Characterization of a regional coastal zone aquifer using an interdisciplinary approach – an example from Weser-Elbe region, Lower Saxony, Germany

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ABSTRACT

In this study, interdisciplinary approaches are considered to characterize the coastal zone aquifer of the Elbe-Weser region in the North of Lower Saxony, Germany. Geological, hydrogeological, geochemical and geophysical information have been considered to analyze the current status of the aquifers. All the information collectively states that the salinity distribution in the subsurface is heterogeneous both horizontally and vertically. Early age flooding also contributed to this heterogeneity. No general classification of groundwater quality (according to some piper diagrams) could be identified. Helicopter-borne electromagnetic data clearly show the presence of freshwater reserves below the sea near the west coast. Groundwater recharge largely happens in the moraine ridges (west side of the area) where both the surface elevation and the groundwater level are high. Consequently, submarine groundwater discharge occurs from the same place. All these information will facilitate to develop the planned density driven groundwater flow and transport model for the study area.

INTRODUCTION

Alike some other countries in the world, the impacts due to climate change in Germany have been investigated by several researchers (e.g., Brasseur et al. 2017; Frondel et al. 2017; Rannow et al. 2010) and institutions (e.g., Climate Service Center Germany (GERICS); Potsdam institute for climate change impact research (PIK)). According to the Umweltbundesamt (2015), the yearly average temperature in Germany may increase by 0.5°C and more for the period of 2021-2050. The precipitation in future might decrease during June to August and increase during December to February. The northern half of Germany, surrounded by several rivers (Elbe, Weser, Ems etc.) is considered to be the most potentially affected area (Umweltbundesamt 2015). The coastal zone of the northern part of Lower Saxony is vulnerable to the potential adverse impacts (such as sea level rise) (Sterr 2008) due to climate change. The drinking and industrial water supply and agriculture largely depend on the fresh groundwater reserve at this region. Understanding the impact of climate change on the groundwater reserve is very much essential at this place. Efficient management of available freshwater reserves in a coastal aquifer needs proper characterization of the groundwater catchment. For better understanding and detailed characterization of coastal groundwater aquifers, several scientific and technical issues should be investigated intensively. An efficient integration between traditional and innovative methods/techniques can facilitate the aquifer characterization enormously. This study applies an interdisciplinary approach to characterize the coastal zone aquifer in Northern Germany.

Background and objective

This study is a part of an ongoing EU financed project - TOPSOIL (2015-2020). TOPSOIL project (www.topsoil.eu) focuses to develop diverse methods and techniques to monitor, model and improve the management of the subsurface. Sixteen pilot projects from five EU countries such as Belgium, Denmark, the UK, Germany and the Netherlands were selected to develop the approaches jointly. These will help to predict climate change impacts, including urban flooding, saltwater intrusion, groundwater quality and available quantity, as well as the impact on changing near surface soil conditions. The main research focus of this pilot area is to assess the salt water and fresh water dynamics in the aquifer that is important for estimating future fresh groundwater reserve. Hence, development of a density driven groundwater flow and transport model have been planned. This paper reports about the characterization of the groundwater aquifers that will facilitate the development of groundwater model. For the aquifer characterization, an interdisciplinary approach has been formulated. This paper also briefly demonstrates how the interdisciplinary approach supports efficiently the catchment characterization.

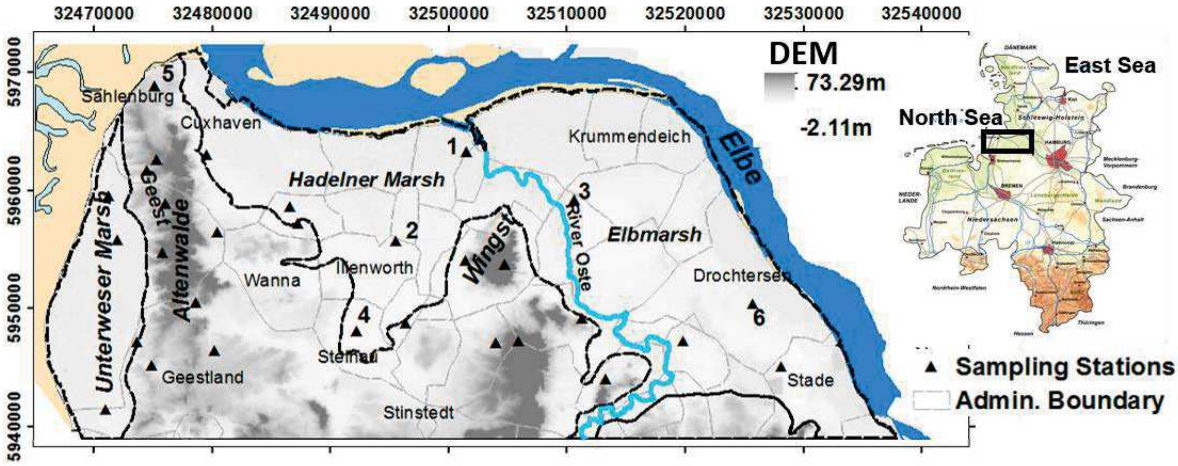

Figure 1. Study area showing topography, major rivers (Elbe and Oste) and groundwater (GW) quality sampling stations for Figure 4.

Study area

The study area (ca. 1700 km^2) is surrounded by the North Sea in the North and the West (ca. 81 km coastline). Elbe River constitutes the east boundary with 35 km long reach. Another major river within the area is the Oste. The topography is relatively flat with some hills (Geest) in the West and the South (ranges between -2.11 m ASL (above sea level) to 73.3 m ASL). The study area is between the moraine ridges of Altenwalde (W) and the River Elbe (E) including the Hadelner Marsh that is widely used for agriculture. It is characterized through low groundwater recharge (ranges between 51 mm/year and 150 mm/year) with saltwater intrusion in the marsh area and high groundwater recharge (ranges between 101 mm/year and 400 mm/year) with a high water table (>10 m ASL) (NIBIS® Kartenserver, 2014a) in the moraine ridges. Most of the recharge occurs during November to January.

The geology of Elbe-Weser region is characterized by Quaternary glacial and interglacial periods. During the Elsterian and the Saalian glaciation, the glacial maximum reached the Central German Uplands, thus the Elbe-Weser region was completely covered by ice several times (Ehlers et al. 2011). During this time massive glaciofluvial sediment bodies were deposited, mainly consisting of sand and gravel. Besides, during the Elsterian glaciation tunnel valleys up to 500 m depth were formed by subglacial erosion and filled predominantly by glaciofluvial sand. The valleys are covered by so called 'Lauenburger Clay' (Kuster and Meyer 1979). Due to sea level rise in the following Eem interglacial, the sea extended into the region bounded by the moraine ridges of Land Hadeln (Höfle et al. 1985). The maximum of the Weichselian glaciation did not reach the Elbe-Weser region (Streif and Köster 1978), so that the area is only influenced by proglacial processes. In the Holocene, the brackish-marine sediments of the marshlands were deposited (Streif and Köster 1978).

Pleistocene, and partly Pliocene sand and gravel form the upper aquifer of the Elbe-Weser region with local variations. The uppermost groundwater storage in the Elbmarsh consists of Weichselian fluviatile sand and glaciofluvial sand of the Drenthe glacial (Saalian). In the Unterweser Marsh and the Geest area, Pleistocene sand forms the upper aquifer. The tunnel valley aquifer consists of Elsterian glaciofluvial sediments. The hydraulic contact between the tunnel valley aquifer and the surrounding Pliocene sand is discontinuous. The Lauenburger Clay is the most important separator in the region between the different aquifers (Elbracht et al. 2016). Hydraulic conductivity values at the region ranges between 10^{-4} and 10^{-3} m/s (Reutter 2011). Cohesive Holocene sediments in the marshlands work as a protective layer for the groundwater, whereas the protection potential of groundwater in the moraine ridges is very low. Groundwater in marshlands has a high salinity in contrast to the moraine ridges where groundwater is fresh (Elbracht et al. 2016).

METHODS

In this study, an interdisciplinary approach has been adopted to characterize the coastal groundwater catchment. This interdisciplinary approach combines several geological, geochemical and geophysical analysis of secondary and primary data. Though data from several geophysical methods are available at the study area, in this study we have limited our analysis to only helicopter-borne electromagnetic (HEM) data (Siemon et al. 2014) to map the horizontal and vertical variability of salinity. Literature and lithological information have been considered to analyze the aquifer structures of the study area. The role of geochemical information is to determine the extent of groundwater pollution and to analyze the salinization process. All these information can be used for density driven groundwater flow and transport model calibration and validation. Finally, this model will be used for the development of an adaptation strategy for climate change, agricultural water management, planning for groundwater withdrawal strategy etc.

HEM data have been obtained from the Federal Institute for Geosciences and Natural Resources, (BGR), Germany. Geological, and hydrogeological information have been taken from the archive of the Geological Survey of Lower Saxony (LBEG), Germany. LBEG's database of mGROWA (Herrmann et al. 2013) provided useful information about the spatial and temporal variation of recharge. Lower Saxony department of water, coastal and nature conservation (NLWKN), Germany, provided information on groundwater level and groundwater quality.

RESULTS

Geophysical investigation of the study area

HEM data provides information about the resistivity of the subsurface that can be interpreted for salinity distribution. Low resistivity values corresponds to saline to brackish water or clay and high resistivity values corresponds to fresh water or sand (Siemon et al. 2018). Figure 2 shows spatial distribution of resistivity at 35 to 40 m depth from the surface. Saline water already occurs in large areas of the north-eastern part of the groundwater catchment. From Figure 2 it is clear that horizontal distribution of salinity is not uniform and it does not correlate with the coastline. Resistivity maps of other depths confirm the inhomogeneity in vertical salinity distribution as well. The occurrence of low resistivities from the North Sea and the Elbe River towards the inland correlates with the early age flooding pattern (Figure 2).

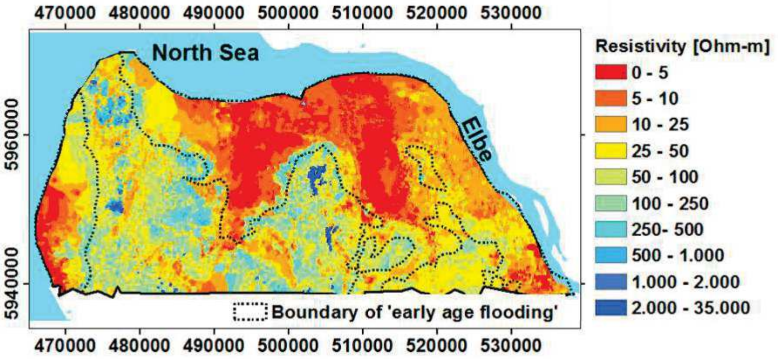

Figure 2. Resistivity distribution at 35 m to 40 m depth. Dotted line showed the boundary of 'early age flooding' (digitised after *NIBIS® Kartenserver 2014b).*

Geochemical analysis

Figure 3 shows a piper trilinear diagram of major anions (Ca^{+2}, Mg^{+2}, Na^{+}, K^{+}) and cations (HCO$_3^{-}$, SO$_4^{-2}$, Cl$^{-,}$ NO$_3^{-}$) in groundwater at three different depths from the surface (year 2014). The diagram indicates that the groundwater quality in the study area is vertically heterogeneous. Piper diagrams from other year's data also show the similar pattern.

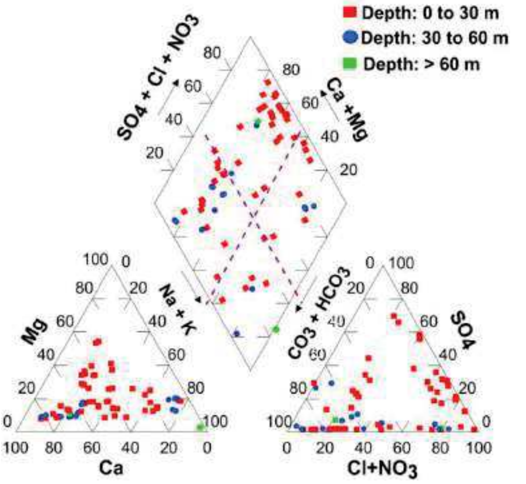

Figure 3. Piper diagram representing the geochemical evolution of groundwater.

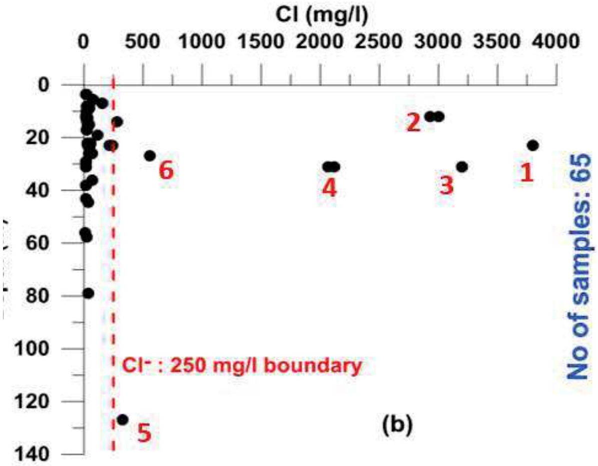

Figure 4. Chloride concentration across the depth of the aquifers (data source: NLWKN).

Not only the vertical distribution but also the horizontal distribution of GW quality is heterogeneous in the study area. Chloride concentration from 67 monitoring wells have been analyzed to observe the chloride distribution and corresponding groundwater pollution due to salinity in the area (Figure 4). In general, the groundwater quality is suitable for drinking purpose. Only at some places, the chloride values exceeded the WHO limit (250 mg/l). It is to be noted that the north-eastern part of the aquifer does not have any monitoring station, hence the saline groundwater has not been represented in the figure. In the Figure 4, some monitoring stations are marked in red color and numbered, who show relatively high chloride content in the groundwater. Stations 1 (at Neuhäuserfelde), 3 (at Moorstrich) and 6 (at Drochtersen) are close to the coast, River Oste and River Elbe, respectively, and the chloride contents are above WHO limit. Stations 2 (at Ilienworth North) and 4 (at Steinau) are relatively far from the coastline and the major rivers, but they show high chloride content within a shallow depth (ranges between 10 m and 36 m below surface). Though station 5 (at Sahlenburg) is close to the coast, it shows relatively low (330 mg/l) chloride content even at ca. 125 m depth. Historical data indicates a slight increase in salinity at this station: from 290 mg/l in 1997 to 330 mg/l in 2014.

Submarine groundwater discharge and freshwater reserves below the sea

Although SDG at the North Sea is reported by some authors (e.g. Moosdorf and Oehler 2017), very few scientific information is available. In this study, geophysical and groundwater level data were used to study the SDG and freshwater reserves close to the North Sea.

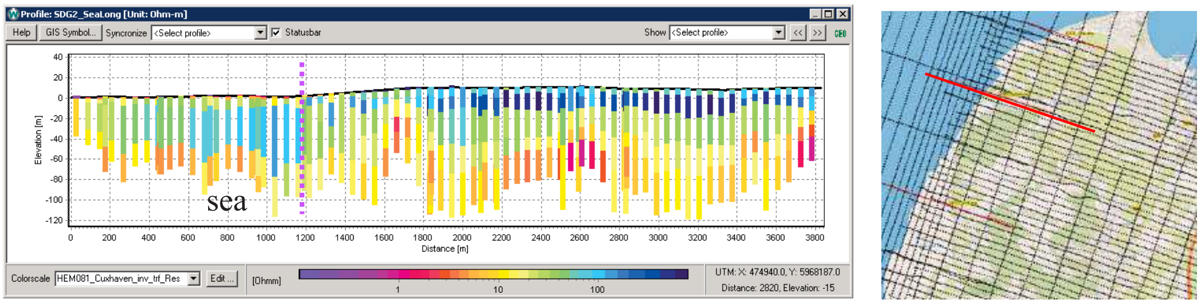

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Figure 5. Fresh groundwater reserve near the coastline of the study area. Left: 2D cross sectional profile, right: position of the profile.

Figure 5 gives a clear indication of freshwater reserves near the western coastline of the study area. Spatial maps of resistivity distribution and several vertical cross-sections (not shown here) show that the horizontal and vertical distribution of freshwater reserve is not uniform. Groundwater level at the Geest area (near the west coast) is relatively high (<10 m ASL) and the groundwater gradients allows a substantial amount of water to flow towards the sea contributing to the global SDG.

DISCUSSIONS

The geological and hydrological condition of the area is complex. Representation of geological structures and hydrogeological properties in the groundwater model needs careful consideration and some simplifications (e.g., drainage canals). The salinity distribution is not uniform both horizontally and vertically. As groundwater quality is not uniform throughout the aquifers, transport model simulation will be complex. Early age flooding also contributed to the heterogeneous salinity distribution within a shallow depth. The high chloride content at some stations represents the infiltration of saline water due to early age flooding. SDG will contribute a vital role in the planning process of groundwater artificial recharge at the Geest hills as injection of water into the aquifer might change groundwater flow pattern at the place. Therefore, site selection will be an important point in order to avoid loss of freshwater. The planned groundwater model will be helpful for the selection of managed aquifer recharge injection and recovery location at the region.

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