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COMMENT

Comment on 'Examining the variation of soil moisture from cosmic-ray neutron probes footprint: experimental results from a COSMOS-UK site' by Howells, O.D., Petropoulos, G.P., et al., *Environ Earth Sci* 82, 41 (2023)

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Introduction

The published article by Howells et al. (2023) attempts to empirically derive the lateral footprint for a single cosmic-ray neutron sensor (CRNS), which is part of the COSMOS-UK network (Evans et al. 2016). The main result is the "*true*" footprint to be 50 m in radius, substantially smaller than previously published estimates. Their conclusion contradicts more than 15 peer-reviewed studies and more than a decade of research on the subject conducted by various international research groups, and thus, it would be considered as a ground-breaking finding if the methods were scientifically sound. However, the methods and arguments presented by the authors have major errors and the presented conclusions are consequently wrong.

Major methodological errors

It is impossible to empirically falsify a radius larger than 60 m using data from a radius smaller than 60 m

The article essentially presents a data set of near-surface point-scale volumetric soil water content (VWC) measurements obtained during 3 h on a single day (2017-07-26). The measurements were taken using a mobile Time-Domain Reflectometry (TDR) sensor over 0–12 cm depth below ground level within a distance of just up to 60 m from the CRNS (p. 3 of 8, first paragraph below Fig. 2 and p. 5 of 8, first paragraph of results section and page 6 of 8, last full paragraph). From this experimental design, it is not possible to draw any relevant conclusion on the CRNS footprint volume, hitherto considered as 0–70 cm in depth, and 0–300

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m in radius as several studies have shown so far (Zreda et al. 2012; Köhli et al. 2015; Schrön et al. 2017).

The variance of soil moisture values within the instrumental measurement footprint, be it big or small, carries no information on the size of the footprint itself

Their main result (that the CRNS footprint is 50 m, page 5 of 8, last sentence) is derived by an arbitrary and unrealistic argument, that *"the true footprint of the COSMOS-UK probe should be relatively uniform"*, and that the *"key statistic here was the standard deviation"* (page 5 of 8, second, i.e., last paragraph of the result section). In fact, the uniformity of spatial soil moisture patterns (and the standard deviation of its measurements) is a characteristic of many different factors (e.g., soil, vegetation, relief) but clearly independent of the existence of a nearby CRNS probe. Moreover, it is standard knowledge that the variation in a set of soil moisture measurements increases with increasing measurement extent (typically obtained with variograms). Hence, the authors simply found typical soil characteristics rather than evidence for the CRNS footprint extent.

In the subsequent analysis, the authors do not consistently follow their own criterion to derive the main result. They define the CRNS footprint as the area with a radial distance for which the standard deviation of soil moisture is lower than observed at the 60 m distance. Here, provided numbers in the text and in Table 2 are inconsistent. The authors find the *"true"* footprint to be a radius of 50 m, despite the fact that their criterion is also valid for all the other smaller radial distances, with the smallest value actually at r = 10 m (page 5 of 8, Tab. 2).

Other methodological errors

Incorrect description of the measurement principle

The authors confuse CRNS with an active, downhole neutron probe, and describe this as the geophysical principle behind CRNS (see page 3 of 8, first paragraph below Fig. 1). Though similar in name, CRNS uses completely different neutron energies, has a completely different response to soil moisture, and has a larger footprint by three orders of magnitude. Considering this obvious lack in knowledge about the measurement principle makes the whole article appear more than questionable in its findings.

Questionable calibration method and data

There is only a single soil water content value derived from CRNS (37.07% VWC at the day of the sampling campaign (2017-07-26), page 5 of 8, second paragraph of results section). Though it is clear that the authors have not operated the CRNS themselves, the manuscript lacks a presentation of how they obtained this value, and neither is there a reference given to the real source. We can speculate that the source was likely the COSMOS-UK website. No key information is given by the authors about this obtained value, about the time, integration period used, standard corrections made and depth of penetration assumed. In the preparation of this comment and in contrast to what the authors claimed in their paper, data on the COSMOS-UK website showed 31% VWC for CRNS and light rain (~4 mm) conditions for this day (CEH 2023, https://cosmos.ceh.ac.uk/sites/RISEH; accessed 2023-01-27). This, together with wrong statements such as "*especially when considering the COSMOS-UK neutron probe product as immediate readings*" (p. 6 of 8, second last paragraph) make the use of this value questionable. In addition, it appears that this single CRNS-related measurement is not even used in the analysis of the study.

Finally, the TDR-derived volumetric water contents on the day of the study (57.96% VWC, Table 2) are about 55% higher than the authors' stated CRNS reading (37.07% VWC), casting further doubts on the validity of measurements. Indeed, COSMOS-UK soil sampling data for the Riseholme site, collected from 18 locations in 5 cm depth increments over 0–25 cm below ground level as part of the CRNS calibration process, indicate an average soil dry bulk density of 1.13 g/cm^3 over the 0–12 cm depth corresponding to the given mobile TDR probe prong length. Assuming a typical soil particle density of 2.65 g/cm^3 (e.g., Blake 2008), a reasonable estimate of the soil porosity would be 0.57 cm^3/cm^3. Therefore, the TDR survey purports to show that the soil was at or near saturation on 26 July 2017, which would seem rather questionable for the time of year in the UK.

In addition, the COSMOS-UK instrumentation includes an array of paired TDT probes at 5, 10, 15, 25 and 50 cm below ground level and on the survey date the 10 cm probes indicate ~ 28–33% soil moisture content, including a modest increase due to the light rainfall event (CEH, https://cosmos.ceh.ac.uk/sites/RISEH; accessed 2023-02-06). This, therefore, casts further doubt on the validity of the authors' TDR survey data.

Inconsistencies and overstatements

The article contains several ambiguities and inconsistencies that call for questioning the quality of the research presented and we just list a few here as examples:

The authors describe the data set with "*an extensive field campaign [that] took place in July 2017*" (page 7 of 8) and a "*spatiotemporal*" analysis of CRNS ("*The evaluation was* *performed by comparing the spatiotemporal variability of the derived maps between the COSMOS-UK footprint and the interpolated maps produced by truth data of the TDT soil moisture sensors.*", p. 4 of 8, last paragraph), while the data are clearly insufficient in space and time to address their research question.

It is unclear what kind of device the authors have used to obtain the VWC values during the field campaign. A Time-Domain Reflectometry sensor (TDR) is stated in the "Datasets and methods" section (e.g. p. 3 of 8, paragraph below Fig. 2), a Time-Domain Transmission sensor (TDT) is specified throughout the abstract. A specific device or brand is not named in either case and no mention is made of whether a generic or soil-specific calibration function was employed. The technical description of the measurement principle, furthermore, is incorrect (*"The TDR's work by passing a current from one probe to another"*). No mention is made of whether the ~ 4 mm of rainfall on the day of the survey affected, or occurred during, the TDR survey. This poses questions about how prepared the authors were in deploying and analyzing the observed data from such measurement devices.

The authors highlight the use of UAV imagery and DEM models in the abstract ("*The results were also compared with the drone orthomosaic and DEM products*", p. 4 of 8, last paragraph) and a range of "*Statistical parameters [were] used to evaluate the agreement between the COSMOS data and the TDR in-situ observations*" (Table 1), while none are used in the analysis and results actually presented.

Misleading use of references and disregarding the state-of-the-art

The authors motivate their study with the wrong statement: "*Yet, to our knowledge, very few studies so far have been concerned with an examination of the COSMOS neutron probe extent and the determination of the factors that affect the measurement footprint representativeness*". The CRNS used in the COSMOS-UK network are not a unique type of sensor but a common technology applied in nationwide networks, and numerous CRNS worldwide follow a comparable setup (Zreda et al. 2012; Hawdon et al. 2014; Peterson et al. 2016; Evans et al. 2016; Andreasen et al. 2017; Nguyen et al. 2019; Vather et al. 2020; Barbosa et al. 2021; Bogena et al. 2022). Unlike incorrectly stated by the authors, there are, in fact, a large number of studies that have been concerned specifically with understanding the footprint extent for different soil water contents (Franz et al. 2012; Köhli et al. 2015; Schrön et al. 2017), different surroundings for CRNS measurements, such as forest, snow and urban environments (Baatz et al. 2015; Heidbüchel et al. 2016; Schattan et al. 2017; Schrön et al. 2018), moderated vs. bare counter signal and footprint (Jakobi et al. 2021; Rasche et al. 2021), neutron transport simulations on the footprint (Franz et al. 2013; Schattan et al. 2019; Li et al. 2019; Köhli et al. 2021) or calibration measurements in the footprint for different conditions (e.g. Bogena et al. 2013; Hawdon et al. 2014).

One of the few works on CRNS cited at all is Zreda et al. (2012). However, the authors wrongly interpret their results, claiming "*that 80% of the free neutrons that a cosmos probe detects come from the first 50 m*", which is not supported by the citation (page 4 of 8, first paragraph, last sentence). In addition, the description of the footprint characteristics is in contradiction to the literature citations given ("*The measurement footprint of a sensor does not depend on soil moisture content*"—while it certainly does) and mathematically and physically incorrect ("*(…) but it is inversely proportional to the atmospheric pressure*"—while it is exponential, ref. page 2 of 8, third paragraph of the introduction).

Köhli et al. (2015) is cited while speculating about hedges that surround the grassland field site in a distance > 100 m, justifying them as "*geophysical barrier*" that limits the CRNS footprint to the field. However, this reference does not support this assumption (p. 6 of 8, first paragraph of discussion section). To the contrary, the reference suggests that this amount of biomass might have a negligible influence.

Conclusions

While some methodological errors and inconsistencies could be addressed in a subsequent correction of the study, the two major errors (Sect. "It is impossible to empirically falsify a radius larger than 60 m using data from a radius smaller than 60 m") and (Sect. "The variance of soil moisture values within the instrumental measurement footprint, be it big or small, carries no information on the size of the footprint itself") render the research and data questionable and invalid. Therefore, we must reject the article by Howells et al. (2023) in the most decisive way as a consequence of fundamental errors, unsupported claims, and questionable results.

Under no circumstances can the conclusions of the study and its recommendations be considered valid, which are for instance:

- "*The presented herein methodological approach can easily be implemented in other similar sites as it does not require any highly sophisticated device and software making it cost effective.*" (page 6 and 7 of 8)

- “*All in all, the methodological approach, proposed by this study, examining the COSMOS footprint is simple, robust, and highly accurate with its assets like its high transferability overpassing its limitation.*" (page 7 of 8).

With our severe scientific concerns raised, we hope that this comment could contribute to restoring the scientific quality standards after the passed peer-review of this article.

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Data availability Not applicable.

Declarations

Conflict of interest Darin Desilets is member of Hydroinnova LLC, USA. Markus Köhli holds a CEO position at StyX Neutronica GmbH, Germany.

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