General

The team around Aarhus University and Aarhus Centre for Water Technology have further developed the technique of Surface Nuclear Magnetic Resonance and have introduced the approach of steady state pulse sequences. In the near past they have published a series of scientific articles on this topic where they systematically investigate different aspects of the fundamentals, measurements, and processing and inversion. The present manuscript describes case studies that are based on the previous work.

The present "technical note" presents data from such measurements at three different sites and bring them in context with complementary information from boreholes and 2D-profiles of electromagnetic measurements.

In general, the manuscript provides data of quality, relevant information for the scientific community and a good standard of scientific conduct.

We thank the reviewer for the comments, and we have addressed the shortcomings in the revised manuscript.

Structure and Content

Even though the shown data is of good quality and relevance, the manuscript is lacking clear statements. For example:

- The application of a new measurement device and the new sounding approach. Is that relevant for the paper? Do the authors want to present the advantage of SS-NMR over FID-NMR. In this case the presented data and corresponding discussion do not reveal this.

  Reply: Our focus is rapid mapping enabled by this approach, with the scope being the ability to map large areas and not a direct comparison between FID and steady-state acquisitions.
  For a direct comparison between FID-NMR and steady state NMR, see Grombacher et al, (2021) where a detailed section illustrates the advantage.

- Correlation with local and regional groundwater regimes. For each site piezometric data from nearby boreholes are presented. Yet, the message is not clear. Is NMR complementary data to piezometric data or does it replace these? Or is it the combination like for confined/artesic aquifers as explained in the text but not supported by data.

  Reply: We thank the reviewer for this comment. We have added details to the manuscript to highlight that these SNMR soundings are independent measurements. The SNMR results can be used independently in unconfined aquifers to draw conclusions on flow base on head gradient without having boreholes as validation. In this manuscript we compare SNMR soundings with water table measurements from piezometers to validate our use of the steady state acquisition for large scale groundwater mapping. Further, it illustrates that the SNMR can be used as a complement to piezometers or borehole water level measures, as an infill between boreholes. However, it is noted that this is not the case in confined/artesian aquifers as the reviewer mentions, since the SNMR is mapping where water resides and not the actual pressure head which determines flow direction.

- The relevance of the TEM resistivity sections is also not obvious. Water contents and resistivities correlate in different fashion for the different sites and partially no correlation is visible or even contradictive. What exactly is the intention of the authors to demonstrate?

  Reply: The TEM resistivity sections were shown to compare adjacent geophysical measurements in the regions with sparse borehole coverage. Further, in areas dominated by meltwater sands and conductive tills, the TEM and NMR signals can be interpreted together as a drop in free water below water table, could coincide with a conductive structure identifying clay structures. Another reason for the comparison is to establish that resistivity measurements are not always capable of resolving water tables, showcasing the capabilities of a combined mapping of SNMR and TEM. The resistivities and water contents correlate in some areas while in others it is hard to determine a trend. In general, the SNMR and TEM has different sensitivities and do not always have comparable results. Yet, in some cases if a trend is visible in both methods, it can be used to resolve a given subsurface layer's properties.
  We have added more explanation and discussion of differences between SNMR and TEM measurements in the revised manuscript.

NMR

The presentation of real NMR surveys with the novel approach is relevant and the data is in general useful for this demonstration. Yet, the authors miss to outline some relevant statements. The aspects of i) frequency offset, ii) tau, iii) pulse moments, iv) regular/alternating pulses, are addressed in section 2.3. Yet, from the description of the data collection at the different sites it is not clear which of the aspects is key to the success of the measurements. Is there anything special in choosing or varying these parameters or is their choice arbitrary?

Reply: It is true that the steady-state acquisitions introduce a number of additional experimental parameters into the data suite – beyond the typical pulse length and current amplitudes. The data presented in this work span first year of development and contains changes in field protocols. The reason our field protocols collect with multiple tau, offsets, and current amplitude is to balance spatial and relaxation time sensitivity. Griffiths et al., (2022) show examples of sensitivity which illustrate how sensitivity varies with currents and different taus. But a more comprehensive look at how each of these parameters affect the depth of the signal is the focus of on-going work. The frequency offset is discussed in greater detail in Grombacher et al., 2022.

The field protocols have been incremented over time to reduce the total number of measurements, but while preserving an ability to produce a satisfactory resolution image. The combinations employed were selected based on examination of sensitivity kernels, and an attempt to remove data redundancy between measurements that shared heavily overlapping spatial/relaxation sensitivities.

Regarding the frequency offset and alternating pulses, the decision in Sunds was made to minimize the influence of a co-frequency harmonic issue. Sunds had a local co-frequency harmonic issue requiring offset, which is described in more detail in Grombacher et al, 2022. The frequency offsets were not necessary for the other campaigns since the Larmor Frequency was several hertz offset from the powerline harmonic.
We have changed parts of the Data collection section to further explain how we have chosen these pulse parameters for each campaign.

One important information remains largely unclear to me in the application of the novel SS-SNMR approach compared to conventional FID-SNMR. In FID-SNMR the spatial sensitivity is varied be increasing the pulse-moment. This results from the effect that successively deeper parts of the subsurface are excited by ~90° angles of excitation while shallower parts mutually cancel out at multiple revolutions. In this manuscript and the cited literature, I did not find a conclusive explanation how the spatial sensitivity varies for SS-SNMR and how then the water content profile with depth is inverted. I apologize if I have missed this information, the authors were quite productive in publishing papers on this topic and the review of the present manuscript required a bit of reading supporting material. The cited article of Griffith 2022 is still not published and was not available for this review.

Reply: The steady state NMR signal's depth is controlled in a similar manner as FID measurements. A sounding approach that increases currents excites deeper parts of the subsurface. This allows both the pulse duration and current amplitude to be manipulated to vary the signal's depth. However, for steady-state measurements several additional factors can now also influence the depth, including the repetition times, alternating versus regular, and the relaxation times at depth. But in practice, the data suites employed (that contain multiple of each of these parameters) provide measurements that all have differences in spatial sensitivity – taken together they still deliver the required information needed to produce a depth profile.

A more comprehensive examination of factors controlling the steady-state signal's depth is the subject of on-going research.

For the Aars field site in Table 2 the authors list 4 different tau at 16 Q each. In Table 1, they list 64 as no. of Q's. I conclude that the total number of Qs is the number of different currents times the number of different tau, is that correct? (Does not apply for the Sound site). And do the different resulting Ernst angles lead to different spatial sensitivities? This needs to be explained or referenced in more detail.

Reply: The 64 measurements are not directly pulse moments, but rather different currents with different pulse protocols. They are not different pulse moments since the 10ms alternating and 10ms regular pulses would have identical current amplitudes, thereby an identical pulse moment. But as seen in Griffiths et al., (2022) Fig. 6, the pulses still have different spatial sensitivity.

We wouldn't think of the different sequences having different Ernst angles, and therefore having different spatial sensitivities. Rather that the different sequences have different performance across the full range of B1 present at depth, and therefore have different spatial sensitivities. The important difference being that the sequences are different in every voxel in the subsurface – not only the specific voxel where the Ernst angle perturbation is occurring.
A more detailed description of the pulse protocols is added to the revised manuscript.

Presentation of field results

A major shortcoming of the manuscript is the compilation of the figures. The authors mix between "Elevation" (above sea level?) for the resistivity cross sections and groundwater tables, and "depth below surface" for the single SNR soundings and the maps. This is largely confusing. In the maps the "depth below surface" is shown for NMR derived water tables and boreholes, but no information about topography is given (only partially qualitatively in the text). The major information about the applicability of SNMR for local groundwater table estimates is therefore missing.

Reply: We thank the reviewer for this comment. After revising the figures, we now only show elevations of water table and the SNMR water content profiles are converted to elevation, with ground surface indicated in every subfigure. After correction, SNMR show even greater resemblance with borehole measurements of water table. Now it is possible to assess groundwater level patterns and possibly flow paths by head gradient.

In various cases, the authors refer to a good agreement of the water content profiles and resistivity sections with the geology observed in the boreholes. But no geologic profiles from boreholes is shown.

Reply: Instead of plotting the borehole data, borehole IDs has been added with a reference to the online open-source Jupiter database (the Danish National Borehole Database operated by the Geological Survey of Denmark and Greenland). Here, full borehole descriptions can be viewed for all areas. We believe that this gives the reviewer or possible readers the ability to see all data used in the comparisons.

Conclusion

The information presented in the present manuscript is very relevant to the scientific and technical community. Yet, the scope of the study is not well presented. With moderate effort to rearrange parts of the text, sharpen the scope of the study and improve the figures, the manuscript can be brought to an acceptable standard.