BUREAU OF RECLAMATION

Snow Water Supply Forecast Program: 2023 SNOFO Projects

University of Colorado: Snow water equivalent data fusion for the Western U.S. to support water resources management

Reclamation Funding: $999,999 **Total Project Cost: $1,084,428**

Despite the considerable attention focused on drought in the West, little work has been done to evaluate the degree to which new snow data sources can mitigate impacts through improved information and decision making. This project will develop a SWE data fusion system (SWE-fusion) for the Western U.S. using a combination of historical snow water equivalent satellite/model-based SWE reanalysis, ground-based SNOTEL data, and, when available, airborne snow observations from 2000 through the funding cycle (i.e. 2026). The primary objective of this research is to provide improved SWE estimates for the region and enable improved decision making during anomalous hydrologic conditions (e.g. drought and rain-on-snow flooding). Related secondary and tertiary objectives aim to: migrate remotely sensed SWE analyses into operational computational environments with the NRCS and NWS River Forecast Centers; and to conduct quantitative and qualitative assessment of the utility of the SWE-fusion snowpack information with regard to informing water resource decisions.

Colorado State University: Integrating field, remote sensing, and physics-based models to improve water supply forecasts in wildfire-impacted basins in the western US

Reclamation Funding: $706,533 **Total Project Cost: $888,897**

At present, no current snow water supply forecasting model can account for the impacts of burned area on snow accumulation, ablation, and runoff generation - this major gap will only be exacerbated by projected wildfire increases in future decades. This project will address key knowledge gaps by leveraging and expanding a network of automated stations and field studies that were initiated following the 2020 Cameron Peak and East Troublesome fires in north-central Colorado. The project will apply key emerging technologies, including 4-component net radiometers, snow temperature sensors to estimate cold content, UAV-based lidar, and ground penetrating radar to measure snow depth and density. The project will use this suite of field observations and findings, in conjunction with satellite-based remote sensing methods, to refine parameterizations in a physically-based snow model, iSnobal/AWSM. The project will evaluate the extent to which wildfire impacts streamflow in these headwater systems and examine how

these impacts can be incorporated into streamflow forecasts. The project will have multiple nested scales - point and plot scale observations, as well as remote sensing methods that include multiple fire-impacted basins in the western US, including the upper Colorado River basin.

University of Colorado: Does integration of airborne lidar with existing snow monitoring technologies improve water supply forecasts in the western United States?

Reclamation Funding: $625,388 **Total Project Cost: $1,060,448**

Airborne lidar mapping of snow depth has emerged as a technology to map basin-wide SWE at a snapshot in time, with potential to improve WSFs. How best to use this emerging snow monitoring technology to improve WSFs remains an outstanding question. This project addresses this problem by considering alternative methods to fuse existing and emerging snowpack data, and then systematically measure the resultant gains in WSF skill afforded by incrementally including more lidar data. Distinct SWE datasets will be used to train, and then validate, a WSF system. The project will characterize how WSF skill changes with the number and timing of lidar surveys utilized and the snow data fusion approach. The project will focus on multiple basins in three study areas (CA, CO, AZ), each of which includes Reclamation projects downstream.

Hydroinnova LLC: Cosmic-ray snow gauges for monitoring snow water equivalent

Reclamation Funding: $323,368 **Total Project Cost: $692,781**

The project will demonstrate and deploy improved methods of measuring snow water equivalent (SWE). The work involves two specific variations of the cosmic ray method that are well suited to measuring large SWE. These methods are easy to install and maintain, are insensitive to ice bridging, and are more flexible than conventional methods such as snow pillows and load cells. This flexibility together with the low environmental impact of the equipment should help minimize permitting issues and therefore encourage widespread adoption. The project will build, test, install, maintain and validate these two types of novel snow water equivalent sensors as part of a demonstration project.

Desert Research Institute: Developing a Cooperative Snow Temperature Survey

Reclamation Funding: $729,521 **Total Project Cost: $729,521**

Snowpack temperature is estimated in models used by federal agencies including the National Weather Service (NWS) River Forecast Centers (RFCs) and US Army Corps of Engineers (USACE) to inform reservoir models. Currently, there is no successful operational method to observe snow temperature profiles. This project will demonstrate the use of an emerging method to collect snow temperature profiles to integrate into snowmelt models. Leveraging the success of the cooperative snow survey program, this project will deploy a non-contact infrared Snow Temperature Profiler (STP) in conjunction with cooperative snow surveys in California (CA),

Nevada (NV), Colorado (CO), and Montana (MT). When combined with the snow water equivalent and snow depth data collected from the snow monitoring campaigns snowmelt rates, timing, and volume can be estimated. The project will implement the novel measurements of snow temperatures into existing research and operational models, and will work with the California-Nevada and Colorado Basin RFC, M3Works, and the USACE to validate, bias-correct or calibrate, snow temperature in operational models.

Truckee-Carson Irrigation District: Airborne Snow Observatory Driven Forecasting in the Truckee-Carson Basins

Reclamation Funding: $972,915 **Total Project Cost: $2,865,532**

Seasonal water supply forecasts are critical for the Operations and Maintenance Contractor for Reclamation's Newlands Projects. Over the past year and a half, Airborne Snow Observatory (ASO) data has been integrated into the California Nevada River Forecast Center's (RFC) season water supply forecast. However, the benefits of direct insertion of ASO data into the RFC forecast have not been fully quantified. This project will collect additional ASO data and continue to quantify forecasting improvements by integrating high-resolution snow water equivalent estimates into streamflow forecasts. In addition, the project will also build out a Weather Research and Forecasting Hydrologic Model (WRF-Hydro) forecasting model for the Truckee and Carson Basins and quantify the seasonal streamflow forecast improvements between the NRCS and RFC to the ASO informed RFC and ASO informed WRF-Hydro forecasts. This project will take place through September 2026 in the Truckee and Carson Watersheds in California and Nevada.

Colorado State University: Demonstration and Evaluation of a Cosmic Ray Neutron Rover as an Emerging Snow Monitoring

Reclamation Funding: $672,267 **Total Project Cost: $859,808**

Traditional in-situ methods only characterize SWE over very small measurement footprints. SWE estimates from satellites have coarse resolutions and limited accuracy, and airborne methods have limited spatial and temporal coverage and can have high costs for ongoing monitoring. Recently, stationary cosmic ray neutron (CRN) sensors have been shown to accurately measure SWE at hourly to daily time steps with a footprint radius around ~200 m. A CRN rover can potentially be mounted on a vehicle to provide on demand SWE estimates at ~670-m intervals over tens of kilometers in a few hours. The primary objective of this study is to demonstrate and evaluate the use of a CRN rover for monitoring SWE. The study region will be the western San Juan Mountains in Colorado. The CRN rover approach will be evaluated by using a rover in a series of progressively more challenging tests. The potential benefits of using the rover measurements to enhance SWE monitoring will be quantified by comparing the SWE estimates from the rover to estimates from adjacent SNOTEL sites and SNODAS products. Technology transfer will be accomplished through partnerships with Reclamation and the Colorado Basin River Forecast Center (CBRFC).

Northern Colorado Water Conservancy District: Airborne Snow Observatory flights and forecasting in the Upper Colorado, Willow Creek, and Fraser basins in the headwaters of the Colorado River

Reclamation Funding: $639,872 **Total Project Cost: $1,111,872**

In this project Northern Water will partner with ASO, Inc. to conduct three ASO snow surveys per year during spring runoff over the next three years over the Colorado River Headwaters. These surveys will be paired with iSnobal model results, and streamflow forecasts and will improve water resources decision-making for Northern Water. Northern will continue to use ASO to inform internal forecasts and coordinate with the Colorado Basin River Forecast Center (CBRFC) to use ASO data collected from this and other projects to improve their experimental and operational streamflow forecasts.

University of Arizona: Improving Water Supply Forecasting in the Colorado Basin with 40+ years of Gridded Snowpack Data

Reclamation Funding: $897,963 **Total Project Cost: $1,001,209**

Recently, there has been growing interest in using gridded snowpack datasets to improve water supply forecasts (WSFs) in the western US. However, many of these gridded datasets do not have the long temporal record needed to train the models producing the WSFs. This project will use the University of Arizona snowpack dataset, which spans 40+ years, to improve WSFs across the Colorado River Basin (CRB). The project will improve these snowpack data using recently developed regression modeling and machine learning of lidar data from across the CRB. The project will investigate how the snowpack data, along with model optimizations of the Sacramento Soil Moisture Accounting (SacSMA), SNOW-17 and Noah-MP models, can be used to enhance streamflow modelling, and will incorporate the gridded snow data into the National Resources Conservation Network's next-generation multi-model machine-learning metasystem (M4) model. The updated models will be used to provide real-time WSFs for various locations across the CRB, such as the Salt-Verde Basin in Arizona as well as more broadly across the CRB using a web decision support tool.

Applied Research Team, Inc.: Mapping Snow Water Equivalent with Weather Radar

Reclamation Funding: $660,216 **Total Project Cost: $998,216**

Combining weather radar with ground-based monitoring can effectively measure SWE at high resolution. Recent advancements in weather radar detection algorithms, particularly dual-polarization radar, present an opportunity to improve the data available to water managers and forecasters. This project focuses on multiple headwater watersheds in the Upper Colorado River Basin and one in the Rio Grande River Basin to demonstrate the technology. Both federal and non-federal weather radar data will be utilized. The increasing number of non-federal radars in the mountainous West further expands the potential benefits of radar-based SWE quantification. Operational forecasting agencies and local water managers will participate in assessing the technology's value for their applications.

University of Oklahoma: Improving the skill of reservoir inflow forecasts over the Colorado River basin using high resolution snow monitoring data and Explainable Artificial Intelligence (XAI) models

Reclamation Funding: $437,706 **Total Project Cost: $646,609**

This project aims at demonstrating the uses of advanced eXplainable Artificial Intelligence (XAI) techniques to utilize existing and high-resolution snow monitoring data to enhance reservoir inflow forecast skills over the Upper Colorado River Basin. A novel deep-learning model will be developed using winter snowpack and Snow Water Equivalent data to simulate the streamflow and reservoir inflows. The novelty of the XAI method lies in its capability to quantify how much dominance of past snow observation in deciding the uncertainty of reservoir inflow forecasting, as well as the impacts from other hydrological variables. The project will validate the AI model results against streamflow observation and the operational SNOW-17 and Sacramento Soil Moisture Accounting (Sac-SMA) model used by the National Weather Service as the status quo together with our project partner and water forecasting agency beneficiary – the Colorado Basin River Forecast Center (CBRFC). The project location includes the Upper Colorado River Basin (UCRB) and its six major water supply reservoirs.

Montana State University: Emerging UAV gamma-ray and LiDAR snow observations for improved water supply modeling in the Missouri headwaters

Reclamation Funding: $991,372 **Total Project Cost: $1,321,503**

This project addresses deficiencies in current snow monitoring through a combination of emerging snow observation technologies (UAV gamma SWE and lidar, plus paired ground-based cosmic ray and gamma SWE) for spatiotemporal characterization of snow in various forest structures and topographies. The additional spatial extent and resolution from the UAV build on conventional snow surveys, and our ground-based methods augment snow pillows. Data from these emerging snow observations will be assimilated into a coupled snow-runoff modeling framework to quantify improvements in water supply forecasting as compared to using only existing snow observation networks. This snow monitoring and water supply forecasting in this project will be deployed in the Tenderfoot Creek experimental watershed and extrapolated to the Upper Missouri Basin.

Colorado River Authority of Utah: Flakes, Flights, and Forecasts: Snowpack Measurement Enhancements in the Uinta Mountain Headwaters

Reclamation Funding: $999,999 **Total Project Cost: $1,999,999**

This project will provide LIDAR airborne snow surveys over a 3-year pilot period to evaluate the improvements in accuracy and reliability of water supply forecasts and the commensurate benefits to water management operations. This will be the first implementation of airborne snow mapping and forecast integration in Utah. The project results will be analyzed against conventional forecasting to examine vulnerabilities in current methods and if ASO-informed forecasting can provide decision-support benefits.

Mountain Hydrology LLC: Airborne Snow Surveys for Water Supply Forecasting in the Wind River Range, WY

Reclamation Funding: $998,428 **Total Project Cost: $1,351,680**

Mountain Hydrology LLC will collaborate with Airborne Snow Observatories, Inc. (ASO), the Wind River Water Resources Control Board (WRWRCB), and the University of Nevada, Reno (UNR) to undertake 3 years of snow surveys in the Wind River Range, Wyoming, and to incorporate results from these surveys into forecast-informed adaptive water and agriculture co-management strategies. The purpose of this project is to improve the quality and usefulness of snow data available in the underserved Wind River and Upper Green River watersheds by deploying and interpreting ASO snow surveys in late spring over 10 watersheds, when current snow monitoring techniques are insufficient to meet management needs. After each spring snow survey, Mountain Hydrology and UNR will test, evaluate, and refine seasonal water supply forecast models using direct insertion of ASO SWE data into Bayesian (statistical) runoff models. The project team, including senior Advisory Board members, will consult with the WRWRCB to develop a decision support tool that identifies potential reservoir and diversion scheduling actions in response to water supply guidance on the Wind River Indian Reservation. Beneficiaries of this work include the Eastern Shoshone Tribe and Northern Arapaho Tribe, whose representatives form the joint WRWRCB; the Bureau of Reclamation, and local irrigators / rural communities who stand to benefit from increased efficiency of water management.

University of Wyoming: Seasonal Snow Water Supply Forecast guided by the Climatic Oscillation using the Non-Gaussian Information Metrics for the Inland Basins

Reclamation Funding: $346,078 **Total Project Cost: $590,822**

This study aims to improve seasonal and sub-seasonal water supply predictions by incorporating effects associated with the modes of low-frequency variability earth oscillations, such as the Pacific/North American pattern (PNA) and the El Niño–Southern Oscillation (ENSO). Cutting edge non-Gaussian information metrics and stochastic snow models will be implemented for seasonal water resource forecasting for Wyoming basins. In this analysis specifically, snow state variables from existing ground-based measurements and satellite remote sensing, and climatic indicators (e.g. PNA and ENSO) will be used to predict water supply. The numerical model framework will be applied to nineteen watersheds in Wyoming.