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“Numerical modelling of climate change impacts on freshwater lenses on the North Sea Island of Borkum” by H. Sulzbacher et al.

Author Comment to Referee #2 by Hans Sulzbacher and Helga Wiederhold

We like to thank Referee #2 for the very profound comments and appreciation of our work. Below we respond (indicated by R) to the comments (indicated by C).

General comments

C: In this paper, a comprehensive description of an extensive hydrological, geophysical and geological dataset of the island of Borkum is presented. This dataset is used for the construction of a hydrogeological model and the calibration of a numerical groundwater flow model. The numerical model is used for the quantification of future scenarios.

I appreciate the ‘holistic’ approach of this study, and the fact that it has clear added values for society. In my opinion, this study is certainly suited for publication. However, I do have some comments that might improve the paper.

Although the description of the hydrological, geological and geophysical data and model calibration is extensive, the description of the numerical model has been given relatively little attention. This model is however important, as it is used for the quantification of future scenarios. Moreover, the title of this paper suggests that numerical modelling is a core focus of the paper. I therefore suggest to expand the description of the numerical model (see also below). As a result, the paper might become too extensive. My other general remark is therefore to reduce the description of (geophysical) dataset and calibration procedure, or change the scope and title of the paper.

In order to improve the structure of the paper and hence, enhance its readability, define some specific objectives in the introduction of the paper. Then, in chapters 3, 4 and 5, try to reduce the amount of words by only mentioning the things that are relevant for these specific objectives.

R: Thank you very much! The paper has two goals: The first one is to illustrate the geophysical and hydrological methods and how they contribute to develop a density-dependent numerical model. The second one is to describe the simulation results with respect to the impact of climate change. Therefore, we prefer not to substantially shorten the description of the methods but change the title to:

Numerical modelling of climate change impacts on freshwater lenses *on the basis of hydro-geophysical data*

The numerical model now has been described in more detail. Two new tables with fixed flow and mass transport parameters have been included in the paper. The choice of the boundary conditions has been elucidated in much more detail during calibration as well as for the sea level rise scenarios.

Be aware that section 3 focuses on what was done in preparation to the modelling. As it is entitled “material and methods” it all refers to pre-work required as input for the ultimate modelling. Results in the context of this study are simulation results

Since we see that you have consistently pointed out the difference between modelling results and measurement results, we propose to rename section 5 “calibration” to “calibration results”

Specific Comments:

C: P 3478, line 1. Abbreviate like: mean sea level (m.s.l.), not the other way around.

R: Corrected

C: 3485l, line 22-24. What kind of numerical model did you use? Can you elucidate this a bit more?

R: Two-dimensional variable density model simulations with FEFLOW indicate that the aquitards consist of non-persistent cohesive material (predominantly clay, so-called patch rock), schematically shown in Fig. 7 (bottom right). The models were designed as vertical NW-SE cross sections through Borkums aquifer with the appropriate spatial dimension and set up with typical average values for all aquifer parameters such as hydraulic conductivity, porosity or specific yield.

C: 3486, line 15-18. Can you elucidate why the numerical model is almost three times as large as the island of Borkum itself? What is the relationship with the (offshore) boundary conditions that have been adopted here?

R: The setup of the three-dimensional numerical model with the finite element code FEFLOW is designed according to the hydrogeological model. The model area incorporates wide parts of the Wadden Sea and is approximately three times as large as the Island of Borkum itself (Fig. 9, left panel, see manuscript). This figure shows "natural" boundary conditions for the sea water - aquifer interface at 1 m depth. (constant head and constant mass transport). It can be seen that this important interface occurs at a very low water depth over wide offshore the island of Borkum, also beyond the outer boundaries of the modelling domain. The correct location of the interface between aquifer and sea in the model is important to the simulation accuracy and can be realized only by a large model area. This is necessary to assure that the "artificial" no-flow boundary conditions for flow and mass transport at the outer edge of the modelling domain don't affect model calibration and simulation results.

C: 3487 , Last two lines and p. 3487, first two lines. I don't understand what you mean with: 'a specified mass boundary condition at the surface nodes of the groundwater table'. Shouldn't this be: A specified flux boundary condition with an assigned (constant) concentration? And why didn't you apply a specified flux?

R: It is correct to set fixed mass concentrations (TDS) at the surface of the aquifer (the water table) to compute the TDS at the subsurface. The mass concentration can be obtained from measurements of the pore water electric conductivity and airborne electromagnetic data as shown in Sect. 3.2. The propagation of the mass concentration from the surface to the subsurface is caused predominantly by recharge modelled as vertical flux using Neumann boundary conditions. Of cause, significant changes of this surface mass concentration generated by important hydrological events like construction of dikes or due to the proceeding flood caused by sea level change have to be constantly adapted during simulation runs.

To achieve reliable prognosis results for sea level rise, the level of constant head boundary conditions representing the surface of the sea water was shifted for each time step during simulation. This was done by means of a linear function, beginning with 0 m in the year 2010 and ending with 0.96 in the year 2100.

Moreover, the area covered by this type of boundary conditions had to be extended more towards the shore, representing the risen mean sea level which will have progressed also in horizontal direction and will have been regularly flooding in 2100 an additional 25 % of the island (Fig. 18 right panel, in the manuscript). This would also imply that the constant mass transport boundary conditions will have to be adapted to full sea water concentration in these additionally flooded areas (see Fig. 1, below)

The mass concentration at the surface of the aquifer is caused mainly by sea spray, flooding events and river upconing of sea water. There is no available data on these influences.

Working with guessed parameters and setting flux boundary condition with an assigned (constant) mass fracture would lead to ambiguous results even if an appropriate fit would be achieved.

The method for setting boundary conditions in the Borkum model is common praxis in density-dependent ground water modelling, as documented in the technical reference manual of the FEFLWO distributer DHI-WASY GmbH
http://www.feflow.info/uploads/media/white_papers_vol1_01.pdf

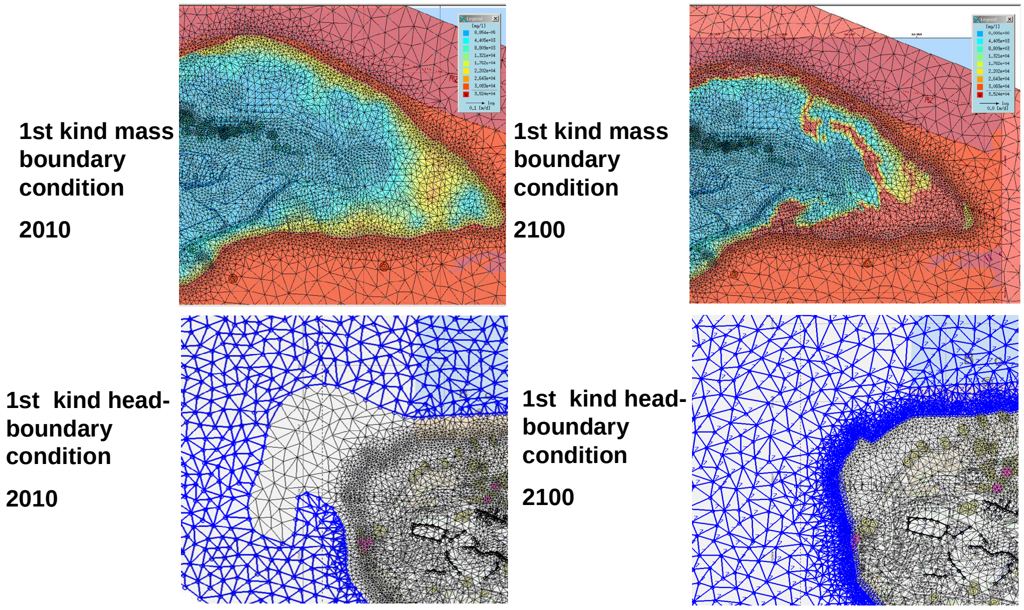

Fig. 1. Adaptation of constant head and constant mass transport boundary condition during simulation of the IPCC A2-szenario, sea level rise of 0.94 until 2100

C: 3487, line 6-10. I would merge these two paragraphs.

R: will be done

C: 3488, line 10. The units of the hydraulic conductivity are missing.

R: will be added

C: Specific comment on the section 4.2 A particular problem in using finite element codes to simulate density dependent groundwater flow and solute transport is the numerical dispersion that is introduced when the element size becomes larger then about 4 times the dispersion length. Typical dispersion lengths are normally no more then 1 meter in relatively homogeneous aquifers. How did you deal with this (i.e., what dispersion length did you use and what is the maximum element size?)

R: A high degree of discretization was chosen in order to assure numerical stability and to be able to resolve the network of open waters and the complex course of the coast line also in horizontal direction, (Fig. 9, right). In particular, this was necessary in areas where high gradients of freshwater-saltwater distribution were detected. Cell sizes down to 10 m were implemented in order to meet the Peclet criterion for the maintenance of numerical stability (Kinzelbach, 1987a). In outer regions of the Wadden Sea without significant flow a relatively coarse net of cell sizes of about 200 m was used.

Fixed flow parameters which were used in the model for all 4 aquifers are summarized in Table 2. For the horizontal hydraulic conductivity k_f, horizontal isotropy k_{fx}/k_{fy}=1 is assumed whereas a vertical anisotropy k_{fx}/k_{fz} of 1 – 20 was determined by model calibration (Sect. 5).

A value of 0.25 is assigned to the specific yield for all four aquifers which is in accordance with the pumping test results (Sulzbacher 2011). Mass transport parameters are presented in table 3. A porosity value of 0.25 was assumed for the whole ground water body, which is in consistent with the results of the MRS measurements (Sect. 3.1.2).

Table 2. Fixed flow parameters.

kf_x/kf_y [m/s]	1
Density ratio	0,0270
Specific yield [1]	0.25
Compressibility [1/m]	0.001

Table 3. Fixed mass transport parameters.

Porosity [1]	0.25
Diffusion [m²/s]	1E-9
Long. dispersion[m]	5
Trans. dispersion[m]	0.5

C: Caption Figure 3: Include the meaning of the dotted line.

Figure 3. Groundwater table of the upper aquifer during March 2010 (water supply wells marked by red circles, location of CLIWAT drillings marked by black stars, mean sea level marked with a dotted line)

C: Caption Figure 4: Omit abbreviation of electrical conductivity (ec).

R: EC is used in the legend inside the figure and should not be omitted therefore

C: Figure 5: in the upper right picture, 'L29.1' is missing.

R: will be corrected

C: Caption Figure 5: second line, after 'bottom panel': cross sectional view along transects T13.9 and L 29.1.

R: Figure 5. (Top) Electrical conductivity (σ) maps at different depths derived from helicopter-borne electromagnetic survey (HEM), (bottom): cross sectional view along the transects T13.9 and L29.1.

R: (Comment: the black line of the "bird" (transceiver) in the cross sections is dropped in the corrected figure)

C: Caption Figure 6: Instead of 'surface of the groundwater table', use 'phreatic surface' or 'water table'. Moreover: line 4: 'at the surface' instead of 'at surface'.

R: Figure 6. Regionalization of electrical conductivity data at the water table by means of data from helicopter-borne electromagnetics (HEM) and apparent formation factors. (Top left panel) electrical conductivities at 0 m m.s.l. from HEM, (bottom left panel) locations of electrical conductivity from manual readings at the water table (see Fig. 4), (top right panel) apparent formation factors at the water table, (bottom right panel) regionalized conductivity map at the surface of the groundwater table.

C: Figure 9: I would omit the left panel of the figure, it does not have an added value.

R: Figure 9. Setup of the numerical model, (left panel) horizontal discretization and mass transport boundary conditions. The blue marked cells represent sea water boundary conditions at a depth of 1 m (TDS = 35000 mg/l), (right panel) discretization of model in areas with high complexity. The model consists of 39 superposed horizontal layers, downwards with increasing distance to each other.

C: Caption Figure 10: Please reformulate this caption

R: Figure 10. Statistical results for hydraulic calibration (x-axis: measured hydraulic head [m], y-axis: computed hydraulic head [m]).

C: Caption Figure 17 (new Fig. 16): Please omit ‘altitude’.

R: Figure 16. Computed groundwater table for 2010 (left) and 2100 (right) by using the ICPP-A2 emission scenario. The groundwater recharge will increase linearly by 10% (average scenario).

C: Page 3486, line 15. I would use ‘code’ instead of ‘programme’.

R: Done

C: line 26. 35000 mg/l instead of 3500.

R: Done