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Interactive Comment

Interactive comment on "Ground-penetrating radar insight into a coastal aquifer: the freshwater lens of Borkum Island" *by* J. Igel et al.

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We would like to thank the reviewer for the thorough review that will help to improve the manuscript.
The reviewer comments (RC) are written in italic and the authors comments (AC) in upright font.

RC1) *The main objective stated in abstract and discussion is to provide data for hydrogeological simulations which I think is basically the paper by Sulzbacher et al. (2012). However, I am missing the link between the GPR measurements of this study (small scale, one point in time, large error of estimated groundwater tables)*

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and the rather large-scale investigation presented in the paper of Sulzbacher et al. (2012). Probably, there are also other studies planned in the framework of the CLIWAT project which may take advantage of the GPR measurements. This point should be elaborated in the introduction and discussion section of the article.

AC1) We will more precisely elaborate the link between the GPR measurements and the groundwater simulation done by Sulzbacher et al. (2012). In the following a short summary is given:

- The GPR investigations focused on an area where only few observation wells were installed.
- Information from GPR data was used to create the conceptual model for hydraulic simulation, i.e. a sandy medium with intercalated clay and silt layers on large areas that show some gaps and thus some leakage (see Sulzbacher et al. (2012)).
- The silty loam layer detected by GPR extending on a large area was directly included as a layer in the hydraulic model.
- The GPR watertable data were included in parts of the model. In areas with a dense distribution of observation wells, only data from the wells were used. In areas where no observation wells were located and consequently kriging errors were high, GPR water tables were included as additional nodes for the interpolation. The spatial distribution of observation wells and their pressure heads is included in the figure showing the GPR water tables (see Fig. 1 in this reply). Albeit its lower accuracy in the absolute values, using additional water tables deduced from GPR data yields a more realistic pressure head model than without using this additional information (see Fig. 3, Sulzbacher et al., 2012).
- The shape of the GWT due to GPR was used to decide where to place additional

hand drillings with temporal observation wells to measure the pressure heads and close larger gaps.

You are right that the GPR measurements show larger errors than observation wells do and represent only one point in time. These drawbacks are already discussed in the Conclusions and Outlook and could be overcome by repeated measurements. However, we do not understand the comment that the presented GPR investigation is only small-scale. Compared to other geophysical and hydrogeological investigations, as ERT, MRS, seismics, direct push or observation wells readings giving information at one point or along short profiles only, GPR data cover a large part of the island and give valuable additional information in areas where well density is poor.

RC2) *The structure of sections 2.2 to 4 is somewhat difficult to read since especially some features of the GPR profiles are already dicsussed in sect 2.2 while the details are hidden but presented in sect 4. I suggest to restrict sect 2.2 to the very technical details of the GPR measurements and add the discussion of the details including all the figures (4 to 6) to sect 4.*

AC2) Using the classic paper scheme of methods, results and interpretation we understand the GPR measurements as a methodical tool. Consequently we will reorder the manuscript in that section 2 will merely show the raw data, in section 4 they are interpreted and discussed in a hydrogeological context, and in section 5 overall conclusions are drawn. Therefore discussing parts of sections 2 and 5 are moved into 4. We propose renaming section 2 measurements and results, and section 4 interpretation and discussion.

RC3) *I have very some reservations regarding the discussion of the large deviations between groundwater table depths measured in the wells and those determined from*

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the GPR measurements as presented in Sect 4.3. Overall, an RMS error of 50 cm with observation wells closer than 30 m to the GPR line is unacceptable. This clearly puts the applicability of GPR-measured groundwater tables for modelling studies into question, which would be unfortunate. In this study, the various error sources listed by the authors require further investigation and especially interpretation (e.g. by merging with other geological information about the spatial distribution of the confining layers, time series of data showing the temporal groundwater dynamics, data from other geophysical investigations conducted within the project, ...) in order to be able to reduce the measurement error. Especially groundwater table depths determined by GPR measurements cannot be compared to pressure heads of a confined aquifer as the authors state correctly. These areas would have to be removed from the comparison but still could contribute to the discussion of the hydraulic situation. Here I strongly encourage the authors to carefully revise this section before publishing the paper.

AC3) We re-analysed the relation of GWT from observation wells and from GPR and will revise this section in the manuscript. We now only use observation well readings carried out at the same time the GPR measurements were done (at maximal 14 days after the GPR measurements). There is only a minor effect of temporal changes in the GWT remaining (changes of GWT from observation wells in this area are at maximum 5–10 cm/month). Furthermore, only wells with their filter in the upper acquifer were taken into consideration. Figure 2 (supplementary material) shows a cross-plot of pressure heads of wells closer than 25 m to GPR lines and uncorrected GPR groundwater tables. GPR shows systematically higher water tables than the pressure heads in the wells. Causes for this shift are:

- Inaccuracies of the velocity model that is used to transform traveltimes into depths.

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- Time-zero correction of the GPR data and systematic errors in picking the reflections.
- Capillary fringe: GPR reflections are caused by changes of dielectric permittivity as a function of water content. Therefore GPR (and every geophysical technique) yields a higher water table than the pressure head in wells, as already explained in the manuscript. We assessed the capillary fringe by a simple experiment to be 13.5 cm (see manuscript). However, the porosity of the sand was 42% for the lab experiment compared to 36% in the field so that the capillary rise height must be larger in situ. Additionally, the reflection point at the GWT depends on the transition zone above and the shape of the GPR signal. A detailed analysis of this relation would go beyond the scope of this paper and would need additional information that is not available and still subject to research.

Therefore, we decided to use the information from the wells for calibrating the GPR water tables and included a figure (Fig. 2 in this reply). Regression shows that a shift of GPR water tables by 45 cm (solid line), minimizes the RMS deviation between wells and GPR from 50 cm to 14 cm. The shift includes all effects mentioned above of which the capillary rise is probably the most important.

Specific comments:

RC) *P 3693, L 16: Is there any overview paper about the CLIWAT project? If yes, please cite.*

AC) There is no overview paper on the overall project, but a web page (http://www.cliwat.eu) where more information can be found. Sulzbacher et al. (2012) give an overview over the activities on Borkum island, which is one of the seven pilot areas in the project.

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RC) *P 3694, L 4-6: Please specify this statement - I suppose the intention was to investigate the depth of the groundwater table but which property of the clayey/silty layers were explored (occurrence, depth, shape, erosion channels, leackages, . . .)? How does (or would) the information from the GPR measurements improve the model investigations presented by Sulzbacher et al. (2012)?*

AC) Occurrence, depth and shape of the clayey/silty layer were explored and directly included into the hydraulic model. Further, the characteristics of the layer, e.g., the presence of erosion channels, was used as soft information and helped to develop the conceptual model (see also AC1 for the details that are explained in the revised manuscript).

RC) *P3695, L 11: this should be volumetric water content*

AC) corrected

RC) *P 3695, L 13: Porosity can only be determined for saturated conditions. In this case $\theta_v = \Phi$ (see sect 4). Please clarify.*

AC) clarified in the text

RC) *P 3695, L 15-16: Sentence misleading, please reformulate: "Two techniques that originally stem from seismics but had been adapted for GPR were used in this study to assess wave velocities.“*

AC) done

RC) *P3696, L1: Please provide a number for "a couple of ..." .*

AC) CMP soundings were carried out at 4 different locations.

RC) *P 3696, L 13-15: How has this fine tuning been done? Has any software been used for picking the signals or has it been done by hand? Please explain in more detail. If the fine tuning has been done by hand, what is the expected accuracy of the results?*

AC) We did not apply any automatic picking. First, the maxima in the semblance analysis were picked and then position and shape of a synthetic hyperbola was manually fitted to the reflections by changing depth of the interface and mean velocity of the upper layer. The mean-velocity model was converted into an interval-velocity model by using the Dix (1955) formula. To our experience, the accuracy is at about 5–10% under good conditions. Defining exact accuracy of CPM based velocity models is difficult as it depends strongly on the wavelet, the antenna pattern, the velocity contrast between the layers, the shape of the interface, the distance in between the interfaces and the S/N ratio of the data. Such analysis is not standard, neither in GPR nor in seismics, and would, e.g., require repeated measurements.

RC) *P3696, L 19: For this CMP, I cannot extract a velocity of 0.065 m ns..1 from Fig 1c. To me the velocity below the groundwater table appears to be at least around 0.08 m ns..1.*

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AC) This is an error and the left subplot shows a wrong velocity-depth model. The values given in the text (0.065 m/ns) are correct and we corrected the plot.

RC) *P 3698, L 7: Please add an introductory sentence explaining that results of a VRP sounding are shown in Fig 2 and explain observed velocity changes also for Fig 2. Alternatively one could also merge Figs 2 and 3 to a 3-column figure.*

AC) The figures will be merged to a 3-column figure.

RC) *P 3698, L 20: Why was exactly this part of the island chosen for the GPR measurements? Was there any specific demand from the groundwater model for exactly this area of the island? Please explain.*

AC) Investigating the whole island with GPR would be too time-consuming for a scientific investigation wherefore we concentrated on the central and eastern part of the island including the eastern waterwork (s. Sulzbacher et al., 2012). We chose this part because at the time of the investigation there was only few information (e.g., observation wells) available (see location of GPR profiles and observation wells Fig. 1 in this reply). Hence, there was a high demand on more information from hydrogeologists and the municipal water supplier.

RC) *P 3699, L 19: Please mention depth of mean sea level in text "... (m.s.l.) at 12 m is marked ..."*

AC) done

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RC) *P 3701, L 6: Please provide depth interval of the peat layer.*

0.8–0.9 m depth in borehole B

RC) *P 3701, L 19: This is a very rough method to determine the height of the capillary fringe. Did the authors make sure that the bulk density/porosity of the material in the tube was the same as in the field and that it does not change during flushing the tube with water? How representative is this single value for the complete area of investigation? In any case the authors should clearly mention that this is a very rough estimation of the height of the capillary fringe which may be different to some extent at other positions along the GPR line.*

AC) This is indeed a rough method and was used to get an orientation. The porosity during the lab experiment was 42% whereas the value for the field, deduced from GPR velocities, is 36%. Hence, the capillary rise in situ should be higher than in the experiment. We do not use this value for correction any more as we now use the data from observation wells (see AC3). The data from the lab experiment will only be used to assess a lower limit for the capillary rise height and to evaluate its plausibility.

RC) *Sect 4.2: Again, here merging the information from section 2.2 to 4 would very likely make the discussion more readable. Please also discuss the sedimentary features indicated in the figures (foreset beds etc) as well as their extension along the profiles in the text.*

AC) We will re-organise these sections as discussed above and discuss some sedimentological features in the GPR sections.

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RC) *P 3703, L 15: Please provide complete range of depths as provided in Fig 9.*

AC) We will discuss both range and spatial distribution in more detail.

RC) *P 3703, L 26-28: Does this mean that Fig. 10 was generated by using information from different antennas? Is there a fixed threshold value (depth) where the authors shifted from using data from the one antenna frequency to the other? Please explain in more detail how the different measurements contributed to the map shown in Fig 10.*

AC) Yes, in areas where the GWT could be detected with 200 MHz antennas, these data were used. If the GWT was too low for the 200 MHz antenna, the 80 MHz data were used when showing clear reflections. No significant shift of the GWT could be observed when comparing both antennas as the first arrival times were deduced. A difference might be expected for other geological environments that show a larger transition zone above the GWT than is the case for the well-sorted sands in the area of investigation. We will add some explaining text in the manuscript.

RC) *P 3704, L 27 ff: The occurence of groundwater level (head) depression cones is a characteristic feature around every existing pumping well while its shape is determined by the pumping rate and the hydraulic properties of the surrounding aquifer. In this context, I do not understand the explanation provided in L 3-6.*

AC) The original formulation might be misleading and will be changed. The explanation in L 3–6 describing differences in between both islands refers to the maximum elevation of the GWT (1.5 m asl on Spiekeroog vs. 3.5 m on Borkum) but not to the existence of depression cones.

RC) *P 3706, L 7-8: Please consider general comment No 3 regarding confined aquifers.*

AC) Will be considered

RC) *P 3706, L 16-27: This paragraph (except for the outlook) should be moved to sect 4. For a future interpretation of the data the authors may also want to consider the paper by van Dam and Schlager (2000).*

AC) The paragraph will be moved to section 4.3.

Van Dam and Schlager (2000) describe reflections in the vadose zone and discuss the magnetic properties of the iron oxides within the sediments as being the most probable cause of the reflections. However, in a later paper (van Dam et al., 2002) they cannot confirm the role of magnetic properties and they relate such reflections to changes of water content that are caused by the iron coating of the grains. In contrast, the reflection we are discussing is below the water table where the sediments are completely saturated. We will add some additional references on this topic.

RC) *P 3707, L 8-10: I am somewhat confused about the statement about the large spatial variability in the groundwater table depth since the groundwater table usually is an equilibrating surface with a larger-scale slope. Given the large RMS error in the analysis of the groundwater table depth mentioned in section 4 and the reasons given for the deviations, I wonder about the value of this statistical analysis. In any case, this analysis should be presented in more detail as part of section 4 in order to confirm this conclusion.*

AC) This statement might have been confusing and will be rephrased. After calibration, the RMS deviation is 14 cm now (see AC3). The common conception of a GWT is a surface with a large-scale slope. This is the general surface of the GWT in Borkum, however, there are places where this simple assumption does not hold. GPR shows strong gradients of the water table in parts of the island. These locations are related to the existence of production wells, large dune valleys or a more complicated geology. However, investigating the details of the subsurface at the specific locations would require an extensive in situ investigation and is beyond the scope of this paper.

Strong gradients can also be found in the pressure heads of some close observation wells. Further, observation wells are for practical reasons often placed in valleys and not on top of the dunes, so that preferably low water tables are measured. GPR, non-destructively covering wide areas, has the potential to reveal areas with high variability that might then be investigated in detail or at least be equipped with more observation wells.

RC) *Figure 1: Resort order of figures a) CMP measurement, b) semblance plot, c) deduced velocity profile. Since HESS is not a geophysics journal, it potentially would help many less informed readers if the different waves discussed on P 3696 L 5-7 would be indicated in the CMP plot. What does the dashed line shown in Fig 1a represent?*

AC) The subfigures will be resorted and we will indicate the different waves in the radar section. The dashed line represents the mean velocity model and will be removed in the new plot for better readability.

Technical corrections

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AC) All suggested corrections will be done.

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Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 9, 3691, 2012.

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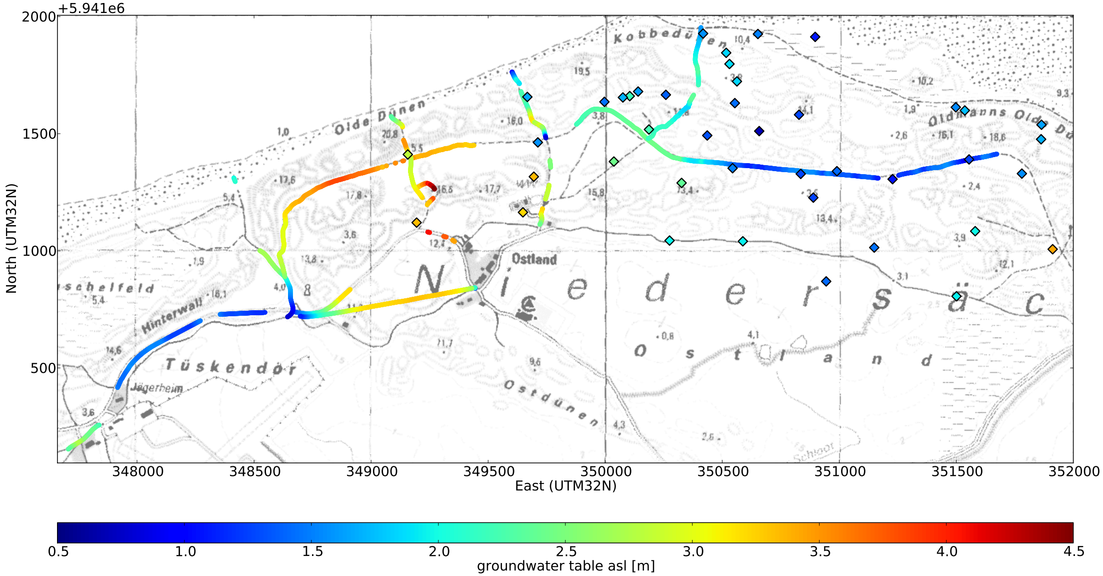

Fig. 1. Uncorrected groundwater tables deduced from GPR (lines) and water tables in the observation wells (diamonds).

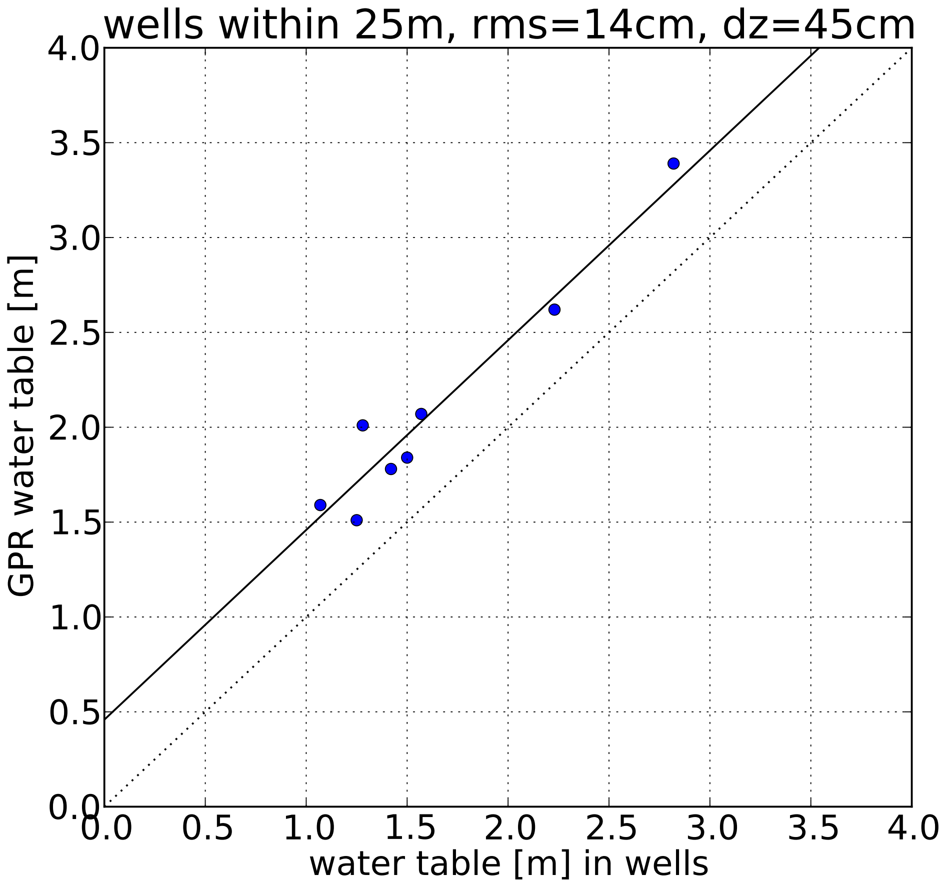

Fig. 2. Uncorrected GPR groundwater tables vs. pressure heads of wells closer than 25 m to GPR lines. The solid line shows a regression that crosses the y-axis at 45 cm.

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