Colorado Airborne Snow Observatory Expansion Plan: Project Report

Prepared on Behalf of Northern Colorado Water Conservation District

6/30/2022

Submitted To:

Northern Water
Attention: Emily Carbone
220 Water Avenue
Berthoud, Colorado 80513

Submitted By:

Lynker Technologies, LLC
Graeme Aggett, Principal and Chief Scientist
3002 Bluff Street, Suite 101
Boulder, Colorado 80301

Boulder, Colorado **DC—Metro** **Pacific—Oahu**

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

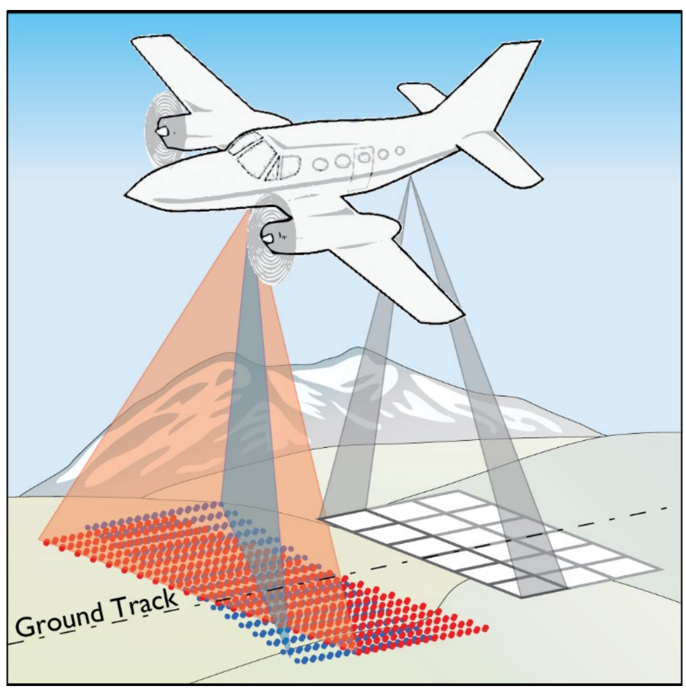


Figure 1. ASO Lidar Technology

7

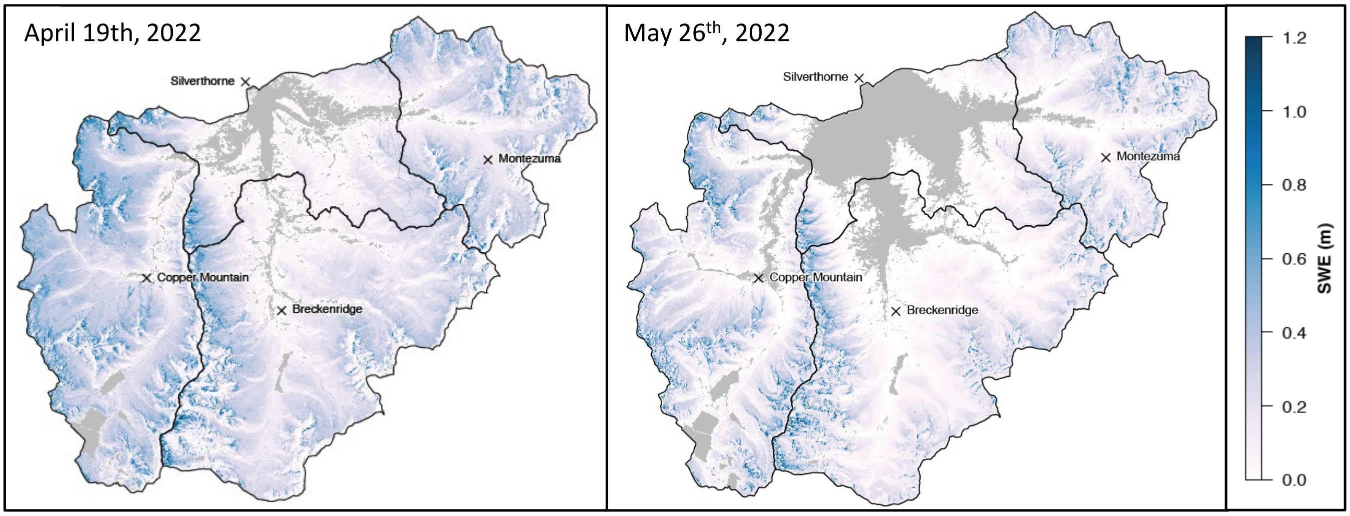


Figure 2.High resolution snow depth grids from the Blue River, 2022

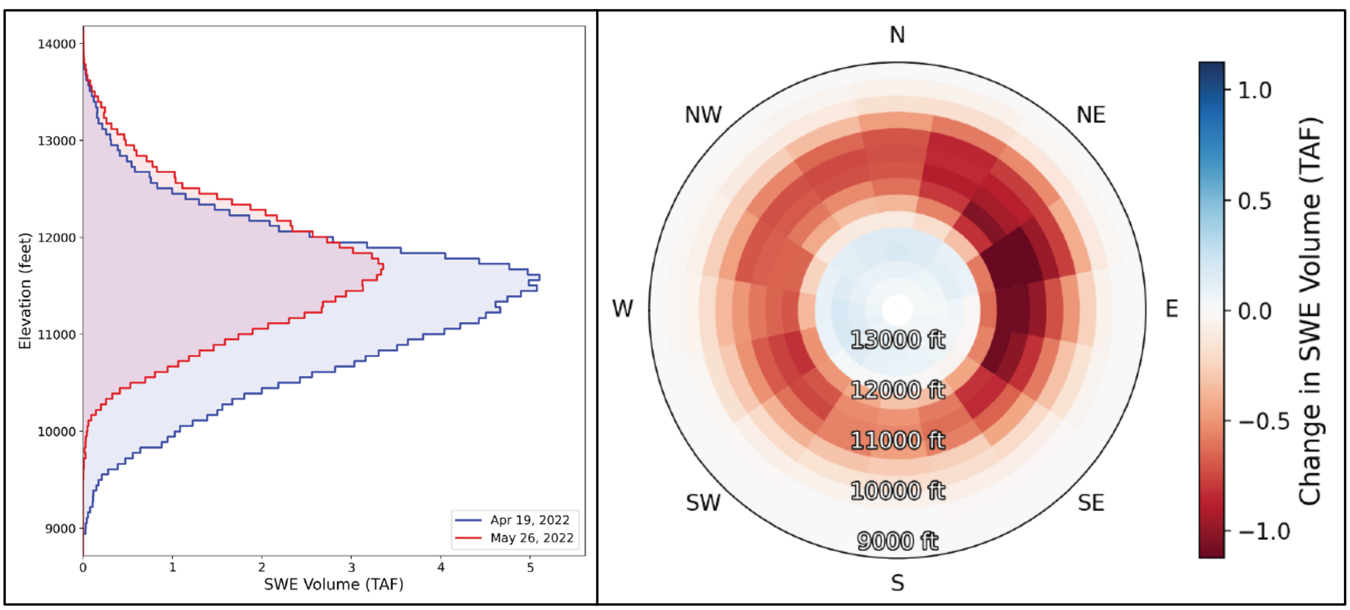


Figure 3. Change In Snow Water Equivalent by elevation band between the two flights. Change in SWE volume by elevation and aspect

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).

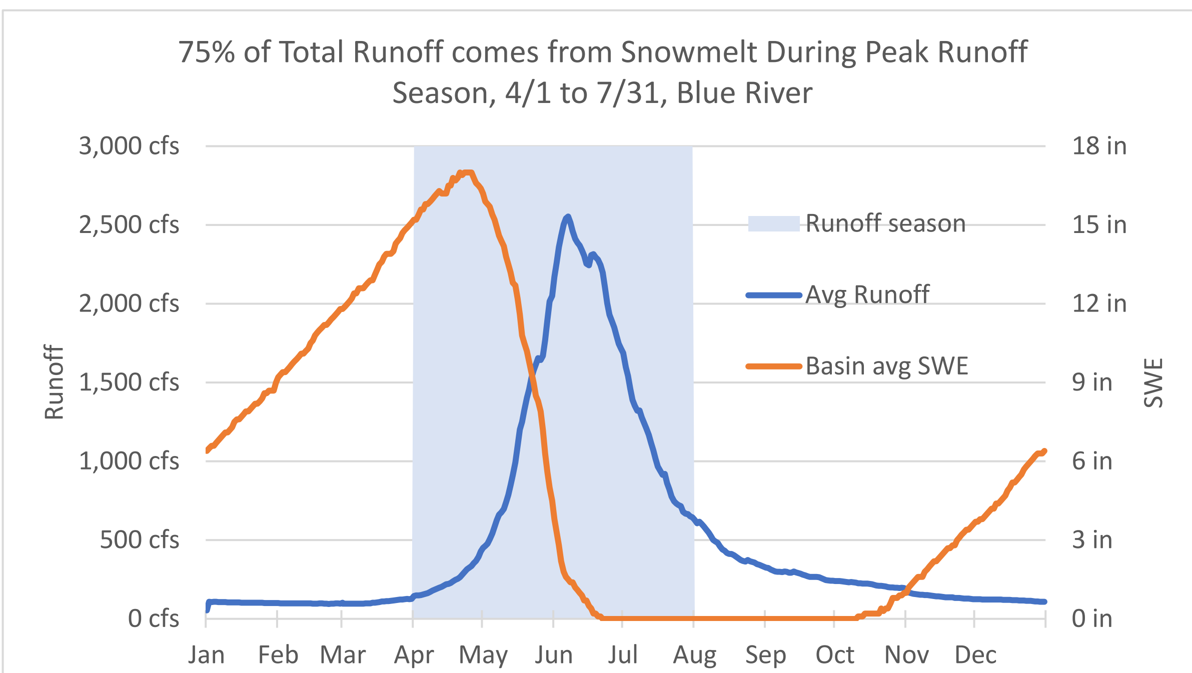


Figure 4. Blue River basin historical average daily runoff (blue) and SWE (orange) from 1991-2020.

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.

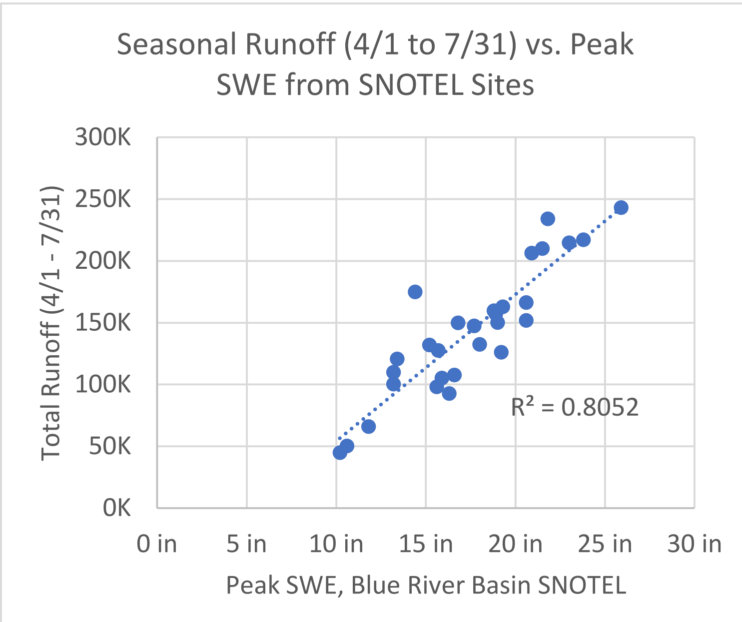


Figure 5. Blue River basin historical total runoff and peak SWE values

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.

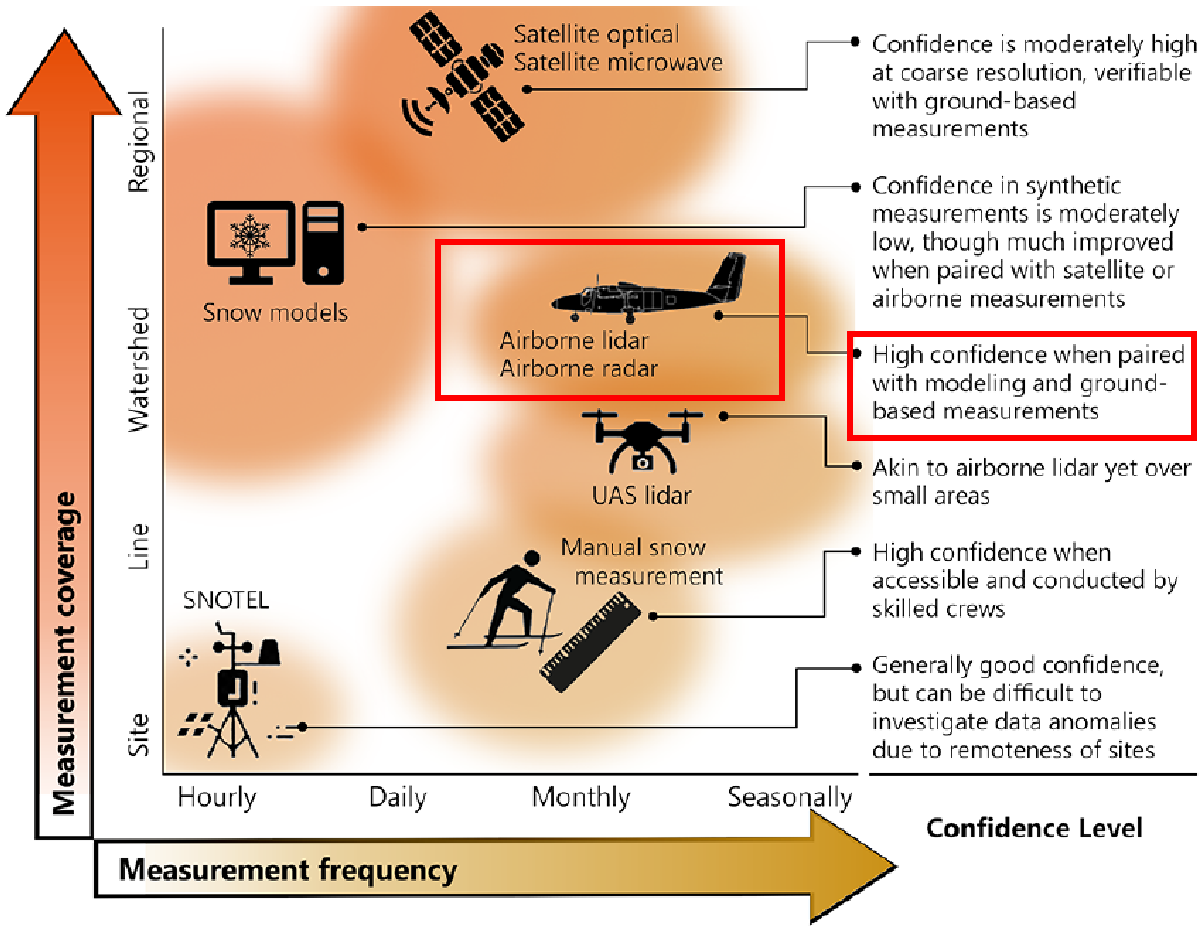


Figure 6. Comparison of Coverage, Frequency and Confidence in Emerging Technologies in Snow (USBR, 2021)

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.

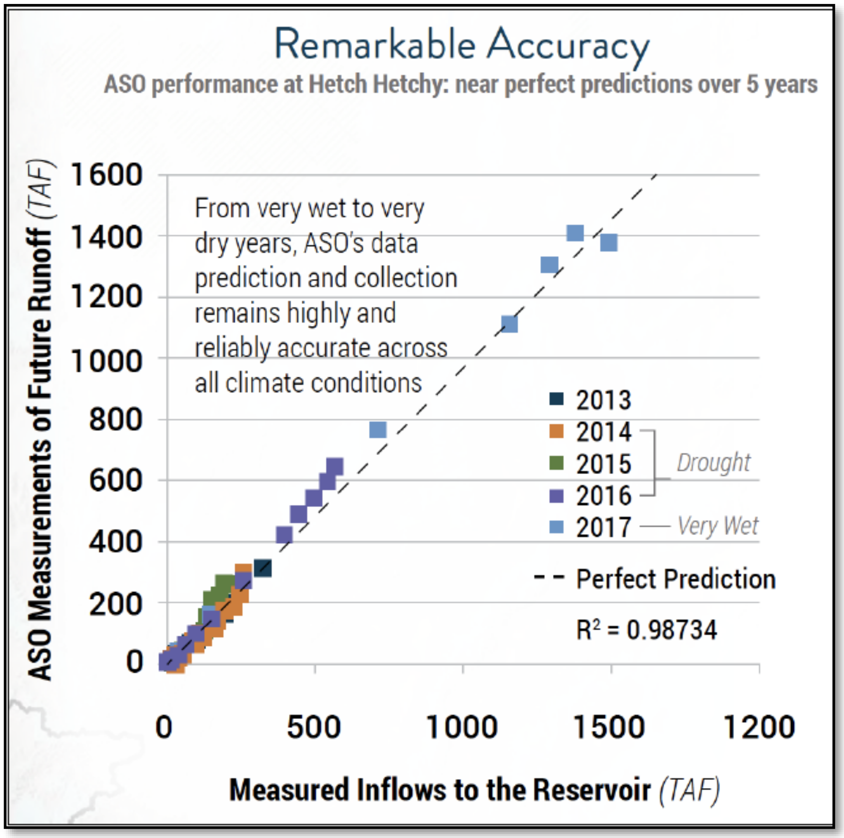


Figure 7. ASO Measurements compared to Hetch Hetchy Reservoir Inflows (CA-DWR 2018)

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.

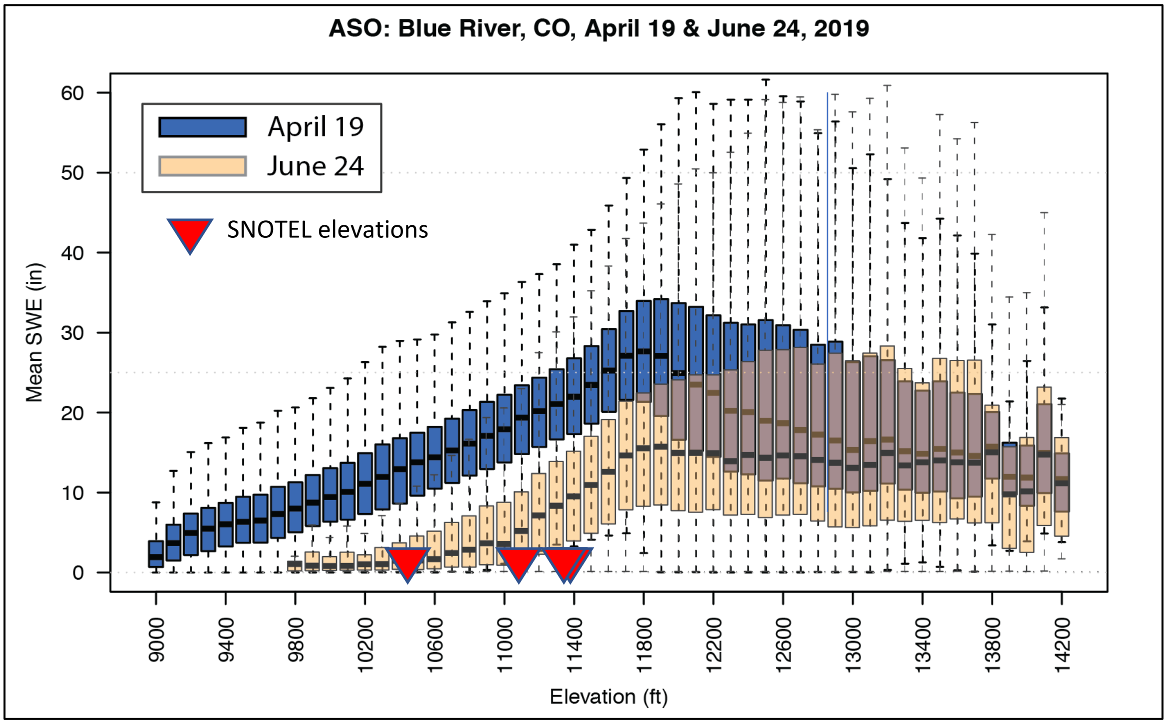


Figure 8. Distribution of Snowpack and SNOTEL Sites, Blue River, 2019

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).

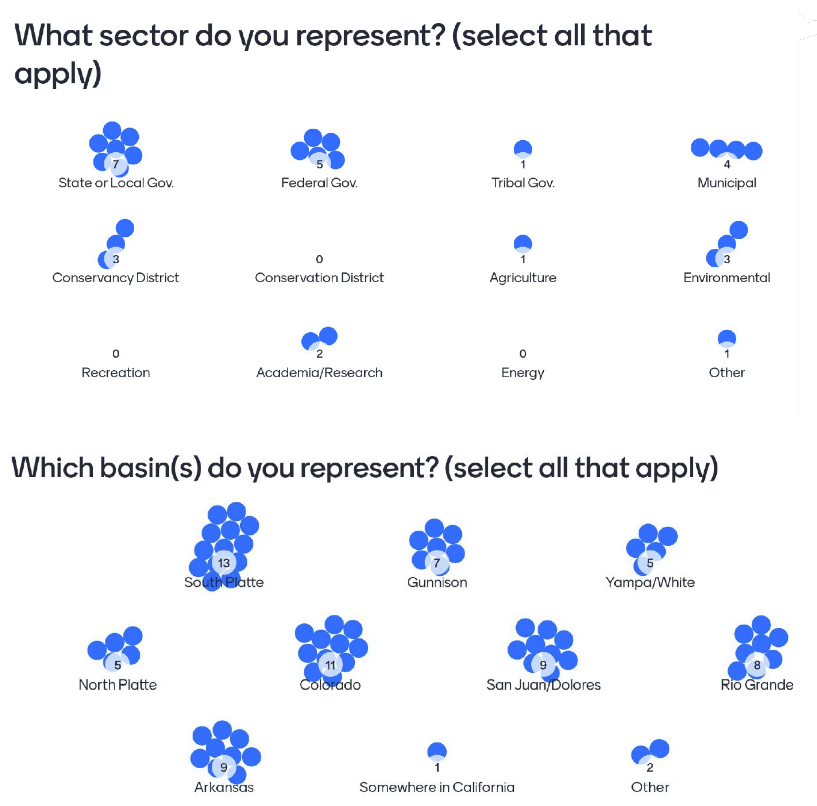


Figure 9. Example Meeting Demographics from Live Meeting Poll

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.

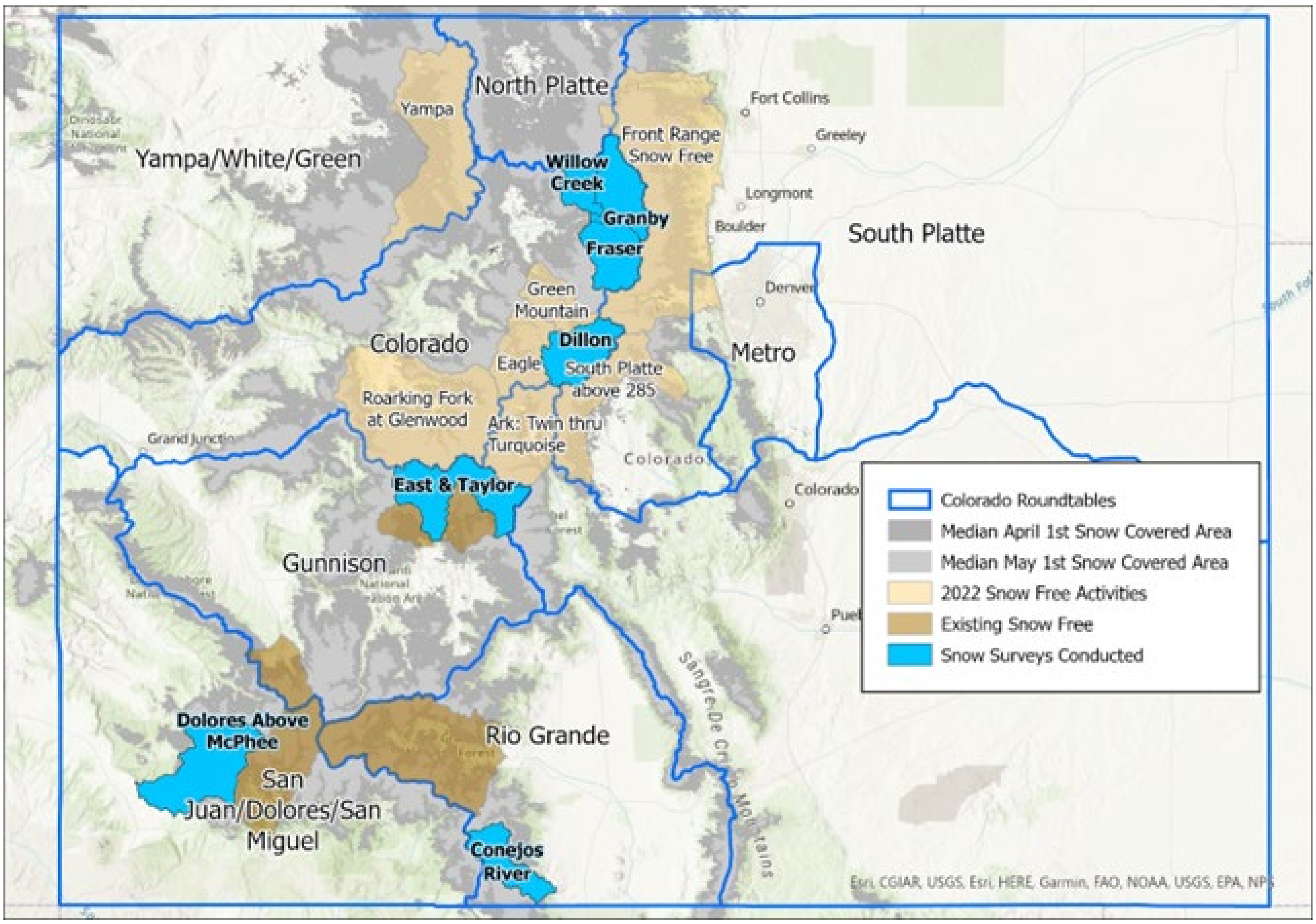


Figure 10. 2022 Water Plan Grant Activities

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.

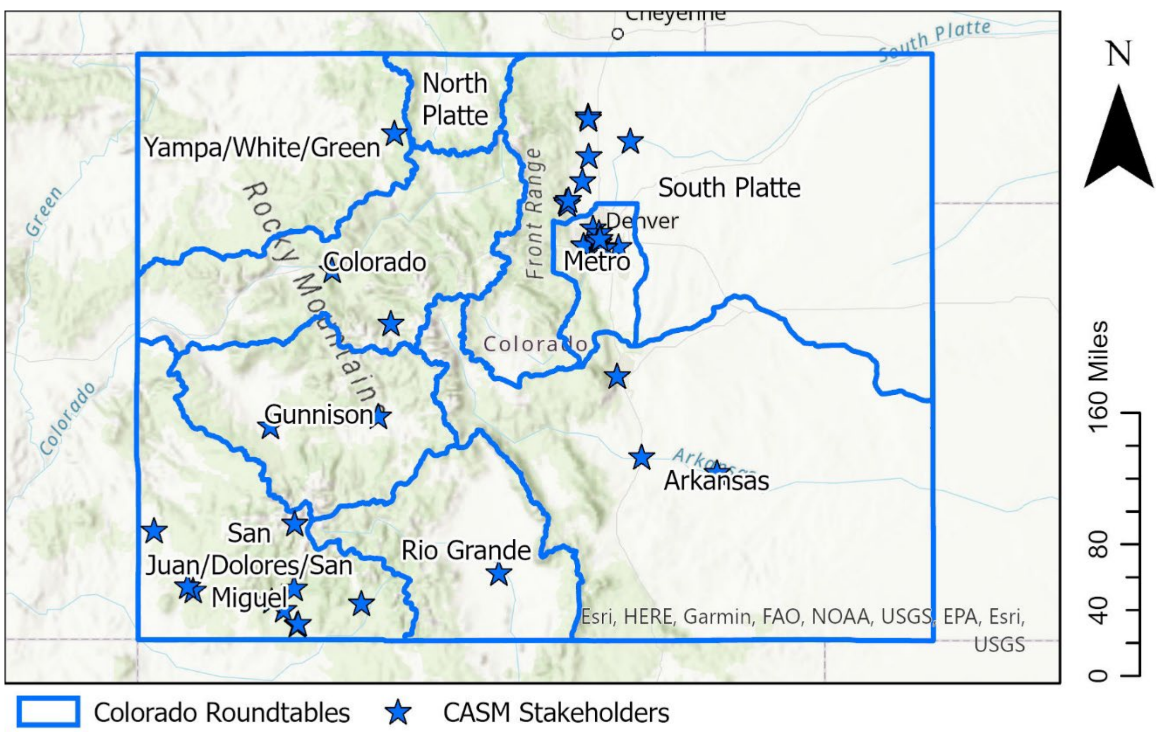


Figure 11. CASM Stakeholder Locations

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.

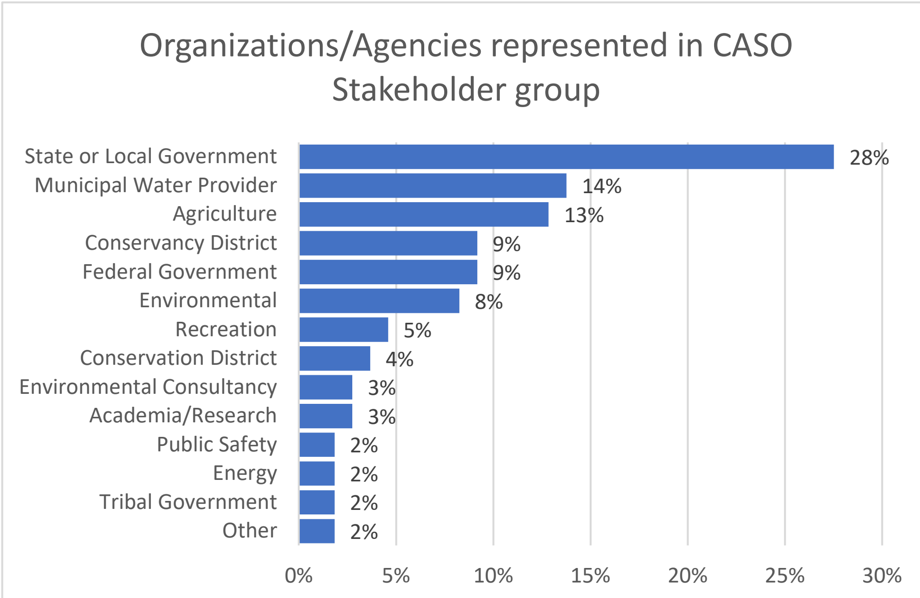


Figure 12. Stakeholder representation in survey

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.

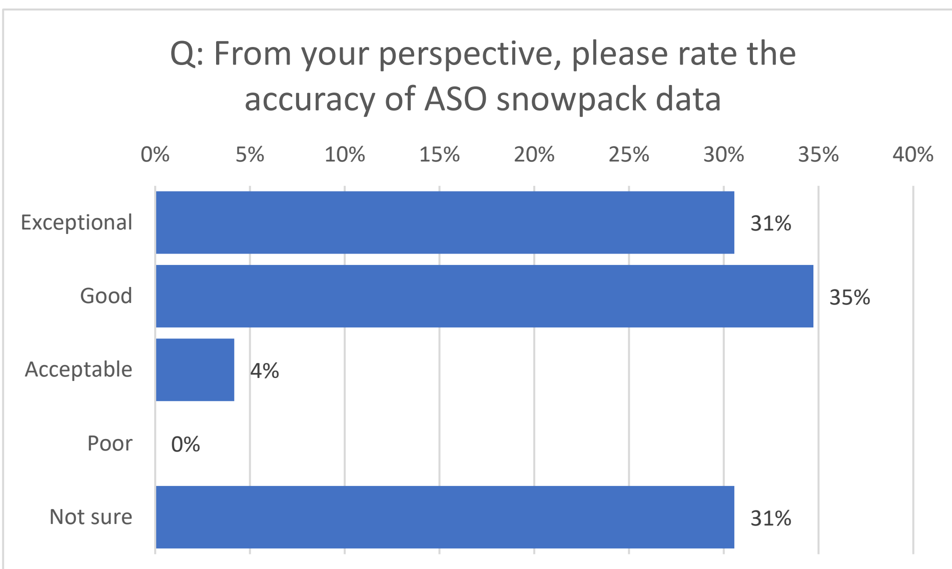


Figure 13. Survey response percentages of total for ASO accuracy

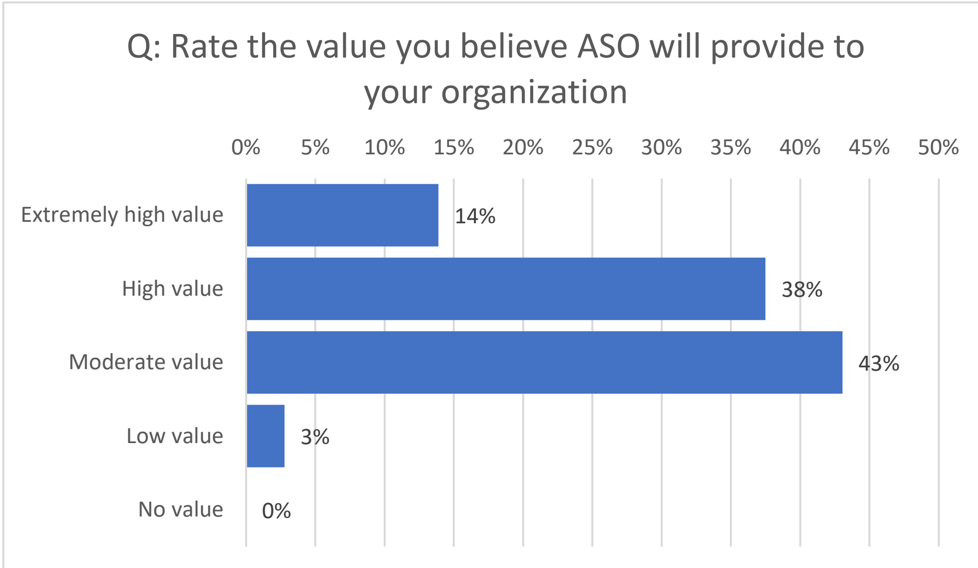


Figure 14. Stakeholder survey results: Rate the value ASO will provide to your organization

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.

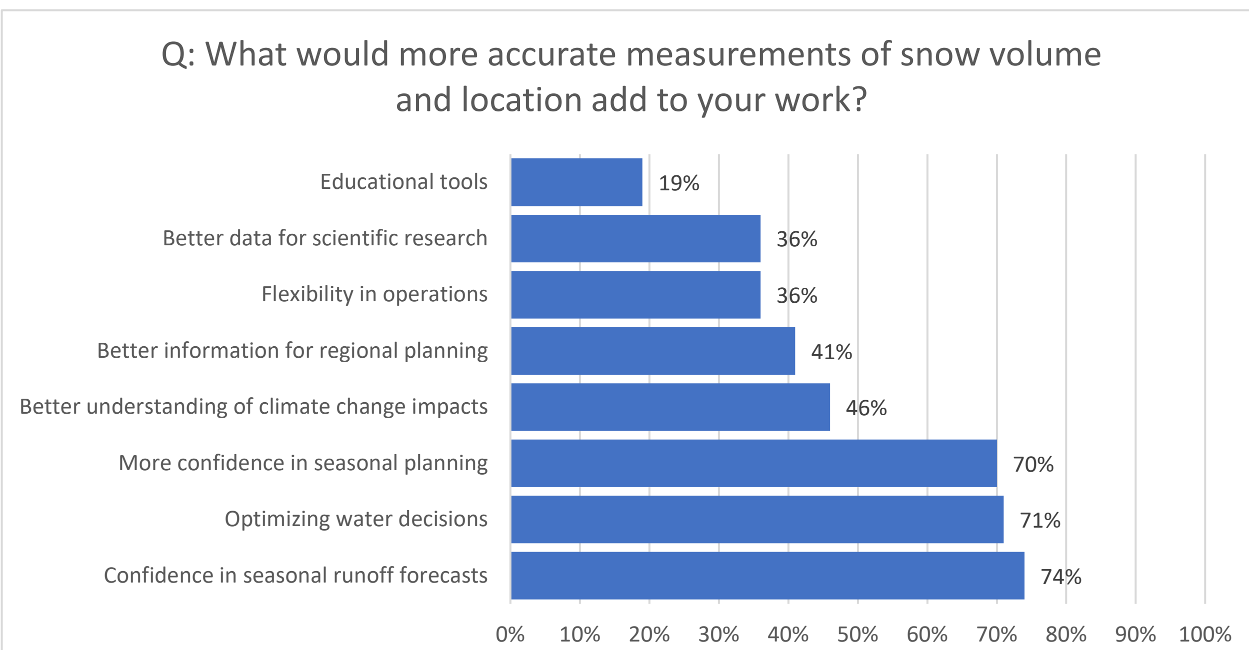


Figure 15. Stakeholder survey results: How would improved accuracy benefit you?

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.

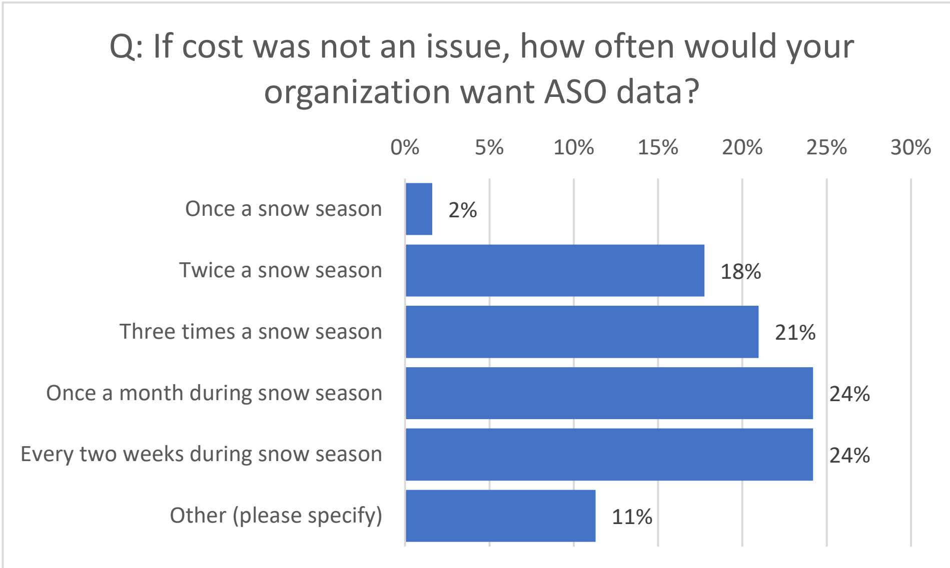


Figure 16. Stakeholder survey results: How often would you want ASO data?

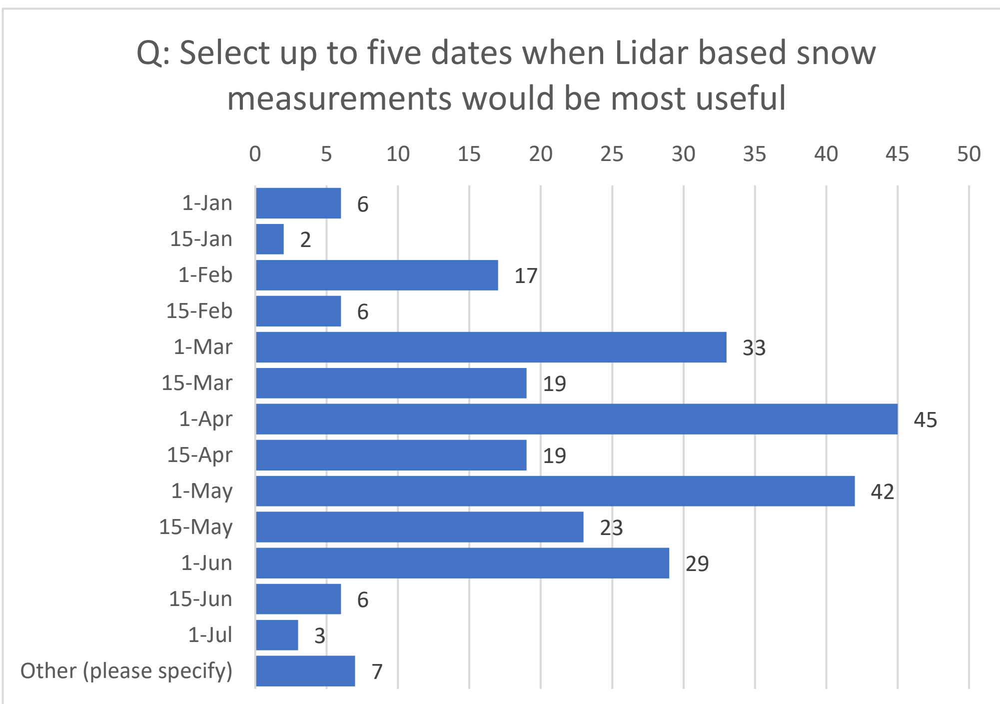


Figure 17. Stakeholder survey results: Ideal Dates for ASO Flights

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.

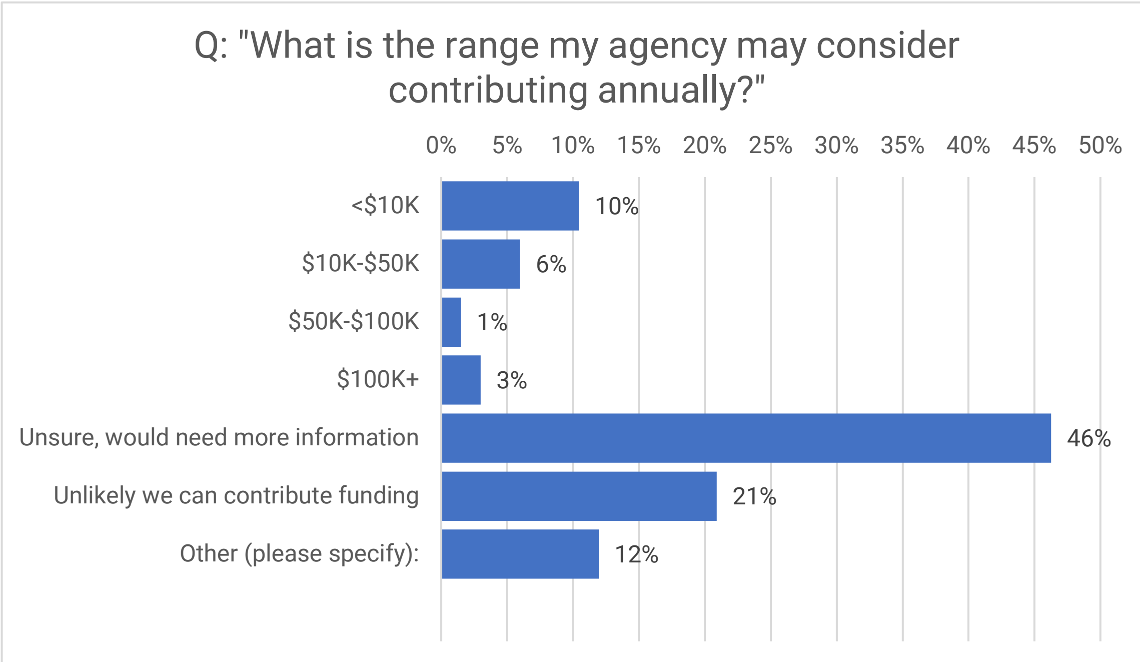


Figure 18. Stakeholder survey results: Willingness to Contribute Funding

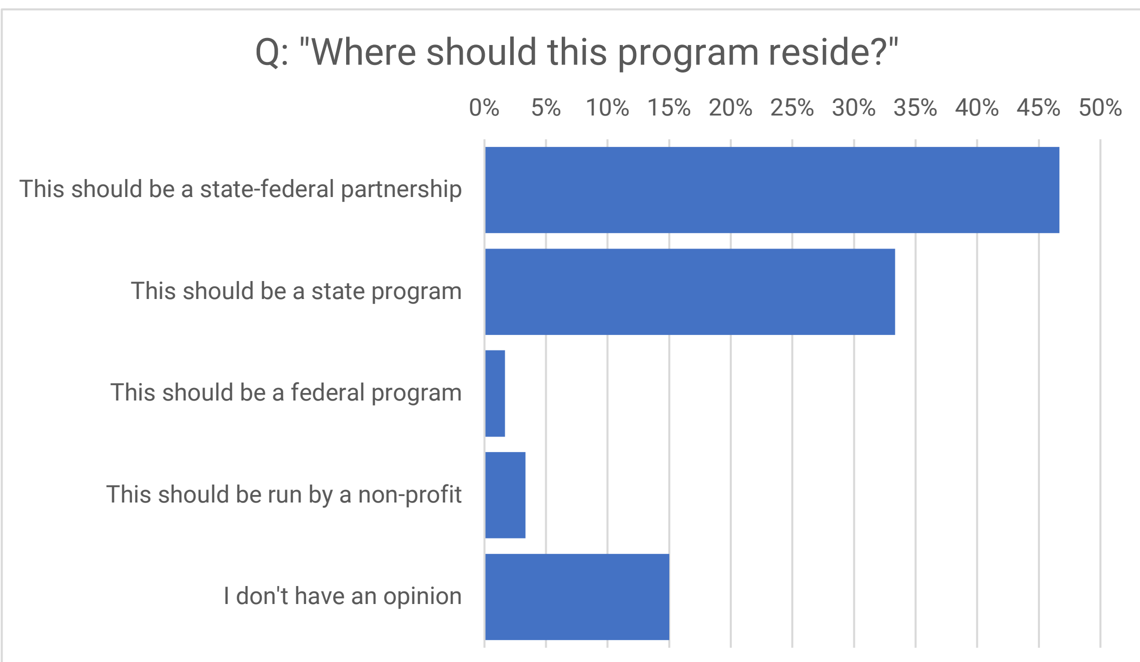


Figure 19. Stakeholder survey results: Ideal program location

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.

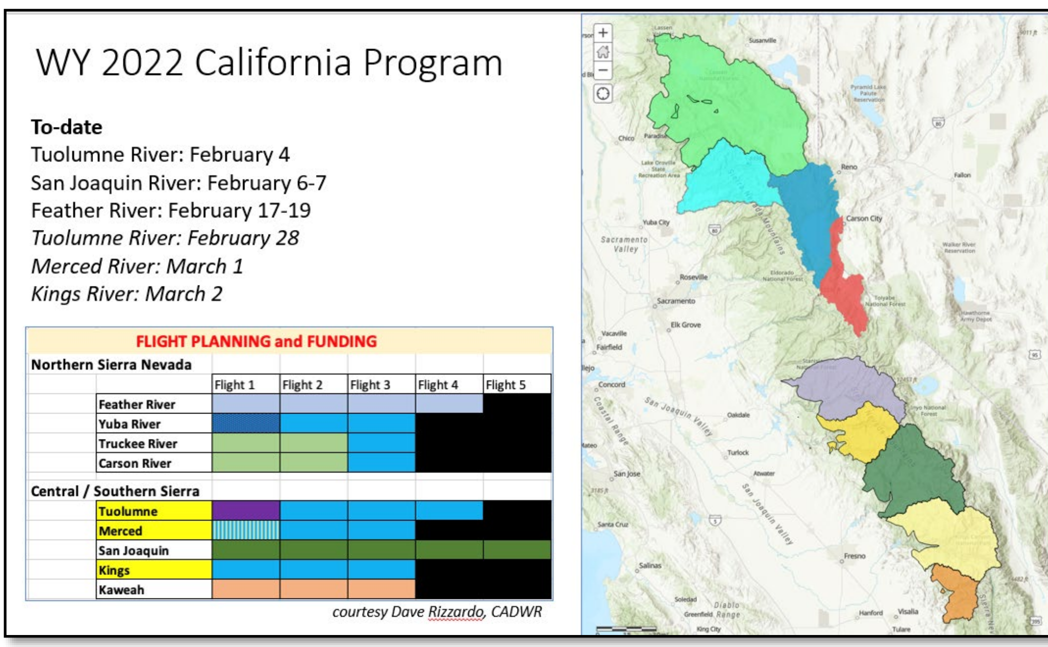


Figure 20. ARSS Implementation Overview, WY 2022

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.

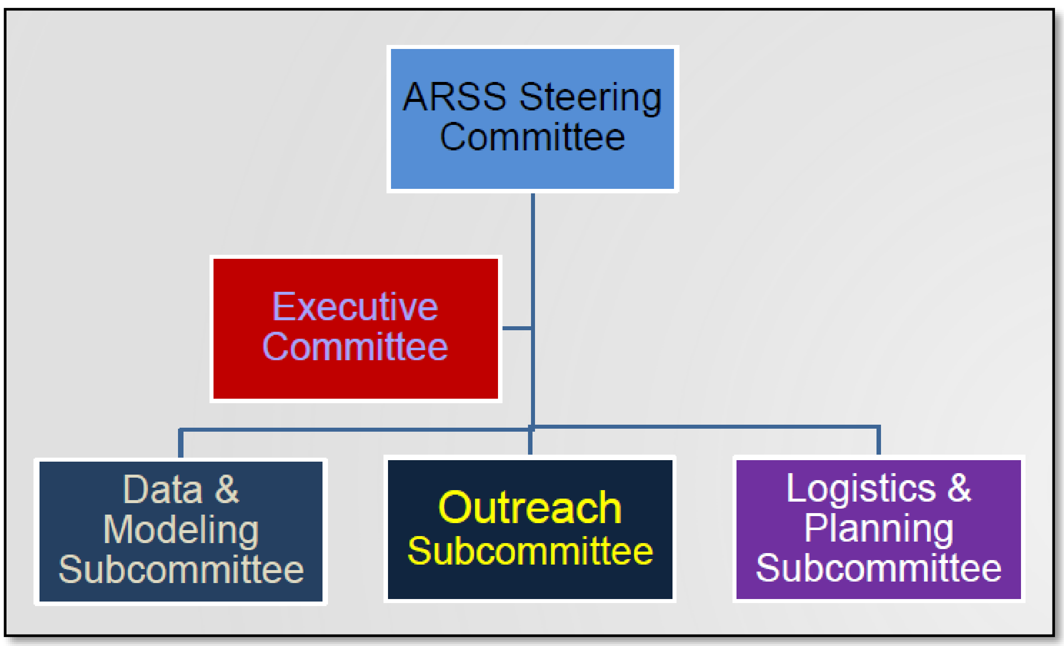


Figure 21. CA-DWR ARSS Committee Structure

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.

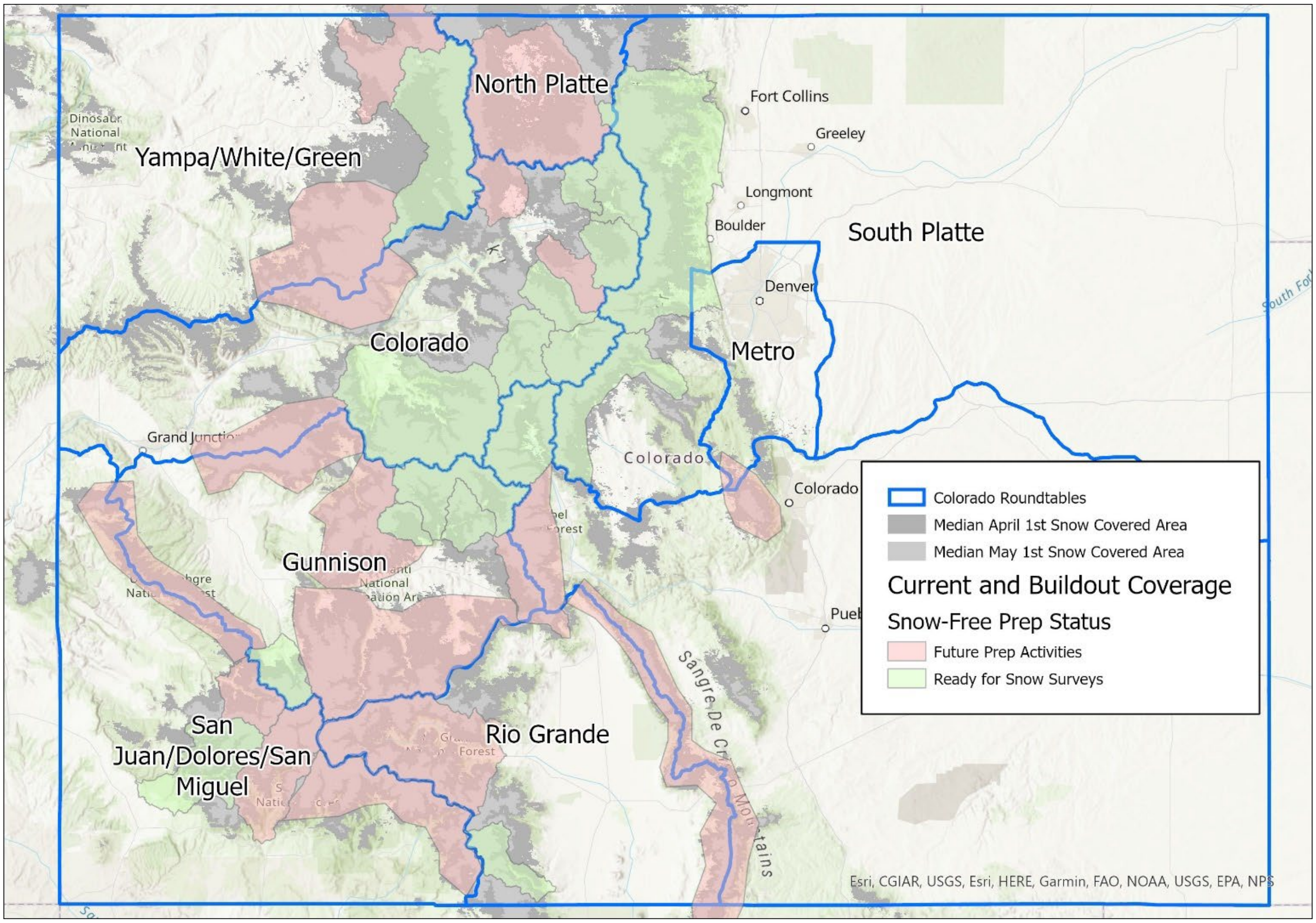


Figure 23. Potential CASM Buildout Coverage Map

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.

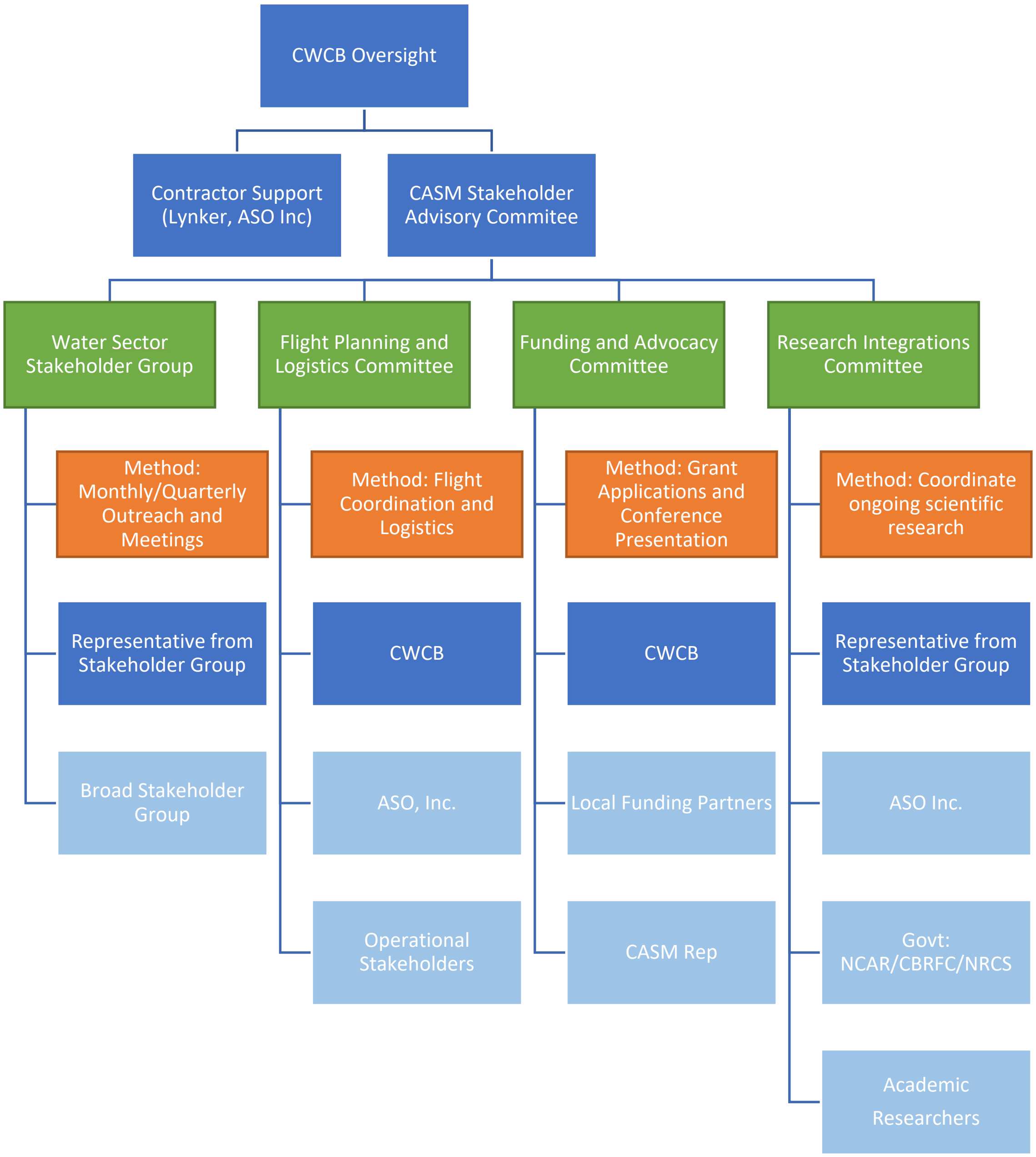


Figure 24. CASM Organizational Structure

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.

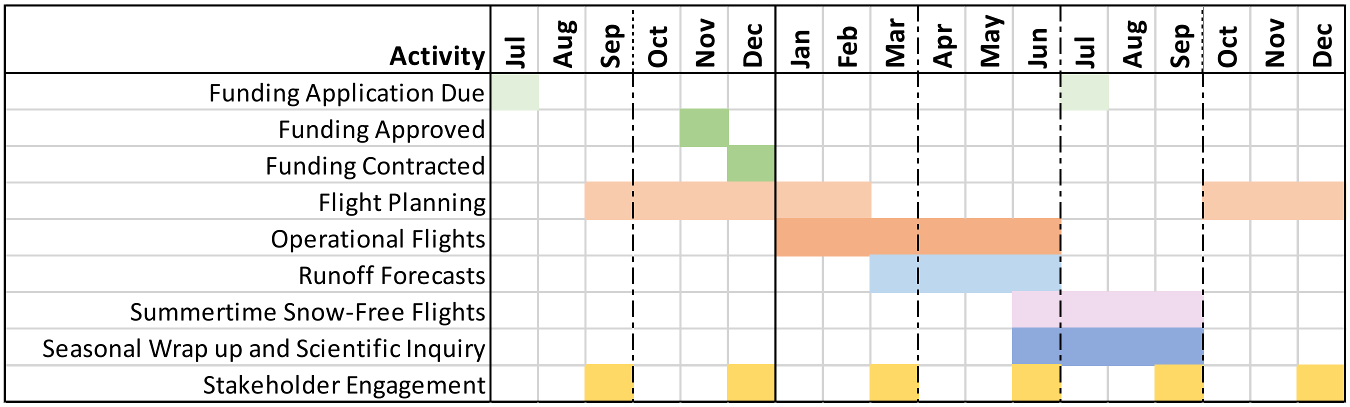


Figure 26. Example Schedule of Annual CASM Activities

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.

7. References

California Department of Water Resources. (2022, March 14th). *California Cooperative Snow Surveys Website, Bulletin 120.* https://cdec.water.ca.gov/snow/bulletin120/

California Department of Water Resources. (2020, November 30th). *Proposed Airborne Remote Sensing for Snowpack. Program Description of Cooperator Needs*

California Department of Water Resources (2018). *Rising to New Challenges For California's Snow Forecasting Program. Web hosted publication (Accessed 6/27/2022 at http://bit.ly/California-ASO)*

Deems, J. (2022, March 7th). *Presentation: ASO WY2022 Update: California.* Colorado Airborne Snowpack Measurement Workgroup Meeting, Colorado, USA.

Durand, M. (2019). NASA Science Plan Update, SnowEx Workshop.

Gochis, D.J., M. Barlage, R. Cabell, M. Casali, A. Dugger, K. FitzGerald, M. McAllister, J. McCreight, A. Rafieei, Nasab, L. Read, K. Sampson, D. Yates, Y. Zhang (2020). The WRF-Hydro® modeling system technical description, (Version 5.1.1). NCAR Technical Note. 107 pages. Available online at: https://ral.ucar.edu/sites/default/files/public/projects/wrf-hydro/technical-description-user-guide/wrf-hydrov5.2technicaldescription.pdf.

Kakalia, Z., Varadharajan, C., Alper, E., Brodie, E. L., Burrus, M., Carroll, R. W., ... & Agarwal, D. A. (2021). The Colorado East River community observatory data collection. *Hydrological Processes*, *35*(6), e14243.

Li, D., Wrzesien, M. L., Durand, M., Adam, J., & Lettenmaier, D. P. (2017). How much runoff originates as snow in the western United States, and how will that change in the future?. *Geophysical Research Letters*, 44(12), 6163-6172.

Milly, P. C., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity is dead: Whither water management?. *Science*, *319*(5863), 573-574.

Natural Resources Conservation Service (2022, March 14th). *Colorado Streamflow Forecast Information*. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/co/snow/?cid=nrcs144p2_063205

Oaida, C. M., Reager, J. T., Andreadis, K. M., David, C. H., Levoe, S. R., Painter, T. H., ... & Famiglietti, J. S. (2019). A high-resolution data assimilation framework for snow water equivalent estimation across the Western United States and validation with the airborne snow observatory. *Journal of Hydrometeorology*, *20*(3), 357-378.

Painter, Thomas H., et al (2016). "The Airborne Snow Observatory: Fusion of scanning lidar, imaging spectrometer, and physically-based modeling for mapping snow water equivalent and snow albedo." Remote Sensing of Environment 184: 139-152.

US Bureau of Reclamation. (2022). *Emerging Technologies in Snow Monitoring: Report to Congress*. US Department of the Interior. https://www.usbr.gov/research/docs/news/EmergingTechnologiesInSnowMonitoring_Report508.pdf

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

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.

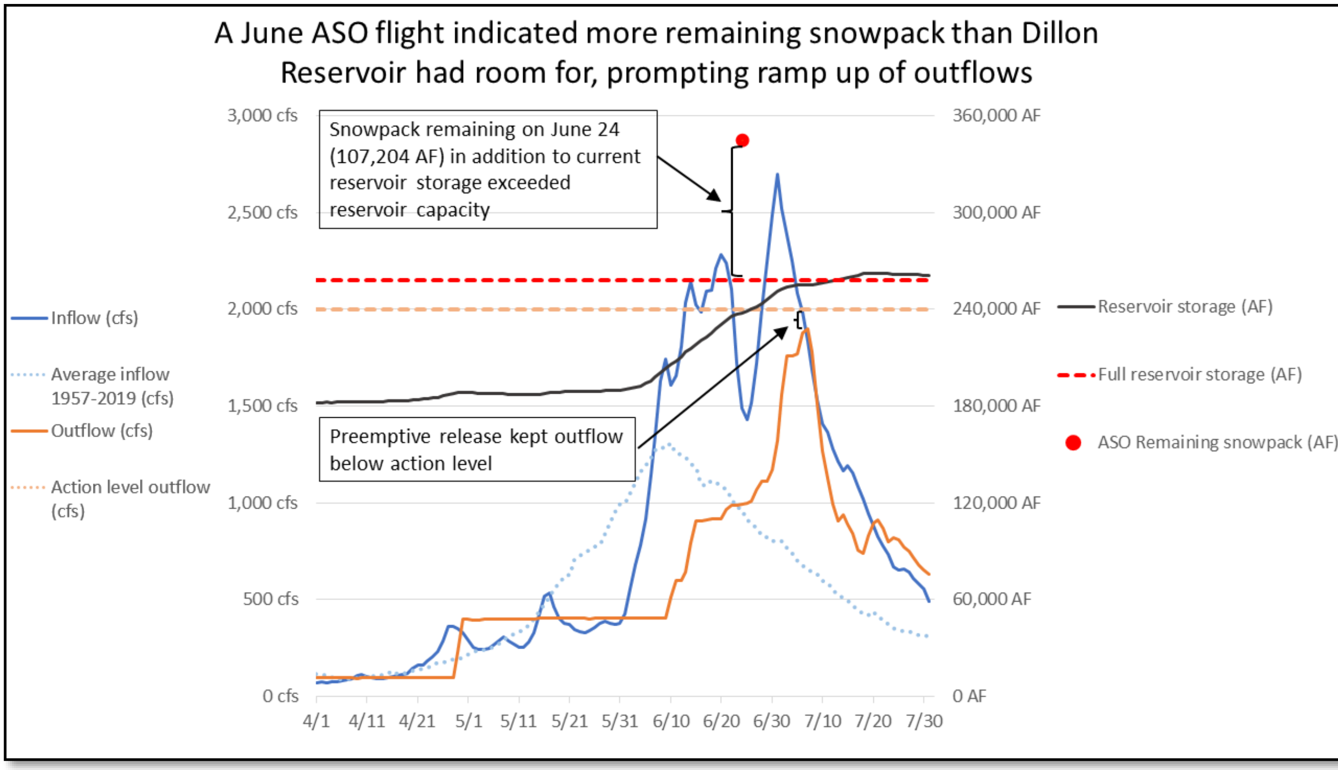


Figure 27. Dillon Reservoir operations in 2019.

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

> **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

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.

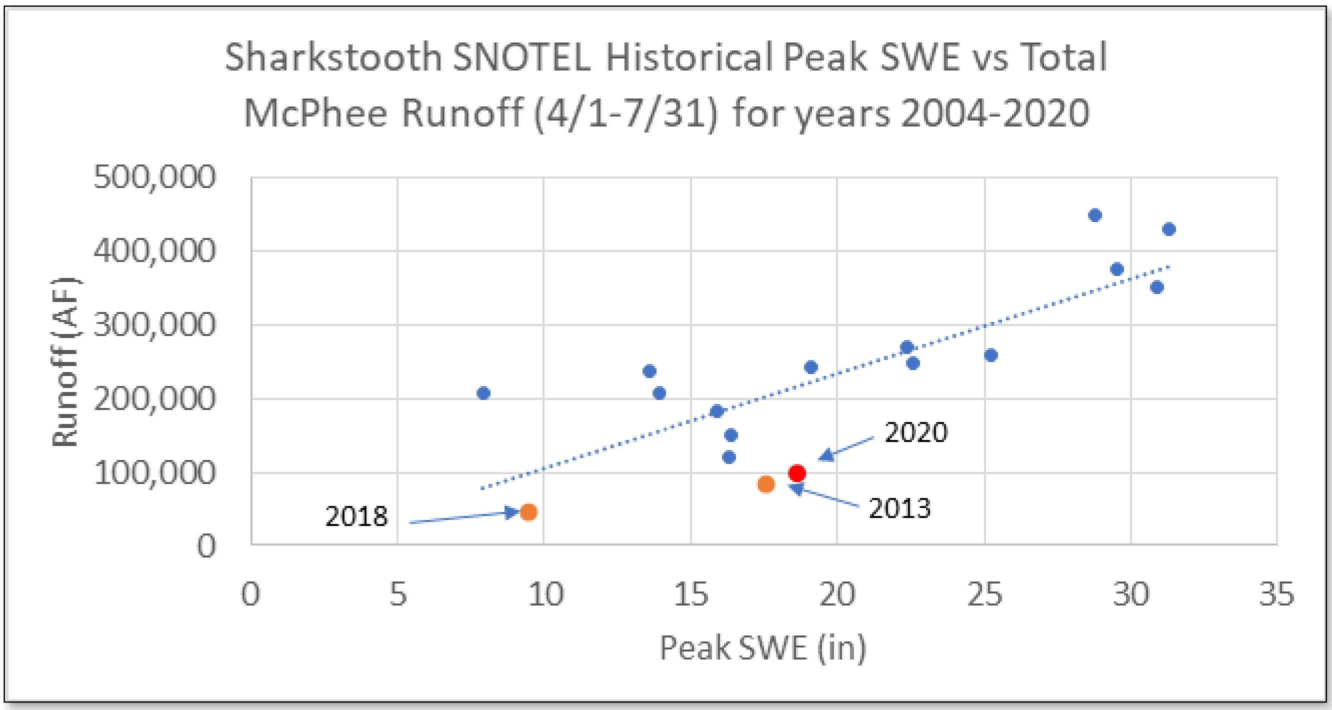


Figure 28. Historical peak SWE at Sharkstooth SNOTEL site vs total runoff into McPhee Reservoir (4/1-7/31) each year. Red dot is 2020. Historically dry years show SNOTEL peak SWE well below average total runoff.

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.

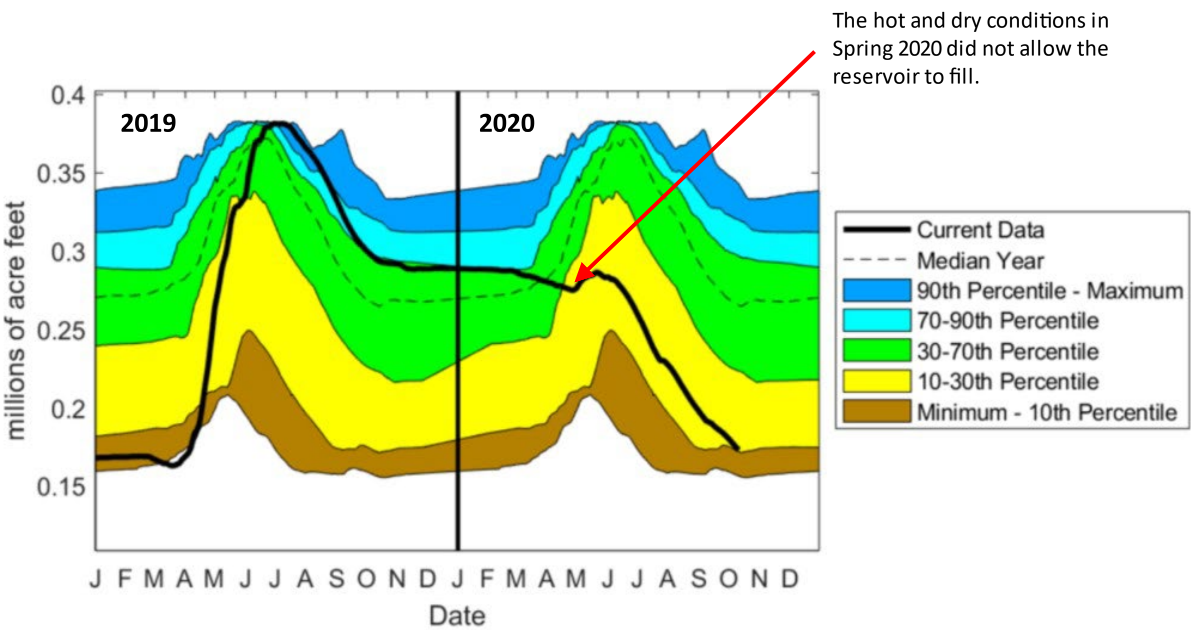


Figure 29. Reservoir storage (AF) in 2019 and 2020. The hot and dry conditions led to little reservoir filling in the spring and then a step drop in the summer.

7.1.3. 2017 McPhee Reservoir Boatable Days

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.

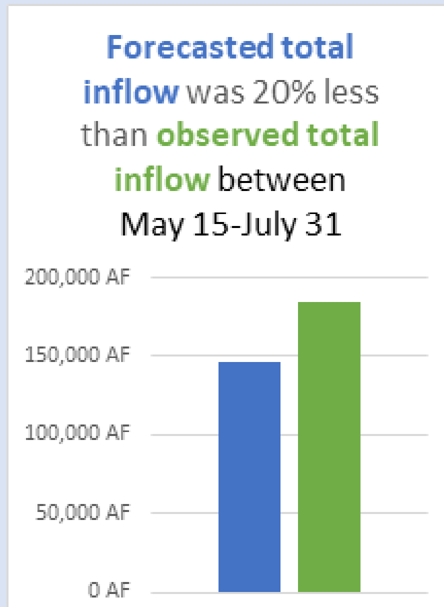
The end of May and beginning of June brought hot and dry conditions, as well as an unanticipated spike in inflows. The reservoir had almost filled, so DWCD managers were forced to increase releases above optimal boatable flows (>1,000cfs) in order to control reservoir elevation. In late June, yet another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

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



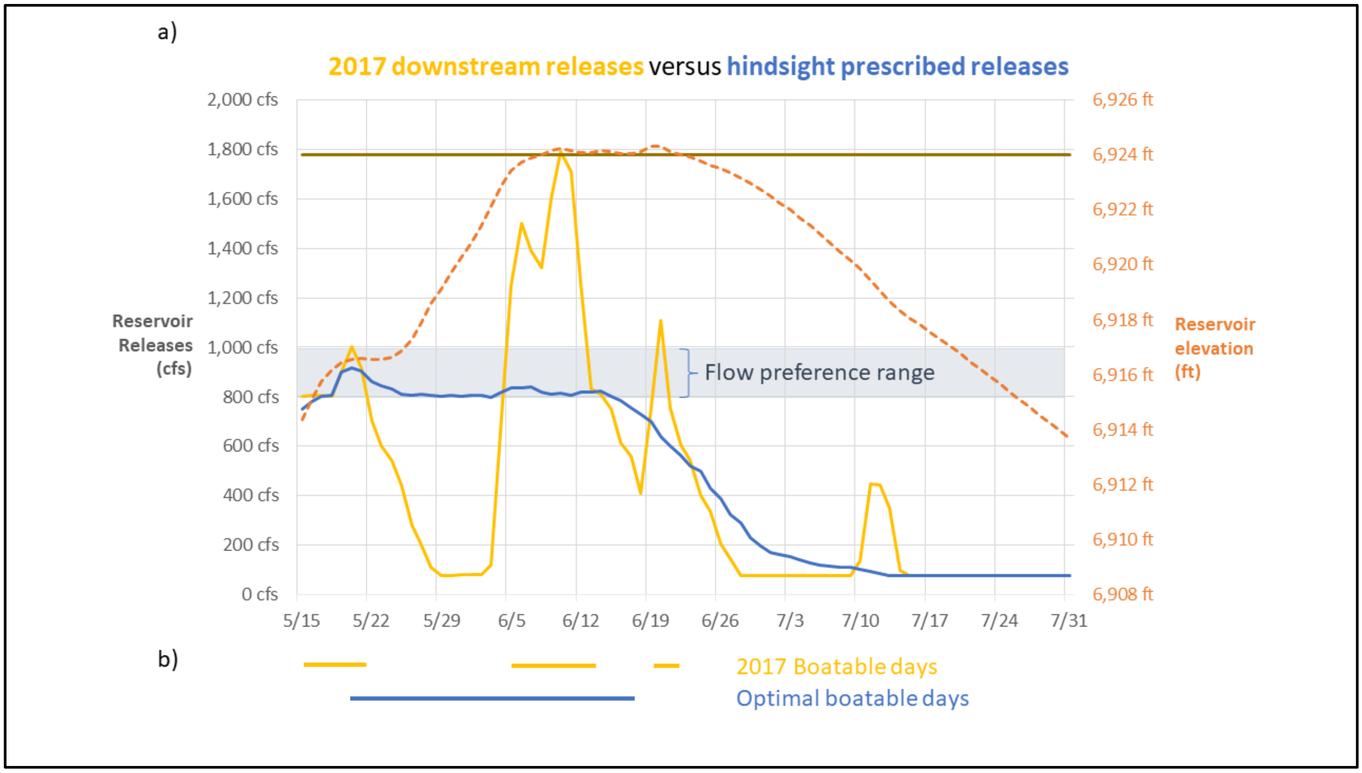


Figure 30. McPhee Reservoir downstream releases versus hindsight prescribed releases

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