Hydrol. Earth Syst. Sci. Discuss., 9, C2165–C2165, 2012

“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 #1 by Hans Sulzbacher and Helga Wiederhold

We thank Referee #1 for the careful review, constructive comments and appreciation of our work. Below we respond (indicated by R) to the comments (indicated by C).

General remarks:

R: We would like not to split the paper but to stay with one paper. 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.

Specific comments:

R: We updated the references. Concerning the organization, please 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”

Other comments and technical corrections:

All spelling comments will be considered and changed in the revised version and are not all listed in the following.

C: P. 3475:

R: will all be done in the revised manuscript. Also older references were chosen to demonstrate the evolution in groundwater modelling techniques during the last decades. Three recent paper from Post and Abarca (2010), Kinzelbach (2010) and Post (2005) are now included.

C: L. 15: Is it easier to understand if you say salinity instead of density?

R: The data acquired on Borkum are electric conductivity data and not chloride data. It is possible to transfer these conductivities into densities or total dissolved solids (TDS) by a constant factor. It is not possible to transfer these data into NaCl because the chloride / TDS ratio is not constant all over the island. Strictly speaking, this is the case only in the vicinity of the coast. Some distance offshore, in particular in the environment of the water works, other ions like Mg+ or So4- make a significant contribution to the pore water conductivity. The use of TDS instead of salinity is therefore much more precise and used for all numerical computations.

C: P. 3476, 5 ff. Drop this sentence, it is already discussing results?

R: These are just suggestions and motivation for the simulation of the climate scenarios and not results. Therefore, we think the sentence should remain in the introduction. Results in the context of this study are simulation results

C: P. 3477: Is Figure 2 needed?

R: we think yes; Fig. 2 is referenced in many locations in the text of the paper and is necessary to understand the calibration procedure. Fonts have been enlarged.

C: P. 3478: Be aware if you also want to discuss results in a section on materials and methods.

R: Results in the context of this study are simulation results. Here are discussed tools for setting up the model.

C: L. 21 ff: Why so low recharge?

R: Because silt and clay predominate near the surface of the terrain and most of the precipitation is drained prior reaching the ground water table.

C: P. 3479: L. 3: What is actually shown? There are different T values? Again, be aware if you think this is results?

R: Table 1. Transmissivities (T) obtained from pumping tests. According to the configuration of the pumping test for all locations of the loggers in the draw down area with 2,5,10 m … distance to the pumping location, transmissivities T(2m), T(5m), T(10m) … were computed and averaged to one transmissivity T at the pumping location. We will revise the panel of Table 1.

C: “Open water levels” are these ponds/lakes?

R: Any water inside the island with an open surface. These are lakes, rivers, creeks, canals, drainage ditches etc. Will be explained better in the manuscript.

C: “Gimlet”?

R:  Gimlet (see dictionary), or auger drill.

C: Sounds like a very low precision with a Trimble, isn’t it more on the order of 1 cm?

R: The accuracy is less than 1 cm in horizontal and less than +- 6 cm in vertical direction.

C: P. 3480, L. 4: open water systems. Are these canals/ditches/rivers?

R: Any water inside the island with an open surface. These are lakes, rivers, creeks, canals, drainage ditches etc. Will be described in manuscript in more detail

C: L. 6: here it says rivers, may show on map?

R: see Fig. 1. The catchment area is described and shown in detail in (Sulzbacher 2011). These open water systems are big enough to say “rivers”. The names are “Hopp” and Tüskendörkill (corrected in manuscript).

C: L. 23: What does “bird” mean in Fig. 5?

R: HEM conductivity data and altitude profile of the helicopter transceiver (bird). The profile where “bird” is mentioned has been dropped in the figure.

C: P. 3481, L. 20: “in order to achieve calibration using a pumping test”. Sentence is unclear.

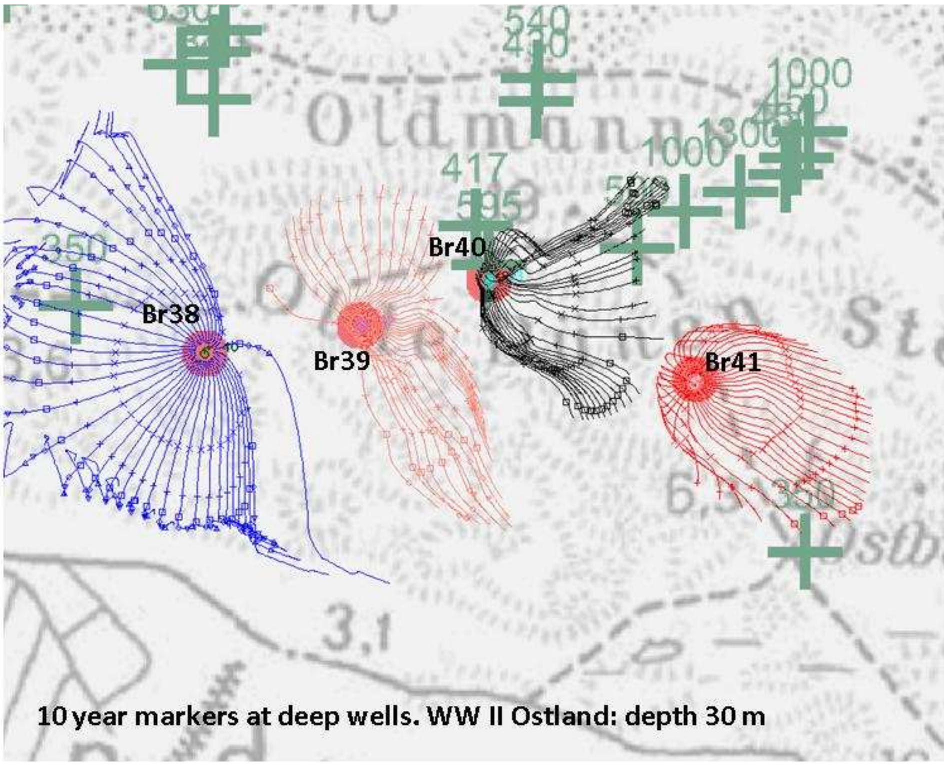
R: Results of pumping tests P-Br38a and P-Br38b, carried out near the CLIWAT-II drilling, as well as pumping test P-OD33 were used to achieve calibration. Will be changed in manuscript

C: L. 24 ff: Again results.

R: Be aware that in this paper results are understood as model results. Otherwise results refer to measurement results. We want to strengthen the point that for the hydrological and geophysical methods there is an extra report that describes the measurement results at length. Here they are just briefly addressed.

C: P. 3482: Drop Section 3.1.3, never really used quantitatively. Reference is Solomon or Cook? Spelling error "per bottle"

R: In the vicinity of water supply well Br-38 quantitative comparisons of computed and measured water age were carried out. Travel times can be determined by the particle tracking module of the numerical model (see Figure). Computed travel times and those, determined by age estimation, agreed fairly well. As proposed, however, by the anonymous referee this section will be dropped to keep close to the focus of the paper.



C: L. 15: The temperatures; are they from shallow groundwater and what is the uncertainty in this. Like saying, if the temperature changes +/- 1 C what effect does this have on the estimated mass concentrations in the very end? In this section you say "strongly" so I think you should address how much it means.

R: The conductivity or the mass concentration computed from conductivities by a linear factor rises by about 4% when the pore water temperature increases by 1 °C. Will be better explained in revised manuscript

C: P. 3483, L. 1: Do I read it correctly that Fa has no meaning at all, while later you say one Fa valued can reflect clay+fresh water or sand+ salt water.

R: of the surface electric conductivity data independent from its hydrogeological meaning. (corrected in manuscript)

C: L. 10 ff: These are results.

R: Be aware that all this 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

C: P. 3484, L. 6 ff: Is this because of submarine groundwater discharge, ie. the dilution?

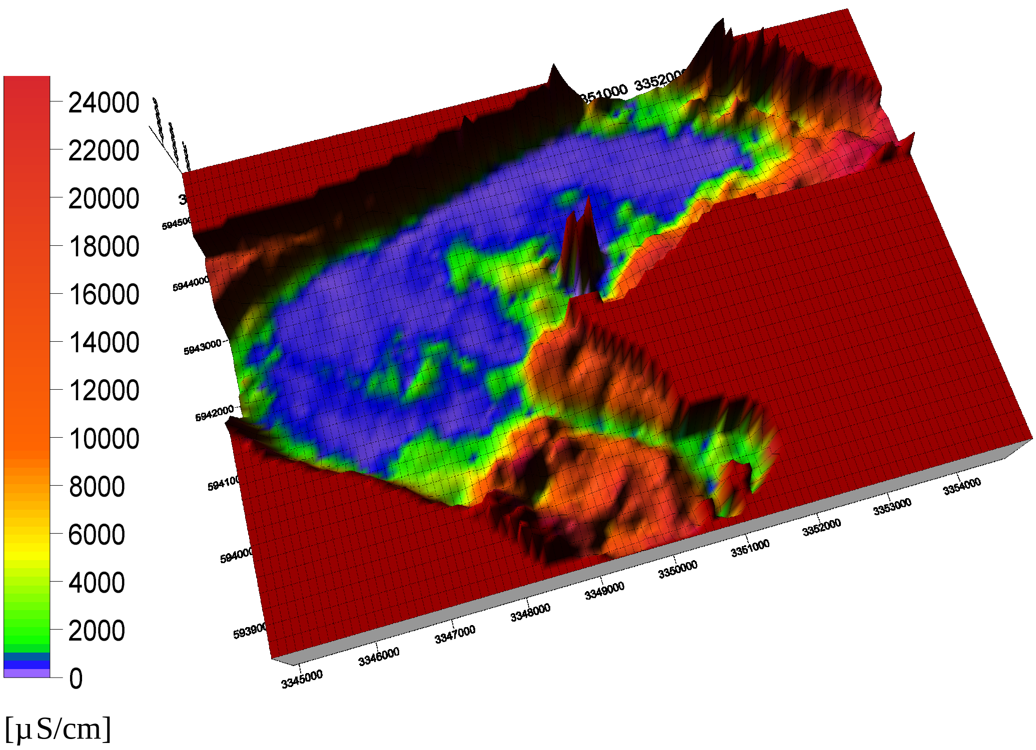
R: ... Manual measurements of the electrical conductivity at the sea water near the shore of Borkum and the analysis of sea water samples in the Laboratory of the Geozentrum in Hannover show that this is approximately the case also in the Wadden Sea around Borkum. Submarine fresh water breakouts from the aquifer therefore play a negligible role.

C: L. 16: Do you mean water table when you say “surface of the aquifer”?

R: yes (“…at the water table referring to water…” changed in manuscript)

C: L. 20: I shouldn’t suggest an extra figure; anyways, it could be nice to see profile of these results as it is difficult to detect the subtle changes in colours on the map.

R: In this 3D-figure one can see individual structures of the pore water electrical conductivity.



C: L. 21: Not clear what is meant by “124 water analysis probes”.

R: In total 124 water sample analyses were conducted from the sea water samples at different locations, from water supply wells, new drillings or Direct Push measurements and evaluated in the laboratory of the Geozentrum in Hannover. From electric conductivities at 5 °C and TDS values M was determined. (will be corrected and described better in the manuscript).

C: L. 24: Say “initial mass”.

R: ….mass transport initial and boundary conditions... See reference of FEFLOW for the right designation http://www.feflow.info/uploads/media/white_papers_vol1_01.pdf

C: P. 3485 Is it relevant to show a "real" geological profile (adding yet another figure)?

R: The hydrogeological structure of the aquifer is rather heterogeneous (see for instance fig. 7 bottom right panel). Therefore we think it is good and sufficient to refer to this two-dimensional schematic cross section as has been done in the manuscript.

C: L. 20: Many times you use adjectives like "sufficiently" close. If so, you need to be define what you mean by this.

R: …..is implemented sufficiently close to reality to meet accuracy demands for the prognosis results (changed in manuscript).

C: L. 20 ff: I have not read these two editorials, but I find that they can not stand alone without arguing what is meant in the context of your modelling. Perhaps yes if it is to extend a model to year 2100.

R: ...too many details do not necessarily improve the model prognosis capabilities. This means that generalizations and simplifications are required and acceptable without loosing prognosis capabilities of the model. (changed in Manuscript).

C: L. 22: Suddenly results again.

R: These are not final modelling results. These are just necessary accompanying schematic calculations, that is, prior 2D analysis with a simplified FEFLOW model. This is necessary to understand the nature of the aquifer separating aquitards prior of the construction of the hydrogeological model and the more realistic 3D numerical model.

C: L. 25 ff: Move to geophysics section?

R: It is discussed here for a better understanding and support of the structure of the hydrological model.

C: P. 3486, L. 7 ff: Results?

R: No modelling results, results of field work discussed in an extra study (Sulzbacher, 2011).

C: L. 9: What is the concept of leaky or missing aquitards?

R: The results of the pumping tests are in accordance with this model concept. In particular, the large transmissivities determined by the tests in the coastal region (P06 in Table 1) are in agreement with the idea of leaky or missing aquitards in this region as it is demonstrated in fig 7 (bottom right panel) . In the centre of the island the smaller transmissivities (P01, P02, P-OD33 Table 1) suggest that layers separating the aquifer are also hydraulically separating and therefore exhibit rather the character of aquicludes (Sulzbacher, 2011). (Description will be improved)

C: L. 21: Recipients, are these the open water systems?

R: yes, must be "of open water…"

C: L. 21: What is meant by complex devolution?

R: the course

C: L. 26: 35000 mg/L.

R: c will be corrected in manuscript

C: L. 28: I am sometimes confused when you just say mass. You mean mass concentration?

R: Mass transport initial conditions and mass transport boundary condition are the right designations http://www.feflow.info/uploads/media/white_papers_vol1_01.pdf; (will be corrected in manuscript)

C: P. 3487, L. 1 ff: I am not sure if I find it acceptable to fix the mass concentration on the surface nodes (=water table). Shouldn't this be part of the solution? No wonder you get "nice results" as the whole Borkum is fixed by known concentrations at all sides. Or am I misunderstanding this? Wouldn't it be more logical to assign a recharge with an associated mass fraction (e.g. increased because of sea spray). A discussion of this would be appropriate, e.g.

R: There are many applications in hydrological modelling where the use of Dirichlet boundary conditions for head or mass concentration is an appropriate method for solving tasks. An example for this can be a well field, in a steady state aquifer where the level of the groundwater table is known and the unknown delivery rates have to be computed. Here the heads have to be fixed by a 1st kind boundary condition. The flow to the wells can be detected then by a water balance tool.

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

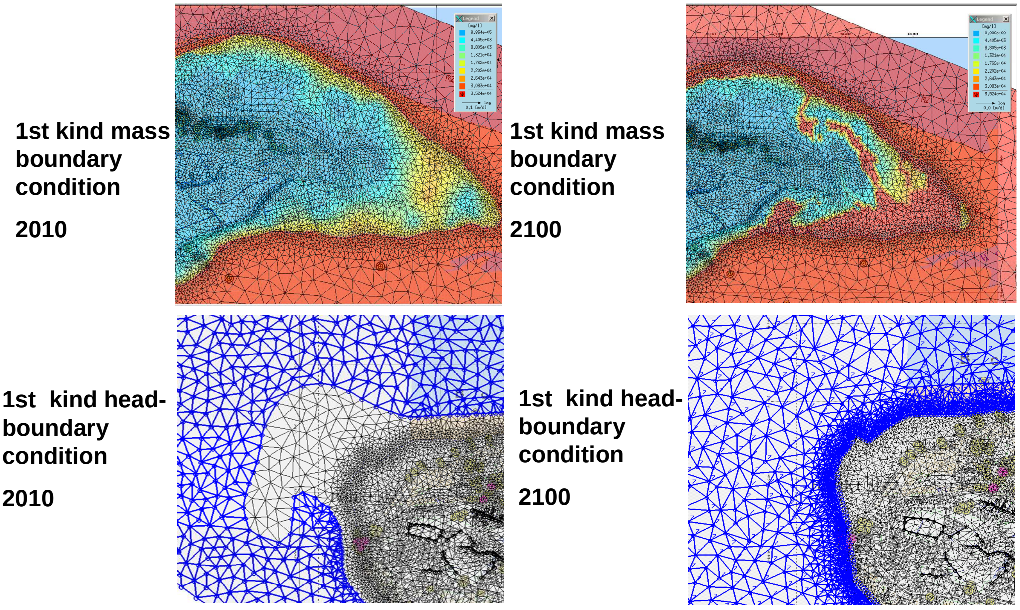


Fig. 1. Adaptation of constant head and constant mass transport boundary condition during simulation of the IPCC A2-szenario, sea level rise of 0.94 until 2100

C: ...in relation to Figure 15, which shows an impressive fit of the simulated EC, the proxy HEM EC, and the EC estimated from the electrical chain. In the top (where EC is fixed?) there is a very good fit, which slightly gets worse with depth, although still impressive, and where you have good arguments why the electrical chain shows differences.

R: …satisfying agreement in the range of the expected calibration accuracy (Fig. 15). Best fit between HEM and computed electric conductivity is achieved at the top slice (the water table) where a comprehensive high resolution data set is available. In particular, the apparent formation factor as define and determined in Sect. 3.1 is known at this location (Fig. 6 top right panel). The match between computed electric conductivities and those obtained by the vertical electrode chains of CLIWAT I and II is also acceptable. Differences between the smoothed HEM model, electric chain data, and computed values at the freshwater-saltwater interface are mainly caused by apparent formation factors.

C: L. 10: So there is an unsaturated zone in FEFLOW as well (parameters?).

R: In areas above the free aquifer an unsaturated zone is considered by FEFLOW. The method and default parameters, which were used for this particular task, are described in the technical reference manual of the FEFLOW distributor DHI-WASY GmbH. http://www.feflow.info/uploads/media/white_papers_vol1_01.pdf

C: L. 10: Some where you should mention how you specified recharge.

R: …. subsurface is caused predominantly by recharge modelled as vertical flux using Neumann boundary conditions. …

For the simulation of the ICPP A2 scenarios the flux boundary conditions which were used for recharge were specified as time varying linear functions, representing the increase of the recharge until the end of the current century.

C: L. 26: Is it true that I count only 9 (nine) time steps to take the model from 1934 to March 2010? I find that hard to believe?

R: The transient hydraulic calibration was conducted beginning with the time after the construction of the great south dike in 1934 until March 2010, being this latter the reference time. The calibration was carried out using large time steps for the discretization of the delivery rate (Fig. 2), in the beginning (first 64 years and then 10 years) followed by shorter steps (three steps of one year and then three steps of one month). Due to the inertia of the system a calibration with a finer time discretization of the abstraction pattern does not yield better calibration accuracy. Each of these delivery intervals was further discretized by the automatic time step control of FEFLOW into about 45 further time steps, resulting in a total of about 360 time steps for one calibration run for the time span between the dike construction and reference time.

C: P. 3488, L. 10: I assume these relate to the 4 aquifers and 3 aquitards, perhaps show better? What did you assign for anisotropy, porosity, dispersion parameters, etc.

R: 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: L. 11: Perhaps add r^2 to give real statistics of the fit?

R: Mean square added in figure.

C: L. 16: Only place you mention tracer (=tritium/helium?), but not in quantitative way, thus I suggest to take this part out completely as it is not fair to the reader to have a section on its sampling/analysis and then not show how it was used directly.

R: The part tracer (=tritium/helium) has been dropped completely.

C: P. 3489, L. 7 ff: This sounds more like data, move to description of site?

R: Not changed

C: L. 14: I wonder if there are any remnants of the previous floodings?

R: While drilling the borehole for pumping test no 4. located near lake Tüskendör, a more than 1 m thick layer of shell deposits at a depth of 1 – 3 m was observed.

C: L. 14: Reword first sentence.

R: Done

C: L. 21: Explain better “Thinned by the system ..”

R: In the marshland area, however, the freshwater lens is thinned due to upconing of sea water from below by the system of drains and creeks.

C: P. 3490, Maybe the list here should come earlier as some looks like repetition. Not in this detailed description

R: List shorted

C: L. 7: Sentence unclear.

R: The more in the past, the more the fluctuations of the delivery rate of the waterworks can be averaged without affecting the calibration accuracy.

C: L. 8: “discretization of the delivery rate” do you mean time stepping? Which makes me think how you implemented this with maybe only 9 time steps?

R: The discretization of the delivery rate and the automatic time stepping of the program during calibration of the mass concentration is the same as the one used for the hydraulic calibration (see Sect. 5.1).

C: L. 17: Sufficiently?

R: ...match acceptably well...

C: L. 23: Fairly?

R: I …..agree, taking into account the underlying inaccuracies, in the range of an acceptable calibration accuracy with the …..

C: P. 3492, L. 2: Fairly?

R: acceptable

C: L. 16: Satisfying?

R: ...in the rage of the expected calibration accuracy...; o.k.

C: P. 3493, L 1 ff: delete + figure 16?

R: Fig 16 deleted

C: P. 3494, L. 6: Why in good agreement with Chang?

R: Citation deleted

C: L. 10 ff: Here the figures are not so easy to understand especially the colouring scheme with hatched areas etc.

R: …for the conservative scenario which can be seen in the fringe plot by the colour transition from yellow to orange to red.

Note: Here a not low-quality monitor and graphics card are required to see the transparent coloured pdf-graphics without shading. The same is valid for Fig. 11, 12 and Fig. 17,18, 19. Quality of figures will be improved in revised manuscript!

C: P. 3496, L. 9: Maybe say which distances the wells are moved? How certain is this?

R: Distances can be seen from the scale in the improved figure.

In regards to the certainty of these results the evolution of the future recharge is a sensitive key parameter estimated from precipitation only, which implies much insecurity.

To see how certain the computed density distribution for the new well configuration is, additional sea level rise scenarios with different recharge rates from 2010 until 2100 (very dry scenario with no recharge increase, average scenario with linear recharge increase of 0-10% and linear increase of recharge 0 – 15%, wet scenario) were carried out. Model results show that for all these scenarios the obtained well configurations for both water works (Fig. 22) are valid and the salinization of the drinking water for all delivery wells remains below the permitted limit.

C: P. 3497, L. 13: Thoroughly.

R: What is wrong?

C: L. 15: Travel times, can not conclude since no data or analysis.

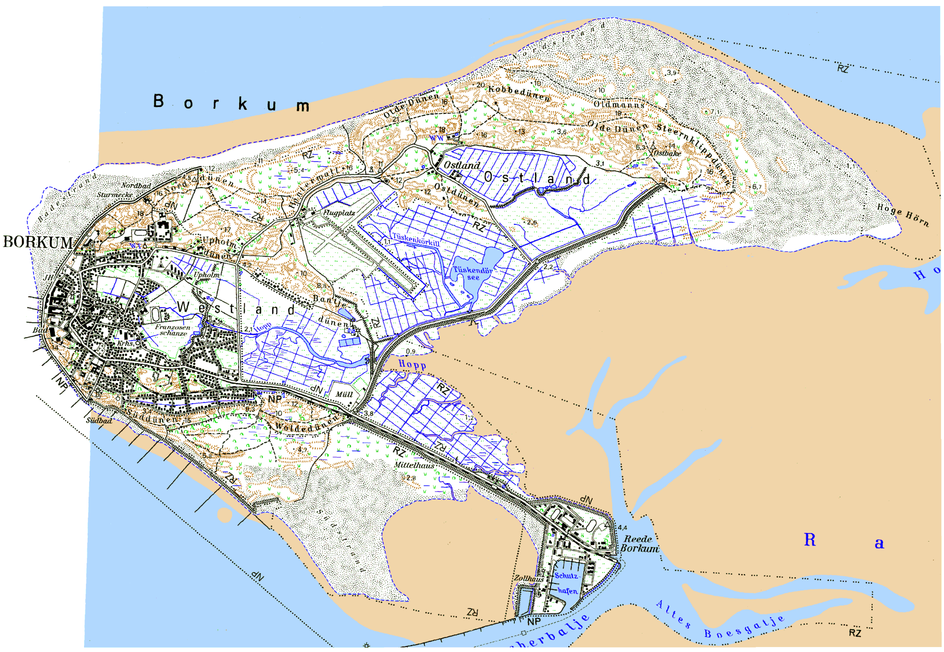
R: All about age estimation has been dropped.

C: Table 1: What do the various T columns mean?

R: Table 1. Transmissivity (T) obtained from pumping tests. According to the configuration of the pumping test for all locations of the loggers in the draw down area with 2,5,10 m … distance to the pumping location, transmissivities T(2m), T(5m), T(10m) … were computed and averaged to one transmissivity T at the pumping location.

C: Figure 1: Show open water systems

R: The system of open water is too complex for showing all details on the map in fig. 1, wherefore I refer to Sulzbacher (2011). In Fig. 5 the network of creeks, trenches and channels can be seen on a grey scale bitmap. It does not make much sense to colorize these open water on the map because in this case there would be too much information on the map. If necessary an additional figure is required.



Open water systems on Borkum (blue), Wadden Sea (brown)

C: Figure 2: Needed? Otherwise, needs larger fonts.

R: Figure 2 needed. Fonts enlarged.

C: Figure 5: What does the line bird mean?

R: ‘Bird’ is the sensor mounted on the helicopter. Curve of helicopter sensor is unimportant and has therefore been dropped in the figure.

C: Figure 6: the sigma w has an odd scale

R: corrected

C: Figure 7: Is the right part needed?

R: Right part of figure is needed to understand the concept of the hydrogeological model and to show the heterogeneity. It is in text referred to.

C: Figure 8: Needed?

R: I think we will omit it. The text should be sufficient to understanding the content.

C: Figure 9, shows how complex the mesh is but also a bit difficult to see.

R: Figure 9 has been improved.

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 with depth.

C: Figure 11, 12, and 13: Low quality

R: Figures will be improved.

C: Figure 14: Is the right part needed? The dashed lines to the left, are they supposed to have the same colour as the solid lines?

R: The right part of the figure is needed for illustrating why the deep screens of WW II get heavy salinity problems and why they have to be switched off. Solid lines in the legend box stand for solid lines and dashed lines in the legend box stand for dashed lines of the same colour.

C: Figure 16: Needed?

R: Figure omitted.

C: Figure 17-19: low quality.

R: Quality of figures will be improved.