HOW WELL COSMIC RAY PROBES MEASURE THE WIDE AREA SNOW WATER EQUIVALENT?

ZUHAL AKYUREK, GOKBEN DEMIR, MUSTAFA BERK DUYGU
Middle East Technical University, Civil Engineering Department, Water Resources Laboratory
06800 Ankara-Turkey

Monitoring snow parameters (snow depth, density, Snow Water Equivalent (SWE) and cover) at regional scale is essential for hydrological studies like the management of water and flood modelling generating from snowmelt. SWE is the most crucial snow parameter for the hydrological studies. Typical methods for measuring SWE include point measurements (snow tubes) and large-scale measurements (remote sensing). In this study we want to present the potential use of the cosmic-ray soil moisture probe (CRP) to measure average daily SWE at a spatial scale between those provided by snow tubes and remote sensing. The CRP measures above-ground moderated neutron intensity within a radius of approximately 300 m. A CRS200B soil moisture probe is installed at 1459 m in November 2016 to monitor the soil moisture at the field scale in a test basin in Turkey. There is a path eddy covariance system with energy balance sensors installed at 100 m north to the cosmic ray probe and daily snow depth has been measured at this location for the water year 2017. The snow depth values were converted to SWE values by using the snow density values. The raw moderated neutron intensity counts were corrected for atmospheric pressure, water vapour, and temporal variability of incoming cosmic-ray flux. The SWE values were negatively correlated with the CRP-measured moderated neutron intensity, giving Pearson correlation coefficients of ~0.92 (2016/2017). A linear regression performed on the calculated SWE values from measured snow depths and moderated neutron intensity counts for 2016/2017 yielded an R^2 of 0.84. The use of Cosmic ray sensor probe in monitoring wide area snow water equivalent is discussed and further planned studies are presented under the umbrella of establishing harmonized monitoring practices, which is one of the aims of HARMOSNOW Cost action.

Keywords: SWE, Cosmic ray probe, CRS200B

INTRODUCTION

Snow cover which is an essential climate variable directly affects the Earth energy balance. It has a number of important physical properties that exert an influence on global and regional energy, water and carbon cycles. Snow accumulation and melting play an essential role within the hydrological cycle and their fluctuations can have a major impact on human activities and the environment. It is well known that landscape-scale snow water equivalent (SWE) measurements are important for applications such as hydrological modelling, flood prediction, water resource management, and agricultural production (Goodison et al., 1987).

Snow information can be extracted from in-situ point measurements or air-borne/space-borne remote sensing observations. Most in-situ snow measurements are still performed using traditional laborious standardized techniques: sampling with snow tubes, digging snow pits and measuring manually the density, temperature, hardness, and other quantities. While these techniques are very robust and straightforward, they are very expensive for larger areas or time spans, prone to human errors and biases, and do not provide all requested quantities or provide only qualitative information of snow parameters. Common techniques for measuring SWE include snow tubes (gravimetric method), snow pillows, and remote sensing (Pomeroy and Gray, 1995). Snow tube sampling is the most common field survey method for determining SWE. Snow surveys with snow tubes are labour intensive, can be difficult to perform in remote locations, and are prone to over- and underestimation of SWE, depending on snowpack conditions (Goodison, 1978). Figure 1 shows one of the measurements performed in the first field campaign of COST action ES1404 HARMOSNOW. One of the aims of this action is to standardize the snow measurement techniques. Snow measurements in remote locations can be provided by snow pillows, but they produce merely a point measurement of roughly 3.5 to 11.5m^2 (Goodison et al., 1981). Measuring shallow snowpacks with snowpillows is still not so accurate due to snow removal by wind transport and melting (Archer and Stewart, 1995). Remote sensing has the capability of measuring SWE at large scales based on the attenuation of microwave radiation emitted from Earth’s surface by overlying dry snow (Dietz et al., 2012). The applicability of remote sensing techniques for SWE monitoring is limited by their coarse measurement resolutions (625 km2), their limitations to accurately measure wet snow, and their shortcomings in measuring forested landscapes. Large-scale (25 km resolution) remotely sensed SWE measurements using microwave radiation for the GlobSnow project (Luojus et al., 2010; Dietz et al., 2012) had RMSE values ranging from 24 to 77mm when compared to snow courses.

Figure 1. Snow depth and SWE measurement from the first field campaign of COST ES1404

The cosmic-ray soil moisture probe (CRP) is a relatively new instrument that was primarily developed for measuring average volumetric soil water content at the landscape scale (Zreda et al., 2008) but also has the potential to be a useful tool for measuring SWE (Desilets et al., 2010). The CRP measures neutrons in the fast to epithermal range, which are emitted from soil and inversely related to soil water content due to the neutron moderating characteristic of hydrogen (H). The CRP is an appealing soil water content measurement tool. The instrument provides landscape-scale measurement area with a radius originally thought to be _300m (Desilets and Zreda, 2013) but recently estimated to be _200m (Köhli et al., 2015). This property can be considered as the main item among its advantages. Secondly, it measures soil water content passively (non-radioactive) and non-invasively (CRP sits above the soil surface). Thirdly, the CRP can be deployed easily in remote areas. Lastly, it provides a continuous measurement of average soil water content, often with a temporal resolution of 1 h. The CRP measurement is based on the moderation of neutrons by hydrogen in water; therefore it is also capable of measuring neutrons moderated by hydrogen in snow, i.e. frozen water. The possibility of measuring SWE from the moderation of neutrons by snow has been known since the late 1970s (Kodama et al., 1979). Kodama et al. (1979) used a cosmic-ray moderated neutron sensor buried beneath the snow to measure SWE. Although their results showed a promising relationship between moderated neutron counts and SWE, the fact that this measuring technique resulted in merely a point measurement. Others have successfully used cosmic-ray probes buried under snowpacks to measure SWE, including a network of buried probes in France and the Pyrenees of Spain (Paquet et al., 2008). Desilets et al. (2010) compared SWE values measured with a CRP installed above ground to that of SWE values measured manually with a snow tube at the Mt Lemmon Cosmic Ray Laboratory, Arizona. Using a CRP to monitor SWE was also tested at the Marshall Field Site, Colorado, USA (Rasmussen et al., 2012). Again, limited details were given on the methods of the study and the empirical relationship used to predict SWE from moderated neutron intensity. Additionally, Rivera Villarreyes et al. (2011) observed the possibility to measure snow with neutron counts from a CRP (model CRS-1000) but only explored the relationship between neutron counting rates and snow cover instead of SWE. Sigouin and Si (2016) developed an empirical relationship to predict SWE from CRP data obtained from a field site in Canada. They used data from 2013/2014 and 2014/2015 winter field seasons.

In this study, it is aimed to present the use of CRP in monitoring the SWE in a footprint of 28 ha area. The relation between the neutron counts and SWE obtained from snow depths is presented.

MATERIALS AND METHODS

Study Area and CRS200B probe

A CRS200B soil moisture probe (Hydroinnova, NM, USA) is installed at 1459 m in a basin which is located in the south part of Turkey. The basin has 526 km^2 area and the elevation varies from 963 m to 3450 m. The median elevation of the basin is 1600 m. The basin's complex karstic geological formation and variable meteorological parameters make the characterization of the hydrological processes challenging. The main aim of installing the CRS200B was to monitor the soil moisture continuously. The setup for the CRP is shown in Figure 2. According to the soil surveys, the texture of the site is silt loam. The field is mostly free from trees and vegetation except for a small cluster at its middle. Polyethylene shielded CRPs are designed to monitor neutron intensity in the range between epithermal to fast. The probes are filled with BF3 gas which is directly connected to a neutron pulse detector module which is also linked to a data logger. Besides neutrons, the system is also capable of measuring barometric pressure, temperature, relative humidity. Within 100 m distance to the probe there is a path eddy covariance system with energy balance sensors and TDR soil moisture probe buried at 5 cm depth to be used in calibration studies. The required power for the system is provided by solar panels. The system provides data each hour to a remote database via satellite telemetry in real-time.

This basin, Cakit, is operated as a test basin to monitor and understand the hydrological processes with the help of several instruments deployed in the basin. CRP is installed to monitor the soil moisture and understand the change in soil moisture in time.

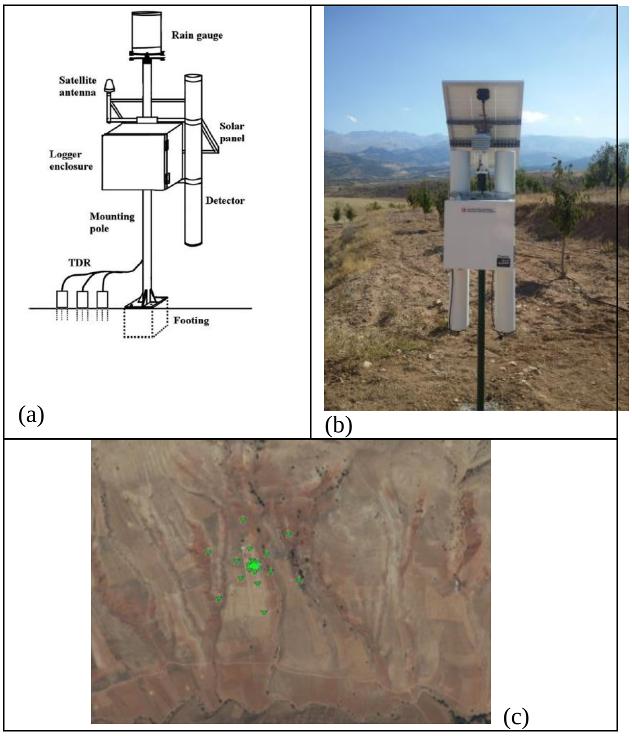

Figure 2. a) Schematic CRP Setup (Hawdon, et al., 2013) b) A sensor installed at the basin c) Locations of the probe and the soils sampled in the footprint of the probe.

Correction of Neurton Counts

In order to measure soil moisture using cosmic ray neutrons, CRPs are being extensively used in many different locations of the world. However, in order to infer the soil moisture amount using CRPs, variations due to environmental factors have to be considered. These factors include atmospheric pressure, atmospheric water vapor and intensity of the incoming neutron flux. Corrected neutron flux is calculated using Eq.1 (Hawdon, et al., 2013).

$$N = N_{raw}\left(\frac{f_P f_{wv}}{f_i}\right) \qquad \text{(Eq. 1)}$$

where;
N: Corrected neutron flux
Nraw: Uncorrected neutron count from the CRP
fp: Correction factor for Atmospheric Pressure Variation
fwv: Correction factor for changes in atmospheric water vapor
fi: Correction factor for incoming neutron intensity

Correction for Atmospheric Pressure Variation:
Neutron flux is measured by CRPs for elevation and air pressure above the sensor. For this reason, neutron counts are corrected for a reference pressure condition. Correction factor for Atmospheric Pressure Variation is calculated using Eq.2.

(Desilets, et al., 2006)

$$f_P = \exp\left[\beta(P - P_{ref})\right] \quad \text{(Eq. 2)}$$

where;

P:Atmospheric pressure (mb)

Pref:Reference atmospheric pressure (mb) (atmospheric pressure at sea level (1013.25 hPa) is generally used.)

β:Atmospheric attenuation coefficient (cm2 g-1 or mb-1)

Correction for Atmospheric Water Vapor Variation:

Atmospheric water vapor also moderates neutrons which will eventually influence the neutron counts. Correction factor for Atmospheric Water Vapor Variation is calculated using Eq.3 (Rosolem, et al., 2013).

$$f_{wv} = 1 + 0.0054\left(\rho_{v0} - \rho_{v0}^{ref}\right) \quad \text{(Eq. 3)}$$

where;

ρ_{vo}^{ref} :Reference absolute humidity (g m-3)

ρ_{vo} :Near-surface absolute humidity (g m-3)

Correction for Incoming Neutron Flux Intensity:

The intensity of incoming primary cosmic ray particles affects the flux of neutrons that reach the Earth's surface. There are neutron monitors measuring the flux of high-energy secondary neutrons around the globe (Simpson, 2000). Flux of high-energy secondary neutrons is not influenced by water availability, thus it is possible to use these measurements to correct CRP data. In order to account for variations in incoming neutron flux, an intensity correction factor should be calculated by normalizing the source intensity to a fixed point in time (Zreda, et al., 2012). Correction factor for Incoming Neutron Flux Intensity is calculated using Eq.4.

$$f_i = \frac{I_m}{I_{ref}} \quad \text{(Eq. 4)}$$

where;

I_m:Selected neutron monitor counting rate at any particular point in time

I_{ref}:Reference counting rate for the same neutron monitor from an arbitrary fixed point in time.

RESULTS

Neutron counts have been obtained at hourly intervals. Correction of neutron counts were made considering atmospheric pressure (Eq.2), atmospheric water vapor variation (Eq.3) and incoming solar intensity (Eq.4). Correcting neutron counts were made by taking the incoming neutron intensity of NMDB monitor at Athens as the reference because this station has the closest cutoff rigidity (~8 GV) to the CRP station located at Cakit basin.

The basin had plenty of snow in 2016/2017 winter season. From the meteorological station close to the CRP sensor, the precipitation in terms of snow is obtained (Fıgure 3). Snow started on 14 December 2016 and stayed on the ground till 18.March.2017. The maximum snow depth was observed on 31 December 2016 as 103 cm. The soil moisture was ~25% before the snow started, after the start of snow the corrected neutron counts were not used for soil moisture estimation. Snow depths measured at the meteorological station were used to compare to the snow depth data and CRP data (Figure 3). Snow depths were converted to SWE values by using the snow densities (0.25 for dry snow and 0.3 for wet snow).

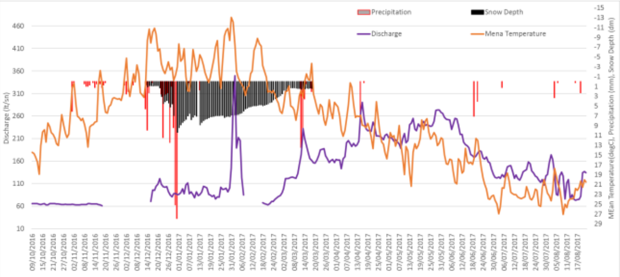

Figure 3. Precipitation, snow depth, temperature values measured at the nearby meteorological station. Discharge values measured at the outlet of the basin.

In the winter (at the end of December), the moderated neutron intensity decreased quite drastically in response to the first snow event of the season. These results are consistent with Desilets et al. (2010) and Sigouin and Si (2016) (Figure 4). The missing data is due to the snow storm affecting data transfer via telemetry. The snow events on 31/12/2016, 12/01/2017 and 25/01/2017 were captured by the CRP.

Figure 4. Moderated neutron intensity

Snow depth values observed at meteorological station were converted to SWE values. In general, moderated neutron intensity shows an expected negative relationship with SWE, resulting in decreased moderated neutron intensity and increased mean SWE. A relatively strong negative correlation between mean SWE and the moderated neutron intensity can be seen from the Pearson's correlation coefficients ~0.92 for 2016/2017 (Figure 5). The correlation shows there is potential for predicting SWE from moderated neutron intensity measured above the snowpack.

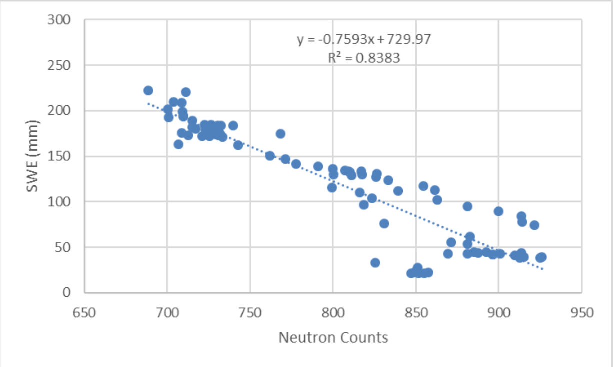

Figure 5. SWE and Neutron counts relationship

The CRP-estimated SWE from moderated neutron intensity measurements are shown in Figure 6. The regression equation was used to estimate SWE based on the moderated neutron intensity in the form of

$$SWE_{CRP} = -0.7593(N_{COR}) + 729.97 \quad \text{(Eq. 5)}$$

where SWE_{CRP} is in mm and N_{COR} is the corrected moderated neutron intensity. The values lower than 50 cm snow depth show clustering in the relationship, which is needed to be studied in detail.

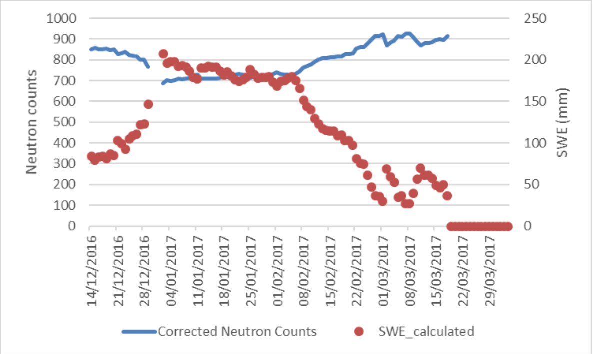

Figure 6. Corrected neutron counts and predicted SWE values

Methodology of calibration of the volumetric soil moisture is presented in the guide by Franz T. (2012). For the SWE calibration a similar approach must be followed. With an assumed footprint of 300 m, snow samples along 25, 75, and 200m radials around the CRP are included in Sigoin and Si (2016). They presented a linear regression equation for the calibration of CRP data. A detailed snow depth and SWE measurements within the footprint of CRP could lead more accurate calibration. In the coming winter season, a detailed snow depth, SWE measurements will be obtained to consider the spatial variation of snow depth, SWE in the calibration.

The CRP measurement is also influenced by the soil water storage in the top of the soil profile beneath the snowpack being measured. It is stated by Niu and Yang (2006) and Sigouin and Si (2016) that CRPs may overestimate SWE by measuring water in soil just below the snow cover. However, the overestimation may be advantageous in some cases because soil water in the surface soil is largely similar to SWE and controls snowmelt infiltration and surface runoff.

CONCLUSION

A simple empirical equation for estimating SWE with the use of a cosmic-ray soil moisture probe was presented. It was found that the relationship between above-ground moderated neutron intensity and SWE estimates based on snow depth meeasurements was well represented by a negative linear function.

There are several advantages associated with measuring SWE using a CRP. The measurement footprint of the CRP (_300m radius) is appealing since it provides a measurement scale between that of the point scale (snow tubes, snow pillows) and large scale (remote sensing). The CRP can be installed in remote locations where consistent snow surveys are not possible. The CRP can provide a continuous estimate of SWE throughout the winter season. CRP SWE estimates can fill the gap of medium scale SWE monitoring.

Acknowledgement

This study is financially funded by TUBITAK (TUBITAK115Y041).

LITERATURE

Archer, D. and Stewart, D.: The installation and use of a snow pillow to monitor snow water equivalent,Water Environ. J., 9, 221–230, 1995.

Desilets, D. and Zreda, M.: Footprint diameter for a cosmic-ray soil moisture probe: Theory and Monte Carlo simulations,Water Resour.Res., 49, 3566–3575, 2013.

Desilets, D., Zreda, M., and Ferré, T. P. A.: Nature's neutron probe:Land surface hydrology at an elusive scale with cosmic rays,Water Resour. Res., 46, 1–7, 2010.

Desilets, D., Zreda, M. & Prabu, T., 2006. Extended scaling factors for in situ cosmogenic nuclides: new measurements at low latitude. Earth Planet. Sci. Lett., Volume 246, p. 265–276.

Dietz, A. J., Kuenzer, C., Gessner, U., and Dech, S.: Remote sensing of snow – a review of available methods, Int. J. Remote Sens., 33,4094–4134, 2012.

Franz, T. E., Zreda, M., Rosolem, R., and Ferre, T. P. A.: Field Validation of a Cosmic-Ray Neutron Sensor Using a Distributed Sensor Network, Vadose J., 11, 1–10, 2012.

Goodison, B. E.: Accuracy of snow samplers for measuring shallow snowpacks: an update, Proc. 35th Annu. Meet. East. Snow Conf.,Hanover, New Hampshire, USA, 36–49, 1978.

Goodison, B. E., Ferguson, H. L., and McKay, G. A.: Measurement and data analysis, edited by: D. M. Gray and D. H. Male, Handbook of Snow: Principles, Processes, Management and Use. Pergamon Press, Toronto, Canada, 191–274, 1981.

Goodison, B. E., Glynn, J. E., Harvey, K. D., and Slater, J. E.: Snow Surveying in Canada: A Perspective, Can. Water Resour. J., 12, 27–42, 1987.

Hawdon, A., McJannet, D. & Wallace, J., 2013. Calibration and correction procedures for cosmic-ray neutron soil moisture probes located across Australia. Water Resources Research, Volume 50, p. 5029–5043.

Kodama, M., Nakai, K., Kawasaki, S., and Wada, M.: An application of cosmic-ray neutron measurements to the determination of the snow-water equivalent, J. Hydrol., 41, 85–92, 1979.

Köhli, M., Schron, M., Zreda, M., Schmidt, U., Dietrich, P., and Zacharias, S.: Footprint characteristics revised for field-scale soil moisture monitoring with cosmic-ray neutrons, J. Hydrol., 6, 1– 19, 2015.

Luojus, K., Pulliainen, J., Takala, M., Derksen, C., Rott, H., Nagler, T., Solberg, R., Wiesmann, A., Metsamaki, S., Malnes, E., and Bojkov, B.: Investigating the feasibility of the globsnow snow water equivalent data for climate research purposes, Geosci. Remote Sens. Symp. (IGARSS), 2010 IEEE Int., 19, 4851–4853, 2010.

Niu, G.-Y. and Yang, Z.-L.: Effects of frozen soil on snowmelt runoff and soil water storage at a continental scale, J. Hydrometeorol., 7, 937–953, 2006.

Paquet, E., Laval, M., Basalaev, L. M., Belov, A., Eroshenko, E., Kartyshov, V., Struminsky, A., and Yanke, V.: An application of cosmic-ray neutron measurements to the determination of the snow-water equivalent, Proc. 30th Int. Cosm. Ray Conf., 1, 761– 764, 2008.

Pomeroy, J. W. and Gray, D. M.: Snowcover: Accumulation, relocation and management, NHRI Science Report No. 7, 1995.

Rasmussen, R., Baker, B., Kochendorfer, J., Meyers, T., Landolt, S.,Fischer, A. P., Black, J., Thériault, J. M., Kucera, P., Gochis, D.,Smith, C., Nitu, R., Hall, M., Ikeda, K., and Gutmann, E.: How Well Are We Measuring Snow: The NOAA/FAA/NCAR Winter Precipitation Test Bed, Bull. Am. Meteorol. Soc., 93, 811–829,2012.

Rivera Villarreyes, C. A., Baroni, G., and Oswald, S. E.: Integral quantification of seasonal soil moisture changes in farmland by cosmic-ray neutrons, Hydrol. Earth Syst. Sci., 15, 3843–3859, doi:10.5194/hess-15-3843-2011, 2011.

Rosolem, R. et al., 2013. The effect of atmospheric water vapor on neutron count in the cosmic-ray soil moisture observing system. Journal of Hydrometeorolgy, Volume 14, p. 1659–1671.

Sigouin M.J.P. and Si, B.C., 2016. Calibration of a non-invasive cosmic-ray probe for wide area snowwater equivalent measurement. The Cryosphere, 10, 1181–1190, 2016. www.the-cryosphere.net/10/1181/2016/ doi:10.5194/tc-10-1181-2016

Simpson, J. A., 2000. The cosmic ray nucleonic component: The invention and scientific uses of the neutron monitor,. Space Science Reviews , 93(1), p. 11–32.

Zreda, M., Desilets, D., Ferré, T. P. A., and Scott, R. L.: Measuring soil moisture content non-invasively at intermediate spatial scale using cosmic-ray neutrons, Geophys. Res. Lett., 35, 1–5, 2008.

Zreda, M., Shuttleworth, W. J., Zeng, X., Zweck, C., Desilets, D.,Franz, T., and Rosolem, R.: COSMOS: the COsmic-ray Soil Moisture Observing System, Hydrol. Earth Syst. Sci., 16, 4079–4099, doi:10.5194/hess-16-4079-2012, 2012.