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Brief communication: Network-wide parameterisation for estimating snow water equivalent through cosmic ray neutron sensors in the Italian Alps

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Abstract. We present a novel approach based on leveraging a network-wide parameterisation to derive snow water equivalent (SWE) with cosmic ray neutron sensing (CRNS) probes. The network comprises 26 sites (1422–2901 m asl) in the Italian Alps. The parameterisation was defined by fitting neutron counts to 35 SWE measurements taken at 6 sites in the first half of the 2023–2024 snow season and validated with 111 SWE data from 2023–2024 and 2024–2025 at 13 sites. Our analysis shows that this approach retains good representativeness of the snowpack, which can be extended to unmonitored sites if they have monitored counterparts at similar elevation. This finding overcomes the need for year-round accessibility and increases the number of potential sites for continuous SWE retrieval.

1 Introduction

Mountain snow is crucial for mountain ecosystems and plays a crucial role in sustaining human activities (Mankin et al., 2015). Its relevance is bound to increase as global projections estimate that in the next decades ~1.5 billion people will be depending on mountain water runoff (Viviroli et al., 2020). The European Alps constitute the main water reservoir for millions of people (Immerzeel, et al. 2020). However, the Alpine snowpack is strongly affected by temperature increase linked to climate change (Lopez-Moreno et al., 2020). Snow persistence in the Alps has substantially declined in the last decades (Hammond et al., 2018) and snowmelt dates are projected to be anticipated by as much as one month by the end of the century (Vorkauf et al., 2021). These circumstances exacerbate the need for accurate and widespread snow monitoring.

From a hydrological point of view, one of the most relevant variables associated with snowpack is its equivalent water mass (i.e. the snow water equivalent, SWE) (Beniston, 2012). The most common way to assess SWE involves *in situ* measurements campaigns where snow depth and bulk density values are taken through coring or snow pits. However, these measurements retain low time and spatial coverage since they are inherently linked to site accessibility, weather

https://doi.org/10.5194/egusphere-2025-6148
Preprint. Discussion started: 28 January 2026

conditions, and personnel availability. An alternative method not requiring the repeated involvement of manpower during the season consists in the adoption of snow scales and snow pillows (Egli et al., 2009), although they are not well suited for deployment on the rough terrains typical of most Alpine valleys (Kinar and Pomeroy, 2015). Recently, new approaches for continuous *in situ* SWE measuring have emerged such as the use of lakes as natural snow scales (Pritchard et al., 2021), ground-penetrating radar (Schmid et al., 2014), and GPS signal variations (Capelli et al., 2021).

Another way to retrieve SWE data comes from cosmic ray neutron sensing (CRNS). CRNS exploits the interaction between neutrons and the hydrogen present in water molecules to give SWE estimates. The adoption of CRNS sensors has gained traction with studies performed in North America (e.g. Sigouin et al., 2016), the Himalaya (e.g. Pokhrel et al., 2024), and Europe (e.g. Gugerli et al., 2019). CRNS sensors allow for great improvements in the time density of SWE datasets of already monitored sites, where manual SWE measurements can be used for their site-specific calibration (Bogena et al., 2020).

Here we present a network of 26 CRNS sensors integrated into existing weather stations along the Italian Alps. We leverage the unprecedented coverage offered by such infrastructure to gain insights about its ability to depict the SWE independently on most of the site-specific features usually adopted. Indeed, the same parameterised relation between neutron counts and SWE is shared by each site of the network. We compared 146 direct SWE measurements, performed at various sites during the 2023–2024 and 2024–2025 snow seasons, with CRNS data to gain insights on the performances of this methodology and its potential reliability even in absence of reference manual data. Of the 146 available manual SWE measurements, we used 35 to calibrate and define the parameterisation.

So far, no studies have investigated the possibility of exploiting CRNS probes to retrieve continuous SWE data from sites not accessible and, therefore, lacking direct measurements needed for calibration. Moreover, to the best of our knowledge, this is the first work that explores the adoption of the same parameterisation for retrieving SWE from neutron counts among sensors placed in an elevation range of ~1.5 km (1422–2901 m asl) and spanning more than 5° in longitude across the Alps. Our work paves the way for the application of CRNS technology in snow monitoring at regional scale, overcoming common criticalities such as site accessibility issues, lack of manpower to perform direct measurements, and safety hazards linked to the harsh mountain environment.

2 Data and methods

The Alps are the most extensive mountain range in Europe, spanning about 1200 km along their W-E axis while being part of eight countries. The Italian Alps make up about a quarter of the total area of the Alps and lie almost entirely south of the main Alpine watershed (Brugnara and Maugeri, 2019).

Our network consists of 26 stations installed across the Italian Alps (Fig. 1), equipped with CRNS sensors developed by Finapp SpA. The elevation range of the network covers almost 1500 m between the lowest and the highest stations, namely Lisser (1422 m asl) and Mosso (2901 m asl). Each sensor was integrated into already existing automated weather stations (AWSs) or, if the AWS framework could not host it, in the immediate proximity. A summary of the main features of each site (e.g. name, coordinates, elevation, and series length) is given in Table S1. The AWSs employing the CRNS sensors are managed by various institutions: the Regional Environmental Protection Agencies (ARPAs) of Veneto and Piemonte, the Office for Hydrology and Dams of the Autonomous Province of Bolzano, the University of Torino, and the Polytechnic University of Torino. The sensors are based on Lithium-doped ZnS(Ag) scintillators capable of detecting and discriminating neutrons and muons (Gianessi et al., 2024). The measurement of the local muon flux allows for an accurate

https://doi.org/10.5194/egusphere-2025-6148
Preprint. Discussion started: 28 January 2026

site-specific correction of the neutron flux without the need of relying on a network of public observatories (Stevanato et al., 2022), which is the standard practice for CRNS technology (McJannets and Desilets, 2023).

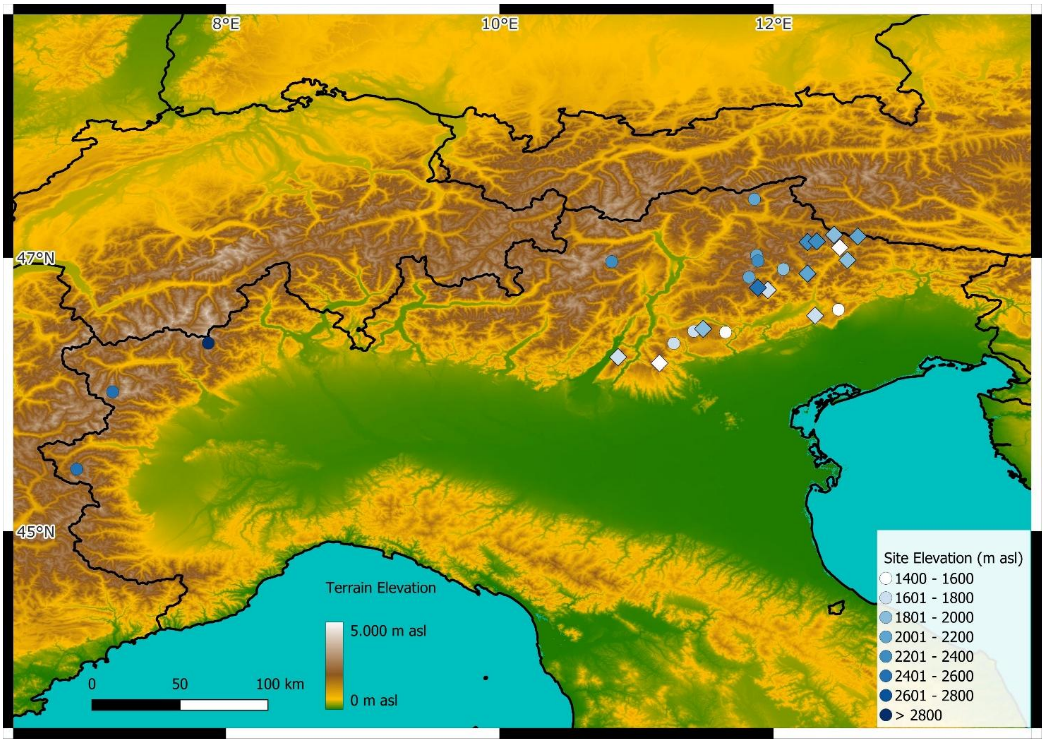

Figure 1: Elevation map of the Alps and northern Italy. Monitored and unmonitored sites of the network are indicated by circles and diamonds respectively; the symbols filling follows a scale of blue to represent the elevation of each site, where darker shades correspond to higher elevations. Produced using Copernicus WorldDEM-90 © DLR e.V. 2010-2014 and © Airbus Defence and Space GmbH 2014-2018 provided under COPERNICUS by the European Union and ESA; all rights reserved.

A CRNS setup for SWE measurement includes a detector buried flush to ground and another detector mounted on a mast, above the snow surface. Each sensor retrieves hourly particle counts, of which the neutron count rate measured by the ground detector represents the main signal, while the muon count rate measured by the mast detector provides the incoming flux reference. We derived the barometric factor correction from onsite atmospheric pressure measurements and subsequently applied it to the count rates. The relative variation in time of the muon count allows the application of a site-specific incoming correction factor to the neutron count rate. We took the baseline neutron count rate (N_0) for each site during periods of absence of snow cover. N_0 varies greatly from each site due to its dependence from elevation, soil composition, and morphology. Using N_0 as a normalisation parameter for the neutron count rates, we obtained the normalised neutron count rate N_r. Then, we computed SWE adopting the formula (Gugerli et al., 2019) reported in Eq. (1):

$$SWE = -\frac{10}{\Lambda} log N_r \, , \tag{1}$$

Where the attenuation length (expressed in cm^{-1}) Λ is (Eq. 2):

$$\Lambda = \frac{1}{\Lambda_{max}} + \left(\frac{1}{\Lambda_{min}} - \frac{1}{\Lambda_{max}}\right) * \left[1 - exp\left(\frac{a_1 - N_r}{a_2}\right)\right]^{-a_3}, \tag{2}$$

We assessed the parameters Λ_{max}, Λ_{min}, a_1, a_2, and a_3 through a calibration process that leveraged 35 direct SWE measurements taken from six sites in the Veneto region (Eastern Alps) between December 2023 and March 2024. This first instance of an interpolation common to multiple sites suggested the possibility of adopting a network-wide parameterisation and prompted the study presented in this work.

At 13 sites of the network, SWE is also manually measured following two different procedures: (i) measuring the density of a single vertical core that spans the entire snowpack from the top to the ground (Berni and Giancanelli, 1966), or (ii) density measurements of multiple horizontal cores obtained from the homogenous layers present in the snowpack. In the first case, the single vertical core is weighted to derive snow bulk density and SWE. In the case of horizontal coring, each core is taken with a cylinder with a volume of 0.5 dm^3 (i.e. length of 18 cm and diameter of 6 cm), then the core is weighted with an analogic or digital dynamometer. If there are layers with thickness lower than the diameter of the corer, the layer density is estimated following the results of Valt et al. (2012). The sum of the SWE computed from each core (e.g. each layer) is assumed to be the SWE of the whole snowpack. It was assessed that the differences between the two methods are within 5% (Valt, 2019). In most of the cases, the direct SWE monitoring practices pre-dates the installation of CRNS sensors and the measurements were not initially meant to be used for performance assessment on this technology. This fact, in combination with the inherent spatial heterogeneity of the snowpack, could hinder the capability of such measurements of being fully representative of the actual SWE at the AWSs. This criticality descends from the absence of a defined standard for taking SWE measurements meant specifically for CRNS validation. To address this matter, we compared the snow depth (HS) measured at the AWSs with the values obtained from manual measurements. For our analysis, we discarded direct SWE measurements taken where the HS differed from the corresponding AWS value by more than 20% for deep snowpack (i.e. HS ≥ 1 m) or more than 20 cm for shallow snowpack (i.e. HS < 1 m).

We obtained (including the 35 used for the calibration) a total of 154 SWE values between the 2023–2024 and the 2024–2025 snow seasons. These measurements are assumed to be representative of the on-site SWE daily average. Therefore, to compare the coring data with the CRNS neutron count rates, we averaged the hourly values of N_r over a 24-hour time span. The calibration dataset was used to define the parameters of Eq. 2 that constitute the core of the network-wide parameterisation. Then, we compared the remaining daily N_r values (i.e. the validation dataset) with the direct SWE measurements at each site. In addition, we computed the mean absolute percentage error (MAPE) to identify site-specific sensible deviations from the theoretical parameterisation. Two stations (namely Mosso and Sestriere) presented MAPEs higher than 50% limited to the data of the 2023–24 snow season. Their sensors were installed when the snow cover was already formed. This fact prevented the standard assessment of N_0, which had to be approximated. The efforts to define a posteriori normalisation value are ongoing, but outside the scope of this work. However, this occurrence remarks that the installation of CRNS probes needs to be performed in absence of snow cover, at least when adopting a network-wide parameterisation. To avoid biases, we decided to not consider for the next steps of the analysis the 2023–2024 data of the two stations.

After these evaluations, we converted the N_r data to average daily SWE (SWE_{CRNS}) according to the presented formula. For each day and site where a reference manual SWE value was available, we identified and coupled with it the correspondent SWE_{CRNS}. In total, we leveraged for our analysis 146 days of coupled manual and SWE_{CRNS} (e.g. 35 for calibration and 111 for validation). Following the methodology adopted by Egli et al. (2009), we computed a least squares fit of the data according to the Eq. (3):

$$SWE_{CRNS} = \alpha \cdot SWE_{manual} \, , \tag{3}$$

We also determined the standard error (SE) of α along with the root mean square error (RMSE) of the SWE_{CRNS} against the manual measurements. This procedure allows us to identify the systematic bias of SWE evaluation by observing how much the value of α approaches 1 (e.g. with α = 1 the evaluation is theoretically unbiased). On the other hand, SE gives

https://doi.org/10.5194/egusphere-2025-6148
Preprint. Discussion started: 28 January 2026

a measure of how much the data are scattered along the predictive line, with the RMSE constituting an average error that can be associated to the estimated SWE values.

Finally, to address the possibility to extend our considerations to unmonitored sites, we evaluated the correlation (r) between their SWE_{CRNS} series. The identification of variables that influence the similarity of SWE patterns is crucial in the effort of overcoming site-specific validation. Monitored sites could act as accuracy proxy for unmonitored locations with which they exhibit high correlation. For this reason, we averaged the resulting r values among subsets depending on the horizontal and vertical distances between each couple of monitored-unmonitored sites to assess the impact of these two variables on the SWE pattern.

3 Results and discussion

The direct SWE measurements used for the analysis range from the minimum value of 20 mm recorded at Larici site on 11 December 2024 to the maximum of 897 mm recorded at Ornella site on 4 April 2024. The median of the manually measured values is 199 mm, while for their SWE_{CRNS} counterparts it is 160 mm. The two series retain extremely similar distributions with interquartile ranges (IQRs) 87–335 mm for the manual and 76–334 mm for the SWE_{CRNS}.

The values of the parameters Λ_{max}, Λ_{min}, a_1, a_2, and a_3 are 114 cm, 21 cm, 0.41, 0.082, and 1.117, respectively. Figure 2 represents the daily averaged N_r (i.e. N/N0) values plotted against the direct SWE measurements for the calibration (Fig. 2a) and validation (Fig. 2b) dataset. The adopted parameterisation of the theoretical SWE curve appears to depict well the data distribution.

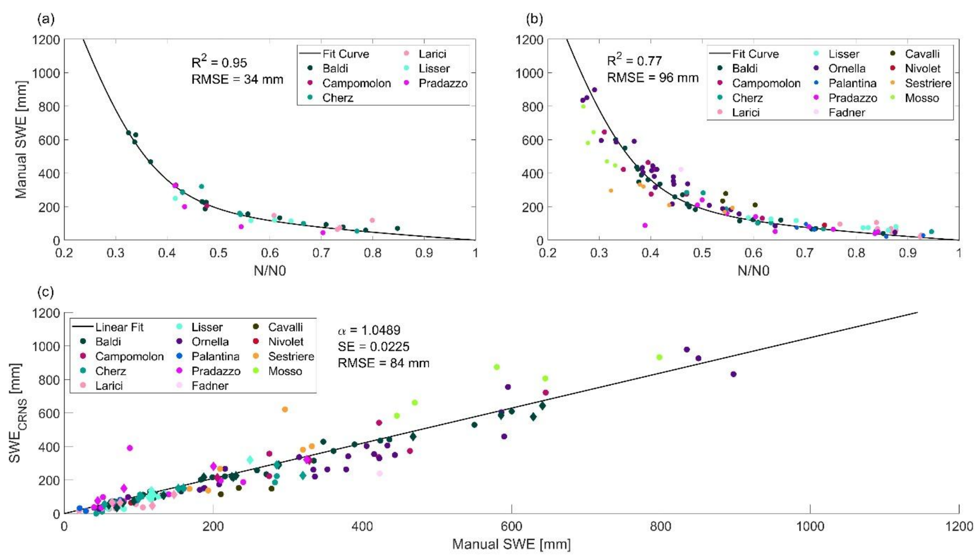

Figure 2: Normalised daily neutron count rate (x-axis) against SWE direct measurements (y-axis) for each site (coloured dots), and regression curve (black line) for the calibration (a) and validation (b) dataset. (c) Manual SWE measurements plotted against SWE_{CRNS}; diamonds and dots represent the calibration and validation dataset respectively; the black line illustrates the linear regression fit.

Figure 3c presents the results of the linear regression. The value of α suggests that the parameterization adopted does not introduce any sensible bias. The SE, which has a value similar to the highest presented by Egli et al. (2009), reflects that the data are scattered along the prediction fit. We attribute this feature to two main causes: (i) the data come from different sites inherently different from one another, and (ii) the possible representativity errors introduced by the manual measurements that, we stress again, were not originally intended for this kind of performance assessment. Even considering these potentially hindering factors, the RMSE computed over the whole series is 84 mm. This result can be considered as a benchmark value when taking into account the error associated with this novel network-wide approach to CRNS parameterisation.

Among the 146 analysed data, in 82 cases (22 in the calibration dataset, 60 in the validation) CRNS estimates were lower compared to the manual SWE measurements. The medians of the underestimated and overestimated manual SWE values are 168 mm and 209 mm, respectively. In fact, it appears that higher SWE values are more likely to be overestimated by CRNS sensors. This phenomenon could be linked to the footprint reduction caused by high snow depth. The uncertainties arising from the increases in the snowpack thickness are well documented (Gugerli et al., 2019) and may lead to an increased sensibility of the sensors to the small-scale spatial variability of snow depth. However, this result could be biased by the relative scarcity of high SWE measurements available. Indeed, more than 70% of the manual SWE data used for our analysis have values lower than 300 mm.

To better address the site sensitivity of our network approach, we looked at the distribution of selected statistical parameters computed separately for each site. The mean absolute errors (MAEs) emerging from the comparison between SWE_{CRNS} data and the manual measurements have an average value of 70 mm, while the average of the site specific RMSEs is 82 mm. However, the MAE and, in a lesser way, the RMSE distributions are skewed towards lower values. In fact, the median MAE and RMSE are 47 mm and 67 mm. These values are comparable with the errors associated with manual SWE measurements, that increase with SWE (e.g. Gugerli et al., 2019) and can be assumed to be in the range 20–50 mm for most of the values in our dataset. Focusing on the distribution of MAPEs for each site, its average and median values are 32% and 29%, respectively. These values are more than double compared to the maximum percentage error of ±13% found by Gugerli et al. (2019). However, that study involved only measurements performed by CRNS probes installed on a glacier, which cancels out possible error contributions from the underlying soil water content (Wallbank et al., 2021).

The relatively high percentage error constitutes the trade-off linked to the choice of applying the same parameterisation to every site of the network. The same choice is intended to expand the spatial coverage of continuous SWE dataset including sites that cannot be subjected to direct measurements campaigns every season due to their inaccessibility. Indeed, the only comparable European CRNS network adopts as standard procedure the seasonal recalibration through manual SWE sampling of each sensor installed (Gottardi et al., 2013). This approach, although it may yield better overall estimations in already monitored sites, limits the number of locations available for installation of CRNS probes. In any case, if needed for site specific studies, any of the SWE_{CRNS} dataset used for our analysis could be improved with the implementation of an *ad hoc* parameterisation defined using the available manual SWE data.

The correlation coefficients computed between the unmonitored and monitored sites (Fig. 3) appear to be influenced by the vertical distances (i.e. the elevation difference) with the average r monotonically decreasing from a maximum of 0.87 when the distance delta is in the range 0-250 m to a minimum of 0.41 in the range 1–1.5 km. On the other hand, horizontal distances do not seem to affect the correlation between sites. In fact, although the maximum r of 0.76 is related to the horizontal distance range 0–50 km, the minimum value of 0.67 is observed in the range 50–100 km. Unmonitored stations data are highly correlated (average r = 0.98) with monitored sites with a vertical and horizontal distance lesser than 250 m and 50 km respectively. Thus, statistical behaviour of unmonitored sites, including an estimate of accuracy and representativeness of SWE measurements, can be inferred from neighbouring monitored sites in that range. In absence of monitored sites meeting those characteristics, a comparison with stations at similar elevations should still yield reasonable

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estimates. Overall, this approach can be adopted to extend the application of CRNS to inaccessible locations further extending the spatial coverage of continuous SWE data while avoiding the necessity of an unfeasible site-specific validation.

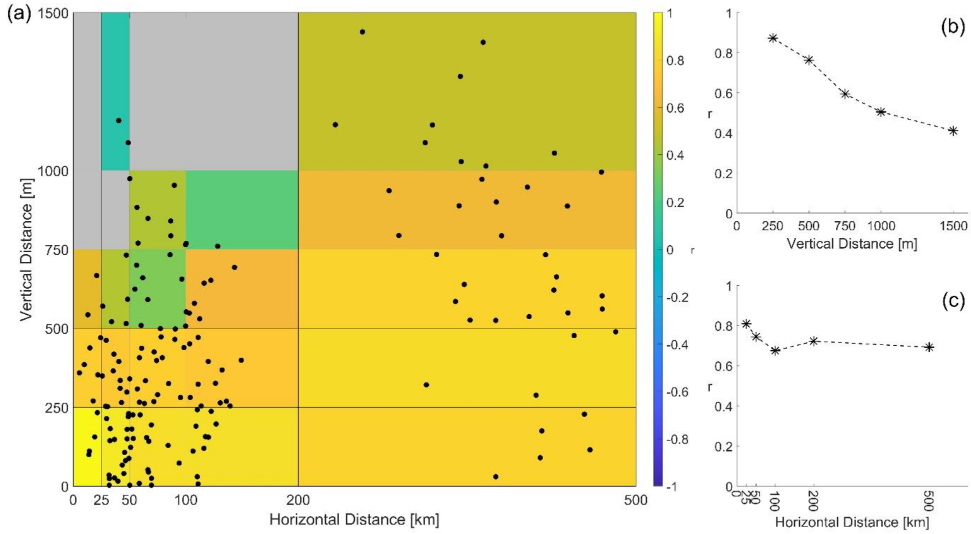

Figure 3: (a) Heatmap of the average correlations classified by the horizontal (x-axis) and vertical (y-axis) distances between unmonitored and monitored stations. The black dots represent each couple of stations for which r was computed. Average r values depending on vertical (b) and horizontal (c) distances. The x coordinates of each point represent the upper limit of its distance class.

4 Conclusions

We presented a network of 26 CRNS sensors integrated into AWSs covering an elevation range of ~1.5 km in the Italian Alps that has been monitoring SWE since the 2023–2024 snow season. All probes retrieve SWE data from neutron counts leveraging the same network-wide parameterisation. This choice is meant to allow for reliable data collection even at inaccessible sites. As far as we know, this is the first instance of a similar feature for SWE measurements involving a CRNS network.

The comparison between the 111 validation direct SWE measurements from 13 sites showed good accordance with the conversion curve obtained through the calibration data (R^2 = 0.77, RMSE= 96 mm). The linear fit features show that this method is not prone to biases. Compared to similar studies involving a single site, the data are more scattered. We trace this back to two factors: underlying differences among the sites, and uncertainties in the manual data. Even so, the RMSE (84 mm) indicates that, even when adopting a network-wide parameterisation, the uncertainty of SWE_{CRNS} is close to the ones typical of the other methodologies presented by Egli et al. (2009). Moreover, the correlation between 13 unmonitored sites and the monitored ones shows that, across the network, SWE_{CRNS} patterns are strongly influenced by elevation while not being sensibly affected by horizontal distances. These results imply that uncertainties on SWE_{CRNS} of inaccessible sites can be inferred from stations at similar elevations, prioritising location in the 0–250 m elevation and 0–50 km horizontal ranges (average r = 0.98).

Applying a network-wide parameterisation vastly expands the roster of available sites for continuous SWE monitoring. In fact, many alpine AWS could host similar equipment resulting in accurate data regardless of the accessibility of the site and the availability of manpower. Moreover, automating data collection in the harsh mountain environment drastically lowers the exposure of workers and researchers to safety risk linked to on-site activities.

Nevertheless, we aim to expand the network as we are confident that an increase in the available data and the elevation range covered will benefit the parameterisation and its overall performances both at monitored and unmonitored sites. In this regard, future research developments should focus on three main points: (i) definition of a standardised methodology for retrieving manual SWE data specifically intended for SWE_{CRNS} validation; (ii) further investigation on the dependency from vertical and horizontal distances in sites comparison; (iii) assessing the impact of other local features (e.g. aspect, soil type) on the correlation between sites.

Data availability

The map presented in Fig. 1 was produced using Copernicus WorldDEM-90 © DLR e.V. 2010-2014 and © Airbus Defence and Space GmbH 2014-2018 provided under COPERNICUS by the European Union and ESA; all rights reserved.

SWE datasets obtained both with manual measurements and CRNS probes at each site of the network belong to the entities that operate the respective AWSs. The data presented in this work can be made available upon request to the corresponding author.

Author contribution

Conceptualization: MG and NC. Formal analysis: MG and EG. Funding acquisition: FA and MF. Investigation: MG, NC, EG, MV, CR, LL, RD, RN, SF, AG, DG, and MF. Methodology: MG, NC, and EG. Visualization: MG. Writing (original draft): MG. Writing (review and editing): all the authors equally.

Competing interests

EG is currently employed by the company that produces the CRNS probes used for this work. The other authors declare that they have no competing interests.

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