Subsurface characterization of a freshwater lens barrier island using geological, geophysical, geochemical and hydrological data - case study Borkum, Germany

Borkum Island, Germany

A part of the Borkum Island 10 days after Kyrill in 2007

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Interdisciplinary approach for subsurface characterization

The dynamics of a freshwater lens below barrier islands largely depends on the interplay of groundwater abstraction, recharge, salt water intrusion and the hydrogeochemical character of the subsurface. Therefore, efficient withdrawal and management of fresh groundwater resources at these islands requires a comprehensive understanding of hydrological, hydrogeological and hydrochemical characteristics of the subsurface and associated flow and transport processes. This study investigates the groundwater catchment of the barrier island of Borkum, Germany, in an integrated way taking the above mentioned disciplines into consideration (Figure 1). The investigations were performed within the scope of the ***CLIWAT project, financed by the European Union in 2008-2012***. During the project period several field campaigns were done conducting pump tests, borehole drilling, direct push tests, geophysical investigations, groundwater and sediment sampling, flow measurements etc. This study compiles and analyze related information to understand the aquifer characteristics and its influence on the freshwater–saltwater interface.

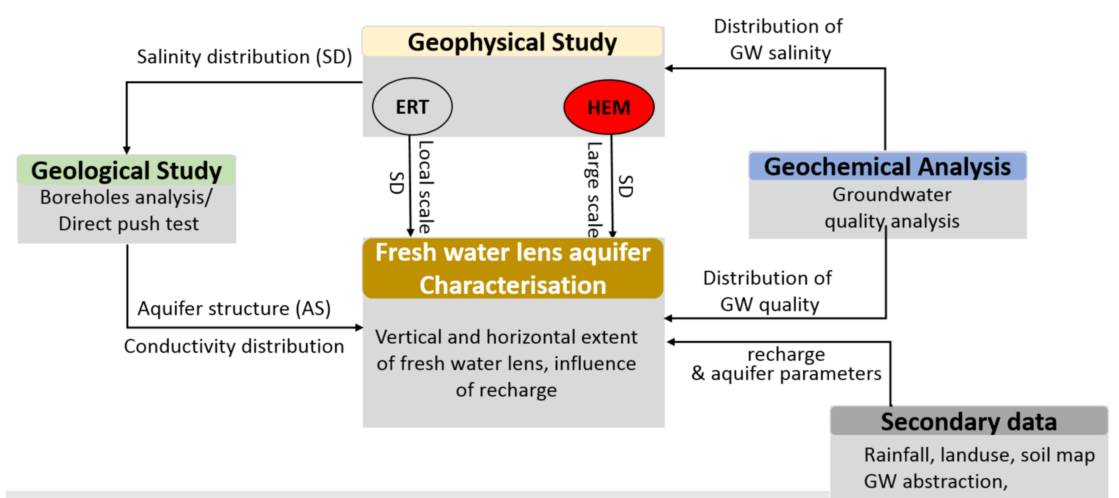

Figure 1: Interdisciplinary approach to understand the fresh water lens aquifer dynamics in Borkum Island

Direct push (DP) tests and Electrical Resistance Tomography (ERT)

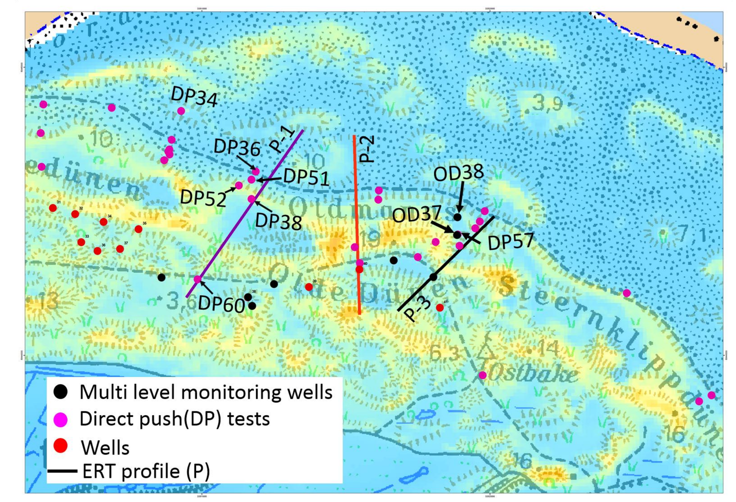

Figure 5: Locations of direct push tests and ERT profiles

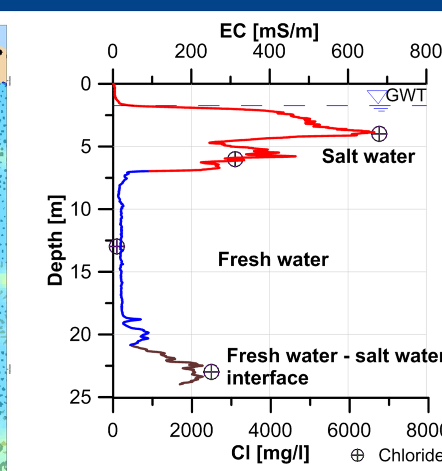

Figure 6: EC and Chloride (Cl) distribution at DP 34. GWT= Groundwater Table

In January 2007, the cyclone Kyrill hit the Northern part of Germany and some parts of the island were flooded. To investigate the impact of that flooding on the fresh water lenses 41 direct push tests and three 2D ERT profiles were conducted (Figure 5). Figure 6 presents a typical DP test showing the Electrical conductivity (EC) distribution over 25 m depth. Three distinct layers, i.e. salt water at the top, fresh water reserve in the middle and the mixing zone at the bottom (20 m to 25 m depth) can be clearly seen.

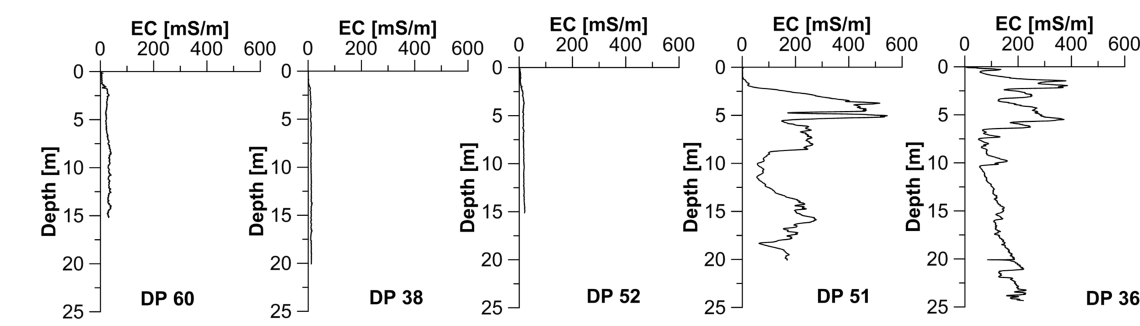

Figure 7: Electrical conductivity (EC) at five DP test points near ERT profile 1 (P-1). DP 60 and DP 38 are close to the P-1. The distances of DP 52, DP 51 and DP 36 from P-1 are 73 m, 49 m and 52 m

Figure 7 shows the EC distribution in 5 DP points along ERT profile 1. It indicates that at DP 36 and DP 51, the near subsurface is already affected by salt water. The other 3 DP tests do not show any indications of the presence of salt water. The chloride concentration at 10 m depth is 1000 mg/l and 50 mg/l for DP 51 and DP 52. The fresh water - salt water interface lies between DP 51 and DP 52. The interface is not sharp (Figure 8). It is to be noted that the DP tests are limited to 25 m depth. So, more deep investigations may be required to determine the vertical limit of fresh water lenses. **A combination of geophysical survey and DP test will provide more information about the interface.**

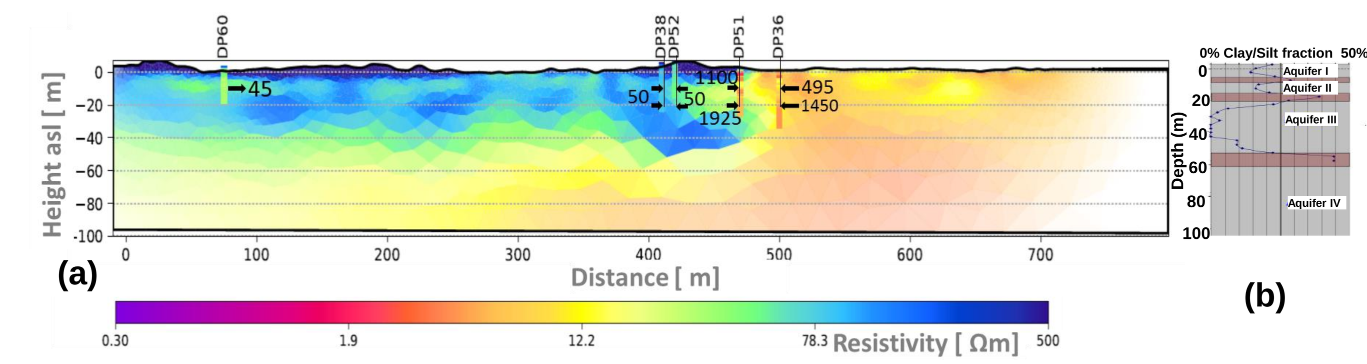

Figure 8: (a) 2D result of ERT profile 1; the numbers inside the profile indicate Cl concentrations in mg/l, (b) statistical evaluation of lithologs and schematic representation of the aquifer up to 100 m (Sulzbacher et al., 2012)

The vertical extent of the freshwater lens is limited to 50 m bsl but in some places it extends up to 70 m (at 220 to 260 m from the left of profile in Figure 8), according to ERT survey. Along the profile, at ca. 10 m depth relatively low resistivity can be seen at some places. This low resistivity values might be due to the presence of silt/clay in the aquifer while Cl concentrations are low (e.g. DP 60). The low resistivity finger at the right side of the freshwater lens is due to presence of salt water, since the measured chloride content at 20 m depth is relatively high. **These analyses indicate that ERT data should be interpreted with lithological information to map salinity distribution.**

Study area - Borkum Island, Germany

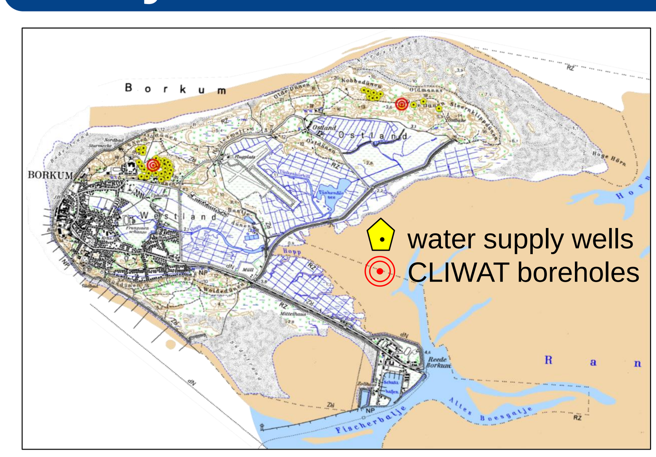

Figure 2: Study area - Borkum Island

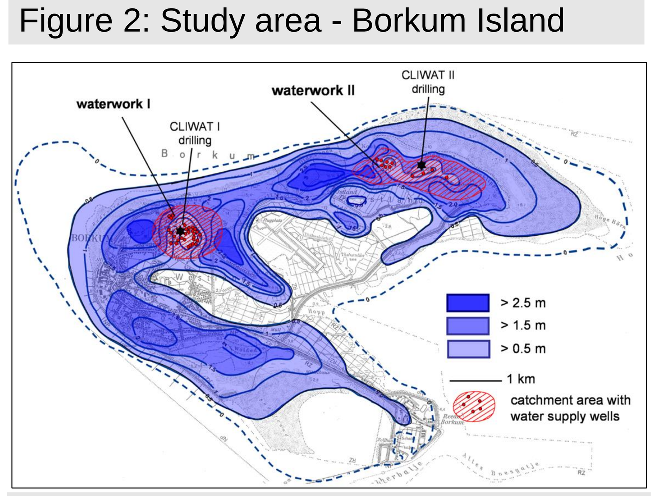

Figure 3: Borkum island with location of WWs and depth to groundwater table (Sulzbacher et al., 2012)

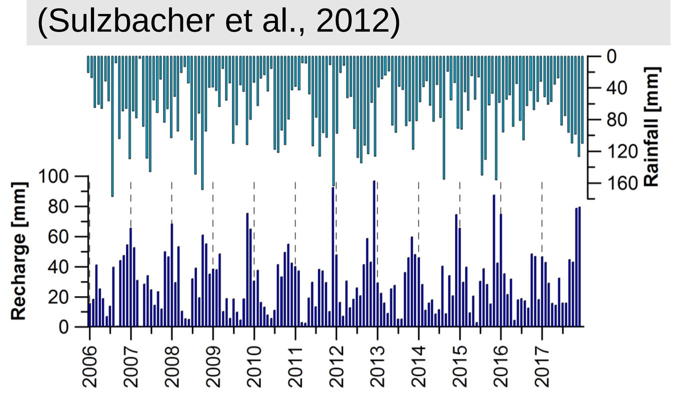

Figure 4. Monthly groundwater recharge and rainfall estimated after the Penman Method

Borkum, a typical barrier island, is the western most of the East Frisian Islands at the North Sea coast of Lower Saxony, Germany. The island consists of mainly dunes towards the ocean side and marshlands towards the land side. In 1934, a dike was built to protect the island from flooding.

- The average elevation of the dune is 4 m with a maximum elevation of 24 m.
- The main feature of this island's hydrogeology is the presence of two freshwater lenses.
- Two waterworks (WW) withdraw water from these lenses and supply water. The maximum permitted abstraction rates are 0.4 Mm^3/year and 0.9 Mm^3/year for WW1 and WW2, respectively (Figure 2).
- The geology of Borkum is characterized by the typical glacial/interglacial sediment sequence of north-western Germany.
- The uppermost sediments of the island consist of fine sand to medium Holocene sand and they are up to 20 m thick. Approx. 20 m below the sea level (bsl) a 2 to 4 m thick glacial till layer acts as an aquitard.
- An aquitard separates the main aquifer into two parts and it is semi-impermeable. The depth of the 2nd aquifer is up to 65 m bsl.
- Groundwater recharge ranges between 325 mm/year and 475 mm/year (Figure 4).
- The groundwater table in the aquifer lies in a very shallow depth (0 to ca. 5 m) and fluctuation is also low (1 to 1.25 m) (Figure 3).
- The hydraulic conductivity of the aquifer varies between $1*10^{-4}$ m/s and $2*10^{-4}$ m/s (Ibenthal, 2014).

Freshwater - Saltwater interface from HEM data

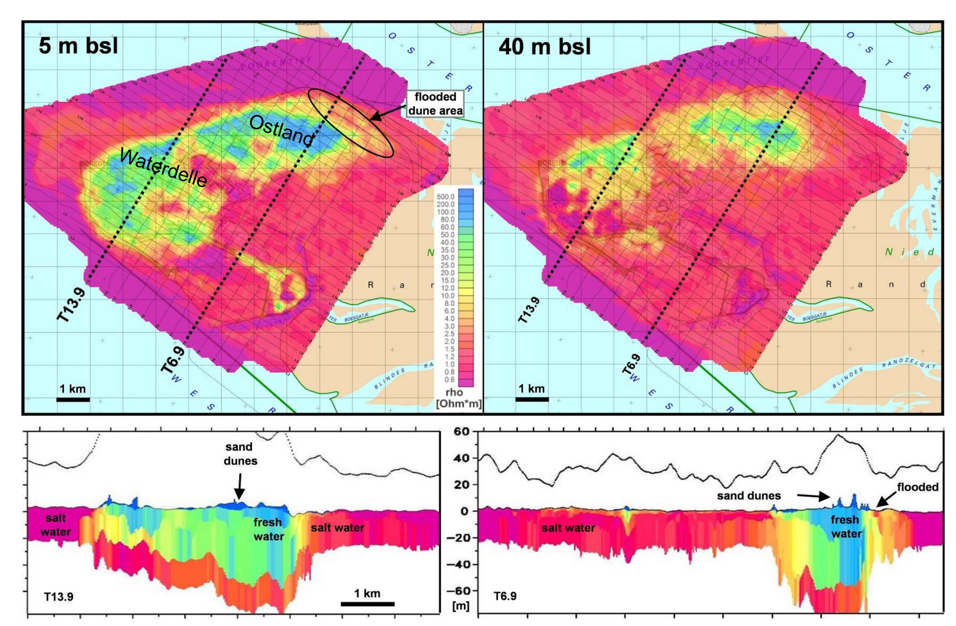

Figure 9: Top: Resistivity (Ωm) maps at different depths derived from a HEM survey, bottom: cross sectional view along transects T13.9 and L6.9

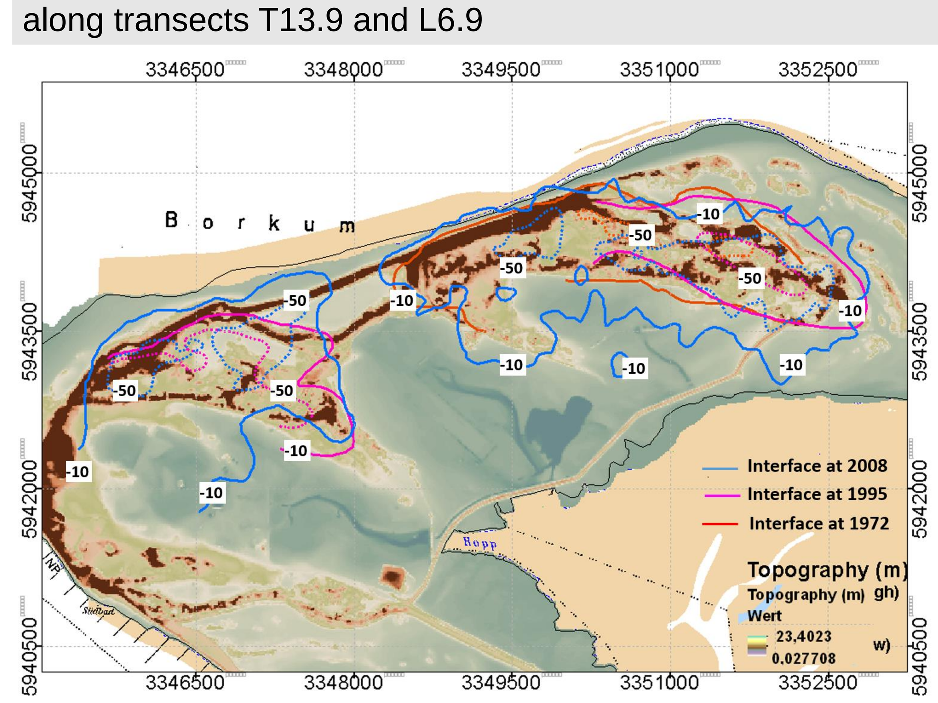

Figure 10: Interface of fresh water-salt water at 10 and 50 m depth measured in 1972, 1995 and 2008 (after Winter 2008)

To investigate the horizontal and vertical extent of fresh water lens, BGR performed a helicopter-borne electromagnetic (HEM) survey in March 2008. Figure 9 (top) gives an excellent overview of the horizontal extent of the fresh water lenses at two different depths. At 5 m bsl, the infiltration of salt water due to flooding in 2007 is clearly visible. It cannot be distinguished at 40 m bsl. Two cross sections (Figure 9, bottom) show the freshwater - saltwater interface over the depth of ca. 50 m. The fresh water lens has an asymmetric shape in the horizontal direction due to geomorphologic outlines. The embedded clay layer between 50 to 60 m bsl might restrict further expansion of freshwater in the vertical direction.

Prior mapping of the extent of the freshwater lens has been performed in the 1970ies and in 1995. Figure 10 shows the interface at 10 m and 50 m depth in three years: 1972,1995 and 2008. The 2008 interface derived from the HEM provides a wider interface that might be due to the extent of coverage of the survey or extension of the interface with time. However, the interface at the west side of the island is almost the same in all three measurements.

Use of HEM data for salinity analysis without the support of lithological information might give a different salinity distribution as both clay and brackish water show low resistivity. Hence, **geological information should be considered together with HEM data.**

Freshwater - Saltwater dynamics (Hydrogeochemistry)

Figure 11 shows the transport of salt water in the vertical direction at location DP 57 in the freshwater lens. Within six months (from Oct 2008 to March 2009), the Cl concentrations in DP 37 and DP 38 reduce sharply at 5 m and 10 m depth but increase at 20 m depth. The salt water at the top mixes with rain water, becomes less saline, flows downwards (due to density gradient and the regional groundwater gradient) and increases the Cl concentrations of the freshwater at the bottom. Similar tendencies can be seen in Figure 11(d) for major anions (SO_4 and Cl) and cations (Ca, Na). Ratios of SO_4, Ca and Na to Cl for a water sample at 5 m depth show a similar signature to that of sea water at the Wadden Sea. It indicates that the salt water at the top layer of DP 57, OD 37 and OD 38 is due to the flooding event in 2007. **With time, the water might have moved further downwards and could stay at the top of the existing bottom of the freshwater lens. Thus, the thickness of the lens might be reduced in some places that should be investigated further.**

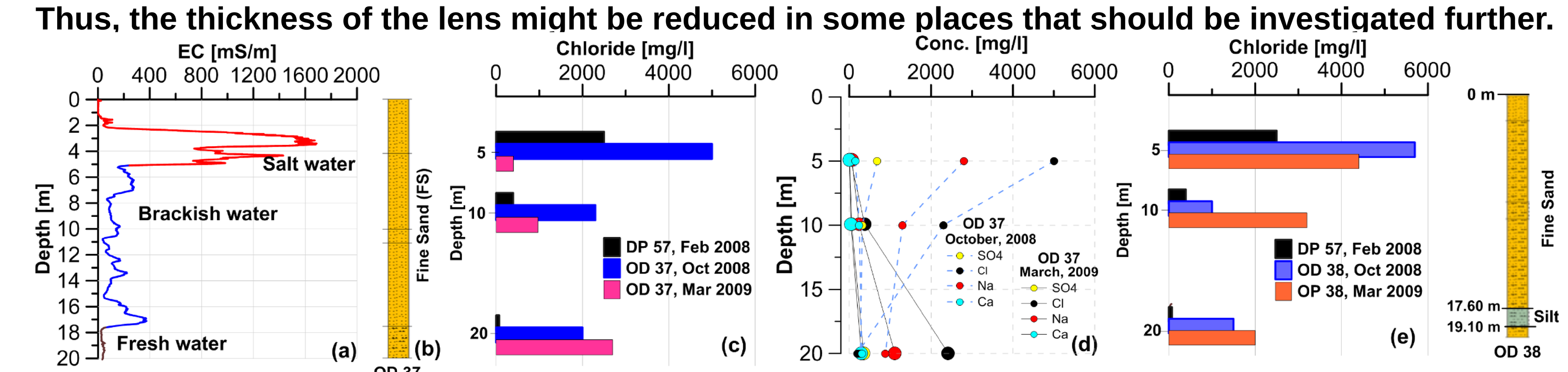

Figure 11: (a) EC distribution below the surface up to 20 m depth obtained from a direct push test: DP 57. (b) lithological profile of OD 37 (2m away from DP 57), (c) transport of salt water with time at OD 37 and DP 57, (d) Sulfate (SO4), Chloride (Cl), Sodium (Na) and Calcium (Ca) concentration at three depths (5 m, 10 m & 20 m) sampled in OD 37 (e) transport of salt water with time at OD 38 and DP 57 (f) Lithological profile of OD 38 (60m away from DP 57)

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Acknowledgements

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