Reply on review of our manuscript HESS-2016-5 “Fresh groundwater resources in a large sand replenishment” by Anonymous Referee #1, #2, #3

Dear Editor,

We would like to thank the reviewers for their effort reviewing our manuscript and their valuable comments.

In the subsequent pages we have explained point by point how we dealt with their comments, arranged from Anonymous Referee #1 to #3. The original reviewer comments are presented in bold italic, and our response is presented in normal text. The marked up manuscript version is added to at the end of this document.

Sincerely,

Sebastian Huizer, on behalf of all authors

AnonymousReferee#1

Received and published: 8 February 2016

The authors investigate the effect of local sand replenishment along a Dutch coastal regional on fresh groundwater resources. Effects of climatic change are also included in the study. A 3D variable-density groundwater flow model is constructed and used to predict long-term effects of the added sand. Results indicate that the sand replenishment can both protect the coastline and secure freshwater resources at the same time. It is concluded that sand replenishment can have that combined positive effect along many other low-lying coastal areas worldwide.

The ms is a valuable and novel contribution to coastal flow research. The ms is well written and organized. Figures are of good quality. The key message is novel and should be made available to the scientific community. However, the manuscript does have room for some substantial improvement that mainly concerns its modeling part. My major points of criticism are given as General Comments, followed by some specific and technical comments that must also be addressed. I recommend acceptance of the manuscript with major revisions.

We would like to thank the Referee for the comments, which are highly appreciated.

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 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 have performed additional simulations for the reference scenario to justify the spatial and temporal discretization: we have performed 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 flow and transport equations were explicitly coupled. The transport step sizes were model-calculated 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 have performed an additional simulation with an implicit coupling of flow and transport equations.

The justification of our chosen values and results of the additional simulations is reported in Appendix A.

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 have changed 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 have added this to referred section of the paper (section 3.1).

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 have added a short table listing the processes and the method of incorporation (Table 2).

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 have clarified 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 have added 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 Proc. 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 Assessment 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. Tidal activity was not simulated by the groundwater model, because this lies beyond the scope of this paper. We have changed and clarified the description in section 3.3.

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 have added a list of the simulated processes to clarify the description (Table 2), and have combined 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 have 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 section 3.3. 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 have added this to the description in the paper (section 3.1).

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 have clarified this in section 4.1.

Specific Comments

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

We have changed 'vulnerable' to 'threatened' and have added 'ecosystems' to the line.

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

We agree, we have modified 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 have replaced the term "regular small-scale" with "large-scale distribution of sand",
and the term "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 have modified the text to 'surface elevation (including bathymetry)'

***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 have added 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 have changed the name to 'fresh groundwater lens'.

13. P5L1f are obvious, delete.

We agree and have deleted the second part of this sentence.

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

We have replaced 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 have deleted "outer", and yes the model boundaries are shown as a black rectangle in Fig. 1.
We have modified and clarified this in the ms (section 3.1).

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.

We have indicated in Fig. 4 which layers are aquitards and which layers are aquifers, and incorporated the parameter values in Table 1.

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

We have modified the text in this paragraph to clarify the subdivision of the phreatic aquifer (section 3.1).

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 have modified the text to clarify the adopted methodology (section 3.1).

19. P7L6. The *linear* relation?

Yes, we have used the linear relation between chloride and TDS. We have added '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 have changed the sentence according to the suggestions. The calibration was performed manually, and we have clarified this in the text (section 3.2). 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 (section 3.2).

21. P9L16. "evenly or randomly" is ill-worded.

We agree, evenly suggests a regular pattern in contrast with randomly.
We have changed the phrasing into "well-distributed".

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

We have shifted the paragraph to the introduction, in section 1.3.

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

We have changed "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 have adapted the position of time-axis (Fig. 10.)

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 ground-water 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 have added references in the ms to Kooi et.al. (2000), Yang et.al. (2013) and Yang et.al. (2015).

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 have added these commas, and have checked the ms for other missing commas.

28. P2L11. "have"

We have changed the sentence to '… application of sand nourishments has …'

29. P3L1. "800 m into the sea"

We have corrected 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 have delete this.
32. P3L17. Consistently use "variable-density" with "-". ***33. P3L23 (and other locations). Replace "scenario's" by "scenarios".***
We have corrected this in the ms.
34. P4L26. Delete "grained".
We have added hyphens to fine and medium to make clear that these words refer to grain size
35. P5L6. "long-term".
We have corrected this in the ms.
36. P5L28. "were simulated".
We have deleted "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 have corrected 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 have deleted 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 have changed the symbols in the zoom plot.

AnonymousReferee#2

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We would like to thank the Referee for the comments, which are highly appreciated.

General Comments

The authors state that the volume of replenished sand in their case is "large". Without a comparison to previous nourishments, the reader cannot judge if the volume 21.5 Mill. m3 is indeed large. Please give some figures for previous measures for comparison.
We agree that the statement "large" is subjective and have removed this statement. In the beginning of the paragraph (section 1.2) we have mentioned the 'traditional' nourishment volume of 12 million m^3, which is (on average) applied yearly along the entire Dutch coast.
The potential negative effects of a mega-nourishment should at least be mentioned briefly. Where does the sand come from? How does the extraction affect currents and wildlife there? What about sandbanks forming downstream which may obstruct shipping?
We think that these issues are not relevant for this paper, and many of these issues are still under investigation within the Nature Coast project. Possible advantages were only mentioned as motivation for the creation of the Sand Engine. We have adapted the text to remove the impression that a mega-nourishment will predominantly have positive effects.
Not sure whether your model cell size is appropriate for the initial steps of freshwater generation in the sand engine, when the freshwater body is still small.
We agree with the Referee, and have performed additional simulations for the reference scenario to justify the spatial and temporal discretization. In order to justify the spatial discretization, additional simulations were performed with horizontal resolutions of 25 m and 100 m and one simulation with an increased vertical resolution. The results of the additional simulations are reported in Appendix A.
Why would a wetter winter lead to a lower volume of fresh groundwater (P10, L21-24). Should a wetter winter not lead to more recharge in NW European climate?
Yes, a wetter winter would lead to a higher volume of fresh groundwater. However, the wetter winter in climate scenarios G_H and W_H coincides with a drier summer (comparing climate scenario G_H with G_L, and W_H with W_L). The increase in the volume of groundwater recharge in the winter season ('wetter winters') is smaller than the decrease of the volume of groundwater recharge in the summer season ('drier summers'). Overall the groundwater recharge increases more in the milder climate scenarios. We have adapted these sentences to clarify the intention (section 4.2).
List references by year of publication, oldest go first (e.g. in Line 20)
In the manuscript preparation guidelines for authors it is stated that 'In terms of in-text citations, the order can be based on relevance, as well as chronological or alphabetical listing, depending on the author's preference.' We have chosen to list in-test citations by alphabetical order.

The manuscript would be a better read after a liberal sprinkling of commas!
We have checked the manuscript for readability, and have added commas were possible.
Not sure about HESS C1-English sources in the references come with a translation? ***e.g. Buma (2013), P 14, L5 and others***
We have translated all Non-English titles to English.

Specific Comments

Page 1, Line 20: use spelling "deltas" not" delta's" ***P. 1, Line 21: usual spelling in English is "Vietnam"***
We have changed this in the ms.
P2, L6: not the whole of the Netherlands is a delta, right? People in Friesland and Limburg would probably not agree
Yes, we have modified the text from 'delta' to 'country'
P2, L10-12: sand nourishment is not only done in the NL, the Germans do it, too, and probably other countries as well
True, this was addressed in section 1.1. However not specifically.
P2, L11-12: how often is sand nourishment usually done? Every year, every five, ten, twenty years?
We have changed the line in the ms.
P2, L15; replace "must rise" by "rises"
We have corrected this in the ms as "is to rise"
P2, L23: Weren't their some presentations on the sand engine at the latest SWIM in Husum? Please cite references if appropriate
Yes, the preliminary results that are described in this paper were presented at the SWIM in Husum.
P2, L28: replace "determined" by "investigated"
We have corrected this in the ms.
P2, L31: please replace "shape" by a more appropriate term describing the geometry
We have adapted the line with more appropriate terms; 'retreat of outer perimeter' and 'increase alongshore extent'
P3, L1: replace "in" by "into" (twice!)
We have corrected this in the ms.
P3, L12: "displacements in seawater intrusion" sounds awkward please rephrase
We have adapted this to "to dynamic changes in seawater …"
P3, L13: no need to define SGD, delete text in parentheses
We agree, and have deleted the definition.

P3, L17/18: does variable density gw flow not include salt transport? (same for P5, L27)
We agree, in the absence of other species there is no need to include salt transport here.
P3, L23 and 24: replace "scenario's" by "scenarios" ***P4, L5: probably "rainbowing" is the correct spelling?!***
We have corrected this in the ms.
P4, L10: delete "clean,"
We have changed this and rephrase the sentence in the ms.
P4, L13-15: how much groundwater is infiltrated, how much is extracted, how much is locally formed?
We have added this information to the paragraph.
P4, L24: replace "are" by "were" (same in Line 28) ***P4, L25-26: an aquifer made up of clay? are you sure?*** ***P5, L1: delete comma*** ***P5, L10: replace "observed" by "read off"***
We have corrected this in the ms.
P5, L12-14: these were on-shore in the dunes, right?
Yes, in the dunes and in some in the hinterland (urban area, polders). We have added 'onshore'
P5, L15-19: the purpose of these wells remains unclear, are they pumping saline/brackish water as interceptor wells? Are they running continuously? Please specify!
Yes, these wells serve as interceptor wells; they control the groundwater level to avoid any possible negative impact of the nourishments. We have clarified this in the paragraph.
P6; L15: add "the" after the second "and"
We have corrected this in the ms.
P6; L27/28: here you use m/d while above (L19) you use SI standards (m, s)
We have used the most common and appropriate unit for each model parameter.
P6; L29-34: the values chosen for these data should be stated somewhere, maybe in a table
We have transferred the values of the model parameter to a table (Table 1).
P7, L32-33: but HOW were they incorporated? and which ones? in what timescale?
The processes (coastal erosion, sea-level rise, and expansions of groundwater drainage and extractions) are visualized in Fig. 5, and the source and method of incorporation of the processes is described in Table 2. We have clarified this in the description of the figure and added a reference in the sentence.
P8, L25: why not use "every three months"?
We have changed "quarter' to "every three months", because this is more explicit.
P9, L17: add "and" instead of comma ***P10, L12: add "the" before "situation"*** ***P11, L3: replace "with" by "by"***
We have corrected this in the ms.

P11, L14-19: not sure whether a comparison to island lenses is appropriate here. This is also no conclusion but a introductory note. Maybe better deleted!

We have moved this section toward the introduction (paragraph 1.3), and have deleted the addition (L17-19) to reduce the focus on island lenses in this section.

P11, L31: since you raise the issue: how many times was the sand engine flooded?

Only certain areas of the Sand Engine have been flooded. Until now there have been two 'major' storms in 2011 and 2013 that lead to large inundations, and several 'minor' storms leading to less extensive inundations. We have added this information to section 5.

Fig. 1: add north arrow
Fig. 1: legend for gray scales?

We have added a north arrow and legend to the figure.

Fig. 3: explain formation names, maybe ages or so?

We have added a legend to the figure with some information about the formations (age, lithology)

Fig. 4: values for general head boundaries? give legend to identify aquitards and aquifers

The values of the general head boundaries were taken from a previous model simulation of the southwest of the Netherlands (Oude Essink et al., 2010). We have added a legend to the figure, in order to clarify the boundaries, and we have added labels to the aquitards and aquifers.

Fig. 5: modified after Vos 2013?

We have corrected this in the figure.

Fig. 8: which year is shown?

This is the year after calibration, before the construction of the Sand Engine (2010 – 2011).
We have added this to the figure caption.

Fig. 10: explain in caption that the labels refer to (climate) scenarios

We have explained this in the figure caption.

AnonymousReferee#3

Received and published: 26 February 2016

This paper describes groundwater modelling of the impact on freshwater resources of a local sand nourishment development off the coast of the Netherlands, called the 'Sand Engine'. The modelling effort includes morphological changes of the 'Sand Engine' caused by wind, currents and tides. The model is loosely calibrated and then used as a predictive tool under different climate scenarios. The paper is very well written and the quality of the figures is very high. Modelling freshwater resources within a moving sand island is interesting and novel. There is an appropriate amount of background detail provided. The technical aspects of the work appear to be sound and the limitations of the modelling effort are well detailed. The conclusion that local sand replenishments can provide both coastal protection and increasing freshwater availability is important and of general interest.

We would like to thank the Referee for the comments, which are highly appreciated.

Referee#3 did not submit general or specific comments.

Fresh groundwater resources in a large sand replenishment

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Abstract. The anticipation of sea-level rise and increases in extreme weather conditions has led to the initiation of an innovative coastal management project called the Sand Engine. In this pilot project a large volume of sand (21.5 million m^3) – also called sand replenishment or nourishment – was placed on the Dutch coast. The intention is that the sand is redistributed by wind, current and tide~~,~~; reinforcing local coastal defence structures and leading to a unique, dynamic environment. In this study we investigated the potential effect of the long-term morphological evolution of the large sand replenishment and climate change on fresh groundwater resources. The potential effects on the local groundwater system were quantified with a calibrated three dimensional groundwater model, in which both variable-density groundwater flow and salt transport was simulated. Model simulations showed that the long-term morphological evolution of the Sand Engine results in a substantial growth of fresh groundwater resources, in all adopted climate change scenarios. Thus, the application of local sand replenishments such as the Sand Engine could provide coastal areas the opportunity to combine coastal protection with an increase of the local fresh groundwater availability.

1 Introduction

Global sea-level rise poses a ~~threat~~ risk for coastal areas, especially when combined with an increase in the frequency and intensity of storm surges (Michael et al., 2013; Nicholls et al., 2010; Wong et al., 2014). Particularly small islands (Chui and Terry, 2013; Holding and Allen, 2015; Mahmoodzadeh et al., 2014), and low-lying ~~delta's~~deltas (Giosan et al., 2014; McGranahan et al., 2007; Oude Essink et al., 2010) are vulnerable to rising sea-levels. Many low-lying deltas such as the Mekong Delta (Viet ~~Nam~~nam) and the Ganges-Brahmaputra delta (Bangladesh) are already frequently subjected to extensive floods, leading to considerable economic losses, property damage, and in severe cases loss of life (Few and Matthies, 2006; de Sherbinin et al., 2011; UNDP, 2004). In addition, many ecosystems and inhabitants of deltas are ~~becoming increasingly vulnerable~~threatened as a result of high subsidence rates, over-exploitation of fresh groundwater resources, and contamination of coastal aquifers (Crain et al., 2009; de Sherbinin et al., 2011; Syvitski et al., 2009; UNDP, 2004). Sea-level rise and storm surges will enhance the pressure on these coastal regions (Kooi et al., 2000; Yang et al., 2013, 2015), and will likely exacerbate the loss of agricultural land, damage of ecosystems and the salinization of fresh groundwater resources (Hoggart et al., 2014; Nicholls, 2010; Oude Essink et al., 2010; Wong et al., 2014).

1.1 Coastal management

In order to protect the livelihood of densely populated coastal areas against climate-related impacts, a growing number of studies recognises the need for the adoption of coastal defence strategies (Giosan et al., 2014; Nicholls et al., 2010; Temmerman et al., 2013; Wong et al., 2014). Fortunately, the awareness of the threats posed by climate change is growing, and coastal defence in a number of countries – especially developed countries – has have been intensified, specifically at vulnerable locations (Goodhew, 2014; Kabat et al., 2009; Sterr, 2008). One example is the Netherlands – a vulnerable low-lying delta country – where coastal defence systems have been reinforced on several occasions, in accordance with its long history of intensive coastal protection (Charlier et al., 2005). Centuries of continuing erosion, flooding and subsidence led first to the implementation of hard engineering methods (e.g. groynes and sea walls), and later soft engineering methods (e.g. sand replenishment or nourishment, van Koningsveld et al., 2008). Since 1990 the application of sand nourishments, particularly beach and shoreface nourishments, has become the dominant coastal defence strategy at the Dutch coast. Sand nourishments are applied on an regular annual basis – where necessary – in order to maintain the position of the coastline (Keijsers et al., 2015; de Ruig and Hillen, 1997).

1.2 Pilot project: Sand Engine

Since 2001, the position of the entire Dutch coastline is successfully maintained with 12 million m^3 of sand nourishments per year. However, the future annual volume of sand nourishments should increase if the coast must is to rise with the sea-level (Deltacommissie, 2008). Research suggests that the annual nourishment volume should be raised to 20 million m^3 yr^{-1} in the nearby future, ; in order to sustain the Dutch coastline in the long run (Giardino et al., 2011; de Ronde, 2008). The anticipation of a substantial growth in the annual nourishment volume incited discussions about the effectiveness of the current regular small scalelarge-scale distribution of sand nourishments. These discussions led to the idea that the substitution of small scale nourishments with local concentrated (mega) nourishments could provide several advantages: be more cost-effective than current practices, and may provide opportunities for promote natural dune growth, reduce ecological stress, and provide more opportunities for recreation (e.g. kite surfing, van Slobbe et al., 2012).

The effectiveness, benefits and drawbacks of concentrated local (mega) nourishments are currently being investigated with a pilot experiment project named the Sand Engine (also called Sand Motor) (Mulder and Tonnon, 2011; Stive et al., 2013). In this experiment project a mega-nourishment of 21.5 million m^3 was constructed at the Dutch coast in 2011, : a few kilometres west from the city of The Hague (Fig. 1). This large bodye replenished of sand will gradually be distributed along the coast by wind, waves and currents, thus incorporating natural forces in engineering methods (so called 'Building with Nature') (Slobbe et al., 2013; de Vriend et al., 2014). The effectiveness of the Sand Engine is determined investigated by extensive research and intensive extensive monitoring:; the surface level elevation (including the sea bed levelbathymetry) is measured frequently to gain detailed knowledge of the volume and direction of sediment transport at this local mega-nourishment (Ebbens and Fiselier, 2010; Tonnon et al., 2011). Recent Mmeasurements in the most recent years

show that the outer perimeter of the ~~shape of the Sand Engine transformed from a~~ 'hook-shaped' peninsula retreated, and the alongshore extent increased ~~' towards a flattened wider shape~~ (de Schipper et al., 2016; Stive et al., 2013). Initially ~~In September 2011~~ the Sand Engine extended approximately 1 km into the sea and was nearly 2 km wide at the shoreline, while in September 2014 it extended approximately 800 m into the sea and was more than 3 km wide at the shoreline (Fig. 1).

1.3 Study objectives

The primary objective of this study is to quantify the potential effect of the Sand Engine ~~(local mega-nourishment)~~ on the regional groundwater system, particularly on fresh groundwater. During the life span of the Sand Engine the (direct) influence of the North Sea is diminished, because of the seaward displacement of the shoreline – and possibly ~~future~~ growth of adjacent dunes. The extension of the beach-dune system and the reduction in seawater intrusion may lead to a growth of fresh groundwater resources. In combination with an increase of groundwater levels, the construction of the Sand Engine may also lead to a decline in the upwelling of saline groundwater and a decreased salt load in adjacent low-lying areas.

The long-term morphological evolution of the Sand Engine – powered by coastal and aeolian sediment transport – will also affect to local groundwater system with time. Erosion and deposition of sand will alter the position of the shoreline and the surface elevation with time, ~~which gives rise to displacements~~ which simultaneously gives rise to dynamic changes in seawater intrusion and submarine groundwater discharge. ~~(groundwater flow out of the aquifer, across the sea floor).~~ The morphological evolution of the Sand Engine and the dynamic nature of thise coastal system ~~may~~ will probably lead to ~~frequent and~~ considerable changes in groundwater head and divide, the direction and velocity of groundwater flow, and the stored volume of fresh groundwater.

One of the innovative aspects of this study is to incorporate detailed predictions of the long-term morphological evolution of the Sand Engine in a 3D numerical model, which ~~considers~~ simulates ~~variable-density~~variable-density groundwater flow ~~coupled with salt transport~~. At the moment no studies have investigated the influence of local mega-nourishments on groundwater systems, and only a few groundwater modelling studies have incorporated a changing morphology in their calculations (Delsman et al., 2014). We also assess the effect of climate change (e.g. sea-level rise) on fresh groundwater resources in the study area, in combination with the morphological evolution of the Sand Engine. To our knowledge, ~~N~~no other studies have integrated the effect of the morphological evolution of coastal areas and climate change on fresh groundwater resources, and the number of quantitative studies that investigate the possibility to combine coastal defence with the protection of fresh groundwater resources are scarce (Oude Essink and Waterman, 2016; Oude Essink, 2001). However, studies on small islands have shown that great losses in the volume of fresh groundwater can occur as a result of decreases in groundwater recharge and sea-level rise, and especially small and thin lenses seem vulnerable to salinization (Chui and Terry, 2013; Holding and Allen, 2015; Mahmoodzadeh et al., 2014). In relation to the morphological dynamics of coastal regions, studies have shown that the erosion and accretion of sand can lead to substantial changes within the beach-foredune area (Bakker et al., 2012; Keijsers et al., 2014), and that climate change might exacerbate coastal erosion (FitzGerald et al., 2008; Zhang et al., 2004). Morphological developments in coastal areas can therefore have a substantial

effect on fresh groundwater resources, and coastal management strategies that compensate, limit, or counteract coastal erosion or seawater intrusion may help to protect fresh groundwater resources.

The paper first describes the construction of the Sand Engine and the characteristics of the study area. It then reviews the methodology for the development of the regional groundwater model, and the model ~~scenario's~~scenarios. Next, the model calibration and model results are described and examined as well as the impact of different climate ~~scenario's~~scenarios on simulated fresh groundwater resources. Finally, the methodology and results are discussed, emphasizing on the limitations and implications for fresh groundwater resources.

2. Site description

2.1 Study area

The construction of the Sand engine was commissioned and designed by the executive branch of the Ministry of Infrastructure and the Environment (Rijkswaterstaat) and the provincial authority of South-Holland (Provincie Zuid-Holland) (Mulder and Tonnon, 2011). Large trailing suction hopper dredgers were used to ~~suck up~~extract sand from several sand pits in the North Sea and to transport thise sand to the project site. The dredged material was stored in the hopper and ~~transported~~ deposited ~~to~~ on the project site with three different techniques: by opening the bottom valves of the vessel on-site ("depositing"), by pumping a mixture of sand and water to the site through a pipeline ("pumping"), and by spraying a mixture of sand and water from the vessel's bow to the site ("rain-bowing"). When the construction of the Sand Engine was completed (in ~~October~~ July 2011), the area above MSL was 1.3 km^2 with a maximum ~~height~~ surface elevation of 7 m MSL (Slobbe et al., 2013).

The Sand Engine peninsula is connected to the main-land by a sandy beach,~~h of 100 to 150 m width, which~~ and is bounded by a coastal dune area called Solleveld. Solleveld ~~with maximum heights between 10 to 20 m MSL. This dune area called Solleveld~~ is relatively small dune area (circa 2 km^2; Fig. 2) with surface elevations ranging from 2 to 16 m MSL, and is used for the production of drinking water ~~since 1887 (Draak, 2012)~~. From the start of the groundwater extractions in 1887 the ~~An increasing~~ demand ~~for~~ and extraction of ~~clean~~drinking, ~~fresh~~ water ~~led to a~~ gradually increased from a maximum of 1 million m^3 per year before 1970, ~~in extraction rates, reaching~~ to a maximum of ~~a maximum of~~ 7.5 million m^3 per year ~~in~~ after ~~the recent period of~~ 2008~~–2015~~ (Draak, 2012). ~~In order to~~However, to be able to ~~be able to~~ extract these ~~considerable~~ increasing ~~groundwater~~ volumes of groundwater ~~from this relatively small dune area~~ without salinization ~~of fresh groundwater resources~~, the drinking water company started with the infiltration of surface water in 1970 ~~in 1970~~. The infiltrated volume of surface water is approximately equal to the volume of fresh groundwater that is extracted from the dunes. Currently the groundwater is extracted from the phreatic aquifer with almost 300 vertical pumping wells, which are located on the sides of twelve elongated infiltration basins [Fig. 2; Zwamborn and Peters, 2000].

Beyond the dunes the area gradually transforms into urban area and low-lying agricultural areas (polders). The low-lying polders have surface elevations of -1 to 1 m MSL, and act predominantly as a groundwater sink, while the urban areas are generally situated in higher areas with surface elevations between 1 and 3 m MSL. The dominant groundwater flow in the upper aquifers flows from the higher urban areas and coastal dunes toward the North Sea and the polders. The relatively low drainage levels in the polders lead also leads to the attraction of deeper saline groundwater, in addition to the drainage of local fresh groundwater.

2.2 Hydrogeology

The subsoil consists of unconsolidated sediments of predominantly fluviatile and marine origin, as shown illustrated by two geological profiles in Fig. 3. The phreatic aquifer containsupper part of the subsoil (10 to 30 m) consists multiple layers of sand, clay and peat of 10 to 30 m thickness, which are were deposited during the Holocene.: primarily fine- to medium-grained sand iIn the higher situated dunes and urban areas the aquifer primarily consists of fine to medium grained sand, and in the low-lying areas primarily of sand and clay in the low-lying areas. However, the lower section of the Holocene deposits However, the lower section of the phreatic aquifer (between -15 and -20 m MSL) consists in both areas in both areas mainly of clay and peat deposits. Deeper aquifers (yellow) and aquitards (orange, blue), as illustrated in Fig. 3,The underlying thick layers of fluviatile and marine sediment are were deposited during the Pleistocene. It should be noted that the geological schematization of the aquifers and aquitards beneath -40 m MSL are based on a limited number of boreholes.

The conceptual fresh-brackish-saline groundwater distribution (blue striped lines; Fig. 3) are based on chloride measurements, performed at multi-level monitoring wells. Chloride measurements in Solleveld indicate that the boundary between fresh and brackish groundwater (1 TDS g $\cancel{l}L^{-1}$) is situated between -20 and -40 m MSL, and the boundary between brackish and saline groundwater (10 TDS g $\cancel{l}L^{-1}$) is situated between -40 and -60 m MSL. The depth of the fresh groundwater lens and the extent of seawater intrusion are controlled by head differences, caused by groundwater pumping, recharge, infiltration, drainage, and salinity..

2.3 Monitoring

In order to timely observe changes in groundwater level, flow and quality an extensive monitoring network was implemented in Solleveld. After the construction of the Sand Engine this monitoring system was expanded and intensified at in the western side part of the dune area. The aim of the expansion of the monitoring system was to observe long termlong-term changes in groundwater level, flow and quality and to observe hydrogeological effects caused by the Sand Engine and previous small-scale nourishments (Buma, 2013). The current monitoring system consists of more than 300 observation wells, where the groundwater level is measured with varying frequency (ranging from wells with hourly frequency to wells that are only observed read off every three months). The groundwater salinity is measured twice every year frequently in at least 50 monitoring wells, with various methods;: groundwater data loggers with measurement of electrical conductivity, electro-magnetic measurements, and analyses for chloride (Buma, 2013). Apart from measurements within the monitoring

system, groundwater level measurements of 61 additional (onshore) monitoring wells were available in the national database of the Geological Survey of The Netherlands.

In addition to the expansion of the monitoring system, additional measures were taken to prevent salinization of fresh groundwater in the dunesthe pumped groundwater. On the western base of the dunes a line of 28 pumping interceptor (pumping) wells was installed in 2012 , in order to maintain the groundwater level, and prevent any (negative) impact of the Sand Engine and previous nourishments on the extracted fresh groundwater in the dunes. However tThese pumping interceptor wells were not included in our study, because of a lack of information on the pumping rates and the expectation that the effects on the regional scale are small to negligible.

In order Tto gain specific information on the geohydrological dynamics within the Sand Engine, eight additional monitoring wells were installed with shallow filters (2 to 10 m below surface) and four monitoring wells with deep filters (16 to 20 m below surface). Since May 2014 the groundwater levels in the monitoring wells are continuously monitored with groundwater data loggers. The salinity of the groundwater is monitored with electro-magnetic measurement within all eight monitoring wells.

3 Method

3.1 Variable-density groundwater model

For the quantification of fresh groundwater resources in the study area we constructed a regional three-dimensional groundwater model, in which variable-density groundwater flow and salt transport was simulated with the computer code SEAWAT (Langevin et al., 2008). SEAWAT has been developed by the United States Geological Survey (USGS), and numerous studies have used the code to simulate variably-density, transient groundwater flow (Heiss and Michael, 2014; Herckenrath et al., 2011; Rasmussen et al., 2012). In SEAWAT the governing flow and solute transport equations are coupled and solved with a cell-centred finite difference approximation. The model domain was discretised in 234 rows, 234 columns, and 50 layers, with a uniform horizontal cell size of 50 m and a varying layer thickness of 1 to 10 m (smallest thickness in upper layers, increasing in underlying layers; Fig. 4). The definition of the discretization and extent of the model were based on three criteria: minimise the effect on simulated groundwater heads and salinities in the study area, limit computation time, and optimise the calculation of the fresh groundwater volume. For the justification of the temporal and spatial discretisation we have performed a grid convergence test (Appendix A).

The model boundaries, as visualized in Fig. 1, were defined either The outer model boundaries were situated perpendicular to the coastline (at the SW and NE sides of the modelmodel; Fig. 1), or parallel to the coastline (the NW and SE side of the model). Model boundaries that were defined perpendicular to the coastline, lie parallel to the dominant groundwater flow direction in the coastal area, and were therefore defined as no-flow boundaries. The other Other outer model boundaries (at the NW and SE side of the model) were defined as illustrated in Fig. 4: 'specified-head' and 'head-

dependent flux' boundary ~~constant-head and general-head boundary~~ conditions (taking into account density differences), which represent~~ing~~ the ~~average North sea level~~ North Sea and local groundwater system, respectively. The 'specified-head' boundary conditions equalled the average level of the North Sea, and were applied to the seafloor. ~~The l~~Local groundwater ~~heads and salinities on the eastern side~~conditions were defined by a previous model simulation of the southwest of the Netherlands (Oude Essink et al., 2010). The base of the model was defined equal to the hydrogeological base of the ~~study area~~model domain, which is approximately -170 m MSL and assumed to be a no-flow boundary.

The subsoil of the model was schematised to four aquifers and three aquitards (Fig. 4), based on borehole data, and the national geological databases REGIS II.1 (Vernes and van Doorn, 2005) and GeoTOP (Stafleu et al., 2013) of the Geological Survey of The Netherlands. The upper part of the phreatic aquifer (above -10 MSL) was subdivided into two hydrogeological zones with distinct hydraulic conductivities, because the geological data showed systematic differences in the sediment composition within the model domain: one zone coincides with most of the low-lying polders and contains predominantly clay, loam and fine sand deposits; the other zone contains most of the elevated areas of the model domain, where mainly fine to coarse sand was deposited during the Holocene. The aquifer parameters and layer elevations were defined uniform for each hydrogeological unit, based on parameter estimations in the national hydrogeological database (Table 1). The ~~effective porosity was set to 0.3 for aquifers and 0.1 for aquitards, the~~ molecular diffusion coefficient was set to 10^{-9} m^2 s^{-1}, and the longitudinal dispersivity was set to 0.2 m with a ratio of transversal to longitudinal dispersivity of 0.1. These values are similar to comparable groundwater models in the same region (Eeman et al., 2011; de Louw et al., 2011; Vandenbohede and Lebbe, 2007, 2012).

~~The phreatic aquifer contained two separate hydrogeological units and was subdivided in two hydrogeological layers, because the geological data showed systematic differences in the sediment composition within the model domain. In low lying polders and in the lower section of the phreatic aquifer (between -10 and -16 m MSL), predominantly clay, loam and fine sand was deposited during the Holocene. In the elevated areas of the model domain and the upper section of the phreatic aquifer predominantly fine to coarse sand was deposited. The hydraulic conductivities in areas and layers with mainly fine to coarse sand (beach, dunes and urban area) were set to 10 m d^{-1}, and the hydraulic conductivities in areas and layers with mainly clay, loam and fine sand were set to 1 m d^{-1}.~~

~~-~~Other model parameters such as recharge, and surface water levels~~, and drainage levels~~ were defined by ~~taking~~spatially distributed and time-average values of the current situation. The average monthly precipitation and reference evapotranspiration between 1981 and 2000 (Royal Netherlands Meteorological Institute, KNMI) were used to estimate the average seasonal (DJF, MAM, JJA, and SON) precipitation and evapotranspiration. Crop and interception factors were used to estimate the actual evaporation in different land use classes (e.g. forest, agriculture, urban areas) (Droogers, 2009; Hooghart and Lablans, 1988; Meinardi, 1994; Statistics Netherlands, 2008). Water levels, depths and widths of canals and ditches were provided by the Delfland Water Authority, and drainage levels were based on local knowledge and estimations from the Netherlands Hydrological Instrument model (de Lange et al., 2014; Massop and van Bakel, 2008). Information on

the extraction of groundwater and the infiltration of surface water in the dune area Solleveld was provided by the drinking water company Dunea.

In the model simulations we have used TDS, where TDS equals salinity [g TDS L~~l~~$^{-1}$], and in the classification of the groundwater salinity we have focused on three ~~groundwater~~ classes: fresh (0 – 1 g TDS ~~l~~L^{-1}), brackish (1 – 10 g TDS L~~l~~$^{-1}$), and saline (10 – 30 g TDS L~~l~~$^{-1}$). For the conversion~~s~~ of chloride ~~measurements~~ to TDS ~~concentrations~~ we have used the linear relation between chloride and TDS in the North Sea; 1 g TDS L~~l~~$^{-1}$ = 0.55 g Cl L~~l~~$^{-1}$ (Millero, 2003). The North Sea TDS in the model domain was estimated at 28 g TDS L~~l~~$^{-1}$ ~~in~~ for all model ~~calculations~~ simulations (density of 1020 kg m^{-3}), based on geo-electrical measurements in the North Sea near Ter Heijde between 1973 and 1997 (Rijkswaterstaat, 2012). This salinity concentration is smaller than the general North Sea concentration (30-35 g TDS L~~l~~$^{-1}$), because of the nearby freshwater discharge from the river Rhine. The TDS concentrations on the SE side of the model were defined by previous model calculations of the southwest of the Netherlands (Oude Essink et al., 2010). ~~[Oude Essink et al., 2010].~~ The TDS concentration of infiltration basins, canals and ditches were set to 0.2 g TDS L^{-1}~~g l^{-1} TDS~~, which is the average TDS concentration found in surface water within the study area. The spatial variation in the salinity of the groundwater recharge was estimated with semi-empirical equations, which were developed to predict the effects of sea spray deposition in coastal areas (Stuyfzand, 2014). Based on meteorological measurements of the wind speed and wind direction at the measurement station in Hoek van Holland in the period 1971 – 2015, the estimated annual mean TDS concentration varied between 0.121 g $^{-1}$ at the coastline to 0.023 g $^{-1}$ at a distance of 5000 m from the high water line.

3.2 Calibration of pre-development conditions

The main purpose of the model calibration was to generate a valid representation of the pre-development conditions of the Sand Engine (prior to March 2010). In order to exclude anomalous effects of recent sand nourishments on groundwater heads and concentrations, only observations prior to 2010 w~~h~~ere included in the model calibration. We considered ~~the calibrated conditions valid~~ three calibration criteria: ~~when~~ the error between simulated and observed groundwater head and TDS concentration ~~is~~ should be similar or smaller than the observed variations in groundwater level (the average standard deviation of observations is 0.4 m) and concentration (the average standard deviation of observations is 0.7 g TDS L~~l~~$^{-1}$), ~~when~~ the error~~s~~ should be ~~are~~ randomly distributed in space, and the simulated distribution of the TDS concentration~~s~~ should correspond~~s~~ with literature (Stuyfzand, 1993).

The calibration ~~method~~ comprised ~~of~~ sensitivity analyses, (restricted) manual model parameter ~~adjustments~~calibration, and comparisons of simulated groundwater heads and TDS concentrations with averaged observations of recent years. Historical processes that promote or diminish seawater intrusion were included in the calibration, because a salinity distribution often takes decades to hundreds of years to reach an equilibrium (Delsman et al., 2014; Webb and Howard, 2011). Examples of ~~Examples of h~~historical processes that have substantially influenced the groundwater salinity in the Dutch coastal area are coastal erosion, sea-level rise, and ~~expansions of~~ groundwater ~~drainage and~~ extractions (Post et al., 2003). These processes were therefore ~~incorporated~~ included in the model simulations to attain a

better match between simulations, and the method of incorporation of the processes is briefly described in Table 2 and visualised and in ~~(~~Fig. 5~~)~~. Other historical changes in for example groundwater recharge and subsidence were not included, because measurements and historical data indicate that these processes probably have a negligible impact on the current head and concentration distribution in the study area (CBS et al., 2012; Hoofs and van der Pijl, 2002).~~ -~~ The ~~calibration~~ simulation ~~period~~ was restricted to the period 1500 – 2010, because the focus of this study lies on the present conditions, and we assume that the most substantial effects on the present salt distribution will probably occur in this period. Before the simulation of the period 1500 – 2010, a transient simulation of the approximate conditions in AD 1500 was executed until ~~The initial conditions consisted of an equilibrium distribution for the approximate conditions in 1500 (Vos and de Vries, 2013). The sea level for this equilibrium model was estimated as -0.30 m MSL (Jensen et al., 1993; Wahl et al., 2013). The equilibrium conditions where generated by a transient simulation of 1500 years, in which~~ the model converged to a dynamically stable state in terms of both groundwater heads and salinity.

In order to attain an optimal calibration result with a limited number of model simulations, ~~a selection of~~ model parameters were manually~~as~~ adjusted with small increments from an initial best guess. The adjustments were performed on a selection of the model parameters: (horizontal and vertical) hydraulic conductivity, drainage resistance, stream bed resistance of canals and ditches, and (longitudinal and transverse) dispersivity. Other parameters such as groundwater recharge and surface water levels were based on measurements, maps or expert knowledge, and were excluded from the calibration. The optimised model parameters that were implemented for the model scenarios are described in Sect. 3.1.

3.3 Morphology and climate scenarios

The effect of the Sand Engine on fresh groundwater resources will primarily depend on the morphological evolution of the coastal area. In order to assess the potential effect of the mega-nourishment on coastal groundwater, we performed model simulations ~~with~~ containing projections of the morphological change of the Sand Engine during the period 2011 ~~to~~ – 2050 (Table 2). The morphological development of the Sand Engine in this period was simulated with the hydrodynamics and morphodynamics model code Delft3D (Lesser et al., 2004). This numerical morphodynamic model was calibrated for the period 2005 – 2010 and validated for the period 1990 – 2005, prior to the construction of the Sand Engine (Fiselier, 2010; Tonnon et al., 2009). Based on representative tidal boundary and wave conditions of the current situation, the model was used to simulate the ~~long-term morphological evolution~~change in bathymetry during the 2011 – ~~to~~ 2050 (Fig. 6).

The predicted ~~morphological development~~change in bathymetry of the Sand Engine was incorporated in the groundwater model as a change in surface elevation, and adapted after ~~for~~ every ~~quarter~~ three months or season in the simulation period. Subsequent changes in the area of inundation, groundwater recharge and thickness of the phreatic aquifer were implemented in the model input files. In addition, changes in the mean water level within the lagoon were ~~the decrease of the tidal range within the lagoon was~~ also included in the model ~~scenario's~~scenarios, ~~with~~ and ~~a~~ the expected maximum ~~increase of the mean~~ water level ~~of~~ equals 0.9 m MSL (de Vries et al., 2015).

In addition to the morphological development of the Sand Engine, climate change may also have an impact on coastal groundwater. For the assessment of the potential impact of climate change on fresh groundwater resources, we have used the KNMI'14 climate change scenarios G_L, G_H, W_L and W_H (KNMI, 2014). These scenarios contain climate projections for the Netherlands for the years 2030, 2050 and 2085, based on global climate models as described in the 5th IPCC Assessment report (IPCC, 2013). The climate projections of sea-level rise, precipitation and potential evapotranspiration for 2030 and 2050 in these scenarios were used to assess the effect of climate change as summarised in Table 3.~~Table 1.~~

All climate change scenarios were simulated for a reference ~~situation~~ case without the Sand Engine, and the current situation with the Sand Engine including the projected morphological evolution. The ~~model simulations for the reference situation~~reference case serves primarily as a comparison to the simulations with the morphological evolution of the Sand Engine. The ~~contrasts~~ dissimilarity between both situations ~~represent~~represents the total impact of the construction of the Sand Engine on local fresh groundwater resources. In turn, t~~T~~he climate change scenarios show the response and sensitivity of local fresh groundwater resources to ~~different degrees of change in sea-level rise,~~ alterations in sea-level rise, precipitation and evapotranspiration ~~in the model domain~~.

4 Results

4.1 Model calibration

For the calibration of the variable-density groundwater model, we compared ~~the simulated distribution of~~the simulated pre-development groundwater head~~s~~ and TDS concentration~~s~~ with recent observations of ~~the~~ groundwater heads and chloride concentration~~s within the model domain~~ (Fig. 7). The calibration was performed with averaged values of recent observations. We think this is acceptable, because of the long-term scope of this study and the deficiency in long-term time-series of head and especially salinity. The absolute mean error between observed and simulated heads ~~is~~ was 0.27 m (RMSE of 0.33 m), and between observed and simulated TDS concentrations ~~is~~ was 1.17 g TDS L^{-1}~~l^{-1}~~ (RMSE of 2.75 g TDS L^{-1}~~l^{-1}~~). The largest deviations in ~~observed and simulated~~ head~~s~~ occur at observation points that are situated near infiltration basins or pumping wells, whereas the deviation~~s~~ in TDS concentration appear~~s~~ to be ~~evenly or randomly~~well~~ ~~-~~ distributed. These deviations ~~in observed and simulated heads and salinities~~ are probably primarily caused by heterogeneity in the phreatic aquifer and~~,~~ spatial variations in the extraction ~~volumes~~ rates of pumping wells.

The groundwater heads of 137 observations points and the chloride concentrations of 55 observations points were used to quantify the error and calibrate the model. Despite this relatively large number of observations points, it is important to note that all observations of chloride and 72% of observations of groundwater heads - that were used in the model calibration - originate from the monitoring system in Solleveld~~, and 72% of observations of groundwater heads~~. The simulation of the groundwater head and especially the TDS concentration are therefore most reliable in Solleveld and the immediate surrounding system. The phreatic groundwater level and depth of the fresh-brackish interface of the calibrated model are shown in Fig. 8. Phreatic groundwater flows from the coastal dunes toward the sea, pumping wells, and low-lying

drained polders. The aquitard beneath the phreatic aquifer (between -16 and -20 m MSL) limits the interaction with the underlying confined aquifer, leading to a substantial head difference across the aquitard (ranging between 0.3 to 1.4 m in multilevel monitoring wells). The fresh groundwater lens below the coastal dunes extents to approximately -30 and -40 m MSL and the interface between brackish and saline groundwater lies between -40 and -50 m MSL, corresponding with the observed depth of the interfaces (~~Fig. 3~~Fig. 11). Drainage in low-lying polders leads to the seepage of brackish or saline groundwater, which ~~leads~~ results in a reduction of the ~~to a thinner~~ fresh groundwater lens thickness (Fig. 8).

In order to assess the performance of the calibrated groundwater model, we have compared simulated groundwater heads and TDS concentrations with recent observations at 8 monitoring locations on the Sand Engine (Fig. 9). The absolute mean error between observed and simulated groundwater heads ~~is~~ was 0.36 m, and between observed and simulated TDS concentrations was 6.5 g TDS ~~l~~L^{-1}. The model appears to underestimate the hydraulic gradient – in particular in the higher regions of the Sand Engine – and groundwater salinities with a concentration higher than 15 g TDS L~~l~~$^{-1}$ (between 6 and 20 m below surface). Probable causes of these discrepancies lie in the initial groundwater level~~s~~ and ~~salinities~~ salinity (strongly influenced by the construction), the underestimation of the vertical anisotropy as a result of small mud drapes in the Sand Engine and varying weather conditions (e.g. recharge, overwash). In addition, the measured TDS concentrations are single point measurements that may not represent the average TDS concentration in the Sand Engine.

4.2 Fresh groundwater resources

The effect of the construction and long-term morphological evolution of the Sand Engine on the volume of fresh groundwater is initially small and similar to the situation without the Sand Engine (Fig. 10). In all model scenarios the volume of fresh groundwater slightly declines in the first years, because of the small size of the freshwater lens in the Sand Engine with respect to the cell resolution and the instability of the initial conditions. However, the gradual growth of the freshwater lens in the Sand Engine and adjacent areas eventually leads to an increase of the volume of fresh groundwater in the model domain of 0.3 to 0.5 million m^3 per year. This increase of the volume of fresh groundwater manifests itself mainly as an outward extension of the fresh groundwater lens in the phreatic aquifer. Underlying aquifers and aquitards may even become more saline, primarily as a result of transient boundary conditions (i.e. historical coastal erosion and on-going sea level rise) leading to continuing historical seawater intrusion. In addition, rising groundwater levels in and around Sand Engine can lead to increases in the infiltration of saline groundwater through the thin aquitard (Fig. 11 and Fig. 12).

The sea-level rise (in total) of 0.15 m in climate ~~scenario's~~scenarios G_L and G_H and 0.25 m in climate ~~scenario's~~scenarios W_L and W_H lead to a decline in the volume of fresh groundwater, because of the increase of seawater intrusion and inundation of the coastal area. However, the effect of sea-level rise is relatively small in respect to the total increase of fresh groundwater (Fig. 10).

The long-term predictions in precipitation and evapotranspiration within the four climate scenarios (Table 3~~Table 1~~) have a limited effect on the total volume of fresh groundwater. The climate scenarios with a strong response (G_H and W_H) ~~and corresponding wetter winters and drier summers~~ lead to a ~~lower~~ smaller volume of fresh groundwater, when compared

with the climate scenarios with a weak response (G_L and W_L) ~~and subsequently smaller change in precipitation and evapotranspiration~~. This is primarily a result of the difference in the net groundwater recharge in the climate scenarios, and the overall (yearly) volume of groundwater recharge is larger in the milder climate scenarios (G_L and W_L). The larger increase in precipitation in winter seasons of climate scenario G_H and W_H, coincides with a stronger increase in evaporation and a smaller increase in precipitation in the summer seasons (Table 3). However, ~~T~~the contrast between these climate scenarios only becomes apparent after 2030, because the precipitation and evapotranspiration patterns are equal until 2030 and diverge ~~in the period~~after 2030 ~~– 2050~~.

In addition to the change in fresh groundwater resources in the beach-dune system, the simulations with the long-term morphological evolution of the Sand Engine show small to negligible increases (smaller than 1 m in 2050) in the ~~thickness of the~~ freshwater lens thickness in low-lying polders. However, changes in the total salt load in drains, canals and ditches are small in the situation with and without the Sand Engine. As a result the construction and morphological evolution of the Sand Engine may lead to small decrease of seawater intrusion, but this effect will probably be small to negligible and limited to small low-lying polders in a ~~close~~ short distance ~~to~~ from the Sand Engine (Fig. 13).

5 Discussion

The model simulations show that the construction of the Sand Engine may result in the growth of the volume of fresh groundwater ~~with~~ by several million m^3. Despite the gradual erosion of the nourished sand – leading to a slow return to the previous state – the volume of fresh groundwater may continue to rise for decades after the construction of the mega-nourishment. However, tidal fluctuations and in particular storm surges will lead to land-surface inundations and consequently to a salinization of fresh groundwater. In addition, the increase in the volume of fresh groundwater is dependent on the ~~pace~~ rate of sea-level rise and the extent to which precipitation and evapotranspiration patterns will diverge from present conditions. This steady increase of the volume of fresh groundwater is in contrast with the reference ~~situation~~ case (without the construction of the Sand Engine) where historical and future sea-level rise lead to a decrease of the volume of fresh groundwater. Our results also suggest that the construction of the Sand Engine may abate the salinization of neighbouring polders, by reducing ~~the~~ upward seepage of saline groundwater. Even though the reduction of the salinization is probably slight and limited to a small area, it might constitute an important mitigation in other applications of mega-nourishments.

~~No other studies have integrated the effect of the morphological evolution of coastal areas and climate change on fresh groundwater resources, and the number of quantitative studies that investigate the possibility to combine coastal defence with the protection of fresh groundwater resources are scarce (Oude Essink, 2001). However, studies on small islands have shown that great losses in the volume of fresh groundwater can occur as a result of decreases in groundwater recharge and sea level rise, and especially small and thin lenses seem vulnerable to salinization (Chui and Terry, 2013; Holding et al., 2015; Mahmoodzadeh et al., 2014). In addition, studies have shown that an increase in the frequency of storm~~

~~surge overwash will exacerbate the salinization of coastal aquifers, although the freshwater lens is generally able to recover over time (Holding et al., 2015; Terry and Falkland, 2010). In relation to the morphological dynamics of coastal regions, studies have shown that the erosion and accretion of sand can lead to substantial changes within the beach foredune area (Bakker et al., 2012; Keijsers et al., 2014b), and that climate change might exacerbate coastal erosion (FitzGerald et al., 2008; Zhang et al., 2004). Morphological developments in coastal areas and islands can therefore have a substantial effect on existing and future fresh groundwater resources. Coastal management strategies that compensate, limit, or counteract coastal erosion or seawater intrusion may therefore help to protect or expand fresh groundwater resources.~~

Comparisons of observ~~ations~~ed and ~~with~~ simulated groundwater heads and salinities show a good correspondence before and after the construction of the Sand Engine, despite large variations between observed and simulated groundwater salinities at individual locations. To some extent these discrepancies can be accounted for by the relatively sharp transition between fresh and salt groundwater, through which small variations in depth can result in large differences in groundwater salinities. Other factors that were not included in the simulations and that probably led to discrepancies in observed and simulated groundwater heads and salinities are: historical events (e.g. changes in groundwater level and salinity ~~after~~ during the construction of the Sand Engine), large inundations of the Sand Engine due to storm-surges (e.g. two major storms in 2011 – 2016 inundated approximately 56% of the Sand Engine), variations in extraction rates of pumping wells, fluctuations in ~~the salinity of the North Sea~~sea salinity and unaccounted vertical layering of the Sand Engine deposits. These factors were not included in the model simulations because of the absence or shortage of data, and the long-term scope of this study. However, the overall ~~correspondence~~ similarity between observations and simulations, in combination with the absence of systematic errors in the model calibration, confirms the reliability of the model. Most of the observations – in particular groundwater salinity - emanate from the monitoring system in the adjacent dune area Solleveld and to a lesser extent the Sand Engine. ~~, t~~The simulated groundwater heads and salinities ~~simulations~~ are therefore most reliable in our area of interest, and the reliability is less ~~. It is less certain to what extent the simulated groundwater head and salinity~~ in other areas ~~correspond with the actual situation~~in the model domain. However, the most substantial changes in groundwater salinity will take place in the area close to the Sand Engine, and variations in groundwater head and salinity in other areas will probably have a small to negligible impact on the potential effects of the Sand Engine.

Considering the scale and nature of our research objective, we neglected small and local variations in hydraulic parameters (e.g. hydraulic conductivity, layer thickness, porosity, and storage coefficient) in the model simulations. Supported by geological data and models, each aquifer and aquitard was defined homogenous and anisotropic, with the exception of the phreatic aquifer. ~~The focus of this study lies therefore on the general processes that influence the potential increase in fresh groundwater resources because of the construction of the Sand Engine.~~ This reduction of the model complexity enhances the ability to differentiate and to understand the simulated processes, and leads to a smaller computation time of the model. However, small or local variations in groundwater head or salinity that are caused by heterogeneity will not be accurately reproduced in the model simulations.

One of the largest uncertainties in the study is the long-term morphological evolution of the Sand Engine, despite extensive calibration and validation and the large number of processes that are included in Delft3D (e.g. wind shear, wave forces, tidal forces, density-driven flows). The highly dynamic nature of the coastal zone, the absence of aeolian transport in the Delft3D simulations, and the lack of understanding of some processes, can lead to incremental differences with reality. ~~However, measurements of the cumulative volumetric change in the period 2011 – 2012 have shown similar volume changes and erosion patterns as were predicted with the morphological model (de Schipper et al., 2014).~~ Even though measurements of the last four years show a reasonable fit with the projections of the sediment volume changes and erosion patterns (de Schipper et al., 2014), future morphological change can turn out to be significantly different from the morphological model. For example, the growth of dune grasses and the exposure of shell deposits may prove to reduce erosion and decelerate the morphological evolution of the Sand Engine, or an accumulation of sand in the lagoon might lead to earlier silt up, and therefore a reduction of seawater intrusion in comparison with the projections. The implementation of one simulation of morphological change in the model calculations is therefore a significant limitation in the estimation of the potential fresh groundwater resources. For a more extensive ~~prediction and estimate~~analysis of the uncertainties in the prediction of the effects on fresh groundwater resources, it is recommended to simulate more morphological scenarios in future studies.

In addition to the long-term morphological evolution of the Sand Engine, large uncertainties also exist in the climatological predictions of sea-level rise, precipitation and evaporation in future decades. Predictions of sea-level rise for the North Sea in 2050 range between 15 to 40 cm above MSL, and model simulations have shown that substantial changes in the growth or volume of fresh groundwater resources can occur within this range. Changes in sea-level rise and the intensity or frequency of storm surges will not only significantly influence fresh groundwater, but will also contribute to coastal erosion and alter the morphological development of the Sand Engine.

6 Conclusions

Local mega-nourishments such as the Sand Engine might become an effective solution for the threats that many low-lying coastal regions face, and with this study we have shown that fresh groundwater resources can ~~grow~~ substantially grow within the lifespan of the nourishment. The results in this study show that for the Sand Engine, the construction of a mega-nourishment can lead to increase of fresh groundwater of approximately 0.3 to 0.5 million m^3 per year. However, the increase in fresh groundwater resources in a mega-nourishment is highly dependent on the shape and location of the mega-nourishment, the precipitation surplus, the frequency and intensity of storm surges, and ~~the local circumstances~~local hydrogeological conditions. Therefore dependent on the design and location of the mega-nourishment this may provide an opportunity to combine coastal protection with the protection of fresh groundwater resources. This study also demonstrated that, with relatively simple modifications, a changing morphology can easily be modelled with a variable-density groundwater model such as SEAWAT.

Appendix A: Grid convergence test

In order to justify that the chosen spatial and temporal discretisation is adequate for reliable numerical quantifications of the potential effect of the Sand Engine on fresh groundwater resources, we have executed a grid convergence test for period 2011 to 2050 (with and without Sand Engine). Current numerical simulations were performed with: a horizontal grid size of 50 m, 50 layers with a variable thickness from 1 (upper layers) to 10 m (lower layers), and stress periods of 90.25 to 92 days (corresponding to seasons). The transport simulations were performed implicitly with the Generalized Conjugate Gradient (GCG) solver, and the transport step sizes were model-calculated based on a Courant number of 1. For the coupling of the flow and transport we have used the explicit approach. In the grid convergence test we have performed one additional with an implicit (iterative with a density criterion of 0.2 kg m^{-3}) to test the temporal discretisation. The spatial discretisation was tested with three additional numerical simulations with higher and lower spatial resolutions: one simulation with a horizontal grid size of 25 m, one simulation with a horizontal grid size of 100 m, and one simulation with the same horizontal grid size of 50 m and an increased vertical resolution of the upper layers. In the upper part of the model, up to a depth of -50 m MSL, the layer thicknesses were lowered with 50% (30 layers were added, up to a total of 80 layers). These additional numerical simulations include no climate change scenario, and were compared to the current numerical simulations that contained a horizontal resolution of 50 m and 50 layers. The initial conditions of all additional numerical simulations were equal to the calibrated pre-development groundwater heads and TDS concentrations.

The comparison of the current simulations with the three additional numerical simulations that contain higher and lower spatial resolutions (Fig. A1), show a similar increase of the volume of fresh groundwater in the model domain during the simulation period of 2011 to 2050. In the situation with the Sand Engine (Fig. A1b), a coarser spatial resolution lowered the projected volume of fresh groundwater (-10% in 2050), and a finer horizontal and vertical spatial resolution raised the projected volume of groundwater (respectively + 4% and +20% in 2050). However, when taking into account the deviations in the volume of fresh groundwater in the reference case (Fig. A1a), the total change in the volume of fresh groundwater becomes smaller; respectively -2%, +0% and +14% in 2050. The additional simulation with an implicit coupling of flow and transport equations shows a small to negligible difference (smaller than 2% during the entire simulation period) with the simulations with explicit coupling of flow and transport equations (Fig. A2). In summary, the additional simulations show relatively small changes in the volume of fresh groundwater, and suggest that an increase in the vertical resolution can even lead to a higher increase in the volume of fresh groundwater.

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Table 1. Hydrogeologic parameters used in the simulations, where the upper part of the phreatic aquifer (1a: above -10 m MSL) was subdivided in two hydrogeological zones (1: fine to coarse sand; 2: clay, loam and fine sand)

Layer	K_H [m d^{-1}]	K_V [m d^{-1}]	n_e [-]
Phreatic aquifer 1a	10 / 1	1 / 0.1	0.3
Phreatic aquifer 1b	1	0.1	0.3
Aquitard 1	0.01	0.001	0.1
Aquifer 2	30	10	0.3
Aquitard 2	2	0.2	0.1
Aquifer 3	5	2	0.3
Aquitard 3	1	0.1	0.1
Aquifer 4	15	3	0.3
Aquitard 4	10	0.03	0.1

Table 2. Simulation of processes and method of incorporation in groundwater model

Process	Source / Simulation	Method of incorporation
Historical coastal erosion (1500 – 2010)	Literature and paleogeographic maps of AD 1500 and AD 1850 (Beets and van der Spek, 2000; Beets et al., 1992; Vos and de Vries, 2013)	Delineation of the shoreline was incorporated in three phases: 1500, 1500-1740, 1740-2010. Phasing based on literature (Fig. 5)
Historical sea-level rise (1500 – 2010)	Literature containing time-series and predictions of historical sea-level rise (Jensen et al., 1993; Wahl et al., 2013)	The period 1500 -2010 was divided in 8 stages, enforcing the average sea-level for each stage (stages are indicated with vertical lines in Fig. 5).
Groundwater extraction (1890 – 2010)	Literature on historical groundwater extraction in Solleveld (Draak, 2012) and time-series of groundwater extraction and infiltration volumes.	The period 1890 -2010 was divided in 6 stages, enforcing the average extraction for each stage (see blue bars in Fig. 5).
Morphological evolution Sand Engine (2011 – 2050)	Simulated with Delft3D (Lesser et al., 2004), with computations of the hydrodynamics, waves, sediment transport and bed change (Mulder and Tonnon, 2011; Tonnon et al., 2009).	For every three month period in 2011 – 2050 the simulated bathymetry was enforced to the groundwater model; by changing the topography, area of inundation, and recharge.
Sea-level rise (2011 – 2050)	Climate projections of sea-level rise in 2030 and 2050 (KNMI, 2014).	The projected sea-level rise in 2030 and 2050 were linearly interpolated. The average sea-level was implemented for every three month period.

Table 3. Model climate change scenarios for the period 2011 – 2050, with two rates of SLR, starting at 0.05 m MSL and seasonal variation in groundwater recharge (DJF, MAM, JJA, SON)

Climate Scenario	Sea-Level Rise	Precipitation 2050 (given per season)	Potential evaporation 2050 (given per season)
No climate change (NoCC)	No sea-level rise [0.05 m MSL]	Equal to present: Period 1981 - 2010	Equal to present: Period 1981 - 2010
G_L	+ 3.75 mm yr^{-1} [2050: 0.20 m MSL]	+3%, +4.5%, +1.2%, +7%	+2.9%, +1.3%, +3.9%, +2.7%
G_H	+ 3.75 mm yr^{-1} [2050: 0.20 m MSL]	+8%, +2.3%, -8%, +8%	+2.4%, +2%, +7.5%, +2.8%
W_L	+ 6.25 mm yr^{-1} [2050: 0.30 m MSL]	+8%, +11%, +1.4%, +3%	+3.2%, +1.7%, +4.4%, +5.8%
W_H	+ 6.25 mm yr^{-1} [2050: 0.30 m MSL]	+17%, +9%, -13%, +7.5%	+2.7%, +2.9%, +10.6%, +4.5%

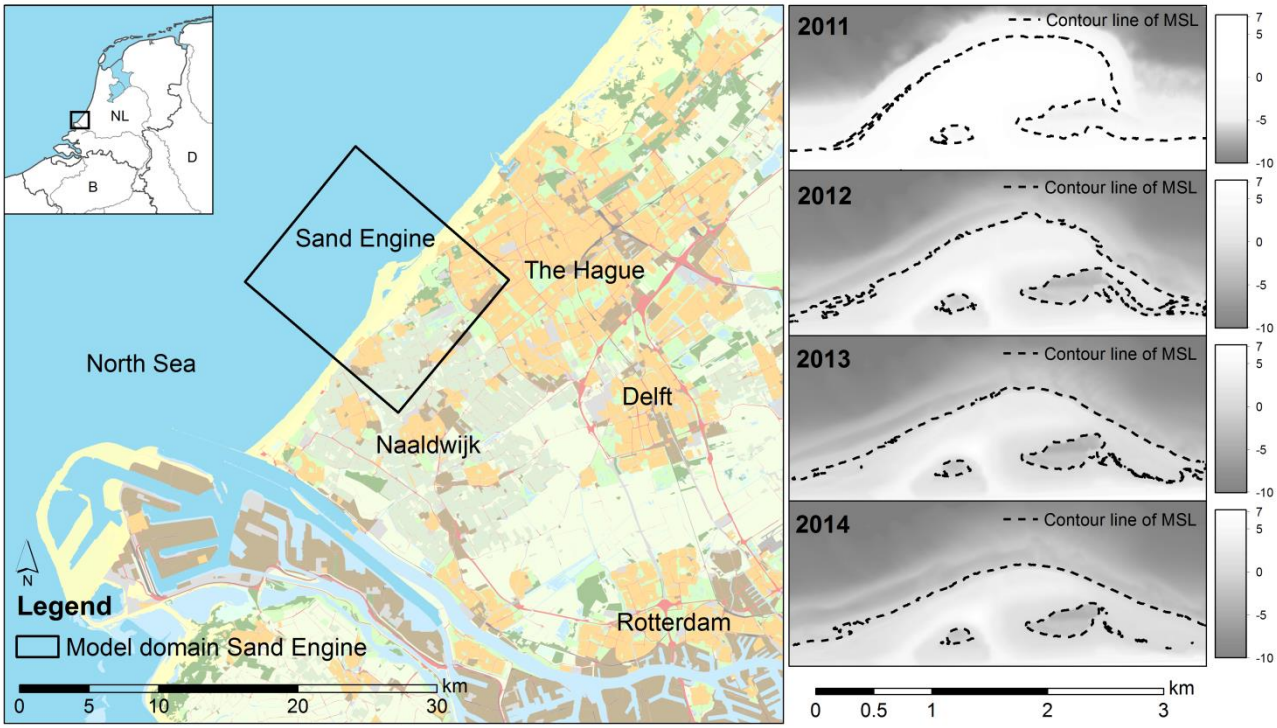

Fig. 1. Situation of the Sand Engine and morphological development in 2011 - 2014

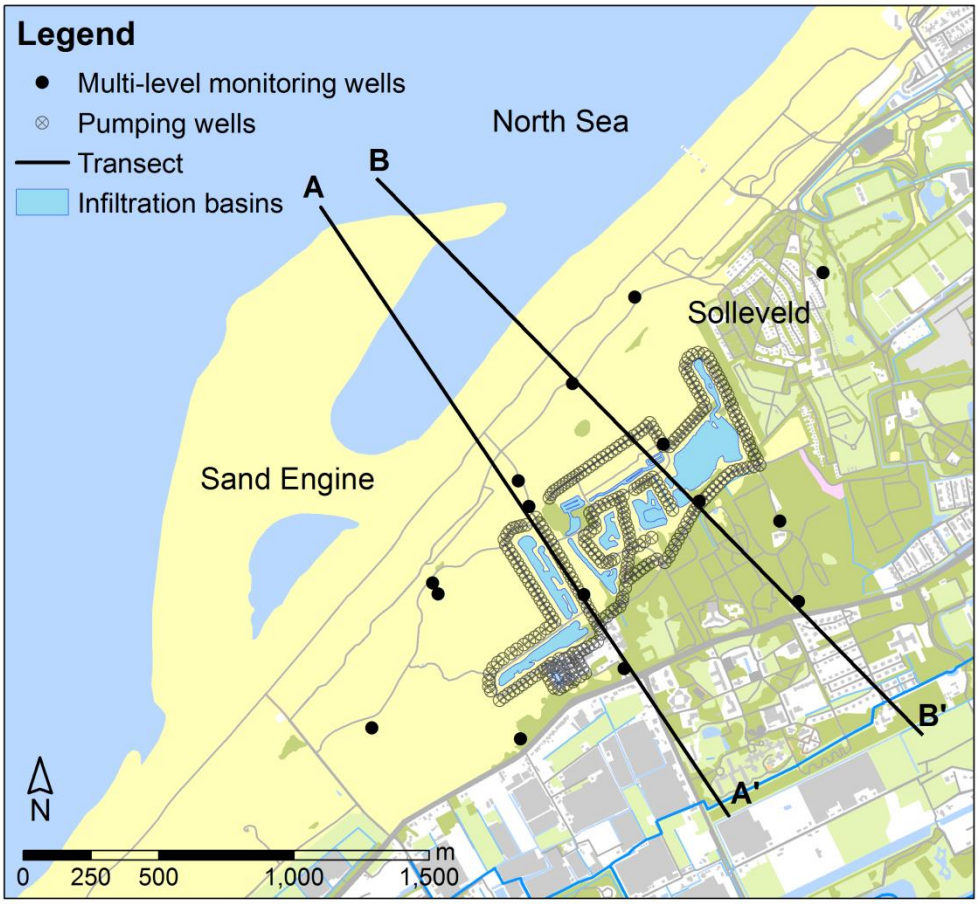

Fig. 2. Map of the dune area Solleveld with multi-level monitoring wells and pumping wells, including transects A and B (geological profiles in **Fig. 3**)

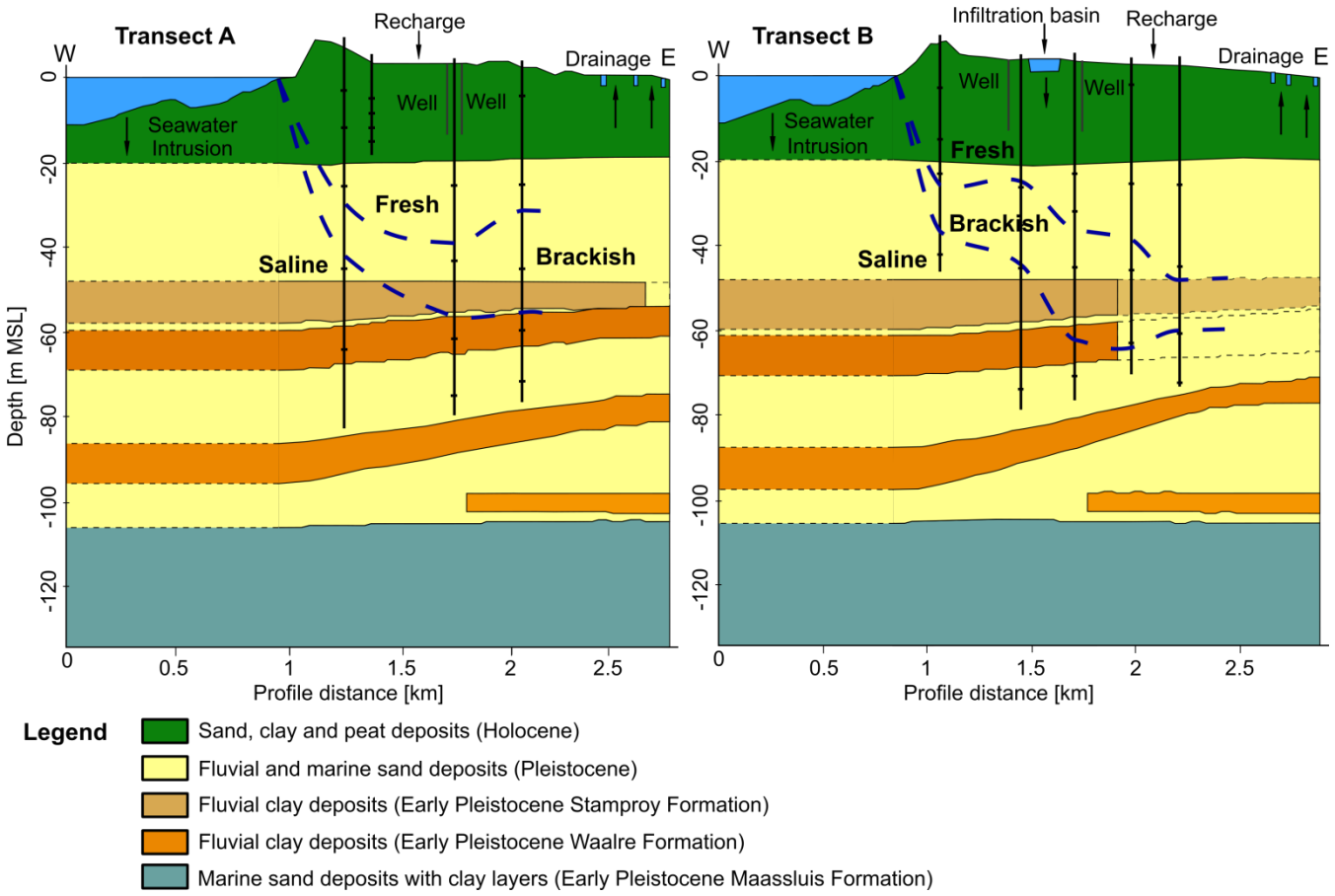

Fig. 3. Geological profiles (based on the databases of the Geological Survey of The Netherlands) across the model domain with conceptual fresh-salt water distribution (locations are shown in **Fig. 2**)

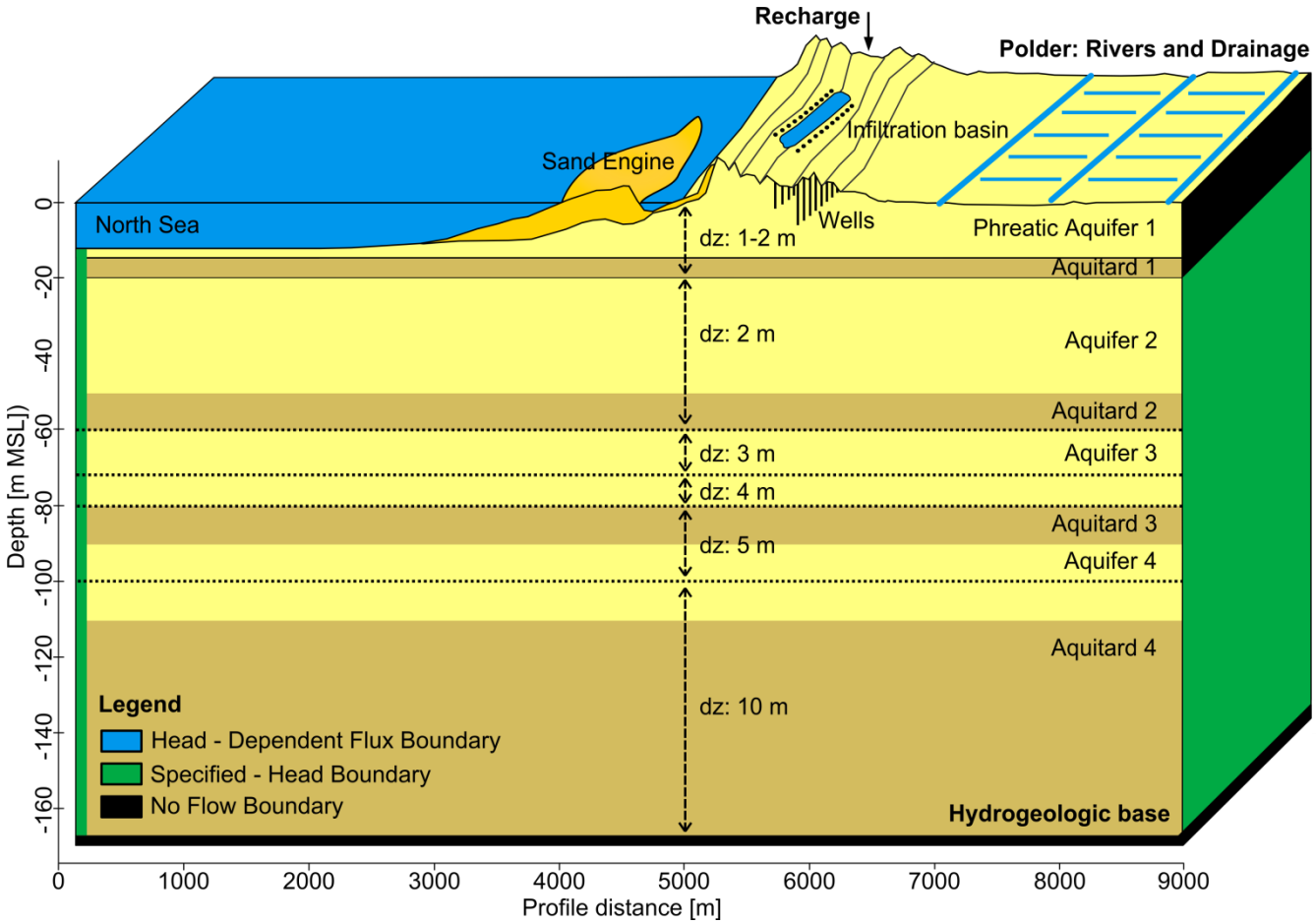

Fig. 4. Conceptual representation of a slice ~~or portion~~ of the model with ~~aquifer parameters~~layer thicknesses and boundary conditions

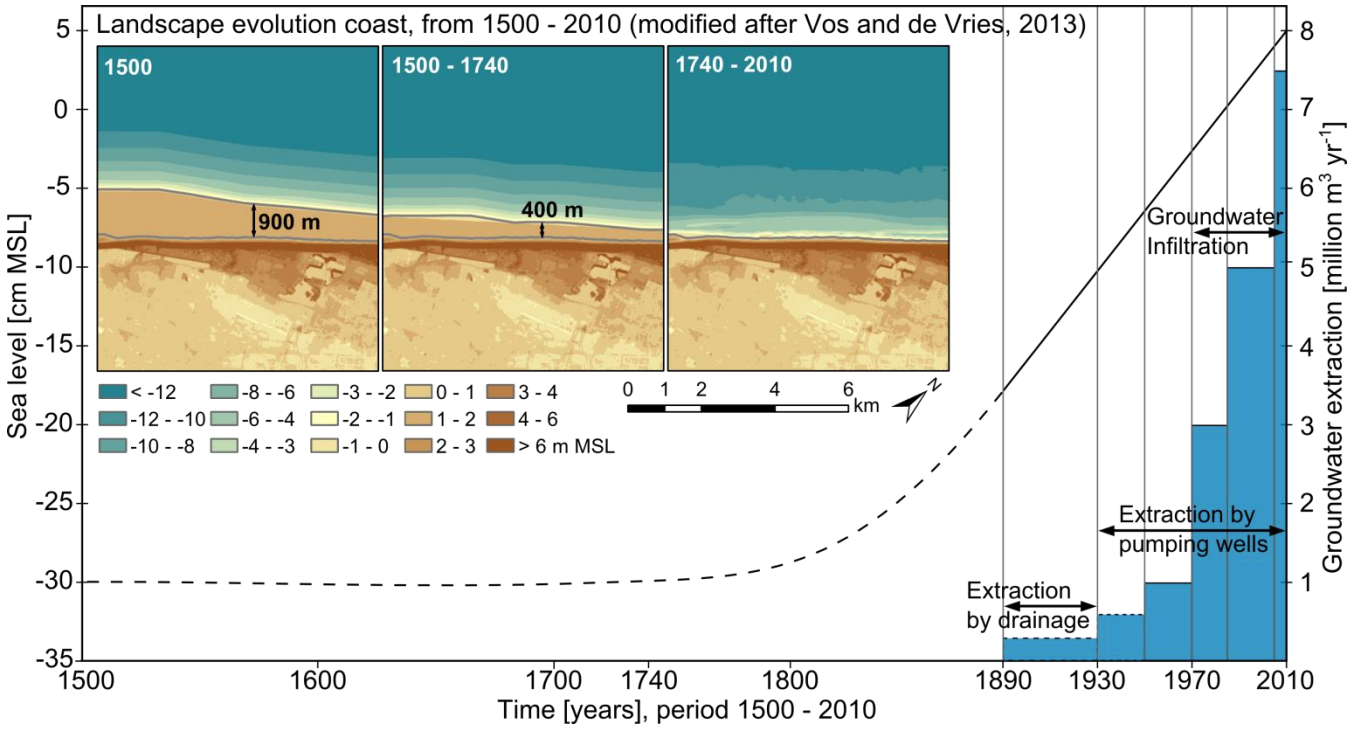

Fig. 5. Simulation of historical coastal erosion (based on paleogeographic maps of Vos and de Vries, 2013), sea-level rise (black line) and groundwater extraction (blue) in the period 1810 – 2010; dashed lines indicate estimates, and vertical grey lines refer to stress periods (CBS et al., 2013).

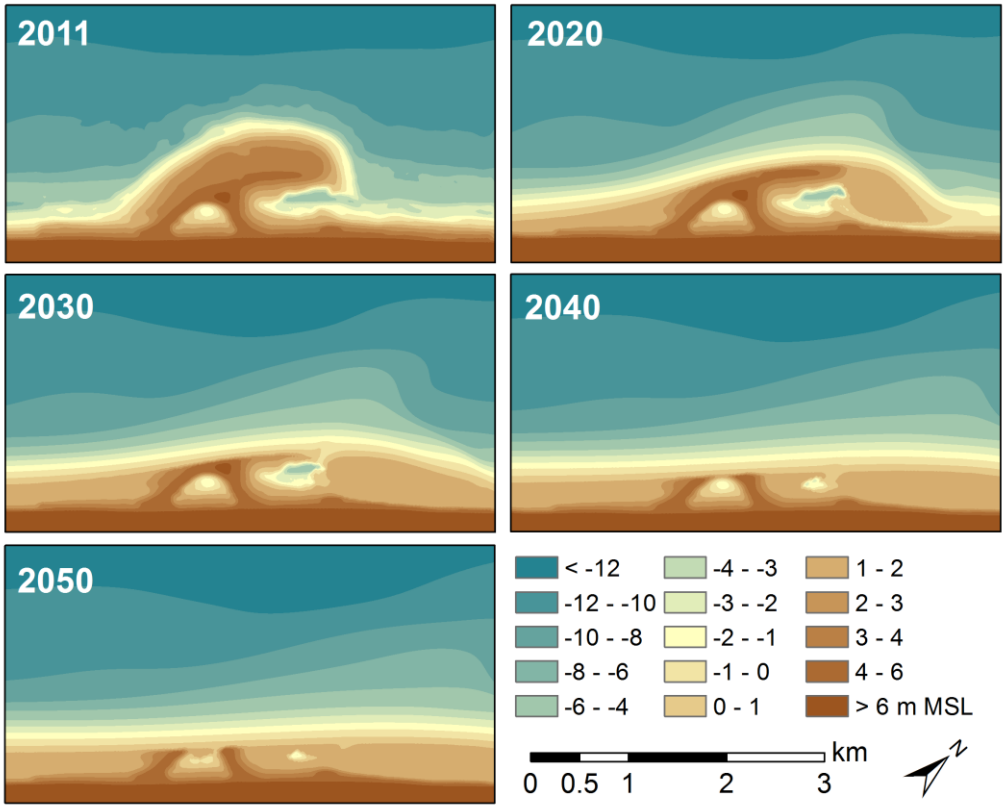

Fig. 6. Simulated morphological development of the Sand Engine from 2011 to 2050, illustrated by contour maps with the terrain elevation (m MSL)

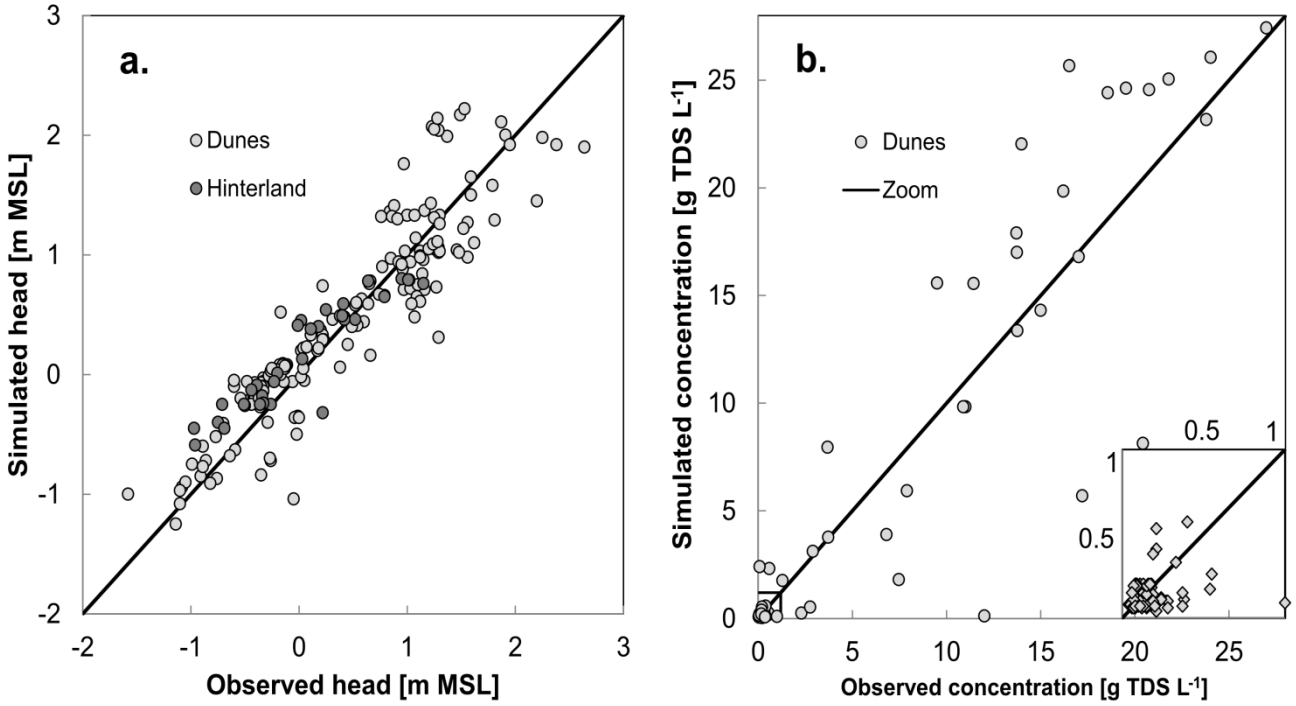

Fig. 7. Comparison of observed and simulated heads (a) and concentration (b)

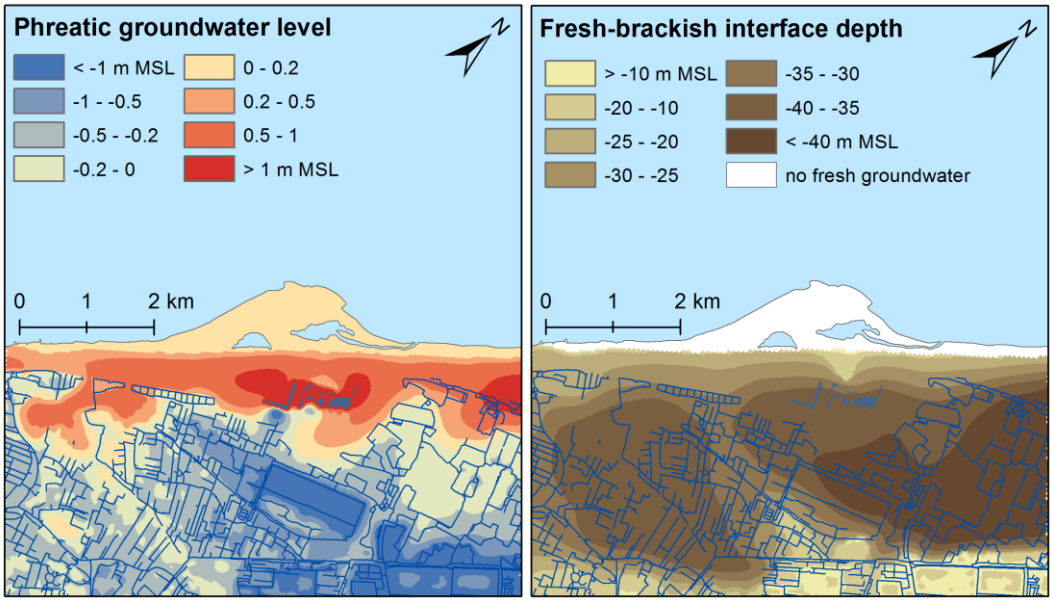

Fig. 8. Phreatic groundwater level (left) and fresh-brackish interface depth (right) after calibration, before the construction of the Sand Engine (2010 – 2011).

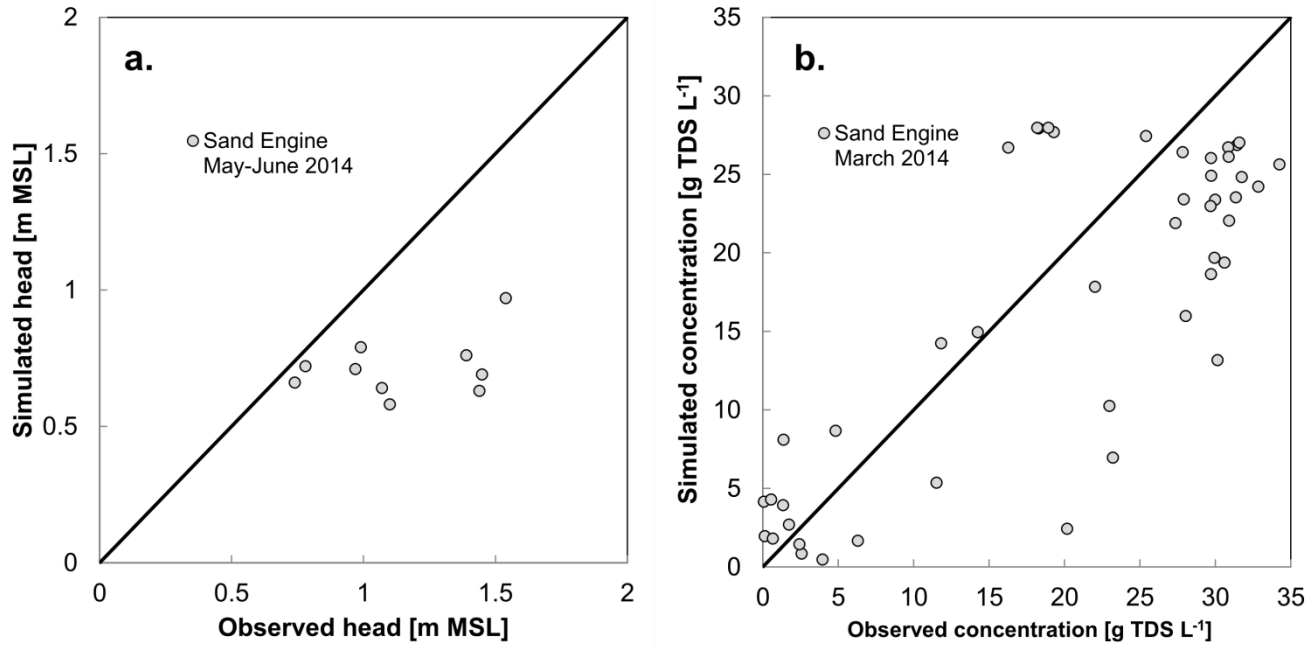

Fig. 9. Comparison of (a) average groundwater heads in May-June 2014 and (b) (single) TDS concentrations of soil samples taken between 10 and 14 March 2014 with model simulations in the Sand Engine.

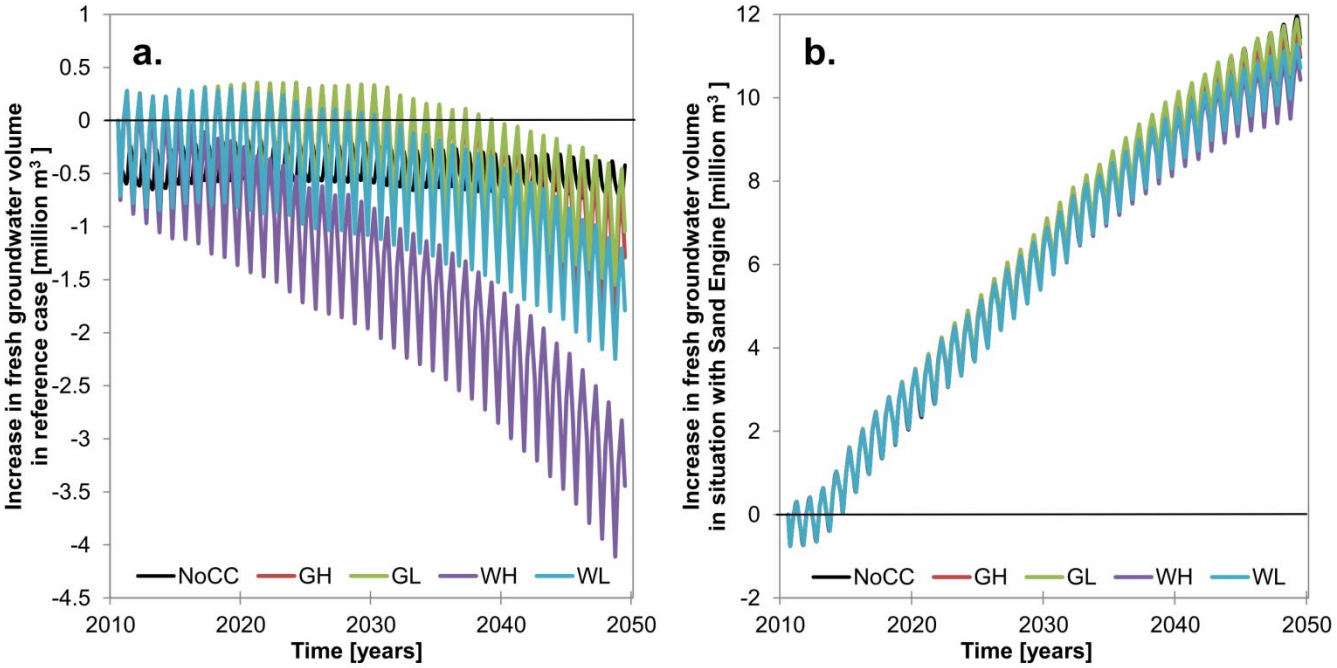

Fig. 10. Increase of the volume of fresh groundwater in the situation without Sand Engine (a) and situation with Sand Engine (b) in the period 2011 to 2050, where the legend refers to (climate) scenarios (as mentioned in Table 3)

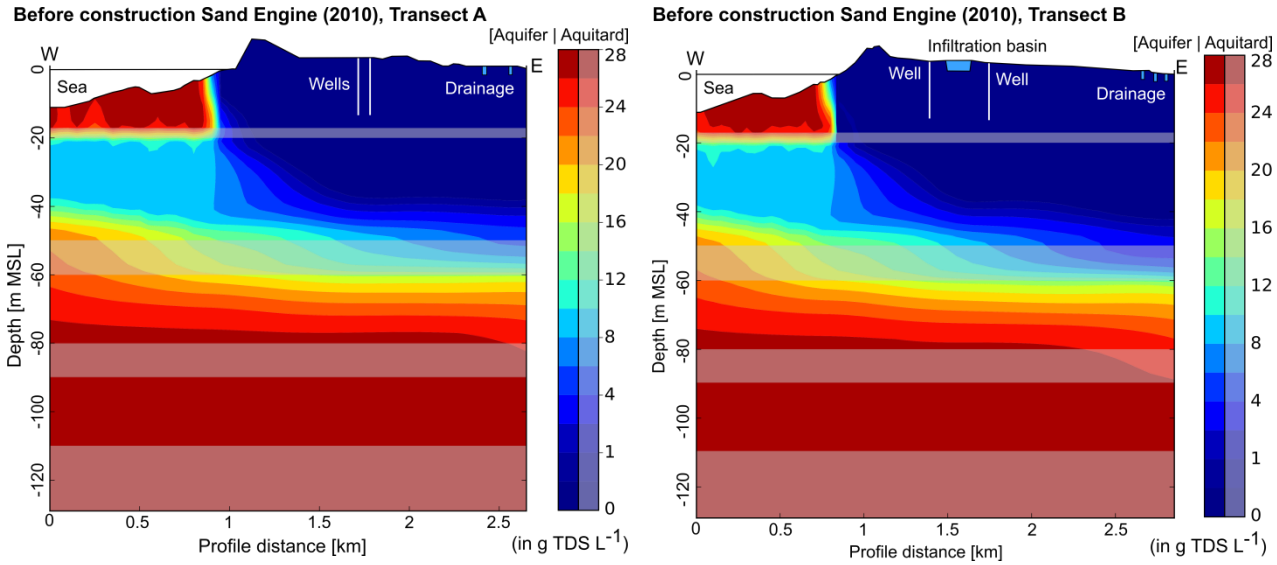

Fig. 11. Transects with the simulated groundwater salinity (in g TDS L-1) in 2010 (pre-development Sand Engine), for transect A and B (as shown in Fig. 2 and Fig. 3)

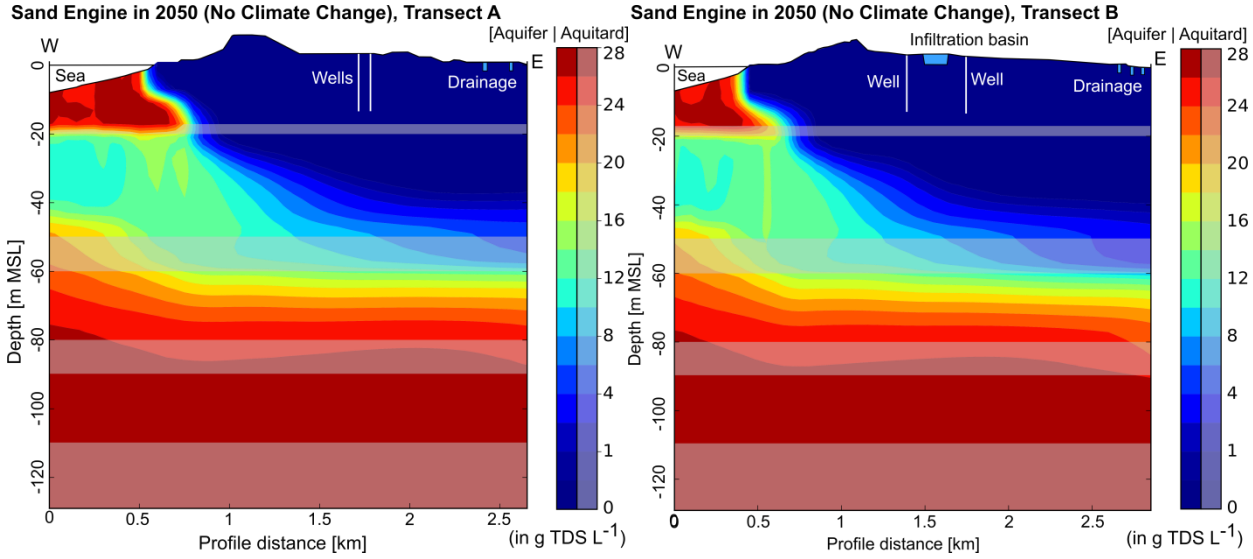

Fig. 12. Transects with the simulated groundwater salinity (in g TDS L^{-1}) in 2050 (including Sand Engine, No Climate Change), for transect A and B (as shown in Fig. 2 and Fig. 3)

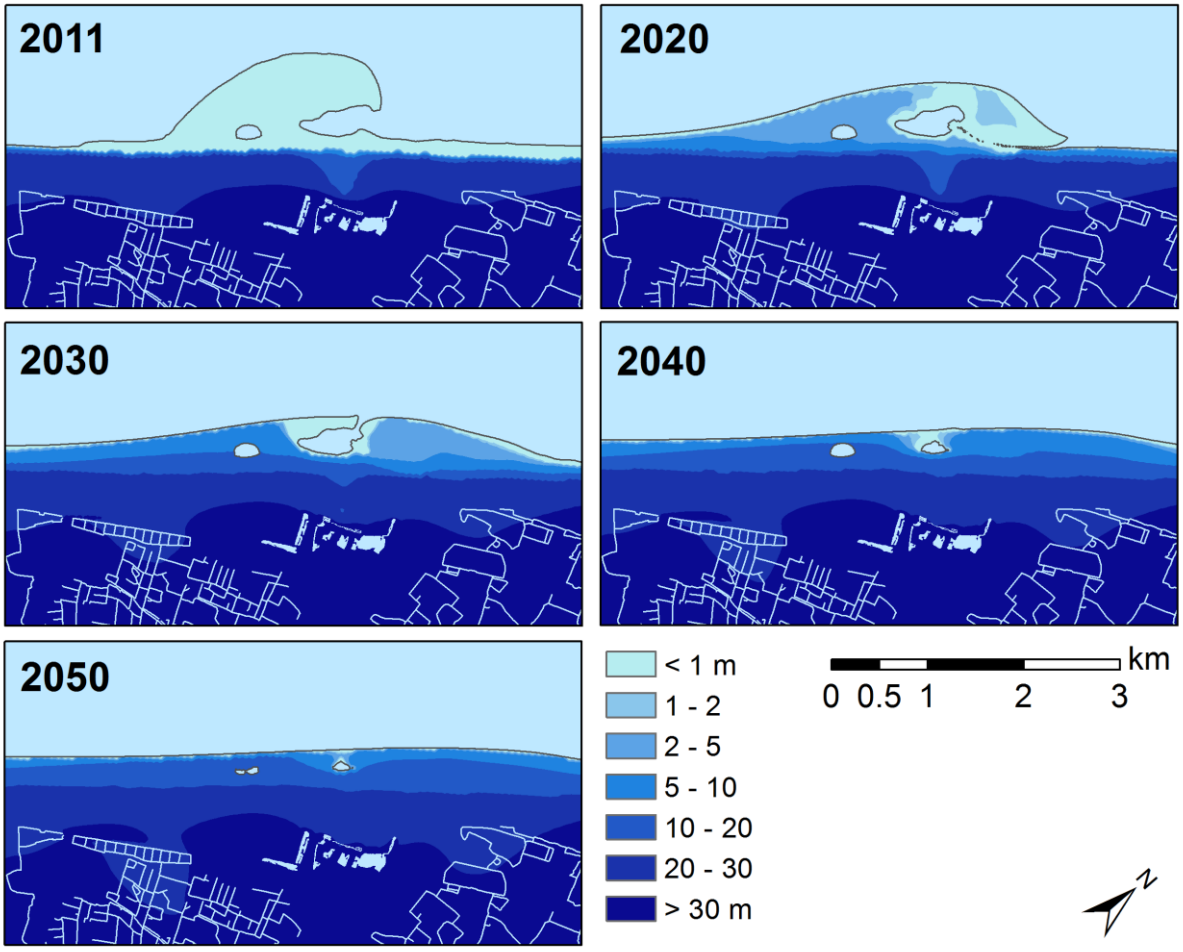

Fig. 13. Thickness of fresh groundwater [m] in reference scenario near the Sand Engine from 2011 – 2050

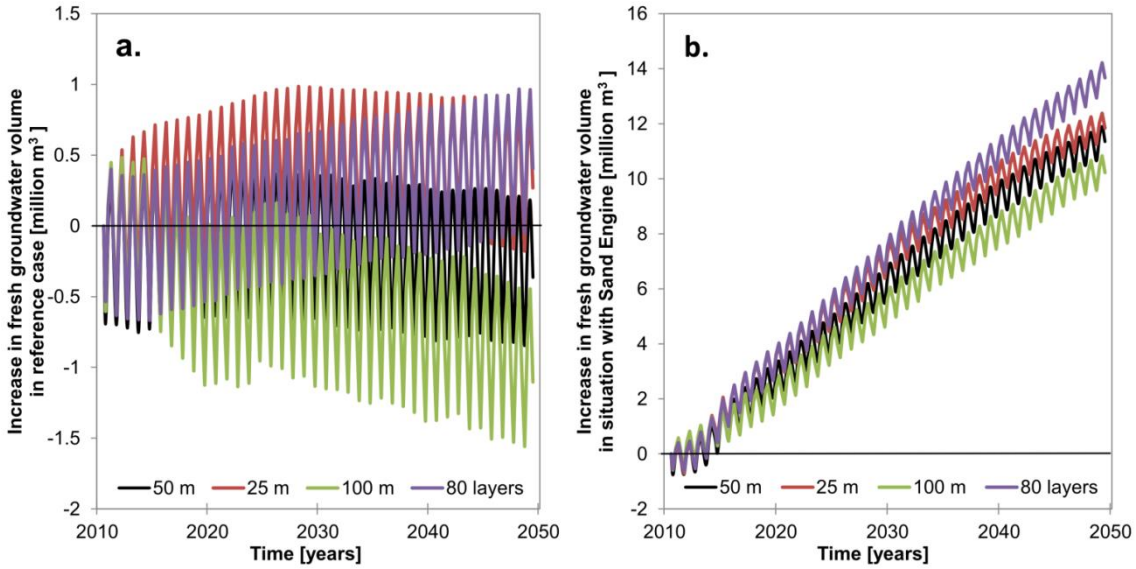

Fig. A1. Increase of the volume of fresh groundwater in the situation without Sand Engine (a) and situation with Sand Engine (b) in the period 2011 to 2050, where the legend refers to the four grid discretisation simulations

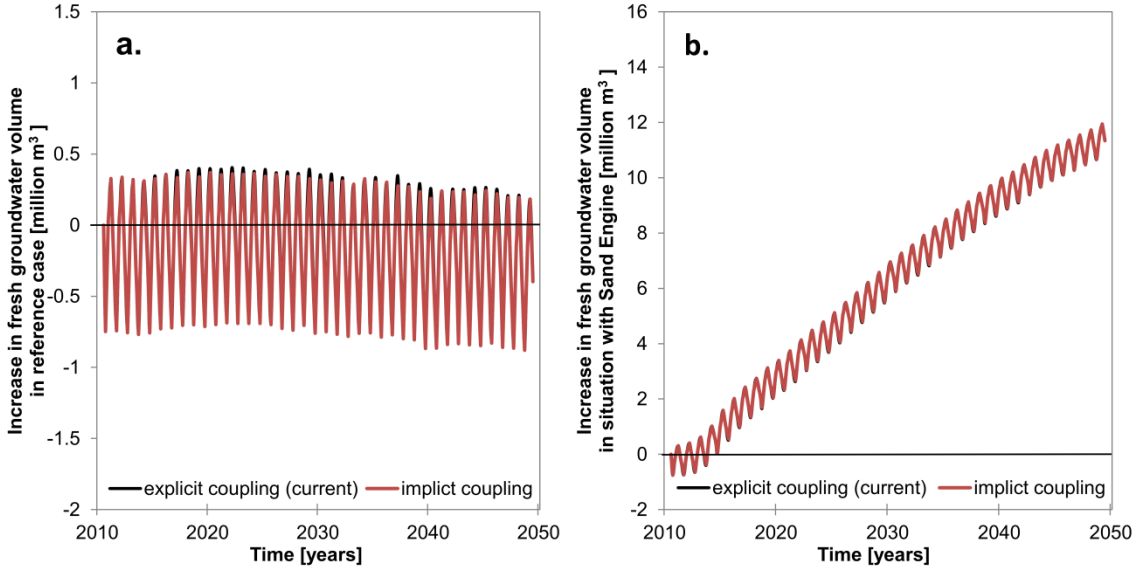

Fig. A2. Increase of the volume of fresh groundwater in the situation without Sand Engine (a) and situation with Sand Engine (b) in the period 2011 to 2050, where the legend refers to the coupling of flow and transport equations

Fresh groundwater resources in a large sand replenishment

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Abstract. The anticipation of sea-level rise and increases in extreme weather conditions has led to the initiation of an innovative coastal management project called the Sand Engine. In this pilot project a large volume of sand (21.5 million m^3) – also called sand replenishment or nourishment – was placed on the Dutch coast. The intention is that the sand is redistributed by wind, current and tide~~, ~~; reinforcing local coastal defence structures and leading to a unique, dynamic environment. In this study we investigated the potential effect of the long-term morphological evolution of the large sand replenishment and climate change on fresh groundwater resources. The potential effects on the local groundwater system were quantified with a calibrated three dimensional groundwater model, in which both variable-density groundwater flow and salt transport was simulated. Model simulations showed that the long-term morphological evolution of the Sand Engine results in a substantial growth of fresh groundwater resources, in all adopted climate change scenarios. Thus, the application of local sand replenishments such as the Sand Engine could provide coastal areas the opportunity to combine coastal protection with an increase of the local fresh groundwater availability.

1 Introduction

Global sea-level rise poses a ~~threat~~ risk for coastal areas, especially when combined with an increase in the frequency and intensity of storm surges (Michael et al., 2013; Nicholls et al., 2010; Wong et al., 2014). Particularly small islands (Chui and Terry, 2013; Holding and Allen, 2015; Mahmoodzadeh et al., 2014), and low-lying ~~delta's~~deltas (Giosan et al., 2014; McGranahan et al., 2007; Oude Essink et al., 2010) are vulnerable to rising sea-levels. Many low-lying deltas such as the Mekong Delta (Viet~~Nam~~nam) and the Ganges-Brahmaputra delta (Bangladesh) are already frequently subjected to extensive floods, leading to considerable economic losses, property damage, and in severe cases loss of life (Few and Matthies, 2006; de Sherbinin et al., 2011; UNDP, 2004). In addition, many ecosystems and inhabitants of deltas are ~~becoming increasingly vulnerable~~threatened as a result of high subsidence rates, over-exploitation of fresh groundwater resources, and contamination of coastal aquifers (Crain et al., 2009; de Sherbinin et al., 2011; Syvitski et al., 2009; UNDP, 2004). Sea-level rise and storm surges will enhance the pressure on these coastal regions (Kooi et al., 2000; Yang et al., 2013, 2015), and will likely exacerbate the loss of agricultural land, damage of ecosystems and the salinization of fresh groundwater resources (Hoggart et al., 2014; Nicholls, 2010; Oude Essink et al., 2010; Wong et al., 2014).

1.1 Coastal management

In order to protect the livelihood of densely populated coastal areas against climate-related impacts, a growing number of studies recognises the need for the adoption of coastal defence strategies (Giosan et al., 2014; Nicholls et al., 2010; Temmerman et al., 2013; Wong et al., 2014). Fortunately, the awareness of the threats posed by climate change is growing, and coastal defence in a number of countries – especially developed countries – has have been intensified, specifically at vulnerable locations (Goodhew, 2014; Kabat et al., 2009; Sterr, 2008). One example is the Netherlands – a vulnerable low-lying delta country – where coastal defence systems have been reinforced on several occasions, in accordance with its long history of intensive coastal protection (Charlier et al., 2005). Centuries of continuing erosion, flooding and subsidence led first to the implementation of hard engineering methods (e.g. groynes and sea walls), and later soft engineering methods (e.g. sand replenishment or nourishment, van Koningsveld et al., 2008). Since 1990 the application of sand nourishments, particularly beach and shoreface nourishments, has become the dominant coastal defence strategy at the Dutch coast. Sand nourishments are applied on an regular annual basis – where necessary – in order to maintain the position of the coastline (Keijsers et al., 2015; de Ruig and Hillen, 1997).

1.2 Pilot project: Sand Engine

Since 2001, the position of the entire Dutch coastline is successfully maintained with 12 million m^3 of sand nourishments per year. However, the future annual volume of sand nourishments should increase if the coast must is to rise with the sea-level (Deltacommissie, 2008). Research suggests that the annual nourishment volume should be raised to 20 million m^3 yr^{-1} in the nearby future, ; in order to sustain the Dutch coastline in the long run (Giardino et al., 2011; de Ronde, 2008). The anticipation of a substantial growth in the annual nourishment volume incited discussions about the effectiveness of the current regular small scalelarge-scale distribution of sand nourishments. These discussions led to the idea that the substitution of small scale nourishments with local concentrated (mega) nourishments could provide several advantages: be more cost-effective than current practices, and may provide opportunities for promote natural dune growth, reduce ecological stress, and provide more opportunities for recreation (e.g. kite surfing, van Slobbe et al., 2012).

The effectiveness, benefits and drawbacks of concentrated local (mega) nourishments are currently being investigated with a pilot experiment project named the Sand Engine (also called Sand Motor) (Mulder and Tonnon, 2011; Stive et al., 2013). In this experiment project a mega-nourishment of 21.5 million m^3 was constructed at the Dutch coast in 2011, : a few kilometres west from the city of The Hague (Fig. 1). This large bodye replenished of sand will gradually be distributed along the coast by wind, waves and currents, thus incorporating natural forces in engineering methods (so called 'Building with Nature') (Slobbe et al., 2013; de Vriend et al., 2014). The effectiveness of the Sand Engine is determined investigated by extensive research and intensive extensive monitoring:; the surface level elevation (including the sea bed levelbathymetry) is measured frequently to gain detailed knowledge of the volume and direction of sediment transport at this local mega-nourishment (Ebbens and Fiselier, 2010; Tonnon et al., 2011). Recent Mmeasurements in the most recent years

show that the outer perimeter of the ~~shape of the Sand Engine transformed from a~~ 'hook-shaped' peninsula retreated, and the alongshore extent increased ~~' towards a flattened wider shape~~ (de Schipper et al., 2016; Stive et al., 2013). Initially ~~In September 2011~~ the Sand Engine extended approximately 1 km into the sea and was nearly 2 km wide at the shoreline, while in September 2014 it extended approximately 800 m into the sea and was more than 3 km wide at the shoreline (Fig. 1).

1.3 Study objectives

The primary objective of this study is to quantify the potential effect of the Sand Engine ~~(local mega-nourishment)~~ on the regional groundwater system, particularly on fresh groundwater. During the life span of the Sand Engine the (direct) influence of the North Sea is diminished, because of the seaward displacement of the shoreline – and possibly ~~future~~ growth of adjacent dunes. The extension of the beach-dune system and the reduction in seawater intrusion may lead to a growth of fresh groundwater resources. In combination with an increase of groundwater levels, the construction of the Sand Engine may also lead to a decline in the upwelling of saline groundwater and a decreased salt load in adjacent low-lying areas.

The long-term morphological evolution of the Sand Engine – powered by coastal and aeolian sediment transport – will also affect to local groundwater system with time. Erosion and deposition of sand will alter the position of the shoreline and the surface elevation with time, ~~which gives rise to displacements~~ which simultaneously gives rise to dynamic changes in seawater intrusion and submarine groundwater discharge. ~~(groundwater flow out of the aquifer, across the sea floor).~~ The morphological evolution of the Sand Engine and the dynamic nature of thise coastal system ~~may~~ will probably lead to ~~frequent and~~ considerable changes in groundwater head and divide, the direction and velocity of groundwater flow, and the stored volume of fresh groundwater.

One of the innovative aspects of this study is to incorporate detailed predictions of the long-term morphological evolution of the Sand Engine in a 3D numerical model, which ~~considers~~ simulates ~~variable-density~~variable-density groundwater flow ~~coupled with salt transport~~. At the moment no studies have investigated the influence of local mega-nourishments on groundwater systems, and only a few groundwater modelling studies have incorporated a changing morphology in their calculations (Delsman et al., 2014). We also assess the effect of climate change (e.g. sea-level rise) on fresh groundwater resources in the study area, in combination with the morphological evolution of the Sand Engine. To our knowledge, ~~N~~no other studies have integrated the effect of the morphological evolution of coastal areas and climate change on fresh groundwater resources, and the number of quantitative studies that investigate the possibility to combine coastal defence with the protection of fresh groundwater resources are scarce (Oude Essink and Waterman, 2016; Oude Essink, 2001). However, studies on small islands have shown that great losses in the volume of fresh groundwater can occur as a result of decreases in groundwater recharge and sea-level rise, and especially small and thin lenses seem vulnerable to salinization (Chui and Terry, 2013; Holding and Allen, 2015; Mahmoodzadeh et al., 2014). In relation to the morphological dynamics of coastal regions, studies have shown that the erosion and accretion of sand can lead to substantial changes within the beach-foredune area (Bakker et al., 2012; Keijsers et al., 2014), and that climate change might exacerbate coastal erosion (FitzGerald et al., 2008; Zhang et al., 2004). Morphological developments in coastal areas can therefore have a substantial

effect on fresh groundwater resources, and coastal management strategies that compensate, limit, or counteract coastal erosion or seawater intrusion may help to protect fresh groundwater resources.

The paper first describes the construction of the Sand Engine and the characteristics of the study area. It then reviews the methodology for the development of the regional groundwater model, and the model ~~scenario's~~scenarios. Next, the model calibration and model results are described and examined as well as the impact of different climate ~~scenario's~~scenarios on simulated fresh groundwater resources. Finally, the methodology and results are discussed, emphasizing on the limitations and implications for fresh groundwater resources.

2. Site description

2.1 Study area

The construction of the Sand engine was commissioned and designed by the executive branch of the Ministry of Infrastructure and the Environment (Rijkswaterstaat) and the provincial authority of South-Holland (Provincie Zuid-Holland) (Mulder and Tonnon, 2011). Large trailing suction hopper dredgers were used to ~~suck up~~extract sand from several sand pits in the North Sea and to transport this~~e~~ sand to the project site. The dredged material was stored in the hopper and ~~transported~~ deposited ~~to~~ on the project site with three different techniques: by opening the bottom valves of the vessel on-site ("depositing"), by pumping a mixture of sand and water to the site through a pipeline ("pumping"), and by spraying a mixture of sand and water from the vessel's bow to the site ("rain-bowing"). When the construction of the Sand Engine was completed (in ~~October~~ July 2011), the area above MSL was 1.3 km^2 with a maximum ~~height~~ surface elevation of 7 m MSL (Slobbe et al., 2013).

The Sand Engine peninsula is connected to the main-land by a sandy beach~~, h of 100 to 150 m width, which~~ and is bounded by a coastal dune area called Solleveld. Solleveld ~~with maximum heights between 10 to 20 m MSL. This dune area called Solleveld~~ is relatively small dune area (circa 2 km^2; Fig. 2) with surface elevations ranging from 2 to 16 m MSL, and is used for the production of drinking water ~~since 1887 (Draak, 2012)~~. From the start of the groundwater extractions in 1887 the ~~An increasing~~ demand ~~for~~ and extraction of ~~clean~~drinking~~, fresh~~ water ~~led to a~~ gradually increased from a maximum of 1 million m^3 per year before 1970, ~~in extraction rates, reaching~~ to a maximum of ~~a maximum of~~ 7.5 million m^3 per year ~~in~~ after ~~the recent period of~~ 2008~~—2015~~ (Draak, 2012). ~~In order to~~However, to be able to ~~be able to~~ extract these ~~considerable~~ increasing ~~groundwater~~ volumes of groundwater ~~from this relatively small dune area~~ without salinization ~~of fresh groundwater resources~~, the drinking water company started with the infiltration of surface water in 1970 ~~in 1970~~. The infiltrated volume of surface water is approximately equal to the volume of fresh groundwater that is extracted from the dunes. Currently the groundwater is extracted from the phreatic aquifer with almost 300 vertical pumping wells, which are located on the sides of twelve elongated infiltration basins [Fig. 2; Zwamborn and Peters, 2000].

Beyond the dunes the area gradually transforms into urban area and low-lying agricultural areas (polders). The low-lying polders have surface elevations of -1 to 1 m MSL, and act predominantly as a groundwater sink, while the urban areas are generally situated in higher areas with surface elevations between 1 and 3 m MSL. The dominant groundwater flow in the upper aquifers flows from the higher urban areas and coastal dunes toward the North Sea and the polders. The relatively low drainage levels in the polders lead also leads to the attraction of deeper saline groundwater, in addition to the drainage of local fresh groundwater.

2.2 Hydrogeology

The subsoil consists of unconsolidated sediments of predominantly fluviatile and marine origin, as shown illustrated by two geological profiles in Fig. 3. The phreatic aquifer containsupper part of the subsoil (10 to 30 m) consists multiple layers of sand, clay and peat of 10 to 30 m thickness, which are were deposited during the Holocene.: primarily fine- to medium-grained sand iIn the higher situated dunes and urban areas the aquifer primarily consists of fine to medium grained sand, and in the low-lying areas primarily of sand and clay in the low-lying areas. However, the lower section of the Holocene deposits However, the lower section of the phreatic aquifer (between -15 and -20 m MSL) consists in both areas in both areas mainly of clay and peat deposits. Deeper aquifers (yellow) and aquitards (orange, blue), as illustrated in Fig. 3,The underlying thick layers of fluviatile and marine sediment are were deposited during the Pleistocene. It should be noted that the geological schematization of the aquifers and aquitards beneath -40 m MSL are based on a limited number of boreholes.

The conceptual fresh-brackish-saline groundwater distribution (blue striped lines; Fig. 3) are based on chloride measurements, performed at multi-level monitoring wells. Chloride measurements in Solleveld indicate that the boundary between fresh and brackish groundwater (1 TDS g lL^{-1}) is situated between -20 and -40 m MSL, and the boundary between brackish and saline groundwater (10 TDS g lL^{-1}) is situated between -40 and -60 m MSL. The depth of the fresh groundwater lens and the extent of seawater intrusion are controlled by head differences, caused by groundwater pumping, recharge, infiltration, drainage, and salinity..

2.3 Monitoring

In order to timely observe changes in groundwater level, flow and quality an extensive monitoring network was implemented in Solleveld. After the construction of the Sand Engine this monitoring system was expanded and intensified at in the western side part of the dune area. The aim of the expansion of the monitoring system was to observe long termlong-term changes in groundwater level, flow and quality and to observe hydrogeological effects caused by the Sand Engine and previous small-scale nourishments (Buma, 2013). The current monitoring system consists of more than 300 observation wells, where the groundwater level is measured with varying frequency (ranging from wells with hourly frequency to wells that are only observed read off every three months). The groundwater salinity is measured twice every year frequently in at least 50 monitoring wells, with various methods;: groundwater data loggers with measurement of electrical conductivity, electro-magnetic measurements, and analyses for chloride (Buma, 2013). Apart from measurements within the monitoring

system, groundwater level measurements of 61 additional (onshore) monitoring wells were available in the national database of the Geological Survey of The Netherlands.

In addition to the expansion of the monitoring system, additional measures were taken to prevent salinization of fresh groundwater in the dunesthe pumped groundwater. On the western base of the dunes a line of 28 pumping interceptor (pumping) wells was installed in 2012 , in order to maintain the groundwater level, and prevent any (negative) impact of the Sand Engine and previous nourishments on the extracted fresh groundwater in the dunes. However tThese pumping interceptor wells were not included in our study, because of a lack of information on the pumping rates and the expectation that the effects on the regional scale are small to negligible.

In order Tto gain specific information on the geohydrological dynamics within the Sand Engine, eight additional monitoring wells were installed with shallow filters (2 to 10 m below surface) and four monitoring wells with deep filters (16 to 20 m below surface). Since May 2014 the groundwater levels in the monitoring wells are continuously monitored with groundwater data loggers. The salinity of the groundwater is monitored with electro-magnetic measurement within all eight monitoring wells.

3 Method

3.1 Variable-density groundwater model

For the quantification of fresh groundwater resources in the study area we constructed a regional three-dimensional groundwater model, in which variable-density groundwater flow and salt transport was simulated with the computer code SEAWAT (Langevin et al., 2008). SEAWAT has been developed by the United States Geological Survey (USGS), and numerous studies have used the code to simulate variably-density, transient groundwater flow (Heiss and Michael, 2014; Herckenrath et al., 2011; Rasmussen et al., 2012). In SEAWAT the governing flow and solute transport equations are coupled and solved with a cell-centred finite difference approximation. The model domain was discretised in 234 rows, 234 columns, and 50 layers, with a uniform horizontal cell size of 50 m and a varying layer thickness of 1 to 10 m (smallest thickness in upper layers, increasing in underlying layers; Fig. 4). The definition of the discretization and extent of the model were based on three criteria: minimise the effect on simulated groundwater heads and salinities in the study area, limit computation time, and optimise the calculation of the fresh groundwater volume. For the justification of the temporal and spatial discretisation we have performed a grid convergence test (Appendix A).

The model boundaries, as visualized in Fig. 1, were defined either The outer model boundaries were situated perpendicular to the coastline (at the SW and NE sides of the modelmodel; Fig. 1), or parallel to the coastline (the NW and SE side of the model). Model boundaries that were defined perpendicular to the coastline, lie parallel to the dominant groundwater flow direction in the coastal area, and were therefore defined as no-flow boundaries. The other Other outer model boundaries (at the NW and SE side of the model) were defined as illustrated in Fig. 4: 'specified-head' and 'head-

dependent flux' boundary ~~constant-head and general-head boundary~~ conditions (taking into account density differences), which represent~~ing~~ the ~~average North sea level~~ North Sea and local groundwater system, respectively. The 'specified-head' boundary conditions equalled the average level of the North Sea, and were applied to the seafloor. ~~The l~~Local groundwater ~~heads and salinities on the eastern side~~conditions were defined by a previous model simulation of the southwest of the Netherlands (Oude Essink et al., 2010). The base of the model was defined equal to the hydrogeological base of the ~~study area~~model domain, which is approximately -170 m MSL and assumed to be a no-flow boundary.

The subsoil of the model was schematised to four aquifers and three aquitards (Fig. 4), based on borehole data, and the national geological databases REGIS II.1 (Vernes and van Doorn, 2005) and GeoTOP (Stafleu et al., 2013) of the Geological Survey of The Netherlands. The upper part of the phreatic aquifer (above -10 MSL) was subdivided into two hydrogeological zones with distinct hydraulic conductivities, because the geological data showed systematic differences in the sediment composition within the model domain: one zone coincides with most of the low-lying polders and contains predominantly clay, loam and fine sand deposits; the other zone contains most of the elevated areas of the model domain, where mainly fine to coarse sand was deposited during the Holocene. The aquifer parameters and layer elevations were defined uniform for each hydrogeological unit, based on parameter estimations in the national hydrogeological database (Table 1). The ~~effective porosity was set to 0.3 for aquifers and 0.1 for aquitards, the~~ molecular diffusion coefficient was set to 10^{-9} m^2 s^{-1}, and the longitudinal dispersivity was set to 0.2 m with a ratio of transversal to longitudinal dispersivity of 0.1. These values are similar to comparable groundwater models in the same region (Eeman et al., 2011; de Louw et al., 2011; Vandenbohede and Lebbe, 2007, 2012).

~~The phreatic aquifer contained two separate hydrogeological units and was subdivided in two hydrogeological layers, because the geological data showed systematic differences in the sediment composition within the model domain. In low lying polders and in the lower section of the phreatic aquifer (between -10 and -16 m MSL), predominantly clay, loam and fine sand was deposited during the Holocene. In the elevated areas of the model domain and the upper section of the phreatic aquifer predominantly fine to coarse sand was deposited. The hydraulic conductivities in areas and layers with mainly fine to coarse sand (beach, dunes and urban area) were set to 10 m d^{-1}, and the hydraulic conductivities in areas and layers with mainly clay, loam and fine sand were set to 1 m d^{-1}.~~

~~-~~Other model parameters such as recharge, and surface water levels~~, and drainage levels~~ were defined by ~~taking~~spatially distributed and time-average values of the current situation. The average monthly precipitation and reference evapotranspiration between 1981 and 2000 (Royal Netherlands Meteorological Institute, KNMI) were used to estimate the average seasonal (DJF, MAM, JJA, and SON) precipitation and evapotranspiration. Crop and interception factors were used to estimate the actual evaporation in different land use classes (e.g. forest, agriculture, urban areas) (Droogers, 2009; Hooghart and Lablans, 1988; Meinardi, 1994; Statistics Netherlands, 2008). Water levels, depths and widths of canals and ditches were provided by the Delfland Water Authority, and drainage levels were based on local knowledge and estimations from the Netherlands Hydrological Instrument model (de Lange et al., 2014; Massop and van Bakel, 2008). Information on

the extraction of groundwater and the infiltration of surface water in the dune area Solleveld was provided by the drinking water company Dunea.

In the model simulations we have used TDS, where TDS equals salinity [g TDS L~~l~~$^{-1}$], and in the classification of the groundwater salinity we have focused on three ~~groundwater~~ classes: fresh (0 – 1 g TDS ~~l~~L^{-1}), brackish (1 – 10 g TDS L~~l~~$^{-1}$), and saline (10 – 30 g TDS L~~l~~$^{-1}$). For the conversion~~s~~ of chloride ~~measurements~~ to TDS ~~concentrations~~ we have used the linear relation between chloride and TDS in the North Sea; 1 g TDS L~~l~~$^{-1}$ = 0.55 g Cl L~~l~~$^{-1}$ (Millero, 2003). The North Sea TDS in the model domain was estimated at 28 g TDS L~~l~~$^{-1}$ ~~in~~ for all model ~~calculations~~ simulations (density of 1020 kg m^{-3}), based on geo-electrical measurements in the North Sea near Ter Heijde between 1973 and 1997 (Rijkswaterstaat, 2012). This salinity concentration is smaller than the general North Sea concentration (30-35 g TDS L~~l~~$^{-1}$), because of the nearby freshwater discharge from the river Rhine. The TDS concentrations on the SE side of the model were defined by previous model calculations of the southwest of the Netherlands (Oude Essink et al., 2010). ~~[Oude Essink et al., 2010].~~ The TDS concentration of infiltration basins, canals and ditches were set to 0.2 g TDS L^{-1}~~g l^{-1} TDS~~, which is the average TDS concentration found in surface water within the study area. The spatial variation in the salinity of the groundwater recharge was estimated with semi-empirical equations, which were developed to predict the effects of sea spray deposition in coastal areas (Stuyfzand, 2014). Based on meteorological measurements of the wind speed and wind direction at the measurement station in Hoek van Holland in the period 1971 – 2015, the estimated annual mean TDS concentration varied between 0.121 g $^{-1}$ at the coastline to 0.023 g $^{-1}$ at a distance of 5000 m from the high water line.

3.2 Calibration of pre-development conditions

The main purpose of the model calibration was to generate a valid representation of the pre-development conditions of the Sand Engine (prior to March 2010). In order to exclude anomalous effects of recent sand nourishments on groundwater heads and concentrations, only observations prior to 2010 w~~h~~ere included in the model calibration. We considered ~~the calibrated conditions valid~~ three calibration criteria: ~~when~~ the error between simulated and observed groundwater head and TDS concentration ~~is~~ should be similar or smaller than the observed variations in groundwater level (the average standard deviation of observations is 0.4 m) and concentration (the average standard deviation of observations is 0.7 g TDS L~~l~~$^{-1}$), ~~when~~ the error~~s~~ should be ~~are~~ randomly distributed in space, and the simulated distribution of the TDS concentration~~s~~ should correspond~~s~~ with literature (Stuyfzand, 1993).

The calibration ~~method~~ comprised ~~of~~ sensitivity analyses, (restricted) manual model parameter ~~adjustments~~calibration, and comparisons of simulated groundwater heads and TDS concentrations with averaged observations of recent years. Historical processes that promote or diminish seawater intrusion were included in the calibration, because a salinity distribution often takes decades to hundreds of years to reach an equilibrium (Delsman et al., 2014; Webb and Howard, 2011). Examples of ~~Examples of h~~historical processes that have substantially influenced the groundwater salinity in the Dutch coastal area are coastal erosion, sea-level rise, and ~~expansions of~~ groundwater ~~drainage and~~ extractions (Post et al., 2003). These processes were therefore ~~incorporated~~ included in the model simulations to attain a

better match between simulations, and the method of incorporation of the processes is briefly described in Table 2 and visualised and in (Fig. 5). Other historical changes in for example groundwater recharge and subsidence were not included, because measurements and historical data indicate that these processes probably have a negligible impact on the current head and concentration distribution in the study area (CBS et al., 2012; Hoofs and van der Pijl, 2002). The calibration simulation period was restricted to the period 1500 – 2010, because the focus of this study lies on the present conditions, and we assume that the most substantial effects on the present salt distribution will probably occur in this period. Before the simulation of the period 1500 – 2010, a transient simulation of the approximate conditions in AD 1500 was executed until The initial conditions consisted of an equilibrium distribution for the approximate conditions in 1500 (Vos and de Vries, 2013). The sea level for this equilibrium model was estimated as -0.30 m MSL (Jensen et al., 1993; Wahl et al., 2013). The equilibrium conditions where generated by a transient simulation of 1500 years, in which the model converged to a dynamically stable state in terms of both groundwater heads and salinity.

In order to attain an optimal calibration result with a limited number of model simulations, a selection of model parameters were manuallyas adjusted with small increments from an initial best guess. The adjustments were performed on a selection of the model parameters: (horizontal and vertical) hydraulic conductivity, drainage resistance, stream bed resistance of canals and ditches, and (longitudinal and transverse) dispersivity. Other parameters such as groundwater recharge and surface water levels were based on measurements, maps or expert knowledge, and were excluded from the calibration. The optimised model parameters that were implemented for the model scenarios are described in Sect. 3.1.

3.3 Morphology and climate scenarios

The effect of the Sand Engine on fresh groundwater resources will primarily depend on the morphological evolution of the coastal area. In order to assess the potential effect of the mega-nourishment on coastal groundwater, we performed model simulations with containing projections of the morphological change of the Sand Engine during the period 2011 to – 2050 (Table 2). The morphological development of the Sand Engine in this period was simulated with the hydrodynamics and morphodynamics model code Delft3D (Lesser et al., 2004). This numerical morphodynamic model was calibrated for the period 2005 – 2010 and validated for the period 1990 – 2005, prior to the construction of the Sand Engine (Fiselier, 2010; Tonnon et al., 2009). Based on representative tidal boundary and wave conditions of the current situation, the model was used to simulate the long term morphological evolutionchange in bathymetry during the 2011 – to 2050 (Fig. 6).

The predicted morphological developmentchange in bathymetry of the Sand Engine was incorporated in the groundwater model as a change in surface elevation, and adapted after for every quarter three months or season in the simulation period. Subsequent changes in the area of inundation, groundwater recharge and thickness of the phreatic aquifer were implemented in the model input files. In addition, changes in the mean water level within the lagoon were the decrease of the tidal range within the lagoon was also included in the model scenario'sscenarios, with and a the expected maximum increase of the mean water level of equals 0.9 m MSL (de Vries et al., 2015).

In addition to the morphological development of the Sand Engine, climate change may also have an impact on coastal groundwater. For the assessment of the potential impact of climate change on fresh groundwater resources, we have used the KNMI'14 climate change scenarios G_L, G_H, W_L and W_H (KNMI, 2014). These scenarios contain climate projections for the Netherlands for the years 2030, 2050 and 2085, based on global climate models as described in the 5th IPCC Assessment report (IPCC, 2013). The climate projections of sea-level rise, precipitation and potential evapotranspiration for 2030 and 2050 in these scenarios were used to assess the effect of climate change as summarised in Table 3.~~Table 1.~~

All climate change scenarios were simulated for a reference ~~situation~~ case without the Sand Engine, and the current situation with the Sand Engine including the projected morphological evolution. The ~~model simulations for the reference situation~~reference case serves primarily as a comparison to the simulations with the morphological evolution of the Sand Engine. The ~~contrasts~~ dissimilarity between both situations ~~represent~~represents the total impact of the construction of the Sand Engine on local fresh groundwater resources. In turn, t~~T~~he climate change scenarios show the response and sensitivity of local fresh groundwater resources to ~~different degrees of change in sea-level rise,~~ alterations in sea-level rise, precipitation and evapotranspiration ~~in the model domain~~.

4 Results

4.1 Model calibration

For the calibration of the variable-density groundwater model, we compared ~~the simulated distribution of~~the simulated pre-development groundwater head~~s~~ and TDS concentration~~s~~ with recent observations of ~~the~~ groundwater heads and chloride concentration~~s within the model domain~~ (Fig. 7). The calibration was performed with averaged values of recent observations. We think this is acceptable, because of the long-term scope of this study and the deficiency in long-term time-series of head and especially salinity. The absolute mean error between observed and simulated heads ~~is~~ was 0.27 m (RMSE of 0.33 m), and between observed and simulated TDS concentrations ~~is~~ was 1.17 g TDS L^{-1}~~l^{-1}~~ (RMSE of 2.75 g TDS L^{-1}~~l^{-1}~~). The largest deviations in ~~observed and simulated~~ head~~s~~ occur at observation points that are situated near infiltration basins or pumping wells, whereas the deviation~~s~~ in TDS concentration appear~~s~~ to be ~~evenly or randomly~~well~~-~~distributed. These deviations ~~in observed and simulated heads and salinities~~ are probably primarily caused by heterogeneity in the phreatic aquifer and~~,~~ spatial variations in the extraction ~~volumes~~ rates of pumping wells.

The groundwater heads of 137 observations points and the chloride concentrations of 55 observations points were used to quantify the error and calibrate the model. Despite this relatively large number of observations points, it is important to note that all observations of chloride and 72% of observations of groundwater heads - that were used in the model calibration - originate from the monitoring system in Solleveld~~, and 72% of observations of groundwater heads~~. The simulation of the groundwater head and especially the TDS concentration are therefore most reliable in Solleveld and the immediate surrounding system. The phreatic groundwater level and depth of the fresh-brackish interface of the calibrated model are shown in Fig. 8. Phreatic groundwater flows from the coastal dunes toward the sea, pumping wells, and low-lying

drained polders. The aquitard beneath the phreatic aquifer (between -16 and -20 m MSL) limits the interaction with the underlying confined aquifer, leading to a substantial head difference across the aquitard (ranging between 0.3 to 1.4 m in multilevel monitoring wells). The fresh groundwater lens below the coastal dunes extents to approximately -30 and -40 m MSL and the interface between brackish and saline groundwater lies between -40 and -50 m MSL, corresponding with the observed depth of the interfaces (~~Fig. 3~~Fig. 11). Drainage in low-lying polders leads to the seepage of brackish or saline groundwater, which ~~leads~~ results in a reduction of the ~~to a thinner~~ fresh groundwater lens thickness (Fig. 8).

In order to assess the performance of the calibrated groundwater model, we have compared simulated groundwater heads and TDS concentrations with recent observations at 8 monitoring locations on the Sand Engine (Fig. 9). The absolute mean error between observed and simulated groundwater heads ~~is~~ was 0.36 m, and between observed and simulated TDS concentrations was 6.5 g TDS ~~l~~L^{-1}. The model appears to underestimate the hydraulic gradient – in particular in the higher regions of the Sand Engine – and groundwater salinities with a concentration higher than 15 g TDS L~~l~~$^{-1}$ (between 6 and 20 m below surface). Probable causes of these discrepancies lie in the initial groundwater level~~s~~ and ~~salinities~~ salinity (strongly influenced by the construction), the underestimation of the vertical anisotropy as a result of small mud drapes in the Sand Engine and varying weather conditions (e.g. recharge, overwash). In addition, the measured TDS concentrations are single point measurements that may not represent the average TDS concentration in the Sand Engine.

4.2 Fresh groundwater resources

The effect of the construction and long-term morphological evolution of the Sand Engine on the volume of fresh groundwater is initially small and similar to the situation without the Sand Engine (Fig. 10). In all model scenarios the volume of fresh groundwater slightly declines in the first years, because of the small size of the freshwater lens in the Sand Engine with respect to the cell resolution and the instability of the initial conditions. However, the gradual growth of the freshwater lens in the Sand Engine and adjacent areas eventually leads to an increase of the volume of fresh groundwater in the model domain of 0.3 to 0.5 million m^3 per year. This increase of the volume of fresh groundwater manifests itself mainly as an outward extension of the fresh groundwater lens in the phreatic aquifer. Underlying aquifers and aquitards may even become more saline, primarily as a result of transient boundary conditions (i.e. historical coastal erosion and on-going sea level rise) leading to continuing historical seawater intrusion. In addition, rising groundwater levels in and around Sand Engine can lead to increases in the infiltration of saline groundwater through the thin aquitard (Fig. 11 and Fig. 12).

The sea-level rise (in total) of 0.15 m in climate ~~scenario's~~scenarios G_L and G_H and 0.25 m in climate ~~scenario's~~scenarios W_L and W_H lead to a decline in the volume of fresh groundwater, because of the increase of seawater intrusion and inundation of the coastal area. However, the effect of sea-level rise is relatively small in respect to the total increase of fresh groundwater (Fig. 10).

The long-term predictions in precipitation and evapotranspiration within the four climate scenarios (Table 3~~Table 1~~) have a limited effect on the total volume of fresh groundwater. The climate scenarios with a strong response (G_H and W_H) ~~and corresponding wetter winters and drier summers~~ lead to a ~~lower~~ smaller volume of fresh groundwater, when compared

with the climate scenarios with a weak response (G_L and W_L) ~~and subsequently smaller change in precipitation and evapotranspiration~~. This is primarily a result of the difference in the net groundwater recharge in the climate scenarios, and the overall (yearly) volume of groundwater recharge is larger in the milder climate scenarios (G_L and W_L). The larger increase in precipitation in winter seasons of climate scenario G_H and W_H, coincides with a stronger increase in evaporation and a smaller increase in precipitation in the summer seasons (Table 3). However, ~~T~~the contrast between these climate scenarios only becomes apparent after 2030, because the precipitation and evapotranspiration patterns are equal until 2030 and diverge ~~in the period~~after 2030 ~~– 2050~~.

In addition to the change in fresh groundwater resources in the beach-dune system, the simulations with the long-term morphological evolution of the Sand Engine show small to negligible increases (smaller than 1 m in 2050) in the ~~thickness of the~~ freshwater lens thickness in low-lying polders. However, changes in the total salt load in drains, canals and ditches are small in the situation with and without the Sand Engine. As a result the construction and morphological evolution of the Sand Engine may lead to small decrease of seawater intrusion, but this effect will probably be small to negligible and limited to small low-lying polders in a ~~close~~ short distance ~~to~~ from the Sand Engine (Fig. 13).

5 Discussion

The model simulations show that the construction of the Sand Engine may result in the growth of the volume of fresh groundwater ~~with~~ by several million m^3. Despite the gradual erosion of the nourished sand – leading to a slow return to the previous state – the volume of fresh groundwater may continue to rise for decades after the construction of the mega-nourishment. However, tidal fluctuations and in particular storm surges will lead to land-surface inundations and consequently to a salinization of fresh groundwater. In addition, the increase in the volume of fresh groundwater is dependent on the ~~pace~~ rate of sea-level rise and the extent to which precipitation and evapotranspiration patterns will diverge from present conditions. This steady increase of the volume of fresh groundwater is in contrast with the reference ~~situation~~ case (without the construction of the Sand Engine) where historical and future sea-level rise lead to a decrease of the volume of fresh groundwater. Our results also suggest that the construction of the Sand Engine may abate the salinization of neighbouring polders, by reducing ~~the~~ upward seepage of saline groundwater. Even though the reduction of the salinization is probably slight and limited to a small area, it might constitute an important mitigation in other applications of mega-nourishments.

~~No other studies have integrated the effect of the morphological evolution of coastal areas and climate change on fresh groundwater resources, and the number of quantitative studies that investigate the possibility to combine coastal defence with the protection of fresh groundwater resources are scarce (Oude Essink, 2001). However, studies on small islands have shown that great losses in the volume of fresh groundwater can occur as a result of decreases in groundwater recharge and sea level rise, and especially small and thin lenses seem vulnerable to salinization (Chui and Terry, 2013; Holding et al., 2015; Mahmoodzadeh et al., 2014). In addition, studies have shown that an increase in the frequency of storm~~

~~surge overwash will exacerbate the salinization of coastal aquifers, although the freshwater lens is generally able to recover over time (Holding et al., 2015; Terry and Falkland, 2010). In relation to the morphological dynamics of coastal regions, studies have shown that the erosion and accretion of sand can lead to substantial changes within the beach foredune area (Bakker et al., 2012; Keijsers et al., 2014b), and that climate change might exacerbate coastal erosion (FitzGerald et al., 2008; Zhang et al., 2004). Morphological developments in coastal areas and islands can therefore have a substantial effect on existing and future fresh groundwater resources. Coastal management strategies that compensate, limit, or counteract coastal erosion or seawater intrusion may therefore help to protect or expand fresh groundwater resources.~~

Comparisons of observ~~ations~~ed and ~~with~~ simulated groundwater heads and salinities show a good correspondence before and after the construction of the Sand Engine, despite large variations between observed and simulated groundwater salinities at individual locations. To some extent these discrepancies can be accounted for by the relatively sharp transition between fresh and salt groundwater, through which small variations in depth can result in large differences in groundwater salinities. Other factors that were not included in the simulations and that probably led to discrepancies in observed and simulated groundwater heads and salinities are: historical events (e.g. changes in groundwater level and salinity ~~after~~ during the construction of the Sand Engine), large inundations of the Sand Engine due to storm-surges (e.g. two major storms in 2011 – 2016 inundated approximately 56% of the Sand Engine), variations in extraction rates of pumping wells, fluctuations in ~~the salinity of the North Sea~~sea salinity and unaccounted vertical layering of the Sand Engine deposits. These factors were not included in the model simulations because of the absence or shortage of data, and the long-term scope of this study. However, the overall ~~correspondence~~ similarity between observations and simulations, in combination with the absence of systematic errors in the model calibration, confirms the reliability of the model. Most of the observations – in particular groundwater salinity - emanate from the monitoring system in the adjacent dune area Solleveld and to a lesser extent the Sand Engine. ~~, t~~The simulated groundwater heads and salinities ~~simulations~~ are therefore most reliable in our area of interest, and the reliability is less ~~. It is less certain to what extent the simulated groundwater head and salinity~~ in other areas ~~correspond with the actual situation~~in the model domain. However, the most substantial changes in groundwater salinity will take place in the area close to the Sand Engine, and variations in groundwater head and salinity in other areas will probably have a small to negligible impact on the potential effects of the Sand Engine.

Considering the scale and nature of our research objective, we neglected small and local variations in hydraulic parameters (e.g. hydraulic conductivity, layer thickness, porosity, and storage coefficient) in the model simulations. Supported by geological data and models, each aquifer and aquitard was defined homogenous and anisotropic, with the exception of the phreatic aquifer. ~~The focus of this study lies therefore on the general processes that influence the potential increase in fresh groundwater resources because of the construction of the Sand Engine.~~ This reduction of the model complexity enhances the ability to differentiate and to understand the simulated processes, and leads to a smaller computation time of the model. However, small or local variations in groundwater head or salinity that are caused by heterogeneity will not be accurately reproduced in the model simulations.

One of the largest uncertainties in the study is the long-term morphological evolution of the Sand Engine, despite extensive calibration and validation and the large number of processes that are included in Delft3D (e.g. wind shear, wave forces, tidal forces, density-driven flows). The highly dynamic nature of the coastal zone, the absence of aeolian transport in the Delft3D simulations, and the lack of understanding of some processes, can lead to incremental differences with reality. ~~However, measurements of the cumulative volumetric change in the period 2011 – 2012 have shown similar volume changes and erosion patterns as were predicted with the morphological model (de Schipper et al., 2014).~~ Even though measurements of the last four years show a reasonable fit with the projections of the sediment volume changes and erosion patterns (de Schipper et al., 2014), future morphological change can turn out to be significantly different from the morphological model. For example, the growth of dune grasses and the exposure of shell deposits may prove to reduce erosion and decelerate the morphological evolution of the Sand Engine, or an accumulation of sand in the lagoon might lead to earlier silt up, and therefore a reduction of seawater intrusion in comparison with the projections. The implementation of one simulation of morphological change in the model calculations is therefore a significant limitation in the estimation of the potential fresh groundwater resources. For a more extensive ~~prediction and estimate~~analysis of the uncertainties in the prediction of the effects on fresh groundwater resources, it is recommended to simulate more morphological scenarios in future studies.

In addition to the long-term morphological evolution of the Sand Engine, large uncertainties also exist in the climatological predictions of sea-level rise, precipitation and evaporation in future decades. Predictions of sea-level rise for the North Sea in 2050 range between 15 to 40 cm above MSL, and model simulations have shown that substantial changes in the growth or volume of fresh groundwater resources can occur within this range. Changes in sea-level rise and the intensity or frequency of storm surges will not only significantly influence fresh groundwater, but will also contribute to coastal erosion and alter the morphological development of the Sand Engine.

6 Conclusions

Local mega-nourishments such as the Sand Engine might become an effective solution for the threats that many low-lying coastal regions face, and with this study we have shown that fresh groundwater resources can ~~grow~~ substantially grow within the lifespan of the nourishment. The results in this study show that for the Sand Engine, the construction of a mega-nourishment can lead to increase of fresh groundwater of approximately 0.3 to 0.5 million m^3 per year. However, the increase in fresh groundwater resources in a mega-nourishment is highly dependent on the shape and location of the mega-nourishment, the precipitation surplus, the frequency and intensity of storm surges, and ~~the local circumstances~~local hydrogeological conditions. Therefore dependent on the design and location of the mega-nourishment this may provide an opportunity to combine coastal protection with the protection of fresh groundwater resources. This study also demonstrated that, with relatively simple modifications, a changing morphology can easily be modelled with a variable-density groundwater model such as SEAWAT.

Appendix A: Grid convergence test

In order to justify that the chosen spatial and temporal discretisation is adequate for reliable numerical quantifications of the potential effect of the Sand Engine on fresh groundwater resources, we have executed a grid convergence test for period 2011 to 2050 (with and without Sand Engine). Current numerical simulations were performed with: a horizontal grid size of 50 m, 50 layers with a variable thickness from 1 (upper layers) to 10 m (lower layers), and stress periods of 90.25 to 92 days (corresponding to seasons). The transport simulations were performed implicitly with the Generalized Conjugate Gradient (GCG) solver, and the transport step sizes were model-calculated based on a Courant number of 1. For the coupling of the flow and transport we have used the explicit approach. In the grid convergence test we have performed one additional with an implicit (iterative with a density criterion of 0.2 kg m^{-3}) to test the temporal discretisation. The spatial discretisation was tested with three additional numerical simulations with higher and lower spatial resolutions: one simulation with a horizontal grid size of 25 m, one simulation with a horizontal grid size of 100 m, and one simulation with the same horizontal grid size of 50 m and an increased vertical resolution of the upper layers. In the upper part of the model, up to a depth of -50 m MSL, the layer thicknesses were lowered with 50% (30 layers were added, up to a total of 80 layers). These additional numerical simulations include no climate change scenario, and were compared to the current numerical simulations that contained a horizontal resolution of 50 m and 50 layers. The initial conditions of all additional numerical simulations were equal to the calibrated pre-development groundwater heads and TDS concentrations.

The comparison of the current simulations with the three additional numerical simulations that contain higher and lower spatial resolutions (Fig. A1), show a similar increase of the volume of fresh groundwater in the model domain during the simulation period of 2011 to 2050. In the situation with the Sand Engine (Fig. A1b), a coarser spatial resolution lowered the projected volume of fresh groundwater (-10% in 2050), and a finer horizontal and vertical spatial resolution raised the projected volume of groundwater (respectively + 4% and +20% in 2050). However, when taking into account the deviations in the volume of fresh groundwater in the reference case (Fig. A1a), the total change in the volume of fresh groundwater becomes smaller; respectively -2%, +0% and +14% in 2050. The additional simulation with an implicit coupling of flow and transport equations shows a small to negligible difference (smaller than 2% during the entire simulation period) with the simulations with explicit coupling of flow and transport equations (Fig. A2). In summary, the additional simulations show relatively small changes in the volume of fresh groundwater, and suggest that an increase in the vertical resolution can even lead to a higher increase in the volume of fresh groundwater.

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Table 1. Hydrogeologic parameters used in the simulations, where the upper part of the phreatic aquifer (1a: above -10 m MSL) was subdivided in two hydrogeological zones (1: fine to coarse sand; 2: clay, loam and fine sand)

Layer	K_H [m d^{-1}]	K_V [m d^{-1}]	n_e [-]
Phreatic aquifer 1a	10 / 1	1 / 0.1	0.3
Phreatic aquifer 1b	1	0.1	0.3
Aquitard 1	0.01	0.001	0.1
Aquifer 2	30	10	0.3
Aquitard 2	2	0.2	0.1
Aquifer 3	5	2	0.3
Aquitard 3	1	0.1	0.1
Aquifer 4	15	3	0.3
Aquitard 4	10	0.03	0.1

Table 2. Simulation of processes and method of incorporation in groundwater model

Process	Source / Simulation	Method of incorporation
Historical coastal erosion (1500 – 2010)	Literature and paleogeographic maps of AD 1500 and AD 1850 (Beets and van der Spek, 2000; Beets et al., 1992; Vos and de Vries, 2013)	Delineation of the shoreline was incorporated in three phases: 1500, 1500-1740, 1740-2010. Phasing based on literature (Fig. 5)
Historical sea-level rise (1500 – 2010)	Literature containing time-series and predictions of historical sea-level rise (Jensen et al., 1993; Wahl et al., 2013)	The period 1500 -2010 was divided in 8 stages, enforcing the average sea-level for each stage (stages are indicated with vertical lines in Fig. 5).
Groundwater extraction (1890 – 2010)	Literature on historical groundwater extraction in Solleveld (Draak, 2012) and time-series of groundwater extraction and infiltration volumes.	The period 1890 -2010 was divided in 6 stages, enforcing the average extraction for each stage (see blue bars in Fig. 5).
Morphological evolution Sand Engine (2011 – 2050)	Simulated with Delft3D (Lesser et al., 2004), with computations of the hydrodynamics, waves, sediment transport and bed change (Mulder and Tonnon, 2011; Tonnon et al., 2009).	For every three month period in 2011 – 2050 the simulated bathymetry was enforced to the groundwater model; by changing the topography, area of inundation, and recharge.
Sea-level rise (2011 – 2050)	Climate projections of sea-level rise in 2030 and 2050 (KNMI, 2014).	The projected sea-level rise in 2030 and 2050 were linearly interpolated. The average sea-level was implemented for every three month period.

Table 3. Model climate change scenarios for the period 2011 – 2050, with two rates of SLR, starting at 0.05 m MSL and seasonal variation in groundwater recharge (DJF, MAM, JJA, SON)

Climate Scenario	Sea-Level Rise	Precipitation 2050 (given per season)	Potential evaporation 2050 (given per season)
No climate change (NoCC)	No sea-level rise [0.05 m MSL]	Equal to present: Period 1981 - 2010	Equal to present: Period 1981 - 2010
G_L	+ 3.75 mm yr^{-1} [2050: 0.20 m MSL]	+3%, +4.5%, +1.2%, +7%	+2.9%, +1.3%, +3.9%, +2.7%
G_H	+ 3.75 mm yr^{-1} [2050: 0.20 m MSL]	+8%, +2.3%, -8%, +8%	+2.4%, +2%, +7.5%, +2.8%
W_L	+ 6.25 mm yr^{-1} [2050: 0.30 m MSL]	+8%, +11%, +1.4%, +3%	+3.2%, +1.7%, +4.4%, +5.8%
W_H	+ 6.25 mm yr^{-1} [2050: 0.30 m MSL]	+17%, +9%, -13%, +7.5%	+2.7%, +2.9%, +10.6%, +4.5%

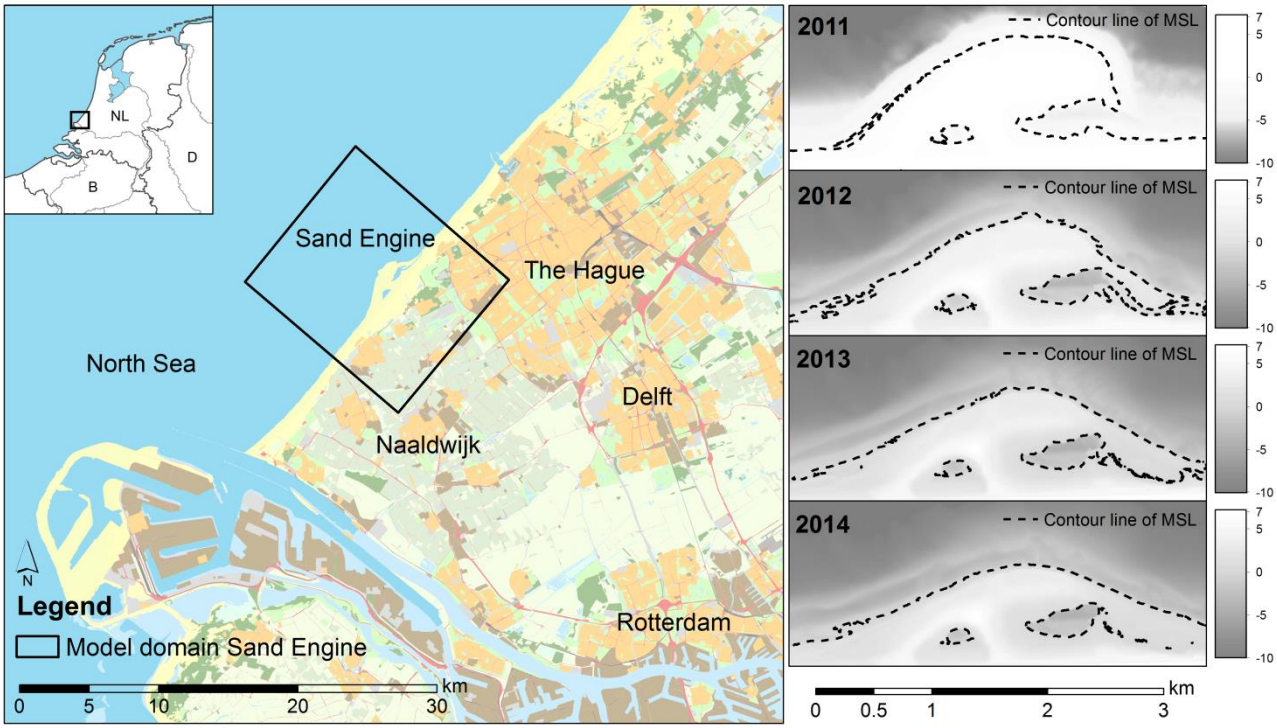

Fig. 1. Situation of the Sand Engine and morphological development in 2011 - 2014

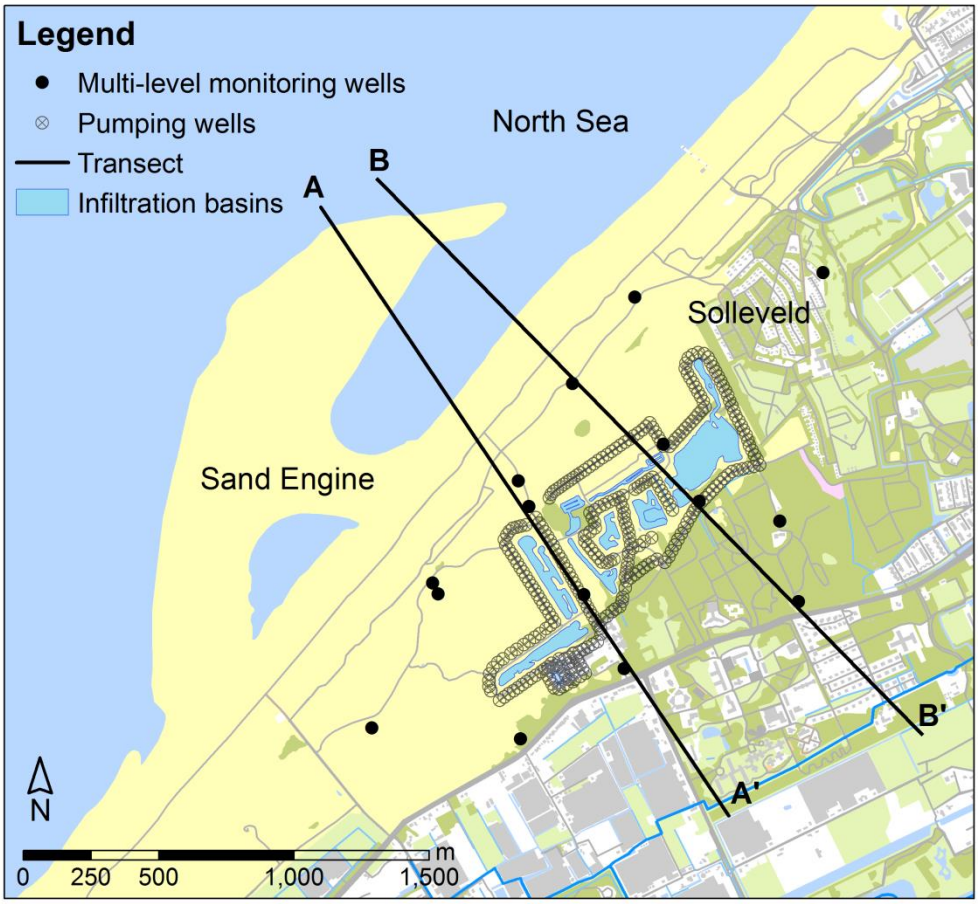

Fig. 2. Map of the dune area Solleveld with multi-level monitoring wells and pumping wells, including transects A and B (geological profiles in **Fig. 3**)

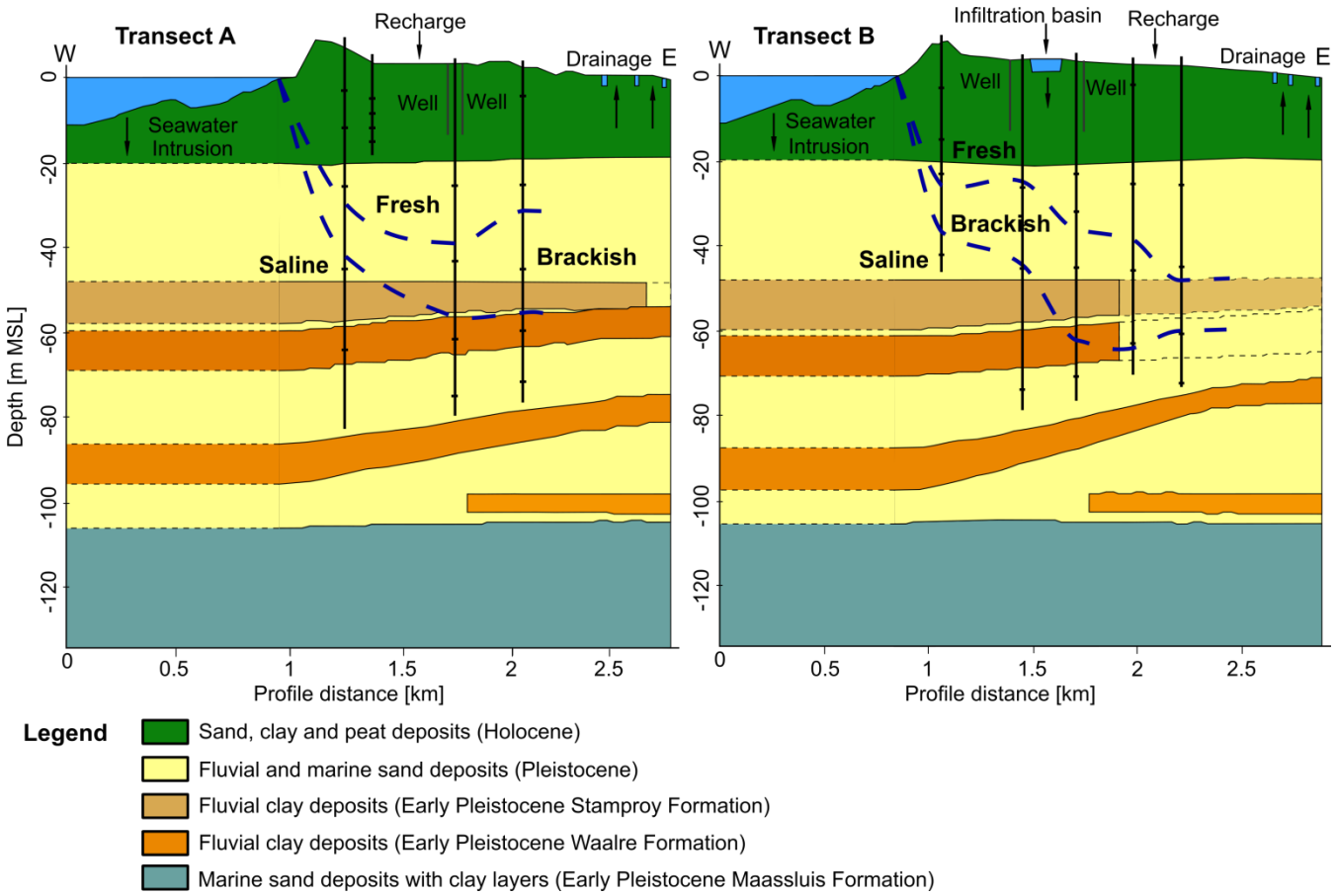

Fig. 3. Geological profiles (based on the databases of the Geological Survey of The Netherlands) across the model domain with conceptual fresh-salt water distribution (locations are shown in **Fig. 2**)

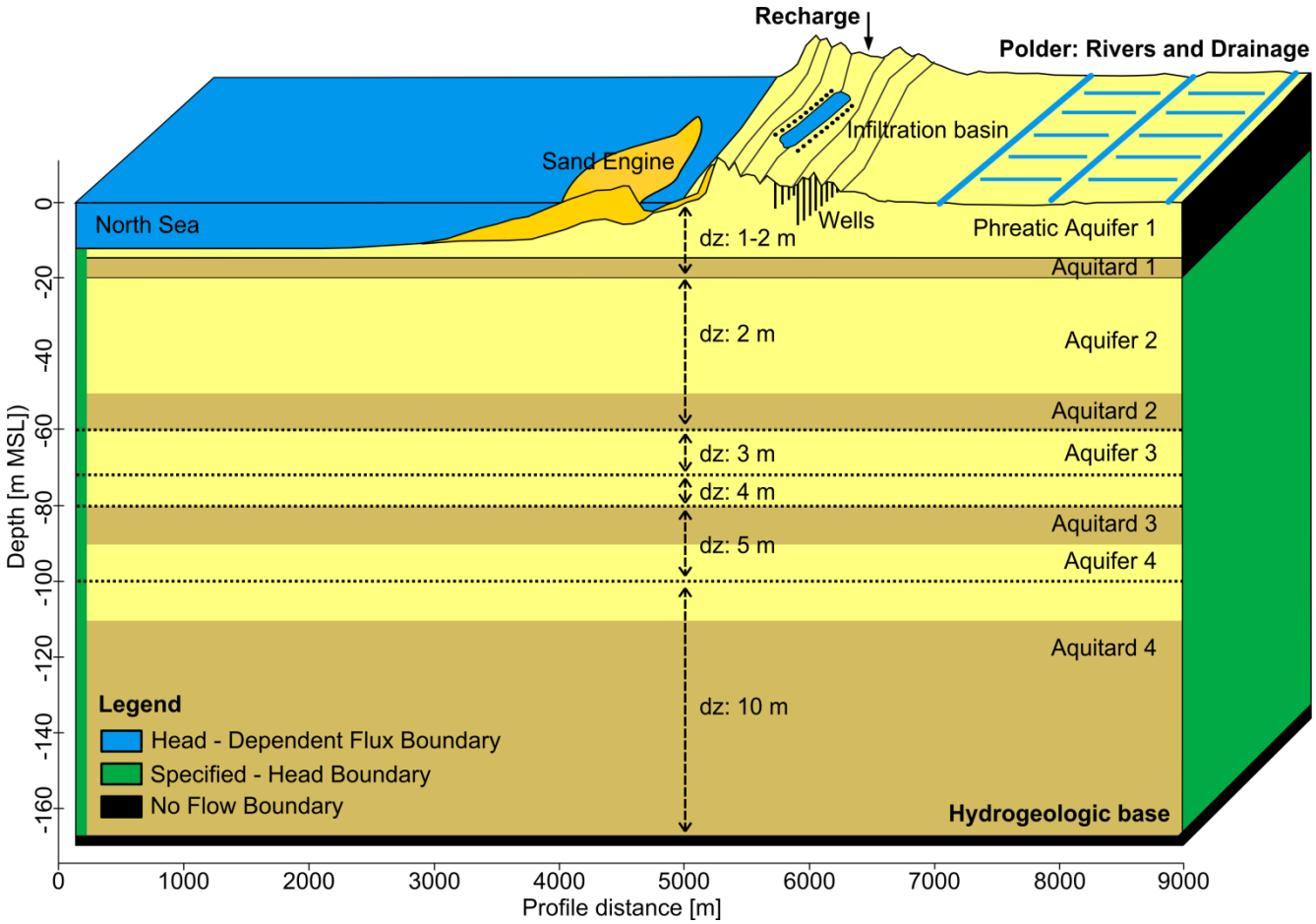

Fig. 4. Conceptual representation of a slice ~~or portion~~ of the model with ~~aquifer parameters~~layer thicknesses and boundary conditions

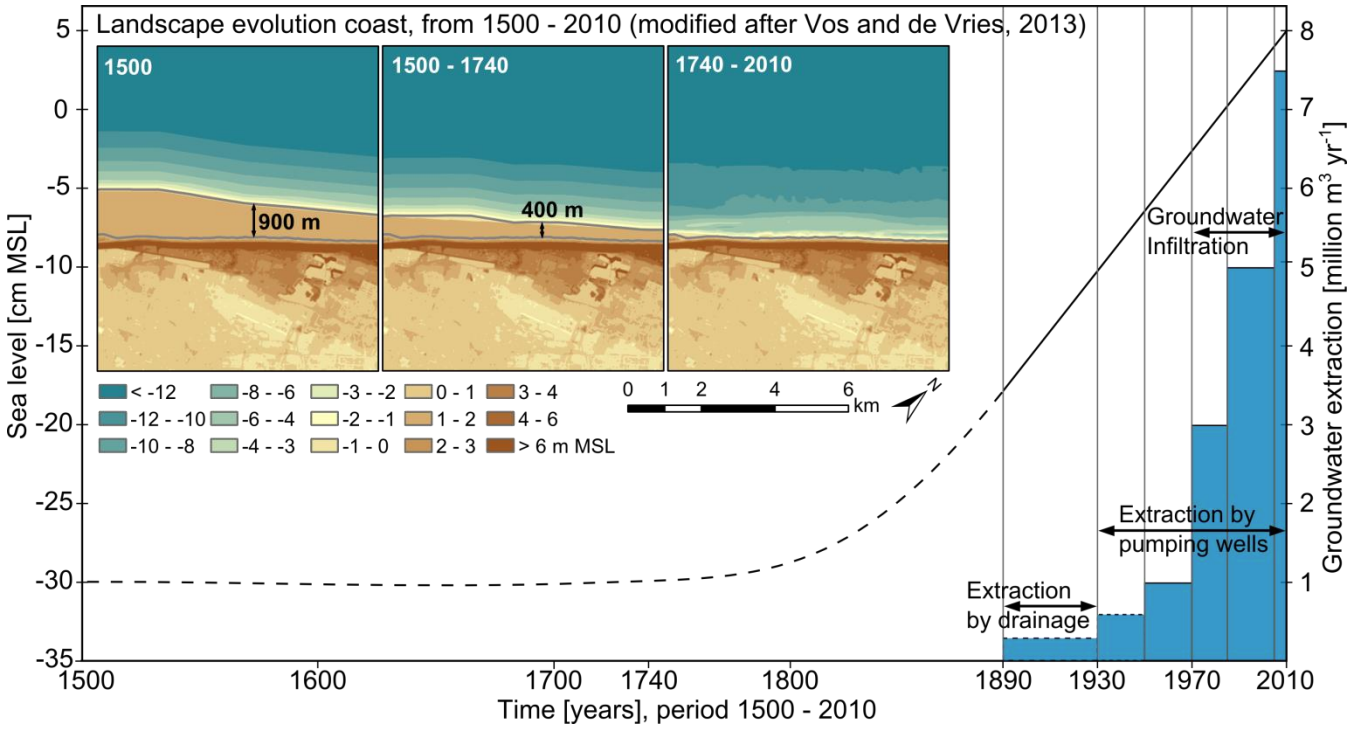

Fig. 5. Simulation of historical coastal erosion (based on paleogeographic maps of Vos and de Vries, 2013), sea-level rise (black line) and groundwater extraction (blue) in the period 1810 – 2010; dashed lines indicate estimates, and vertical grey lines refer to stress periods (CBS et al., 2013).

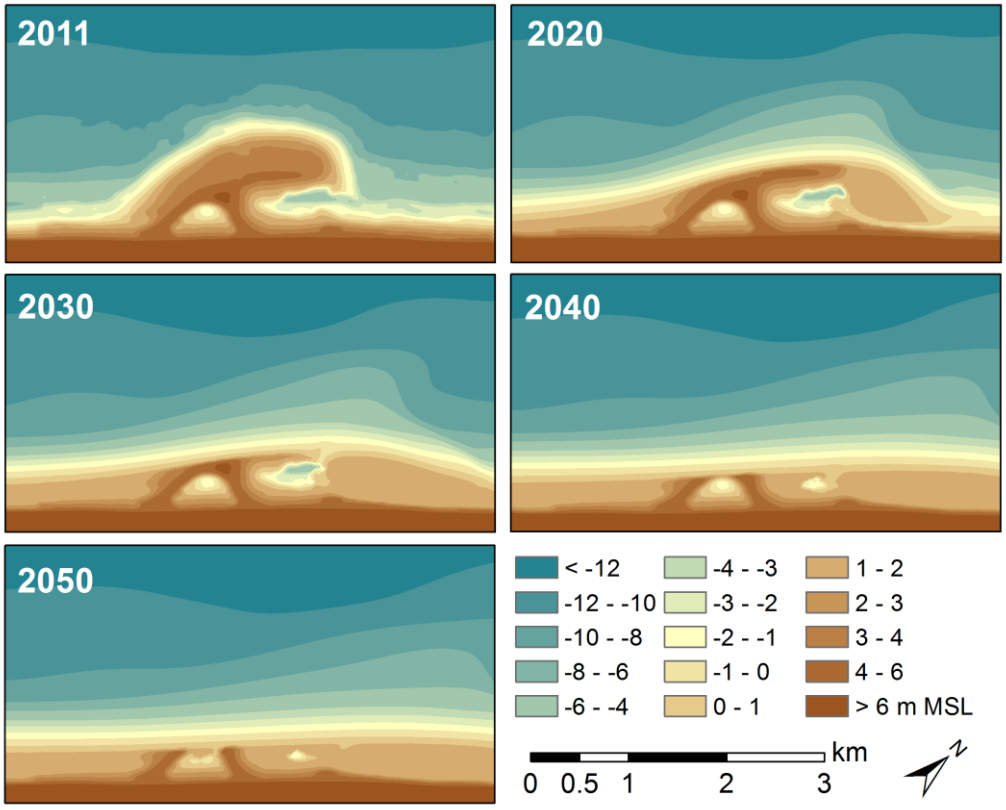

Fig. 6. Simulated morphological development of the Sand Engine from 2011 to 2050, illustrated by contour maps with the terrain elevation (m MSL)

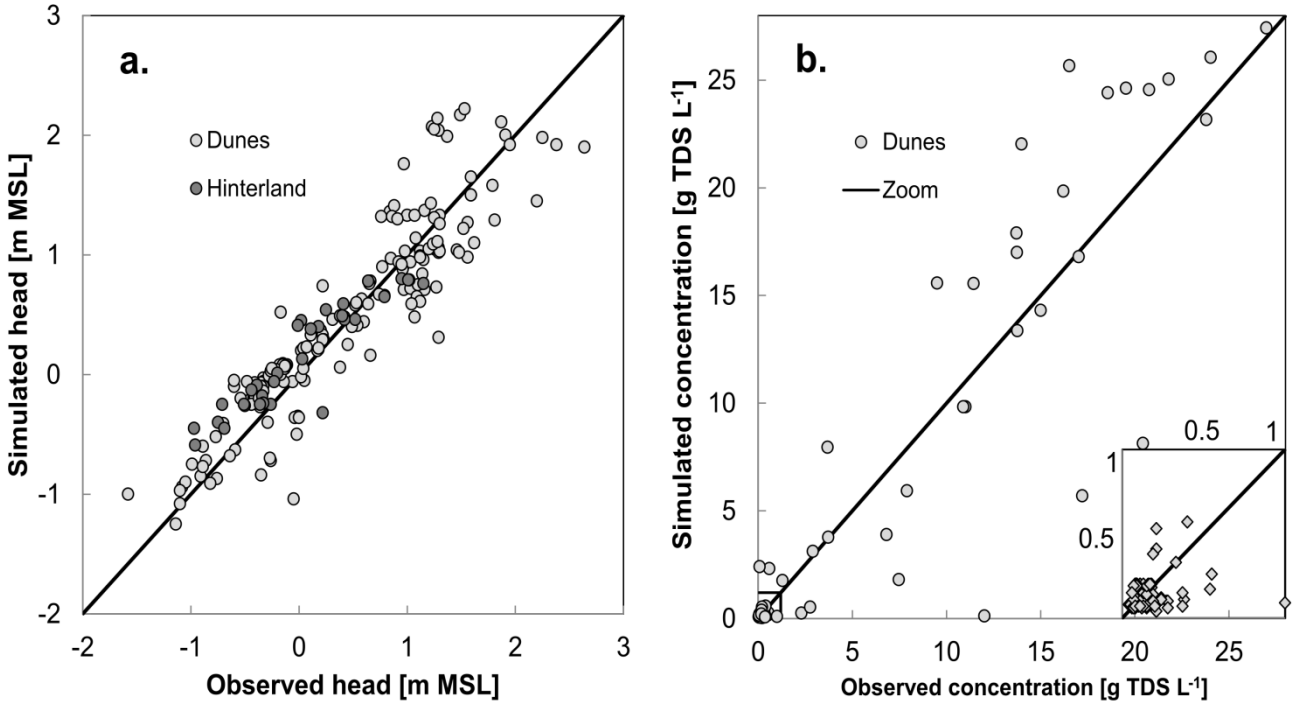

Fig. 7. Comparison of observed and simulated heads (a) and concentration (b)

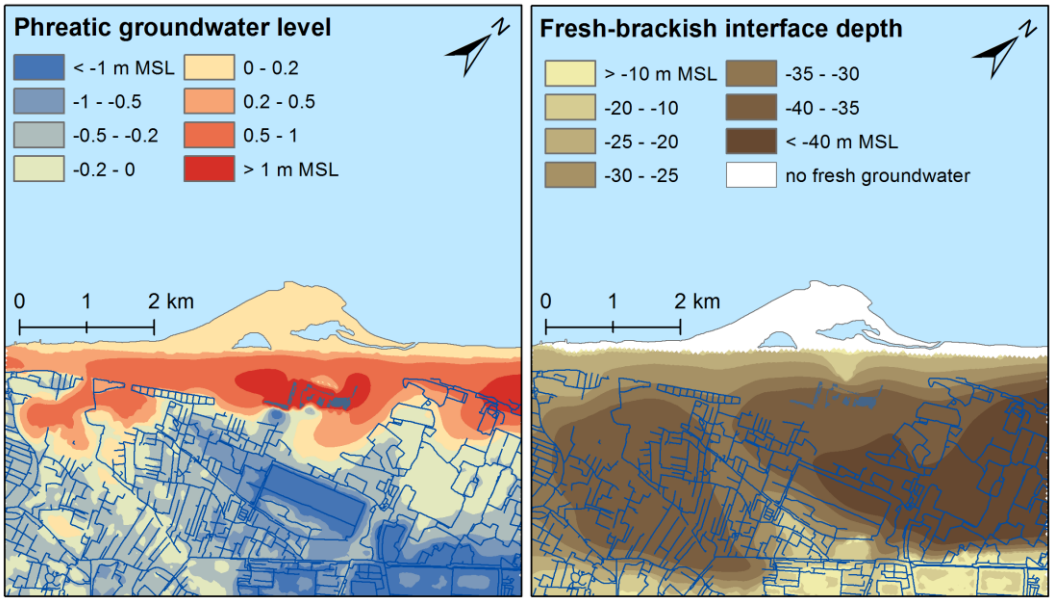

Fig. 8. Phreatic groundwater level (left) and fresh-brackish interface depth (right) after calibration, before the construction of the Sand Engine (2010 – 2011).

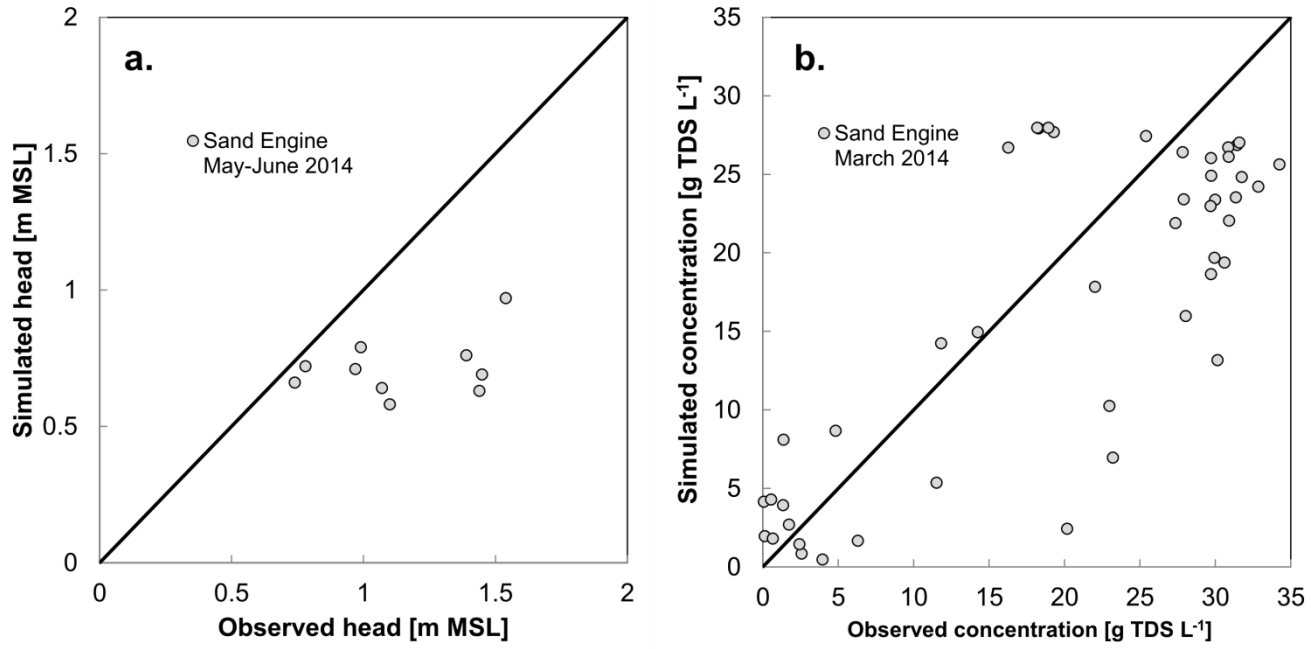

Fig. 9. Comparison of (a) average groundwater heads in May-June 2014 and (b) (single) TDS concentrations of soil samples taken between 10 and 14 March 2014 with model simulations in the Sand Engine.

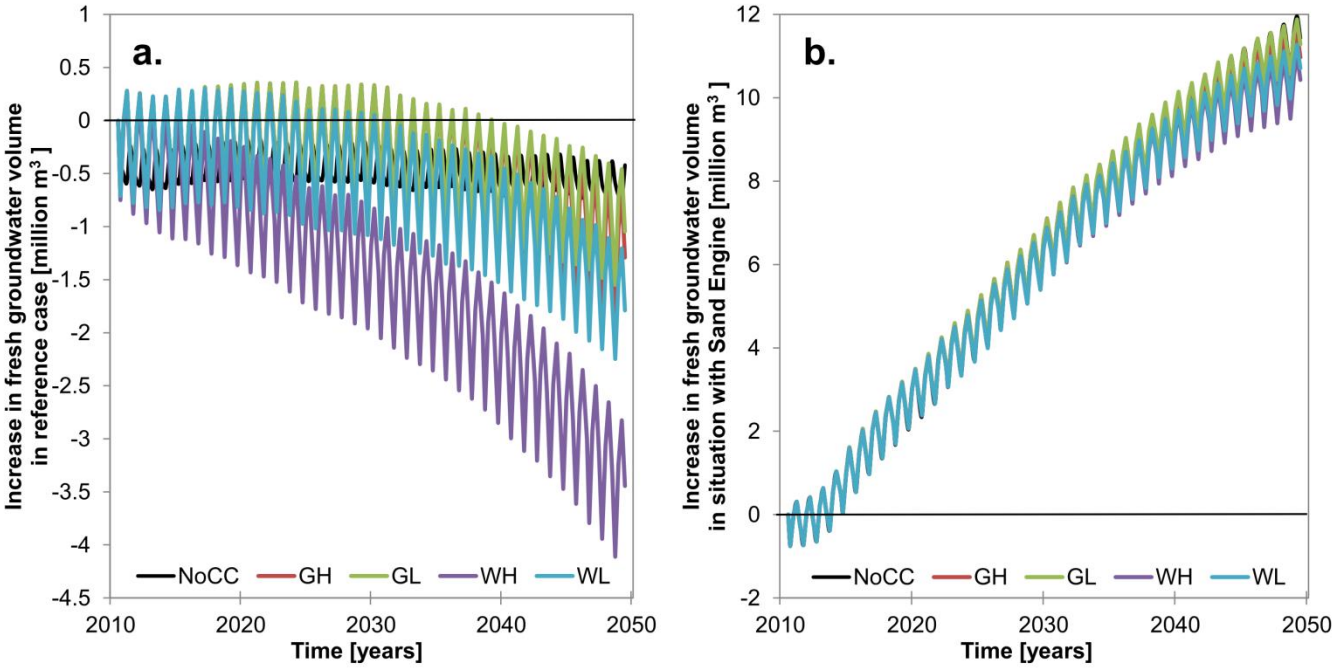

Fig. 10. Increase of the volume of fresh groundwater in the situation without Sand Engine (a) and situation with Sand Engine (b) in the period 2011 to 2050, where the legend refers to (climate) scenarios (as mentioned in Table 3)

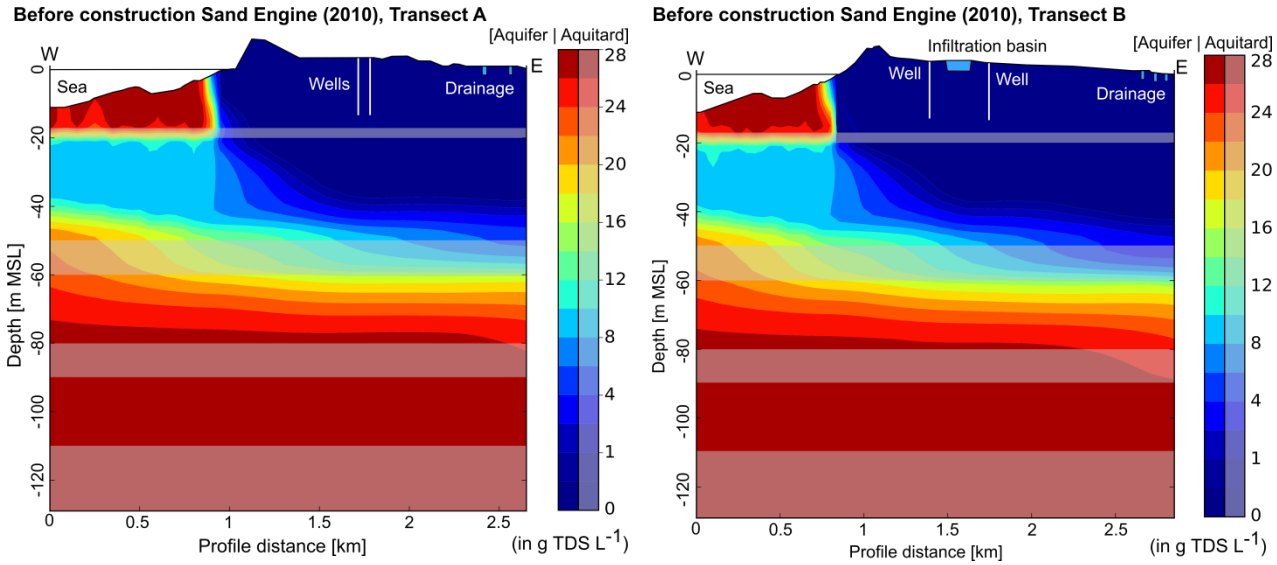

Fig. 11. Transects with the simulated groundwater salinity (in g TDS L-1) in 2010 (pre-development Sand Engine), for transect A and B (as shown in Fig. 2 and Fig. 3)

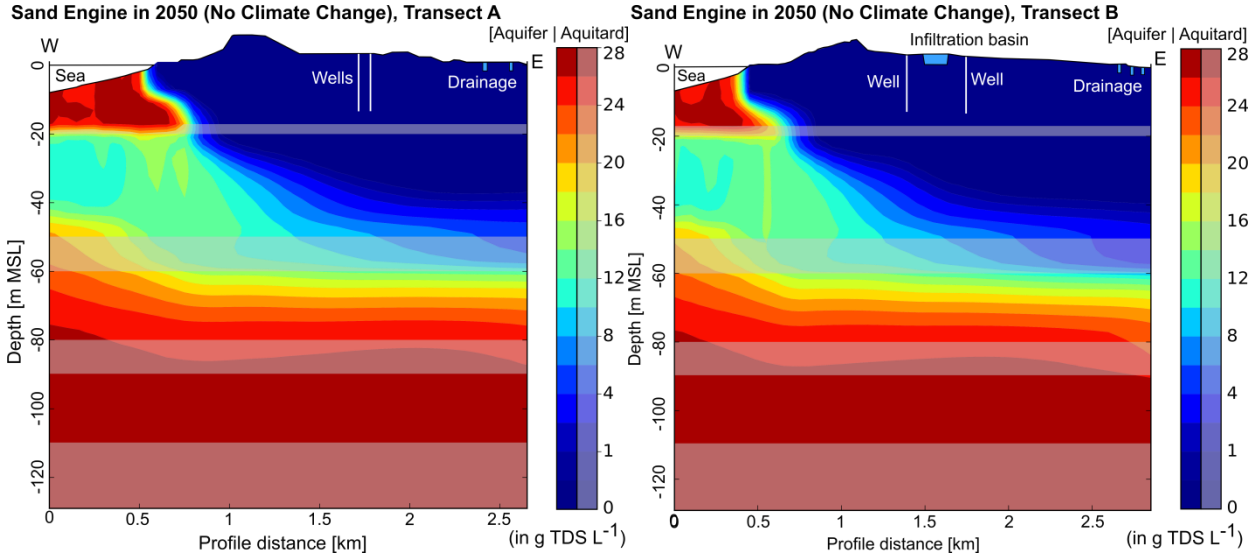

Fig. 12. Transects with the simulated groundwater salinity (in g TDS L^{-1}) in 2050 (including Sand Engine, No Climate Change), for transect A and B (as shown in Fig. 2 and Fig. 3)

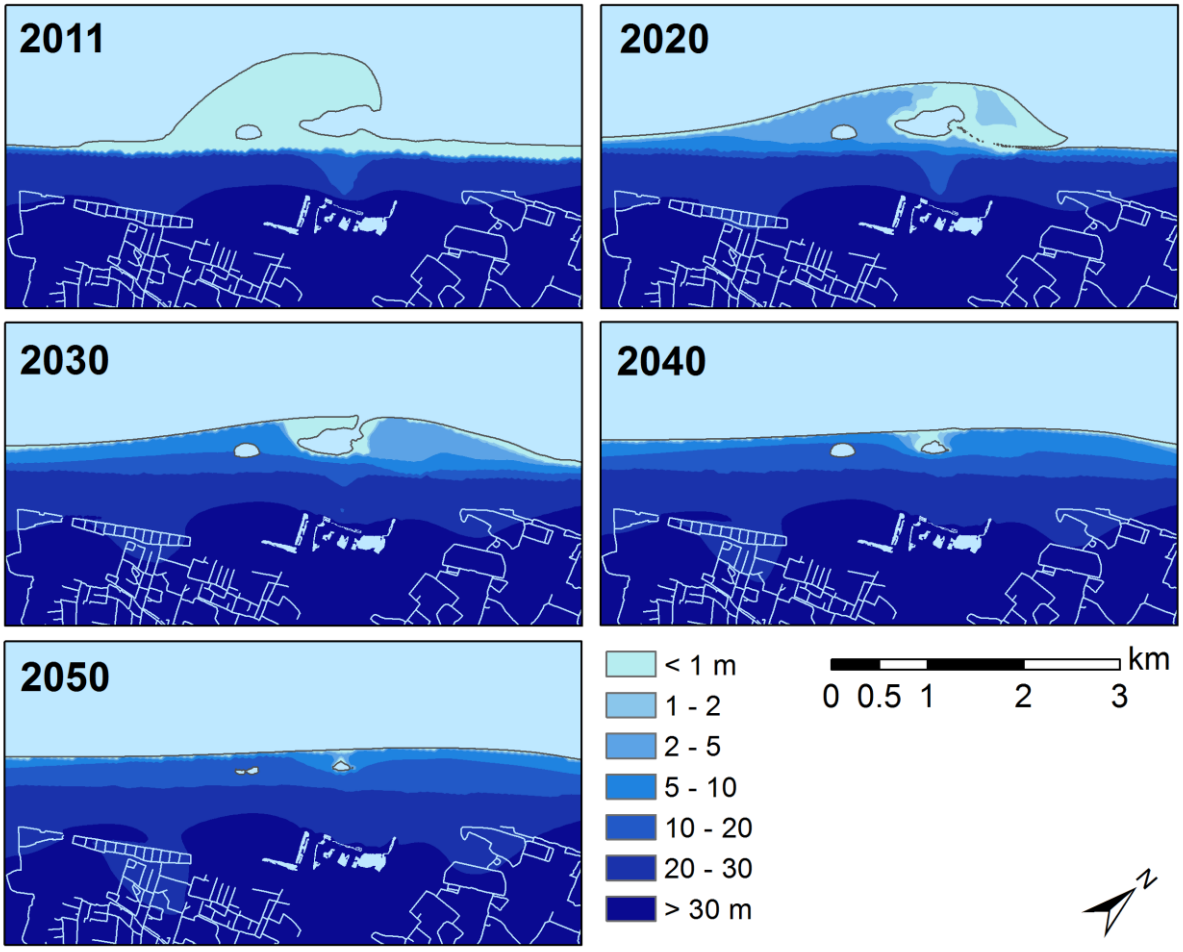

Fig. 13. Thickness of fresh groundwater [m] in reference scenario near the Sand Engine from 2011 – 2050

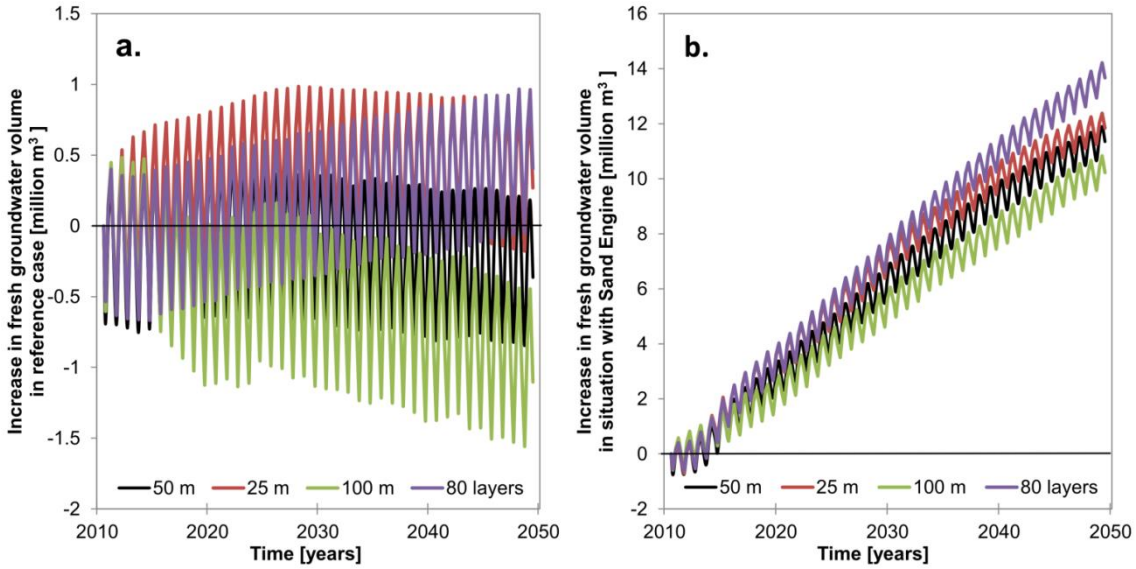

Fig. A1. Increase of the volume of fresh groundwater in the situation without Sand Engine (a) and situation with Sand Engine (b) in the period 2011 to 2050, where the legend refers to the four grid discretisation simulations

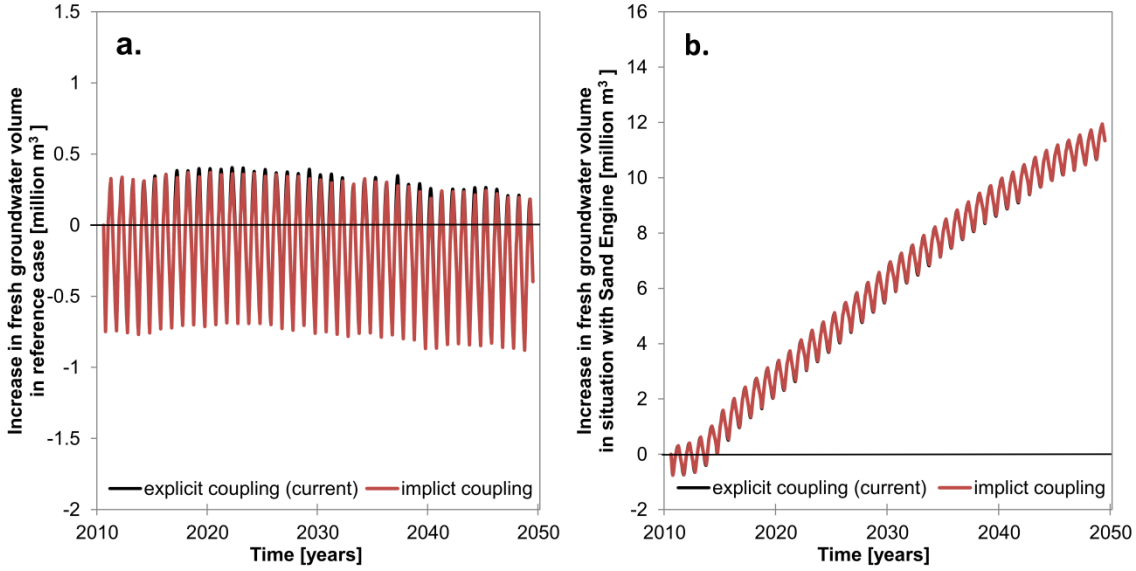

Fig. A2. Increase of the volume of fresh groundwater in the situation without Sand Engine (a) and situation with Sand Engine (b) in the period 2011 to 2050, where the legend refers to the coupling of flow and transport equations