Modelling the Climate Change Impact on Seawater Intrusion in the Coastal Aquifer of Bremerhaven, North Germany

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ABSTRACT
Climate change is expected to induce sea level rise in the German Bight, which is part of the North Sea, Germany. Climate change may also modify river discharge of the river Weser flowing into the German Bight, which will alter both pressure and salinity distributions in the German Bight. To study the long-term interaction between sea level rise, discharge variations, and coastal aquifer flow dynamics, a three-dimensional saltwater intrusion model was designed using the fully coupled surface-subsurface numerical model HydroGeoSphere. The model simulates the coastal aquifer as an integral system considering complexities such as: (i) hydrodynamic factors (e.g. tidal fluctuations, variable-density flow, irregular land surface, boundary conditions), and (ii) anthropogenic factors (e.g. dyke, drainage canals, gates). The model simulates a real case of tidal activity for the period from April-08 to April-22 2009. In addition, three climate change scenarios are simulated until the year 2100 where the seaside boundary condition is obtained from an external hydrodynamic model: (i) mean sea level rise (MSLR) of 1 m, (ii) decrease of river Weser discharge (yearly average) from 326 $m^3 s^{-1}$ to 200 $m^3 s^{-1}$, and (iii) increase of river Weser discharge from 326 $m^3 s^{-1}$ to 2000 $m^3 s^{-1}$. Results demonstrate that the position of the seawater-freshwater interface as well as drainage discharge will be affected by climate change. The obtained results are useful for coastal engineering practices and drinking water resource management.

Keywords: seawater intrusion, climate change, coupled approach

INTRODUCTION

The German Bight, as part of the North Sea, has shown a MSLR of about 20 cm during the last 100 years. The river Weser discharges into the German Bight. That river Weser estuary is heavily influenced by the tides. Altered tidal dynamics is also expected due to the MSLR (Pickering et al., 2012). Climate change also leads to the change of river discharge from hinterland (Huang et al., 2013) and therefore the salinity of the estuary. Those processes change the sea level or salinity of the estuary, and consequently influence the seawater intrusion to the coastal aquifer belonging to the estuary. Yang et al. (2013) numerically simulated two-dimensional coastal flow dynamics, assuming a fully coupled surface-subsurface approach of the coastal aquifer Unterweser, accounting for all processes relevant to coastal flow dynamics. Zorndt and Zhang (2013) investigated the impact of climate change and tidal activity on hydrodynamics and salinities in the river Weser and its estuary using SELFE, which is a semi-implicit Eulerian-Lagrangian finite-element model for hydrodynamic cross-scale ocean circulation (Zhang and Baptista, 2008).

The aquifer under investigation has an area of around 108 km^2. The west boundary contacts to the river Weser estuary. Flow and transport boundary conditions are obtained from results provided by Zorndt and Zhang (2013). The inland is protected by a dyke along the shoreline. Drainage canals drain inland water via two outlet gates through the dyke to the estuary. The operation of the gates is tide-dependent and one-way, which means that seaward water flow is allowed during low-tide, but during high-tide, landward flow is inhibited and the gates are closed.

Using the fully coupled surface-subsurface approach of the numerical model HydroGeoSphere (Therrien et al. 2010), objectives of this study are: (i) to apply the coupled surface-subsurface HydroGeoSphere model to the 3D coastal aquifer considering hydrodynamic factors (e.g. tides) and anthropogenic factors (e.g. dyke, drainage canals), and (ii) to use the 3D model to predict and evaluate seawater intrusion effects on groundwater resources under climate change. The results of this study are potentially important for coastal engineering, protection practice of coastal infrastructure, and coastal aquifer water management.

MATHEMATICAL MODEL

HydroGeoSphere is a 3D numerical model describing fully-integrated variably-saturated subsurface and surface flow and variable-density solute transport. HydroGeoSphere uses the diffusive-wave approximation of the St. Venant equation for surface water flow. In order to represent the drainage canals, HydroGeoSphere is adapted to include a 1D canal domain, which is composed by 1D segments. Flow and transport in the canal domain share the same equations with the 2D surface domain, which are the diffusive-wave approximation of the St. Venant equation for flow and the advective-dispersive-diffusive transport equation. The one-way canal water flow through the gates is achieved by monitoring the hydraulic gradients at the gates.

SIMULATION AND RESULTS

In this study, the subsurface domain is discretized by vertically oriented 3D prisms, the surface domain is discretized by 2D triangular faces, and the canal domain is discretized by 1D segments. Parameter values are chosen from previous work for the investigated site (Yang et al., 2013). Time-variable heads and salinity during tidal activity are prescribed to the sea side boundary. Recharge is prescribed to the land surface. The model firstly ran for the year 2009 to reach a steady state for flow and transport, using the average sea levels and salinity of the year 2009. The steady state results of the year 2009 were calibrated using 111 groundwater level measurements. The modelling shows good fit between observed and simulated groundwater levels after calibration with PEST. The calibrated results were used as initial conditions for the following three climate change scenarios: (i) MSLR of 1 m, (ii) decrease of river Weser discharge (yearly average) from 326 $m^3\ s^{-1}$ to 200 $m^3\ s^{-1}$, and (iii) increase of river Weser discharge from 326 $m^3\ s^{-1}$ to 2000 $m^3\ s^{-1}$.

Result 1. Change of groundwater table

The simulated results show that 1 m of MSLR causes a groundwater table rise of 50 cm for most of the aquifer. Decrease of the river Weser discharge to 200 $m^3\ s^{-1}$ has relative little to no effect on the groundwater table, while increasing the river Weser discharge to 2000 $m^3\ s^{-1}$ causes 10 cm decrease of groundwater table for most of the land area because larger discharge of freshwater into the Weser estuary leads to a decrease of water pressure in the estuary. As a consequence of dropping pressure, subsurficial flow rates into the estuary increase and, hence, the groundwater table drops.

Result 2. Change of salinity

The simulated results (Figure 1) show that 1 m of MSLR results in about 200 m advance of the contaminated area in the deeper aquifer. Decrease of the river Weser discharge to 200 m^3 s^{-1} has no significant effect on the contaminated aquifer area, while, increasing the river Weser discharge to 2000 m^3 s^{-1} causes about 1400 m retreat of contaminated area in deeper aquifer.

Result 3. Change of discharge rates at gates

Simulated results (Figure 2) indicate that about 150% increase of discharge rate will result from 1 m of MSLR, and 60% of decrease of discharge rate will result from the increase of the river Weser discharge to 2000 m^3 s^{-1}. Decreasing the river Weser discharge to 200 m^3 s^{-1} has not significant effect on changing the discharge rate.

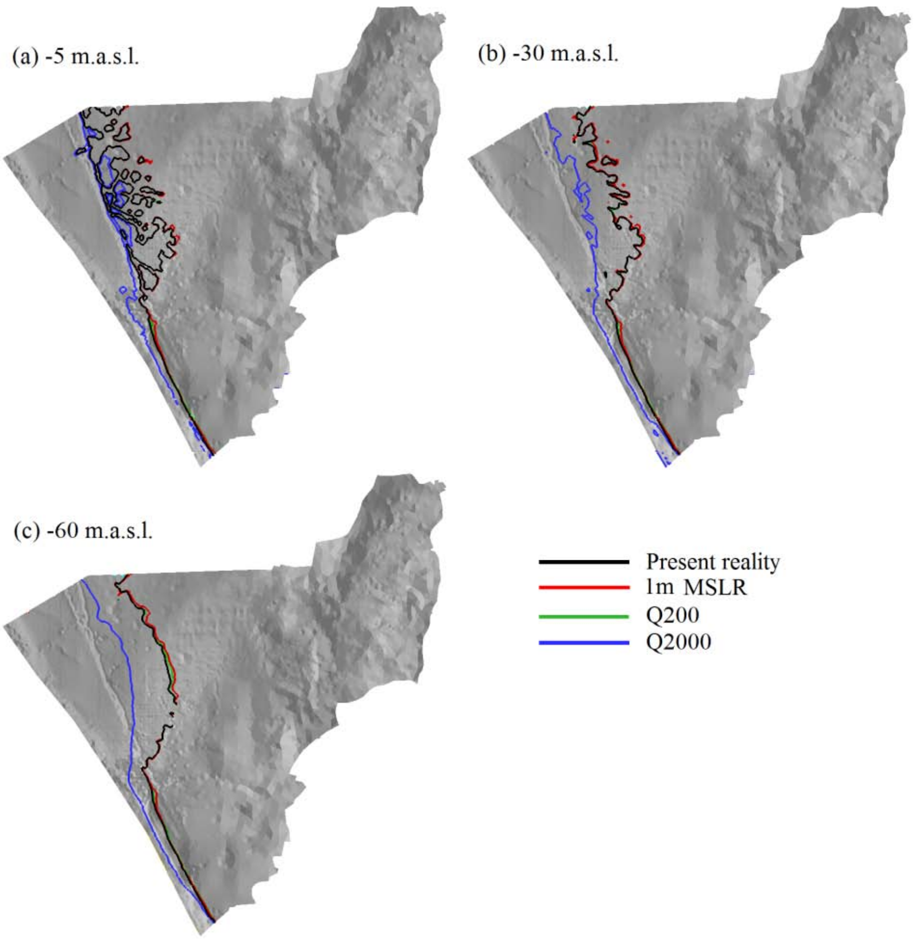

Figure 1. The iso-salinity lines of salinity = 0.671 PUS (drinking water standard) for each climate change scenario at different aquifer depths. For a colored figure please refer to an electronic version.

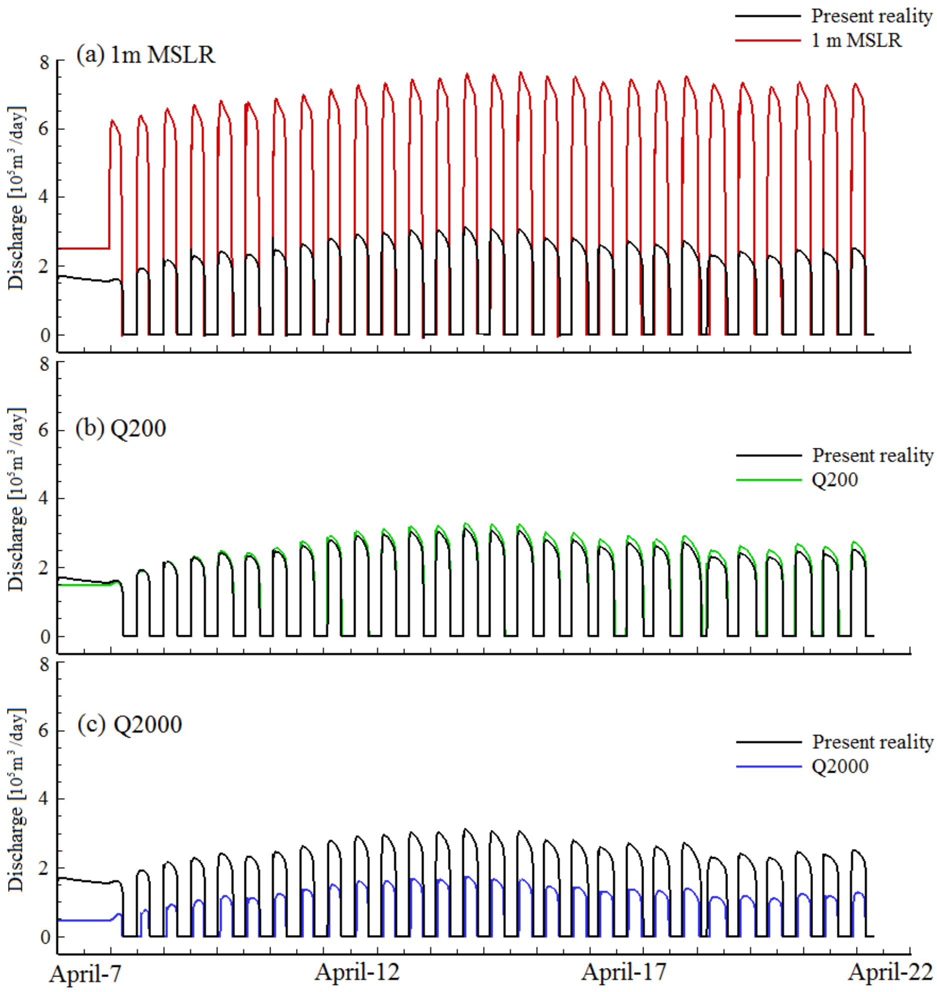

Figure 2. Comparison of the discharge rate at the south gate between "present reality" and each climate change scenario. For a colored figure please refer to an electronic version.

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