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COSMIC RAYS NEUTRON SENSING IS A MATURE TECHNOLOGY FOR SNOW WATER EQUIVALENT MEASUREMENT

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Abstract:

Snow represents a fundamental water resource for mountain and lowland areas. Despite its relevance, the monitoring of the equivalent amount of water stored in mountain snowpack (Snow Water Equivalent - SWE) poses great challenges due to the remoteness and elevation of the areas of interest. The paucity and uncertainties of SWE estimations are therefore common issues, which entails an urgent need for proximal sensors providing continuous and reliable measurements. Systems based on Cosmic-Rays Neutron Sensing (CRNS) have reached a level of maturity suitable for widespread field application in remote areas. After proper calibration, a CRNS probe can infer SWE from the detection of neutrons, particles flowing from space and strongly interacting with water. During the 2023/2024 winter season, 20 Finapp CRNS systems were operative on the mountains of the Veneto region, Italy. They were deployed by the Regional Agency of Environmental Protection of Veneto (ARPAV) and integrated into the pre-existing meteo-nivological stations network. We here present the performance assessment of the CRNS measurements by comparing them with SWE values obtained from field campaigns and computational models.

1 Introduction

Neutrons have long been used to estimate the amount of water in the soil, exploiting their strong interaction with the nucleus of hydrogen atoms [Gardner and Kirkham, 1952; Visvalingam and Tandy, 1972]. This method, described as the Neutron Scattering Method in the WMO Guide to Instruments and Methods of Observation [WMO, 2023], is invasive and most notably needs the use of an artificial source of fast neutrons, a feature that inevitably limits its widespread use, let alone permanent installation on fields. At the same time, the possibility of measuring water content in soil (or Soil Moisture - SM) or the water equivalent of snow (SWE) by the absorption of atmospheric neutrons naturally produced by cosmic rays was understood. The strong dependence of the neutrons flux near the Earth surface on the SM had been observed, but was considered just a nuisance in the study of space weather [Hendrick and Edge, 1966]. The possibility of effectively using the natural source of cosmic-ray neutrons instead of an artificial source was proposed for the measurement of SWE first [Kodama et al, 1979] and then for SM [Kodama et al, 1985], achieving acceptable statistical accuracy of measurement with invasive sensors. With a crucial step forward, the measurement of SM by CRNS was announced as a mature, non-invasive technique by Zreda, Desilets and others in 2008 [Zreda et al, 2008] and has since then become an established technique. Networks of sensors have been installed in various countries for the purpose of large-scale monitoring of SM trends [Zreda, 2012; Evans et al, 2016; Andreasen et al, 2017; Bogena et al, 2022] and the procedure for proper use and calibration has been published as a IAEA-TECDOC by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture [IAEA, 2017].

Although SM is nowadays the most well-known and widely used application of CRNS, the history of its application to SWE measurement is no less rich. Besides being the first proposed application by Kodama in 1979, it was already between 1998 and 2004 that Électricité de France developed and installed its own network of CRNS probes for SWE monitoring on the French Alps and the Pyrenees, which reached a number close to 40 probes and is still operational [Paquet and Laval, 2006; Gottardi et al, 2013]. Research on this application has reflourished since 2010 to include different configurations of detection [Desilets et al, 2010; Sigouin and Si, 2016; Schattan et al, 2017; Howat et al, 2018; Gugerli et al, 2019] and it was included in the WMO SPICE - Solid Precipitation Intercomparison Experiment [Nitu et al, 2018], where the dwindling availability of ^{3}He, the key sensitive material of the traditional neutrons detectors, was mentioned as their most critical limitation. This is due to the global shortage of ^{3}He stockpiles following a fast-growing demand, pointed out by the US Congress in 2010, as ^{3}He is not extracted from natural resources and it's a subproduct of the maintenance of nuclear arsenals instead [Morgan and Shea, 2010]. Nowadays that issue has been overcome by the development of new detectors based on easily available technologies, like the Finapp detector which is based on a cheaper and safer solid scintillator material, which makes it light, compact and suitable for widespread field applications [Gianessi et al, 2024].

2 Methods

The Finapp CRNS detector is based on a lithium-doped ZnS(Ag) scintillator material, capable of detecting and discriminating neutrons and muons [Cester et al, 2016; Stevanato et al, 2019]. The importance of measuring the local flux of muons is related to another key hurdle of CRNS systems: the need for a reference measurement of the incoming cosmic neutrons flux, which usually relies on a network of public observatories [McJannet and Desilets, 2023]. By monitoring the local muons flux, that is found to be correlated with the incoming neutrons flux, Finapp is capable of contextually providing its own autonomous and site-specific reference [Stevanato et al, 2022]. A Finapp system for SWE measurement is composed of two parts: an IP68 metal box buried into the ground and an IP67 plastic box mounted on a mast. The ground box contains the main detector, whose neutrons count rate is used for the SWE calculation, with its read-out electronics. The mast box contains the reference detector and the electronic master board managing the whole system, including power-supply and data delivery. Figure 1 shows pictures of a Finapp SWE system integrated into a pre-existing meteorological station on the Dolomites, Italy.

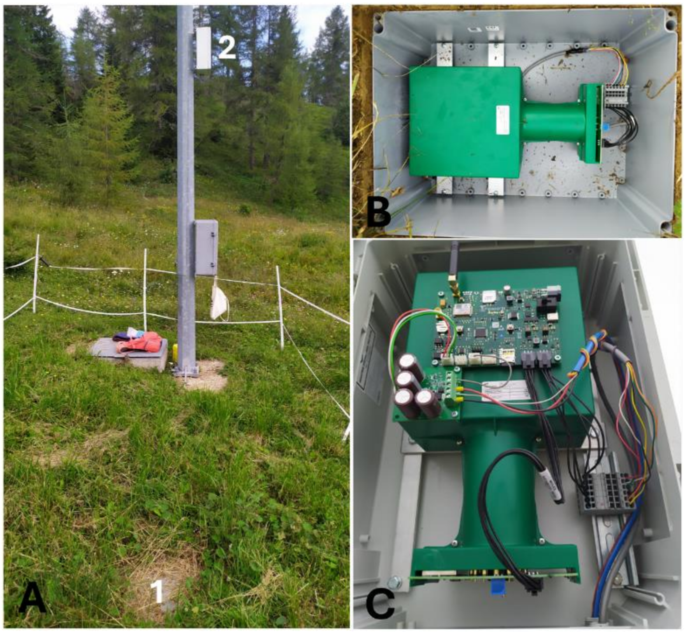

Figure 1: Pictures of a Finapp CRNS system for the measurement of SWE. Panel A: panoramic view of the Finapp system integrated in a pre-existing meteorological station, with labels showing (1) the ground box and (2) the mast. Panel B: the ground detector inside the metal box. Panel C: the reference detector and the master board inside the mast box.

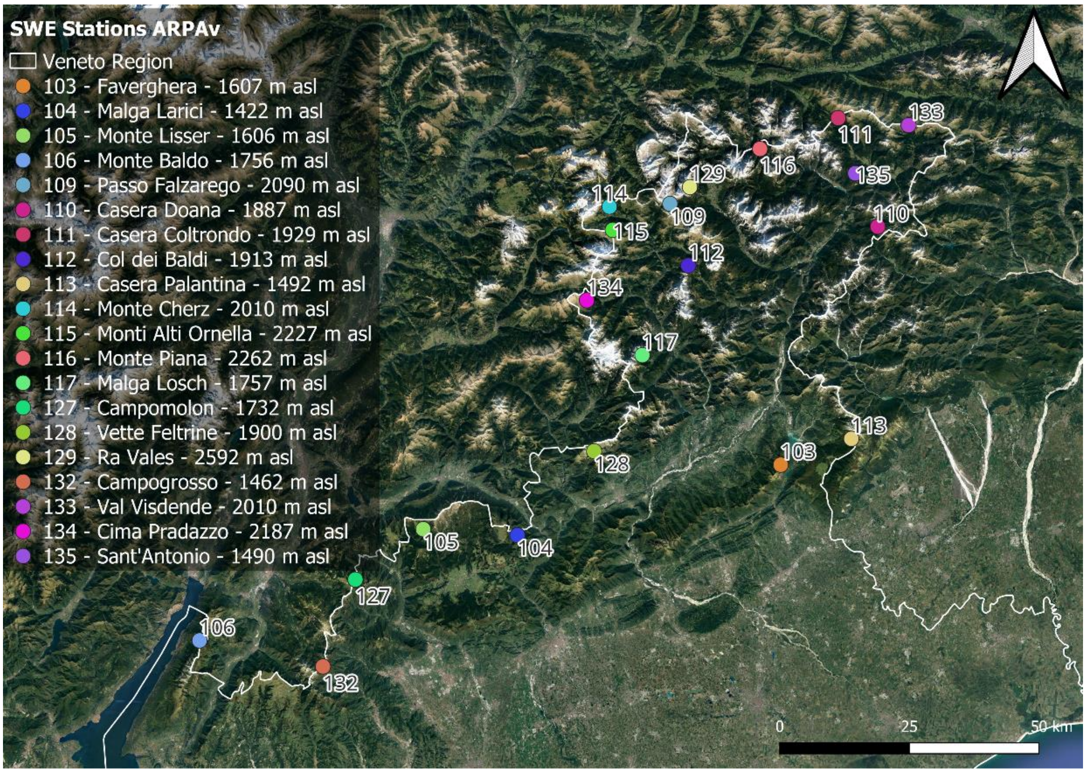

Figure 2: Map of the locations of the 20 probes of the ARPAV network installed before the 2023/2024 winter season, with ID and elevation.

Table 1: The 20 active stations during the 2023/2024 winter season, listed by elevation. The main lithology and soil texture are also reported.

Station label	Elevation [m a.s.l.]	Area	Main Lithology	Main soil texture
105 Monte Lisser	1422	Pre-Alps	limestone	Silty Clay Loam
132 Campogrosso	1462	Pre-Alps	dolomite	Silt Loam
135 Sant’Antonio	1490	Dolomites	dolomite	Clay Loam
113 Casera Palantina	1492	Pre-Alps	limestone	Loam
104 Malga Larici	1606	Pre-Alps	limestone	Silt Loam
103 Faverghera	1607	Pre-Alps	limestone	Silty Clay Loam
132 Campomolon	1732	Pre-Alps	limestone	Silt Loam
106 Monte Baldo	1756	Pre-Alps	limestone	Clay Loam
117 Malga Losch	1757	Dolomites	limestone	Clay Loam
110 Casera Doana	1887	Dolomites	dolomite	Clay Loam
128 Vette Feltrine	1900	Dolomites	limestone	Loam
112 Col dei Baldi	1913	Dolomites	conglomerate	Sandy Loam
111 Casera Coltrondo	1929	Dolomites	limestone	Loam
114 Monte Cherz	2010	Dolomites	conglomerate	Sandy Loam
133 Val Visdende	2010	Dolomites	conglomerate	Loam
109 Passo Falzarego	2090	Dolomites	dolomite	Sandy Loam
134 Cima Pradazzo	2187	Dolomites	dacite	Loam
115 Monti Alti Ornella	2227	Dolomites	conglomerate	Sandy Loam
116 Monte Piana	2262	Dolomites	dolomite	Sandy Loam
129 Ra Vales	2592	Dolomites	dolomite	Sandy Loam

As the 2023/2024 winter season approached, the Regional Agency for Environmental Protection of Veneto (ARPAV) deployed the first full network of Finapp SWE probes across the mountains of the Veneto Region, Italy. 25 probes were acquired, with 20 installed in 2023 and the remaining 5 in 2024, as shown in Figure 2. The network spreads between the Dolomites mountain range and the minor ranges known as Pre-Alps, and it spans elevations ranging from about 1400 m to 2600 m a.s.l.. The total mountain area of Veneto (defined by having an elevation > 600 m a.s.l.) covers approximately 5000 km^2 and reaches a maximum altitude of 3343 m a.s.l.. Table 1 reports a list of the 20 stations active during the 2023/2024 winter season, with details about their location including the elevation, main lithology and main soil texture. This information, obtained from public geological maps[1], allows to appreciate the significant variability of environments included in the present study. Most Finapp probes were integrated in nivological stations where a nivometer was operational and the snow height had been monitored for years. Where available, modelled SWE values derived by nivometers and meteorological data were provided for comparison, based on the SNOWPACK computational model [Bartelt and Lehning, 2002]. In some sites, regular on-site coring by expert technicians was performed during the whole winter season, by means of either total vertical coring [Berni and Giancanelli, 1967] or snowpack stratigraphic profiles [Valt et al, 2012]; in other sites only occasional or no coring data were available.

3 Results and discussion

SWE was calculated from particles counts following established procedures. The barometric factor correction, based on the local measurement of atmospheric pressure, was applied to both neutrons and muons count rates, then the relative variation of muons counts in time was used as the incoming correction factor to be applied to the neutrons counts [Stevanato et al, 2022]. For each station, the baseline value for neutrons count rate, the so-called N_0, was taken in mid-October in absence of snow coverage. N_0 is a site-specific parameter that depends on the elevation, soil and morphology. Defining N_r as the corrected neutrons count rate normalized to N_0, previous literature on the topic established the following general formula to derive SWE [Howat et al, 2018; Gugerli et al, 2019]:

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

where:

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

Some slightly different values for the set of 5 parameters a_1, a_2, a_3, Λ_{min} and Λ_{max} are found in literature [Jitnikovitch et al, 2021]. The main result of the present work is the validation of a set of parameters by interpolation on the SWE values obtained by on-site coring campaigns. The interpolation is shown in Figure 3 and its parametrization is reported in Table 2. It is significant to note how a single set of parameters proved suitable for sites with very different characteristics of elevation, lithology, and soil texture,

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[1] Soil texture was retrieved from the portal geomap.arpa.veneto.it; main lithography from the portal www.pcn.minambiente.it

suggesting that it is universal for this sensing configuration. Figure 4 shows the seasonal SWE variation at four locations chosen to span the said variability of sites characteristics.

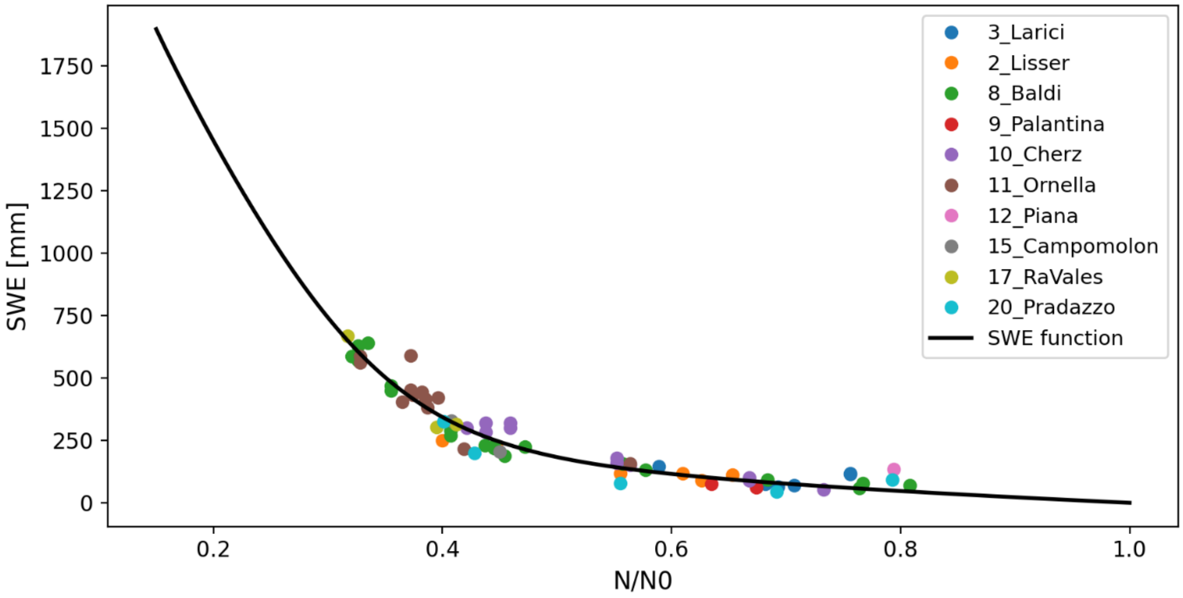

Figure 3: optimal parametrization of the function to convert neutrons count rate to SWE. Colored dots represent on-field coring: the obtained values of SWE (y-axis) are put in relation to the normalized neutrons counts (x-axis). The black curve is the conversion formula parametrized with the set of parameters reported in Table 2.

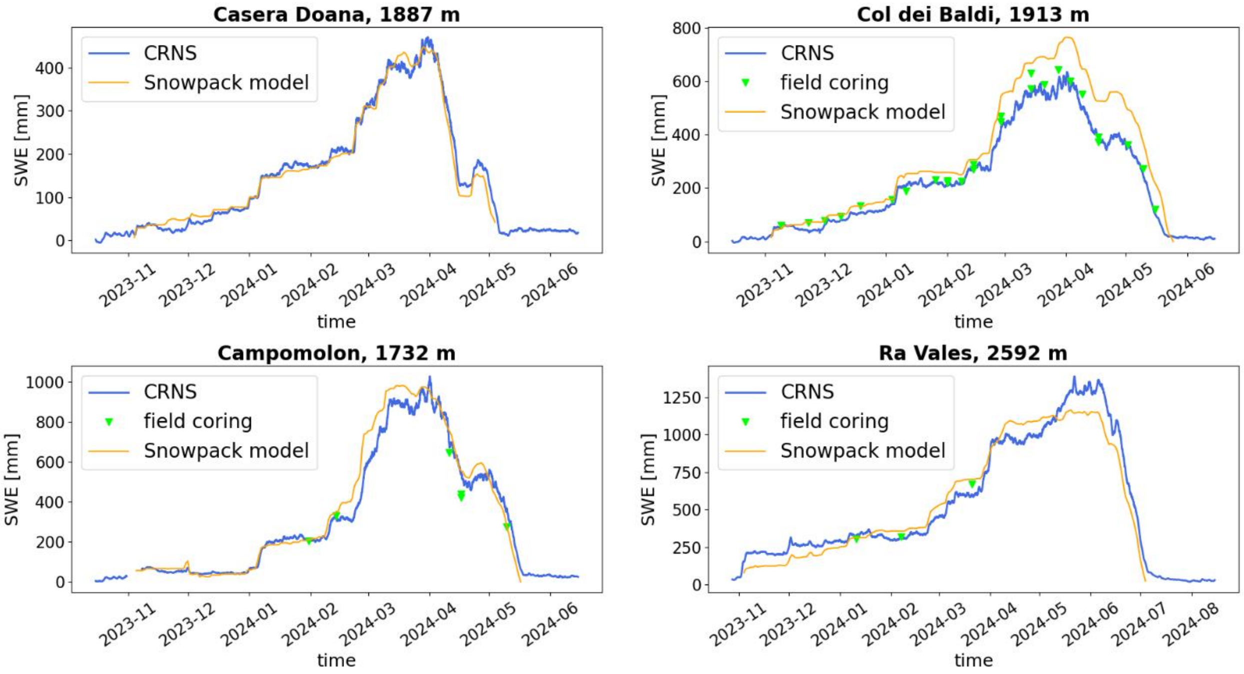

Figure 4: season SWE plots from different sites, characterized by different elevation and soil properties as listed in Table 2. SWE derived by the CRNS measurement is compared to SWE estimated by the SNOWPACK model and to field coring, where available.

Table 2: optimal set of parameters for the conversion formula

Parameter	a_1	a_2	a_3	Λ_{min}	Λ_{max}
Value	0.4	0.082	1.117	21	114

4 Conclusions

Measuring SWE by Cosmic Rays Neutron Sensing is an established approach with a long history, but its widespread application has been limited by technological hindrances. Recent technological improvements brought to the market innovative detectors that overcome those limitations and provide systems suitable for a large-scale deployment in remote locations. This work presented the results of the first season of activity of the new full network of CRNS systems for real-time monitoring of SWE in the mountains of Veneto, Italy. The sensors were easily integrated into pre-existing meteo-nivological stations and supplied off-grid by solar panels with buffer batteries. A universal parametrization for the conversion formula was found and good agreement was demonstrated between the SWE measured by CRNS and by direct coring, implying that the CRNS technology can successfully provide reliable continuous measurements also in remote areas, usually unreachable by personnel during the winter season.

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