Hydrol. Earth Syst. Sci. Discuss., 9, C3947–C3953, 2012
www.hydrol-earth-syst-sci-discuss.net/9/C3947/2012/

Hydrology and Earth System Sciences Discussions

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

J. Igel et al.

jan.igel@liag-hannover.de

Received and published: 24 August 2012

We would like to thank the reviewer I. Moeller for the thorough review and the constructive comments that will help to improve the manuscript.

RC1) *The greatest weakness of the manuscript is figs. 4-6. They are too small, the scale is too small and the vertical exaggeration is too large to be able to actually see what is argued in the text about the reflection interpreted as the ground water table. Clear figures are needed, where one can see that the reflections display the characteristics of the groundwater table, e.g. crossing dipping reflections caused by sedimentary structures. From my experience with GPR surveys in similar environ-*

ments on Danish Wadden see barrier islands, we are not able to identify a reflections caused by the groundwater table. The figs. 4-6 serves as the documentation that you are able to detect the groundwater table - then you have to produce figures that actually are showing it. I know it is hard to produce good quality figures with GPR sections. One way is to turn the figure into landscape and/or split the profile in more sections like in Nielsen et al 2009 in your References list. This will enlarge the figures. Less vertical exaggeration also make more structures visible. Additional figures with a shorter part of the GPR profiles where the water table reflection is visible are also needed. I will also address this problem to the editors: You need to make space in the journal for the size of figures needed to display the GPR sections properly.

AC1) As you mention, it is difficult to produce good quality GPR sections with the limited space of a journal paper. We will rework the figures. As for the size of the figures, we have no influence on this as it is given by the template of the journal. We provided high resolution graphics so it is possible to zoom into the figures in the pdf file. We prefer to keep an axis ratio similar to Fig. 4 and Fig. 5, because the groundwater table (GWT), which causes a blurry reflection with a smooth morphology, can be clearly recognised with a high vertical exaggeration. If we split the profiles in more sections to enable a lower vertical exaggeration, this would indeed reveal many sedimentological structures. However, the morphology of the GWT will not be obvious. Further, splitting the long profiles would drastically increase the size or number of figures. As the focus of the paper is on hydrology and not sedimentology, we do not think that it is helpful to show the whole radar profiles with lower vertical exaggeration in the main article. But as suggested, we will implement additional figures showing shorter parts of the radar profiles with magnification so that the reflection characteristics that are described in the text can be clearly recognized, as e.g. dipping sedimentological reflections crossing the horizontal GWT reflection. Further, we propose to prepare figures as supplementary material showing the radar section split into several subplots with a low vertical exaggeration for interested readers.

Our experience is that it is possible to identify reflections caused by the GWT in such geological environments under certain circumstances. This is also the experience of further authors that are cited in the manuscript (e.g., Tronicke et al., 1999). Whether the groundwater table can be seen in CO GPR sections or not depends on a variety of factors. In some areas of the island, we were also not able to determine the GWT, however, on the predominant number of profiles we got a clear reflection. The most important limiting factors are:

- centre frequency: high frequencies will not cause a clear reflection due to the gradient of the capillary fringe that depends on the pore-size distribution
- distance of the GWT to the ground surface: too close is not good (interference of GWT reflection with direct waves) and too far is not good as well (limited depth of investigation)
- wave attenuation of the subsurface: e.g. temporal saltwater flooding or high clay content limit the depth of investigation and can cause severe antenna ringing
- stratigraphy: if many sedimentological interfaces exist it might be a challenge to distinguish stratigraphic reflections from GWT reflections.

RC2) *A figure showing the survey area including positions of the data collected is required as the first figure and related to the text on page 3692 line 24 to page 3693 line 2. This figure should also include a map showing the location of the survey area on a regional scale - not all readers know where Borkum is located. All names of localities mentioned in the text should be on these maps.*

AC2) We prepared a map of the survey area including the location of Borkum island.

RC3) *On page 3693 line 12-13 a significant almost local reference is missing: Lindhorst et al 2008. Sedimentary Geology 206, 1-16.*

AC3) This reference on GPR used for sedimentological investigation on Sylt island will be included.

RC4) *There is a disagreement between the text on page 3696 line 18-22 and fig. 1. The resulting velocity model of the CMP in fig. 1 shows that velocity decreases down to 0.08 m/ns. In the text is stated that the velocity is 0.065 m/ns and that the velocities below the water table is at 0.065 m/ns within a variation of 10 %. This inconsistence between text and figure must be cleared out. Furthermore the velocity analysis does not include all jumps in rms velocity. Including a peak in the semblance analysis around 115 ns will decrease the velocity of the lower layer.*

AC4) Thank you for this remark, this was indeed an error in the plot. The left subplot shows a wrong velocity-depth model but the values given in the text (0.065 m/ns) are correct. We corrected the plot and also took all reflections into consideration that show a distinct peak in the semblance analysis.

RC5) *On page 3698 line 22 is referred to fig. 10. Normally one should number the figures in the order they are referred to. The solution here is the survey area figure requested for in 2).*

AC5) The figure numbering will be correct with the additional figure 1 being used as location map (see 2).

RC6) *On page 3699 line 17: "The non-linear depth axis is calculated using ...". Does that mean you are not taking the topography of the water table into account in your display. It is possible to create a 2D velocity field and carry out a migration and depth conversion of the GPR profiles so that you get a depth axis that is valid for the entire section.*

AC6) The topography of the GWT was not taken into consideration for the non-linear depth axis, so that in a strict sense it is valid only for a certain height of the GWT (here the mean height along the profile was used). The depth axis of this plot was meant only for illustration. For the deduction of the groundwater model we picked the reflection traveltimes in the unmigrated radar sections and did a time-depth conversion basing on the picked layers and a topographic correction afterwards. This yields correct depth of the reflections as long as the structures are not too steep, which is always the case for the GWT.

We re-processed our data and did a depth migration taking topography and 2d velocity distribution into consideration and prepared new figures showing the depth-converted radar sections. However, we had to use a smoothed velocity model as otherwise the high velocity contrast at the groundwater table would have caused migration artefacts and a distorted wavelet at this boundary.

RC7) *On page 3699 line 22-23 is stated that "A migration of the data was not necessary as the reflections were not steep". A migration not only moves dipping reflection to the right position but do also make diffraction hyperbolas collapse. It looks like some parts of the data are disturbed by diffraction hyperbolas and a migration would be appropriate.*

AC7) Indeed, there are some diffraction hyperbolas in the radar sections. Some

of them might be of geological origin, other might stem from cables or pipes. These hyperbolas were now refocused by the migration (see 6.). However, in the unshielded 80 MHz antenna data, we also have some diffraction hyperbolas and reflections that stem from surface objects like a metal fence on top of the dune in Fig. 4 and they will not disappear by a migration when using the correct subsurface velocities.

RC8) *On page 3702 line 23-25: "... an area above 5 m depth with predominantly cross bedding structures that are typical for aeolian sedimentation. Below, layering is horizontal and the material is interpreted as marine deposit". This is a rough sedimentary interpretation, marine sedimentation in e.g. the coastal zone and beach ridges also produce dipping structures and cross bedding structures, e.g. Nielsen et al 2009.*

AC8) We will rephrase the text and add an amendment that dipping structures can be of both, marine (beach) or aeolian origin and refer to Nielsen et al, 2009, e.g. However, in our case an aeolian origin of the dipping structures and a marine origin of the horizontal structures below is more likely, because of:

- a steep inclination of the structures (at least 23°, but probably higher as we do not know the strike of the structures, which would require a 3d GPR survey)
- dipping structures reach into the dunes (this feature is visible in one of the new subplots)
- analysis of the hand drillings (grain-size distributions, shell detritus).

RC9) *On page 3703 line 17-20: the statement should be possible to see in the figures, ad 1).*

AC9) This statement is more obvious in the reworked figures.

RC10) *In "5 Conclusions and outlook" is added new information (paragraph on page 3706 line 16 to page 3707 line 2 and sentences on page 3707 lines 8-10). These subjects should be discussed before the "Conclusions and outlook" and the osutlook of this can then be stated in "Conclusions and outlook".*

AC10) The discussion of this feature will be moved to chapter 4, "Results and interpretation" and we will only discuss further investigation of the cause of the reflection in the Outlook.

RC11) *On page 3706 line 16-18. The statement "An interesting feature can be seen in Figs. 5 and 6: in the centre part of the profile, a weak blurry reflection can be recognised ..." is not possible to see in the figures in their present quality.*

AC11) We rework the plots in order to highlight these features and put some symbols on the radar sections to point to the specific reflections.

RC) *Page 3692 line 3: the abbreviation GPR is used without being spelt out the first time.*

AC) The abbreviation GPR will be explained when used for the first time.

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