Merging High-Resolution Airborne Snowpack Data with Existing Long-Term Hydrometeorological Observations to Improve Water Supply Forecasting

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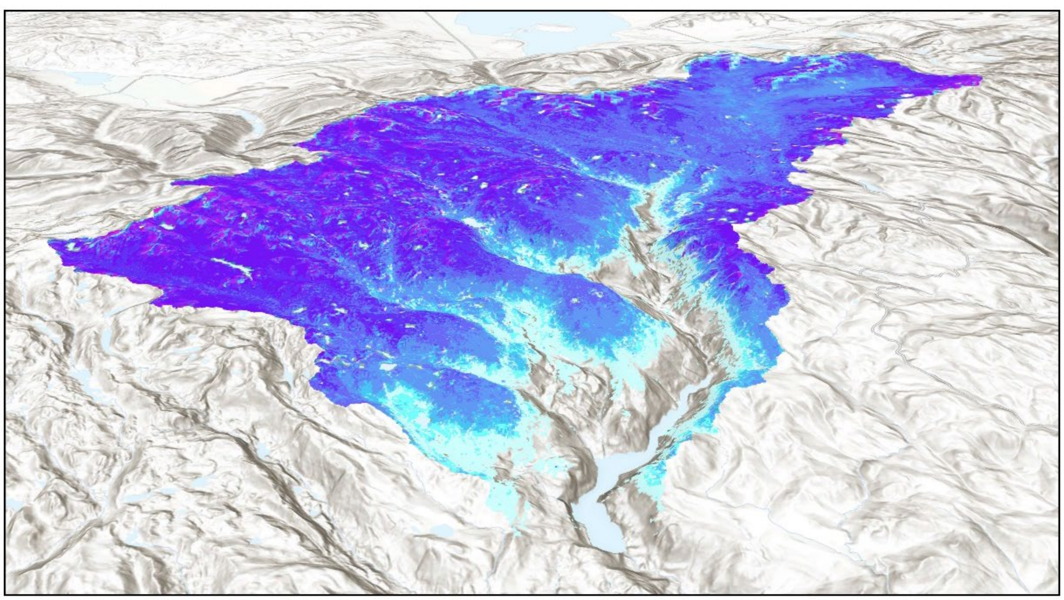

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14. ABSTRACT
Mountain snowpack is a critical observation for seasonal streamflow forecasting in the Western United States. The Airborne Snow Observatory (ASO) methodology generates maps of snow depth, snow water equivalent, (SWE) and albedo from airborne lidar and spectrometer measurements that inform snowpack modeling. In this work, we evaluate how traditional snow pillow station-based estimates of basin-wide SWE compare to more spatially complete estimates from ASO, and the impact these differences have on streamflow modeling and forecasts. While the ASO flights provide excellent spatial resolution and coverage of high elevation areas, observations are limited to flight times. Assessing the relationship between stations, which monitor continuously, and ASO flights, which capture a snapshot in time, this project identified that approximately 5-10 ASO flights, combined with stations, are sufficient to define 95% of the variability in the remaining flights. The ASO data are also assimilated into SUMMA, or the Structure for Unifying Multiple Modeling Alternatives, to evaluate the potential improvement for water supply forecast models. Using several approaches for when flights were assimilated, results suggest that including ASO SWE estimates near peak SWE can substantially improve ensemble streamflow predictions by removing much of error that accumulated from uncertain precipitation through the winter season.

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Snow Water Equivalent, Airborne Snow Observatory, Water Supply Forecasting

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Merging high-resolution airborne snowpack data with existing long-term hydrometeorological observations to improve water supply forecasting

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Acronyms and Abbreviations

ASO	Airborne Snow Observatory
CBRFC	Colorado Basin River Forecast Center
CDWR	California Department of Water Resources
ESP	Ensemble Streamflow Prediction
JPL	Jet Propulsion Laboratory
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
LIS	Land Information System
Reclamation	Bureau of Reclamation
SUMMA	Structure for Unifying Multiple Modeling Alternatives
SWE	Snow water equivalent
WRF-Hydro	Weather Research and Forecasting Model Hydrological modeling system

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Executive Summary

Measuring mountain snowpack has long been central to seasonal streamflow forecasting in the Western United States. Recent advances in airborne remote sensing have added tremendous observational capacity through increased spatial resolution and coverage across otherwise inaccessible topography. Airborne Snow Observatory (ASO, Painter et al. 2016) datasets are an example of high-resolution snow products that are not yet widely used in streamflow forecasting models. ASO was developed at NASA's Jet Propulsion Laboratory (JPL) in 2013 and transferred to ASO, Inc. in 2019 when the program ended at NASA. ASO uses a plane-mounted lidar and imaging spectrometer to drive a licensed workflow that provides snow depth, snow water equivalent (SWE), and albedo. ASO also updates a distributed snow model called iSnobal (Marks et al. 1999), that provides snow density for calculating SWE from snow depth and can be used to provide snow estimates between flights when run continuously.

A growing number of water managers, led by early adopters such as the California Department of Water Resources (CDWR) and the San Joaquin River Restoration Program[1], report anecdotal successes using ASO data to understand current snow conditions more confidently in their basins of interest. These recent advances in observational ability, however, have outpaced research toward developing efficient and cost-effective strategies for leveraging the new high-resolution data in streamflow forecasting systems. Existing forecasting methods rely on calibrated hydrologic models or statistical approaches, both of which benefit from the longer observational records available at index stations, such as the snow sensors supported by CDWR. Hydrologic model calibration often compensates for biases in snowpack representation or precipitation inputs, and it is not yet known how new spatially detailed measurements can improve these model forecasts. Few studies exist that have demonstrated the use of ASO data in near real-time modeling frameworks to support water management decisions, and those that are published have assimilated ASO into snow models but not hydrologic models used to predict water supply runoff volumes.

Hedrick et al. (2018) directly assimilated ASO measurements into an iSnobal model of the Tuolumne River Basin with a 50 m lateral resolution. This study demonstrated that ASO data can account for errors in the meteorological forcing data and local processes that redistribute snow, with much of this error captured by the first flight if it occurs around peak snow accumulation. Recent presentations at scientific conferences hint at the ongoing work to include ASO data in water supply models. Meyer et al. (2020) describe the ongoing effort to assimilate ASO-informed iSnobal output into the models used by the Colorado Basin River Forecast Center (CBRFC), which rely on a simple temperature-based index melt model. Lahmers et al. (2020) demonstrate the use of the assimilation capabilities of the NASA Land Information System (LIS) to include ASO information in the Weather Research and Forecasting Model Hydrological modeling system (WRF-Hydro). Results in the Tuolumne River basin suggest ASO may be able to reduce biases in both snowpack and streamflow relative to an open-loop simulation (i.e. a simulation without assimilating data).

[1] https://www.usbr.gov/newsroom/newsroomold/newsrelease/detail.cfm?RecordID=63168

This project explores the value of using existing ASO measurements to support water supply forecasting in the Tuolumne River basin with a focus on three tasks:

1) evaluating the use of ASO to support snow statistical analyses,
2) evaluating the use of ASO for statistical water supply forecasting methods, and
3) evaluating the use of ASO in dynamical Ensemble Streamflow Prediction (ESP) frameworks.

Snow statistical analyses predict basin mean SWE by combining ASO flights, which represent a point in time when the flight was flown, with ground station data, which are continuous in time. The analyses also identify where additional in-situ snow monitoring stations can be located to best improve estimates of basin-wide SWE. Analysis from the Tuolumne indicates that approximately 5-10 ASO flights, combined with stations, are sufficient to define 96% of the variability in the basin-averaged SWE from the remaining flights. However, this relationship starts to break down for times with very high or low SWE conditions, indicating that more flights or additional products are needed to improve the estimation of that relationship. Adding a new station at very high elevation would improve these relationships.

With relatively simple regressions, statistical forecasting using the combined ASO and station timeseries improved predictions of streamflow into the Hetch Hetchy Reservoir relative to the station-only estimates. Using observations of snow, however, only predicts about 90% of the variance in streamflow. Adding the precipitation that remains for the season increases the performance of these predictions, capturing 96-98% of the variance. The need to capture the uncertainty in future precipitation supports exploring the use of ASO data in ESP frameworks.

Assimilating ASO in a calibrated Structure for Unifying Multiple Modeling Alternatives (SUMMA) watershed model improved model volume forecasts, even with a relatively simple direct insertion approach that directly replaces the modeled snow states with the observations. Flights near peak SWE correct errors in winter precipitation and provide the most improvement in model forecast skill, while subsequent scenes provide less improvement and may even reduce model skill if not assimilated carefully. Other assimilation approaches (e.g. Ensemble Kalman Filter) that update more model states may support further forecast improvement. Increasing resolution and the representation of late season (high elevation) model snow will likely also improve late season simulation.

1.Methods, Results, and Discussion

Two manuscripts containing pertinent data and results (one pertaining to the statistical research tasks and one pertaining to the dynamical ESP modeling) are being finalized and submitted to a refereed journal. The principal investigator of this work will update this section and appendices to include the submitted manuscript once the journal peer review process has been resolved and information is ready for public dissemination.

2.Data

2.1 Statistical analysis files

Share Drive folder name and path where data are stored:
\\bor\DO\TSC\Jobs\DO_NonFeature\Science and Technology\2018-PRG-Airborne Snow Observations for Water Supply Forecasting\DATA
Point of Contact name, email, and phone: Lindsay Bearup, lbearup@usbr.gov, 303-445-3919
Short description of the data: Jupyter notebooks documenting statistical approaches. Note that Hetch Hetchy inflows were obtained from Hetch Hetchy Water and Power under the condition that they were not released. ASO, Inc. provided snow pillow information that was quality controlled from the CDWR, here: https://cdec.water.ca.gov/snow/current/snow/ and ASO data used in this study are available here: https://nsidc.org/data/ASO_50M_SWE/versions/1
Keywords: Snow Water Equivalent
Approximate total size of all files: 500 Kb

2.2 SUMMA input and output files

Share Drive folder name and path where data are stored:
\\bor\DO\TSC\Jobs\DO_NonFeature\Science and Technology\2018-PRG-Airborne Snow Observations for Water Supply Forecasting\DATA
Point of Contact name, email, and phone: Lindsay Bearup, lbearup@usbr.gov, 303-445-3919
Short description of the data: NetCDF input and output files and text configuration files to reproduce SUMMA model runs. This includes files for the following simulations:

1) ESP hindcasts run open loop, stop at forecast point then run all ESP
2) Same as 1) but update with ASO on flight date then run a set of ESP through the remainder of the season, resulting in one set of ESP outputs for each ASO flight.
3) Same as 1) but update until ASO then ESP, but continue until next ASO flight and make ESP
4) Same as 1) but assimilate only the ASO flight closest to April 1

Keywords: Water supply forecasting, Hydrologic Modeling
Approximate total size of all files: 1 Gb

References

Hedrick, A. R., Marks, D., Havens, S., Robertson, M., Johnson, M., Sandusky, M., Marshall, H. P., Kormos, P. R., Bormann, K. J. & Painter, T. H. (2018). Direct insertion of NASA Airborne Snow Observatory-derived snow depth time series into the iSnobal energy balance snow model. *Water Resources Research*, *54*(10), 8045-8063.

Lahmers, T. M., Kumar, S. V., Rosen, D., Dugger, A. L., Gochis, D., Santanello Jr, J. A., Gangodagamage, C. & Dunlap, R. (2020, December). Assimilation of NASA's Airborne Snow Observatory snow measurements for improved hydrological modeling: A case study enabled by the coupled LIS/WRF-Hydro system. In *AGU Fall Meeting Abstracts* (Vol. 2020, pp. H019-08).

Marks, D., Domingo, J., Susong, D., Link, T., & Garen, D. (1999). A spatially distributed energy balance snowmelt model for application in mountain basins. *Hydrological processes*, *13*(12-13), 1935-1959.

Meyer, J., Skiles, M., Kormos, P., Havens, S., Hedrick, A. R., Trujillo, E., & Marks, D. G. (2020, December). Spatially distributed process-based snowmelt modeling in the East River Watershed, Colorado: Assessment against in situ observations and operational forecasts. In *AGU Fall Meeting Abstracts* (Vol. 2020, pp. H047-02).

Painter, T. H., Berisford, D. F., Boardman, J. W., Bormann, K. J., Deems, J. S., Gehrke, F., Hedrick, A., Joyce, M., Laidlaw, R., Marks, D., Mattmann, C., McGurk, B., Ramirez, P., Richardson, M., Skiles, S. M., Seidel, F. C. & Winstral, A. (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.

Appendix A: Gutmann et al. 2022

Draft Title: *Statistical Approaches for Using Airborne Snow Observatory Data in Water Supply Forecasting*

Draft Abstract

The majority of runoff in the western United States is derived from snowmelt, making the measuring and mapping of snow a critical component for water resource management. Federal and state-run programs support a long history of snow measurements at point locations throughout the west. Although many of these stations now provide temporally continuous snow measurements, they lack complete information on the spatial distribution of snowpack. Over the last decade, the development of airborne lidar workflows for snow depth measurement has filled in these spatial gaps, with the ability to create high resolution maps of snow across a watershed. Combining the temporal record of the station data with the spatial richness of the lidar-derived maps presents an opportunity to support better estimates of snow water equivalent (SWE) across a basin. Here, we compared historical measurements with mapped snow in the Tuolumne River Basin, where there is a relatively long record of airborne lidar data from the Airborne Snow Observatory (ASO) and many nearby in situ stations for analysis. ASO mapped snow and in situ measurements are highly correlated in time. Using a simple linear regression to predict basin mean SWE from multiple stations resulted in a correlation coefficient of 0.99 and a root mean squared error of 12 mm. We show that 5 to 10 flights are sufficient to define 96% of the variability in basin SWE as determined in a leave-one-year out cross validation statistical experiment. Evaluating the correlations on a cell-by-cell basis suggests that new stations should be installed at very high elevations to maximize new information. Ultimately, the use of flights to develop relationships with long term stations permits us to project basin mean SWE back in time for model calibration, to interpolate between available flights, and to project mean SWE to the present prior to a new flight request.

Appendix B: Wood et al. 2022

Draft Title: *Ensemble Streamflow Prediction using Airborne Snow Observatory Datasets*

Draft Abstract

Measuring mountain snowpack has long been central to seasonal streamflow forecasting in the Western United States. Snow water equivalent (SWE) observations are used directly in a statistical regression framework to predict spring runoff, termed a water supply forecast (WSF), and can be assimilated into a watershed hydrology model to produce ensemble streamflow predictions (ESP). Recent advances in airborne remote sensing of snow provide a new, high spatial resolution observation that has potential value to improve the skill of WSFs in watersheds with seasonal snowpack, yet few published quantitative analyses of the marginal benefits of such projects exist. We assess and benchmark the skill of water supply forecasts for the Hetch Hetchy Reservoir in the Tuolumne River basin, California, focusing on the impact of spatial SWE observations from the lidar-based Airborne Snow Observatory (ASO). We compare the skill of runoff forecasts from a calibrated SUMMA semi-distributed watershed model with and without the assimilation of ASO observations, for 58 forecast initializations during 2013-2019. A direct assimilation approach was used in both sequential and non-sequential modes. Forecasts from all approaches showed high skill, and ASO was found to marginally improve forecast accuracy over model-only forecasts, with an increase in r2 from 0.94 to 0.98 calculated over the entire forecast series, and benefits varying from year to year. Assimilating only one ASO observation per year near April 1 provided nearly all the benefits of repeated assimilations, correcting for model snow accumulation errors, and late-season assimilations slightly degraded forecast performance. The greatest value of high-resolution snow observations may come through judicious application in real-time forecasting, coupled with use in model calibration and improvement efforts.