Hydrol. Earth Syst. Sci. Discuss.,
https://doi.org/10.5194/hess-2019-540-AC1, 2020

Hydrology and Earth System Sciences
Discussions

Interactive comment on "Combining resistivity and frequency domain electromagnetic methods to investigate submarine groundwater discharge (SGD) in the littoral zone" *by* Marieke Paepen et al.

Marieke Paepen et al.

marieke.paepen@ugent.be

Received and published: 30 March 2020

This manuscript presents an interesting set of methods and data to generate a complete overview of a study area on the coast of Belgium. The use of geophysical methods is very extended in the study of groundwater in coastal setting and combined methods optimizing their use can be applied in other regions. There are several relevant facts presented and discussed that can be valuable for the scientific community but the text needs improvement in multiple sections to provide a more specific message and to align better the content of the manuscript.

» We would like to thank anonymous referee #1 for the very constructive review. It is

clear that part of the message we wanted to deliver is lost by the way the manuscript is structured, especially the results section. Below we give an answer to all the specific comments (our responses are between: "» «"). The necessary changes will be made in the revised manuscript. «

ABSTRACT

The abstract can be improved. General descriptions as lines 10-14 or very specific details about geophysical methods can be replaced by a more clear overview of the research conducted and the new insights provided by this manuscript.

» We believe that a good abstract should always first describe the general context. Before highlighting the techniques we have used and the complementary methodology, it is thus important to address the importance of submarine groundwater discharge. This indicates why it is important to study this phenomenon. We will remove specific details, such as page 1 lines 18-22. And insist on the new insights brought by our methodology. «

INTRODUCTION

The concept of SGD has to be polished. Along with the text, it can be inferred that authors refer in most of the cases to fresh or terrestrial SGD even if in the introduction there is a brief mention about recirculated/saline SGD. I think the authors should update this way of referring to SGD. To get an update about this topic they can start by the beginning: Moore, W.S., Church, T.M., 1996. Submarine groundwater discharge. Reply to Younger (1996). Nature 382, 122. And keep track of the recent advances especially about the saline part of SGD that is what it is usually a more unknown element for the hydrology community: Rodellas, V., Stieglitz, T. C., Andrisoa, A., Cook, P. G., Raimbault, P., Tamborski, J. J., Radakovitch, O. (2018). Groundwater-driven nutrient inputs to coastal lagoons: The relevance of lagoon water recirculation as a conveyor of dissolved nutrients. Science of the Total Environment, 642, 764-780

» We indeed refer in most cases to only terrestrial/fresh SGD. In particular, using resistivity methods, we rely on the contrast of salinity to identify fresh/terrestrial water discharge. Detecting saline SGD is not possible with the used methods. We anticipated that most readers would be familiar with this broader context so that we focused on geophysics in the introduction. Since this is unclear, we will make this clearer throughout the text and keep the suggested references in mind. «

Or by recent reviews/discussions: Taniguchi, M., Dulai, H., Burnett, K. M., Santos, I. R., Sugimoto, R., Stieglitz, T., Burnett, W. C. (2019). Submarine groundwater discharge: Updates on its measurement techniques, geophysical drivers, magnitudes, and effects. Frontiers in Environmental Science 7. Duque, C., Michael, H.A., Wilson, A.M. (2020). The subterranean estuary: Technical term, simple analogy, or source of confusion? Water Resources Research 56.

» Thank you for highlighting these interesting, recent papers. We will incorporate them in the introduction. «

The introduction would benefit from being more specific, in its current state it is too broad without a clear thread about what wants to be showed. The review of multiple cases studying SGD is not really showing what are the gaps in the current use of methods or research questions that need to be addressed. For example lines 15-17, page 3 are out of context and could be deleted as well as page 2, lines 31-33. On the contrary, page 3, lines 26-31 is a good example of how should be done the introduction, adding references to these sentences would be a better way to probe the utility of this study showing cases about SGD with spatial and temporal variability/the challenge of work in coastal settings /studies discussing the problem of the gap between land and sea. I suggest a full reorganization of this section rewriting part of it.

» In the introduction, we try to focus on the use of geophysics in coastal environments, because the methodology we propose is based on such techniques. It might indeed seem very or even too broad. It gives an overview of the most common uses of geo-

physical methods in a coastal zone, their potential and their limitations. We will focus on the most important aspects (lateral and vertical resolution, acquistition speed) and put more emphasis on the gaps and addition this new methodology brings. This was the main objective of the paragraph page 3, L26-31. «

Some additional references that can be useful: Stieglitz, T., Rapaglia, J., Bokuniewicz, H. (2008). Estimation of submarine groundwater discharge from bulk ground electrical conductivity measurements. J. Geophys. Res. Ocean. 113, 1–15; Stieglitz, T., Taniguchi, M., Neylon, S. (2008). Spatial variability of submarine groundwater discharge, Ubatuba, Brazil. Estuar. Coast. Shelf Sci. 76, 493–500. Kinnear, J.A., Binley, A., Duque, C., Engesgaard, P.K. (2013). Using geophysics to map areas of potential groundwater discharge into Ringkøbing Fjord, Denmark. Lead. Edge 32.

» Thank you for pointing these out. «

STUDY AREA

The geology elements used in the discussion must be initially presented in the study area section. For example, it is mentioned a clay layer very important for the interpretation of the data but it is not explained previously. Also, this layer can be probably inserted in the geophysical interpretation in the figures as lithological columns (or any other graphical way) to probe the reliability of the method.

» We are referring to the clay layer which bounds the phreatic aquifer in the text. This is the Kortrijk Formation, which is discussed in this section. In the results section, we also mention a local clay layer (page 9 line 3) in the tidal inlet. A description of this one will be included in the study area. «

What is the local water problem that wants to be solved in the study area? It is mentioned in the text but not clearly. Is any interest in increasing the pumping rate? In the text, it is said that the pumping rate has been decreased in the last years.

» The pumping rate has indeed been decreased, so at the moment there is - at that

location - no problem with attraction of salt water from the sea. But the potable water is scarce in the region, especially in Summer when lots of tourists visit, and so a comprehensive understanding of the hydrogeological system is important for the sustainable management of the “shallow” groundwater reserves, this will be explained in the study area section. By comparing with Lebbe (1981), we can see how the decrease in pumping affects the freshwater discharge. And the idea is to compare this study area, in a next step, with another zone of the Belgian coast where larger quantities (around 10 times more) are being pumped from the dune aquifer, but where they also infiltrate treated wastewater to enable this. But it is, at the moment, not possible to increase the pumping rate at the Westhoek mainly for two reasons. First, the facility is located in a nature reserve and so there are strict regulations. Also, some wells show an increased salinity, since old seawater from the polders (which is much closer to the wells compared to the sea) is being attracted. «

METHODOLOGY

In general, it should be mentioned how many measurements/cross-sections have been collected for each method.

» To complement the information in the map (Figure 1), we will include the details it in the methodology section. «

Page 5, line 20. Is this needed to be explained for any reason? If the collection is easier and faster there is no reason to use the other method.

» With continuous resistivity profiling (CRP), a larger part of the injected current directly flows in the conductive saltwater layer. And so, the sensitivity of marine electrical resistivity (MER) to resistivity variations in the sediments will be higher, so there are cases where you could opt for MER. This is already described in the introduction, page 3 lines 10-16. «

Page 5, lines 24-25. Is this an innovation of this study compared with others?

» Most other studies are performed in zones that have smaller tidal differences and which are less rough compared to the North Sea. In this study, we prove that it is possible to perform these kind of measurements on the North Sea or in similar conditions. «

Page 6 lines 10-12. I think the data generated by broken electrodes must be removed both from the text and the figures, they do not provide any value.

» We are open on the set-backs we had with the equipment. It shows that with less channels, you can still obtain reliable inversion models. It also has an impact on the sensitivity of the high tide inversion models compared to the ones from low tide conditions (less data are available). «

RESULTS AND DISCUSSION

One of the main issues in the text is the disorganization in the section results and discussion. This makes it difficult to read and the final message is not well transmitted. I strongly encourage a complete reorganization of the results and discussion, for example by dividing the text into the following sections with a heading:

- CRP data (clear specific presentation of the data without mixing with other sections)

- FDEM data (clear specific presentation of the data without mixing with other sections)

- ERT data (clear specific presentation of the data without mixing with other sections)

- Advantages of the combined methodology (compared with previous studies)

- Geophysical innovations (technical improvements, novelties, and new approaches)

- Seasonal SGD changes and over the last 20 years (showing the data from previous reports)

I think that the approach to present the data as “they were collected in the field” is not working well enough to be justified.

» We opted for the “field collection order”, because it justified the choices we made during the 2 years of the field campaign, starting with the Eastern part of the study area, and then moving to the West. We understand this might be more difficult to read, since we mix multiple methods and figures in many of the paragraphs. We will therefore follow your recommendation in the revised manuscript. Based on the above proposed sections, we will create the following subdivisions: 1) FDEM data, since this is the first method we explored. 2) Land ERT data, which proves that the features observed with FDEM are in fact related to freshwater discharge. 3) CRP data, to extend the ERT profiles, allowing to visualize groundwater discharge offshore. 4) Quality appraisal of the ERT/CRP inversion models, explaining figure 8 in detail. 5) Seasonal variation of the discharge. 6) Long-term evolution, comparing with data from 1980. 7) Advantages of the proposed methodology. «

Along with the text, there are multiple mentions to a “freshwater tongue” below the salty water. This is a well-established field of research that the authors should check to put into context their findings. For example: Robinson, C., Gibbes, B., Li, L. (2006). Driving mechanisms for groundwater flow and salt transport in a subterranean estuary. Geophys. Res. Lett. 33, 3–6. : : :And all the following papers based on modeling and field observations. There are dozens but this is one of the first ones.

» We feel that this does not fall in the scope of this study. The objective of this study is not to describe this phenomenon as a new discovery (this is indeed well documented), but to fully image this saltwater lens using geophysics. How this lens is formed in the Westhoek was already extensively discussed by Vandenbohede, A. and Lebbe, L.: Occurrence of salt water above fresh water in dynamic equilibrium in a coastal groundwater flow system near De Panne, Belgium, Hydrogeological Journal, 14(4), 462-472, https://doi.org/10.1007/s10040-005-0446-5, 2006a. We think this reference is the most appropriate as it describes the situation at the study site. In fact, the western Belgian coastal plain is one of the first area where this freshwater tongue was observed, by Luc Lebbe and his co-authors back in the 70s and 80s. At that time,

there was serious doubts about the possible occurrence of saltwater above freshwater. «

Avoid referring to figures as right/left side, better say any cardinal direction or even mark in the figure the parts that want to be highlighted.

» This might indeed be confusing. We’ll change this to North, East, South, West or dune-/seaside. «

Page 9, line 1. How do you know the origin of the brackish water?

» The artificial tidal inlet was monitored very closely during multiple years with EM borehole logging, since it was potentially threatening the freshwater reserves, this will be more clearly indicated in the text. Those data clearly shows an initially freshwater aquifer progressively infiltrated by saltwater. Now that infiltration does not occur anymore, the hydraulic gradient tends to transport this water back to the sea. Recent EM logs show that the salinity progressively decreases. We, therefore, know that seawater entered the inlet and a remnant of that is still present in the aquifer. «

Page 9, lines 8-12. The discussion about the comparison with previous surveys is totally out of context, as said before, better create a full section of comparison where the old data are also presented maybe even graphically. This applies also for the following comparisons in other pages.

» See previous comment on the structure, we agree that this might be easiest to read. An extra figure will be included to graphically show the differences. «

Page 10, lines 10-13. This paragraph seems to be out of context. Better move a section about geophysical innovations/progress as said before. The same for other paragraphs where geophysical technical aspects are commented.

» We agree. We will include this comment in the section dedicated to the geophysical innovation. «

Page 10, line 22. What is the dike between the beach and the dunes? This should be presented in the study area section.

» It should be in fact “dyke”, it is an embankment constructed in front of the coastal cities, to prevent from flooding. «

Page 10, line 22. The effect of local heterogeneities is ambiguous, specify better or remove.

» There are clay lenses within the phreatic aquifer, and we think those might have an influence on the local distribution of fresh and salt water. However, clays have a low resistivity and cannot be easily identified in saline environment. We will extend the explanation. «

Page 11. Line 2, is an example of the wrong use of recirculated water. The authors can refer simply to mixing between fresh and salty, or maybe to variable density-driven flow, but recirculated here is not meaning what the authors want. In general. they should check this along with all the text after reading the general references provided before.

» As mentioned before, we will make a better distinction between terrestrial FSGD and a mix of saline and fresh discharge. «

Page 11, lines 10-20. These methods of testing the results should more clearly be specified in the methods section.

» The calculation of the DOI is a common way to assess the robustness of ERT inversion results. There is a large paragraph in the processing section (3.1.3), this addresses the validation method that is used, this part will be expanded into a separate section (3.1.4. Interpretation and Inversion model appraisal). For additional information on the DOI, we refer to Oldenburg, D.W., and Li, Y. 1999 [Estimating depth of investigation in dc resistivity and IP surveys, Geophysics, 64(2), 403-416, https://doi.org/10.1190/1.1444545] and others. We think that the new structure for the result section will also help to present this validation more clearly. «

CONCLUSIONS

Following the structure proposed for results and discussion, the conclusions can be more structured highlighting the novelties and new insights of this study.

» The novelties will be better highlighted. «

Page 12, line 15-16. Not needed, delete.

» This sentence will be removed. «

FIGURES

The figures are especially relevant in this manuscript as they contain all the data presented, it is, therefore, essential that they are as clear as possible. The figure captions can be improved, technical data as error and dates can be removed (these data can be added in a table for example or commented in the text). A legend including all the lines in the figures (dotted black, dotted white, continuous: : :) would help in the interpretation, it is quite difficult for the reader to do it in its current state.

» We will include a legend in the figures which contain ERT profiles. The full black lines are at intersections between resistivity profiles, dotted black lines show the overlap between profiles, and the dotted white line is representing the bathymetry. Following the comment on the results and discussion section, all marine, perpendicular CRP profiles will be placed on a single figure, while the two land ERT profiles are put on a separate figure. «

Another important improvement would be to differentiate the water column over the aquifer. As this is a research about groundwater, the properties of the sea are not that needed in the figures and would help in the graphical interpretation of the results.

» It is important to understand that the water column is part of the inverse problem for CRP, in the sense that its resistivity is needed to solve it and has an influence on the obtained results in the aquifer. The larger the water column, the lower the sensitivity

in the aquifer. The bathymetry is indicated by the dotted white line. The water column conveys essential information, but we understand that removing the seawater makes the interpretation easier. We propose to do the following: the colour of the seawater layer will be uniform (green/blue) in figure 4, 5, and 6 and the resistivity of the layer is kept in figure 8. In line with the reorganization of the results section, the land ERT profiles will be placed on a separate figure, while the perpendicular CRP profiles (both low and high tide) are put on one plate. «

If there are specific areas of the cross-sections the authors want to refer to during the explanations, they can mark them in the figures to facilitate the link between text and figures.

» The tidal inlet, groundwater outflow, the Kortrijk Formation and other relevant elements will be indicated on the inversion profiles. «

I understand that the location of the cross-section in the figures corresponds with the spatial location, even if this is not clearly stated. The authors can add a reference point so the reader can know always how far is from the shoreline (i.e, distance to the high/low tide mark/dunes/).

» The low water line will be added as a reference point (0 m) on the figures with the land and marine ERT cross-sections. «

Also, all the profiles must have the same markers, for example, the dash lines in figure 4 are only in two of the cross-sections. In general, any improvement to give a better overview of the location of the cross-section would benefit the figures.

» We will make the necessary modifications. Also, the addition of a legend will partly resolve this confusion. «

It is not clear reading the figure caption of figure 7 what are the differences between A, B, C and D.

» These are horizontal slices of the subsurface with the electrical conductivity. The ap-

proximate depth of investigation given by the coil configuration of A, B, C, and D would be 0.9-1.8, 1.5, 2.1, and 6 m respectively. However, the depth at which the signal sensitivity is highest is somewhat ambiguous, since it also depends on the distribution of conductivity. The approximate depth values are not good indications in highly conductive conditions. Therefore, we cannot use them to refer to specific depth. Although for some people it would feel natural to use these values, they have no physical meaning here, and it is better to just provide the coil configurations. But to make the comparison in figure 7 easier, we will also add the approximate depths of investigation as pseudodepths. «

Figure 8 is difficult to follow even after reading the text (maybe because it is quite brief). A presentation of the results adapted to the purpose might be considered instead of presenting the data in the same format as in the analysis of the results (for example showing the difference in resistivity between inversion models).

» The fact that the three inversions look very similar is actually what we want to show. It gives us confidence about the inversion results. This remark is why we additionally show the depth of investigation (DOI). The zones with a higher DOI are the areas where there is a larger difference in resistivity between the inversions that use 0.1 and 10 times the reference resistivity, meaning that the confidence in the results is somewhat lower. We will try to better guide the reader through this figure. «

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-540, 2020.