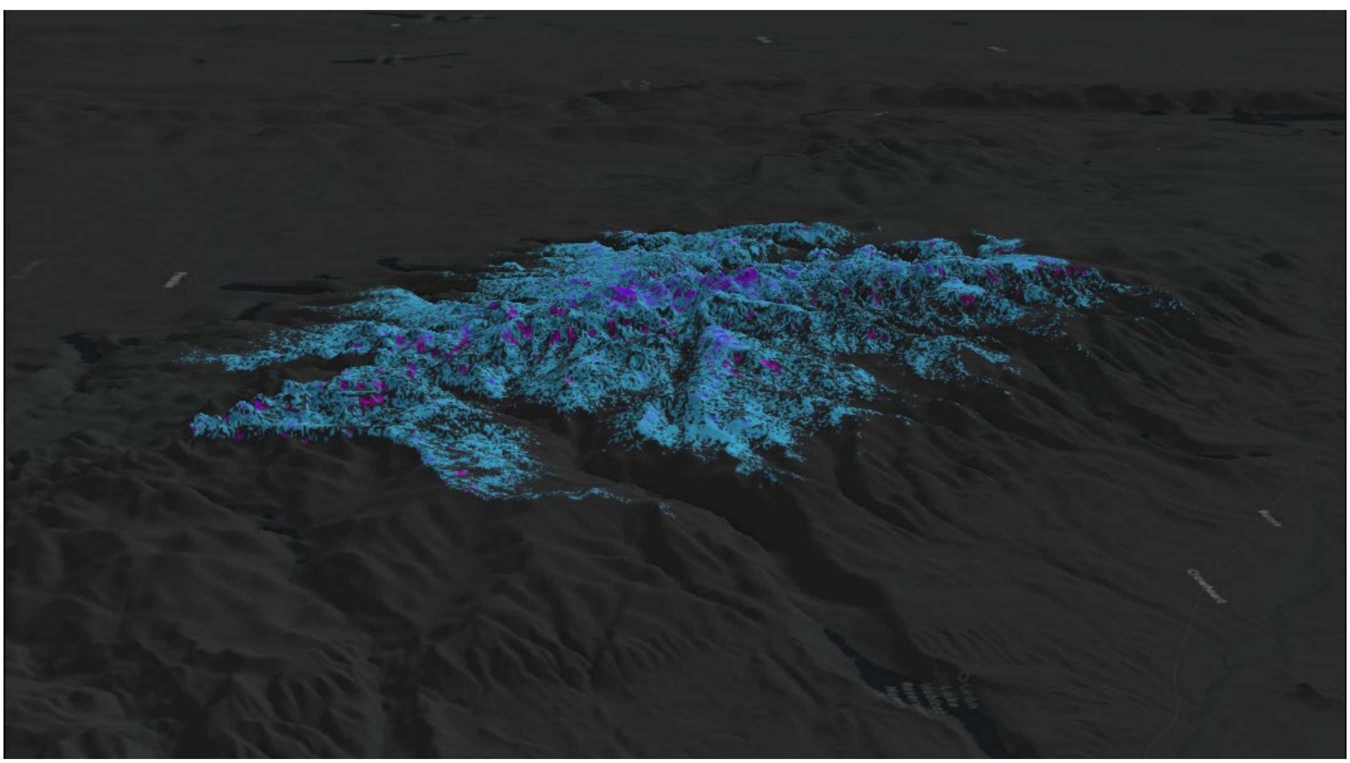
BUREAU OF RECLAMATION

Baseline Airborne Snow Observatory Flights for Basins with Poor Existing Coverage

Snow Water Supply Forecasting Program
Research and Development Office
Science and Technology Project SN1
TSC Final Report No. ENV-2022-114



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Lindsay Bearup, PhD, PE

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The Bureau of Reclamation's Snow Water Supply Forecasting Program, as established by the Snow Water Supply Forecasting Program Authorization Act, 2020, aims to advance emerging snow monitoring technologies and ultimately improve water supply forecasts. The Emerging Technologies in Snow Monitoring Report to Congress (Reclamation 2021a) provides more information on the program and the emerging technologies identified for advancement. The project described in this report is the result of initial program funding. The goal of this project is to catalog, identify and fund Airborne Snow Observatory (ASO) flights for subbasins in underserved snowmelt driven watersheds in the Western United States. As a result of this project, ASO flew its first flight in Wyoming, in the Northern Wind River Range, providing 50-meter snow water equivalent estimates. The area met the selection criteria and provided benefits to stakeholders in basins on both sides of the Continental Divide.

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Disclaimer

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The Snow Water Supply Forecasting Program (Research and Development Office, Bureau of Reclamation) sponsored this research. This work was also made possible through conversations with Jeffrey Deems and others with the Airborne Snow Observatory, Inc., Elizabeth Cresto (Reclamation Wyoming Area Office), and forecasters with the Colorado River Basin Forecast Center (Ashley Nielson and Patrick Kormos).

Baseline Airborne Snow Observatory Flights for Sub-basins with Poor Existing Coverage

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Prepared by:

Bureau of Reclamation
Technical Service Center
Denver, Colorado

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LINDSAY BEARUP Digitally signed by LINDSAY BEARUP
Date: 2023.08.29 09:20:13 -06'00'

Prepared by: Lindsay Bearup, PhD, PE
Civil Engineer – Hydrologic, Applied Hydrology I

KRISTIN MIKKELSON Digitally signed by KRISTIN MIKKELSON
Date: 2023.08.29 09:38:45 -06'00'

Peer Review by: Kristin Mikkelson, PhD, PE
Civil Engineer – Hydrologic, Applied Hydrology I

Acronyms and Abbreviations

%	percent
3DEP	3D Elevation Program
ASO	Airborne Snow Observatory
CASM	Colorado Airborne Snow Measurement
CBRFC	Colorado Basin River Forecast Center
CDEC	California Data Exchange Center
CDWR	California Department of Water Resources
GPS	global positioning system
HUC8	Hydrologic Unit Code 8
JPL	Jet Propulsion Laboratory
lidar	light detection and ranging
m	meter
NASA	National Aeronautics and Space Administration
NSIDC	National Snow and Ice Data Center
NRCS	Natural Resource Conservation Service
Reclamation	Bureau of Reclamation
SNOTEL	SNOw TELemetry
SWE	snow water equivalent
TAF	thousand acre-feet
WYAO	Wyoming Area Office

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Executive Summary

The Bureau of Reclamation's Snow Water Supply Forecasting Program, as established by the Snow Water Supply Forecasting Program Authorization Act, 2020, aims to advance emerging snow monitoring technologies and ultimately improve water supply forecasts. The Emerging Technologies in Snow Monitoring Report to Congress (Reclamation 2021a) provides more information on the program and the emerging technologies identified for advancement. The project described in this report is the result of initial program funding.

The goal of this project is to identify and fund Airborne Snow Observatory (ASO) flights for subbasins in underserved snowmelt driven watersheds in the western United States. Underserved basins are identified based on the following criteria:

1. Poor existing terrestrial snow data coverage, i.e. lack of SNOw TELemetry (SNOTEL) or similar stations

2. Lack of local/state/federal government funding for ASO data collection

3. Breadth and diversity of water stakeholders dependent on snowmelt from the basin, including under-represented communities.

As a result of this project, ASO, Inc. flew its first flight in Wyoming, in the Northern Wind River Range. The area met the three selection criteria, providing benefits to stakeholders in basins on both sides of the Continental Divide. The ASO flight provided snow depth at 3-meter (m) resolution, snow depth at 50 m resolution, snow water equivalent (SWE) estimates at 50 m resolution, and snow albedo at 50 m resolution.

1 Introduction

Snowmelt dominates runoff in the western United States, with major western mountain ranges receiving over 70 percent (%) of their total annual runoff from snow (Li et al. 2017). Quantifying the amount of water stored in the snowpack, or snow water equivalent (SWE), is therefore a critical component of managing water resources in the region. Historically, snow measurements came primarily from in-situ snow surveys and monitoring stations, such as California Data Exchange Center (CDEC) sites managed by the California Department of Water Resources (CDWR) and SNOw TELemetry (SNOTEL) sites managed by the Natural Resource Conservation Service (NRCS). While these stations provide continuous estimates of SWE, they are limited to point locations that do not provide complete information across a watershed. Snowpack varies across a watershed due to wind redistribution, variability in storm patterns, and land surface properties such as aspect and land cover.

Over the last decade, the Airborne Snow Observatory (ASO) methodology has been developed and refined to estimate SWE from plane-based lidar (light detection and ranging). This aerial approach provides high resolution information across a watershed, effectively providing a more spatially detailed snapshot of SWE across the variable snowpack. Originally developed at National Aeronautics and Space Administration's Jet Propulsion Laboratory (NASA JPL), the data processing workflow is now licensed exclusively to ASO, Inc. While some areas, such as basins in California and Colorado, have been successful in funding ASO flights to support their water management decisions, many basins do not have the momentum and funding resources to begin building a record of flights. A recent study by the Bureau of Reclamation (Reclamation) in the Tuolumne River Basin found that after completing 6-10 ASO flights, statistical relationships can be built quantifying SWE across a basin (Reclamation 2021b). These statistical relationships can reduce the future number of flights needed, therefore proving additional value to the early flights. Coupled with the initial investment needed to bring a new basin online, the cost to develop a robust ASO dataset in a basin has been a challenge in some areas that lack financial resources or stakeholder coordination.

The goal of this project is to identify and fund Airborne Snow Observatory (ASO) flights for subbasins in underserved snowmelt driven watersheds in the Western United States. Here, underserved basins are identified based on three criteria:

1. Poor existing terrestrial snow data coverage (Section 2.1)
2. Lack of local/state/federal government funding for ASO data collection (Section 2.2)
3. Breadth and diversity of water stakeholders dependent on snowmelt from the basin, including under-represented communities. (Section 2.3).

This report summarizes the project's approach to site selection (Section 2), results (Section 3), and conclusions (Section 4). The project is the result of initial funding under the Snow Water Supply Forecasting Program, established by the Snow Water Supply Forecasting Program Authorization Act, 2020. This program aims to advance emerging snow monitoring technologies

and ultimately improve water supply forecasts. The Emerging Technologies in the Snow Monitoring Report to Congress (Reclamation 2021a) provides more information on the program and the emerging technologies identified for advancement.

2 Site Selection

2.1 Identifying snow station coverage

Although many are in remote locations, snow monitoring stations must be installed in areas that are accessible, which often precludes private land, wilderness area, and areas that are not geologically stable or safe. Snow pillows are used to measure SWE and are typically located on flat spots in openings below tree line to provide some protection from wind redistribution of snow. Currently, the combined CDEC and SNOTEL networks have approximately 900 snow pillow sites across the western United States. Other sources of SWE information, such as snow courses, were not considered in this study, but likely reflect similar spatial coverage as automated stations.

This project evaluated station locations from the SNOTEL and CDEC networks to identify the number of stations in each subbasin, defined here by Hydrologic Unit Code 8 (HUC8). This analysis supports criterion 1 by identifying watersheds with poor existing terrestrial snow data coverage (Figure 1).

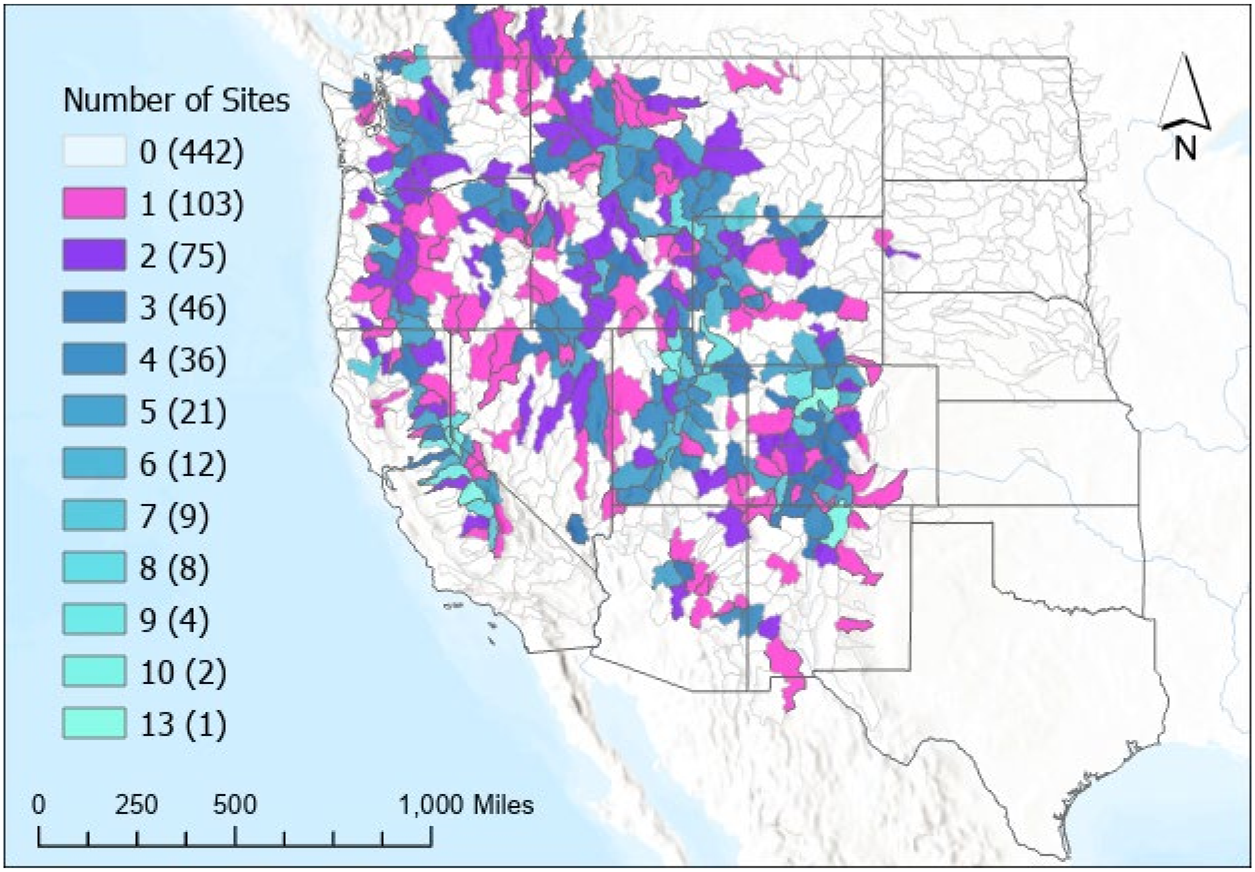

Figure 1.—Density of SNOTEL and CDEC stations aggregated by HUC8 across the 17 Western States with the number of HUC8s in each with a given number of sites shown in the legend in parentheses.

Station and spatial data for analysis were obtain from the following sources:

- SNOTEL: NRCS Interactive Maps for Active SNOTEL Sites, accessed 9/28/2022 here: www.nrcs.usda.gov/wps/portal/wcc/home/quicklinks/imap
- CDEC: Active Snow Sensor list accessed 11/22/2021 here: cdec.water.ca.gov/reportapp/javareports?name=SnowSensors
- HUC8 watersheds shapefiles accessed 11/19/2021 here: www.usgs.gov/national-hydrography/access-national-hydrography-products
- Global Seasonal Mountain Snow Mask of Wrzesien et al. 2019: accessed 9/7/2022 here: zenodo.org/record/2626737#.YxjwnXbMKUk
- Fraction of streamflow derived from snow based on the analysis of Li et al. 2017.

The HUC8 boundaries included in Figure 1 are limited to watersheds that intersect with the ephemeral or seasonal snow classifications of Wrzesien et al. 2019. HUC8 boundaries shown that are not shaded (gray outline only) represent areas that typically receive snow for at least part of the year but do not have any SNOTEL or CDEC stations. To further highlight watersheds with poor existing terrestrial snow data coverage that are dependent on snowmelt, Figure 2 shows the fraction of streamflow derived from snow (fQsnow, Li et al. 2017) across HUC8 watersheds that have one or fewer stations. Note that the dataset from Li et al. 2017 does not extend east of Colorado.

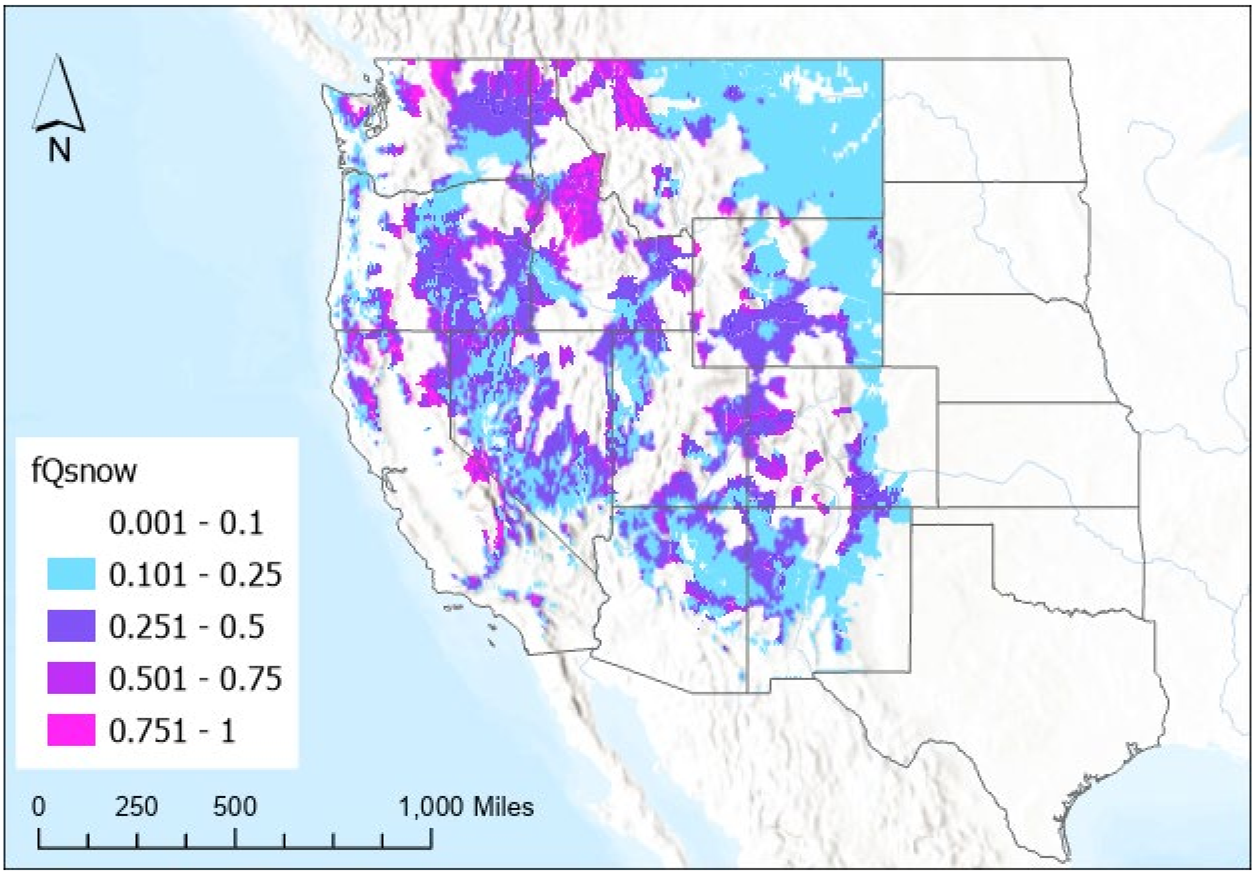

Figure 2.—Snow-derived runoff as a fraction of total runoff (fQsnow, Li et al. 2017) for watersheds with 0-1 SNOTEL or CDEC sites.

The pink and purple shading in Figure 2 highlights areas where snowmelt is an important source of runoff, and where the snowpack may be under observed. These areas, such as central Idaho, northeastern Washington, or southern Wyoming/Western Colorado, can be further evaluated for the suitability and need for ASO flights.

2.2 ASO methodology and existing coverage

ASO, Inc. currently uses a twin-engine turbo prop aircraft equipped with scanning lidar, imaging spectrometer, and global positioning system (GPS) implemented specifically for snow data collection. The scanning lidar provides surface topography of either the snow or land surface. The imaging spectrometer provides snow coverage and albedo. Albedo is a measure of reflectivity and informs how the snowpack will absorb energy and melt. The subsequent processing and relative data set registration ensures subtracting the ground surface from the snow surface results in accurate snowpack depth, meaning it prioritizes relative precision between flights over global georeferencing. Each basin requires a snow-free lidar dataset to ensure accurate representation of the ground surface.

Where it was available and suitable for use, ASO, Inc. previously used existing snow-free lidar datasets (e.g. from the U.S. Geological Survey's 3D Elevation Program, or 3DEP, available here: www.usgs.gov/3d-elevation-program). The use of existing elevation data can help reduce the cost and expedite the schedule of bringing a new basin online by eliminating the need for a snow-free flight; however, evaluation and incorporation of the data into the ASO, Inc. workflow is non-trivial and can result in higher uncertainties in the final product. Moving forward, ASO, Inc. plans to stop using 3DEP data until product specifications meet their complete requirements for snow depth calculations.

The ASO methodology uses observations of snow density and snow modeling to determine SWE from snow depth maps. In addition to a summary report and figures, the basic datasets currently provided by ASO, Inc. include:

- Snow depth at 3-meter (m) resolution
- Snow depth at 50 m resolution
- SWE at 50 m resolution
- Snow albedo at 50 m resolution.

Through 2022, nearly 200 ASO flights have been flown in the western United States. Basins flown, about to be flown, or under active discussion to fly (Jeffrey Deems personal communication 8/17/2022) are shown in Figure 3. To identify when flights were flown, we cross-referenced the ASO, Inc. shapefile with ASO datasets provided by two publicly available sources:

- National Snow and Ice Data Center (NSIDC): flights from 2013-2019, available here: nsidc.org/data/aso

- ASO, Inc: flights from 2020 to present, available here: data.airbornesnowobservatories.com.

Figure 3 illustrates the spatial coverage of ASO activities, color-coded based on the year the basin was first flown. In addition to the spatial coverage provided by ASO, Inc., NSIDC also hosts 2016 data for the Olympic Mountains, which was included in Figure 3. Note that some areas were partially flown in some years, for example early flights in the East River near

Gunnison, CO did not include the full area shown below. Not shown here, are lidar datasets available from research activities, such as NASA's SnowEx campaign in Grand Junction, CO and other areas throughout the western United States.

Prior to 2022 and the flight funded through this project, ASO coverage was largely limited to Colorado and California (Figure 3). In addition to stakeholder momentum, described more in Section 2.3, Colorado and California are also likely to experience cloud-free conditions that are conducive to gathering airborne lidar datasets.

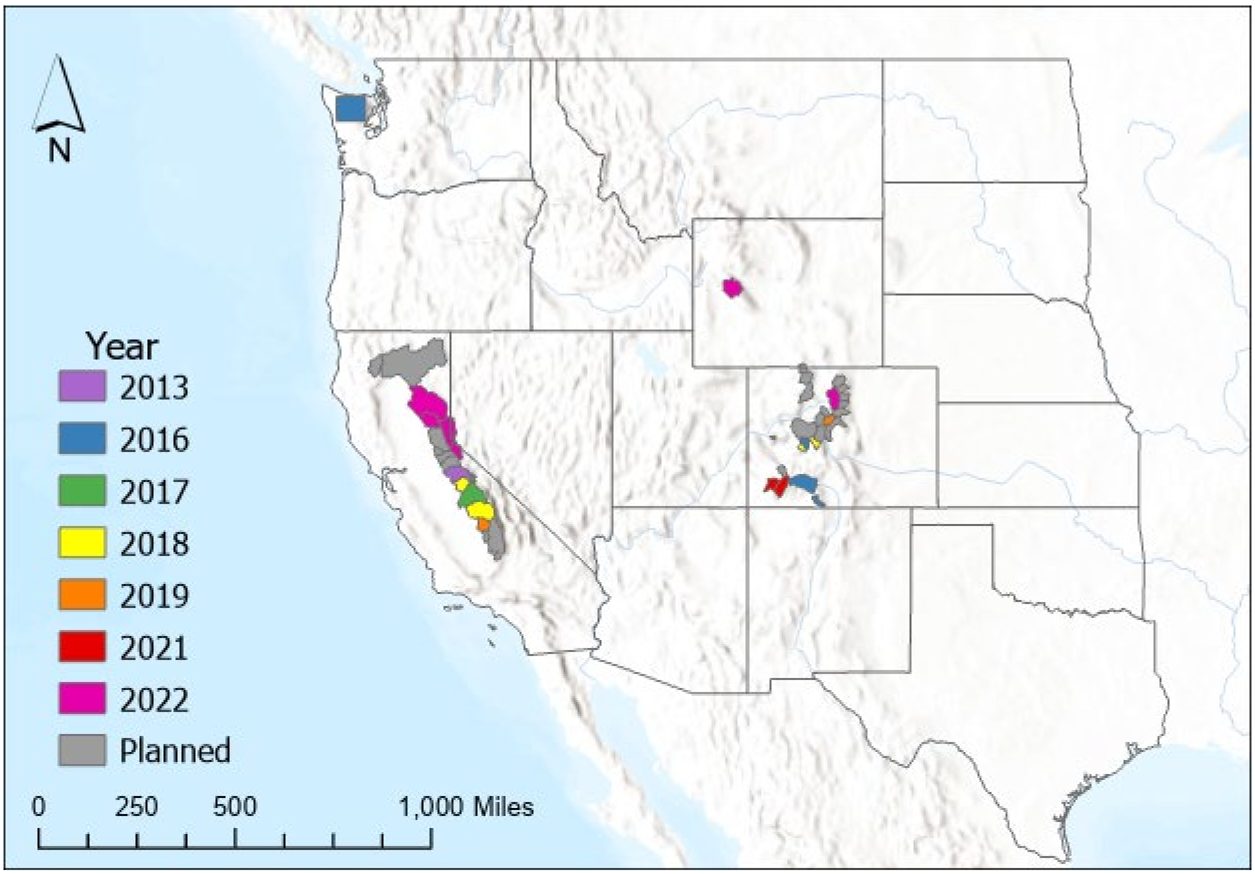

Figure 3.—ASO flight coverage, including past and planned future flights. Basin color indicates the year the first flight was flown in the basin.

2.3 Stakeholder Involvement

Recent activity and planned flights in California and Colorado (Figure 3) reflect coordinated efforts to obtain high-resolution spatial snow datasets at the state level. In California, CDWR was an early adopter of ASO products. More recently, Colorado stakeholders, largely driven by water providers and districts such as Denver Water, Northern Water, and the Dolores Water Conservancy District formed the Colorado Airborne Snow Measurement (CASM, coloradosnow.org/) program, to coordinate ASO funding and flight activities. Other states, such

as Wyoming and Utah, and tribal lands (Figure 4) do not currently have programs in place to help establish flights in new basins or coordinate funding for ongoing flights. These areas represent opportunities for this project to support bringing ASO to underserved communities such as tribal lands (Figure 4)

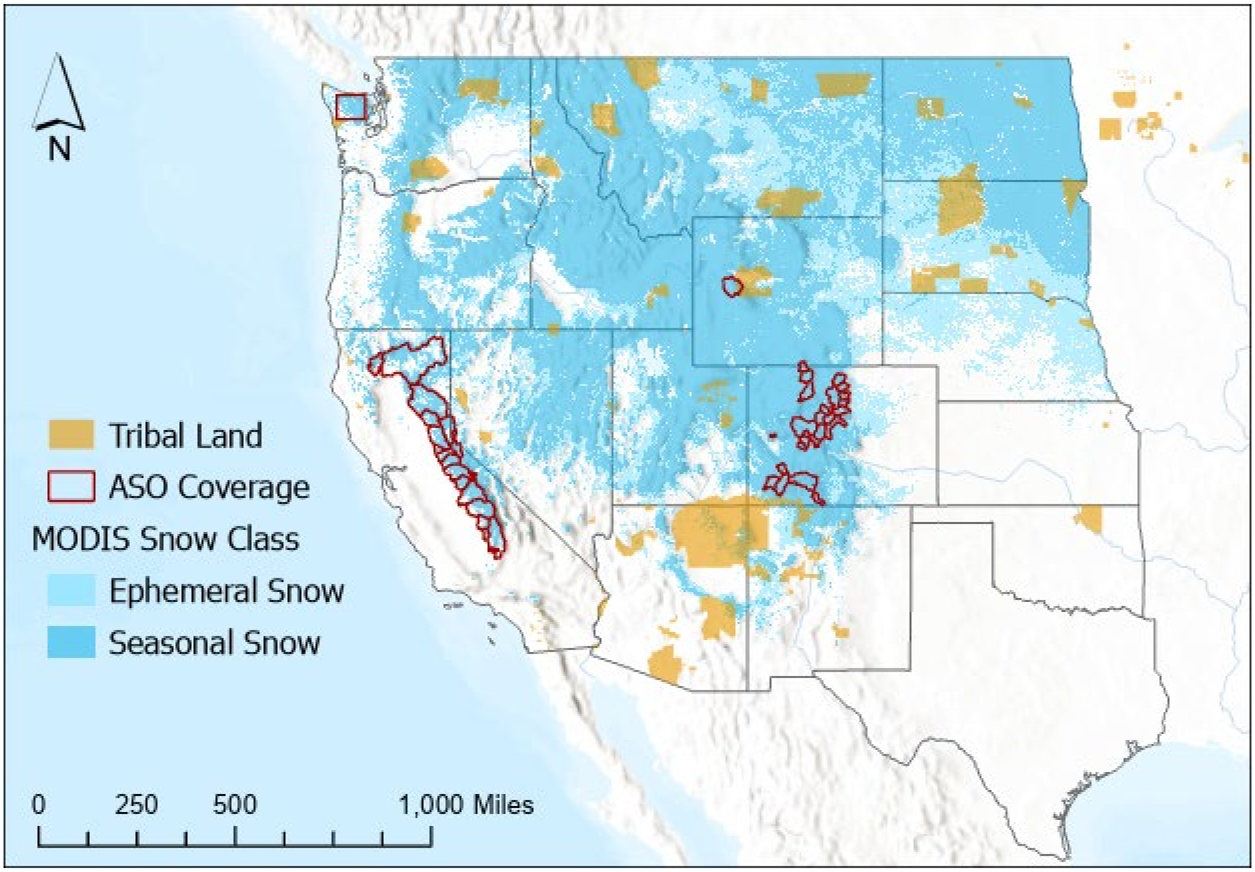

Figure 4.—Tribal land (Federal and Tribal land dataset) in the Western United States, mapped with snow and ASO coverage datasets described in Sections 2.1-2.2.

We used Figures 1-4 to identify and prioritize areas where observations are limited. After identifying areas for further consideration, this project reached out to water managers and hydrologists to discuss the use and need for flights, as well as coverage options and timing to support management decisions. These stakeholder engagements were critical in identifying where flights would be useful and used, as well as refining priority flight areas within the HUC 8 subbasins.

3 Results

3.1 Selected Basin and Flight Results

The flight area selected for funding as part of this project is located in the northern Wind River Range in western Wyoming (Figure 5). The western side of the domain drains to the Green River in the headwaters of the Colorado River. Conversations with Colorado Basin River Forecast Center (CBRFC) forecasters (Ashley Nielson, personal communication 7/29/2021) revealed that SWE observations are limited in this part of the basin due to wilderness constraints on SNOTEL locations. Operators described how much of the SWE is unobserved and at high elevations (e.g., above 10,000 feet), and the highest SNOTEL site near the proposed flight area is Gunsight Pass at 9,820 feet elevation (Figure 6). Unobserved high elevation snow suggests late May or early June flights may be helpful for forecasters to understand remaining SWE once the stations have melted out.

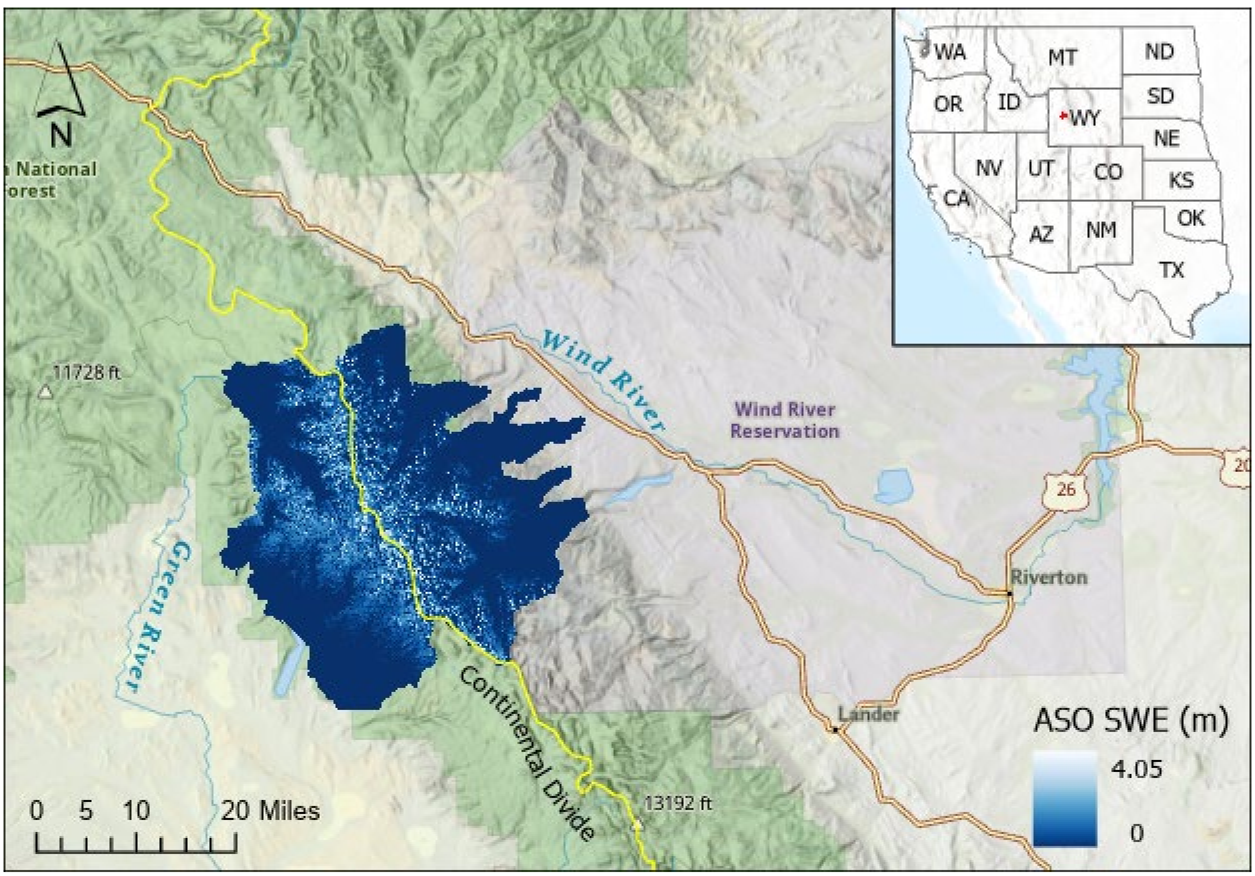

Figure 5.—Location map of northern Wind River ASO flight.

The eastern side of the domain drains to the Wind/Bighorn River, part of the water supply for Reclamation's Yellowtail Unit in the Missouri Basin. Reclamation's Wyoming Area Office (WYAO) manages Bull Lake and Boysen Reservoirs, which receive most of their water from snowpack in the Wind River Range. Operating Bull Lake is particularly challenging because there are no SNOTEL stations in the watershed above the reservoir. In April of 2022, WYAO operators described how the two SNOTEL stations they usually use to guide operations were providing mixed information (Elizabeth Cresto, personal communication 4/26/2022). One station (St. Lawrence Alt, 8620 feet) had completely melted out several months early and peak streamflow was abnormally low, suggesting not much water remained in the watershed. The other station (Cold Springs, 9630 feet) was still snow covered and looking "better than normal", with the station reporting over 130% of normal SWE. The higher elevation of the Cold Springs SNOTEL station suggests more snow may remain at elevations above what is reported by the stations, similar to the western side of the domain. WYAO operators also mentioned that late-season flights would be useful in this area to provide confidence to communicate with local water users that more snow is available fill Bull Lake, supporting decisions often made in June and July. To this end, we decided that a late season flight over this domain was advisable as it also aligned well with contract timing for the flight and an active weather pattern that provided late season precipitation in the area.

Overall, this domain was chosen for an ASO flight as it met all three criteria stated in Section 2. For example, watersheds in the northern Wind River Range meet the first selection criterion of poor existing terrestrial snow data coverage (Section 2.1), as described by stakeholders on both sides of the Continental Divide. Wyoming also does not have a coordinated ASO effort, reflecting the lack of local, state, and federal government funding for these activities and therefore meeting the second selection criterion (Section 2.2) developed for this project. In addition, many of the watersheds on the eastern side of the flight area are partially in the Wind River Reservation, providing coverage for an often-under-represented community and thus meeting the third selection criterion (Section 2.3).

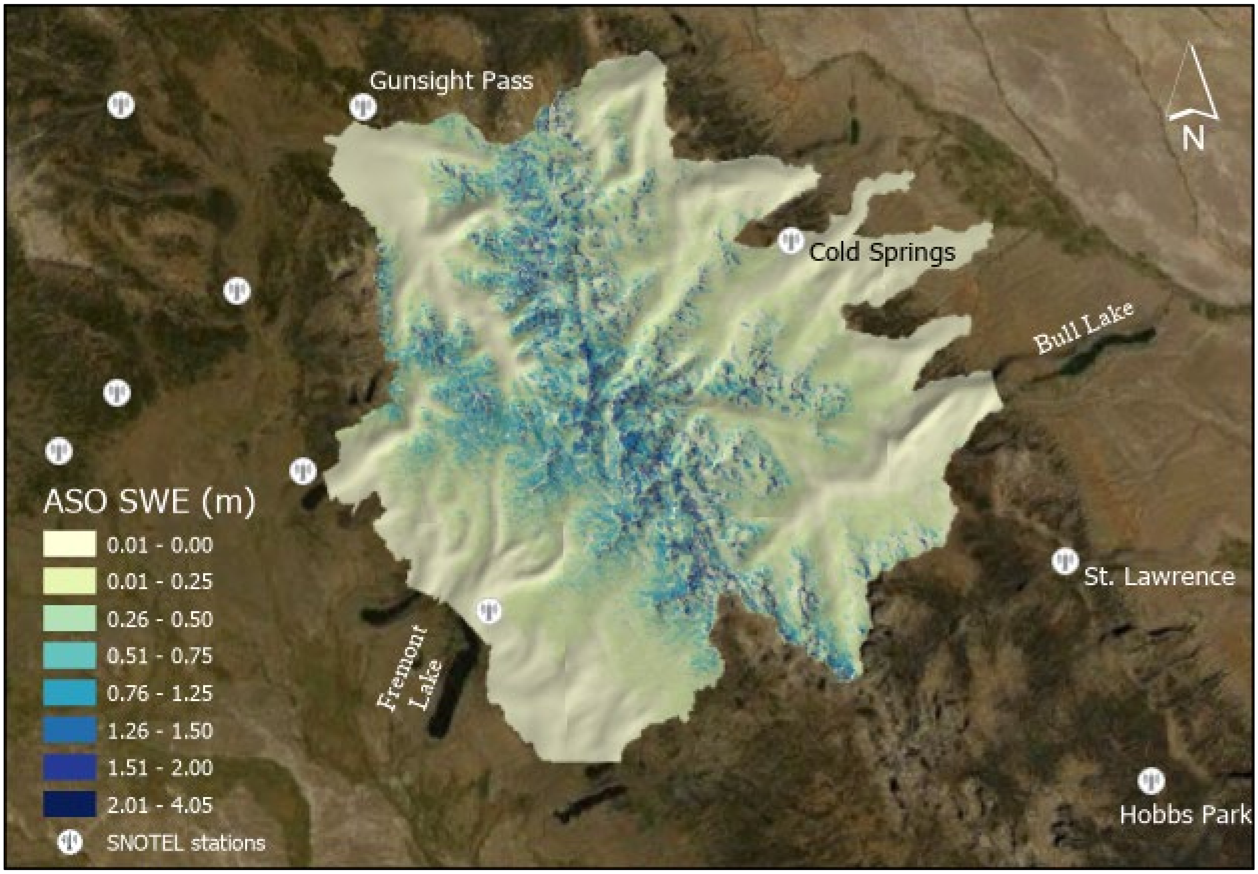

Figure 6.—ASO snow water equivalent (in meters) for the June 11, 2022, flight in the north Wind River Range, Wyoming.

After waiting for a break in storms that brought challenging cloud cover, ASO was able to collect the lidar dataset on June 11, 2022, estimate SWE, and provide data and the final report on June 16, 2022. For more details on the results of the flight, such as SWE totals, uncertainty ranges, and cloud cover impacts, see the ASO report attached in Appendix A. In brief, the ASO flight found that in June, the snowline was at or above 9,800 feet in the northern Wind River Basin, which indicates that the Cold Springs SNOTEL site could not lend information about the amount of available water remaining in snowpack. The ASO flight found that in this subbasin, there was 157 +/- 16 thousand acre-feet (TAF) of SWE remaining in the basin. In the adjacent Green River basin, the snowline was observed to be around 9,600 feet with an estimated 192 +/- 19 TAF of SWE remaining in the higher elevations. Overall, this flight emphasizes the need for water managers to better understand the spatial distribution of snowpack across the entire basin to properly manage water in snowmelt-dominated watersheds.

3.2 Experimental Water Supply Forecasts

The CBRFC directly inserted SWE estimates from the June 11, 2022, ASO flight to produce experimental forecasts of seasonal (April through July) runoff volumes in the Upper Green River (Patrick Kormos, personal communication 11/8/2022). While the modeling and comparison methodology is under refinement, initial results for the under-observed Upper Green River domain show a promising increase in forecast accuracy (Figure 9 - Figure 9). CBRFC forecasters suspect that ASO was particularly beneficial to modeled forecasts in the Upper Green River watershed due to the lack of station information in this area. that would normally be used to refine or update the CBRFC's models. Forecast improvement from ingesting ASO also benefited from timing of the ASO flight, which was late in the snow season and captured precipitation events in late May through early June.

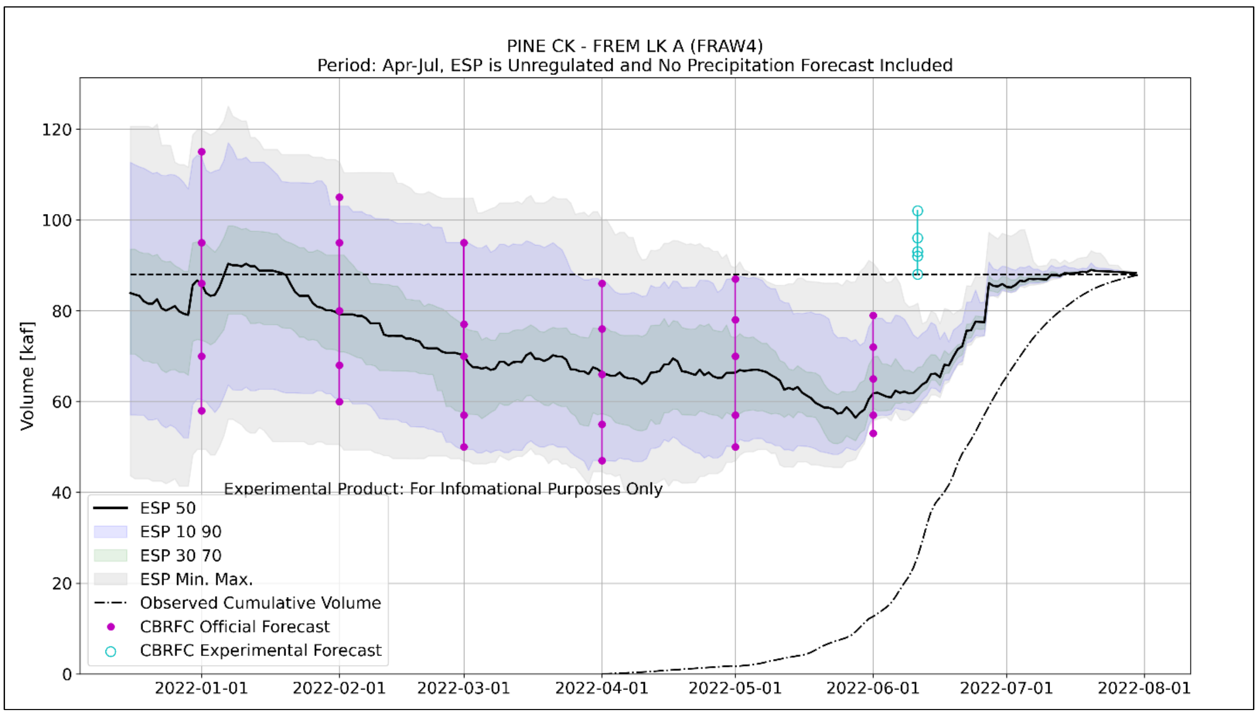

Figure 7.—CBRFC official (purple) and experimental (teal) seasonal runoff forecasts for Pine Creek (FRAW4). FRAW4 had full ASO coverage. Figure credit: Patrick Kormos (CBRFC).

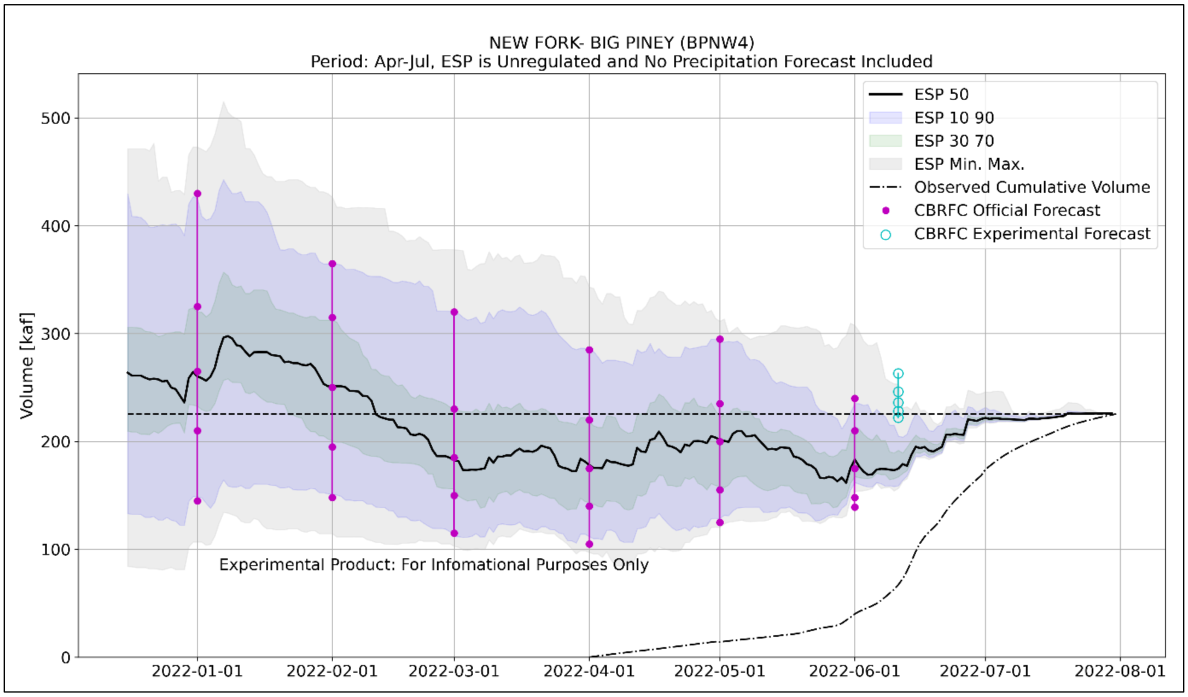

Figure 8.—CBRFC official (purple) and experimental (teal) seasonal runoff forecasts for the New Fork River near Big Piney (BPNW4). The ASO flight covered about a third of the BPNW4 catchment area. Figure credit: Patrick Kormos (CBRFC).

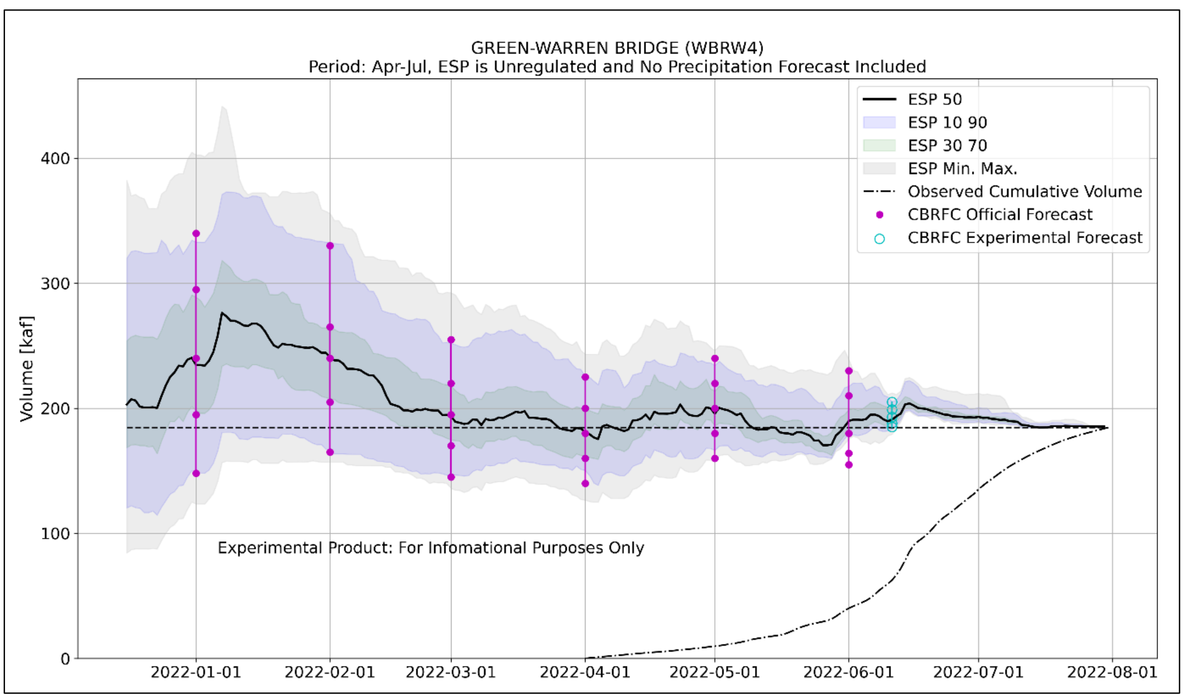

Figure 9.—CBRFC official (purple) and experimental (teal) seasonal runoff forecasts for the Green River at Warren Bridge (WBRB4). The ASO flight covered most of the high elevation terrain in the WBRB4 catchment area. Figure credit: Patrick Kormos (CBRFC)

3.3 Data Availability

ASO data and reporting for the North Wind Rivers flight sponsored by this project are available at: data.airbornesnowobservatories.com/.

4 Conclusions

The ASO methodology can provide high resolution SWE information across spatial scales relevant to streamflow forecasting and reservoir operators. In addition to the initial investment needed to bring a new basin online, the cost to develop a robust ASO dataset in a basin has been a challenge in some areas that lack financial resources or stakeholder coordination. The goal of this project is to identify and fund ASO flights for basins in underserved snowmelt driven watersheds in the western United States. Here, underserved basins are identified based on three criteria:

1. Poor existing terrestrial snow data coverage (Section 2.1)
2. Lack of local/state/federal government funding for ASO data collection (Section 2.2)
3. Breadth and diversity of water stakeholders dependent on snowmelt from the basin, including under-represented communities. (Section 2.3).

As a result of this project, the ASO flew its first flight in Wyoming, in the northern Wind River Range. The area met the three selection criteria and provided benefits to stakeholders in basins on both sides of the Continental Divide. Another potential flight area identified through this study was the mountain ranges of northeastern Arizona and northwestern New Mexico located within the Navajo Nation.

5 References

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Appendix A – ASO report

ASO, Inc. (2022) ASO Survey Report: Northern Wind River Range, WY, Survey dates: June 11, 2022. Report delivered June 16, 2022. Available at: https://data.airbornesnowobservatories.com/