Assessment of snow water equivalent reanalyses and improving snow process simulations in rainfall-runoff model across Northern Italy

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Introduction

Snow plays a critical role in the Mediterranean mountainous region by storing winter precipitation and releasing meltwater during spring and summer, which helps regulate water resources. However, direct measurements of Snow Water Equivalent (SWE), crucial for mountain hydrology and water management, are often limited. Due to these limitations, alternative approaches such as large-scale reanalysis products and rainfall-runoff models are commonly used, though both methods face significant challenges. Large-scale reanalysis products face several limitations including sparse data assimilation, coarse spatial resolution, and simplified orographic precipitation. Similarly, rainfall-runoff models encounter challenges with input data accuracy, precipitation-phase determination, and simplified snow thermodynamics. This study follows a two-phase approach to validate and improve snow monitoring in Northern Italy. First, we evaluate the reliability of SWE estimates from multiple large-scale reanalysis products and a streamflow-calibrated rainfall-runoff model against a high-resolution national reference dataset (IT-SNOW). Second, we explore various strategies for integrating SWE data into model calibration to improve SWE simulations.

Materials and methods

This study evaluates SWE estimates across more than 100 catchments in Northern Italy for the period 2010-2020. We used the IT-SNOW dataset (Avanzi et al., 2023) as reference, which provides SWE estimates at 500 m resolution through comprehensive assimilation of satellite and in-situ measurements. Against this dataset, we evaluated three reanalysis products derived from land-surface models (Table 1) and the SWE simulation by the GR6J-CemaNeige rainfall-runoff model (Coron et al., 2017; Valéry et al., 2014) calibrated with streamflow observations. Comparisons were performed both at the gridded and catchment scale.

Table 9. Main characteristics of the reanalysis datasets used in this study.

Dataset	Coverage	Resolution	Atmospheric model	Land surface model	Produced by
IT-SNOW (Avanzi et al., 2023)	Italy, 2011- present	0.5 km, Daily	Station data + Radar merge	S3M	CIMA
ERA5-Land (Muñoz-Sabater et al., 2021)	Global, 1950-present	9 km, Hourly	IFS (ERA5 atmospheric forcing)	CHTESSEL	ECMWF
Cerra-Land (Verrelle et al., 2022)	Europe, 1984-2020	5 km, Hourly	HARMONIE-AROME (CERRA atmospheric forcing)	SURFEX	COPERNICUS
VHR-REA_IT (Raffa et al., 2021)	Italy, 1981-2023	2.2 km, Hourly	COSMO-CLM	TERRA-URB	CMCC

In the second part of the analysis, to improve the SWE simulations with the GR6J-CemaNeige model, we implemented three distinct calibration strategies using both streamflow and IT-SNOW data with the Kling-Gupta Efficiency (KGE) as objective function: i) a sequential approach where the CemaNeige snow parameters are first optimized with SWE data, followed by GR6J calibration of the other parameters based on streamflow observations, ii) a NSGA-II multi-objective optimization to identify Pareto front solutions, and iii) a weighted objective function combining streamflow and SWE fitting. These multi-objective calibration strategies aimed to optimize both streamflow (KGE_Q) and snow water equivalent (KGE_SWE) simulations, and compare their relative performance and optimal parameter distributions.

Results and concluding remarks

The evaluation of reanalysis products revealed significant variations in SWE estimates, in both snow cover extent and magnitude (Figure 1a). ERA5-Land showed the closest alignment with the IT-SNOW reference dataset at lower elevations (0-1200m), while the streamflow-calibrated CemaNeige-GR6J model showed the best estimates in regions above 1200 m (Figure 1b). CERRA-Land showed strong agreement with reference dataset in high-elevation winter conditions, but overestimated SWE during summer months (Figure 1b). VHR-REA underestimates SWE across all elevation bands throughout the year.

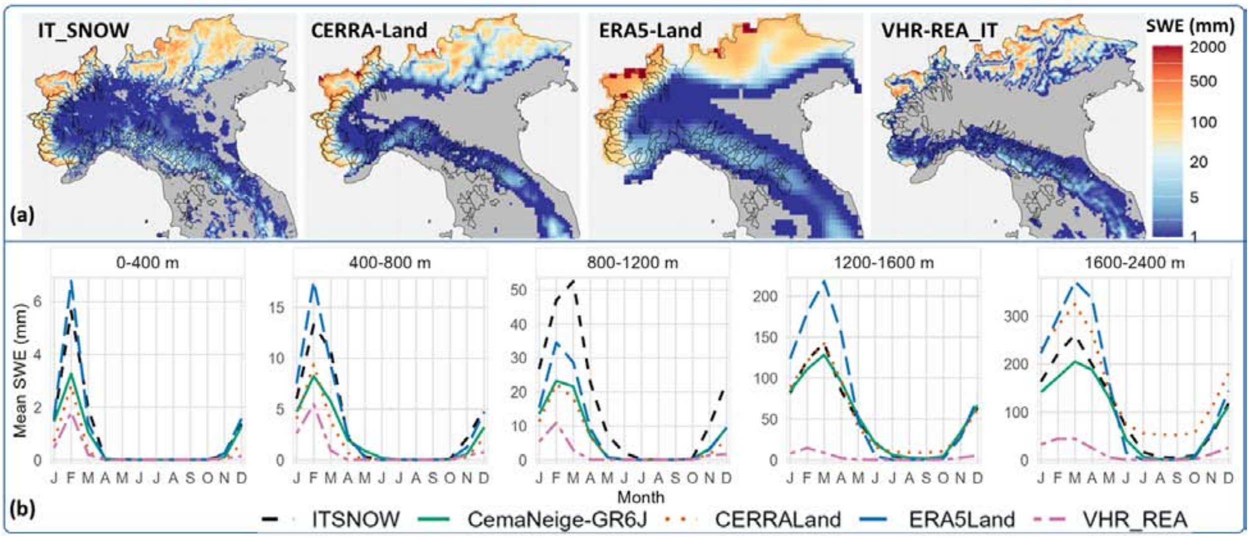

Figure 1. Spatial and seasonal patterns of SWE in Northern Italy (2010–2020). (a) Mean annual SWE distribution of gridded reanalysis products; (b) Monthly SWE seasonality averaged over catchments within each elevation band.

On the other hand, the integration of IT-SNOW data into the rainfall-runoff model calibration process significantly improved SWE simulations while maintaining high-quality streamflow simulations, demonstrating the value of incorporating multiple data sources. Future research will focus on parameter equifinality and uncertainty quantification across these catchments. This analysis will advance regionalization studies by enhancing parameter transferability to ungauged basins, particularly valuable given the sparsity of SWE observations in many regions.

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