SWE ESTIMATION FOR HYDROLOGIC APPLICATIONS: COMBINING WEATHER RADAR AND MACHINE LEARNING

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ABSTRACT: Snow water equivalent (SWE) estimation is critical for water resource management and forecasting in snow-dominated regions. Current SWE measurement technologies are limited in their ability to provide temporally and spatially continuous data across large watersheds. This study analyzes radar data in 2022, 2023, and 2024 Snow Years covering 1986 km^2 in the Upper Conejos River basin, the headwaters of the Rio Grande River in Colorado's Southern Rocky Mountains, USA. This research presents a novel approach integrating Airborne Snow Observatories, Inc. LiDAR data (ASO) with ground-based dual polarization weather radar and machine learning techniques to enhance SWE estimation. SnowQ™ is a patent pending technology for estimating SWE contained in snowpacks based on radar data. The method is tailored for SWE estimation in areas with sparse direct measurements at watershed scales relevant to water resources management. We apply a Forward Generation approach, using parameters calibrated from one snow season to predict SWE in the other snow seasons. Results of 9 test cases show strong agreement between radar-based estimates and ASO measurements, with R^2 values consistently above 0.85 across multiple years. These results demonstrate the temporal transferability of calibrated parameters and the effectiveness of the method at the sub-watershed level. The approach has significant implications for improving hydrological forecasting and water resource management in snow-dominated watersheds, offering the potential for more available, spatially comprehensive, and timely estimation of SWE across different snow seasons. The ability of weather radar to measure SWE directly makes it an important addition to the suite of current snow measurement tools, complementing existing technologies.

KEYWORDS: Dual Polarization, Weather Radar, LiDAR, Snow Water Equivalent, SWE, Airborne Snow Observatories, ASO, Machine Learning

1. INTRODUCTION

Recent advancements in weather radar detection algorithms present new opportunities to enhance information available to water managers and streamflow forecasters. Dozier et al. (2016) identified persistent snow accumulation patterns that can be leveraged for Snow Water Equivalent (SWE) estimation by remote sensing. Several remote sensing methods have shown promise for estimating snow depth, despite challenges and limitations. The Airborne Snow Observatories, Inc. produces LiDAR SWE data (ASO). It has emerged as one of the most accurate technologies for measuring and mapping snow depth. ASO snow depth is estimated by comparing snow-covered and snow-free conditions, which is then converted to SWE using snow density estimates from in-situ measurements and physically based snowpack modeling. ASO is high-resolution, area-wide snow depth data, as demonstrated by Grünewald et al. (2014) and Painter et al. (2016). Limitations of ASO are its high cost and the temporal discontinuity of flights, requiring a human pilot for cloud-free data collection, weather permitting. Thus, the need for ongoing research.

The applications of ground-based weather radar in hydrology are documented in several studies. Einfalt et al. (2004) provide a roadmap for radar use in urban hydrology, highlighting the application of radar rainfall data for modeling urban drainage systems. At larger watershed scales, Vieux (2016) and Vieux and Imgarten (2012) explore the ability of X-band dual polarized radar data to enhance hydrologic modeling. Bedient et al. (2018, chap. 11) discuss the application of radar in physics-based distributed hydrologic modeling. These studies collectively underscore the versatility and critical importance of weather radar technology in advancing urban hydrological research and practice. Ground-based dual polarization weather radar, hereafter referred to as radar, is an improvement over conventional single polarization systems, utilizes horizontal and vertical polarized microwave signals to characterize

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snowflakes. This technology improves the estimation of ice water content (IWC) as particles fall through the atmosphere (Ryzhkov and Zrnić, 2019). The ability of radar to detect IWC, which when combined with fall velocity, results in direct measurement of SWE by radar (Radar SWE). This makes radar an important addition to the suite of snow measurement tools.

This study extends the analysis reported in Vieux and Vieux (2023) to include another year of ASO and radar data with expanded analysis, for the same basin. The study presented herein leverages dual polarization for SWE measurement over multiple snow seasons, comparing results from ASO used as reference SWE. While recent progress in radar polarimetry has enhanced the accurate measurement of IWC aloft as a radar-based flux, various processes affect the accumulation of this IWC flux once it reaches the ground as SWE. SnowQ™, used in this study, is a patent pending technology for estimating SWE contained in snowpacks based on radar data.

2. RESEARCH METHODS

The research methods involve comparing Radar SWE estimates with ground measurements from ASO using georeferenced maps. Zonal statistical averages of ASO and Radar SWE are calculated for each sub-watershed to assess spatial variability across the Conejos River basin and accuracy. At specific point locations, SWE measurements are directly obtained from precipitation gauges or snow pillows, such as those in the Western U.S. SNOTEL network, providing additional validation data.

Machine learning techniques, trained on 50-meter resolution ASO data from three Snow Years, are employed to identify spatial patterns of SWE deposition at synthesized stations, referred to as 'manufactured' stations. These stations are created in polar coordinates, referenced to the radar's azimuth and range, and then geolocated. Radar SWE and ASO seasonal accumulations at each manufactured station are aggregated into sub-watersheds, allowing for comparison with ASO data aggregated to the same areas. Computing zonal statistics enables the inter-comparison of mean ASO and Radar SWE depth by sub-watershed area. The 'Observed' SWE used for training at each manufactured station is synthesized using ASO as the reference depth, and time series from available SNOTEL station(s) located nearby. Radar SWE is calibrated to ASO in each Snow Year to derive parameters controlling the IWC flux at each manufactured station.

The approach, termed Forward Generation, utilizes parameters calibrated from one snow season to predict SWE in subsequent snow seasons. Thus, cross-validation of the zonal statistics is computed for the Radar SWE in each Snow Year across 25 sub-watershed areas, averaging 80 km² each, within the 1,986 km² upper Conejos River basin.

3. RESULTS

Findings from this study consist of analysis of three years of radar data for the Conejos River basin. Forward Generation is performed with radar data collected from October 1st through April or May each year. An example is provided in Figure 1 for Snow Year 2024, estimated with parameters derived from a previous season, Snow Year 2022. As seen in Figure 1, the Radar SWE is in close correspondence with Manufactured SWE throughout the period and at the end accumulation on March 30th, 2024.

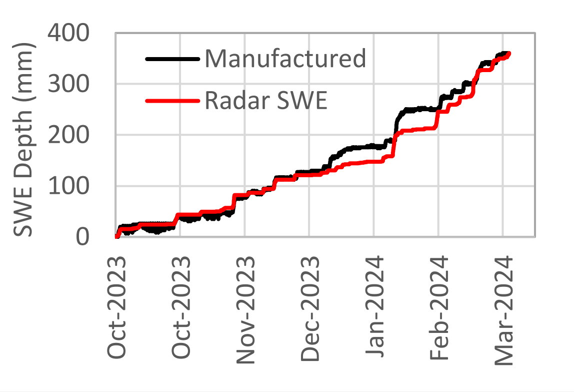


Figure 1: Calibrated results at a manufactured location station using ASO as the reference depth and time series from the nearest SNOTEL station

In this optimization, Root Mean Square Error (RMSE) is minimized with a single set of optimal parameters for the entire season. The loss function is computed as the RMSE for each hourly time step. While there are some deviations in mid-December and mid-January, there is generally good agreement. The periods of deviation could be due to differing atmospheric conditions, or the SNOTEL station received larger amounts of SWE than at the manufactured station used as the reference time series.

3.1 *Forward Generation and Cross-Validation*

Calibration is performed for each snow season, 2022, 2023, and 2024, and then used in Forward Generation to predict SWE in other seasons, 2022, 2023, and 2024. Results for each of the test cases are computed by plotting the Radar

SWE versus ASO for each sub-watershed and compiling the trendline slope and R^2.

Figure 2 shows the map accumulation of seasonal Radar SWE (mm) ending on April 2, 2024, using the 2022 parameters (as in Figure 1 above). Prevailing winds from west to east enhance accumulations in leeward regions near ridgelines on the western side of the Conejos River basin, particularly in the upper reaches. The map delineates sub-watershed boundaries in black and the Conejos River main channel in red. The SWE accumulation map highlights the variation of Radar SWE within each sub-watershed due to terrain and surface winds. Along the Conejos River that runs from north to south on the eastern side of the river basin, there is an elongated zone of low to zero accumulation at lower elevations. This is likely due to melting.

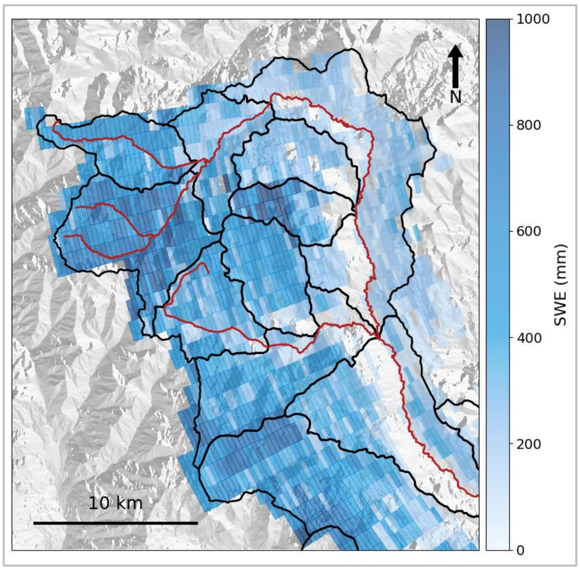
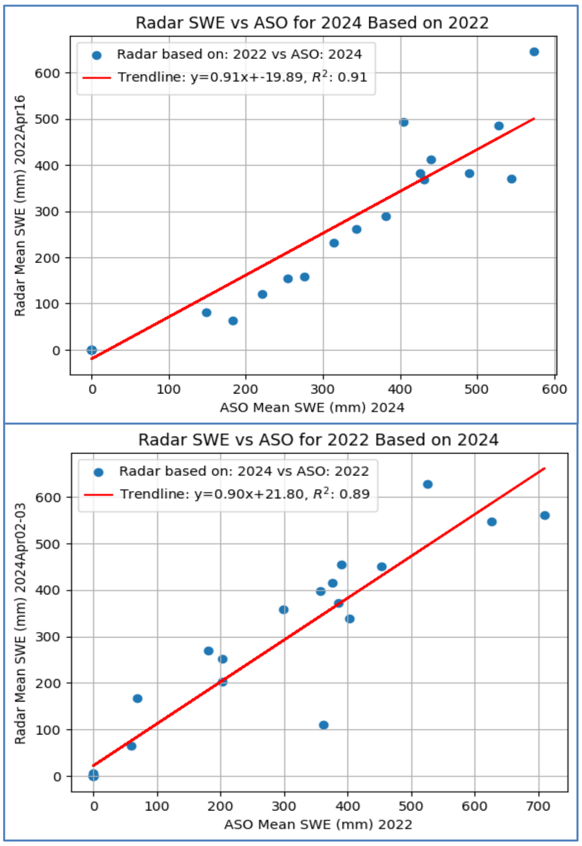


Figure 2: Radar SWE (mm) accumulation as of 2024-04-02 projected onto the Conejos River sub-watersheds (black) and main channel (red)

Figure 3 presents the validation between Radar SWE and ASO. Validation of Radar SWE vs. ASO for 2024 based on 2022 (top) and 2022 based on 2024 (bottom) shows high accuracy and low bias, with trendline slopes of 0.91 and 0.90, and R^2 values of 0.91 and 0.89, respectively.


Radar SWE vs ASO for 2024 Based on 2022

Radar SWE vs ASO for 2022 Based on 2024

Figure 3: Validation of Radar SWE vs ASO for 2024 based on 2022 (top) and 2022 based on 2024 (bottom)

Cross-validation performed across the three years (2022-2024) yielded the comparison of 6 independent cases, each showing consistent statistical agreement, as presented in Table 1.

Table 1: Validation summary trendline statistics for Radar SWE based on different Snow Year parameters.

	Parameter Year					
	2022		2023		2024	
Radar Year	Slope	R^2	Slope	R^2	Slope	R^2
2022	0.89	0.98	0.88	0.89	0.90	0.89
2023	0.85	0.92	0.85	0.96	0.86	0.89
2024	0.91	0.91	0.87	0.85	0.94	0.94

Excluding the 3 cases where the parameter and radar year are the same, the trendline slope averages 0.88, and R^2 is 0.89. The similarity in trendline slopes and high R^2 values indicate strong agreement between Radar SWE and ASO. The degree of temporal stability in the relationship between Radar SWE and ground-level SWE measured by ASO is important for the method's potential in forecasting and long-term water resource management.

Figure 4 illustrates the SWE map for 2022 accumulation estimated using 2023 parameters (left panel) and the time series of SWE (right panel) at a selected manufactured station indicated by a red dot on the map. The time series compares 'Observed' SWE (blue line) with Radar SWE (red circles), showing close agreement.

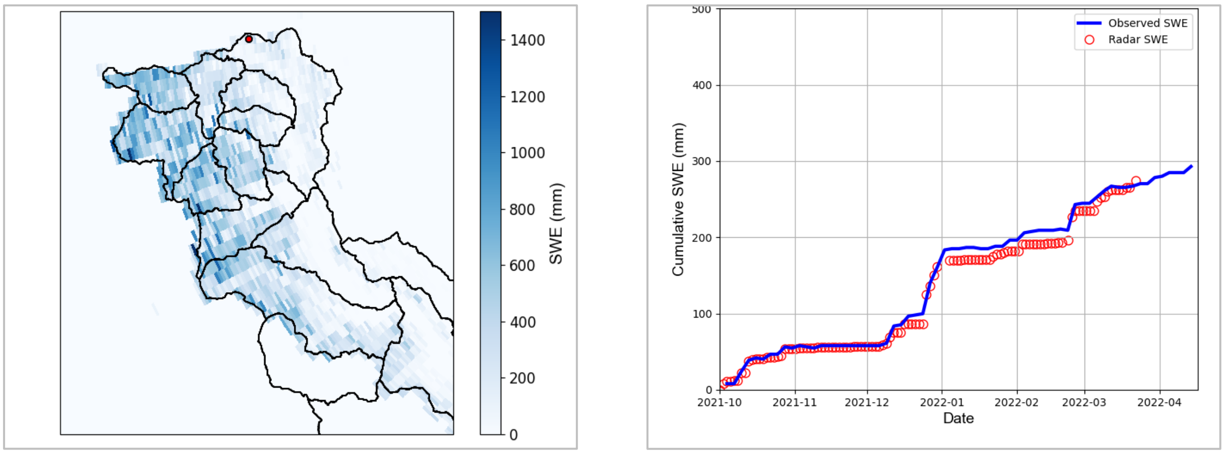


Figure 4: Left: Radar SWE map for Snow Year 2022 Based on 2023 and selected manufactured station (red dot). Right: Time series at the selected manufactured station shown as ‘Observed’ SWE in blue and red circles Radar SWE.

4. DISCUSSION

The integration of radar technology with machine learning techniques for SWE estimation presents both promising results and several important considerations for hydrological forecasting in snow-dominated watersheds.

4.1 *Timing of SWE Measurements*

We selected dates with available ASO flights that approximately coincide with peak SWE, primarily in early April. In the absence of an April flight, a later ASO flight on May 5, 2023, was used. For these ASO flight dates, Radar SWE was estimated from hourly radar data up to the corresponding ASO flight date. Selecting dates before significant melting occurs is crucial for accurately assessing the SWE stored in the snowpack just before snowmelt and reservoir inflow. The timing of ASO measurements is dictated by water management needs, weather conditions, and available resources, whereas Radar SWE is continuously monitored. Continuous Radar SWE monitoring is beneficial for efficient water resource management, as it provides timely data on the availability and spatial-elevational distribution of SWE, which is critical for managing environmental releases and hydropower generation throughout the season.

4.2 *Performance of Manufactured Stations*

The use of "manufactured" stations, generated via SNOTEL point measurements and ASO, shows potential for expanding our understanding of SWE distribution in areas where direct measurements are sparse. The close correspondence between Radar SWE and ASO/SNOTEL measurements throughout the study period suggests that this approach could be valuable for filling spatial and temporal gaps in snow monitoring networks.

4.3 *Forward Generation and Parameter Transferability*

Forward Generation demonstrates significant temporal transferability of calibrated parameters between snow seasons. Parameters derived from one year (e.g., 2022) were successfully applied to radar data in subsequent years (e.g., 2024) and vice versa, yielding comparable bias and accuracy across each test case. Notably, the accuracy statistics when using parameters from different years were nearly identical to those obtained when parameters were based on the same year as the radar data.

This consistency suggests a robust temporal stability in the relationship between radar measurements and ASO. The observed transferability implies that the method can potentially provide reliable SWE estimates using historical calibration parameters, enhancing its practical applicability for operational forecasting.

4.4 Spatial Variability and Scale

The analysis at the sub-watershed level provides valuable insights into the spatial variability of SWE. The high correlation between Radar SWE and ground-truth data at this scale is promising for watershed-level water management. Further investigation is needed to assess performance across different spatial scales, such as basin-wide versus sub-watershed levels and elevation-temperature zones where melting occurs during the season.

4.5 Limitations and Future Work

While the results are promising, several limitations should be addressed in future work.

- The impact of varying snow conditions (e.g., dry vs. mixed phase precipitation) on Radar SWE estimates needs further investigation.
- The performance of the method in different geographic and climatic settings should be tested.
- Testing of other sources of reference SWE is needed to identify feasibility of using other remote sensing, climatic maps, and snow models.
- Long-term stability of the calibration parameters and the potential need for periodic recalibration should be assessed.

4.6 Broader Implications

This research contributes to the broader field of remote sensing of snow in hydrology and demonstrates the potential for leveraging existing and future gap-filling radar infrastructure for improved snow monitoring. Where radar coverage exists, data collection is especially cost efficient. The approach could be valuable in regions where traditional snow monitoring networks are sparse or where the deployment of specialized snow-sensing equipment is challenging.

5. SUMMARY

This study integrates dual polarization weather radar technology with ASO using machine learning to enhance SWE monitoring for hydrological forecasting in snow-dominated watersheds. Analyzing three years of radar data from the Conejos River basin, Colorado, USA, we employ machine learning algorithms calibrated with high-resolution remotely sensed snow measurements, ASO. Our methodology applies derived parameters both prospectively and retrospectively, yielding hydrologically significant results. The research demonstrates the potential for improved quantification of IWC flux and its translation to ground-level SWE. The ability of weather radar to measure SWE directly makes it an important addition to the suite of currently available snow measurement tools and complements existing technologies, such as ASO.

In conclusion, while challenges remain, this study represents a significant step towards more available, spatially comprehensive, and timely estimation of SWE by radar, which could fill unmapped periods between ASO flights, enhance streamflow predictions and help optimize water resource allocation in snow-dominated watersheds. This approach addresses critical hydrological challenges in the Western United States and in other snow-dependent regions globally.

6. ACKNOWLEDGEMENT

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7. REFERENCES

Bedient, P.B., W.C. Huber, B.E. Vieux, (2018). Hydrology and Floodplain Analysis. Sixth Edition, Pearson.

Dozier, J., Bair, E. H., & Davis, R. E. (2016). Estimating the spatial distribution of snow water equivalent in the world's mountains. Wiley Interdisciplinary Reviews: Water, 3(3), 461-474.

Einfalt, T., Arnbjerg-Nielsen, K., Golz, C., Jensen, N. E., Quirmbach, M., Vaes, G., & Vieux, B. (2004). Towards a roadmap for use of radar rainfall data in urban drainage. Journal of hydrology, 299(3-4), 186-202.

Grünewald, T., Bühler, Y., and Lehning, M.: Elevation dependency of mountain snow depth, The Cryosphere, 8, 2381–2394, https://doi.org/10.5194/tc-8-2381-2014, 2014.

Vieux, B.E., J.M. Imgarten, (2012). On the scale-dependent propagation of hydrologic uncertainty Using High-Resolution X-Band Radar Rainfall Estimates. J. of Atmospheric Research. Volume 103, pp. 96-105.

Painter, T. H., Berisford, D. F., Boardman, J. W., Bormann, K. J., Deems, J. S., Gehrke, F., ... & 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.

Ryzhkov, A. V., & Zrnić, D. S. (2019). Radar polarimetry for weather observations (Vol. 486). Cham, Switzerland: Springer International Publishing.

Vieux, B.E., 2016. Distributed Hydrologic Modeling Using GIS. Third edition, Springer International Publishing AG, ISBN 978-94-024-0930.

Vieux, B.E. and J.E. Vieux. (2023). Measuring Snow Water Equivalent with Weather Radar, International Snow Science Workshop, Bend, Oregon