Snow Water Supply Forecasting Program Implementation

Report to Congress

Mission Statements

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated Island Communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Report to Congress

prepared by

Research and Development Office

Cover Photo: Tennessee Creek near the confluence of the East Fork Arkansas River in winter with snow on the Continental Divide (Reclamation).

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Executive Summary

Snow plays an important role in water supply across the Western United States. The Snow Water Supply Forecasting Program Authorization Act of 2020 (Section 1111, Title XI of Pub. L. 116-260) established the Snow Water Supply Forecasting Program (Program) within the Department of the Interior (DOI). Reclamation, acting on behalf of the Secretary of the Interior, is implementing the Program to advance emerging technologies to enhance snow monitoring and subsequent water supply forecasts.

Program implementation has centered around funding projects through (1) an external Notice of Funding Opportunity (NOFO) for non-federal applicants and (2) collaborating with Program partners, and (3) supporting collaborations with United States Department of Agriculture (USDA) and National Oceanic and Atmospheric Administration (NOAA) to advance their use of snow monitoring information in water supply forecasting pursuant to language in the FY 2022-2024 Conference Joint Explanatory Statements and associated funding.

The Program administered NOFOs in fiscal year (FY) 2023 and 2024, with another planned for 2025. Through these solicitations, the Program has selected 20 projects, totaling $16.7 million in Program funding to support the advancement and use of snow monitoring technologies for water supply forecasting. The FY 2024 NOFO focused on the implementation of aerial LiDAR snow surveys. The Program will focus future external funding opportunities on awards supporting operational aerial LiDAR snow surveys.

Program investments with NOAA and USDA have focused on advancing the capabilities of NOAA National Weather Service (NWS) River Forecast Centers (RFCs) and the USDA Natural Resources Conservation Service (NRCS). Through these efforts, 8 projects have been developed, totaling $4.2 million in Program funding. Approximately 3% of total enacted funding has supported Program administration.

Table 1: Enacted and Program obligated funding FY 2022-2024.

Fiscal Year	General Program ($)	NOAA USDA Support ($)	Total Enacted ($)	Obligated ($)
2022	5,000,000	1,500,000	6,500,000	6,500,000
2023	7,000,000	1,500,000	8,500,000	8,500,000
2024	5,000,000	1,500,000	6,500,000	6,497,738
Total	17,000,000	4,500,000	21,500,000	21,497,738

Introduction

The Snow Water Supply Forecasting Program Authorization Act of 2020 (Section 1111, Title XI of Pub. L. 116-260) established the Snow Water Supply Forecasting Program (Program) within the Department of the Interior (DOI). Reclamation is implementing the Program to advance emerging technologies to enhance snow monitoring and subsequent water supply forecasts. The Act requires the submittal of a Program implementation report to the Committee on Natural Resources and the Committee on Appropriations of the House of Representatives and the Committee on Energy and Natural Resources and the Committee Appropriations of the Senate. This is a one-time reporting requirement pursuant to the language of Section 1111(f) of the statute. This report provides a summary of (1) the snow monitoring technology landscape, (2) external funding opportunities implemented by the Program, (3) collaboration with Program partners, and (4) the Program's support of advancing NOAA and USDA's use of snow monitoring technologies in operational water supply forecasting.

Technology Overview

Airborne Technologies
Airborne technologies use sensors mounted on piloted airplanes or unmanned aerial vehicles. The sensors measure variables such as snow depth, snow covered area, water content, and albedo. Measurements from airborne platforms may be used to supplement ground-based measurements and as inputs to models of snowmelt and water supply. NOAA operates a longstanding airborne snow survey program and private industry offers aerial LiDAR snow survey services. Despite technological advances in recent decades, aircraft-based technologies are limited by costs and tradeoffs between accuracy, spatial coverage, and frequency of measurement.

Satellite-Based Technologies
Satellite-based technologies include sensors mounted on satellite platforms and measure variables such as snow-covered area, snow depth, snow water content, and albedo. Measurements from space-based technologies may be used to supplement ground-based measurements and verify models of snowmelt and water supply. NASA has deployed several space-based technologies for snow measurement. Sensors on NOAA and private satellites also provide snow observation capabilities. Satellite-based technologies can be limited by cloud cover, spatial coverage, and frequency of measurement.

Ground-Based Technologies
Ground-based technologies measure snow on the ground, usually in a single location or in a small area. Measurements typically include snow characteristics such as snow depth and snow water content, along with various meteorological variables. Ground-based technologies provide valuable statistics that inform models and forecasts of water availability. The NRCS and California Department of Water Resources (CA-DWR) are interagency collaborators that maintain the two major ground-based snow monitoring networks in the Western U.S. Ground-

based technologies now include automated sensors that conduct continuous measurements for more than 1,000 station locations in the Western U.S. Emerging ground-based technologies include instrumentation that measure an expanded set of snow and weather variables. These also include instrumentation that has a lower environmental impact or lower maintenance requirements than existing technologies.

Modeling Technologies

Modeling plays an important role in both estimating snowpack and translating snow measurements, along with forecasted future weather, into water supply forecasts. Data fusion is a modeling technique that has advanced rapidly over the past decade with innovation in machine learning methods. Data fusion is a form of statistical modeling that blends a range of available snow monitoring observations (ground, airborne, or space-based) to estimate snowpack water volume and other characteristics. By integrating observational data from multiple sources, these approaches can fill in the gaps in available data but must be carefully applied and verified. These estimates are often made at a daily time interval for spatial domains from basin to continental scale.

Hydrological and statistical models are also used to generate water supply forecasts. A range of approaches exist; some explicitly simulate how snowpack is expected to build and melt over the season, while others directly translate inputs (e.g. current snow, streamflow, and soil moisture) into a water supply forecast. Regardless of the approach, it is important to maintain and advance these forecast models such that they are compatible with new snow information and can maximize benefits in the form of forecast skill improvement.

External Funding Opportunities

The Program facilitated NOFOs in FYs 2023 and 2024. The NOFOs sought proposals for projects that demonstrate and/or deploy emerging technologies in snow monitoring, deploy existing snow monitoring technologies in poorly monitored areas, or improve the use of snow monitoring data to enhance water supply forecasts. In FY 2024, the Program focused on funding projects implementing aerial LiDAR snow survey flights.

NOFOs award recipients include local governments, public utilities, irrigation districts, private industry, and academic or research institutions. The NOFOs have been highly competitive. In each NOFO, the funding amount requested from applications that the application review committee evaluated to have technical merit exceeded available funding. $16.7 million of Program funding has been awarded to recipients selected through the FY 2023 and 2024 NOFOs.

Interagency Collaboration

Reclamation is working with partner agencies to implement the Program, providing coordination and leadership to realize enhanced water supply forecasting and water management. In addition to NOAA RFCs and USDA NRCS, collaboration has been established with the United States

Geological Survey (USGS), the USDA Agricultural Research Service (ARS), the United States Army Corps of Engineers (USACE), the National Aeronautics and Space Administration (NASA), CA-DWR, and NOAA Office of Water Prediction (OWP). Each of these agencies has a unique history and role in developing, deploying, and using snow measurement technologies. Robust interagency partnerships help the Program maximize its benefits for forecasting and water management.

Program Support of USDA and NOAA

The Program is funding activities in support of USDA and NOAA to advance of the use of snow monitoring data in operational water supply forecasting. Approximately $4.2 million of appropriated funds have been awarded in these activities. Additionally, a project selected through the FY24 NOFO fulfills the objective of supporting USDA and NOAA.

USDA NRCS
The Program is funding USDA NRCS National Water and Climate Center (NWCC) and its collaborators to:

- Expand the in-situ SNOTEL monitoring network.
- Utilize airborne and remotely sensed snow monitoring data to optimize SNOTEL station network design.
- Develop and demonstrate capabilities of NRCS's statistical forecasting tools to utilize measurements from airborne snow monitoring technologies.

NOAA
The Program coordinated projects with NOAA's NWS Colorado River Basin Forecast Center (CBRFC) and the California Nevada River Forecast Center (CNRFC) to:

- Advance high-resolution process-based hydrological modeling for water supply forecasting to better realize the value of high-resolution snow monitoring observations.
- Develop tools to systematically evaluate new snow monitoring datasets for water supply forecasting as they become available.
- Utilize satellite derived snow and atmosphere observations in hydrological modeling.
- Apply machine learning tools to blend all available snow monitoring observations to input into water supply forecast models.
- Develop a satellite derived multi-decadal operational snow surface properties suite for the U.S. West.

Appendix 1: Funded Activities Summary Table

The tables in this appendix provide a summary of activities that the Program has funded through external grants (NOFOs) and the direct support of snow monitoring and water supply forecasting of NOAA and USDA. The tables also includes 7 activities that were initiated in 2021 prior to start of the programmatic activities.

Table A-1. Summary of snow monitoring activities funded through external grants or in support of NOAA and USDA snow monitoring and forecasting.

	Activity Name	State(s)	River Basin(s)	Technology	Recipient	Partners (*see acronym definitions below table)	Federal Funding
1	Snow water equivalent data fusion for the Western U.S. to support water resources management	all	all	satellite observations, data fusion	University of Colorado	NRCS, NOAA NWS CBRFC, CNRFC, Cal-DWR	$999,999
2	Integrating field, remote sensing, and physics-based models to improve water supply forecasts in wildfire-impacted basins in the western US	all	all	snow temperature sensors, UAV-based LiDAR surveys, ground penetrating radar, modeling	Colorado State University	NOAA NWS CBRFC, USDA-ARS, US Forest Service, USGS, City of Greeley, City of Fort Collins, Larimer and Weld Irrigation Company, Northern Colorado Water Conservancy District	$706,533
3	Does integration of airborne LiDAR with existing snow monitoring technologies improve water supply forecasts in the western United States?	AZ, CA, CO	Tuolumne, Merced, San Joaquin, Black, Verde, East, Taylor	data fusion, modeling	University of Colorado	NWS NOAA CBRFC, USACE, Oregon State University, Salt River Project, University of Arizona	$625,388
4	Cosmic-ray snow gauges for monitoring snow water equivalent	CA, CO	Yuba River, Conejos River	ground-based snow gauges	Hydroinnova LLC	University of Nebraska-Lincoln, UC Berkeley	$323,368
5	Developing a Cooperative Snow Temperature Survey	CA, CO, MT, NV	Upper Colorado, Sierra Nevada, Upper Missouri	snow temperature sensors, modeling	Desert Research Institute	USDA-NRCS, USACE, NOAA NWS CBRFC, CNRFC, Cal-DWR, UC Berkeley, RPM Systems Corp, Southern Feather Water and Power Agency, Upper Gunnison River Water Conservation District, Yuba Water Agency, Nevada Irrigation District, Placer County Water Agency, El Dorado Irrigation District, Pacific Gas & Electric	$729,521

	Activity Name	State(s)	River Basin(s)	Technology	Recipient	Partners (*see acronym definitions below table)	Federal Funding
6	Airborne Snow Observatory Driven Forecasting in the Truckee-Carson Basins	CA, NV	Truckee-Carson Rivers	aerial LiDAR surveys, modeling	Truckee-Carson Irrigation District	NOAA NWS CNRFC, USACE, Cal-DWR, US District Court's Water Master Office, Pyramid Lake Paiute Tribe, ASO Inc.	$1,431,940
7	Demonstration and Evaluation of a Cosmic Ray Neutron Rover as an Emerging Snow Monitoring	CO	Dolores, Animas, Uncompahgre	vehicle mounted mobile ground-based sensor	Colorado State University	NOAA NWS CBRFC, Dolores Water Conservancy District, Tri-County Water Conservancy District, Center for Snow and Avalanche Studies	$672,267
8	Airborne Snow Observatory flights and forecasting in the Upper Colorado, Willow Creek, and Fraser basins in the headwaters of the Colorado River	CO	Upper Colorado, Willow Creek, Fraser Creek	aerial LiDAR surveys, modeling	Northern Water Conservancy District	NOAA NWS CBRFC, Colorado Water Conservation Board, ASO Inc.	$639,872
9	Improving Water Supply Forecasting in the Colorado Basin with 40+ years of Gridded Snowpack Data	AZ, CO, NM, NV, UT, WY	Colorado River	satellite observations, data fusion, modeling	University of Arizona	NOAA NWS CBRFC, Salt River Project	$897,963
10	Mapping Snow Water Equivalent with Weather Radar	CO, NM	East, Taylor, Plateau, Tomichi, Conejos	ground-based radar, data fusion	Applied Research Team, Inc.	NOAA NWS CBRFC, Colorado Water Conservation Board, Rio Grande Basin Round Table	$660,216
11	Improving the skill of reservoir inflow forecasts over the Colorado River basin using high resolution snow monitoring data and Explainable Artificial Intelligence (XAI) models	CO, UT, WY	Colorado River	satellite derived snow covered area, modeling	University of Oklahoma	NOAA NWS CBRFC, Deltares	$437,706

	Activity Name	State(s)	River Basin(s)	Technology	Recipient	Partners (*see acronym definitions below table)	Federal Funding
12	Emerging UAV gamma-ray and LiDAR snow observations for improved water supply modeling in the Missouri headwaters	MT	Smith River	UAV gamma ray and LiDAR surveys, ground-based cosmic ray and gamma ray stations, data fusion	Montana State University	USFS, University of Maryland, Syracuse University	$991,372
13	Flakes, Flights, and Forecasts: Snowpack Measurement Enhancements in the Uinta Mountain Headwaters	UT	Duchesne, Utah Lake	aerial LiDAR surveys, modeling	Colorado River Authority of Utah	NOAA NWS CBRFC, Utah Dept. of Natural Resources, Central Utah Water Conservancy District, Upper Colorado River Commission, Jordan Valley Water Conservancy District, Duchesne County Water Conservancy District, The Nature Conservancy, Trout Unlimited, ASO Inc.	$999,999
14	Airborne Snow Surveys for Water Supply Forecasting in the Wind River Range, WY	WY	Wind River, Upper Green River	aerial LiDAR surveys, modeling	Mountain Hydrology LLC	NOAA NWS CBRFC, Shoshone and Arapaho Tribes, USFWS, WY State Engineers Office, ASO Inc.	$998,428
15	Seasonal Snow Water Supply Forecast guided by the Climatic Oscillation using the Non-Gaussian Information Metrics for the Inland Basins	WY	Snake, Madison, Yellowstone, Wind, Bighorn, Shoshone, Powder, Tongue, Belle Fourche, Cheyenne, Upper North Platte, Sweetwater, Lower North Platte, Laramie, South Platte, Little Snake, Upper Green, Lower Green, and Upper Bear	satellite observations, data fusion, modeling	University of Wyoming	Wyoming State Climate Office	$346,078

	Activity Name	State(s)	River Basin(s)	Technology	Recipient	Partners (*see acronym definitions below table)	Federal Funding
16	Wings Over Weber	UT	Weber River	aerial LiDAR surveys	Utah Division of Water Resources	NOAA NWS CBRFC, Great Salt Lake Watershed Enhancement Trust, Office of the Great Salt Lake Commissioner, Weber River Water Users Association, Davis and Weber Counties Canal Company, ASO Inc.	$975,844
17	Fusing LiDAR and In-Situ Community Measurements to Improve Estimates of Snowpack	CA, CO, OR	Truckee-Carson River, Blue River, Deschutes River	aerial LiDAR surveys, data fusion	Oregon State University	NOAA NWS CNRFC, CBRFC, NRCS, USACE, State of Alaska Department of Natural Resources, NV5 Geospatial	$946,203
18	The utility of aerial LiDAR snow surveys to improve water supply forecasts across the western United States: comparing the relative importance of current snow conditions and future weather	CA, CO, OR	McKenzie River Basin	aerial LiDAR surveys, data fusion	Oregon State University	NRCS, University of Colorado, ASO Inc.	$971,862
19	Fusing Airborne and CubeSat Methods for Snow Estimation and Supply Forecasting into Salt River Project Reservoirs	AZ	Salt and Verde Rivers	aerial LiDAR surveys, satellite-derived snow-covered area, data fusion	Arizona State University	Salt River Project, ASO Inc.	$974,265
20	Snow Water Supply Forecasting in the Upper San Joaquin River Watershed	CA	San Joaquin River	aerial LiDAR surveys, data fusion	Friant Water Authority	NOAA NWS CNRFC, ASO Inc.	$702,169
21	Water Year 2024 airborne LiDAR snow surveys to support NOAA pilot modeling activities	CA	Trinity, American, San Joaquin, Truckee-Carson	aerial LiDAR surveys, data fusion, modeling	USBR California-Great Basin Region	NOAA NWS CNRFC, CBRFC, ASO Inc.	$1,110,231

	Activity Name	State(s)	River Basin(s)	Technology	Recipient	Partners (*see acronym definitions below table)	Federal Funding
22	Optimizing Station Network Design and Forecast Informed Data Collection	CA, CO	San Joaquin, Tuolumne, Upper Gunnison, Blue, Dolores, Conejos	in situ stations, aerial LiDAR surveys	National Center Atmospheric Research	NRCS	$170,962
23	Expanding Distributed Modeling at the RFCs	CA, CO, OR, UT, WY	Animas, Crystal, Frying Pan, East, Elk, Green, Black, Weber, San Joaquin, Yuba, Carson, Klamath, Tuolumne	modeling	Research Triangle Institute	NOAA NWS CNRFC, CBRFC	$649,832
24	Application of real-time and derived snow water equivalent data for water resources decision-making at two Western River Forecast Centers	CA, CO, OR, UT, WY	Animas, Crystal, Frying Pan, East, Elk, Green, Black, Weber, San Joaquin, Yuba, Carson, Klamath, Tuolumne	data fusion, modeling	Research Triangle Institute	NOAA NWS CNRFC, CBRFC	$649,970
25	Advancing Distributed Process Based Snow Modeling Capability for Use in CBRFC Water Supply Forecasting	UT, CO, WY	Upper Colorado River Basin	Satellite derived snow characteristics and atmospheric variables	University of Utah	NOAA NWS CBRFC	$645,270
26	Development of a Snow Water Equivalent "Landing Strip" for User Towards Improved CBRFC forecasts	UT, CO, WY	East, Blue, Yampa, Animas, Upper Green, Great Salt Lake	modeling, aerial LiDAR surveys, data fusion	Boise State University	NOAA NWS CBRFC	$460,000
27	A multi-decadal operational snow surface properties suite for the U.S. West	All	All	satellite derived snow characteristics	University of Colorado	NOAA NWS CBRFC, CNRFC, NWRFC, NRCS	$750,000
28	Improving operational snow assimilation skill through improved spatial analysis and operational processes	All	All	data fusion, modeling	Research Triangle Institute	NOAA NOHRSC, NOAA NWS CBRFC, CNRFC, NWRFC, MBRFC, WGRFC, NRCS	$399,903

	Activity Name	State(s)	River Basin(s)	Technology	Recipient	Partners (*see acronym definitions below table)	Federal Funding
29	Partnership to Enhance In-Situ Snow Monitoring Network and Forecasting	CO, ID, MT, OR, UT	many	ground-based instrumentation arrays	NRCS	NRCS	$375,700
30	Baseline Airborne Snow Observatory Flights for Basins with Poor Existing Coverage	WY	Wind River, Bighorn River, Green River	aerial LiDAR surveys	USBR Technical Services Center	NOAA NWS CBRFC, ASO Inc.	$449,422
31	Comparing Airborne Snow Observatory Data to Current River Forecasts in the Truckee-Carson Basins	CA, NV	Truckee-Carson Rivers	aerial LiDAR surveys	USBR Lahontan Basin Area Office	NOAA NWS CNRFC, US Army Corps of Engineers, Truckee-Carson Irrigation District, Cal-DWR, US District Court's Water Master Office, Pyramid Lake Paiute Tribe, ASO Inc.	$449,418
32	Integrated Modeling and Remote Sensing of Snow to Improve Runoff Forecasts in High Elevation Basins	CO	Colorado Big-Thompson	satellite observations	USBR Eastern Colorado Area Office	USGS, Northern Water Conservancy District	$125,500
33	Enhancement of San Joaquin Snow Monitoring Program	CA	San Joaquin River	aerial LiDAR surveys	USBR San Joaquin River Restoration Program	NOAA NWS CNRFC, Friant Water Authority	$305,882
34	Exploring the Utility of CU-SWE Estimates for Water Supply Forecasting in the Colorado River Basin	CO	Colorado River	satellite observations, data fusion	USBR Upper Colorado Basin Region	University of Colorado	$298,039
35	Assessing the Utility of New Satellites to Advance State of the Art Snow Forecasting Capabilities	CA, CO, WY	Shoshone, Tuolumne, Flathead, Big Thompson, NF American, Taylor River, East River, Roaring Fork, Upper Navajo River, Wind River, Carson Rivers	satellite observations, airborne LiDAR surveys	USBR Albuquerque Area Office	National Center for Atmospheric Research, NRCS, NOAA NWS CBRFC	$183,774

*Partner Acronym Definitions

NOAA NWS CBRFC: National Oceanic and Atmospheric Administration National Weather Service Colorado Basin River Forecast Center

NOAA NWS CNRFC: National Oceanic and Atmospheric Administration National Weather Service California-Nevada River Forecast Center

NOAA NWS NWRFC: National Oceanic and Atmospheric Administration National Weather Service Northwest River Forecast Center

NOAA NWS MBRFC: National Oceanic and Atmospheric Administration National Weather Service Missouri Basin River Forecast Center

NOAA NWS WGRFC: National Oceanic and Atmospheric Administration National Weather Service West Gulf River Forecast Center

USACE: United States Army Corps of Engineers

USGS: United States Geological Survey

NRCS: USDA Natural Resource Conservation Service

Cal-DWR: California Department of Water Resources

USFWS: United States Fish and Wildlife Service

Appendix 2: Funded Activities Summary Map

Map of SWSFP snow monitoring activities and funding recipients. Multiple activities have footprints that are regional or West-wide and are not represented by field locations noted on the map.