

Interactive comment on “Fresh groundwater resources in a large sand replenishment” by S. Huizer et al.

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Received and published: 4 April 2016

We would like to thank the Referee for the comments, which are highly appreciated. We will improve the raised issues.

General Comments

“1. P6L1-6. The authors give details on the spatial grid. The last phrases indicate that the authors are aware of spatial discretization problems inherent to variable-density flow simulations. However, it appears that the authors have not conducted a grid convergence test. Does that spatial discretization exclude numerical round-off and truncation errors? The simulations are certainly transient (the authors should say so), so have the authors examined the effect of temporal discretization? What is the time-step size? Which time-stepping scheme is adopted, constant, adaptive, error-controlled? Both

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the spatial and temporal discretization must be justified. All of this must be clarified in the revised ms version.”

We agree with the Referee, and will perform additional simulations for the reference scenario to justify the spatial and temporal discretization: we will perform additional simulation with horizontal resolutions of 25 m and 100 m and one simulation with an increased vertical resolution. The flow simulations were performed with stress periods of 90.25 to 92 days (corresponding to seasons), which were further divided into 3 time steps, resembling approximately one month for each flow time step. The transport simulations were performed implicitly with the Generalized Conjugate Gradient (GCG) solver, and the transport step sizes were model-calculated (DT0 equal to zero) based on a Courant number of 1. Additionally we have used a transport step size multiplier of 1.02. In order to justify the temporal discretization we will perform an explicit transport simulation. The justification of our chosen values and results of the additional simulations will be reported in a supplement; in the paper we will refer to the supplement.

“2. P6L7-14. Please clearly explain the definition of BCs, this is not clear from Fig. 4. A 2D slice might be helpful. What is a general-head BC? Does the constant-head BC apply to the top of the sea or to the sea floor?”

We will change the names of the general-head BC and the constant-head BC in the text and in figure 4 to respectively ‘Head-Dependent Flux Boundary’ and ‘Specified-Head Boundary’, in order to clarify the boundary conditions. The constant-head boundary applies to the sea floor, and we will add this to referred section of the paper: P6L10-14.

“3. P7L31-34 (and other locations). It should be clarified and clearly listed which processes both models simulate, and how they are incorporated. For example, how is coastal erosion incorporated in the groundwater model? While I do understand that Delft3D is a sediment transport model, I do not see that it can also simulate erosion? Please clarify. Also, how was sea-level rise incorporated in the groundwater model? Your model is not a box-type model domain so your beach is actually inclined. As a

consequence, more beach surface area is inundated as a result of sea-level rise. This changes the type of BC of beach nodes from Dirichlet to Neumann. How was this issue dealt with? And also, it appears from P8L27 that tidal activity was simulated by the groundwater model, is this correct? If so, more details on that BC are required: which tidal signal was imposed, how does the time-step size change as a results of tidal activity? How was that tidal BC incorporated on the beach boundary?"

To clarify which processes are simulated and incorporated in the groundwater model, we will add a short table listing the processes and the method of incorporation. The processes that are referred to in section P7L31-34 are visualized in Fig. 5. This figure illustrates how these processes are incorporated in the groundwater model. The historical coastal erosion is based on paleogeographic maps by Vos and de Vries (2013), the reference to this source was shown in Fig. 5. We will clarify this in the description of the figure.

The morphological change of the Sand Engine was based on simulations with Delft3D (Lesser et al., 2004), with computations of the hydrodynamics, waves, sediment transport and morphology. We will add references to papers in which this is described:

- Mulder, J. P. M. and Tonnon, P. K.: "Sand Engine" : Background and design of a mega-nourishment pilot in the Netherlands, in Proceedings of International Coastal Engineering Conference 32, pp. 1–10, Shanghai, China., 2011.
- Tonnon, P. K., van der Werf, J. and Mulder, J. P. M.: Morphological simulations, Environmental Impact Assesment Sand Engine (in Dutch), Deltares, Delft., 2009.

Sea-level rise was incorporated in the groundwater model by performing successive simulations. In each successive simulation or model the level of inundation was determined by comparing the sea-level with the surface level, the boundary conditions were adapted accordingly (P8L24-26). Tidal activity was not simulated by the groundwater model, because this lies beyond the scope of this paper. We will add a brief description and clarification to the paragraph 3.3.

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“4. Section 3.2 Initial Conditions. It is unclear to me which model(s) you run to attain initial conditions. I would believe it is computationally almost impossible to simulate a coupled morphodynamic-groundwater model for 510 years that includes sediment transport, erosion, saltwater intrusion, sea-level rise, tidal activity, submarine freshwater discharge, variable-density groundwater flow, salt transport. That simulation alone would require a very rigorous choice of spatial and temporal discretization and the small time-step size would very significantly increase the CPU times. Again, listing of processes simulated by which model is obligatory here. Also, it appears from P8L4f that you are simulating the salt distribution at the onset of your actual simulation. This implies that the salt concentration in the North Sea is not at steady state, which requires clarification.”

The morphodynamic simulations were only used for the projection of the morphological evolution of the Sand Engine, the historical coastal erosion was determined by maps in Fig. 5. We will add a listing of the simulated processes to clarify the description, and we will combine this with the request in the previous comment. The ‘salt distribution’ refers to groundwater salinities, for the salt concentration in the North Sea we have assumed a constant value of 28 g TDS L⁻¹.

“5. How was the newly simulated sand distribution communicated to the groundwater model? Was the spatial grid deformed corresponding to the newly simulated bathymetry? Did you re-mesh the model area? How was the sea-zone represented: high-K zone? Which K does the sea have?”

Yes, the spatial grid was deformed corresponding to the newly simulated bathymetry. And yes, we re-meshed the model area. The whole process was simulated by a series of successive ‘deformed or re-meshed’ groundwater models, as described briefly in P8L24-26. The sea-zone was excluded from the simulations, and the sea boundary conditions were applied to the seafloor. As mentioned in the response to comment 2, we will add this to the description in the paper (P6L7-14).

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“6. Section 4.1 Model Calibration. It must be clarified and justified here that you calibrated on steady-state (recent) values of head and salinity. That calibrated steady-state model is then used to run transient scenarios. Hence, the transient model is, strictly speaking, uncalibrated!”

Yes, we have used averaged values of head and salinity in the calibration. We have made this choice because of the limited availability of long time-series of heads and salinity, and the long-term focus of the paper. We will clarify this in section 4.1, and address this in the discussion P11L27-32.

Specific Comments

“7. P1L24. Inhabitants are not vulnerable, ecosystems are.”

We will change ‘vulnerable’ to ‘threatened’ and add ‘ecosystems’ to the line.

“8. P2L6. Are the Netherlands a delta? Either call it “region” or “country, or simply delete.”

We agree, we will modify this to ‘country’.

“9. P2L19f. This is ill-phrased. What you mean is that instead of putting a little bit of sand everywhere, people think about putting a lot of sand on one point in space. The term “small-scale” is misleading here because it is actually a large-scale distribution of sand that is being replaced by point-wise replenishment of sand. This needs to be written in appropriate terms.”

We will replace the term “small-scale” with “frequent large-scale distribution of sand”, and “local mega-nourishments” with “concentrated (mega) nourishments”.

“10. P2L23. The “surface level including the sea bed level” is simply the bathymetric surface, or even simpler the bathymetry”.

We will modify the text to ‘surface elevation (including bathymetry)’

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“11. P4L24. It is unclear which unit the phreatic aquifer is. I am guessing the green unit in Fig. 3? A legend in Fig. 3 would be helpful.”

Yes, the green unit corresponds with the Holocene deposits, and contains the phreatic aquifer and underlying aquitard. We will add a legend to Fig. 3 to clarify the colours.

“12. P4L34. There is no freshwater lens in your coastal aquifer. To my understanding, freshwater lenses only form below islands and in coastal aquifers under heavy influence of groundwater extraction that pushes the saltwater-freshwater interface upwards forming a lens on the seaside of the pumping wells. Neither is the case here.”

The term ‘freshwater lens’ refers to the existence (and development) of fresh groundwater on top of saline groundwater in the coastal aquifer. We will change the name to ‘fresh groundwater lens’.

“13. P5L1f are obvious, delete.”

We agree and will delete the second part of this sentence.

“14. P5L10. Swap words: “frequently measured”. Also, how frequently?”

We will replace this with ‘twice every year’

“15. P6L7. Delete “outer” since all boundaries are along the outside. Also, some boundaries are parallel to the coastline, so the first phrase needs rewording. Please indicate the location of your model area in Fig. 2. As is, it is unclear where exactly you are modeling. Is it the rectangle in Fig. 1?”

We will delete “outer”, and yes the model boundaries are shown as the rectangle in Fig. 1. We will modify and clarify this in the ms.

“16. P6L15-20. Please indicate in Fig. 4 which is an aquifer and which is an aquitard. All units could simply be named aquifer 1,2,. . . aquitard 1,2,. . . , phreatic aquifer etc., and a legend should be given. Also, please put all the parameter values in a table and delete from the text.”

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We will indicate in Fig. 4 which layers are aquitards and which layers are aquifers and put the parameter values in a separate table.

“17. P6L22f. I do not see the phreatic aquifer nor the two hydrogeological layers in any figure. This must be clarified.”

We will modify the text in this paragraph to clarify the subdivision of the phreatic aquifer.

“18. P6L29ff. Do you mean spatially or temporally averaged values? Surely, the simulation is transient, then are all these values constant-in-time and spatially distributed?”

In this section we mean temporally averaged values, for example seasonally averaged for recharge and yearly averaged values for surface water levels. These model parameters were all spatially distributed. Yes, the simulation is transient, and these values are therefore constant per season for recharge, and constant for the whole simulation for surface water levels. We will modify the text to clarify the adopted methodology.

“19. P7L6. The *linear* relation?”

Yes, we used the linear relation between chloride and TDS. We will add ‘linear’ to the text.

“20. P7L27. Delete “method” and “of”. Replace “adjustment” by “calibration”. How was the model calibration done, manually, PEST? Please clarify. Same for P8L10-14, how did you actually find the values of the finally calibrated parameter?”

We will change the sentence according to the suggestions. The calibration was performed manually, and we will clarify this in the text. We manually adjusted the values of a selection of model parameters (as mentioned in P8L10-14) within realistic ranges to attain the best calibration fit. The adjustments were made from an initial best guess of the values. We clarify the text in both paragraphs to clarify the adopted methodology.

“21. P9L16. “evenly or randomly” is ill-worded.”

We agree, evenly suggest a regular pattern in contrast with randomly. We will change

the phrasing into “well-distributed”.

“22. P11L12-24 are Intro material and should be shifted.”

We will shift the paragraph to the introduction, in paragraph 1.3 on P3L21.

“23. P13L9. Unclear which “local circumstances” you mean. Either clarify or delete.”

We will change “local circumstances” to “local hydrogeological conditions”.

“24. Fig. 10. What causes the oscillations? Tidal activity? This must be explained and it must be said, which tidal signal is applied. A scale on the time axis is missing, probably 2011-2050? Simulating tidal activity for 40 years would require a very small time-step size. Or did you only consider the lunar cycle in the change of the sea level?”

The oscillations are caused by seasonal changes in recharge (winter, spring, summer, autumn). Tidal activity was not included in the simulations. Both figures to contain a time axis with labels from 2010 to 2050, however this may be difficult to read in figure 10a. We will adapt the position of time-axis.

“25. Fig. 11 (and corresponding interpretation in text). Did you consider the morphological situation of 2050 as a steady state? What happens after 2050?”

No, the morphological situation will continue to change after 2050. However we have limited the morphological simulations to this period, because the main effects of the Sand Engine on fresh groundwater resources become apparent in this period.

“26. Literature. References on the effect of tidal activity and storm surges on coastal freshwater resources could be mentioned: - Kooi, H., Groen, J., Leijnse, A., 2000. Modes of seawater intrusion during transgressions. *Water Resources Research* 36, 3581-3589. - Violette, S., Boulicot, G., Gorelick, S.M., 2009. Tsunami-induced groundwater salinization in southeastern India. *Comptes Rendus Geoscience* 341, 339-346. - Yang, J., Graf, T., Herold, M., Ptak, T., 2013. Modelling the effects of tides and storm surges on coastal aquifers using a coupled surface-subsurface approach. *J. Contam.*

Hydrol. 149, 61-75. - Yang, J., Graf, T., Ptak, T., 2015. Sea level rise and storm surge effects in a coastal heterogeneous aquifer: a 2D modelling study in northern Germany. Grundwasser 20, 39-51.”

We will consider the mentioning of some of these references, and were appropriate.

Technical Comments

“27. P2L4, P2L14, P2L31 (and many other locations in the ms). Please add a comma: “Fortunately,”, “Since 2001,”, “In September 2011,”. I found approximately 30 missing commas.”

We will add these commas, and will check the ms for other missing commas.

“28. P2L11. “have””

We will change the sentence to ‘... application of sand nourishments has ...’

“29. P3L1. “800 m into the sea””

We will correct this in the ms.

“30. P3L2. Fig. 2 not 1”

We think both figures are appropriate, however Fig. 1 contains images of the morphological change

“31. P3L4. Delete “(local mega-nourishment)”, it is now clear.”

We agree, and will delete this.

“32. P3L17. Consistently use “variable-density” with “-“. 33. P3L23 (and other locations). Replace “scenario’s” by “scenarios”.”

We will correct this in the ms.

“34. P4L26. Delete “grained”.”

We will add hyphens to fine and medium to make clear that these words refer to grain size

“35. P5L6. “long-term”.”

We will correct this in the ms.

“36. P5L28. “were simulated”.”

We will delete “and salt transport”, which makes the original “was simulated” correct.

“37. P10L12. “similar to the situation”. 38. P10L21. “volume of groundwater”. 39. P10L22. Replace “lower” by “smaller”. 40. P11L3. Replace “with” by “by”. 41. P11L5. Replace “pace” by “rate”. 42. P13L5. Swap words: “substantially grow”.”

We will correct this in the ms.

“43. Table 1. Plus the effect of the Sand Engine gives a total of 10 scenarios? Please clarify.”

Yes, this table only contains the climate change scenarios. We will delete the words ‘model’, and change to ‘climate (change) scenario’.

“44. Fig. 7b. Give values of the zoom plot a different symbol to better differentiate.”

We will change the symbols in the zoom plot.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-5, 2016.

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