Mapping the fresh-saltwater interface in the coastal zone using high-resolution airborne electromagnetics

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Introduction

A major part of the drinking water in the Netherlands is derived from groundwater stored in coastal and inland aquifers. The water occurs through natural processes, but in some areas artificial infiltration of lake and river water in the coastal sand dunes is necessary to support the demand for clean drinking water in the densely populated country. In fact, artificial infiltration along the Dutch coast has been common practice for decades and is an essential part of the drinking water supply. The sustainability of this approach demands detailed knowledge of the fresh–saltwater balance to avoid salinization of the aquifers. The availability and quality of the groundwater are typically estimated using groundwater models, which can be used to forecast the behaviour of groundwater systems to external stresses, such as climate change. The reliability of groundwater models hinges on measurements such as hydraulic heads, stream flow rates, permeability of the subsurface and in coastal regions the boundary conditions for the coastal edge of the model. Here, a limiting factor is often the lack of offshore data since it is logistically difficult and costly to drill in the seabed.

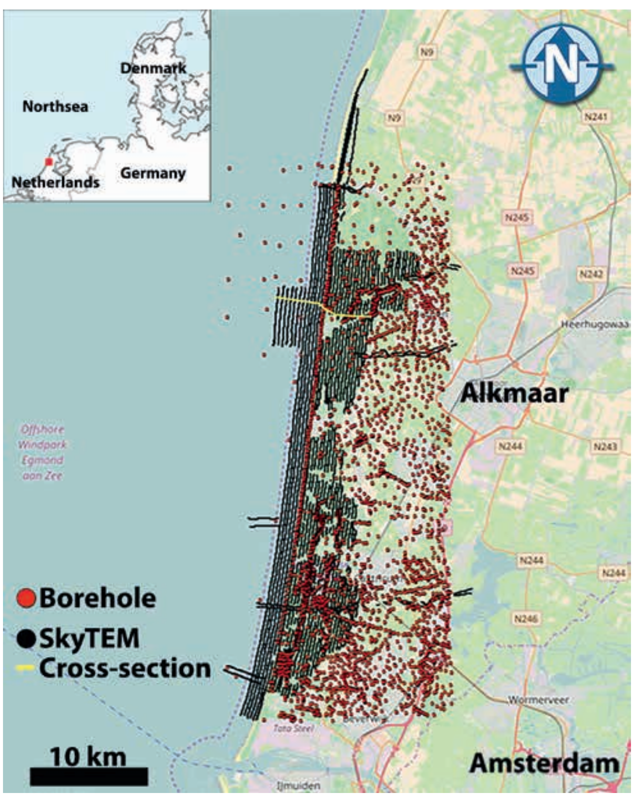

Figure 1 Location of the study site. The black dots are SkyTEM measurements and the red dots are boreholes. The yellow line highlights the location of the cross-section shown in Figure 3.

Airborne electromagnetics are increasingly being used to support groundwater management through high-resolution large-scale mapping of aquifer properties. The method provides strong sensitivity to important hydrogeological units such as the fresh-saltwater interface and clay layers (which often constitute the base of the aquifers). Hence, AEM has been widely used to address issues such as mapping saltwater intrusion (Gunnink et al., 2012; Jørgensen et al., 2012) and aquifer delineation (Chandra et al., 2016; Schamper et al., 2013). One of the key advantages of the method is that it is airborne, allowing areas, which would otherwise be difficult to access, to be mapped in a cost-effective manner. As demonstrated in the present study, the fresh-saltwater interface and coastal boundary conditions of the groundwater model can be determined by combining onshore and offshore airborne electromagnetics.

Study area and methodology

The 156 km^2 study area is located along the Dutch coast west of Alkmaar and approximately 25 km north-west of Amsterdam (Figure 1). The majority of the study area is an area of natural beauty with beaches, 20-30 m high dunes, inland polders and rich fauna and wildlife. However, the area also contains infrastructure such as roads and cables. Groundwater extraction in the area provides drinking water for the two million inhabitants of the North Holland Province. The hydrogeological setting is composed of 50-150 m-thick Holocene and Pleistocene sand deposits,

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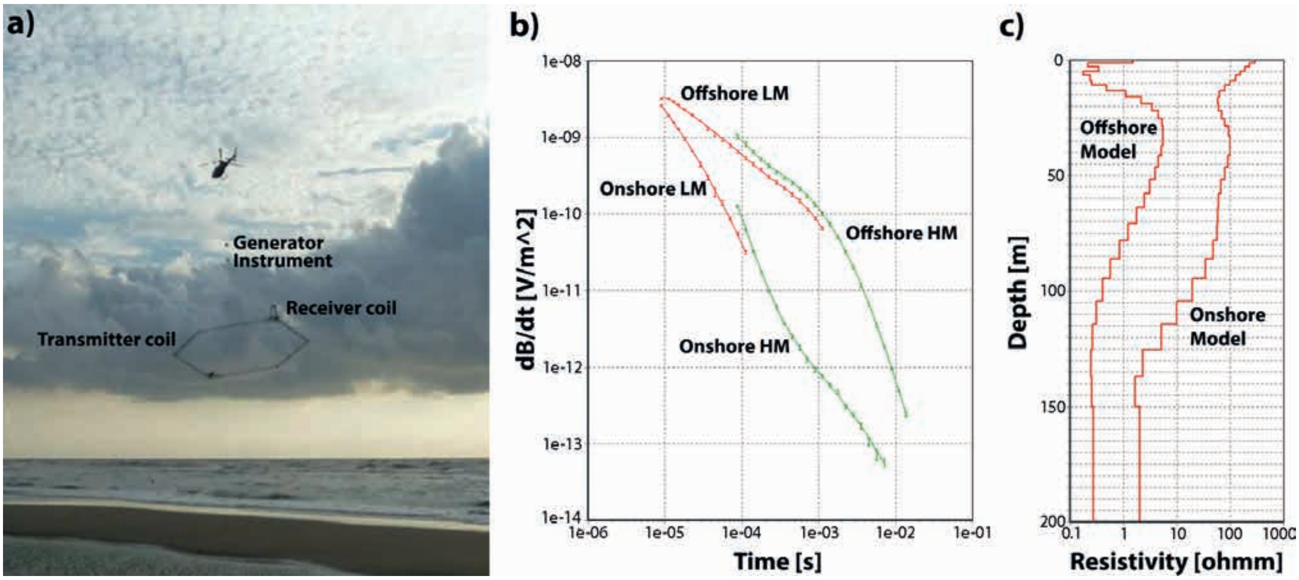

Figure 2 a) SkyTEM system flying over the North Sea b) Sounding curves from onshore and offshore measurements indicating Low Moment (LM - red) and High Moment (HM - green) parts of the data c) Corresponding onshore and offshore inverted models.

and local semi-permeable clay layers of varying thickness and spatial distribution. These clay layers typically act as the base of the aquifers or separate the primary and secondary aquifers. Groundwater is extracted from sand deposits, which compose the thick aquifers, where water is gathered through natural processes and artificial infiltration of river and lake water in the dunes. The phreatic water table is located about 1-20 m above sea level and the fresh-saltwater interface has been observed in a few boreholes at depths more than 110 m below sea level at distances of 3 km from the sea. The location of the fresh-saltwater interface varies greatly throughout the area, dependent on local clay layers, the distance from the sea and the amount of groundwater extraction. Drinking water is extracted from an elevation of -50 to -80 m.

The methodologies used in this study consist of AEM data and ground truth from boreholes. Figure 1 shows the locations of boreholes and collected AEM data. A total of 3664 boreholes provide information on the clay layers and fresh-saltwater interface. However, the majority are shallow boreholes; 1989 boreholes are less than 20 m deep (54.3% of the total), while only 222 boreholes are more than 100 m deep (6% of the total). The dense network of boreholes highlights the fact that the clay layers are not contiguous, making it difficult to map solely with boreholes. The AEM survey was carried out using the SkyTEM system (Sørensen and Auken, 2004). The system consists of a non-conductive frame suspended under a helicopter (Figure 2a). The transient electromagnetic method involves pulsing a strong current through the transmitter coil attached to the frame. This current generates a primary magnetic field; when turned off abruptly secondary eddy currents are induced in the ground. These currents begin to decay and the time derivative of the associated (secondary) magnetic field is measured in a pick-up coil attached to the system. Typical measurement times are from a few micro seconds until some milliseconds after current turn off. The measurement is repeated several times to enhance the signal-to-noise ratio. The rate of change and the magnitude of the secondary magnetic fields depends on the resistivity distribution in the ground (Christiansen et al., 2006). For example, clay sediments and aquifers influenced by saltwater intrusion are characterized by low resistivity, whereas layers of sand or gravel have a high resistivity. The AEM system was configured in a dual-moment setup, with the low-moment (weak current pulses) optimized for near-surface resolution and the high moment (strong current pulses) optimized for deeper resolution down to 150 m depth with the given hydrogeology. A large moment was crucial in order to gain the required depth of investigation when surveying offshore in a highly conductive environment. The transmitter area was 500 m^2, with a peak current of 95 Ampere and 4 transmitter loop turns. The low moment only uses 1 turn and a 10 Ampere peak current.

Prior to the survey, forward modelling was carried out, which revealed that the selected system was capable of imaging below at least 10 m of seawater with a resistivity of 0.2 ohm-m. The AEM survey was carried over eight days in September, 2011. The full survey consists of 762 line km of data which corresponds to a total of 30.480 unique soundings. The lines were separated by 150 m and were flown both onshore and offshore. The offshore flights took place during low-tide periods in order to reduce the saltwater column's thickness to penetrate as deep as possible. Different measurement configurations were used for offshore and onshore production. The off-time, that is the time where the ground response is measured, was increased from 20 milliseconds to 40 milliseconds. This was done to compensate for the expected high signal amplitudes when surveying over the conductive North Sea. Additionally, the offshore flights were oriented parallel to the coastline to map perpendicular to any potential outflow of freshwater. An example of sounding curves from onshore and offshore measurements is shown in Figure 2b. The resulting models are highlighted in Figure 2c. Preliminary interpretations of the acquired AEM data were performed daily in order to adjust the survey protocols, if necessary.

After data collection, data contaminated by man-made installations such as buildings, power lines, cables and roads were trimmed using the software package Aarhus Workbench (Auken et al., 2009, www.aarhusgeosoftware.com). This is done to ensure that the data contains only ground responses. Although the survey area is in an area of natural beauty, it was strongly influenced by infrastructure. Around 32% of the measured data had to be removed in the processing step. However, this also means that there were 68% of high-quality data left. In order to ensure high lateral resolution the flight speed was limited to 12 m per second. However, in the dune areas, characterized by rapid topography changes, the flight speed was slightly higher. With a flight speed of 12 m per second, the lateral distance between soundings, after averaging, is approximately 22 m. The average flight altitude, which has a strong impact on the vertical resolution, was about 30 m, which ensured a high signal to noise ratio. After initial processing the data was interpreted using the AarhusInv (Auken et al., 2015) algorithm with a spatially constrained inversion (Viezzoli et al., 2008) set-up providing a quasi-3D resistivity model of the ground.

Results and discussion

To derive hydrogeological features in the airborne geophysical data, a number of resistivity cross-sections and mean-resistivity maps were created. The geophysical interpretations cover a far more extensive region compared to the boreholes, allowing the spatial extent of clay layers and possible saltwater intrusion in the aquifers to be investigated over a larger region.

Onshore geological layers governing the water flow

Several local clay layers are evident in the resistivity models throughout the study site. An example is shown in the resistivity cross-section in Figure 3. The cross-section is 5 km long with an elevation range of -140 m to +40 m and oriented west-east. The resistivity models are not shown below the depth of investigation. The exact location of the cross-section is shown in Figure 1. Borehole information from within a search radius of 80 m from the cross-section has been plotted on top of the resistivity cross-section. The resistivity values in the cross-section are, as expected, substantially different onshore and offshore. Onshore, the resistivity is high (above 70 ohm-m) in an elevation of +25 m to -15 m; especially for dune areas which are characterized by a high resistivity of more than 200 ohm-m. A conductor (5-10 ohm-m) appears in an elevation of -15 m to -35 m, but it is only apparent in a profile distance of 5000 to 2800 m, where it abruptly ends. Beneath the conductor, there is another thick sequence of high resistive material (above 70 ohm-m) which ends in an elevation of -99 m. In -99 m elevation there is another conductive layer with a resistivity of less than 5 ohm-m. By comparing with the borehole information, a number of hydrogeological features can be detected. The upper 40 m are characterized by a high resistivity of more than 70 ohm-m, which corresponds to sand when comparing with the boreholes in a profile distance of for instance 3700 m and 4400 m. The higher resistivity of more than 200 ohm-m, which is evident in the dunes, is owing to the fact that the dunes are located above the groundwater table, which increases the resistivity. The 20-m thick conductor, which is situated below the 40 m sand, corresponds well with the Bergen clay layer. Below the Bergen clay there is another saturated sand layer with a thickness of about 64 m. The two sand layers, which are separated by the Bergen clay, constitute the primary and secondary aquifers. The spatial extent of the Bergen clay layer is clearly seen in the mean-resistivity map from an elevation of -20 to -30 m, which is shown in Figure 4. The sharp spatial outline of the Bergen clay is owing to coastal deposition processes.

Saltwater intrusion and freshwater lenses extending into the North Sea

A notable conductive layer is found throughout the cross-section at an elevation of -99 m when onshore. Comparison with the borehole in a profile distance of 4100 m reveals that the sediments at that elevation are constituted by sand, which should appear as a high-resistivity formation. A total of 34 watchers have been installed in the bottom of the deep boreholes in the study site, and they reveal that the low-resistivity of below 5 ohm-m can be attributed to saltwater intrusion in the aquifer. The salt watchers measure total dissolved solids values in the conductive layer in the range of 11.000 to 16.000 milligram/liter indicating brackish water with poor drinking water quality. All salt watchers measurements were found to be in agreement with the airborne geophysical measurements. Offshore, the cross-section can be described by a three-layer model beginning in 0 meters elevation. The top 0-20 m consists of a layer with a resistivity of 0.2 ohm-m, and below that there is a 40 to 80 m thick layer with a resistivity of 5-30 ohm-m. At the bottom of the profiles is a layer of low resistivity at less than 0.2 ohm-m. Below this layer we quickly loose sensitivity owing to the conductive nature of the formation. The three-layer model offshore corresponds to the outflow of freshwater from the dunes and sand aquifers and into the North Sea, which is characterized by a seawater resistivity of 0.2 ohm-m. The outflow of freshwater is considerable, and the freshwater lenses can be seen in the geophysical data as far

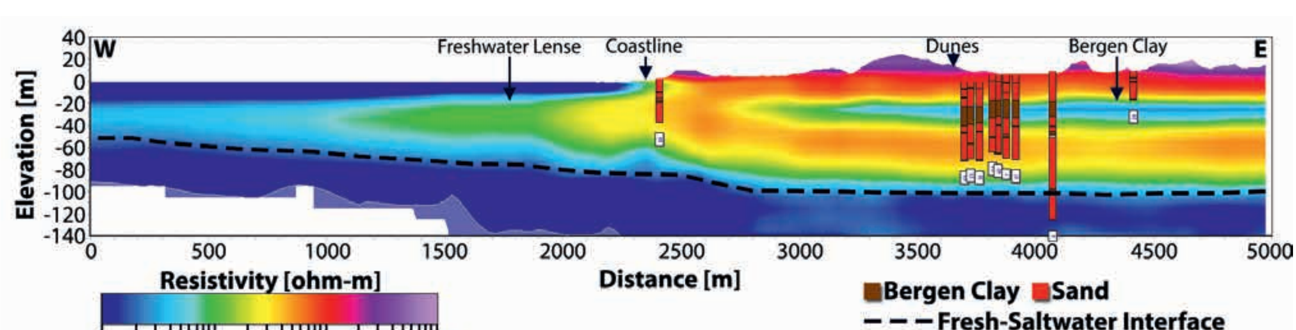

Figure 3 3D resistivity cross-section with boreholes. The cross-section has been blanked with the depth of investigation.

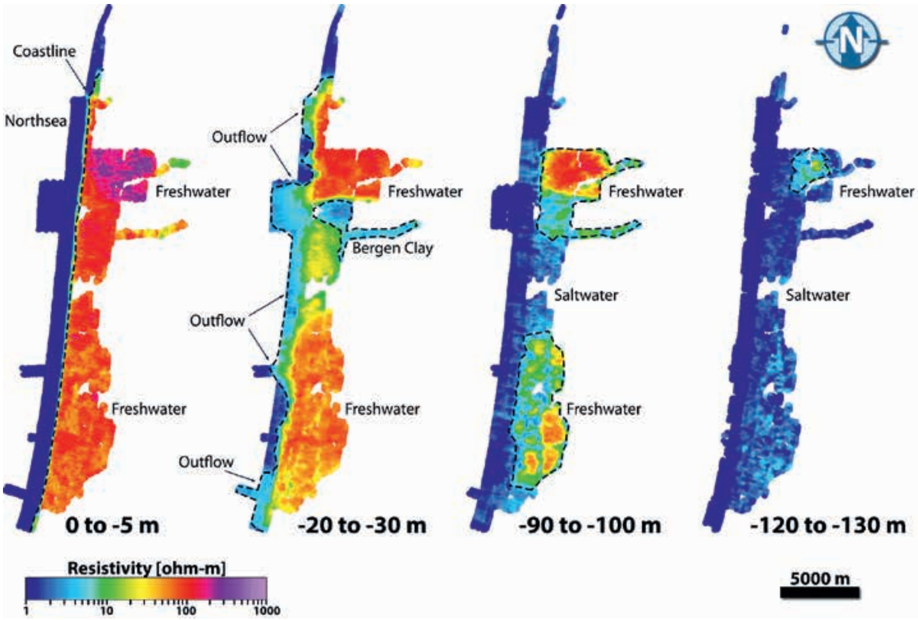

Figure 4 Mean-resistivity maps in four different elevation intervals.

as 2 km from the coastline. It is expected that the higher the resistivity in the freshwater lenses, the better the water quality (less salinity corresponds to more resistive). Figure 4 shows mean-resistivity maps in four different elevation intervals, which provide an insight into the extent of saltwater intrusion and freshwater lenses. At an elevation of 0 to -5 m, there is no outflow of freshwater into the North Sea, but the outflow is clearly seen in an elevation of -20 to -30 m. The outflow of freshwater to the North Sea varies along the coastline, which could be attributed to the presence of local clay layers or topographical changes. In an elevation of -90 to -100 m there is little or no outflow. Onshore the saltwater intrusion is clearly seen in a major part of the study site in the mean-resistivity map from -90 to -100 m. There is a sharp contrast with higher resistivity/freshwater in the northern part of the study site, adjacent to the location were the Bergen clay formation is found. Hence, the presence of freshwater in that region could be attributed to water flow variations caused by the clay layers, but this requires further investigation. At an elevation of -120 to -130 m, saltwater intrusion encompasses nearly the entire aquifer. Figure 5 shows the elevation to the fresh-saltwater interface as per derived from the airborne geophysical data with the 5 ohm-m threshold. The interface varies greatly throughout the survey area, generally ranging from an elevation of -50 to -140 m. In the northern part of the survey area, the saltwater is found at an elevation of only 0 to -10 m. The interface positioning is crucial for the groundwater modelling.

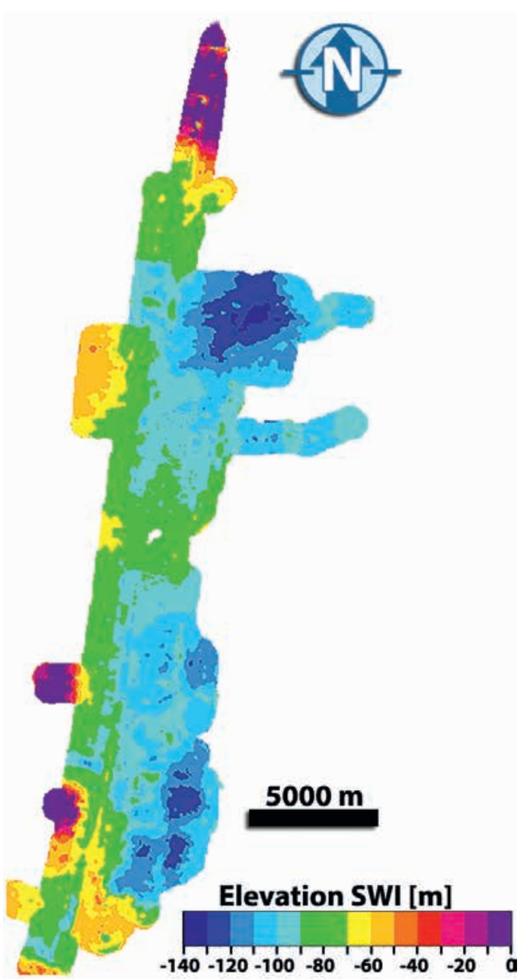

Figure 5 Elevation of the fresh–saltwater interface as indicated by a 5 ohm-m resistivity threshold.

Conclusion

Airborne electromagnetic mapping of the coastal aquifer near Alkmaar provides unique insight into the water quality of the aquifers, and will help to facilitate informed groundwater management. The AEM surveys were designed to give optimal performance for the local environment, both onshore and offshore, by using a specially designed measurement sequence and a high magnetic transmitter moment. The fresh-saltwater interface was mapped with high resolution, while simultaneously acquiring information on clay layers critical to modelling groundwater flow. The geophysical mapping revealed a ~2km-long freshwater lens extending into the North Sea below more than 15 m of sea water. This highlights the fact that building groundwater models in coastal regions, based only on onshore drillings, may lack information critical to ensuring accurate forecasts. AEM has the ability to provide essential offshore data. The demonstrated methodology is feasible in coastal zones throughout the world, and may help to enhance the understanding and management of the coastal aquifer systems.

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