April 21 survey.* ***Figure 2.b.*** *Distribution of SWE volume (TAF) by aspect and elevation for the May 25 survey. See* ***Figure 9*** *and* ***Figure 10*** *for more descriptive plots.*

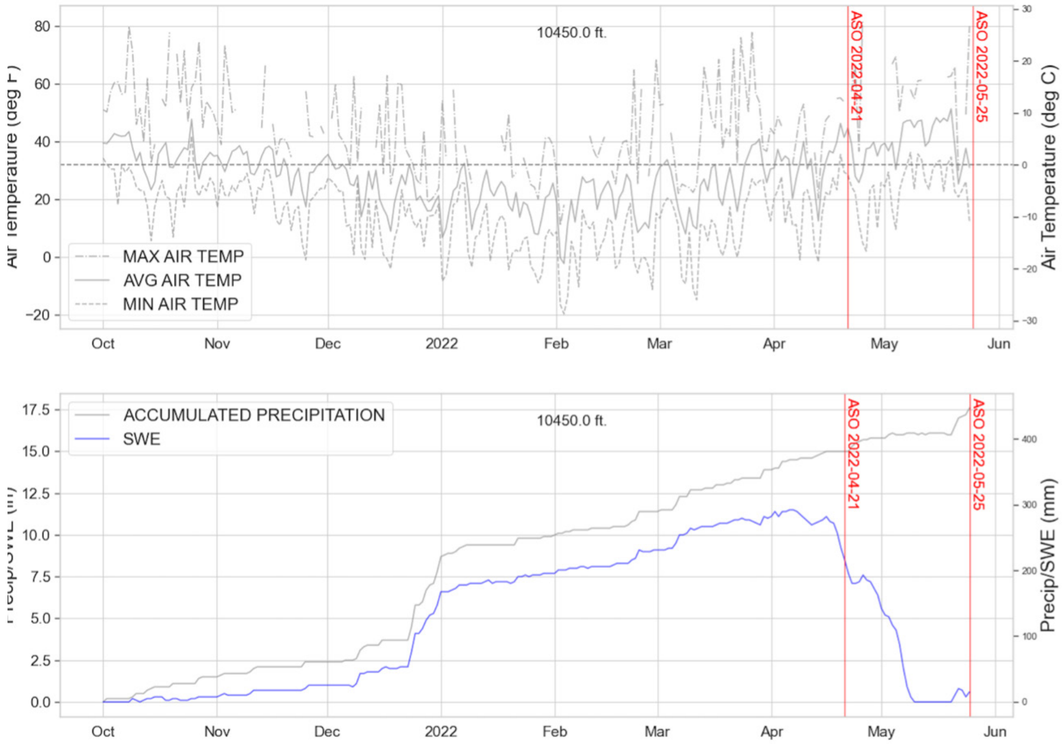


Figure 3. Daily meteorological conditions at Saint Elmo SNOTEL (elevation 10450 ft). Note: the raw daily data shown has been downloaded directly from NRCS and has not been quality checked. There may be noise or incorrect data present. Precipitation data will only be shown if the featured station records it, and the air temperature plot shows daily max, mean, and min values. ASO surveys are marked with red vertical lines.

from this storm contributed 100% of the snow depth at both of these locations, and therefore the bulk snow density at these areas should be more consistent with fresh snow that has settled for four days than base snowpack that has endured the full length of the snow season. We expect that the bulk snow density on May 25 will therefore reflect these recent accumulations.

Evaluation of ASO snow depth measurements

Snow-free, planar surfaces, common between the snow-on and snow-off datasets, are used to co-register the elevation datasets throughout the basin. This relative registration process ensures that in areas without snow, we measure a snow depth of 0, and forces snow depth accuracy throughout. At 3 m resolution, the standard deviation of snow depth distribution was 0.02 m, unbiased. At 50 m resolution, the snow depth uncertainty based on a rigorous bare surface evaluation is less than 0.02 m.

Point-to-point comparison of ASO 3 m resolution snow depths and densities at in-situ sensor locations is shown in **Table 2**.

Table 2. Comparison of ASO with SNOTEL and manual snow depths. Note: ASO long-term depth uncertainty is ± 8 cm.

Site name	Elevation (ft)	Date	Site depth (cm)	ASO depth (cm)	Depth difference (cm)
Park Cone pit	11486	5/25/22	70	71	1
Upper Taylor SNOTEL	10640	5/25/22	0	0	0
Park Cone SNOTEL	9600	5/25/22	0	0	0
				Mean	0.3

Snow density constraint

ASO field collections

A snow pit was excavated for snow density sampling on May 25 in the Taylor in the Park Cone vicinity (38.80393°, -106.60086°, 11480 ft elevation), by the LBNL SFA Field Team. In 0.7 m (or 27.5”) of snow a bulk snow density of 441 ± 5 kg/m^3 was reported in a warm/wet snowpack (**Figure 4**).

In addition, two snow pits were excavated on May 18 – one week prior to Taylor survey – in the neighboring East River basin. At Pit 1, the ASO Field Team sampled an exposed area near Ohio Pass (318048 E, 4301043 UTM Zone 13, 10090 ft elevation) where a bulk snow density of 501 kg/m^3 was recorded in 0.6 m (or 23") of snow. At Pit 2, the Lawrence Berkeley National Lab (LBNL) field crew sampled a forested area at Poverty Gulch (38.95654° N, -107.08391° E, 9616 ft elevation) where a bulk snow density of 428 kg/m^3 was recorded in 0.8 m (or 31”) of snow. These measurements were taken prior to the May 21 snowfall event and therefore reflect the bulk density of the base snowpack prior to the storm.

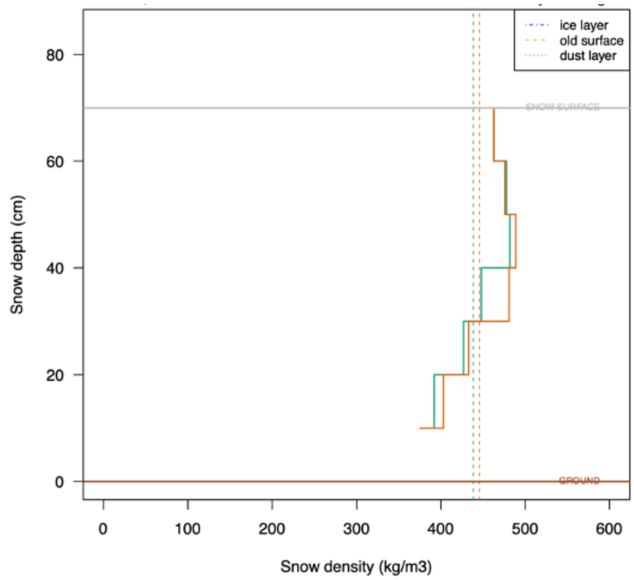


Figure 4. Snow density (kg/m^3) profile for the snow pit dug by the LBNL SFA Field Team on May 25, 2022.

We can estimate the post-storm bulk snow density at these locations – using fresh snow density estimates from the SNOTEL data of 100 kg/m^3 and a densification rate of 18 kg/m^3/day (based on the scientific literature in lieu of nearby reliable SNOTEL data). The resulting estimates are 444 kg/m^3 at Ohio Pass and 393 kg/m^3 at Poverty Gulch (**Table 3**) – note the fresh snow reduced the bulk density by 8-11 % (see calculations in **Table 4** in the "Additional data / remarks" section). The projected values for snow density are consistent with the Park Cone value reported from May 25.

Snow course measurements

There were two snow course locations that were monitored in the May 1 surveys in the Taylor River basin: Park Cone and Saint Elmo on April 28 (**Table 5**). The mean bulk snow density measured at these locations was 333 kg/m^3.

It is important to adjust for ongoing densification as these measurements are now 27 days old and with the fresh snowfall it is difficult to make a robust adjustment to these measurements to account for densification and other changes.

With the relatively long interval between the snow course observations and the airborne survey date (27 days), the high temporal variability in the snowpack right now and challenge of fresh snow contributions - we cannot use these snow course measurements to constrain bulk snow density on May 25.

Sensor measurements

Of the three automated stations operating in or adjacent to the Taylor River basin (**Table 6**), all had melted out by mid-May and while two stations had received fresh snow on May 21, by May 25, the snow had melted such that none of the stations had a robust snow density signal. The only SNOTEL station with any snow in the region that surrounds the Taylor is at Schofield Pass (10653 ft), which is reporting a snow density of 573 kg/m^3 on May 24 in 0.6 m (or 22”) of snow. Based on our experience, and the snow pit measurements, this value seems very high.

The snow pillow network is no longer useful for constraining bulk snow density.

Regional measurements

In such a dynamic snowpack, and with very few robust measurements of snow density, we expand our assessment of the available in-situ data throughout the region to include SNOTEL locations across Colorado (**Table 7**). We exclude May 1 snow course information from this analysis because these measurements are now too old.

The collated information shows a mean of 467 ± 58 kg/m^3 from the SNOTEL network, note the high variability in bulk snow density across the region (**Table 7**). The SNOTEL and snowpit measurements from the Taylor on May 25 compare relatively well to regional statistics.

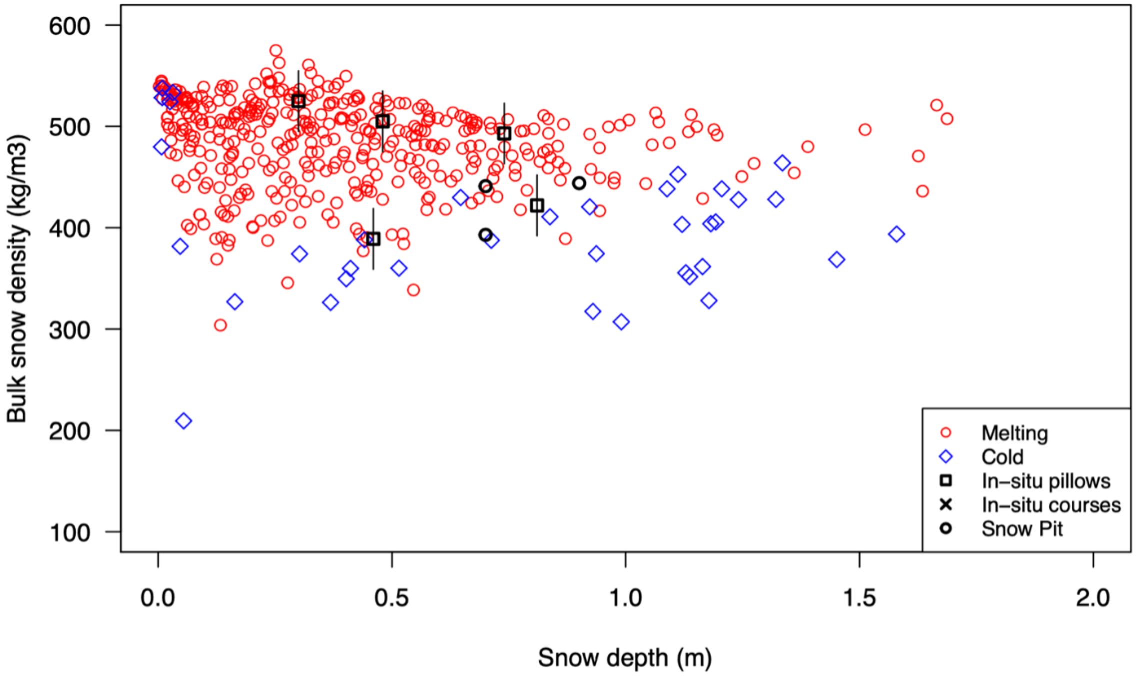


Figure 5. *Observed and modeled bulk snow density (kg/m³) by snow depth (m). Squares represent density observations at snow pillows on May 25, 2022, Xs represent density observations at snow courses, circles represent ASO Field Team observations. Red circles represent modeled densities of melting snow (cold content = 0), blue diamonds represent modeled densities of cold snow (cold content < 0).*

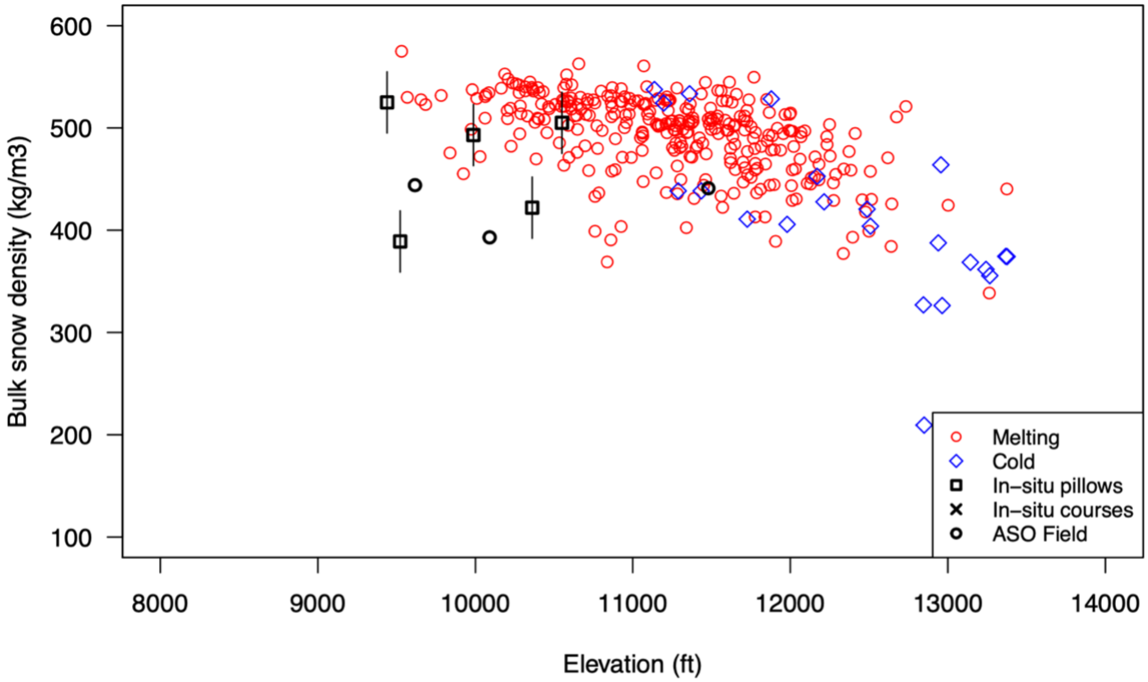


Figure 6. *Observed and modeled bulk snow density (kg/m³) by elevation (ft). Squares represent density observations at snow pillows on May 25, 2022, Xs represent density observations at snow courses, circles represent ASO Field Team observations. Red circles represent modeled densities of melting snow (cold content = 0), blue diamonds represent modeled densities of cold snow (cold content < 0).*

Physically-based model - iSnobal

As this is the second survey of the Taylor River watershed this season, the iSnobal model has been updated with information from our previous survey on April 21.

When plotted against snow depth (**Figure 5**) the model compares well with the in-situ guidance – here we weight the snow pit values higher than the regional snow pillow values, which is reflected through the vertical uncertainty bars on these points. The in-situ measurements were obtained from snow with depths < 1 m – leaving deeper snow unconstrained. When examined by elevation (**Figure 6**), the snow pit information suggests that the model may be overestimating bulk snow density at elevations < 12000 ft.

At collocated pixels, we rely on our manual snow pit measurements (**Table 3**), which reveals a significantly large overestimation by the model (85 kg/m^3 or 16%). There is insufficient information to make any further conclusions.

Table 3. *Comparison of modeled ASO snow density prior to adjustment with manual snow pit snow densities (data source: LBNL SFA Field Team).*

Pit site	Type	Elevation (ft)	Date	Pit depth (m)	In-situ Density (kg/m^3)	ASO model density (kg/m^3)	Difference (kg/m^3)
Park Cone	snow pit	10480	5/25/22	0.7	526	441	+85

Snow density refinement

From this information, the model is overestimating bulk snow density by approximately 14% at all elevations and in particular when snow depths are < 0.6 m – an adjustment is required to remove these biases. We rescaled bulk snow density at depths < 0.6 m to 85% of their original value (for example scaling bulk densities of 560 kg/m^3 to 476 kg/m^3) and for deeper snow we rescaled the densities to 93% of their original value (for example scaling bulk densities of 510 kg/m^3 to 474 kg/m^3).

After density adjustment the mean bulk density was 480 ± 53 kg/m^3 and at collocated pixels, the overestimation is reduced to (14 kg/m^3 or 3%).

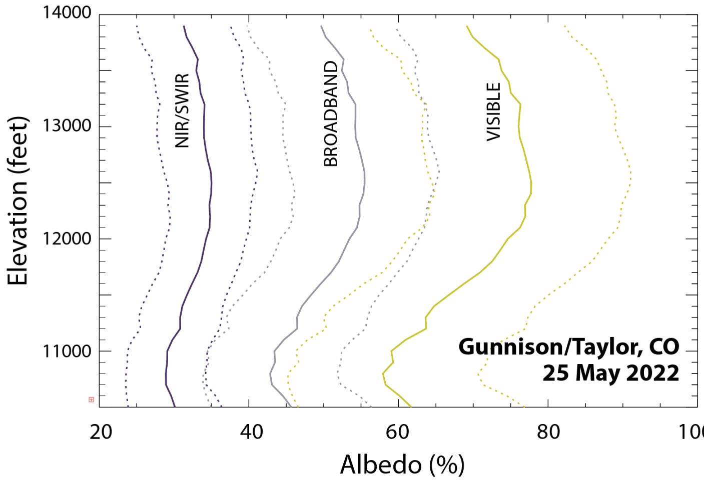
Using the un-adjusted model (open-loop) densities, the basin SWE volume was 46 TAF. The model adjustments bring the basin SWE down to 43 TAF. To get a sense of the scale of impact of these density adjustments on basin SWE, additional sensitivity testing reveals that with a very low snow density (mean of 434 kg/m^3), the basin SWE would be 41 TAF, and with a very high snow density (mean of 469 kg/m^3), the basin SWE would be 44 TAF.

Snow albedo

As described in Painter et al. (2016), in addition to the scanning lidar, ASO also carries a pair of visible to shortwave infrared imaging spectrometers from which we retrieve broadband albedo (400-2500 nm wavelength), visible albedo (400-700 nm), and near-infrared to shortwave-infrared (700-2500 nm). The latter two albedos are generated to ultimately constrain iSnobal and WRF-Hydro, as well as other physically-based models.

Solar radiation is the primary energy source for snowmelt. The snow albedo describes the fraction of incoming solar energy that is reflected by the snow surface.

The broadband albedo values in the Taylor River on May 25 range from around 40% at low elevations to 55% in the mid elevations. The NIR/SWIR values (30-35%) are consistent with the generation of large snow grains due to melt/freeze metamorphism (65-75% absorption), and the visible albedo values (45-70%) suggest extreme impacts due to the presence of dust (40-55% absorption) at the lowest elevations. The higher elevations received a good bit of new snow, dramatically increasing the visible albedo (**Figure 7.a.**). For comparison, **Figure 8.a.** shows the albedo profiles from the adjacent East River on May 18, prior to the snowfall, with strong albedo reductions at all elevations due to dust on the snow surface.



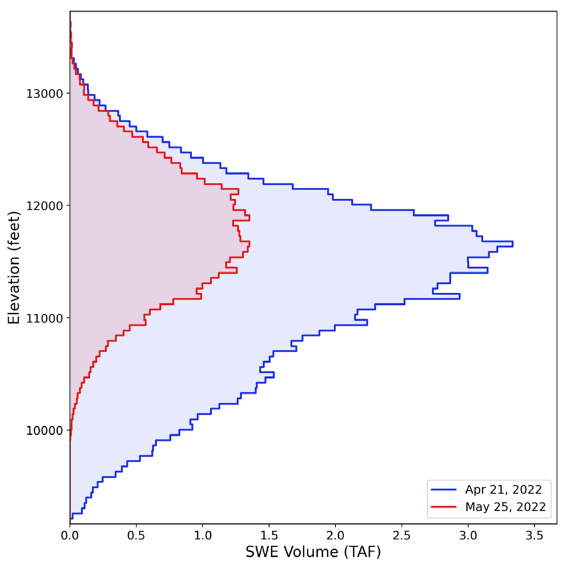
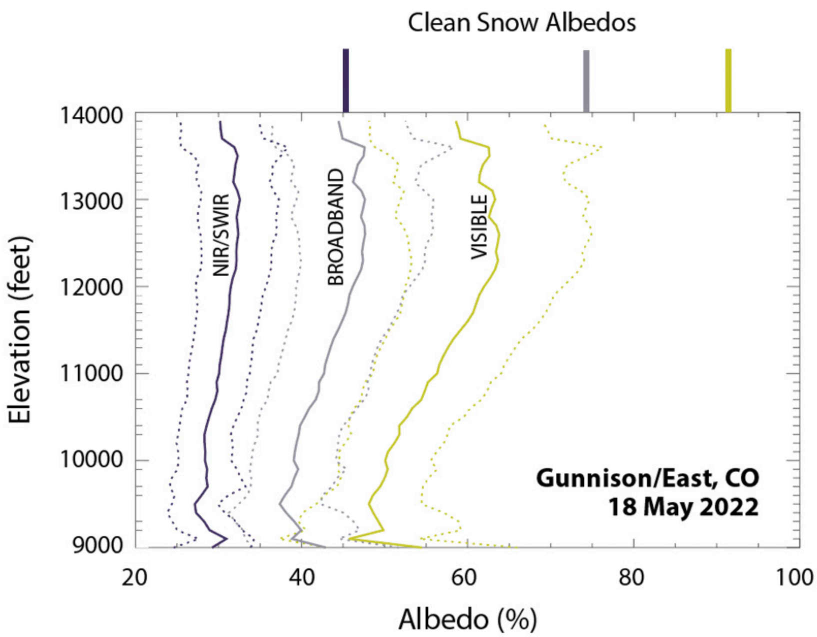


Figure 7.a. Snow albedo (%) by elevation (ft) on May 25 with mean (solid lines) and ± 1 standard deviation (dotted lines) for near and shortwave infrared (dark blue), broadband (gray), and visible (green) wavelengths. 7.b. Distribution of SWE volume (TAF) across elevations; red represents the May 25 survey, blue represents the April 21 survey.



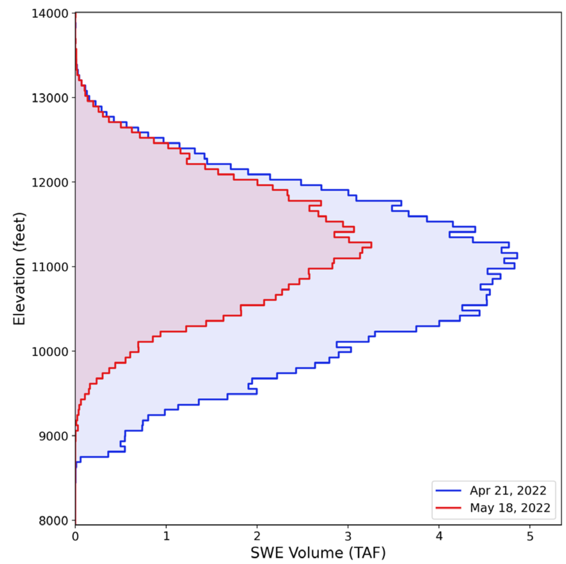


Figure 8.a. Snow albedo (%) by elevation (ft) on May 18 with mean (solid lines) and ± 1 standard deviation (dotted lines) for near and shortwave infrared (dark blue), broadband (gray), and visible (green) wavelengths, with clean snow albedo in each wavelength denoted by hash marks above the plot. 8.b. Distribution of SWE volume (TAF) across elevations; red represents the May 18 survey, blue represents the April 21 survey.

For this time of year, relatively clean snow that has undergone melt/freeze cycles would have albedos of approximately 92% (visible), 74% (broadband), and 45% (NIR/SWIR), absorbing 8%, 26%, and 55% of incoming solar radiation in those respective wavelengths. The recent new snowfall initially would have had even higher albedos, but has since experienced melting, and where the new snow thickness is less than 30 cm / 12 in, the old snow surface is starting to influence visible albedos and is thus additionally hastening melt (**Figure 9**).

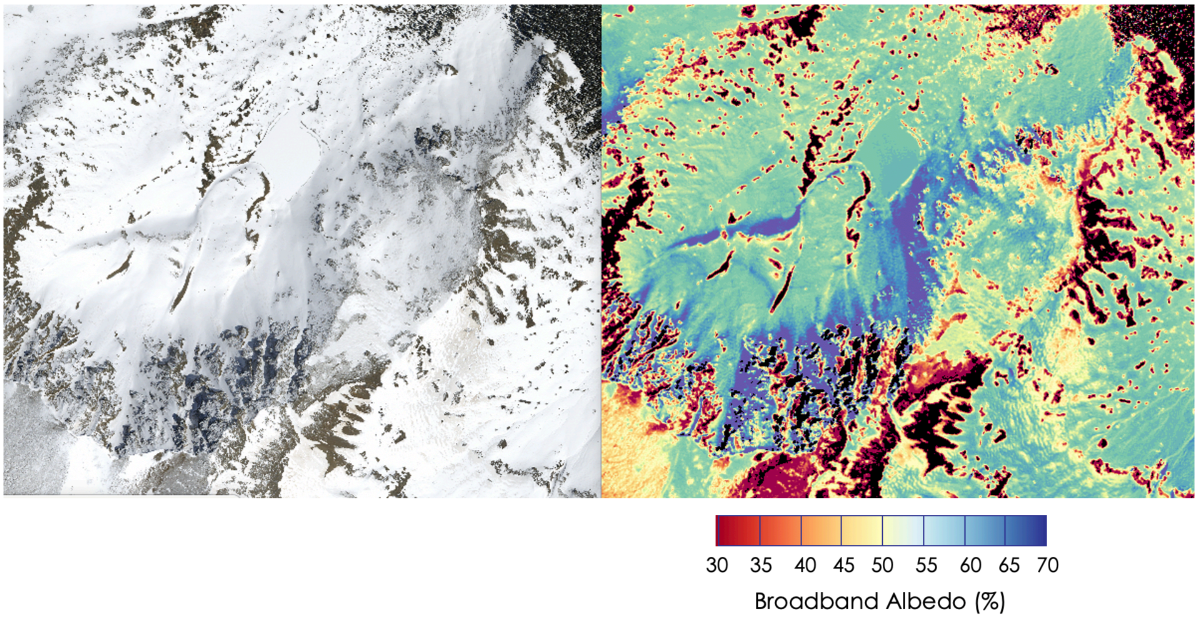


Figure 9. *ASO visible images (left panel) from three of the hundreds of ASO spectral bands over the Upper Taylor River near Larson Peak. Corresponding snow albedo maps (right panel) showing the dramatic impact of dust on snow albedo/solar absorption and the snowpack energy balance.*

Additional data / remarks

Table 4. Scenario calculations showing the potential impact of 4-6" of fresh snowfall on bulk snow densities at snow pit locations for various pre-storm snow depths.

		Prior to May 21 Base snowpack	May 21 contribution Fresh snow (on May 25)	
	Snow density (kg/m3)	501	172	Estimated from in-situ and 18 kg/m3/day
	Depth (m)	0.60	0.13	Fresh snowfall 4-6"
Ohio Pass	Layer, proportion of depth	0.83	0.17	
Snow Pit	Fresh-adjusted snow density (kg/m3)	444		
	% reduction in snow density	11%		
		Prior to May 21 Base snowpack	May 21 contribution Fresh snow (on May 25)	
	Snow density (kg/m3)	428	172	
	Depth (m)	0.8	0.13	
Poverty Gulch	Layer, proportion of depth	0.86	0.14	
Snow Pit	Fresh-adjusted snow density (kg/m3)	393		
	% reduction in snow density	8%		

Table 5. Snow density, depth, and SWE estimates from the snow course network (data source: NRCS).

Site name	Site code	Elevation (ft)	Date	Density (kg/m³)	Time adj. (day)	Adj. density (kg/m³)	Depth (m)	SWE (m)
Saint Elmo	06L05	10400	4/28/22	315.79	-27	315.79	1.0	0.3
Park Cone	06L02	9600	4/28/22	350	-27	350	0.5	0.2

*Table 6. Snow density, depth, and SWE estimates from the SNOTEL network (data source: NRCS). *Excluded from snow density analysis.*

Station name	Station code	Elevation (ft)	Date	Density (kg/m³)	Depth (m)	SWE (m)
Upper Taylor*	1141	10717	5/25/22	NA	NA	0.0
Saint Elmo*	1100	10450	5/25/22	NA	NA	0.0
Park Cone*	680	9621	5/25/22	0.0	0.1	0.0

Additional data / remarks

Table 7. Snow density, depth, and SWE estimates from the regional SNOTEL network (data source: NRCS).

Station Name	Elevation (ft)	Date	Depth (m)	Density (kg/m³)
Elliot Ridge	10549	24-May	0.5	505
University Camp	10360	24-May	0.8	422
Park Reservoir	9987	25-May	0.7	493
Bear Lake	9522	13-May	0.5	389
Wild Basin	9439	24-May	0.3	525

Table 8. Volume of SWE (AF) by subbasin and elevation range (ft).

Elevation range (ft)	Taylor River	Lottis Creek
9000 - 9999	9	0
10000 - 10999	3694	192
11000 - 11999	23496	1343
12000 - 12999	14915	412
13000 - 13999	604	4

Table 9. Change in volume of SWE (AF) since April 21 survey by subbasin and elevation range (ft).

Elevation range (ft)	Taylor River	Lottis Creek
9000 - 9999	-5884	-1058
10000 - 10999	-27047	-3073
11000 - 11999	-36989	-2908
12000 - 12999	-6457	-148
13000 - 13999	-200	0

Additional data / remarks

Table 10. Total area (mi²), snow-covered area (mi²), band coverage (%), SWE volume (AF), and mean SWE depth m) by elevation range (ft).

Elevation range (ft)	Total area (mi²)	Snow-covered area (mi²)	Band coverage (%)	SWE volume (AF)	Mean SWE depth (in)
9000 - 9999	61	1	2	9	< 1
10000 - 10999	86	50	59	3694	1
11000 - 11999	77	74	96	23496	6
12000 - 12999	29	28	99	14915	10
13000 - 13999	2	2	100	604	7

*Table 11. Other SWE (TAF) and runoff forecasts (TAF) products for the Taylor River basin round the time of the May 25 airborne survey (data sources: Colorado SNODAS Dashboard and CBRFC Taylor River - Taylor Park Reservoir (TPIC2) Water Supply Forecast page). *Recent CU-SWE estimates have been adjusted using ASO data as guidance.*

SWE estimates	Date	SWE (TAF)
SNODAS	5/25/22	6
AJRO forecasts	**Date**	**10% / 50% / 90% exceedance (TAF)**
CBRFC	5/1/22	107 / 90 / 79
CBRFC	5/15/22	NA / 87 / NA
NRCS	5/15/22	102 / 83 / 66
AJRO forecast	**Date**	**SWE (TAF)**
CBRFC ESP	5/25/22	86

Additional data / remarks

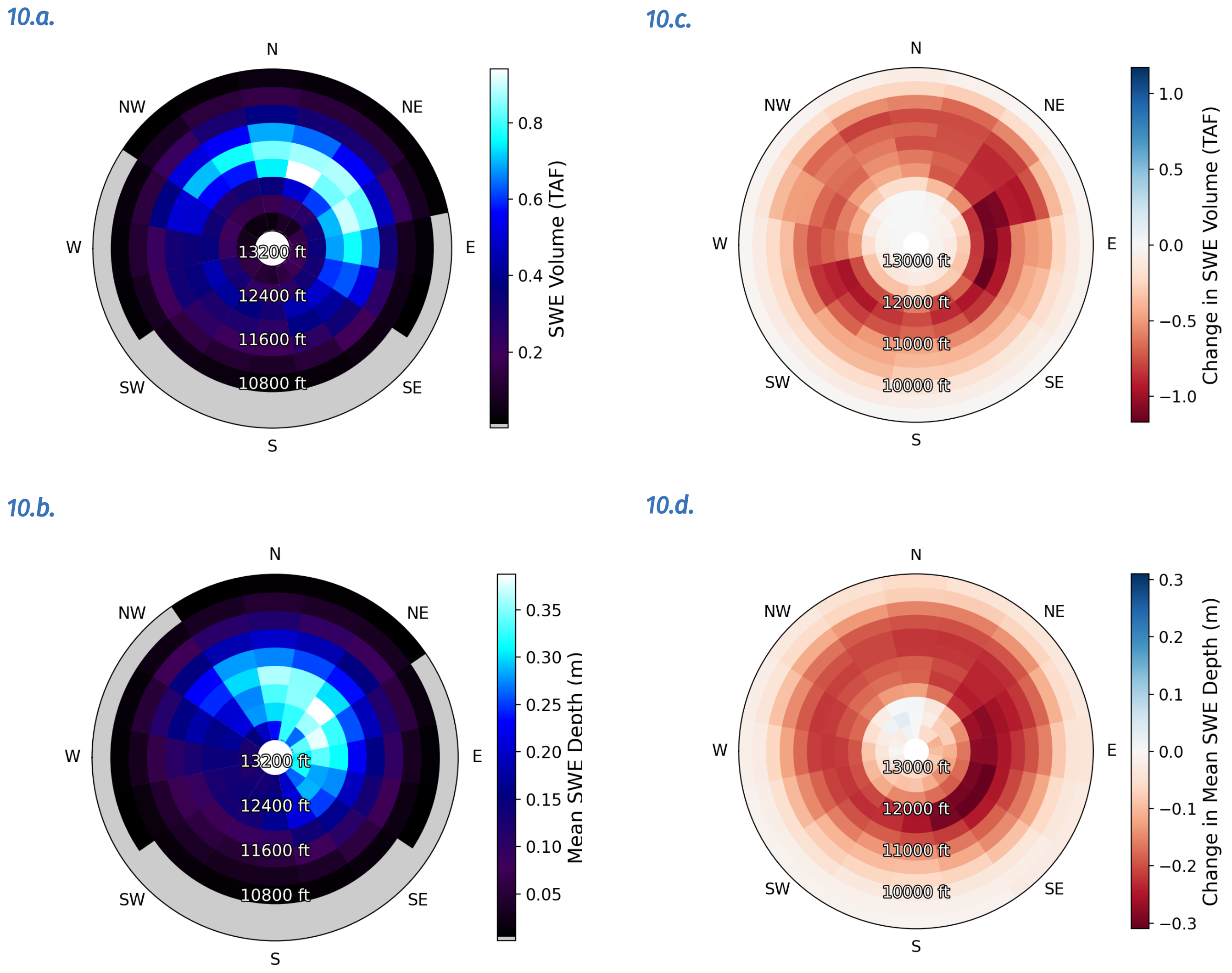
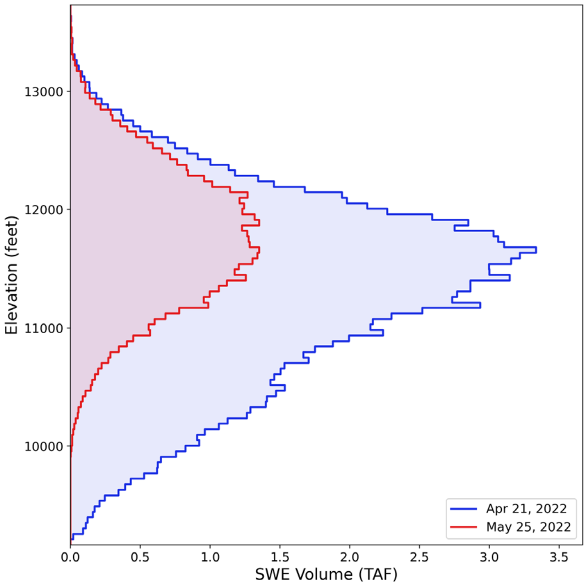


Figure 10. Aspect/elevation SWE and SWE difference plots. 10.a. & b. SWE volume (TAF) and depth (m) from May 25 survey; 10.c. & d. SWE volume (TAF) and depth (m) change from April 21 survey to May 25 survey.

Additional data / remarks

11.a.



11.b.

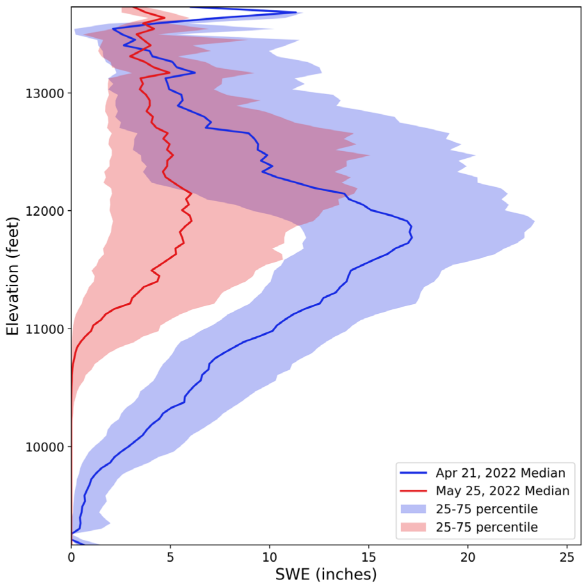


Figure 11. *Difference plots of SWE volume (TAF) and depth (in) across elevations.* ***11.a.*** *Distribution of SWE volume (TAF) across elevations; red represents the May 25 survey, blue represents the April 21 survey.* ***11.b.*** *Distribution of SWE depth (in) across elevations; red represents the May 25 survey, blue represents the April 21 survey; solid lines represent median SWE depth (in), lighter color bands represent the 25th to 75th percentiles.*

ASO Survey Report

Colorado River at Windy Gap, CO

Survey date: May 26, 2022

Report delivered May 29, 2022

Airborne Snow Observatories, Inc. is a public benefit corporation with a mission to provide high-quality, timely, and accurate snow measurement, modeling, and runoff forecasts to empower the world's water managers to make the best possible use of our planet's precious water.

Historical data and reports can be found at:
data.airbornesnowobservatories.com

Survey Date: May 26, 2022
Survey # of Water Year 2022: 2
Report Delivered: May 29, 2022
Version: 0

Full basin SWE: 170 ± 25 TAF
Change in SWE since Apr 18, 2022: -199 TAF
Estimated snowline: 9800 ft

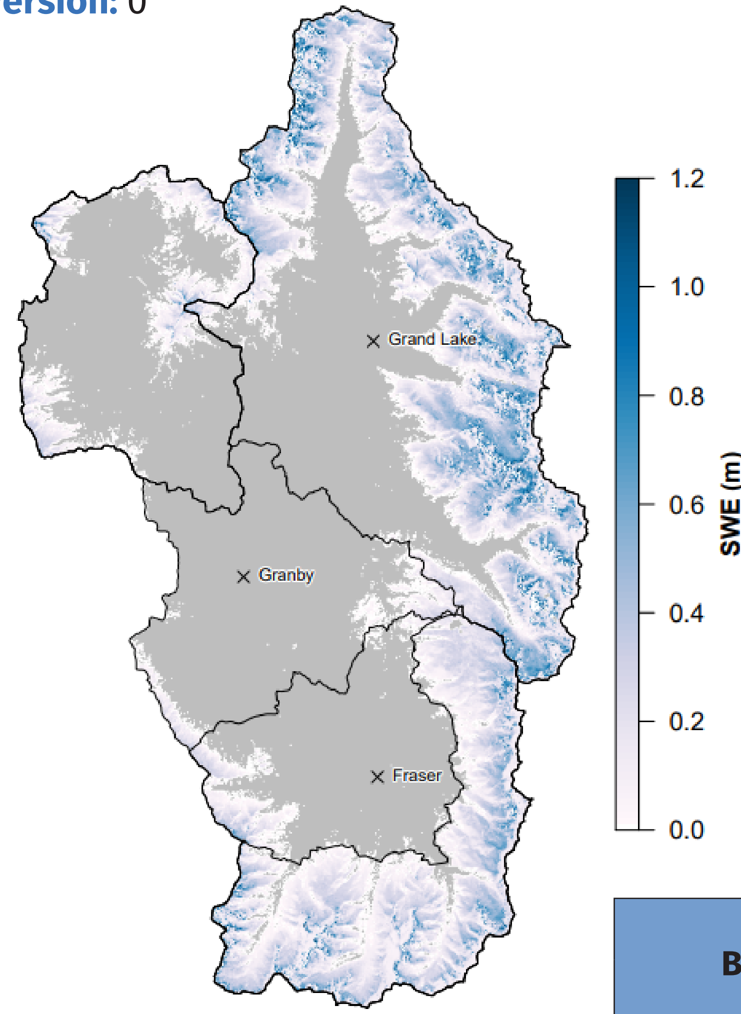


Figure 1. Spatial distribution of SWE depth (m).

Table 1. Estimated SWE volume (TAF) for the Colorado River at Windy Gap and subbasins for the current survey (May 26) and the previous ASO survey on April 18.

Basin	Estimated SWE volume (TAF)	
	April 18	May 26
Full Basin	369	170
Uncertainty range	*351 - 387*	145-195
Fraser River	122	54
Lake Granby	176	109
Willow Creek	48	6
Fraser River at Granby	NA	55
Moffat	NA	51

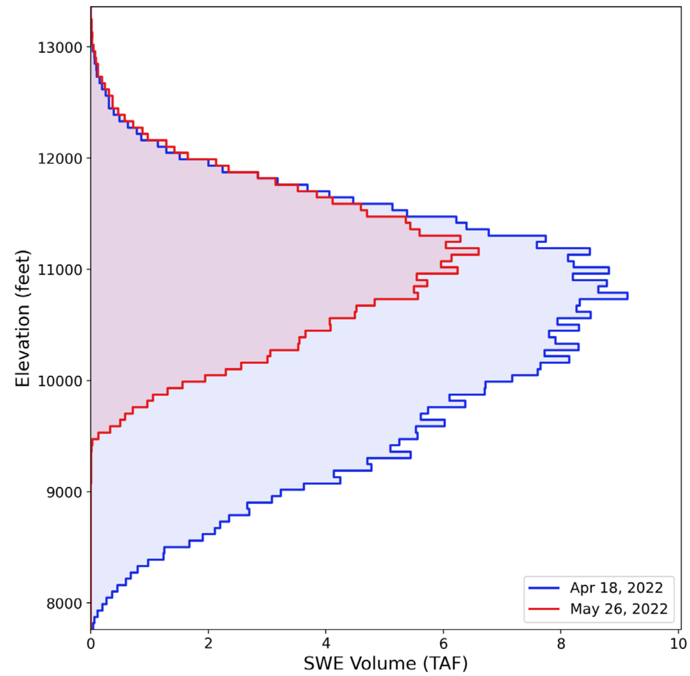
Summary of background conditions

Southwest Colorado received a significant series of storms in mid-late December during which much of the water year's snowpack was deposited. January and the first half of February were exceptionally dry with very little precipitation – rain or snow. Since late February there have been a series of smaller snowfall events to freshen up the snow surface, but nothing substantial. The desert dust deposition that started earlier in the season has continued and even increased in frequency as of late, resulting in substantial dust accumulation at and near the snow surface and a very dirty snowpack surface.

From the automated station information, peak SWE occurred in the first week of May above 10000 ft (after our April 19 survey of the basin). The snowpack then underwent a period of rapid snowmelt with warming surface air temperatures until May 21 when a storm event brought 0.1-0.4 m (or 4-11") of fresh snow to the basin. A few days later on May 25 a second storm deposited < 0.1 m (or 1-5") of fresh snow – based on two SNOTEL stations above 10,00 ft. At lower elevations the fresh snowfall contributions were minimal. The fresh snowfall not only paused snowmelt through freshening of the snow surface but increased the SWE (**Figure 3**) and likely also impacted bulk snow density.

Fresh snow typically has a much lower density than snow that has had time to settle. The fresh snow from the two storms (combined) contributed 15-84% of the snow depth at Lake Irene and Berthoud Summit SNOTEL locations respectively. The bulk snow density on May 26 will therefore reflect the recent accumulations.

2.a.



2.b.

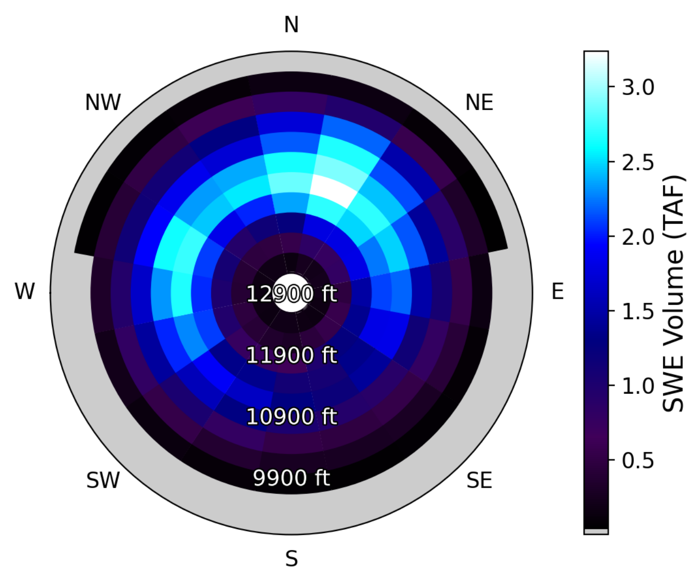


__Figure 2.a.__ Distribution of SWE volume (TAF) across elevations; red represents the May 26 survey, blue represents the April 18 survey. __Figure 2.b.__ Distribution of SWE volume (TAF) by aspect and elevation for the May 26 survey. See __Figure 12__ and __Figure 13__ for more descriptive plots.

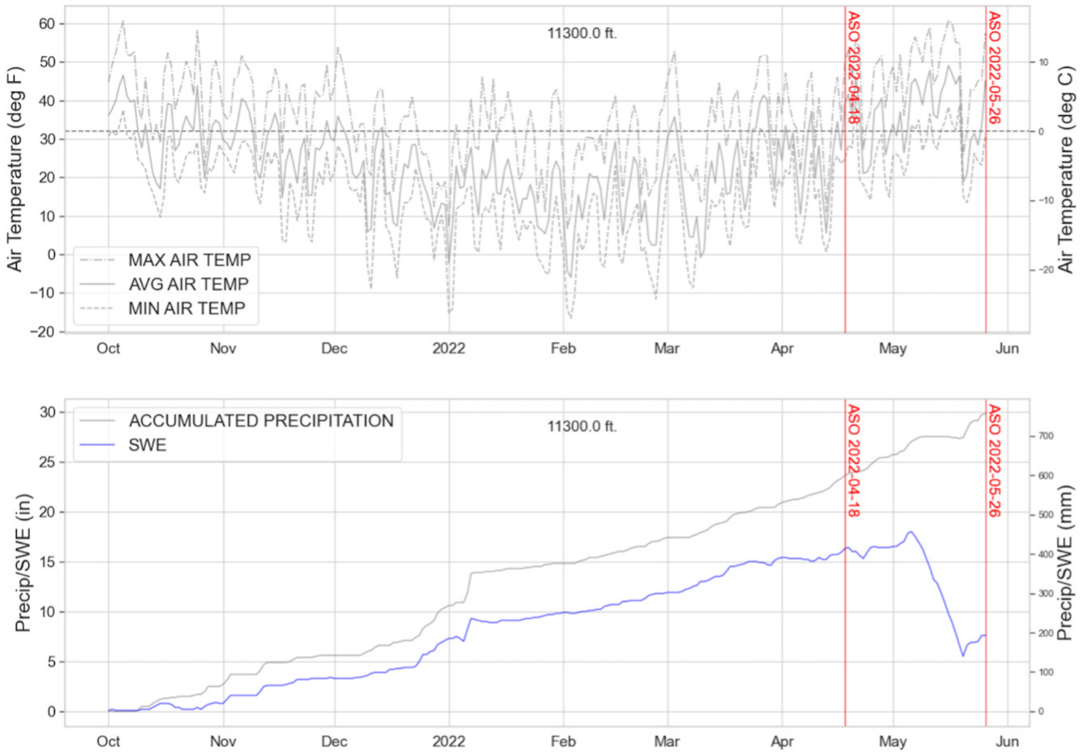


Figure 3. Daily meteorological conditions at Berthoud Summit SNOTEL (elevation 11300 ft). Note: the raw daily data shown has been downloaded directly from NRCS and has not been quality checked. There may be noise or incorrect data present. Precipitation data will only be shown if the featured station records it, and the air temperature plot shows daily max, mean, and min values. ASO surveys are marked with red vertical lines.

Evaluation of ASO snow depth measurements

Snow-free, planar surfaces, common between the snow-on and snow-off datasets, are used to co-register the elevation datasets throughout the basin. This relative registration process ensures that in areas without snow, we measure a snow depth of 0, and forces snow depth accuracy throughout. At 3 m resolution, the standard deviation of snow depth distribution was 0.01 m, unbiased. At 50 m resolution, the snow depth uncertainty based on a rigorous bare surface evaluation is less than 0.02 m.

Point-to-point comparison of ASO 3 m resolution snow depths and densities at in-situ sensor locations is shown in **Table 2**.

Snow density constraint

ASO field collections

Three snow pits were excavated for snow density sampling on May 26 in the Fraser basin by the USGS (**Table 3**). The variability in the bulk density values reflect the impact of the fresh snowfall, where lower bulk snow densities were observed in shallow snowpack – where the contribution of fresh snow to the overall snowpack depth is higher. In such a shallow snowpack, the 162 kg/m^3 observed at Ranch Creek reflects fresh snow density only and helps to place a lower bound on the bulk snow densities where the recent storm deposited snow on previously bare ground. Whereas a bulk snow density of 447 kg/m^3 is more representative of areas where the fresh snow fell on established base snowpack. These measurements also suggest that the fresh snowfall fell down to ~9500 ft elevation.

Table 2. Comparison of ASO and SNOTEL station snow depths. Note: ASO long-term depth uncertainty is ± 8 cm.

Station name	Elevation (ft)	Date	Station depth (cm)	ASO depth (cm)	Depth difference (cm)
Berthoud Pass	11315	05/26/2022	64	79	15
Berthoud Summit	11300	05/26/2022	61	57	-4
Lake Irene	10700	05/26/2022	94	79	-15
Blue Ridge	10668	05/26/2022	74	65	-9
Willow Creek Pass	9540	05/26/2022	56	47	-9
Ranch Creek	9531	05/26/2022	0	0	0
Phantom Valley	9030	05/26/2022	0	0	0
Stillwater Creek	8720	05/26/2022	0	0	0
Devils Thumb	8689	05/26/2022	0	0	0
				Mean	-2.4

Table 3. Comparison of modeled ASO snow density prior to adjustment with manual snow pit snow densities (data source: USGS).

Pit site	Easting	Northing	Elevation (ft)	Date	Depth (m)	Density (kg/m^3)
Berthoud Pass	433409	4406260	11315	05/26/2022	0.4	259
Blue Ridge	416790	4422956	10668	05/26/2022	0.9	447
Ranch Creek	435036	4418430	9531	05/26/2022	0.1	162

Snow course measurements

There were 13 snow course locations that were monitored in the May 1 surveys in the basin, that were surveyed between April 26 - May 2 (**Table 4**). These data are now 27 days old and the mean density during the survey window of 317 ± 80 kg/m³ has changed significantly – particularly in the past few weeks (**Figure 4**).

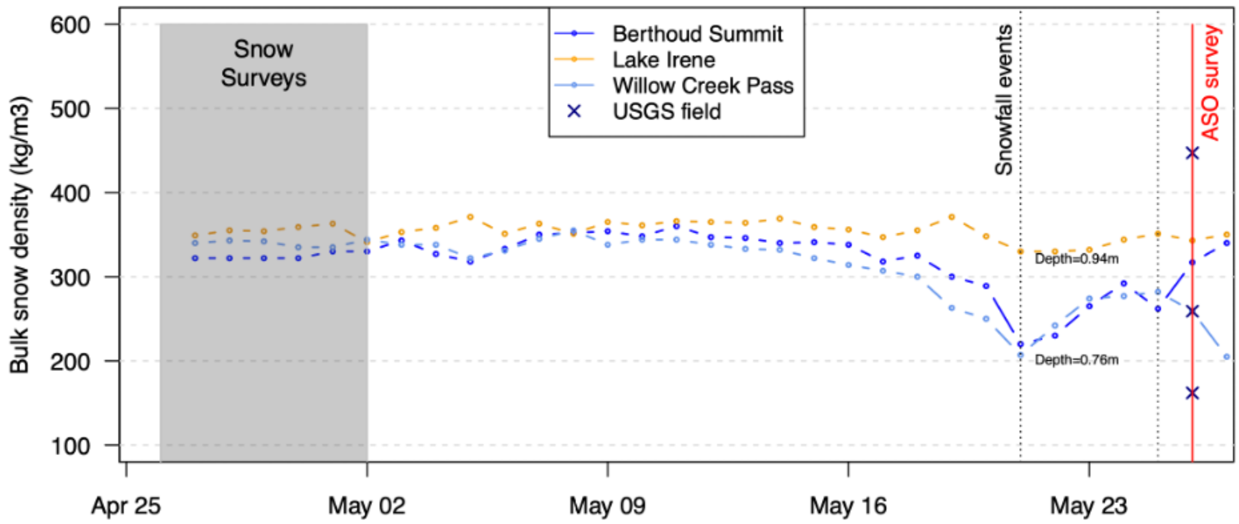


Figure 4. *Daily snow density timeseries at reliable SNOTEL stations for bulk snow density estimation in the Windy Gap region showing the change between the snow surveys (grey block), the snowfall (dotted line), and the airborne survey on May 26 (red line) (data source: NRCS).*

It is important to adjust for ongoing densification as these measurements are now 27 days old and with the fresh snowfall it is difficult to make a robust adjustment to these measurements to account for densification and other changes.

With the relatively long interval between the snow course observations and the airborne survey date (27 days), the high temporal variability in the snowpack right now and challenge of fresh snow contributions - we cannot use these snow course measurements to constrain bulk snow density on May 26.

Sensor measurements

Of the seven automated stations operating in the Windy Gap basin (**Table 5**), locations below 9100 ft have melted out (two stations) and two locations have stopped monitoring by May 26 (through lack of snow depth or SWE) – leaving three SNOTEL locations at which we can estimate bulk snow density. The daily snow density timeseries at these locations are shown in **Figure 4** – the mean snow density from these locations is 306 kg/m³ but the range is large 259 – 343 kg/m³.

Like the USGS field collections, the bulk density estimates at the SNOTEL stations appears to be heavily influenced by the fresh snowfall which is particularly notable in shallow snow. We have high confidence in the SNOTEL network for constraining bulk snow density but recognize that the fresh snow impacts must be accounted for.

Physically-based model - iSnobal

As this is the second survey of the Windy Gap this season, the iSnobal model has been updated with information from our previous survey on April 18. On May 26 the mean bulk snow density in the model is 477 ± 50 kg/m^3, a value only slightly higher than the observations in the Windy Gap basin suggest.

It is important that the model captures the bulk density impacts of the recent storm events. An examination of the model prior to the storm (May 19), immediately after the storm (May 20) and on the day of the ASO survey (May 26) shows that the basin-median snow depth increased from during the storm from 0.47 m to 1.1 m (or 23" snow accumulation) – which was then reduced via compaction and perhaps snowmelt by May 26 (**Figure 5**). Correspondingly, the modeled snow density shows a significant reduction (542 to 290 kg/m^3) with the deposition of fresh snow on May 20, which then settles by May 26 to a basin-mean of ~ 386 kg/m^3 (**Figure 6**). The model dynamics are consistent with fresh snow accumulation, though without ASO data immediately prior to the storm it is difficult to evaluate model performance during the storm.

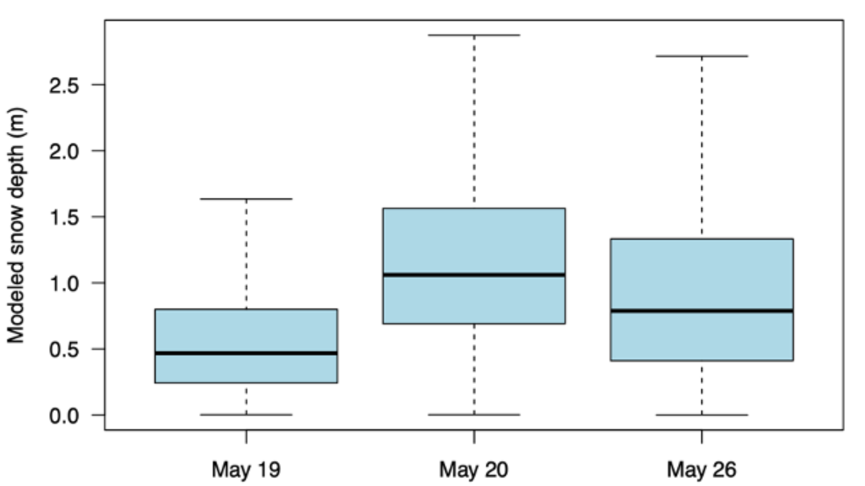


Figure 5. *Modeled snow depths (m) during the May 20 storm.*

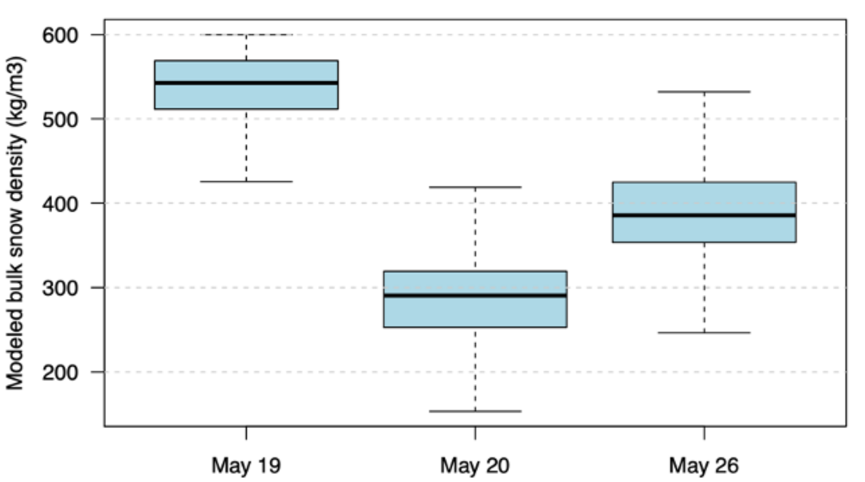


Figure 6. *Modeled bulk snow densities (kg/m^3) during the May 20 storm.*

On May 26, ASO survey date, when plotted against elevation (**Figure 7**) the model seems to be overestimating bulk snow density, particularly at elevations < 10000ft. At these lower elevations, the fresh snow in the model has already densified from fresh snow values of ~170 kg/m^3 (based on in-situ snow pit measurements) to > 450 kg/m^3 in many locations – after five days of settling. The densification rate to achieve this would need to be ~55 kg/m^3/day which is very high and 2-5 times the expected densification rates after fresh snowfall.

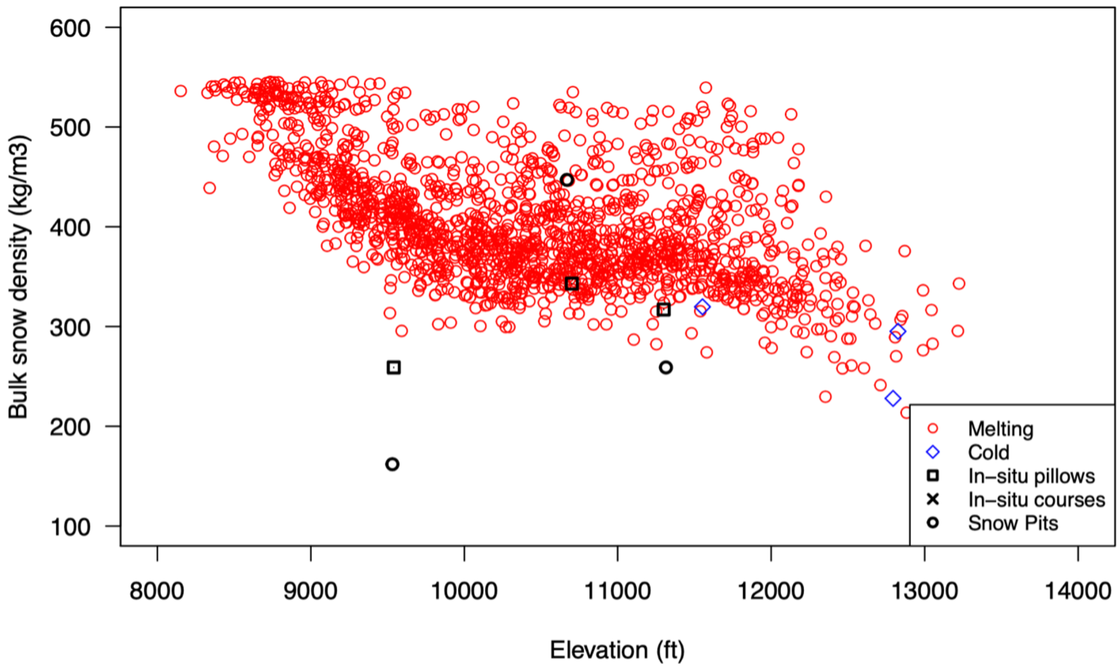


Figure 7. Observed and unadjusted modeled bulk snow density (kg/m^3) by elevation (ft). Squares represent density observations at snow pillows on May 26, 2022, Xs represent density observations at snow courses, circles represent snow pit density observations. Red circles represent modeled densities of melting snow (cold content = 0), blue diamonds represent modeled densities of cold snow (cold content < 0).

When plotted against snow depth (**Figure 8**), we observe that the overestimations are structured with snow depth – with the largest overestimations occurring in shallow snow. While the model captured the storm and generally displayed physically consistent dynamics of state variables (bulk snow density and snow depth), when examined in detail there are some issues with the fresh snow density dynamics that need to be constrained. Note: the model is tracking reasonably well with the in-situ measurements in deeper snow > 0.8 m, which is where we expect much of the SWE to be located – and the areas in the model where we see bulk density overestimation are occurring in shallow snow where much less of the basin SWE volumes are located.
At collocated pixels with the SNOTEL stations, we confirm the overestimation in the model with increasing overestimation at lower elevations (shallower depths) – **Figure 9.a.** At the manual snow pit locations (**Table 3**), a direct comparison reveals a significantly large overestimation by the model. There is insufficient information to make any further conclusions.

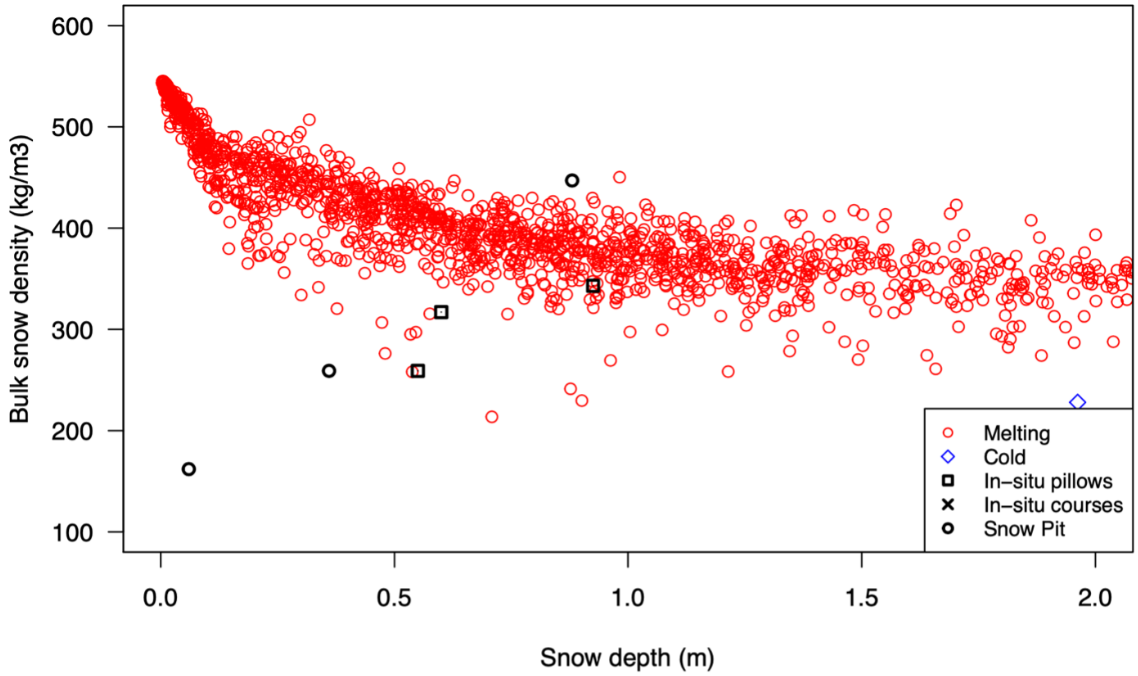


Figure 8. Observed and unadjusted modeled bulk snow density (kg/m³) by snow depth (m). Squares represent density observations at snow pillows on May 26, 2022, Xs represent density observations at snow courses, circles represent snow pit density observations. Red circles represent modeled densities of melting snow (cold content = 0), blue diamonds represent modeled densities of cold snow (cold content < 0).

Pit site	Elevation (ft)	In-situ density (kg/m³)	Unadjusted model density (kg/m³)	Density difference (kg/m³)
Berthoud Pass	11315	259	351	92
Blue Ridge	10668	447	417	-30
Ranch Creek	9531	162	404	242

Table 4. Comparison of modeled ASO snow density prior to adjustment with manual snow pit snow densities (data source: USGS). See Table 3 for location coordinates.

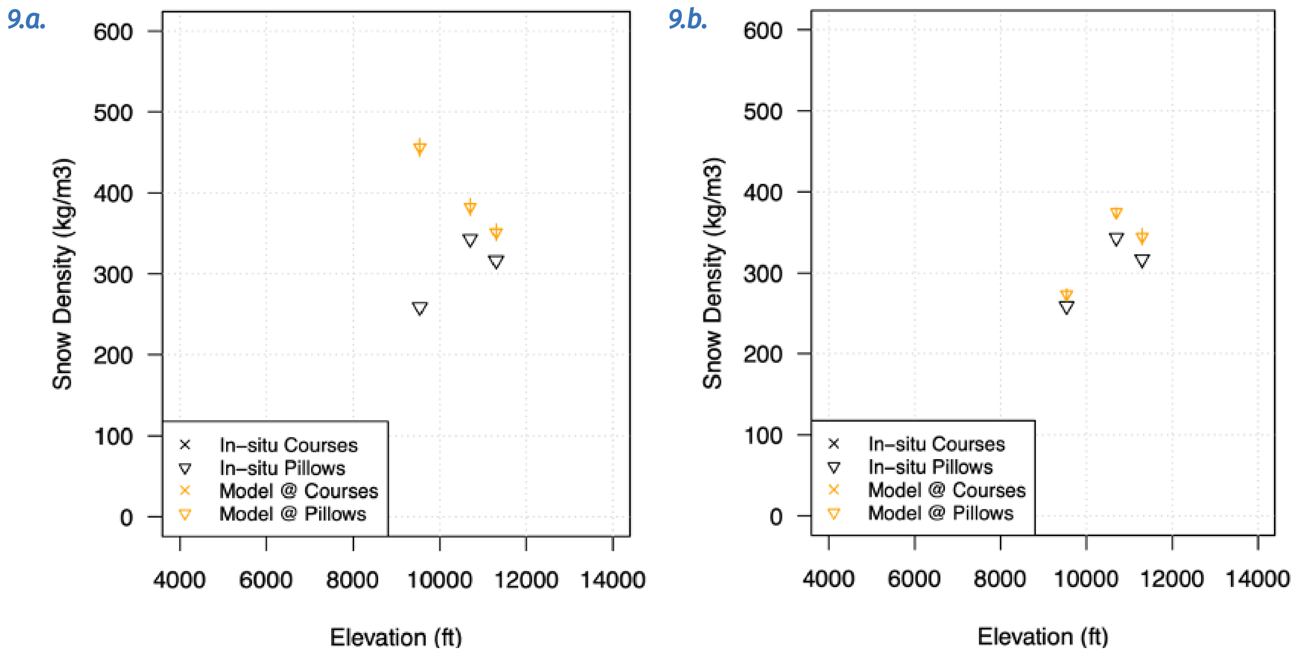


Figure 9. Model comparison at collocated snow courses and snow pillows in the Windy Gap before (9.a.) and after (9.b.) the density adjustment. The vertical bars show the variability in the model (±1σ) within the nine surrounding pixels. After adjustments, the modeled bulk snow densities are much more consistent with the in-situ measurements. (Note: the locations of these snow pillows and snow courses come from NRCS and we caution that there is uncertainty with these coordinates).

Snow density refinement

From the available information, the model appears to be overestimating bulk snow density when snow depth is less than 0.8 m and an adjustment is required to remove these biases. Using a statistical function generated from polynomial regressions between the modeled snow density and in-situ densities with snow depth we rescale snow densities, with heavier reductions applied to pixels with shallow snow. For example, in very shallow snow (< 0.4 m) densities are scaled to ~60% of their original value (for example reducing densities of 500 kg/m^3 to 300 kg/m^3) and in deeper snow (> 0.8 m) densities are scaled to 98% of their original value.

After density adjustment the biases at the SNOTEL stations were reduced from 90 kg/m3 to 24 kg/m3 (Figure 8b). The resulting basin-wide mean bulk snow density was 333 kg/m3. Note: this is a spatial value integrated over the entire basin and includes areas with only fresh snow and thus appears low.

To capture impact of the uncertainty in the snow density adjustment on basin SWE we also run two snow density scenarios: 1) only snow densities in depths < 0.5 m are adjusted and 2) only snow densities in depths < 0.3 m are adjusted.
Using the un-adjusted model (open-loop) densities, the basin SWE volume was 195 TAF. The model adjustments bring the basin SWE down to 170 TAF. To get a sense of the scale of impact of the

density adjustments on basin SWE, additional sensitivity testing show a basin SWE sensitivity of 5-8%, with scenario 1 producing 178 TAF and scenario 2 producing 184 TAF. For these scenarios the basin-mean bulk snow densities were 374 and 364 kg/m3 respectively.

As noted in our report from the April 18 survey, the snow-free reference elevation data set for the Windy Gap domain contains several artifacts that, while not very significant from an absolute elevation standpoint, introduce an unquantified uncertainty in our snow depth measurements, where our depth uncertainty and therefore detection level amount to about 5cm. This measurement challenge is reflected in the higher-than-typical range of differences in the comparisons with in-situ data. To help constrain this uncertainty, we conducted a couple of snow depth sensitivity experiments, biasing our depth calculations by ±8cm. These end-member depth scenarios propagate to a SWE range from 156 to 185 TAF, or ±9% of our reported basin SWE volume. We know the impact of depth uncertainty on SWE is less than this 9%, as our low-snow detection is well-constrained by the optical imagery showing snow absence, and also due to the bulk of the snow-free data issues being confined to about a third of the basin area. Thus we estimate the combined depth and density uncertainties to amount to 15% of the basin SWE volume.

Snow albedo

As described in Painter et al. (2016), in addition to the scanning lidar, ASO also carries a pair of visible to shortwave infrared imaging spectrometers from which we retrieve broadband albedo (400-2500 nm wavelength), visible albedo (400-700 nm), and near-infrared to shortwave-infrared (700-2500 nm). The latter two albedos are generated to ultimately constrain iSnobal and WRF-Hydro, as well as other physically-based models.

Solar radiation is the primary energy source for snowmelt. The snow albedo describes the fraction of incoming solar energy that is reflected by the snow surface.

The NIR/SWIR albedo values in the Windy Gap on May 26 (~30-40%) are consistent with the generation of large snow grains due to melt/freeze metamorphism (60-70% absorption), and the visible albedo values (>80%) reflect fresh snow deposition (**Figure 10.a.**). The broadband albedo, which is most critical for understanding the snow energy balance, ranges from 45 to 60%, which translates to 40-55% solar absorption. For this time of year, relatively clean snow typically has albedos of approximately 92% (visible), 74% (broadband), and 45% (NIR/SWIR), translating into associated absorption of 8%, 26%, and 55%.

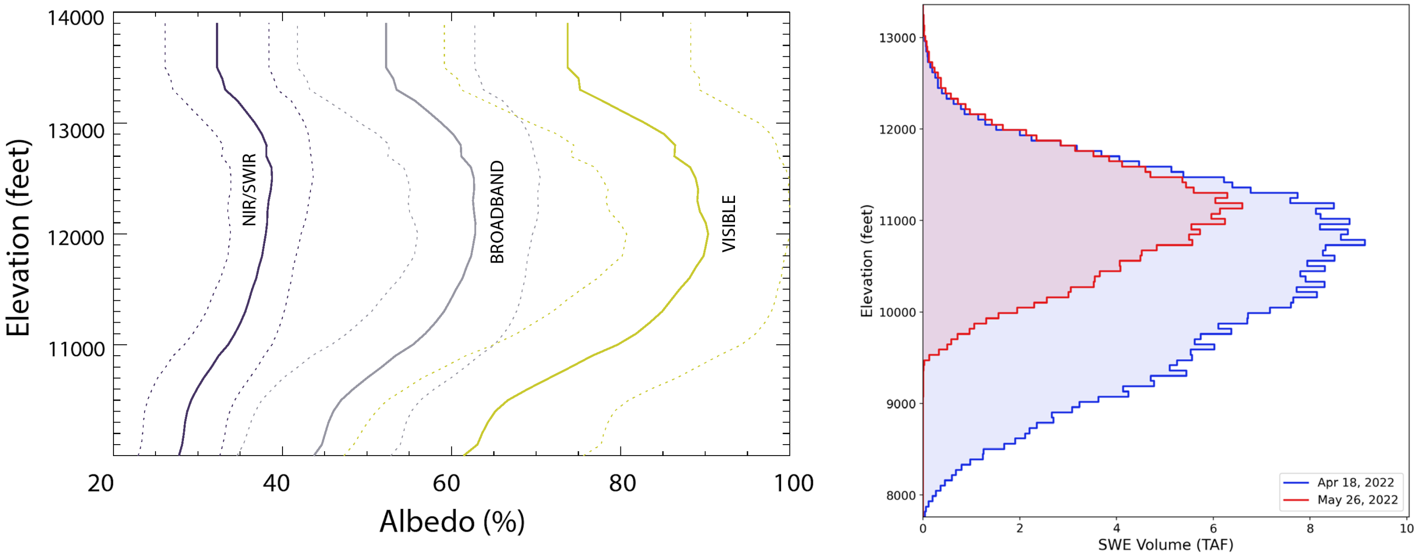


Figure 10.a. *Snow albedo (%) by elevation (ft) on May 26 with mean (solid lines) and ± 1 standard deviation (dotted lines) for near and shortwave infrared (dark blue), broadband (gray), and visible (green) wavelengths, with clean snow albedo in each wavelength denoted by hash marks above the plot.* *10.b.* *Distribution of SWE volume (TAF) across elevations; red represents the May 26 survey, blue represents the April 18 survey.*

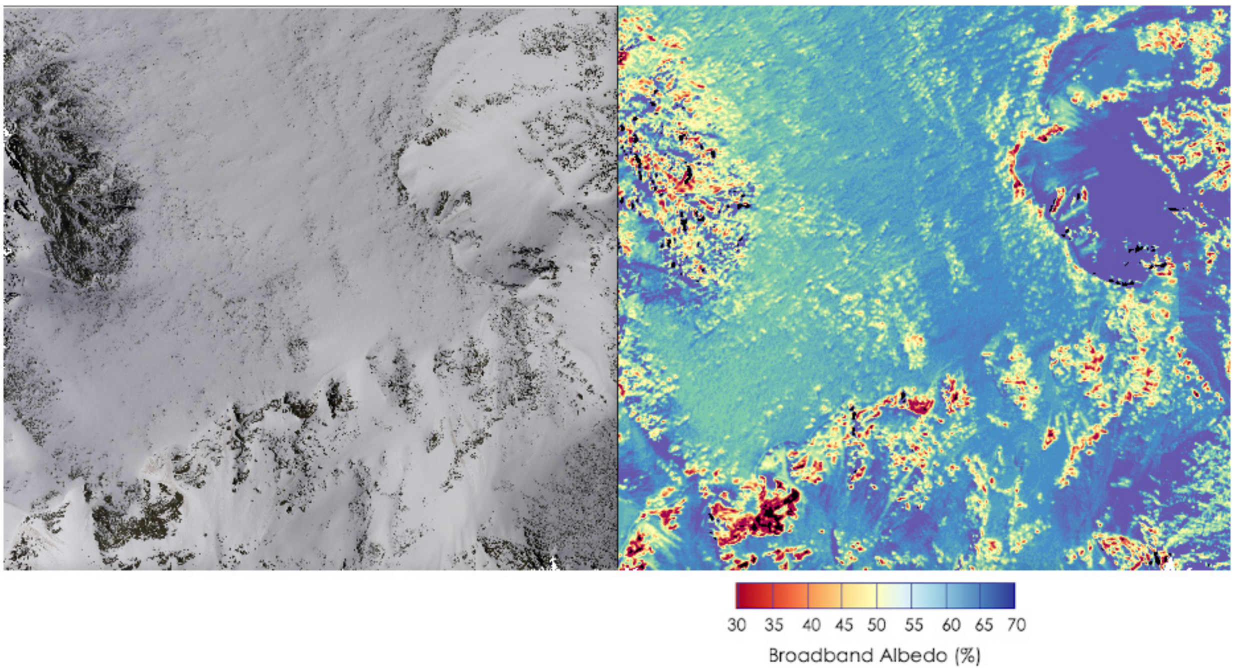


Figure 11. *ASO visible images (left panel) from three of the hundreds of ASO spectral bands over the Windy Gap basin high country. Corresponding snow albedo maps (right panel) showing impacts of recent snow and subsequent warming & melt on snow albedo/solar absorption and the snowpack energy balance.*

Additional data / remarks

Table 5. Snow density, depth, and SWE estimates from the snow course network (data source: NRCS).

Site name	Site code	Elevation (ft)	Date	Density (kg/m³)	Time adj. (day)	Adj. density (kg/m³)	Depth (m)	SWE (m)
Lake Irene	05J10	10700	4/29/22	202	-27	202	1.2	0.2
Niwot	05J24	9750	4/29/22	145	-27	145	0.8	0.1
Berthoud Pass	05K03	9700	4/28/22	366	-28	366	1.0	0.4
Arrow #2	05K12	9668	4/27/22	364	-29	364	0.8	0.3
Vasquez	05K19	9600	4/26/22	264	-30	264	1.0	0.3
Willow Creek Pass	06J05	9540	5/2/22	342	-24	342	0.8	0.3
Hidden Valley	05J13	9480	4/29/22	317	-27	317	0.6	0.2
Ranch Creek	05K18	9400	4/28/22	355	-28	355	0.8	0.3
Lapland	05K07	9300	4/26/22	313	-30	313	0.4	0.1
Park View	06J02	9160	5/2/22	300	-24	300	0.4	0.1
Deer Ridge	05J17	9000	4/29/22	300	-27	300	0.2	0.1
North Inlet Grand Lake	05J09	9000	4/30/22	400	-26	400	0.2	0.1
Granby	05J16	8600	5/2/22	450	-24	450	0.1	0.0

Additional data / remarks

Table 6. *Snow density, depth, and SWE estimates from the SNOTEL network (data source: NRCS).*

Station name	Station code	Elevation (ft)	Date	Density (kg/m^3)	Depth (m)	SWE (m)
Berthoud Summit	335	11300	5/26/22	317	0.6	0.2
Fool Creek	1186	11150	5/26/22	NA	NA	0.3
Lake Irene	565	10700	5/26/22	343	0.9	0.3
Willow Creek Pass	869	9540	5/26/22	259	0.6	0.1
Phantom Valley	688	9030	5/26/22	NA	0.0	0.0
Stillwater Creek	793	8720	5/26/22	NA	0.0	0.0

Table 7. *Volume of SWE (AF) by subbasin and elevation range (ft).*

Elevation range (ft)	Fraser River	Fraser River at Granby	Granby	Willow Creek	Moffat	Full basin
8000 - 8999	0	0	0	0	0	0
9000 - 9999	2937	3583	3283	653	2479	7525
10000 - 10999	21922	22761	44464	3178	19962	70385
11000 - 11999	25259	25257	54456	1705	24945	81583
12000 - 12999	3697	3747	6386	38	3780	10503
13000 - 13999	26	25	72	0	26	123

Additional data / remarks

Table 8. Change in volume of SWE (AF) since April 18 survey by subbasin and elevation range (ft).

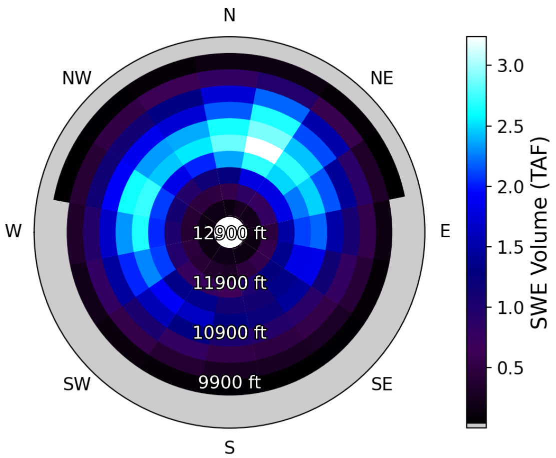
Elevation range (ft)	Fraser River	Fraser River at Granby	Granby	Willow Creek	Moffat	Full basin
7000 - 7999	0	NA	0	0	NA	-358
8000 - 8999	-8160	NA	-5194	-3263	NA	-27110
9000 - 9999	-27096	NA	-24191	-24911	NA	-86275
10000 - 10999	-23554	NA	-33289	-12536	NA	-70625
11000 - 11999	-9100	NA	-5519	-1275	NA	-15894
12000 - 12999	186	NA	987	-1	NA	1204
13000 - 13999	5	NA	19	0	NA	24

Table 9. Total area (mi²), snow-covered area (mi²), band coverage (%), SWE volume (AF), and mean SWE depth m) by elevation range (ft).

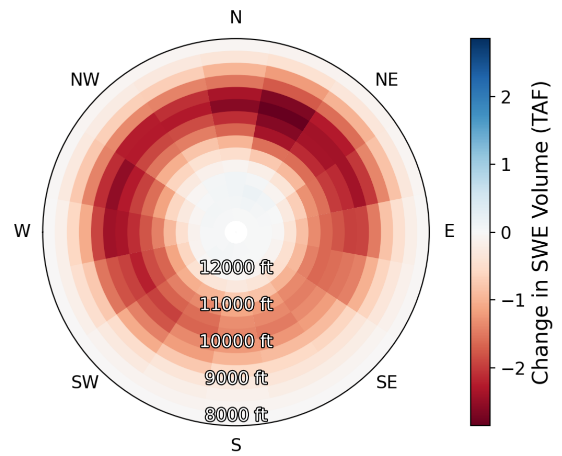
Elevation range (ft)	Total area (mi²)	Snow-covered area (mi²)	Band coverage (%)	SWE volume (AF)	Mean SWE depth (in)
7000 - 7999	13.6	0	0	0	0
8000 - 8999	239.1	.2	0	0	0
9000 - 9999	235.9	72.3	.1	0	0
10000 - 10999	172.8	156.6	31	7525	1.9
11000 - 11999	104.8	104.1	91	70385	8.4
12000 - 12999	21.2	21.2	99	81583	14.7
13000 - 13999	.4	.4	100	10503	9.3

Additional data / remarks

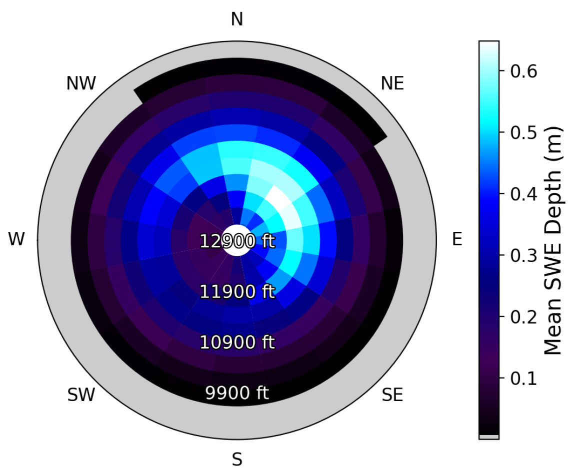
12.a.



12.c.



12.b.



12.d.

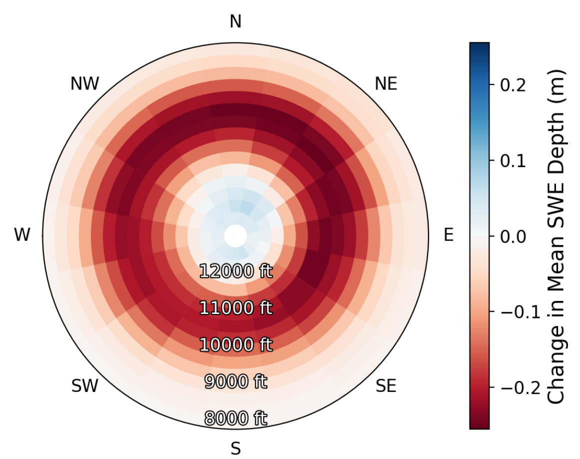
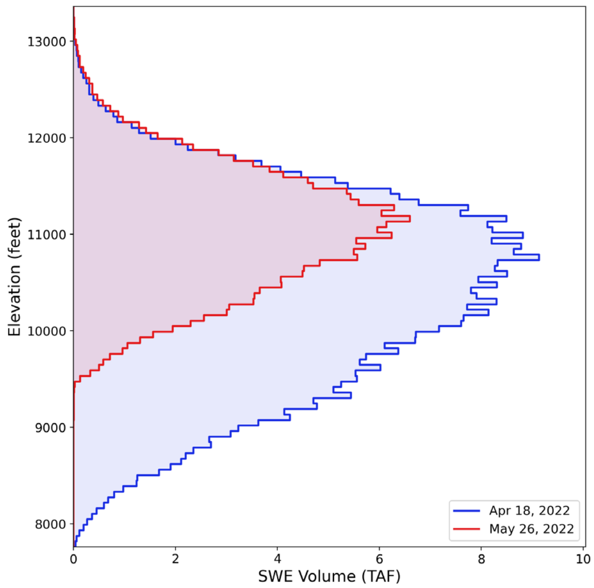


Figure 12. Aspect/elevation SWE and SWE difference plots. 12.a. & b. SWE volume (TAF) and depth (m) from May 26 survey; 12.c. & d. SWE volume (TAF) and depth (m) change from April 18 survey to May 26 survey.

Additional data / remarks

13.a.



13.b.

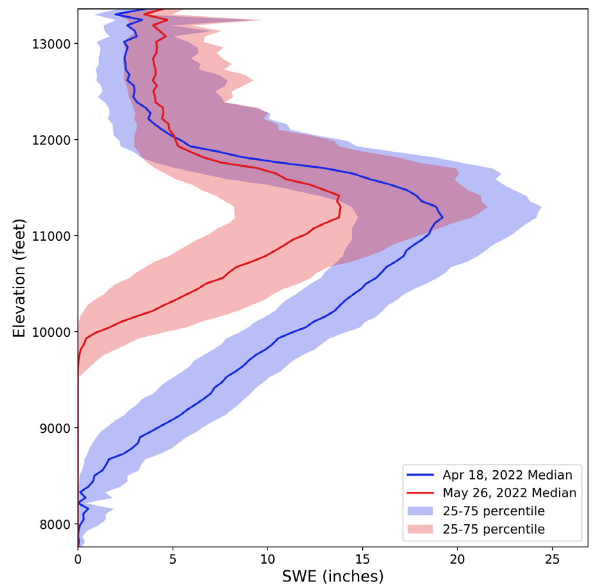


Figure 13. *Difference plots of SWE volume (TAF) and depth (in) across elevations.* ***13.a.*** *Distribution of SWE volume (TAF) across elevations; red represents the May 26 survey, blue represents the April 18 survey.* ***13.b.*** *Distribution of SWE depth (in) across elevations; red represents the May 26 survey, blue represents the April 18 survey; solid lines represent median SWE depth (in), lighter color bands represent the 25th to 75th percentiles.*