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Response to the Reviewers

Reviewer comments are presented in italics, while the authors' responses are in blue.

1 Referee Comments and Responses

Anonymous Referee 2:

The paper describes the simulation neutron count rates using a gridded hydrological model, which estimates soil water content in different depth layers. The simulated counts are compared with CRNS neutron counts to optimise the model (mHM) calibration. This approach addresses the issue of the variable measurement depth of CRNS. In simulating neutron counts, published models are used such as COSMIC, or the CRNS neutron count to soil moisture calibration function is inverted. However, these relationships are further fitted through optimisation of the N_0 parameter, and different published schemes for vertical soil moisture content weighting are tested. Other mHM parameters are also optimised, but how this is done and in what order, is not explicitly described. Which parameters are optimised is only shown in the supplementary information, and the results and discussion do not cover these parameters.

Firstly, we want to sincerely thank the reviewer for dedicating their time and expertise to review our work. Your insightful comments have significantly improved our manuscript. We will provide a comprehensive response to address your comments and suggestions.

[Line 52:] by this point or earlier you should say why there could be an issue with depth averaging.

Several studies investigated depth-weighting schemes and hydrogen pools' effects on measurement depth. Franz et al. (2012) showed that shallow wetting fronts impact measurement depth in sandy soils with non-uniform moisture profiles. Baroni and Oswald (2015) tested three different depth weighting techniques (vertically varying weights, uniform weights, and taking the effect of above-ground biomass into account), which yielded different measurement depths varying from 23 to 28 cm. Using vertically varying weights and taking into account other hydrogen pools gave the best measurement depth estimates.

[Line 70:] delete 'eventually'

This is also noted by reviewer 1 (comment number 11), we will make the suggested change in the manuscript.

[Line 75:] still no intro as to the motivation to do this - rather than use the derived SM!

We appreciate the reviewer feedback. The primary methodological focus is on inverting soil hydraulic parameterization in mHM/COSMIC by directly comparing modelled neutron counts with measured ones. To obtain soil moisture accurately from CRNS measurements, one needs prior knowledge of the soil moisture profile. However, CRNS typically lacks this information, which mHM can provide. We will improve the introduction to make sure readers understand the primary motivation of our study more clearly.

[Line 86:] still not clear what is the objective of this study?

The objective of this study is to establish a framework to incorporate CRNS data into the mesoscale Hydrological Model (mHM) by comparing empirical and physics-based approaches for neutron count estimation to improve soil water content parameters in mHM across different vegetation types in Germany. To do this we compared modelled with neutron counts to infer soil hydraulic parameters. We will clarify this main goal in the manuscript to help readers better understand.

[Line 89:] If the objective is a technical comparison of methods, then why do this at grid scale, not a point scale, actually at the CRNS station? This may have complicating factors e.g. mixed land cover, soils, and topography modelled across a grid cell.

Using soil moisture (SM) directly simplifies the process but may not account for CRNS depth variability under different soil wetness conditions. The COSMIC approach, being more physics-based, allows for depth integration and the non-uniform contribution of signals with depth. CRNS measurement is based on a spatial footprint of around 150 m together with a vertical penetration depth of typically up to $\sim$ 15-80 cm depth. Sub-grid heterogeneity in mHM is captured explicitly within its multiscale parameter regionalization (MPR) technique (Samaniego et al., 2010). We simulated the neutron counts in mHM at the location where the CRNS instrument is installed to measure neutron counts. We used the extracted input data in mHM specific to the CRNS location, including temperature and precipitation from the German Weather Service (DWD), along with other data sources discussed in the data availability section.

[Line 99:] there seems to be an implicit assumption that working with simulated counts is better than using CRNS derived SM - did you test this?

No, we have not performed the test. But the reason for this preference is that mHM provides soil moisture data at different layers, whereas CRNS derived SM values represent an integrated value and we do not know uniquely which simulated layered soil moisture corresponds to the CRNS derived SM value, which even depends on the vertical SM distribution. However, also COSMIC is based on some assumptions and internal parameters, and thus may be more straighforward, but not necessarily more accurate.

[Line 102-3:] does this mean different land cover in grid or between grid cells?

We address land cover variations within each individual grid cell. In our study, the mHM model utilizes a fixed grid cell size of 0.015625°(approximately 1.2 km^2), with one grid cell assigned to represent each individual site.

[Line 108:] homogeneous at the CRNS hectare scale, but not at 1 km scale! - see photo of Grosses Burch. Please be more specific – and how might in-grid heterogeneity affect optimisation?

In the mHM model, the sub/in-grid heterogeneity is explicitly captured with its multiscale parameter regionalization (MPR) technique (Samaniego et al., 2010).

[Line 115:] Are these seasonal biomass fluctuations included in the CRNS count simulation?

No, this is not feasible as data of biomass changes were not available. However, Boeing et al. 2022 indicated that the saisonal changes of biomass are rather irrelevant, even in Hohes Holz, as soil moisture changes are the much larger source of variation represented by the CRNS measurements.

[Line 159-160:] 'the sensitivity to the highest…' re-phrase, this is not clear.

We will revise the sentence to make it more clear in the revised manuscript.

[Line 170:] delete 'time constant'.

We will make the suggested change in the manuscript.

[Line 183-87:] it may make sense to use grid averages for mHM, but this complicates the evaluation of the methods – how representative is the CRNS station of the wider grid properties? If the station is not representative of the grid, then inappropriate parameter changes are forced to match soil moisture or CRNS counts to soil properties that do not match the CRNS site.

Thank you for your comment, The spatial resolutions in mHM are defined at different levels:
L1 and L2: 0.01562° x 0.01562° is eq.$\sim$ 1.2 x 1.2 km^2. Level 1 (L1) describes the spatial resolution, as which dominant hydrological processes are modelled and Level 2 (L2) describes the resolution of the meteorological forcing data.
L0: 0.001953125° × 0.001953125°. Level 0 (L0) describes the sub-grid variability of relevant basin characteristics, which include information on soil, vegetation, topography and geology, among other basin relevant geophysical characteristics. These sub-grid heterogeneities are reflected to generate effective model parameters (e.g., soil porosity, field capacity, lattice water content) in mHM with the multiscale parameter regionalization (MPR) technique (Samaniego et al.,2010).

CRNS data was preferred over any other ground-based measurements i.e., point-scale (TDR, FDR) and satellite data, due to its ability to provide a horizontal footprint of around 150 m together with a vertical penetration depth of $\sim$ 15-80 cm depth. These feature make them relevant for the modelling scale, along with its higher temporal resolution that allow us to capture the fine details of soil moisture changes. We used site-specific input data and calibrated parameters to establish the mHM model at each site and by this we address the CRNS station's spatial comparability with the grid-level model simulations.

[Line 187:] How can varying N_0 properly account for biomass changes? Biomass is dynamic in time, while N_0 is constant in time?

A correction for biomass changes could by introduced in two ways, either with a separate correction factor on the measured neutrons or with a temporal dependency on the N_0 constant (Baatz et al., 2014). Mathematically, the two approaches are similar. However, due to the lack of biomass data, usually no correction is considered in this study. Vather et al. (2020) emphasizes the importance of considering changes in biomass, but especially in situations with sudden changes in biomass, such as harvest in agriculture or clearings in forestry. The study demonstrates how the difference in hydrogen content within the measurement area leads to different calibration values (N_0 values). While N_0 should ideally be constant across different study areas once all environmental hydrogen sources are considered, it can vary due to the presence of growing biomass, as observed in the study by Hawdon et al. (2014). In their research, they found that approximately 80% of N_0 variation could be attributed to the effects of biomass, but only after accounting for other hydrogen sources. So, while N_0 itself does not change with time, its variation across study areas can indirectly reflect changes in biomass levels and as such indicate missing biomass corrections. Those corrections are complicated since temporal biomass data is usually not available.

[Line 212:]change 'neutrons' to neutron flux or count rate. Eq. 9 is bulk density here the same as Eq. 1? (a different undefined symbol is used here and in Eq. 10)

Thank you for pointing out, we will make the suggested change in the revised manuscript: "neutrons" to neutron count rate. Regarding Eq. 9 and Eq. 10, the COSMIC method employs the bulk density and lattice water for each model soil depth. However, in Equation 1, the same bulk density is used for the Desilets method. To enhance clarity, we will make the change in the manuscript by replacing the ϱ_{bulk} to ϱ_{b} in the manuscript.

$$X_{\text{soil}}(z) = \Delta z \varrho_{\text{b}} \tag{9}$$

[Line 238:] These symbols are not in Eq.14 ? what are L_{30} and L_{31}?

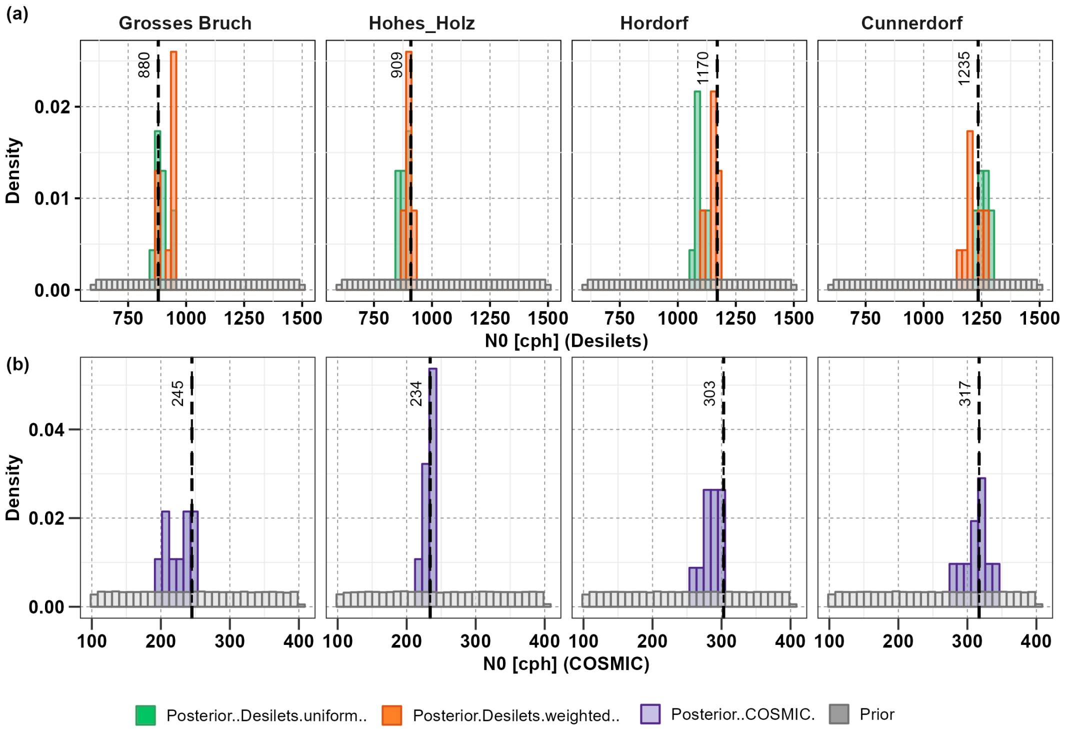
L_3 represents the fast neutron soil and water attenuation lengths, according to literature Shuttleworth et al. (2013); Rosolem et al. (2014), these values have been expressed as L_3 = -31.65 + 99.29ϱ_{b}, with the parameters correlated to soil bulk density. Where ϱ_{b} (g cm^3) is the soil bulk density. L_3 are site-specific parameters, and we integrated them into the mHM model as part of the parameters to be optimized.

[Line 257:] Table 2 shows model performance measures, not model parameters and their ranges - please add table of model parameters optimised. (it is in supplementary)

We will make the suggested change in the revised manuscript.

[Line 269:] presentation of results is confusing, as it does not show hydraulic parameters (only refers to Table S1). Plots and tables only show CRNS parameters. Fig. 4 – add units (... are these counts per hour?)

In this study, we used a total of 29 parameters for the Desilets method and 31 parameters for the COSMIC method which includes hydrologic processes related to: snow, soil moisture, and neutron counts dynamics. For clarity, we have included box plots showing the other parameters in Figure S3 in the supplementary materials. Regarding Figure 4, the unit for N_0 is counts per hour (cph), which represents the site-specific, time-invariant calibration parameter. We will include the units in the figure in the revised manuscript.



[Line 301:] This gives the impression that what has been done here is to optimise neutron count match, by varying some model parameters, especially N_0, and some root depth parameters ....there could be an issue that while counts may agree well, systematic bias in SM could be compensated for by varying N_0; i.e., better efficiency in simulating neutron counts may not necessarily lead to better efficiency in SM modelling. Section 3.2, Fig. 5 and Fig.6 should show these also as CRNS SM plots, as the non-linear counts to SM hides the magnitude of discrepancies.

Our primary goal was to optimize the agreement between modeled neutron counts and observed neutron counts from the three method i.e., Desilets method ($N_{\mathrm{Des,U}}$, $N_{\mathrm{Des,W}}$) and COSMIC method (N_{COSMIC}). A direct comparison between the model and observation is feasible only via neutron counts because CRNS soil moisture is an integrated value, while mHM represents soil moisture in different layers. By improving the modeling of neutron count measurements, we are inherently improving the representation of SM in mHM.

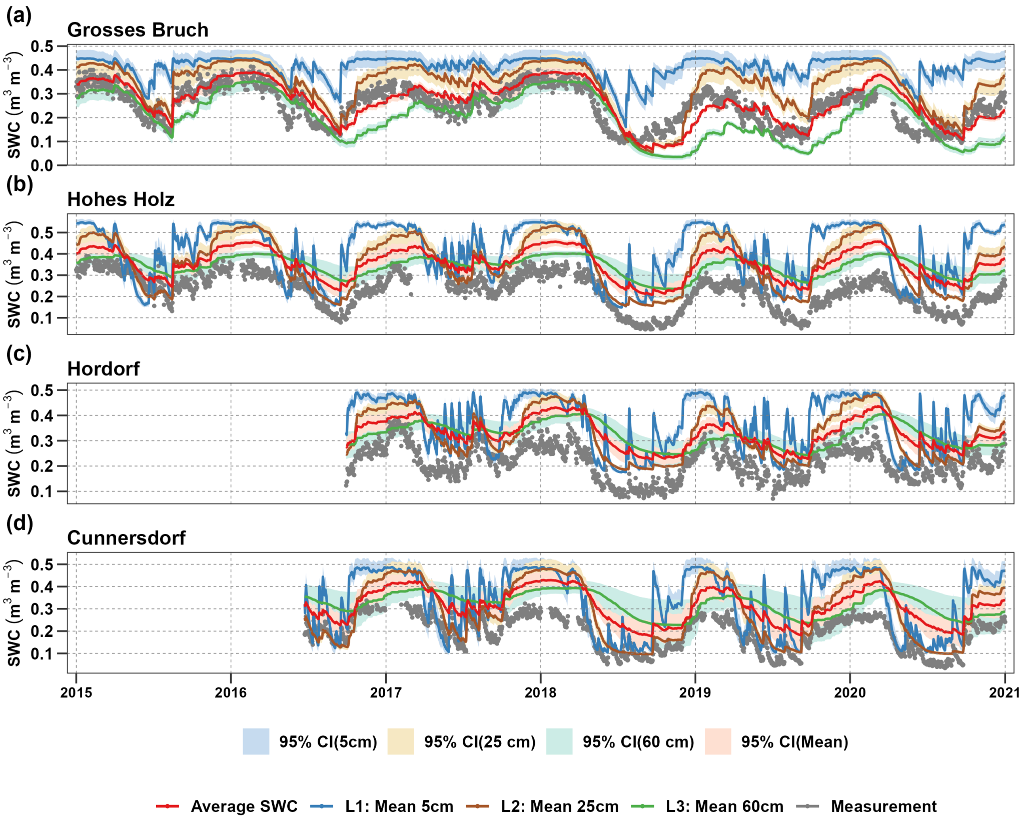


Figure 1. Observed soil water content from CRNS vs simulated data from mHM in 0–5, 5-25, and 25–60 cm depth .

[Line 410:] This study does not assess the absolute soil water quantity (most results are presented as neutron counts).

Thank you for your comment. We will revise these texts making it clear that our study does focus on capturing neutron counts and not absolute soil water content, in the revised manuscript.

[Line 412-13:] 'Incorporating CRNS data. . . ' this statement is untrue and does not makes sense. This is misleading as it implies data assimilation, whereas neutron data is not incorporated, it is simulated by mHM and then compared with observed counts.

We are sorry for this confusion. The reviewer is correct; namely, we simulate neutron data within the mHM model and subsequently compare it with observed counts, rather than incorporating observed neutron data directly. We will revise the relevant sections to accurately reflect this statement.

[Line 450:] 'After optimizing the soil hydraulic properties. . . 'This is not properly described in the method – is this done after CRNS parameters are optimised or at the same time in some form of iteration? How did you do this? Fig.9 – surely belongs in Results?

We understand that this part was not very clear in the submitted version of the manuscript; and we will make every attempt to clarify it in the revised manuscript. In brief, we have optimized the soil moisture, snow, and neutron counts related parameters simultaneously, as illustrated in the flow diagram. We will provide a clearer description in the methodology section, outlining how this simultaneous parameter optimization is achieved through iterative methods.
Regarding Fig.9, we present the result of neutron counts corresponding to optimized parameter sets.

References

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