Colorado Airborne Snow Observatory Expansion Plan: 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."

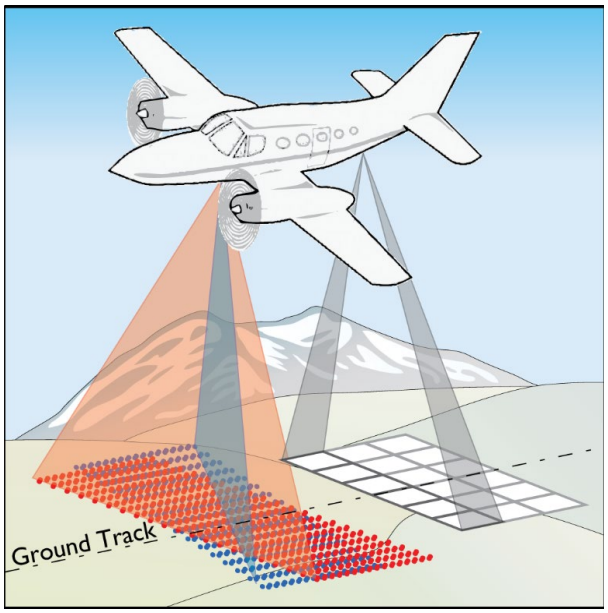
Nathan Elder
Raw Water Operations Manager
Denver Water

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.

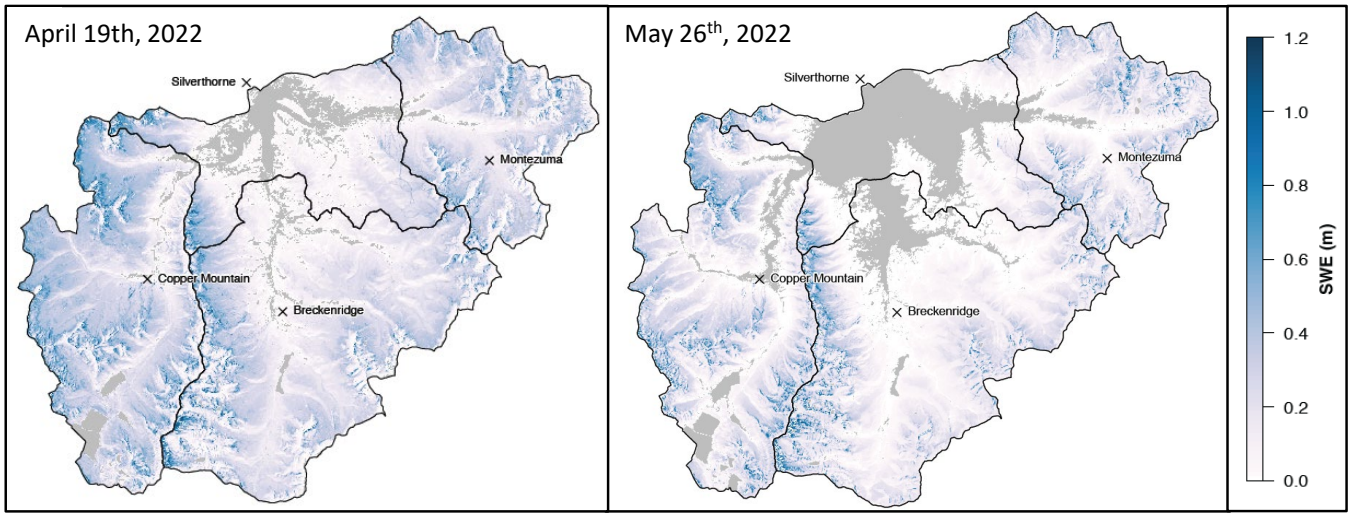
What does ASO Inc. provide?

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).

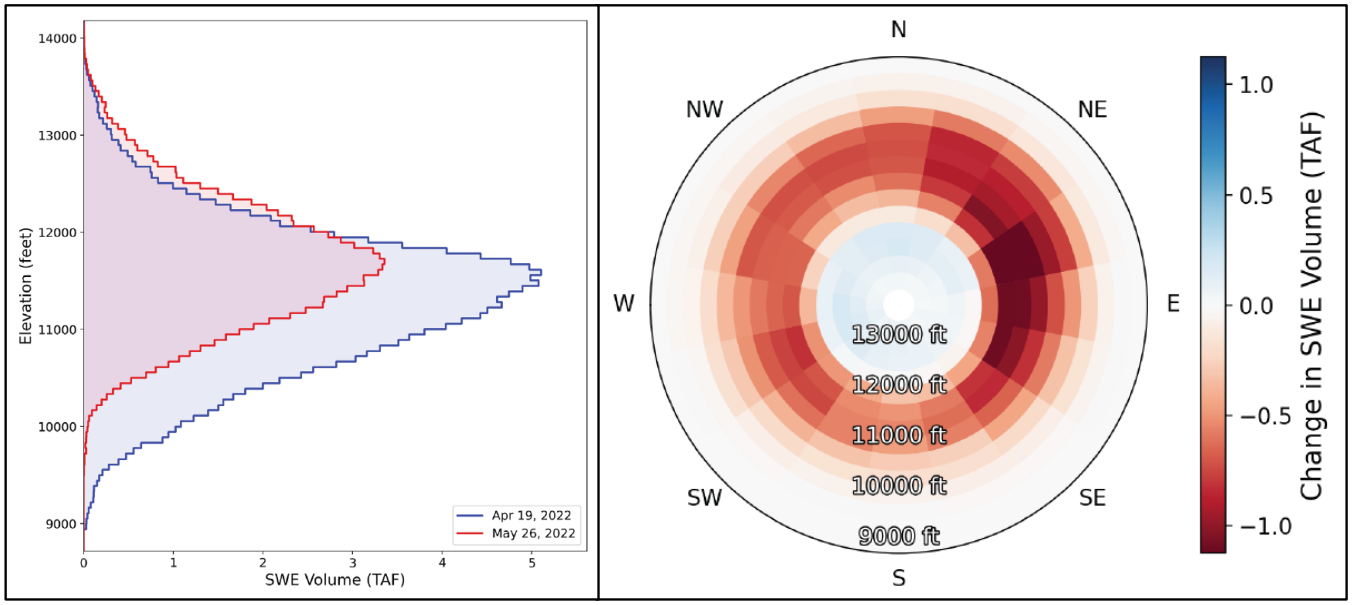
Historical data review shows that these ASO measurements are within 5-10% of the actual water contained in the snowpack at the time of the survey, though total runoff varies due to uncertainty in seasonal precipitation following the final ASO surveys of the season. Using ASO's current equipment, a single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



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.

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:

> *"[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*

- 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

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 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.

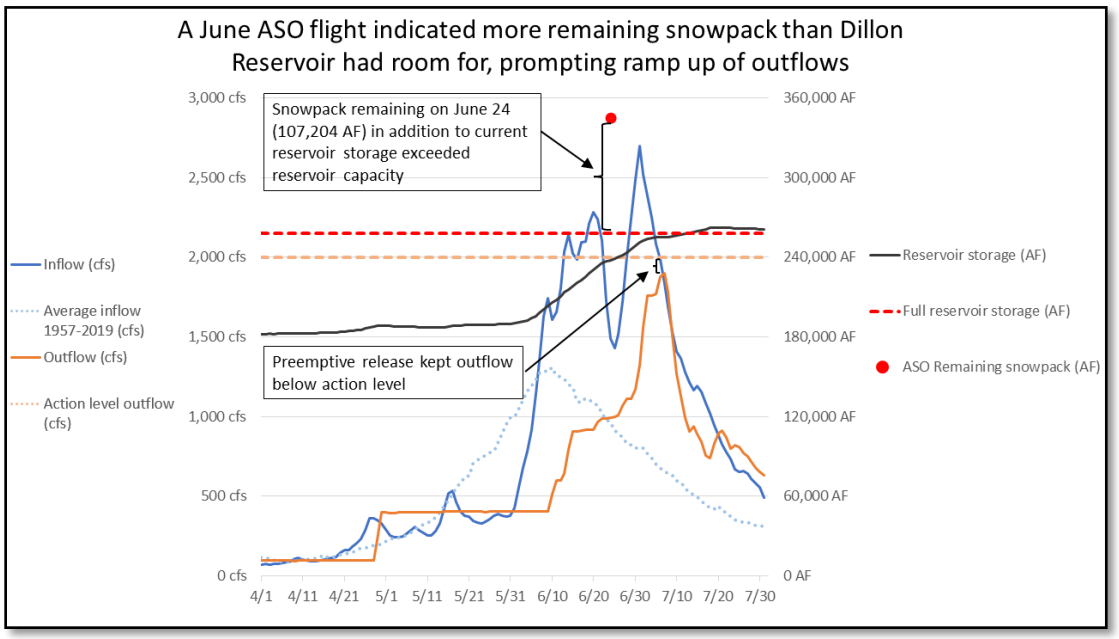


Figure 1. Dillon Reservoir operations in 2019.

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

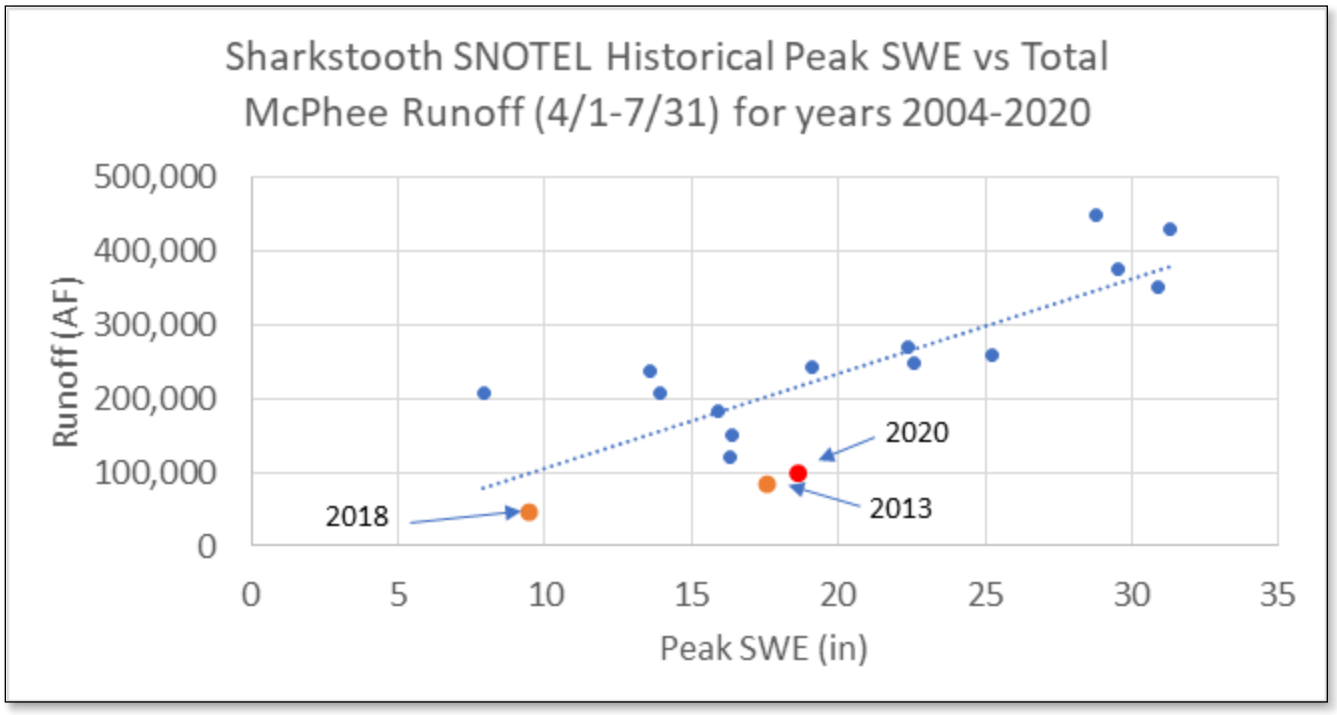


Figure 2. Historical peak SWE at Sharkstooth SNOTEL site vs total runoff into McPhee Reservoir (4/1-7/31) each year. Red dot is 2020. Historically dry years show SNOTEL peak SWE well below average total runoff.

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.

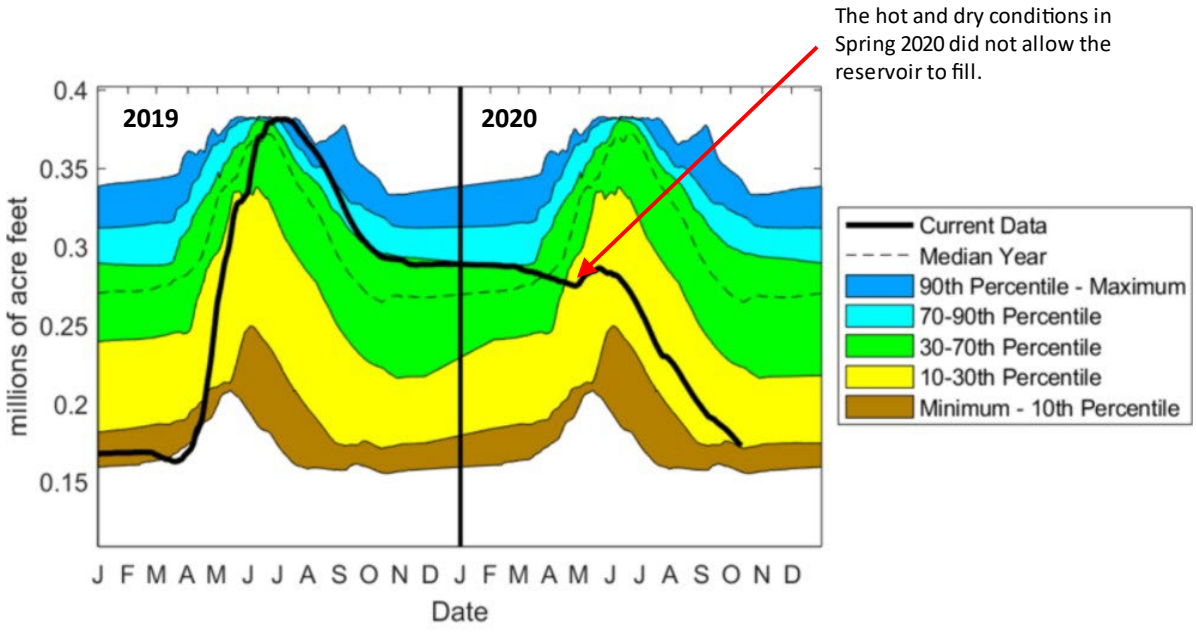


Figure 3. Reservoir storage (AF) in 2019 and 2020. The hot and dry conditions led to little reservoir filling in the spring and then a step drop in the summer.

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.

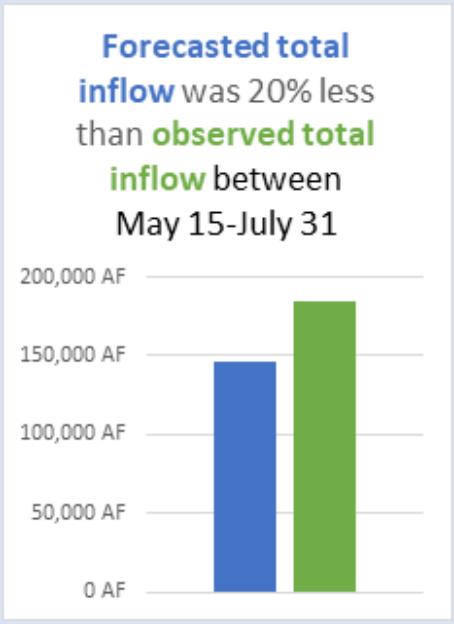
In the early spring of 2017, runoff forecasts from the Colorado Basin River Forecast Center (CBRFC) indicated an average or above average year, and DWCD expected to meet all operational goals. However, cold weather in late April reduced inflows more than what DWCD managers had anticipated, causing the 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.

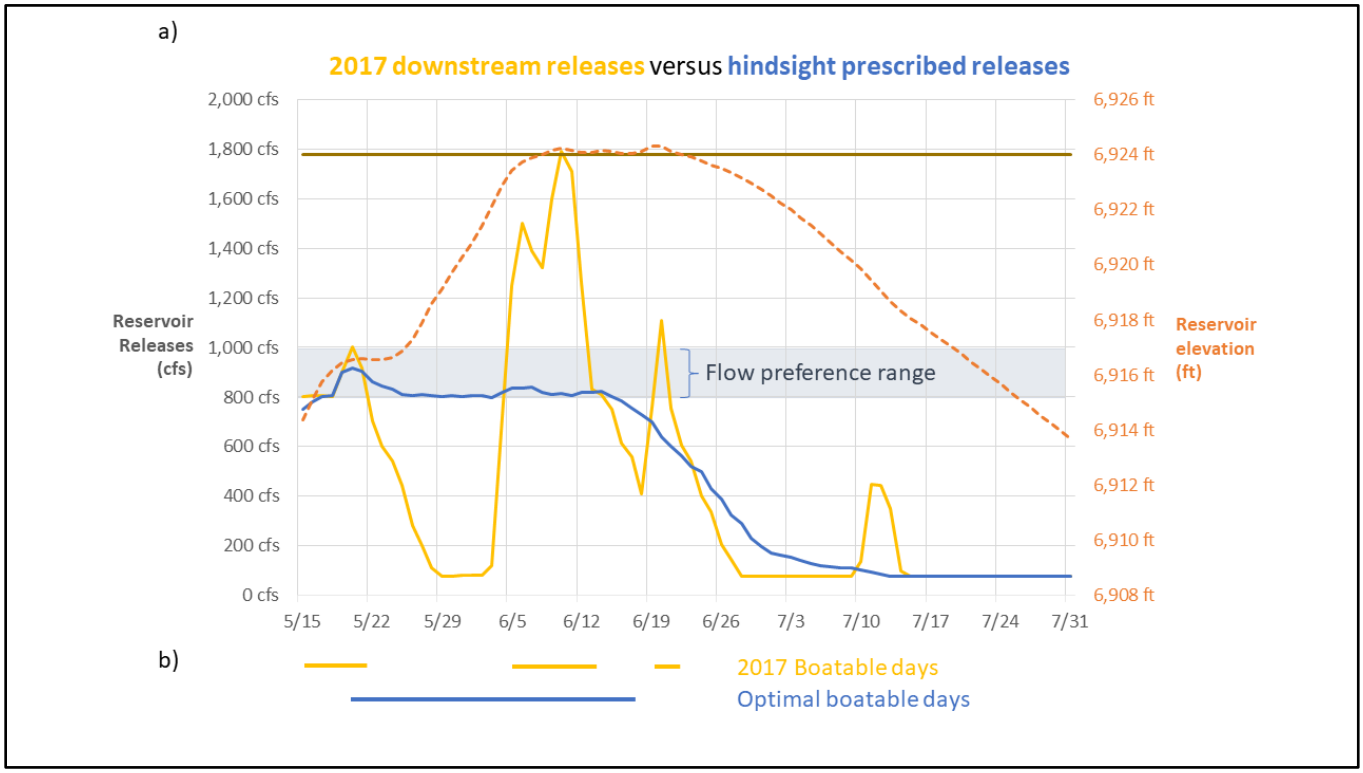


Figure 4. McPhee Reservoir downstream releases versus hindsight prescribed releases