Hydrology and Earth System Sciences Discussions

Interactive comment on "Assessing impacts of climate change, sea level rise, and drainage canals on saltwater intrusion to coastal aquifer" *by* P. Rasmussen et al.

E.S. van Baaren (Referee)

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Author comment to Referee #1 E.S. van Baaren by P. Rasmussen et al.

We thank Referee #1 for the careful review and constructive comments. Please find our reply (*AC)* after each reviewer comments (**RC**) in the following.

RC: Scientific Significance: Good;

- Combination of existing interesting concepts (skyTEM, SEAWAT model etc) in a practical case study. The article shows that a good understanding of the geohydrological system can help an area to become self-sufficient in its fresh water supply, even when the sea level rises or the groundwater recharge decreases.

- I miss the up scaling to other areas: what information do we need and what information is just interesting (what kind of measurements for example and measurements vs model) to implement the solution (the practical question of climate proof groundwater extractions) in other areas.

AC: The model studies show that the chloride concentrations in abstraction wells at risk are most sensitive to the stage of the drainage canals and to the groundwater recharge. We will include this aspect in the discussion section of the paper.

RC: What is the concrete solution for this area (in terms of m3/year, location extractions, optimization of the system)? Who is going to implement that solution? Why or why not?

AC: For the most likely climate change scenario (scenario 1) the abstraction wells at risk of increasing chloride concentrations above the drinking water standards are the 2-3 wells located closest to the eastern coast line. These wells account for around 20% of the total abstraction or 50000 m^3/yr. We could suggest the local waterworks to gradually reduce the abstraction from these wells while monitoring the chloride concentrations and gradually expand the well field located in the main recharge area with 1-2 new wells during the next couple of decades. Another possibility would be to control salt water intrusion by establishing positive hydraulic barriers by freshwater injection. This option would potentially have other benefits besides controlling sea water intrusion. This option was already mentioned in the discussion. The decision on the best solution will require a proper cost benefit analysis, which is out of scope for this paper. However, the established model will be an important decision support tool for future decision making by the local authorities. We will elaborate a bit more on this aspect in the discussion section of the paper.

RC: Scientific Quality:

Fair / good: As described in the discussion (but missing in the results): calibration of the model is only done with head measurements. The differences in chloride concentration / fresh water lens between the model and the (skyTEM) measurements (fig 7) is quite large. If infiltration/seepage fluxes in the model are not corresponding with the current field data, it is hard to predict the influence of sea level rise. Sea level rise can cause more seepage or a henge area from infiltration to seepage with salinization as a result.

- A) Can you give a better/complete comparison between the chloride interfaces model and measurements?

- B) Additional calibration of the model with the skyTEM and borehole measurements will increase the reliability of your model.

- C) Or can you maybe include in the discussion what parameters are likely to change in what direction after calibration by using the new measurements?

AC: At the time of calibration only groundwater head measurements from 30 wells (no time series) and one time series of drainage water level from one gauging station were available. Also the transient drainage canal water level data were used for calibration of the model. This will be clarified in the revised manuscript where the following will be inserted.

- *A) Chloride measurements are quite scarce in the study area. However, recent groundwater sampling from the new monitoring well (results received after paper submission), show a very good agreement between the modeled depth to the concentration of the WHO drinking water standard for chloride compared to well log estimates (Fig. 8) and the new chloride concentrations measured on depth specific groundwater samples from the well. We will include these data in Figure 8 for comparison and illustration of the good agreement. As correctly mentioned by both reviewers 1 and 2 the data does not compare well with the SkyTEM results at the deep investigation well. This underpins the importance and value of joint inversion of model and SkyTEM parameters (Carrera et al., 2010) as further described below.*

- *B) We agree with the reviewer. Additional calibration of the model against the SkyTEM data may improve the model; on the other hand model results can also help improving the SkyTEM inversion and interpretation (Carrera et al., 2010). The inversion and interpretation of geoelectrical and electromagnetic measurements, such as e.g. SkyTEM measurements also have shortcomings and uncertainties. Hence, model results can also contribute to the interpretation of SkyTEM data and ideally joint inversion of SWI and SkyTEM (geoelectrical) parameters should be performed (Carrera et al., 2010). However, joint inversion of SkyTEM data and SWI model is not trivial and is beyond the scope of the paper. In the present study two different inversion models have been tested for the SkyTEM data: a 5-layer model and a more detailed 19-layer model. In the paper we present results from the 19-layer model. The results from the 5-layer model are quite different; it shows a very limited fresh water lens to the south-east compared to the 19-layer model for the north-west – south-east profiles (Fig. 7). When comparing NE-SW SkyTEM profiles the 5-layer model shows a more uniform bottom of the freshwater lens compared to the 19-layer model, which in this case is in better agreement with the SWI model. The comparison between the two inversion models illustrates that inversion of SkyTEM data is not straight forward in an area affected by saltwater since the resistivity distribution is a function of both chloride concentration and geological heterogeneity (see also Gunnink et al., and Jørgensen et al., this issue). Hence, the resulting salinity distribution is associated with substantial uncertainty and it is difficult to use the results directly in a quantitative calibration exercise. Instead, the data have been used for a more qualitative type of validation where visual comparison of the saltwater distributions has been performed. Based on this comparison we find that the model is able to describe the general pattern of freshwater/salt water distribution satisfactorily, however, with significant discrepancies locally. In conclusion we agree with the reviewer that further calibration is needed on both the SWI model and the SkyTEM model to improve both, and this work is in progress. As the inverted data became available at the very end of the project this was not possible within the project as this work is quite time consuming. Anyway, we definitely find the data worth publishing in its current form. We find that the established SWI model partly based on experiences and data obtained from other studies on Danish Chalk aquifers (e.g. Bonnesen et al., 2009) in some parts of the study area better depict the actual (directly observed) situation in the Chalk aquifer than the SkyTEM interpretations. This is for instance the case at the new deep investigation well (see reply A above). We have added a short paragraph in the discussion to describe required future work on joint inversion.*
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- *C) We will include a short description of how and where we believe the SkyTEM model results can improve the calibration of the SWI model and how and where the SWI model may improve the SkyTEM model results.*

RC: Presentation Quality:

Good: The article is well written, nice to read with clear figures. The authors are clear about the calibration process and assumptions.

RC: Comments and questions:

RC: - P 7973: can you indicate the location of Boto Nor and the Marrebaek on figure 2?

AC: These locations will be added to the figure.

RC: - P 7974: can you include a cross-section of the geology (figure) including depth?

AC: A new figure will be included in the final manuscript.

RC: - P 7976 first half: what is the yearly mean groundwater recharge in m3/yr for the model area and the whole area compared to the pumping m3/yr (is there enough water?)?

AC: The mean groundwater recharge for the model area is 8.460.000 m^3/yr, where the total groundwater abstraction is 400.000 m^3/yr, or 4.7 % of the recharge

RC: - P. 7983: is there no change in sea level rise between the phases 1-4? Is that realistic or why did you use this assumption?

AC: Due to the post-glacial rebound in the area the uplift have outbalanced the sea level rise and is considered to be negligible having in mind other uncertainties of the hydrogeographic development over the same period. This will be clarified in the revised manuscript.

RC: - P. 7983: no flow boundary is used along the outer boundaries. Is there for example no outflow on the western boundary and no inflow on the northern boundary (bases on the elevation map fig 2)?

AC: As the focus area of the model simulations are in the central eastern part of the model area we find the approximation of no-flow for the northern boundary reasonable, and it is to some extent confirmed by the though coarser DK-model (Højberg et al. 2008 – see references in paper)

RC: - P. 7985: Can you explain why there is almost no difference in the residual error between a with and a without density model?

AC: The stage of the drainage canal is controlling the groundwater head in the barrier island area between the drainage canals and the eastern shore line where also the majority of head measurements for model calibration are measured. The density of the saltwater in the Baltic Sea is quite low compared to the density of standard ocean water (salinity is less than 1/3 of standard ocean water) meaning that density effects are less significant.

RC: - P. 7985: what were the main changes in the parameters before and after calibration?

AC: The sensitive parameters in the calibration process were the vertical hydraulic conductivity of the clayey till, the horizontal hydraulic conductivity of the upper chalk aquifer layers, and the drain conductance. This has been clarified in the revised manuscript.

RC: - P. 7988: large difference is depth 150 mgl^{-1} interface measurements and model. See comments at 'scientific quality'.

AC: …Yes, there is a quite large difference between the estimated depth to the 150 or the 250 mg/l interface by the model and SkyTEM, while there's a very good agreement between the model, the well log and chloride concentrations in level-specific water samples from the deep investigation well. This demonstrate that joint inversion will benefit both SWI model performance and SkyTEM resistivity models as mentioned in the replies A and B in the "scientific quality" section above, and also in the reply to reviewer #2, who addressed the same issue.

RC: - P 7995: line 16: more than 100 yr; this is not shown in the table / measurements?

AC: …"and in a few cases more than 100 yr" has been deleted in the revised version this information is not of significance in the context and has been removed to avoid confusion

RC: - P 7995 / table 9: the 3H/3He age in years is constant for all wells (>75 yr), except 1 well (75 yr). What does > 75 mean, can it be much more than 75 yr? Why can you compare those

constant values with the simulated travel times?

AC: …there are generally no measurable or only very low 3H (tritium) and tritiogenic He (trit-He) contents in the groundwater sampled from the chalk aquifer <u>(trit-3He = 3He formed during the decay of radioactive 3H)</u> - except in well 242.317 where an elevated trit-3He content is observed that corresponds to an estimated 3H/3He age of 75 yr (Table 9.). The very low 3H and 3He contents in all other wells make it impossible to assign an absolute tracer age by the applied tracers. However, the absence of these environmental tracers show that the sampled groundwater is older than the water in well 242.317 i.e. older than 75 years (or > 75 yr as indicated). We have included a small paragraph clarifying this in the revised manuscript and cited two relevant papers (Weismann et al., 2002; Troldborg et al., 2008) discussing comparisons between simulated travel times (groundwater model ages) and groundwater tracer ages, which is already in the reference list. In six out of nine wells there's a reasonable agreement between the tracer age and the simulated travel times. Both datasets agree that the groundwater ages in the upper chalk at depths of less than 20 m are relatively old and generally pre-modern. This is confirmed by the absence of any human impact on the groundwater chemistry as no contaminants are found in the water supply wells indicating that the groundwater was recharged before 1950 (Hinsby et al, 2001).

RC: - Table 6: hydraulic conductivity clay and chalk is quite large ($5*10^6$ m/s)

AC: Correct – however, the clay is shallow clayey till, which generally exhibits relatively high K values due to root holes, fractures and sand lenses, - likewise the upper part of the chalk has been exposed to Quaternary glaciations causing a fracturing of the upper part of the chalk as indicated by the borehole propeller flow log and increased the K-values significantly (Fig. 8)

RC: Small notes:

P. 7971 first line: 'patterns. This will challenge' instead of 'patterns will challenge'

P. 7972 l (=line) 5: remains

P. 7972 l 6: wedge is

P. 7974 l15: ground surface is

P. 7976 l 25: name in figure 5 is just 179, can you make this consistent?

P. 7976 l 27: 242.44B in not on the map

P. 7981 l 12: table 1 refers to 6 model phases, not to climate scenarios

P. 7985: can 4.4 be a part of 4.3?

P. 7994 l 7: shows

References: Sanchez et al 2012 is missing

Figure 7: orientation west-east and south-north?

Figure 9 b: too small

Figure 11 d: this is scenario 1 instead of 0?

Figure 11 d text: row 68 instead of 62

AC: The final manuscript will be corrected according to all 'small notes'.