



# 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<sup>3</sup>) – 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 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 et al., 2015; Mahmoodzadeh et al., 2014), and low-lying delta's (Giosan, 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) 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 inhabitants of deltas are becoming increasingly vulnerable 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 will enhance the pressure on these coastal regions 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, 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 intensified, specifically at vulnerable locations (Goodhew, 2014; Kabat et al., 2009; Sterr, 2008). One example is the Netherlands – a vulnerable low-lying delta – 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 sand nourishments, particularly beach and shoreface nourishments, has become the dominant coastal defence strategy at the Dutch coast. Sand nourishments are applied on a regular basis in order to maintain the position of the coastline (Keijzers et al., 2014a; van Slobbe et al., 2012).

## 1.2 Pilot project: Sand Engine

Since 2001 the position of the entire Dutch coastline is successfully maintained with 12 million m<sup>3</sup> of sand nourishments per year. However the future annual volume of sand nourishments should increase if the coast must rise with the sea-level (Delta Committee, 2008). Research suggests that the annual nourishment volume should be raised to 20 million m<sup>3</sup> yr<sup>-1</sup> in the nearby future, in order to sustain the Dutch coastline in the long run (Giardino et al., 2011; Ronde, 2008). The anticipation of a substantial growth in the annual nourishment volume incited discussions about the effectiveness of the current regular small-scale nourishments. These discussions led to the idea that the substitution of small-scale nourishments with local mega-nourishments could provide several advantages: more cost-effective than current practices, 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 local mega-nourishments are currently being investigated with a pilot experiment named the Sand Engine (also called Sand Motor) (Mulder and Tonnon, 2011; Stive et al., 2013). In this experiment a mega-nourishment of 21.5 million m<sup>3</sup> was constructed at the Dutch coast in 2011, a few kilometres west from the city of The Hague (Fig. 1). This large body 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’) (van Slobbe et al., 2012; de Vriend et al., 2014). The effectiveness of the Sand Engine is determined by research and extensive monitoring; the surface level (including the sea bed level) 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). Measurements in the most recent years show that the shape of the Sand Engine transformed from a ‘hook-shaped peninsula’ towards a flattened wider shape (de Schipper et al., 2014; Stive et al., 2013). In September 2011 the Sand Engine extended approximately 1 km



in the sea and was nearly 2 km wide at the shoreline, while in September 2014 it extended approximately 800 m in 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 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 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 the coastal system may 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 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.

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. Next, model calibration and model results are examined as well as the impact of different climate scenario's on simulated fresh groundwater resources. Finally, 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 sand from several sand pits in the North Sea and to transport the sand to the project site (Ministerie van Verkeer en Waterstaat, 2010). The dredged material was stored in the hopper and transported to 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 2011), the area above MSL was 1.3 km<sup>2</sup> with a maximum height of 7 m MSL (van Slobbe et al., 2012).

The Sand Engine is connected to the main land by a sandy beach of 100 to 150 m width, which is bounded by a coastal dune area with maximum heights between 10 to 20 m MSL. This dune area called Solleveld is relatively small (circa 2 km<sup>2</sup>; Fig. 2), and is used for the production of drinking water since 1887 (Draak, 2012). An increasing demand for clean, fresh water led to a gradual increase in extraction rates, reaching a maximum of 7.5 million m<sup>3</sup> per year in the recent period of 2008 – 2015. In order to be able to extract these considerable groundwater volumes 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. 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 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 polder lead also 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 fluvial and marine origin, as shown by two geological profiles in Fig. 3. The phreatic aquifer contains multiple layers of sand, clay and peat of 10 to 30 m thickness, which are deposited during the Holocene. In the higher situated dunes and urban areas the aquifer primarily consists of fine to medium grained sand, in the low-lying areas primarily of clay. However, the lower section of the phreatic aquifer (between -15 and -20 m MSL) consists in both areas mainly of clay and peat deposits. Deeper aquifers (yellow) and aquitards (orange, blue), as illustrated in Fig. 3, are 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 l<sup>-1</sup>) is situated between -20 and -40 m MSL, and the boundary between brackish and saline groundwater (10 TDS g l<sup>-1</sup>) is situated between -40 and -60 m MSL. The depth of the fresh water 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 the western side of the dune area. The aim of the expansion of the monitoring system was to observe long 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 every three months). The groundwater salinity is measured 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 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 the pumped groundwater. On the western base of the dunes a line of 28 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. However these pumping 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.

To 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.

The outer model boundaries were situated perpendicular to the coastline (at the SW and NE sides of the model; Fig. 1), parallel to the dominant groundwater flow direction in the coastal area, and therefore defined as no-flow boundaries. Other outer model boundaries (at the NW and SE side of the model) were defined as illustrated in Fig. 4: constant-head and general-head boundary conditions (taking into account density differences), representing the average North sea-level and local groundwater system, respectively. The local groundwater heads and salinities on the eastern side 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, 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 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 aquifer parameters and layer elevations were defined uniform for each hydrogeological unit, based on estimations in the national hydrogeological database. The effective porosity was set to 0.3 for aquifers and 0.1 for aquitards, the molecular diffusion coefficient to  $10^{-9} \text{ m}^2 \text{ s}^{-1}$ , and the longitudinal dispersivity 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  $10 \text{ m d}^{-1}$ , and the hydraulic conductivities in areas and layers with mainly clay, loam and fine sand were set to  $1 \text{ m d}^{-1}$ .

Other model parameters such as recharge, surface water levels, and drainage levels were defined by taking 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 [ $\text{g TDS l}^{-1}$ ], and in the classification of the groundwater salinity we have focused on three groundwater classes: fresh ( $0 - 1 \text{ g TDS l}^{-1}$ ), brackish ( $1 - 10 \text{ g TDS l}^{-1}$ ), and saline ( $10 - 30 \text{ g TDS l}^{-1}$ ). For the conversions of chloride measurements to TDS concentrations we have used the relation between chloride and TDS in the North Sea;  $1 \text{ g TDS l}^{-1} = 0.55 \text{ g Cl l}^{-1}$  (Millero, 2004). The North Sea TDS in the model domain was estimated at  $28 \text{ g TDS l}^{-1}$  in all model calculations (density of  $1020 \text{ kg m}^{-3}$ ), 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 ( $30\text{--}35 \text{ g TDS l}^{-1}$ ), 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]. The TDS concentration of infiltration basins, canals and ditches were set to  $0.2 \text{ g l}^{-1}$  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  $0.121 \text{ g l}^{-1}$  at the coastline to  $0.023 \text{ g l}^{-1}$  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 were included in the model calibration. We considered the calibrated conditions valid when the error between simulated and observed groundwater head and TDS concentration is similar or smaller than the observed variations in groundwater level (the average standard deviation of observations is  $0.4 \text{ m}$ ) and concentration (the average standard deviation of observations is  $0.7 \text{ g TDS l}^{-1}$ ), when the errors are randomly distributed in space, and the simulated distribution of TDS concentrations corresponds with literature (Stuyfzand, 1993).

The calibration method comprised of sensitivity analyses, (restricted) model parameter adjustments, 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 historical processes that 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 in the model simulations to attain a better match between simulations and observations (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 period was restricted to 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.

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 were 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 simulations, a selection of model parameters was adjusted with small increments: (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 projections of the morphological change of the Sand Engine during the period 2011 to 2050. 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 during the 2011 to 2050 (Fig. 6).

The predicted morphological development of the Sand Engine was incorporated in the groundwater model as a change in surface elevation for every quarter 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, the decrease of the tidal range within the lagoon was also included in the model scenario's with a maximum increase of the mean water level of 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 1.

All climate change scenarios were simulated for a reference situation without the Sand Engine and the situation with the Sand Engine including the projected morphological evolution. The model simulations for the reference situation serve primarily as a comparison to the simulations with the morphological evolution of the Sand Engine. The contrasts between both situations represent the total impact of the construction of the Sand Engine on local fresh groundwater resources. The climate change scenarios show the response and sensitivity of local fresh groundwater resources to different degrees of change 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 groundwater heads and TDS concentrations with recent observations of the groundwater head and chloride concentration within the model domain (Fig. 7). The absolute mean error between observed and simulated heads is 0.27 m (RMSE of 0.33 m), and between observed and simulated TDS concentrations is  $1.17 \text{ g l}^{-1}$  (RMSE of  $2.75 \text{ g l}^{-1}$ ). The largest deviations in observed and simulated heads occur at observation points that are situated near infiltration basins or pumping wells, whereas the deviation in concentration appears to be evenly or randomly distributed. The deviations in observed and simulated heads and salinities are probably primarily caused by heterogeneity in the phreatic aquifer, spatial variations in the extraction volumes 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 - 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 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 extends 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). Drainage in low-lying polders leads to the seepage of brackish or saline groundwater, which leads to a thinner fresh groundwater lens (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 0.36 m, and between observed and simulated TDS concentrations 6.5 g TDS l<sup>-1</sup>. 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<sup>-1</sup> (between 6 and 20 m below surface). Probable causes of the discrepancies lie in the initial groundwater levels and salinities (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 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<sup>3</sup> per year. The sea-level rise (in total) of 0.15 m in climate scenario's G<sub>L</sub> and G<sub>H</sub> and 0.25 m in climate scenario's W<sub>L</sub> and W<sub>H</sub> 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 1) have a limited effect on the total volume groundwater. The climate scenarios with a strong response (G<sub>H</sub> and W<sub>H</sub>) and corresponding wetter winters and drier summers lead to a lower volume of fresh groundwater, when compared with the climate scenarios with a weak response (G<sub>L</sub> and W<sub>L</sub>) and subsequently smaller change in precipitation and evapotranspiration. The contrast between these climate scenarios only become apparent after 2030, because the precipitation and evapotranspiration patterns are equal until 2030 and diverge in the period 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 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 distance to the Sand Engine (Fig. 11).



## 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 several million m<sup>3</sup>. 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 decades after the construction of the mega-nourishment. In addition, the increase in the volume of fresh groundwater is dependent on the pace 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 (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; Keijzers 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 observations 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. groundwater level and salinity after the construction of the Sand Engine), large inundations of the Sand Engine due to storm-surges, variations in extraction rates of pumping wells, fluctuations in the salinity of the North Sea 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 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, the simulations are therefore most reliable in our area of interest. It is less certain to what extent the simulated groundwater head and salinity in other areas correspond with the actual situation. 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, 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 of the uncertainties in the prediction of 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 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<sup>3</sup> 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 and the local circumstances. 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.

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## References

- Bakker, M. A. J., van Heteren, S., Vonhögen, L. M., van der Spek, A. J. F. and van der Valk, B.: Recent Coastal Dune Development: Effects of Sand Nourishments, *J. Coast. Res.*, 282(3), 587–601, doi:10.2112/JCOASTRES-D-11-00097.1, 2012.
- 5 Buma, J. T.: Monitoringsplan drainagemaatregel Solleveld; Monitoring van grondwater en functioneren drainagemaatregel, Deltares, Utrecht., 2013.
- CBS, PBL and Wageningen UR: Jaarlijkse hoeveelheid neerslag in Nederland (Yearly volume of precipitation in the Netherlands), (indicator 0508, versie 05, 23 maart 2012)., [www.compendiumvoordeleefomgeving.nl](http://www.compendiumvoordeleefomgeving.nl). CBS, Den Haag; Planbur. voor Leefomgeving, Den Haag/Bilthoven en Wageningen UR, Wageningen. [online] Available from:
- 10 <http://www.compendiumvoordeleefomgeving.nl/indicatoren/nl0508-Neerslagsom-in-Nederland.html?i=9-54>, 2012.
- CBS, PBL and Wageningen UR: Zeespiegelstand langs de Nederlandse kust en mondiaal (Sea-level along the Dutch coast and global) 1891-2012, (indicator 0229, versie 08, 24 september 2013)., [www.compendiumvoordeleefomgeving.nl](http://www.compendiumvoordeleefomgeving.nl). CBS, Den Haag; Planbur. voor Leefomgeving, Den Haag/Bilthoven en Wageningen UR, Wageningen. [online] Available from: <http://www.compendiumvoordeleefomgeving.nl/indicatoren/nl0229-Zeespiegelstand-Nederland.html?i=9-54>, 2013.
- 15 Charlier, R. H., Chaineux, M. C. P. and Morcos, S.: Panorama of the History of Coastal Protection, *J. Coast. Res.*, 21(1), 79–111, doi:10.2112/03561.1, 2005.
- Chui, T. F. M. and Terry, J. P.: Influence of sea-level rise on freshwater lenses of different atoll island sizes and lens resilience to storm-induced salinization, *J. Hydrol.*, 502, 18–26, doi:10.1016/j.jhydrol.2013.08.013, 2013.
- Crain, C. M., Halpern, B. S., Beck, M. W. and Kappel, C. V: Understanding and managing human threats to the coastal marine environment., *Ann. N. Y. Acad. Sci.*, 1162, 39–62, doi:10.1111/j.1749-6632.2009.04496.x, 2009.
- 20 Delsman, J. R., Hu-a-ng, K. R. M., Vos, P. C., de Louw, P. G. B., Oude Essink, G. H. P., Stuyfzand, P. J. and Bierkens, M. F. P.: Paleo-modeling of coastal saltwater intrusion during the Holocene: an application to the Netherlands, *Hydrol. Earth Syst. Sci.*, 18, 3891–3905, doi:10.5194/hess-18-3891-2014, 2014.
- Delta Committee: Working together with water; A living land builds for its future. Findings of the Deltacommissie 2008. [online] Available from: <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Working+together+with+water#9> (Accessed 12 May 2015), 2008.
- 25 Draak, R.: Waterwinning in de Duinen (Water extraction in the Dunes), *Holland's Duinen*, 60, 50–54 [online] Available from: <http://www.vliz.be/imisdocs/publications/24654.pdf> (Accessed 13 May 2015), 2012.
- 30 Droogers, P.: Verbetering bepaling actuele verdamping voor het strategisch waterbeheer, Utrecht., 2009.





- Ebbens, E. and Fiselier, J.: Monitoring- en evaluatieplan Zandmotor, DHV B.V., 2010.
- Eeman, S., Leijnse, A., Raats, P. A. C. and van der Zee, S. E. A. T. M.: Analysis of the thickness of a fresh water lens and of the transition zone between this lens and upwelling saline water, *Adv. Water Resour.*, 34(2), 291–302, doi:10.1016/j.advwatres.2010.12.001, 2011.
- 5 Few, R. and Matthies, F.: *Flood Hazards and Health: Responding to Present and Future Risks*, Earthscan, London., 2006.
- Fiselier, J.: Projectnota/ MER, Aanleg en zandwinning Zand motor Delflandse kust (Sand Engine Delfland coast: project plan and assessment of the environmental impact report), DHV BV, Amersfoort, The Netherlands., 2010.
- FitzGerald, D. M., Fenster, M. S., Argow, B. a. and Buynevich, I. V.: Coastal Impacts Due to Sea-Level Rise, *Annu. Rev. Earth Planet. Sci.*, 36(1), 601–647, doi:10.1146/annurev.earth.35.031306.140139, 2008.
- 10 Giardino, A., Mulder, J. P. M., de Ronde, J. and Stronkhorst, J.: Sustainable Development of the Dutch Coast: Present and Future, *J. Coast. Res.*, (61), 1–7, doi:10.2112/SI61-001.1, 2011.
- Giosan, L.: Protect the world's deltas, *Nature*, 516(729), 5–7, 2014.
- Goodhew, T.: Coastal Flood Defences - Strategies for Protection in the United Kingdom, in *Water Resources in the Built Environment: Management Issues and Solutions*, edited by C. A. Booth and S. M. Charlesworth, pp. 233–248, John Wiley & Sons, Ltd, Chichester, UK., 2014.
- 15 Heiss, J. W. and Michael, H. A.: Saltwater-freshwater mixing dynamics in a sandy beach aquifer over tidal, spring-neap, and seasonal cycles, *Water Resour. Res.*, 50(8), 6747–6766, doi:10.1002/2014WR015574.Received, 2014.
- Herckenrath, D., Langevin, C. D. and Doherty, J.: Predictive uncertainty analysis of a saltwater intrusion model using null-space Monte Carlo, *Water Resour. Res.*, 47(5), W05504, doi:10.1029/2010WR009342, 2011.
- 20 Hoggart, S. P. G., Hanley, M. E., Parker, D. J., Simmonds, D. J., Bilton, D. T., Filipova-Marinova, M., Franklin, E. L., Kotsev, I., Penning-Rowsell, E. C., Rundle, S. D., Trifonova, E., Vergiev, S., White, a. C. and Thompson, R. C.: The consequences of doing nothing: The effects of seawater flooding on coastal zones, *Coast. Eng.*, 87, 169–182, doi:10.1016/j.coastaleng.2013.12.001, 2014.
- Holding, S., Allen, D. M. and M.: From days to decades: numerical modelling of freshwater lens response to climate change stressors on small low-lying islands, *Hydrol. Earth Syst. Sci.*, 19(2), 933–949, doi:10.5194/hess-19-933-2015, 2015.
- 25 Hoofs, J. and van der Pijl, Y.: *Kartobibliografie van de Waterstaatskaart (1865-1991)*, Ministerie van Verkeer en Waterstaat, Rijkswaterstaat, Meetkundige Dienst (RWS, MD), afd. IEBD, Delft, The Netherlands. [online] Available from: <http://publicaties.minienm.nl/documenten/kartobibliografie-van-de-waterstaatskaart-1865-1991>, 2002.



- Hooghart, J. C. and Lablans, W. N.: van Penman naar Makkink: een nieuwe berekeningswijze voor de klimatologische verdampingsgetallen, de Bilt, the Netherlands., 1988.
- IPCC: Climate Change 2013: The Physical Science Basis Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2013.
- Jensen, J., Hofstede, J. L. A., Kunz, H., de Ronde, J., Heinen, P. F. and Siefert, W.: Long term water level observations and variations, in Coastal Zone; Proceedings of the Symposium on Coastal and Ocean Management, pp. 110–130, New Orleans, LA, USA. [online] Available from: [http://www.kwaad.net/JensenEtAl\\_1993.pdf](http://www.kwaad.net/JensenEtAl_1993.pdf) (Accessed 30 April 2015), 1993.
- 10 Kabat, P., Fresco, L. O., Stive, M. J. F., Veerman, C. P., van Alphen, J. S. L. J., Parmet, B. W. A. H., Hazeleger, W. and Katsman, C. A.: Dutch coasts in transition, *Nat. Geosci.*, 2(7), 450–452, doi:10.1038/ngeo572, 2009.
- Keijzers, J. G. S., Giardino, A., Poortinga, A., Mulder, J. P. M., Riksen, M. J. P. M. and Santinelli, G.: Adaptation strategies to maintain dunes as flexible coastal flood defense in The Netherlands, *Mitig. Adapt. Strateg. Glob. Chang.*, doi:10.1007/s11027-014-9579-y, 2014a.
- 15 Keijzers, J. G. S., Poortinga, A., Riksen, M. J. P. M. and Maroulis, J.: Spatio-temporal variability in accretion and erosion of coastal foredunes in the Netherlands: Regional climate and local topography, *PLoS One*, 9(3), doi:10.1371/journal.pone.0091115, 2014b.
- KNMI: KNMI'14 : Climate Change scenarios for the 21st Century - A Netherlands perspective, edited by B. van den Hurk, P. Siegmund, A. Klein, T. Eds, J. Attema, A. Bakker, J. Beersma, J. Bessembinder, R. Boers, T. Brandsma, H. van den Brink, S. Drijfhout, H. Eskes, R. Haarsma, W. Hazeleger, R. Jilderda, C. Katsman, G. Lenderink, J. Loriaux, E. van Meijgaard, T. van Noije, G. J. van Oldenborgh, F. Selten, P. Siebesma, A. Sterl, H. de Vries, M. van Weele, R. de Winter, and G.-J. van Zadelhoff, Scientific Report WR2014-01, KNMI, De Bilt, The Netherlands. [online] Available from: [www.climate-scenario.nl](http://www.climate-scenario.nl), 2014.
- 20 Van Koningsveld, M., Mulder, J. P. M., Stive, M. J. F., van der Valk, L. and van der Weck, A. W.: Living with Sea-Level Rise and Climate Change: A Case Study of the Netherlands, *J. Coast. Res.*, 24(2), 367–379, doi:10.2112/07A-0010.1, 2008.
- De Lange, W. J., Prinsen, G. F., Hoogewoud, J. C., Veldhuizen, A. A., Verkaik, J., Oude Essink, G. H. P., van Walsum, P. E. V., Delsman, J. R., Hunink, J. C., Massop, H. T. L. and Kroon, T.: An operational, multi-scale, multi-model system for consensus-based, integrated water management and policy analysis: The Netherlands Hydrological Instrument, *Environ. Model. Softw.*, 59, 98–108, doi:10.1016/j.envsoft.2014.05.009, 2014.



- Langevin, C. D., Thorne Jr., D. T., Dausman, A., Sukop, M. C. and Guo, W.: SEAWAT version 4: a computer program for simulation of multi-species solute and heat transport, in U.S. Geological Survey Techniques and Methods Book 6, p. 39. [online] Available from: <http://pubs.er.usgs.gov/publication/tm6A22> (Accessed 30 April 2015), 2008.
- Lesser, G. R., Roelvink, J. A., van Kester, J. A. T. M. and Stelling, G. S.: Development and validation of a three-dimensional morphological model, *Coast. Eng.*, 51(8-9), 883–915, doi:10.1016/j.coastaleng.2004.07.014, 2004.
- De Louw, P. G. B., Eeman, S., Siemon, B., Voortman, B. R., Gunnink, J., van Baaren, E. S. and Oude Essink, G. H. P.: Shallow rainwater lenses in deltaic areas with saline seepage, *Hydrol. Earth Syst. Sci.*, 15(12), 3659–3678, doi:10.5194/hess-15-3659-2011, 2011.
- Mahmoodzadeh, D., Ketabchi, H., Ataie-Ashtiani, B. and Simmons, C. T.: Conceptualization of a fresh groundwater lens influenced by climate change: A modeling study of an arid-region island in the Persian Gulf, Iran, *J. Hydrol.*, 519(PA), 399–413, doi:10.1016/j.jhydrol.2014.07.010, 2014.
- Massop, H. T. L. and van Bakel, P. J. T.: Nationaal Hydrologisch Instrumentarium - NHI, Modelrapportage, Deelrapport Buisdrainage. [online] Available from: <http://nhi.nu/>, 2008.
- McGranahan, G., Balk, D. and Anderson, B.: The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones, *Environ. Urban.*, 19(1), 17–37, doi:10.1177/0956247807076960, 2007.
- Meinardi, C. R.: Groundwater recharge and travel times in the sandy regions of the Netherlands, VU University Amsterdam. [online] Available from: <http://dare.uvu.vu.nl/handle/1871/12739>, 1994.
- Michael, H. A., Russoniello, C. J. and Byron, L. A.: Global assessment of vulnerability to sea-level rise in topography-limited and recharge-limited coastal groundwater systems, *Water Resour. Res.*, 49(4), 2228–2240, doi:10.1002/wrcr.20213, 2013.
- Millero, F. J.: Physicochemical Controls on Seawater, in *Treatise on Geochemistry; Volume 6: The Oceans and Marine Geochemistry*, edited by H. Elderfield, pp. 1–21, Elsevier, Amsterdam., 2004.
- Ministerie van Verkeer en Waterstaat: Projectplan voor de realisatie van de pilot Zandmotor (Projectplan for the realisation of the pilot Sand Engine), , 27 [online] Available from: <http://www.dezandmotor.nl/uploads/2011/03/projectplan-waterwet.pdf>, 2010.
- Mulder, J. P. M. and Tonnon, P. K.: “Sand Engine”: Background and design of a mega-nourishment pilot in the Netherlands, in *Proceedings of International Coastal Engineering Conference 32*, pp. 1–10, Shanghai, China. [online] Available from: <https://icce-ojs-tamu.tdl.org/icce/index.php/icce/article/viewArticle/1454> (Accessed 6 May 2015), 2011.
- Nicholls, R. J.: Impacts of and responses to Sea-Level Rise, in *Understanding Sea-Level Rise and Variability*, edited by J. A. Church, P. L. Woodworth, T. Aarup, and W. W. Wilson, pp. 17–51, Wiley-Blackwell., 2010.



- Nicholls, R. J., Brown, S., Hanson, S. and Hinkel, J.: Economics of Coastal Zone Adaptation to Climate Change, Washington D.C., USA., 2010.
- Oude Essink, G. H. : Improving fresh groundwater supply—problems and solutions, *Ocean Coast. Manag.*, 44(5-6), 429–449, doi:10.1016/S0964-5691(01)00057-6, 2001.
- 5 Oude Essink, G. H. P., van Baaren, E. S. and de Louw, P. G. B.: Effects of climate change on coastal groundwater systems: A modeling study in the Netherlands, *Water Resour. Res.*, 46(10), n/a–n/a, doi:10.1029/2009WR008719, 2010.
- Post, V. E. A., van der Plicht, H. and Meijer, H. A. J.: The origin of brackish and saline groundwater in the coastal area of the Netherlands, *Netherlands J. Geosci. / Geol. en Mijnb.*, 82(2), 133–147 [online] Available from: <http://cio.eldoc.ub.rug.nl/root/2003/NethJGeosciPost/?pLanguage=en&pFullItemRecord=ON> (Accessed 7 May 2015), 2003.
- 10 Rasmussen, P., Sonnenborg, T. O., Goncear, G. and Hinsby, K.: Assessing impacts of climate change, sea level rise, and drainage canals on saltwater intrusion to coastal aquifer, *Hydrol. Earth Syst. Sci. Discuss.*, 9(7), 7969–8026, doi:10.5194/hessd-9-7969-2012, 2012.
- Rijkswaterstaat: Zoutgehalte in de Noordzee langs de kust (Salinity in the North Sea along the coast), North Sea Atlas, Part I. Water Syst. [online] Available from: <http://www.noordzeeloket.nl/en/spatial-management/north-sea-atlas/watersysteem/zoutgehalte.aspx>, 2012.
- 15 Ronde, J. G. De: Toekomstige langjarige suppletiebehoefte, Deltares, Delft., 2008.
- De Schipper, M. A., de Vries, S., Stive, M. J. F., de Zeeuw, R. C., Rutten, J., Ruessink, B. G., Aarninkhof, S. G. J. and van Gelder-Maas, C.: Morphological development of a mega-nourishment; first observations at the Sand Engine, in *Coastal Engineering Proceedings*, pp. 1–6, Seoul, Korea. [online] Available from: <https://journals.tdl.org/icce/index.php/icce/article/view/7797> (Accessed 30 April 2015), 2014.
- 20 De Sherbinin, A., Warner, K. and Ehrhart, C.: Casualties of climate change, *Sci. Am.*, 304(1), 64–71 [online] Available from: <http://www.nature.com/scientificamerican/journal/v304/n1/full/scientificamerican0111-64.html> (Accessed 7 May 2015), 2011.
- Van Slobbe, E., Vriend, H. J., Aarninkhof, S. G. J., Lulofs, K., Vries, M. and Dircke, P.: Building with Nature: in search of resilient storm surge protection strategies, *Nat. Hazards*, 65(1), 947–966, doi:10.1007/s11069-012-0342-y, 2012.
- 25 Stafleu, J., Maljers, D., Busschers, F. S., Gunnink, J. L., Schokker, J., Dambrink, R. M., Hummelman, H. J. and Schijf, M. L.: GeoTop modelling, TNO, Utrecht., 2013.
- Statistics Netherlands: Bestand Bodemgebruik (File Landuse), CBS, The Hague, Netherlands. [online] Available from: <https://www.pdok.nl/nl/service/wms-cbs-bestand-bodemgebruik-2008-bbg-2008>, 2008.



- Sterr, H.: Assessment of Vulnerability and Adaptation to Sea-Level Rise for the Coastal Zone of Germany, *J. Coast. Res.*, 24(2), 380–393, doi:10.2112/07A-0011.1, 2008.
- Stive, M. J. F., de Schipper, M. A., Luijendijk, A. P., Aarninkhof, S. G. J., van Gelder-Maas, C., van Thiel de Vries, J. S. M., de Vries, S., Henriquez, M., Marx, S. and Ranasinghe, R.: A New Alternative to Saving Our Beaches from Sea-Level Rise: The Sand Engine, *J. Coast. Res.*, 290(5), 1001–1008, doi:10.2112/JCOASTRES-D-13-00070.1, 2013.
- Stuyfzand, P. J.: Hydrochemistry and Hydrology of the Coastal Dunea area of the Western Netherlands, Vrije Universiteit Amsterdam., 1993.
- Stuyfzand, P. J.: Predicting the effects of sea spray deposition and evapoconcentration on shallow coastal groundwater salinity under various vegetation types, in 23rd Salt Water Intrusion Meeting, pp. 401–404, Husum, Germany., 2014.
- 10 Syvitski, J. P. M., Kettner, A. J., Overeem, I., Hutton, E. W. H., Hannon, M. T., Brakenridge, G. R., Day, J., Vörösmarty, C. J., Saito, Y., Giosan, L. and Nicholls, R. J.: Sinking deltas due to human activities, *Nat. Geosci.*, 2(10), 681–686, doi:10.1038/ngeo629, 2009.
- Temmerman, S., Meire, P., Bouma, T. J., Herman, P. M. J., Ysebaert, T. and de Vriend, H. J.: Ecosystem-based coastal defence in the face of global change., *Nature*, 504(7478), 79–83, doi:10.1038/nature12859, 2013.
- 15 Terry, J. P. and Falkland, A. C.: Responses of atoll freshwater lenses to storm-surge overwash in the Northern Cook islands, *Hydrogeol. J.*, 18(3), 749–759, doi:10.1007/s10040-009-0544-x, 2010.
- Tonnon, P. K., van der Werf, J. and Mulder, J. P. M.: Morfologische berekeningen MER Zandmotor, Deltares, Delft., 2009.
- Tonnon, P. K., van der Valk, L., Holzhauer, H., Baptist, M. J., Wijsman, J. W. M., Vertegaal, C. T. M. and Arens, S. M.: Uitvoeringsprogramma Monitoring en Evaluatie Pilot Zandmotor, Deltares & Imares., 2011.
- 20 UNDP: Reducing Disaster Risk - A Challenge for Development, United Nations Development Programme, New York., 2004.
- Vandenbohede, A. and Lebbe, L.: Effects of tides on a sloping shore: groundwater dynamics and propagation of the tidal wave, *Hydrogeol. J.*, 15(4), 645–658, doi:10.1007/s10040-006-0128-y, 2007.
- Vandenbohede, A. and Lebbe, L.: Groundwater chemistry patterns in the phreatic aquifer of the central Belgian coastal plain, *Appl. Geochemistry*, 27(1), 22–36, doi:10.1016/j.apgeochem.2011.08.012, 2012.
- 25 Vernes, R. W. and van Doorn, T. H. M.: Van gidslaag naar hydrogeologische eenheid: toelichting op de totstandkoming van de dataset REGIS II, Nederlands Institute of Applied Geoscience TNO, Utrecht, The Netherlands. [online] Available from: <http://library.wur.nl/WebQuery/clc/1892708> (Accessed 11 May 2015), 2005.
- Vos, P. and de Vries, S.: 2e generatie palaeogeografische kaarten van Nederland (versie 2.0), Deltares, Utrecht., 2013.



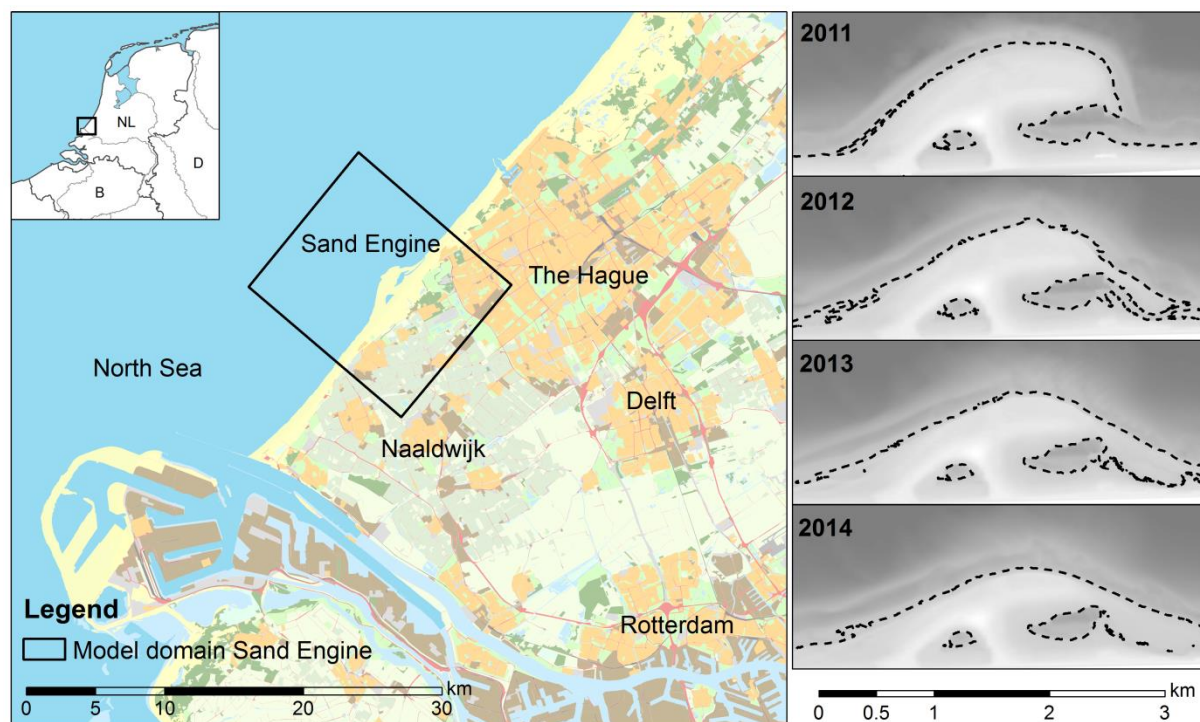
- De Vriend, H., Aarninkhof, S. and van Koningsveld, M.: “Building with nature”: the new Dutch approach to coastal and river works, *Proc. ICE - Civ. Eng.*, 167(1), 18–24, doi:10.1680/cien.13.00003, 2014.
- De Vries, S., Radermacher, M., de Schipper, M. A. and Stive, M. J. F.: Tidal dynamics in the Sand Motor lagoon, in *E-proceedings of the 36th IAHR World Congress*, pp. 1–6, The Hague, Netherlands., 2015.
- 5 Wahl, T., Haigh, I. D., Woodworth, P. L., Albrecht, F., Dillingh, D., Jensen, J., Nicholls, R. J., Weisse, R. and Wöppelmann, G.: Observed mean sea level changes around the North Sea coastline from 1800 to present, *Earth-Science Rev.*, 124, 51–67, doi:10.1016/j.earscirev.2013.05.003, 2013.
- Webb, M. D. and Howard, K. W. F.: Modeling the transient response of saline intrusion to rising sea-levels., *Ground Water*, 49(4), 560–9, doi:10.1111/j.1745-6584.2010.00758.x, 2011.
- 10 Wong, P. P., Losada, I. J., Gattuso, J.-P., Hinkel, J., Khattabi, A., McInnes, K. L., Saito, Y. and Sallenger, A.: Coastal systems and low-lying areas, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability.*, pp. 361–409, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2014.
- Zhang, K., Douglas, B. C. and Leatherman, S. P.: Global Warming and Coastal Erosion, *Clim. Change*, 64(1/2), 41–58, doi:10.1023/B:CLIM.0000024690.32682.48, 2004.
- 15 Zwamborn, M. H. and Peters, J. H.: *Uitbreiding waterwinning Solleveld, Milieu-effectrapport*, Kiwa N.V., Nieuwegein., 2000.



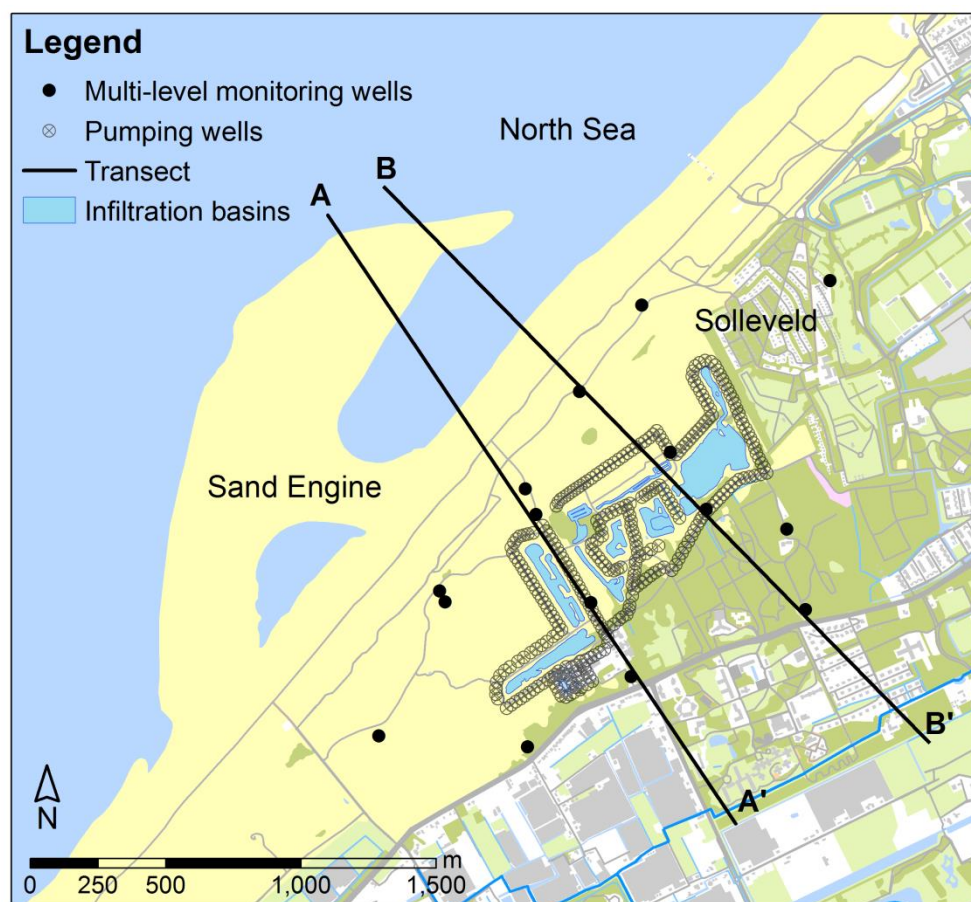


**Table 1.** Model climate change scenarios for the period 2011 – 2050, with two rates of SLR, starting at 0.05 m MSL and seasonal variation in groundwater recharge (DJF, MAM, JJA, SON)

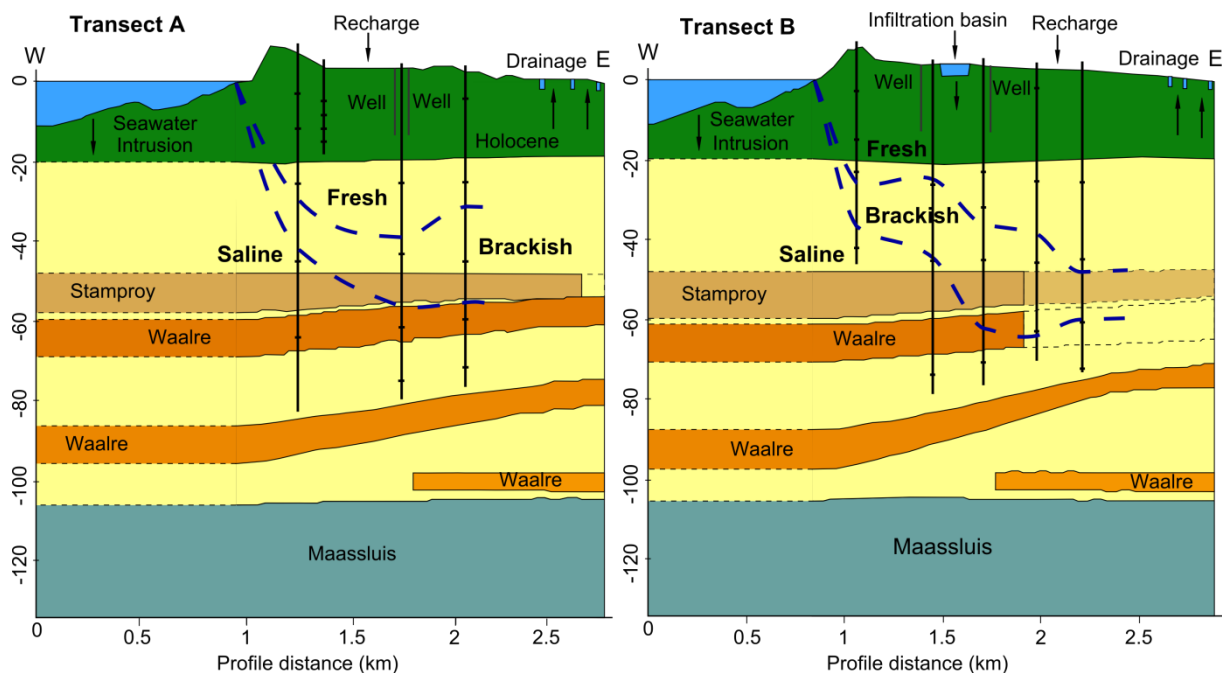
| Model Scenario                  | Sea-Level Rise                                     | Precipitation 2050<br>(given per season) | Potential evaporation 2050<br>(given per season) |
|---------------------------------|--|--|--|
| No climate change<br>(NoCC)     | No sea-level rise<br>[ 0.05 m MSL ]                | Equal to present:<br>Period 1981 - 2010  | Equal to present:<br>Period 1981 - 2010          |
| Climate scenario G <sub>L</sub> | + 3.75 mm yr <sup>-1</sup><br>[ 2050: 0.20 m MSL ] | +3%, +4.5%, +1.2%, +7%                   | +2.9%, +1.3%, +3.9%, +2.7%                       |
| Climate scenario G <sub>H</sub> | + 3.75 mm yr <sup>-1</sup><br>[ 2050: 0.20 m MSL ] | +8%, +2.3%, -8%, +8%                     | +2.4%, +2%, +7.5%, 2.8%                          |
| Climate scenario W <sub>L</sub> | + 6.25 mm yr <sup>-1</sup><br>[ 2050: 0.30 m MSL ] | +8%, +11%, +1.4%, +3%                    | +3.2%, +1.7%, +4.4%, +5.8%                       |
| Climate scenario W <sub>H</sub> | + 6.25 mm yr <sup>-1</sup><br>[ 2050: 0.30 m MSL ] | +17%, +9%, -13%, +7.5%                   | +2.7%, +2.9%, +10.6%, +4.5%                      |



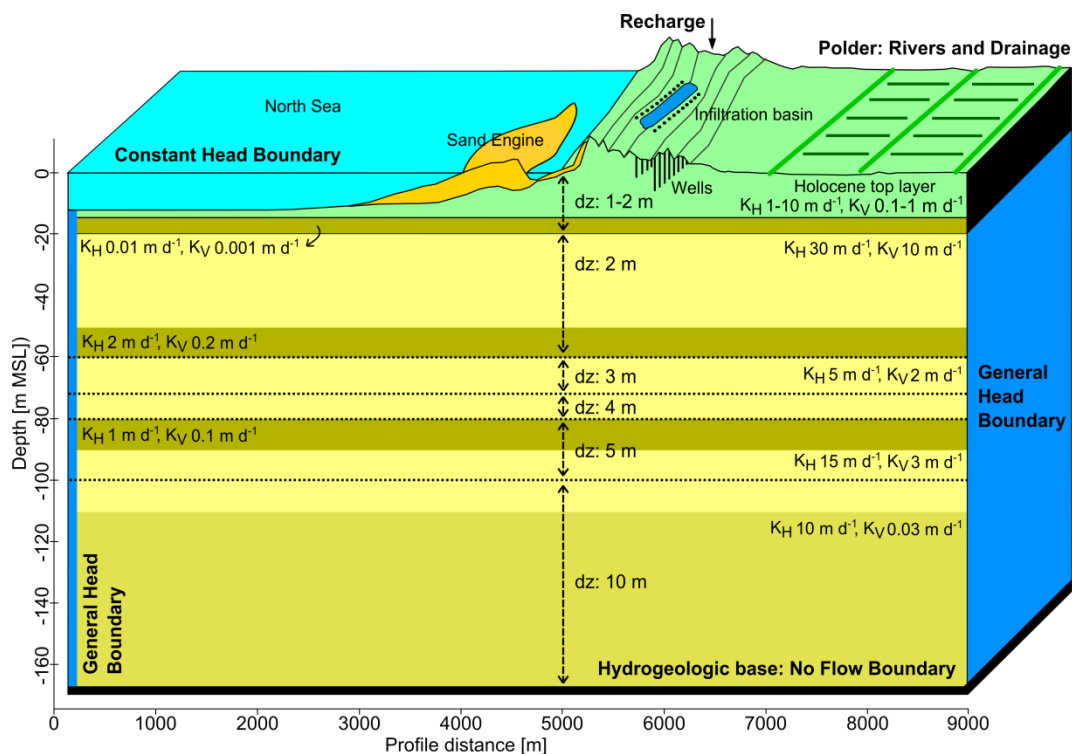
**Fig. 1.** Situation of the Sand Engine and morphological development in 2011 - 2014



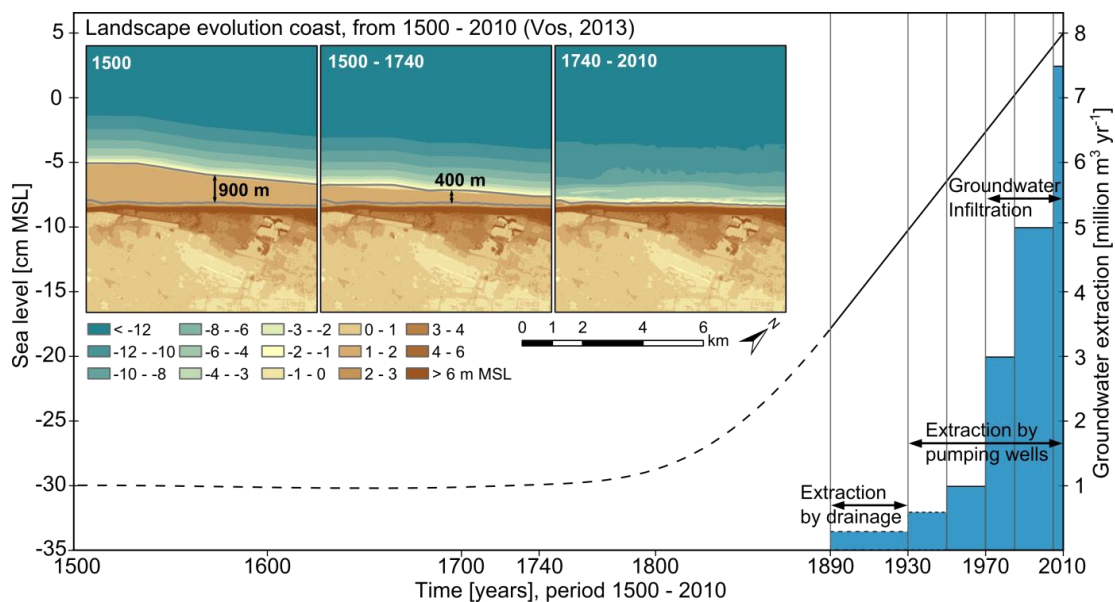
**Fig. 2.** Map of the dune area Solleveld with multi-level monitoring wells and pumping wells, including transects A and B (geological profiles in Fig. 3)



**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**)

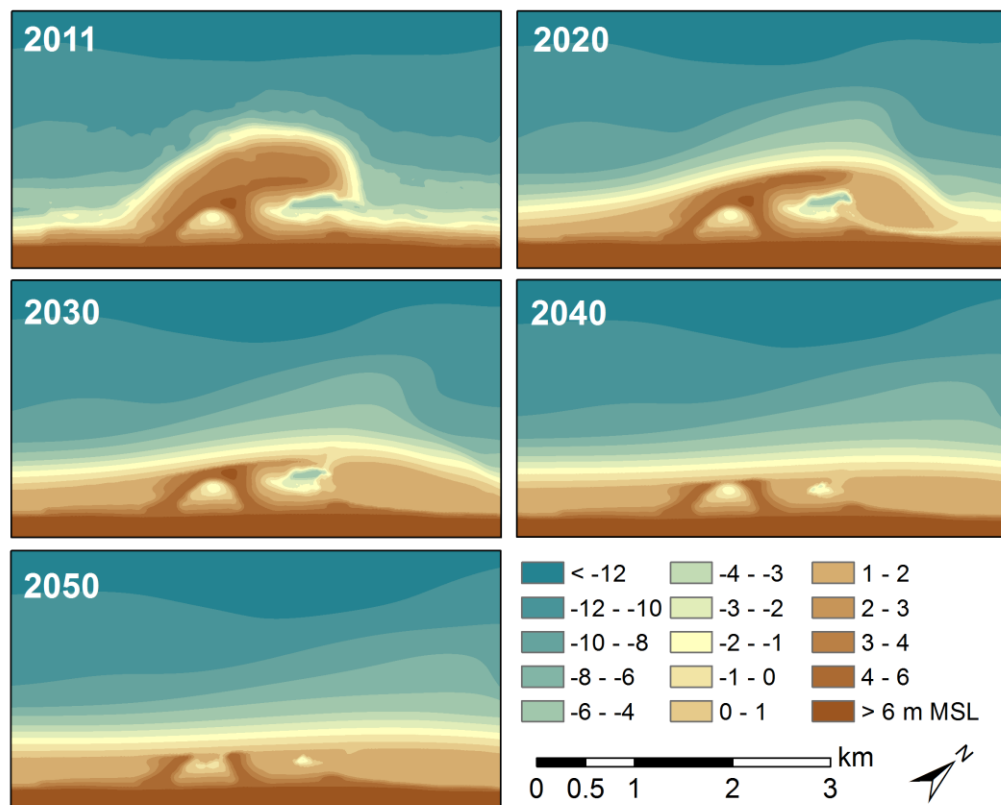


**Fig. 4.** Conceptual representation of a slice or portion of the model with aquifer parameters

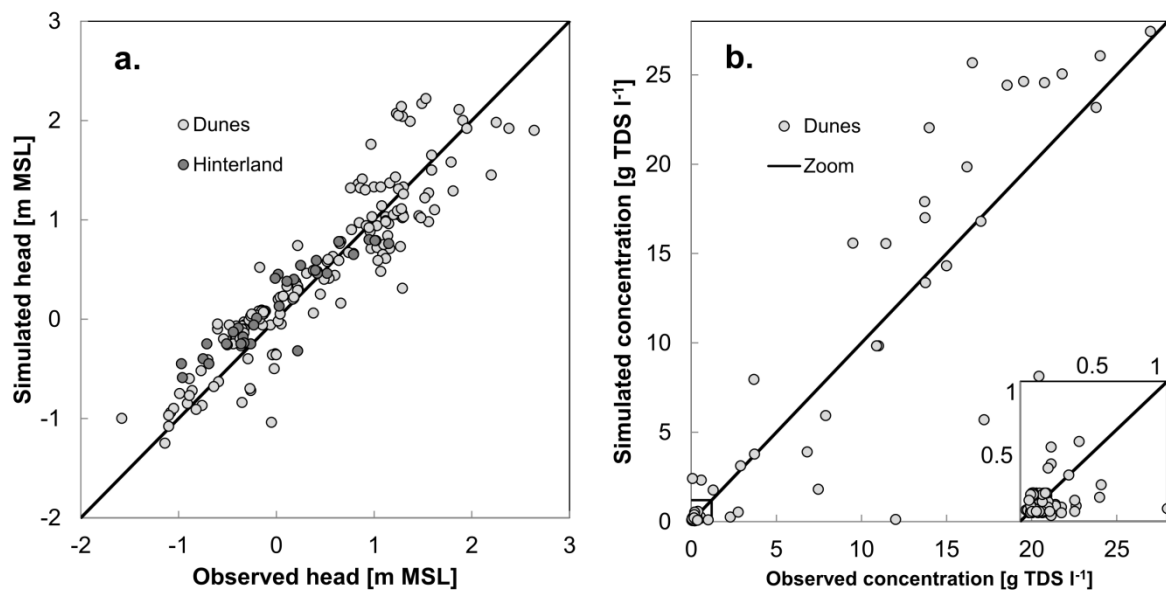


**Fig. 5.** Simulation of historical sea-level rise (black line) and groundwater extraction (blue) in the period 1810 – 2010; dashed lines indicate estimates vertical grey lines refer to stress periods (CBS et al., 2013).

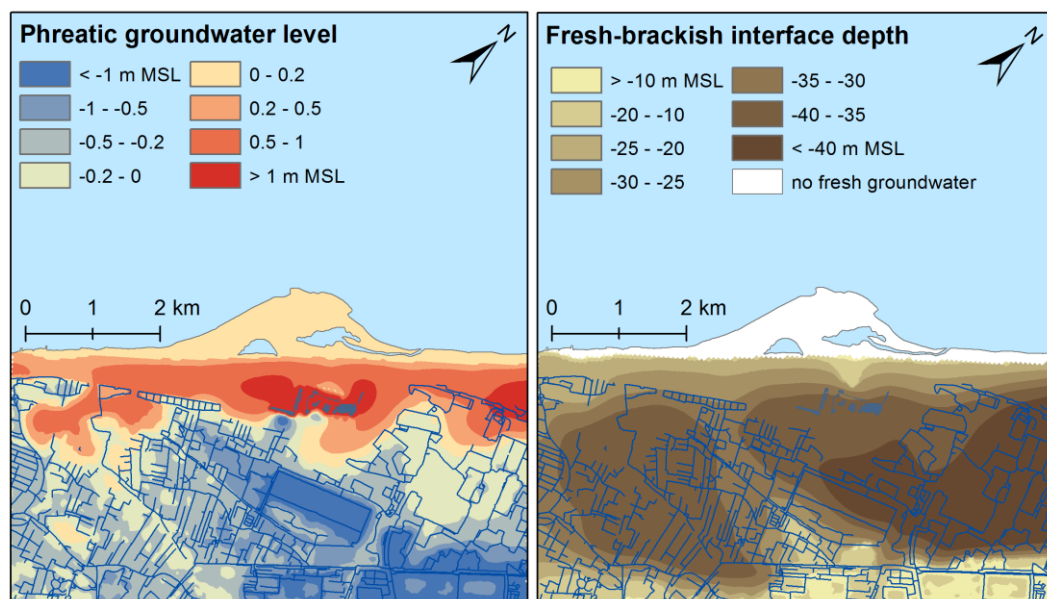




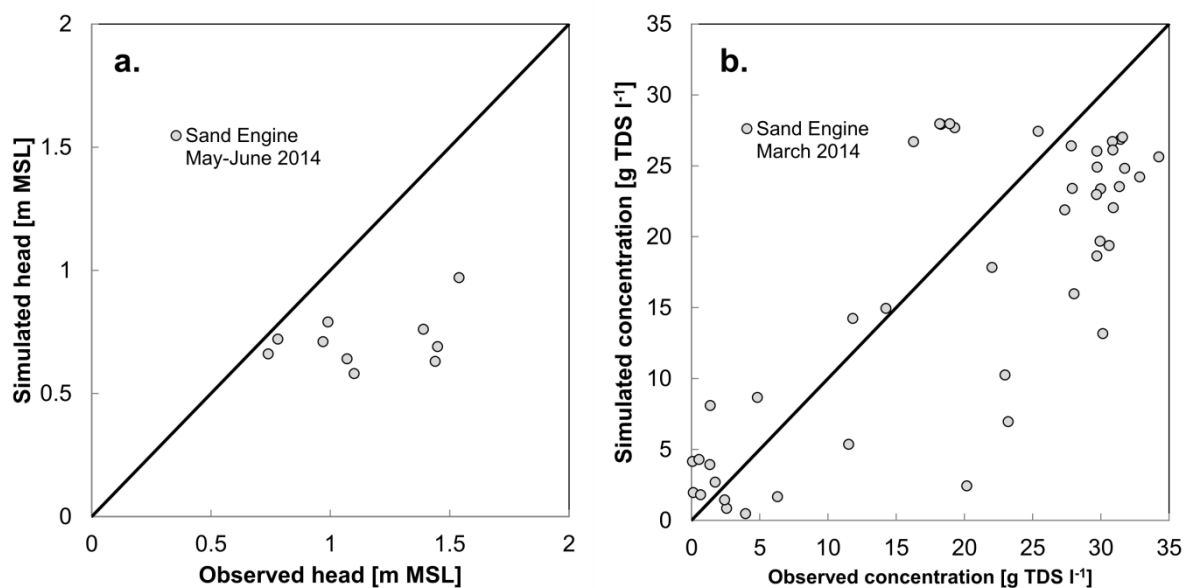
**Fig. 6.** Simulated morphological development of the Sand Engine from 2011 to 2050, illustrated by contour maps with the terrain elevation (m MSL)



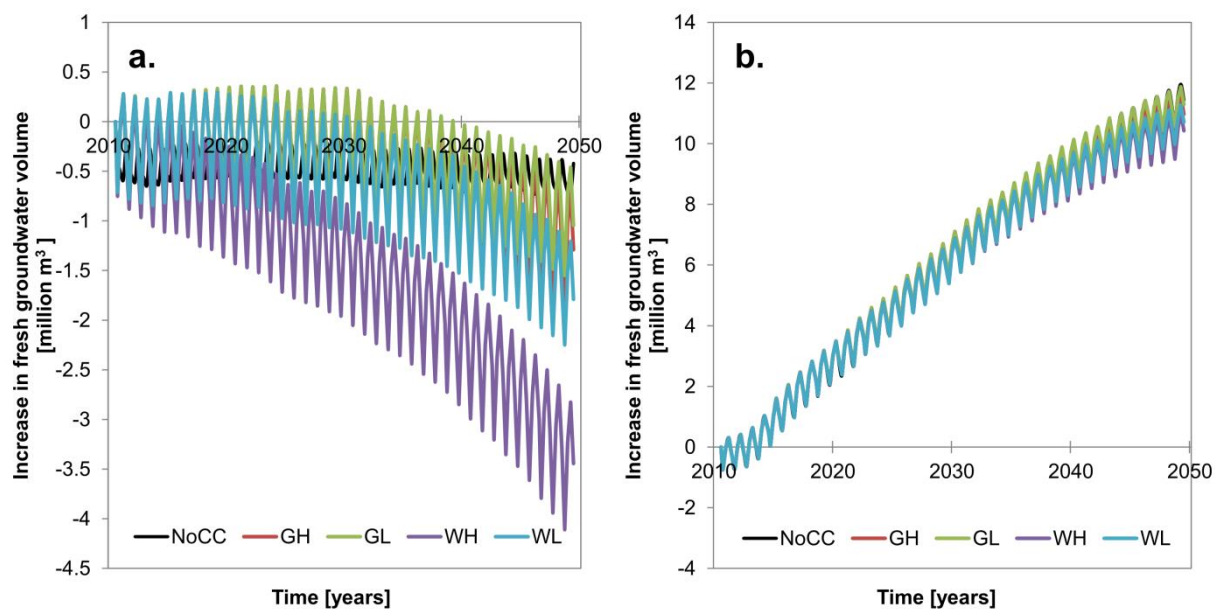
**Fig. 7.** Comparison of observed and simulated heads (a) and concentration (b)



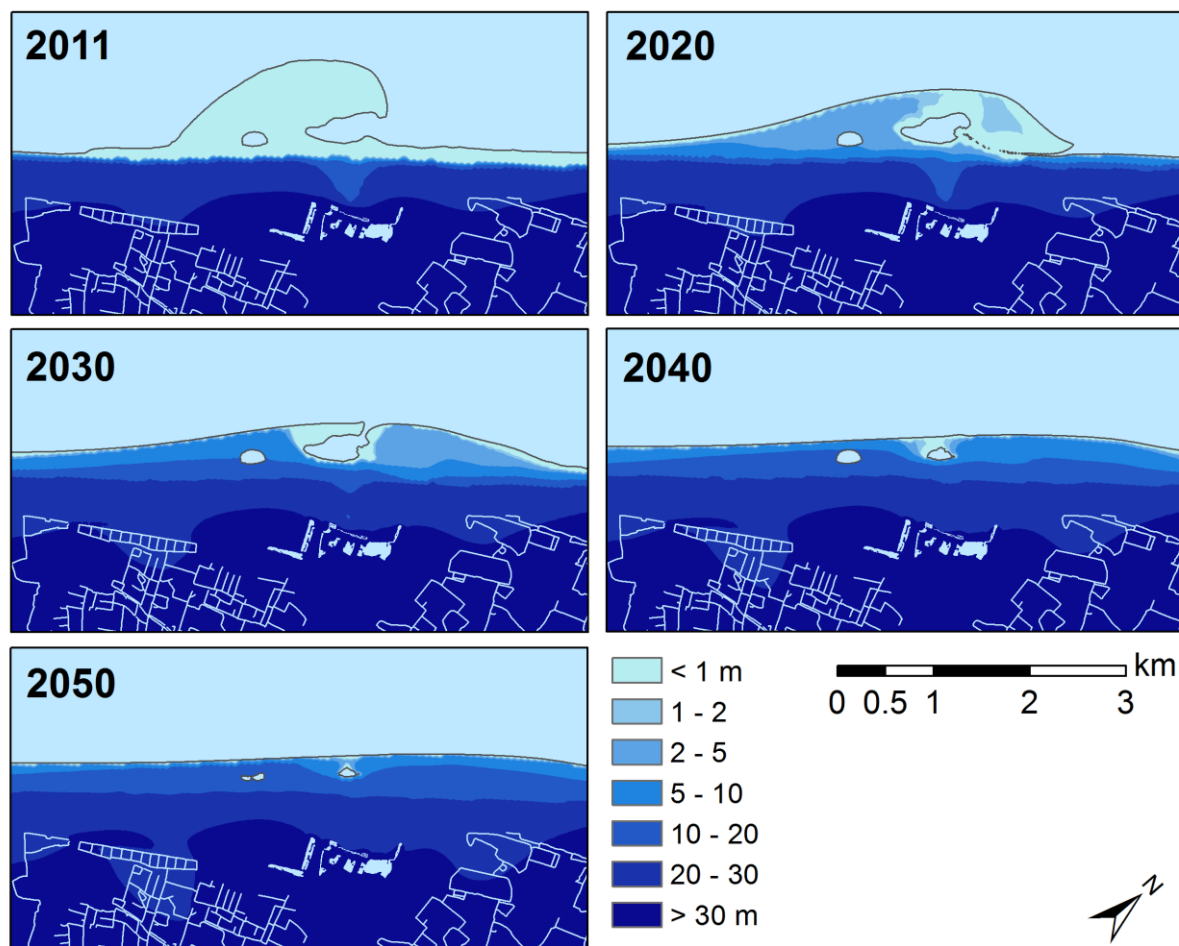
**Fig. 8.** Phreatic groundwater level (left) and fresh-brackish interface depth (right) after calibration



**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



**Fig. 11.** Thickness of fresh groundwater [m] in reference scenario near the Sand Engine from 2011 - 2050