Review of manuscript hess-2022-356 (revised version)

Technical note: High density mapping of regional groundwater tables with steady-state surface nuclear magnetic resonance – three Danish case studies

General assessment

The authors touched many aspects of the first review in their revision. By consequently showing the elevation of water tables instead of depth below surface as in the first version, the estimates from the SNMR data can be assessed as being much more plausible than before. The discussion of the results has been extended by introducing possible reasons for the remaining discrepancies between the different data sets.

However, there are still inconsistencies that need to be clarified, and, unfortunately, the manuscript still has significant linguistic deficits that have to be corrected before publication. Thus, I suggest moderate revisions.

Author response:
We thank the reviewer for the detailed comments. Below is a detailed description of changes made to the manuscript.

Details
The page and Line numbers refer to the document with marked changes (hess-2022-356-ATC1_comments.pdf)

P4L96: The sentence “Furthermore,…” can be erased or should be reformulated.

Author response: Deleted redundant sentence.

P4L97: with > at

Author response: Changed “*with*” to “*at*” in P4L96.

P4L102: redundant information

Author response: Deleted sentence

P4L103: What do you mean by “having relaxation time and spatial overlapping”? A tradeoff between resolving spatial information and discovering the relaxation times of the signals? Please clarify.

Author response: Thank you for the comment. We have added a description of how this statement should be understood and clarified the sentence. As mentioned in later comments, by increasing the pulse length the penetration depth increases. If we change repetition times instead, we can better resolve the relaxation time, more explanation in Griffiths et al., (2022). More information is added is added to the manuscript in P4101-103.

The sentence has been clarified from:

"The pulse protocols and current amplitudes were chosen based on having relaxation time and spatial sensitivity."
P4L101-104
To:
"Pulse protocols and current amplitudes are varied to encode both spatial and relaxation time information in the collected data set. Variable current amplitudes are used to manipulate the depths of origin of the signal, while relaxation time information is encoded through manipulation of the repetition time. This is because varying the repetition time alters the induced steady-state amplitude, which is based on the underlying relaxation times (Griffiths et al., 2022)."

P4L101-103: As already suggested in my first review, I would prefer a figure with an example of a sensitivity function or at least the reference to Griffith et al. (2022). You replied to the corresponding comment by giving detailed information on the sensitive depth ranges related to specific pulse lengths. Please include this information also in the manuscript, at least.

Author response: We have added the information to the manuscript with the sentence above including these details.

P5L117: As stated later in the manuscript, the water tables in the boreholes have been acquired up to a few decades ago. It is necessary to mention this important detail already here in the Section "Methods" together with a statement on the plausibility of comparing this data with the recent estimates from SNMR.

Author response: We have added a few sentences at the end of the method section to clarify the plausibility of the borehole measurements.

P5L116-119:
"*Water table measurements range from a year to several decades old. It is plausible that these water tables have varied considerably by extraction. However, the consistency of these water table measurements across the borehole database suggests a relatively stable system throughout the years. By reproducing water table estimates consistent with available borehole data, we demonstrate the ability of surface NMR to reliably estimate the water table surface."*

P5L121: Please give information on min and max values of layer thicknesses in the kernel.

Author response: Added the minimum and maximum of layer thicknesses and now reads:
P5L122:
"The kernels are discretized by a 26-layer model with increasing thickness at depth from 0.5m to 5.0m, to a total depth of 50m."

P6L145: "north-east" > Seems to be "north-west" according to Fig. 2a.

Author response: Changed in P6L143 from "*north-east*" to "*north-west*".

P6L152: "The elevation varies…" Reformulation is necessary.

Author response: The sentence has been reformulated from:

"The elevation of the water table varies 12m in the area."

To P6149-150:
"The water table elevation ranges from 11m to 22m in the area."

P6L152: "The middle field…" Sentence is redundant and unnecessary.

Author response: The sentences have been deleted.

P6L156: "The data…" Reformulation is necessary. SNMR measures water content instead of pressure head. "Rather" is the wrong word in this context.

Author response: The sentence has been deleted and replaced. From:
"The data can also be explained if the aquifer is confined because the SNMR data is identifying where the water resides rather than the pressure head."

To P6154-156:
"The SNMR results identify the physical location of water at depth and not the hydraulic head, as such if the aquifer is confined, there will be differences between SNMR estimated water tables and the pressure head from wells. "

P7L157: "The borehole…" > "Borehole data in this area…"

Author response: Changed to read P6L156:
"Borehole data in this area.."

P7L171: Please comment on the fact that this underlying till is obviously not resolved by the TEM data.

Author response: A comment on the TEM data here is added. On inspection the TEM identifies resistivities of 90 ohmm to 60 ohmm which is in the range of Danish tills. It does not, however, resolve the upper high resistive sand which is an extremely difficult target for tTEM as it is very shallow and resistive.

Added P7166-167:
"The TEM profile identifies a layer of 90 ohmm to 60 ohmm which is consistent with Danish tills. The shallow resistive sand layer is difficult to resolve with TEM."

P7L185: Include Grombacher et al. (2022) here as a reference for this procedure.

Author response: Added the reference in P7181.

P9L188: Fig.3a shows a decrease of elevation of water tables towards west, not north.

Author response: Added west, but there is still a considerable change in water table towards the north and will now read:
P9184-185
"A slight decrease in elevation of the water table is visible towards the north-west part of the area.."

P9L191: “borehole data has been acquired …”

Author response: Fixed.

P9L194: Not “uniform” at all, the water table varies within 10 m from east to west.

Author response: Sentence has been deleted.

P9L104: Reformulation is necessary. I do not understand what this statement is pointing to.

Author response: The sentence was reformulated from:

“The duality of T_2^* and water contents could explain some of these consistencies and a limitation of only using water contents as a mean of identifying aquitards.”

To P9L197-198:
“As there is little data influence, the data is fitted without altering the water content from the starting model of 10% in S6. In general, …”

P11L218: Please reformulate and clarify, “flow path” is not the correct feature in this context.

Author response: The statement was changed from “*flow path*” to “*flow direction*” in P11212

P11L219: “northern most” > “most northern”

Author response: Changed

P11L223: Please explain: Why did you not use a different resolution?

Author response: A clarification is added here to explain why this resolution is not changed. The sentences are changed from:
“The resolution of the model is an important aspect for determining the water table, and if targets are generally deeper, a different resolution could be used. This is not the case here where most of the water table estimations is ranging from 5~m to 10~m. Similarly, the eastern most sounding have a similar effect.”

To P11L215-218:
“Similarly, the eastern most sounding have a similar effect. The discretization of the model is an important aspect of estimating the layer thicknesses. The discretization reflects the decrease in sensitivity with depth and adding more layers would make the inversion more regularized. As most of the water table depths are 5~m to 10~m these issues are not as profound.”

P11L237: Less saturated or unsaturated conditions are not possible beneath the water table. An increasing clay content is the only reliable explanation.

Author response: Thank you for the comment. We have reformulated and emphasized that it would be an increase in clay content.
P11L224-226

"The conductive unit coincides with a decrease in water content at 45~m to 55~m elevation for S5, S7, and S8. By the SNMR results alone, the decrease could indicate a unit containing more bound water, i.e., an increase in clay content."

P11L239: wrong word in this context: "perturb" (the same for P16L309)

Author response: In P11L227 has been changed to "*identify*".
In P16L293 to "*investigated*".

P12L244: Reformulation is necessary: "Therefore,…"

Author response: The sentence has been clarified from:
"*Therefore, most of the discrepancy at this location is likely due to how the SNMR and TEM results being placed several hundreds of meters away from each other.*"

P12L233-234
"*The projection of SNMR water contents onto the TEM profile is likely the reason for this inconsistency.*"

P12L251-257: In other words, the comparison of TEM and NMR in Fig.5b is meaningless. As already mentioned in the first review of this manuscript, it is not necessary to show this data. We do not learn anything from it.

Author response: As the TEM is the only other data available, we think that it is important to show this data and the influence that the projection might have on the results. We have changed the description of these inconsistencies and point to the fact that these effects often occur when dealing with several data types.

Changed from:
"*Since the profile is located along a TEM line, the SNMR water content profiles are projected about 100~m to 200~m onto the resistivity profile. The geology changes quite rapidly in these glacial landscapes, which could explain parts of these differences. Additionally, TEM and SNMR arises from different geophysical phenomena, which implies that a change in water content is not necessarily seen in the resistivity profile and vice versa.*"

P12L238-239
"*SNMR soundings projected 100m to 200m could measure a different subsurface as changes in geological conditions may occur at these length scales in glacial landscapes.*"

P13L274: "decrease amount of…" > "decreased number of…"

Author response: Fixed.

P15L284: Reformulation and clarification is necessary: clayey layers are conductive but most likely appear with high water content in reality. However, we do not see this clay-bound water with SNMR.

Author response: We have clarified the sentence adding that it would be low free water units for the SNMR. From:
"*Furthermore, comparison with the high spatial coverage of tTEM showed good agreement in finding conductive and low water bearing units.*"

To P15L266-267:
"Furthermore, comparison with the high spatial coverage of tTEM showed good agreement in finding conductive units as low free water units for the SNMR."

P15L286: As you explained in the reply of my first review, such development is planned for future research. You should give this information also here as an outlook.

Author response: Added an outlook to the end of this sentence.
"… and will be investigated further in future research."

P15L292: There are some examples in the literature demonstrating that this combination is indeed promising. Please cite at least one or two of them here.

Author response: Added two references

P13L275-276:
Irons, T.P., Martin, K.E., Finn, C.A., Bloss, B.R. and Horton, R.J., 2014. Using nuclear magnetic resonance and transient electromagnetics to characterise water distribution beneath an ice covered volcanic crater: The case of Sherman Crater Mt. Baker, Washington. *Near Surface Geophysics*, *12*(2), pp.285-296.

Behroozmand, A.A., Auken, E., Fiandaca, G. and Christiansen, A.V., 2012. Improvement in MRS parameter estimation by joint and laterally constrained inversion of MRS and TEM data. *Geophysics*, *77*(4), pp.WB191-WB200.

P16L296: I question this statement. Some water table estimates in your study are consistent with the borehole data, and some are not. I acknowledge the explanations and discussion on the differences, but the terminus "consistence" points to a conclusion that cannot be given at this state for various reasons.

Author response: Thank you for your comment. We generally use "consistent" when the majority of measurements are comparable with other data such as boreholes or TEM data.
We have changed the sentence to read "consistent with most borehole".

P15L279-280
"However, the water level estimation by the largest gradient in the water content profile has been consistent with most borehole measurements."

First of all, as you also mention at some point in the manuscript, the water table in boreholes is actually a pressure head that, from a physical viewpoint, cannot be in consistence with the elevation of the saturated zone that is measured by SNMR – even for unconfined aquifers you have to consider the capillary fringe. The difference might irrelevant in your areas but we do not know for sure. Second, we are not yet able to identify the confidence bounds of the water table estimates from SNMR. As you explained in your reply on the first review, the corresponding analysis is still ongoing and I am very curious about it. Last but not least, your data does not show ground truth, because there are years and decades between borehole data acquisition and the NMR measurements.

Author response: A comment on capillary fringe is added. Since the capillary fringe in sand aquifers are limited to below 1m it is hard to resolve these differences in the model.

P16L296-298
"Another aspect is that the water table estimate from the SNMR includes the capillary fringe. However, the difference would be limited in this study as all aquifers are sand aquifers and would have a small capillary fringe (Bevan et al., 2005) compared to the discretization of the model."

We agree that the confidence bounds are a very important aspect of these estimates. It is difficult to estimate uncertainties with the regularized deterministic inversion. The stochastic inversion results will be interesting to see how these confidence bounds vary.

We have added a description of the uncertainties in using boreholes for comparisons. We agree that the borehole data is not necessarily ground truth, but the borehole data base represents our best approximation of ground truth. Despite the time periods between the different borehole observations of water table, they remain consistent with one another giving confidence that we can still use these data for comparison with the SNMR results.