

Interactive Discussion: Author Response to Referee #1

Spatio-temporal soil moisture retrieval at the catchment-scale using a dense network of cosmic-ray neutron sensors

Maik Heistermann et al.

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RC: Reviewer Comment, AR: Author Response, ☐ Manuscript text

Dear Referee,

we would like to thank you very much for your positive comments and constructive suggestions to our manuscript. We very much appreciate the time and effort that you have invested in your report.

Based on your report, we have already started to revise our manuscript. Please find below our detailed responses to all the points you have raised in your report. We will continue to address these points, and are confident that the manuscript will substantially improve as a consequence. Yet, the final implementation of changes will also depend on another referee report that is still to be submitted in the interactive discussion.

Kind regards,
Maik Heistermann
(on behalf of the author team)

1.1. General comments

RC: *[...] my main concerns are with the presentation quality of the paper: the length and structure of the manuscript could be substantially improved (see specific comments). Therefore, I would like to suggest major revisions.*

AR: We will restructure and shorten the manuscript according to the following suggestions of the referee (see our responses below).

1.2. Structure

RC: *While this is a discussion paper, I would encourage the authors to be more concise and structured when presenting their findings (examples are given below). There are sections which seem to be excessively long. That would hopefully help address another issue, which is the often “downplaying” of the study findings (examples also given).*

AR: We will shorten the manuscript where possible. We also appreciate the referee's concern on "downplaying" the results. We will certainly aim to remove statements that appear unnecessarily critical towards the outcomes of our own study. Yet, we consider it important to clearly and unambiguously emphasize any limitations of our

results, especially as this is the first attempt of inferring spatio-temporal representations of soil moisture from a dense CRNS network, and as we had to make a number of assumptions. We hope that the referee will agree.

RC: *Moreover, during the discussion the implications of the findings and potential benefit of the application of these novel analyses are shown/discussed but in a scattered manner throughout “Results and discussion” section. I would recommend condensing them in a subsection within “Summary and conclusions”. Below I outline specific examples:*

AR: We suggest to split the former section 6 (Summary and conclusions) to two sections: the new section 6 would be "Lessons learned", in which we highlight the main lessons with regard to homogenisation/ N_0 -estimation and the retrieval of spatial patterns from the dense network; the new section 7 would be a very brief "Conclusions" section. We think that this is also in line with what you suggested in your comment 1.7.

1.3. Presentation of aims and objectives

RC: *In Section 1.2. Aims and objectives: research questions and specific objectives of the study are presented between lines 65-95 and surely could be condensed. If you would wish to keep all the text, separate clearly in “aims and objectives” and “justification”. That would help structuring further the manuscript.*

AR: We agree that it would improve the readability if we moved the specific objectives of the study to a dedicated subsection (1.3: Specific objectives). We will also revise the specific objectives based on our response to comment 1.6. Finally, we will move the overview of the manuscript structure (ll. 96-102 of the original manuscript) to a separate subsection (1.4: Manuscript structure).

1.4. Section 4.4

RC: *Section 4.4. has effectively three subsections “Unconstrained model”, “Constrained model” and “Forward operator”. Please give these index numbers 4.4.1., 4.4.2 and 4.4.3. (similar to what you have done in section 4.1.). Also, lines 319-340 from subsection Unconstrained model: please try to shorten and restructure. Only in line 327 you say what you have actually done in the study and before that you give several examples (319-327). I would encourage you to first say what you did and then give the examples.*

AR: As suggested by the referee, we will number the subsections “Unconstrained model”, “Constrained model” and “Forward operator”. We will also shorten the presentation of the unconstrained approach. However, we would like to keep the order in which it is presented. That is because the terminology and notation with regard to m , p , and $m(p)$ is, in our opinion, best introduced by example.

1.5. Section 5.2.

RC: *Section 5.2. between lines 473-484. – text can be shortened, and arguments presented more concisely. For example, line 472 “Clearly, the agreement is less than perfect. Still, the general pattern suggests”, can be rephrased to “While the agreement is not perfect, the general pattern suggests...”.*

AR: We will adopt the referee’s suggestion for the first sentence of that paragraph, and will further shorten the text that originally extended from ll. 473-484.

1.6. Align section 5 with specific objectives

RC: *In general, in Section 5: try to restructure main discussion points (5.1. to 5.5.) in a way that it follows the flow of your aims and objectives.*

AR: We agree that it would be helpful to better align the structure of the results section with the study objectives/research questions. In fact, the structure of section 5 already aligns quite well with the aims outlined in the introduction. Yet, the correspondence between the individual sub-sections of section 5 to the aims should be more explicit. To that end, we will adjust both the aims *and* the structure of section 5: the first research question in the new section 1.3 (see comment 1.3) will be split in two; the former sections 5.4 and 5.5 will be put in one section with two sub-sections. The result could look like this:

RQ1 *How robust is the standardization of the sensitivity?* - addressed in section 5.1

RQ2 *Can we find a uniform N_0 for the entire study area?* - to be addressed in section 5.2

RQ3 *What do the differences between the soil moisture estimates at the CRNS footprint scale tell us about soil moisture patterns at the catchment scale?* - to be addressed in section 5.3

RQ4 *How does soil moisture vary within and between the sensor footprints?* - to be addressed in section 5.4, with subsection 5.4.1 being "Spatial interpolation of soil moisture", and subsection 5.4.2 being "Comparison of interpolation results against SoilNet observations"

1.7. Summary and conclusions

RC: *Section 6 Summary and conclusions (which are then called “main lessons learned along these steps”) needs to be more concise. Shortly introduce the “main lessons” and then expand on them in 6.1. and 6.2.*

AR: Please refer to our response to comment 1.7.

1.8. Practical guidance for future dense CRNS networks

RC: *Section 4.3. is particularly good, as uncertainties have been very well acknowledged and explained. Moreover, the limitations of the study are thoroughly and openly discussed. However, I encourage the authors to include a short comment in discussion on the applicability and reproducibility of the set-up (of dense CRNS networks) and perhaps provide examples of what would be the minimum number of CRNS probes to be included in a similar set-up in order to assess CRNS SWC spatiotemporal variability in a reliable way at the catchment (in this case 1 km²) scale.*

AR: The referee suggests to discuss requirements to the design of dense CRNS set-ups in future experiments. While this is an important comment, it becomes apparent that the requirements strongly depend on the specific aims of such experiments. Specifically, we will always face the trade-off between coverage (seek for adjacent footprints) and resolution (seek for strong overlap). Ideally combining the design of such a network with a-priori knowledge on the spatial variability of soil moisture in the target area is, in our opinion, the key to better resolve that trade-off. That is certainly a focus of our future research efforts, and we will attempt to briefly address this issue in the conclusions section.

1.9. Figure 1

RC: *Figure 1: In the legend you refer to “Climate gauge” and in caption to “Climate station” and in the text (line 169) you use the term meteorological station. Please choose one term only. Besides, from the figure it does not become apparent where the peaty soils within this catchment are located. From the text we understand that location 23 is on peaty soils, but what is the extend of these? Would it be possible to include the soils on this map too? May be in a separate panel? Finally, the manual samples locations: they seem to be very close to the CRNS sensors, which is ok, but visually it is impossible to distinguish*

how many you had around each CRNS probe. Could you include information on their number (e.g. in Table 1)?

AR: We will use the term climate gauge both in the figure, the caption, and the main text. With regard to highlighting the areas of predominantly organic soils, we still have to find an optimal solution: we will either include it in Figure 1, or, as suggested by the referee, in Table 1 (see comment 1.13).

With regard to the manual sampling locations close to the CRNS sensors, these were always five. Details were explained in Fersch et al. (2020). We will add a sentence to the caption of Fig. 1 to emphasize that fact again.

1.10. Figure 3

RC: *Figure 3: Is it correct that the rover can sense neutron intensity between 7000 and 11000 cph? (this is just a question, rather than an improvement suggestion)*

AR: Yes, that was the observational range in the present study context, using the UFZ roving CRNS.

1.11. Figure 5

RC: *Figure 5: great figure. Could you include the legend also on the right panel for consistency? Also, optionally name the panels as a),b) and c), this will help you shorten the text related to that figure.*

AR: As suggested, we will also add a legend to the right panel of this figure. However, we prefer to keep addressing the panels by "left", "center", and "right", instead of (a), (b), and (c).

1.12. Figure 6

RC: *Figure 6: another very clear figure. However, I wonder why precipitation is presented as mm/6h and the SWC at the panel below in daily values? I guess it is ok if the width of the cell representing a day on the bottom panel is matched with the width 4 bars of rain.*

AR: We think that the vertical bars of 6 hourly rainfall depths provide a helpful supplement to the cumulative precipitation curve, as they display event dynamics more intuitively, while the resolution of 6 hours is a good compromise between hourly and daily. The horizontal width of the bars is matched to the time axis.

1.13. Table 1

RC: *Table 1: to address my comment on Figure 1, perhaps you can include an extra column to this table "Dominant soil type" or give percentage of the soil types present within each footprint.*

AR: Please refer to our response to the comment 1.9. We will either include that information in the figure or in the table.

1.14. Table 2

RC: *Table 2: Under each header add the units, if applicable. That might avoid having a lengthy caption and faster to understand to readers.*

AR: As suggested, we will include the units in the column headers.

1.15. Other comments

RC: *Line 9-11: Do you need to enumerate all the static effects and temporally dynamic factors in the abstract? Shorten sentence if possible.*

AR: We will shorten the sentence so that it reads: "[...] we apply a state-of-the-art procedure to correct the observed neutron count rates for static effects (heterogeneity in space, e.g. soil organic matter) and for the influence of the dynamic effects (heterogeneity in time, e.g. barometric pressure)."

RC: *Line 14: you mention already here “constrained interpolation”, which is great. Could you also please mention what you will refer later on as “unconstrained” to improve clarity and keep consistent?*

AR: We agree, though we decided to introduce the term "unconstrained" a bit later in the abstract as it provides a better context to understand the difference. The corresponding sentence is then: "The comparison with independent measurements [...] shows that the constrained interpolation approach outperforms the 'unconstrained' Ordinary Kriging [...]"

RC: *Line 44: on “isolated” sensor footprints only. Change “only” for “mainly”, as there are already several key studies published using CRNS rovers.*

AR: We will replace "only" by "mainly".

RC: *Line 51-57: Am I correct that here you present the main aim of the study? If so, please restructure this paragraph first stating the main aim and then the justification. (the content is good, but the flow can be improved).*

AR: It is correct that this paragraph outlines the overall aim of the study. We will try to make this clearer in the revised version.

RC: *Lines 67 – 78: The first question or specific objective has been given more space compared to questions 2 and 3. Could you please make this section more concise? In that way the “weight” of the three specific objectives seems equally distributed.*

AR: We will shorten the description of the first objective in order to achieve a better balance.

RC: *Line 94: Abbreviation FDR is not defined previously. Could you please include “Frequency domain reflectometry” here?*

AR: We will include "Frequency Domain Reflectometry" to explain FDR at its first occurrence of in the manuscript.

Line 102: change to “We then present and discuss the corresponding results (section 5). . .” – as Results and Discussion are presented simultaneously.

AR: Will be implemented as suggested.

RC: *Line 109: please provide information on what portion of the catchment is covered with grassland (in percent) and forest (in percent) to give a better idea of the heterogeneity in land use to which you refer in Line 60.*

AR: We will add the corresponding percentages of forest and grassland coverage.

RC: *Line 113: Section 3.1. Overview does not add anything to point 3. Data. In fact, you state “as already pointed out”. Thus, I would remove the current Section 3.1.*

AR: We will remove section 3.1 of the original manuscript.

- RC:** *Line 138-142: Section 3.3. is unnecessarily long and can be shortened to two sentences. Alternatively fuse current sections 3.3. and 3.6. as one, giving it an appropriate name. The measurements described in these two sections are used to do the continuous correction of the signal.*
- AR:** As suggested, we will shorten section 3.3 (on incoming neutron flux) and merge it with the former section 3.6 (on meteorological data). Altogether, this will become the new section 3.2: "Incoming cosmic-ray neutron flux and meteorological observations".
- RC:** *Line 144: “As we mention in section 1.1. we require local measurements of the soil water content and the soil bulk density” – you don’t actually mention soil bulk density in current section 1.1. Either include it there or rephrase this sentence.*
- AR:** We thank the referee for pointing out this inconsistency. We prefer to leave the statement in section 1.1 as it is because the transfer function could also be calibrated for gravimetric soil water content, without the need to determine soil bulk density. Instead, we will adjust the above sentence in the section on "Local measurements of soil water content and other soil variables" simply by dropping the reference to section 1.1 (which is not required as the actual calibration procedure is outlined in the methods section). Hence, the above sentence becomes: “We require local measurements of the soil water content and the soil bulk density [...]"
- RC:** *Line 146: Do “several measurement techniques” refer to the techniques outlines in sections 3.4.1., 3.4.2. and 3.4.3.? If so, please change to “the following measurement techniques”.*
- AR:** As suggested, we will change the sentence to "[...] the following measurement techniques were applied to meet these requirements."
- RC:** *Line 168: Current section 3.6 should be moved after current section 3.1., as the meteorological data is relevant to all the CRNS analysis. Also, see my comment on using “climatic gauge”, “climate station” or “meteorological station”.*
- AR:** Will be implemented accordingly (merged with section on incoming neutron flux).
- RC:** *Line 172: Section 3.7 does not really present data (since you do not use it for analysis and merely to create figure 1). I would remove this section as the information is already provided in the caption of Figure 1. Optionally, add the hyperlink from the current section 3.7 to the caption of Fig. 1.*
- AR:** We agree. Originally, this section was intended to avoid the redundant repetition of the obligatory license acknowledgement. However, we already had to include elongated statements in the figure captions, so we can elongate these just a bit more and drop this section instead.
- RC:** *Line 173: replace “incl.” with “including”.*
- AR:** Will be done.
- RC:** *Line 411: SMT100 cluster (SoilNet) should be defined/mentioned earlier, as for example in line 90. In line 431 you refer to the same as “FDR-cluster”. Choose one term and stick to it.*
- AR:** We prefer to stick with FDR.
- RC:** *Line 484: “... Fig.5 is both encouraging and disappointing” – put first disappointing and then encouraging, as this is the order in which you present them afterwards. Also, why would you say disappointing about a Figure you include in a publication? Choose a different less negative word. There are several places in the manuscript where you downplay the results of your research (see my comment about line 611 for example).*

AR: We will change "disappointing" to "unfavourable" and switch the order to "both unfavourable and encouraging".

RC: *Line 486: "The vertical shades in the left panel indicate that the theta (Ni) is highly uncertain." You refer here to the percentiles, but which ones/which grey shades? The 5-95 percent or the 25-75 percent ones? Be more specific. Also you can see from this left panel that the uncertainty is larger in the wetter range and smaller in the drier range. Acknowledge that instead of saying that they all are highly uncertain. See my comments about downplaying your results.*

AR: We will be more specific with regard to the discussion of the uncertainty as represented by width of the grey shades.

RC: *Line 605-607: While limitations are honestly acknowledged the paragraph ends on a negative note, which does not reflect the main outcome. I would recommend rephrasing along the lines "While both the unconstrained and the constrained approaches failed to fully simulate the dry area in the southwest of the SoilNet area, the constrained captured it relatively better."*

AR: We tend to disagree with that suggestion. This is maybe a misunderstanding, because our sentence "Both models fail to reproduce the dry region in the eastern part of the area" refers to the eastern part, not to the south-western part, as pointed out by the referee. For this eastern dry spot, both interpolation approaches fail the same, so the statement suggested by the referee does not apply. We also do not think that it constitutes a problem that the last sentence of the paragraph addresses an issue that is not a "success". We hence prefer to keep the statement as is.

RC: *Line 611: "largely" outperform seems like an overstatement (downplaying the overall good results of your study). I would remove "largely". If you mean that the unconstrained model outperforms during a prolonged period of time, modify text accordingly.*

AR: We will remove the term "largely", as suggested by the referee.

RC: *Line 622: typo. Change "reliably" to "reliability".*

AR: We will fix the typo.

RC: *Line 629: I understand the willingness to emphasize the "heterogeneous" in here, as it is a key word in this study. However, not entire convinced about "heterogeneous hydro-meteorological conditions". Are you not considering that precipitation, temperature and barometric pressure measured at the climate station are all the same for all sensors? I would recommend saying "dynamic" or rephrase.*

AR: The referee is correct that the term "heterogeneous" might in this context be misleading as it implies heterogeneity in space while we mean, as the referee correctly suspected, heterogeneity in time. We will hence replace "heterogeneous" by "dynamic", as suggested by the referee.

RC: *Line 725: typo. Change "August 2910" to the corresponding year.*

AR: We will fix the typo.