FREQUENCY-DOMAIN HELICOPTER-BORNE EM SURVEY IN ZEELAND (NL) TO DELINEATE THE 3D GROUNDWATER SALINITY DISTRIBUTION

Bernhard Siemon[1], Esther van Baaren[2], Willem Dabekaussen[3], Joost Delsman[2], Jan Gunnink[3], Marios Karaoulis[2], Tommer Vermaas[2], Perry de Louw[2], Gualbert Oude Essink[2], Pieter Pauw[2], Huitte Bootsma[2], Annika Steuer[1], Uwe Meyer[1]

[1]Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany [2]Deltares, The Netherlands [3]Geological Survey of the Netherlands (TNO), The Netherlands

Background

In Zeeland, at the southwestern part of The Netherlands, the availability of fresh water for agricultural purposes is not obvious. Canals and ditches are mainly brackish to saline due to saline seepage (upward flowing groundwater of saline origin), which originates from old marine deposits and salt water transgressions during historical times. The only available fresh groundwater is present in the form of freshwater lenses floating on top of the saline groundwater (de Louw et al. 2015). These lenses are thin (<3 m fresh water) in saline seepage areas, between 5–30 m thick in areas with sandy creek ridges and up to 120 m thick in dune areas, where the spatial extent of the freshwater lenses is large. This fresh groundwater is vital for agricultural, industrial, ecological, water conservation and drinking water functions. In addition, sea level rise, changes in recharge and evapotranspiration pattern and (indirectly) land subsidence will intensify the future pressure on coastal fresh groundwater even more.

Project FRESHEM Zeeland

Based on the results of a small-scale frequency-domain helicopter-borne electromagnetic (FDHEM) survey in Zeeland in 2009 (de Louw et al. 2011), a consortium of Deltares, TNO and BGR started the project FRESHEM Zeeland (FREsh Salt groundwater distribution by Helicopter ElectroMagnetic survey in the Province of Zeeland) to survey the entire Province of Zeeland (van Baaren et al. 2016). The main goal of FRESHEM is to produce a 3D chloride distribution model of the groundwater by the use of FDHEM in combination with ground-truth measurements, advanced modelling techniques and knowledge of the groundwater system and geology.

Figure 1. Map of all survey areas in Zeeland. Two surveys (135–136) were conducted in 2009, all other surveys (160–174) in 2014 and 2015.

Airborne Surveys

The 15 airborne surveys of the FRESHEM project (Figure 1) were conducted within 3 × 2 weeks in October 2014, March and August/September 2015. In most surveys, a line separation of 300 m was used. In addition, in five areas (blue) the line separation was reduced to 100 m in order to achieve increased lateral resolution. Together with the two surveys of 2009 as part of an EU-Interreg-IV project CLIWAT (http://www.cliwat.eu/) at 200 m line separation, more than 9,600 line-km of data were obtained.

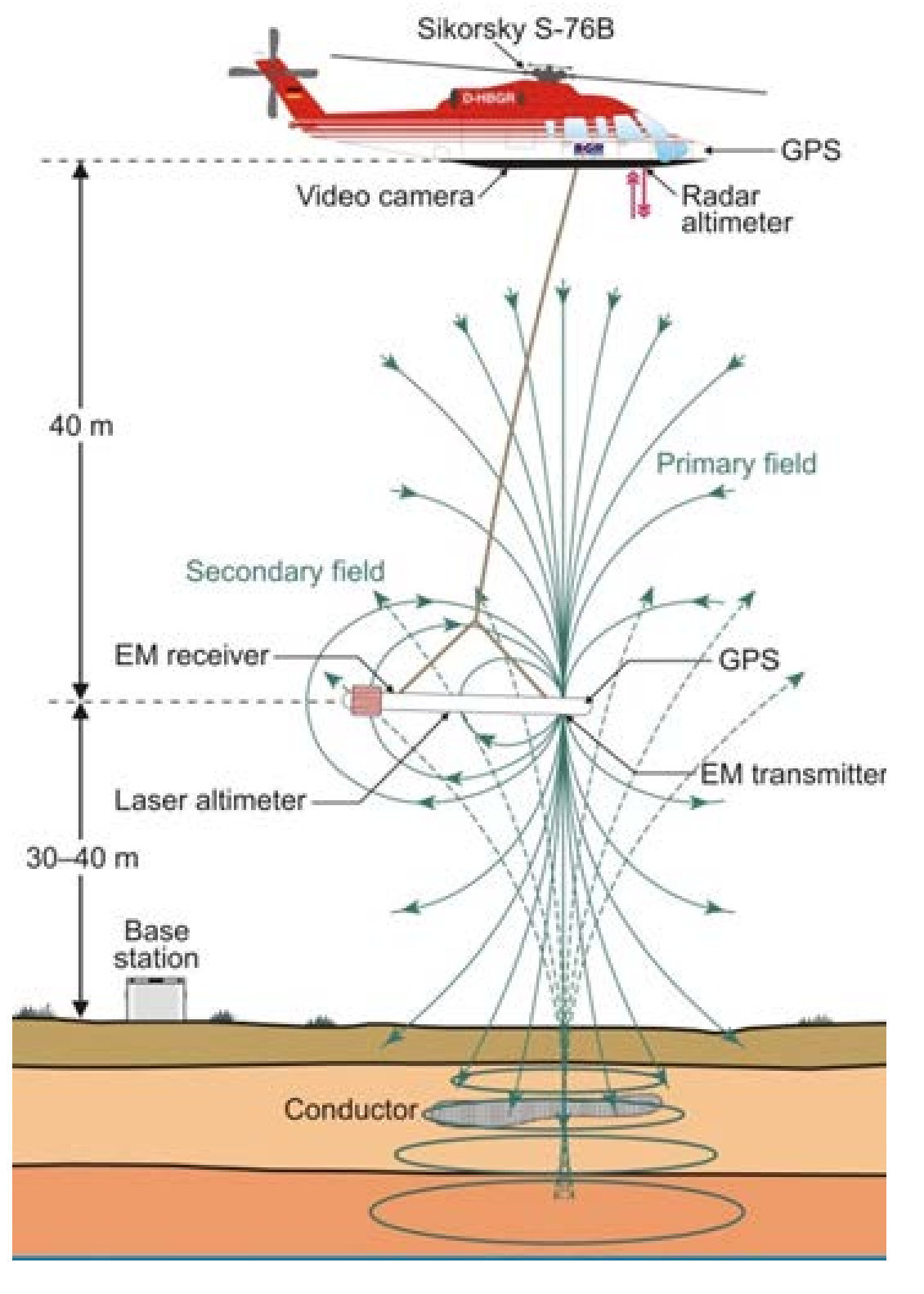

Figure 2. Sketch of BGR's airborne geophysical system.

Airborne System

The EM device used (Figure 2) is a FDHEM (Resolve) measuring system that allows fast investigation of the upper about hundred metres of the Earth's subsurface (Siemon et al. 2009). It consists of 5 horizontal-coplanar coil systems (operating frequencies f = 0.38, 1.8, 8.3, 41, and 130 kHz) and one vertical-coaxial coil system (f = 5.4 kHz). Position, magnetic and radiometric data are also measured.

The processing of the FDHEM data and particularly the correction for man-made effects (cultural noise) is described in Siemon et al. (2011).

Inversion of FDHEM Data

As one of the first surveys, a high-resolution survey covering the Canal Zone Gent-Terneuzen (160 in Figure 1) was conducted (van Baaren et al. 2016). In this pilot study area, the inversion set-up was evaluated. The inversion strategies used were single-site Marquardt-Levenberg inversion (SSI) as well as laterally and spatially constrained inversion (LCI, SCI). The inversions were tested using diverse starting models with and without a-priori data derived from ground-truth and/or 3D (hydro-)geological model data. These were conducted based on both few (≤ 6) model layers, i.e. inverting for resistivity and thickness, and many (20) model layers with fixed thicknesses below a variable cover layer (Siemon et al. 2009). The most reasonable results within this pilot study were achieved using SSI and LCI (both standard and sharp) with no external starting models. This enables reproduction of small-scale up-coning effects along ditches (Figure 3) and avoids misleading inversion results due to dubious starting models derived from existing groundwater and geological models based on 100 m × 100 m × 0.5 m grids.

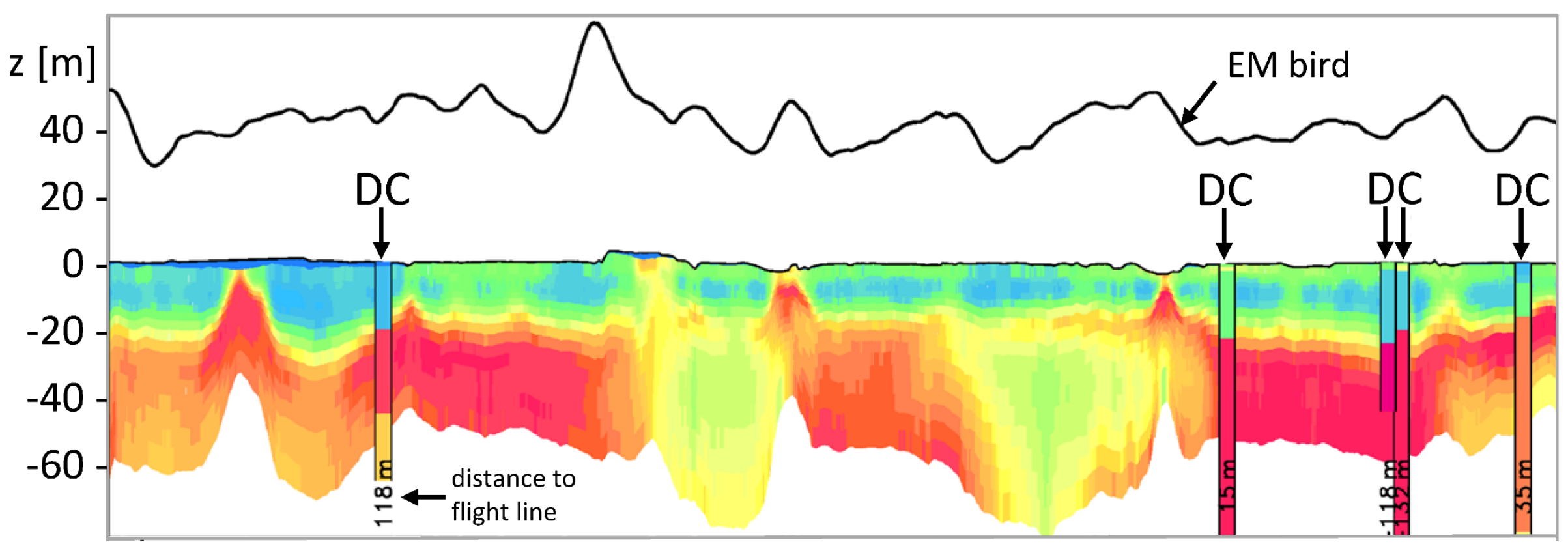

Figure 3. Example of a S–N cross-section (dashed line in Figure 6) showing the bulk EC of FDHEM and DC models (colour scale see Figure 4).

Spatial Bulk EC Distribution

The result of the inversion is the bulk electrical conductivity (EC) which depends on both the lithology (particularly clay) and the chloride concentration of the groundwater. An example cross-section and the resulting bulk conductivity maps at several elevations are shown in Figures 3 and 4, respectively. The correlation with ground geophysical results (e.g. geoelectric DC models and EC data) is impressively high.

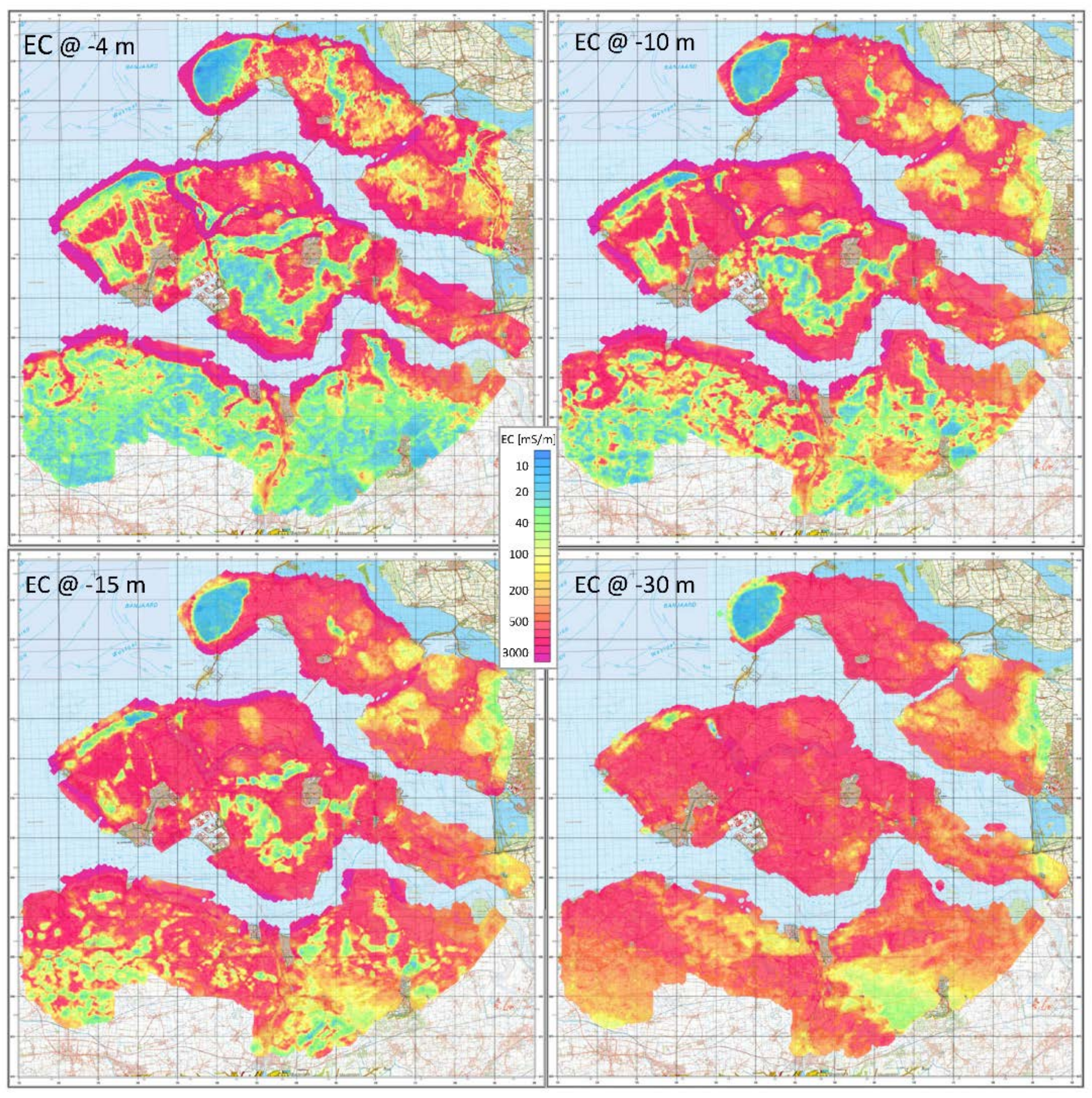

Figure 4. Bulk EC derived from 1D inversion (SSI) of FDHEM data at four elevations in m NAP (Normaal Amsterdams Peil).

Conclusions

The results of this study demonstrate that FDHEM inversion models are able to successfully outline the depth of sharp freshwater-saltwater interfaces. The fit of these regional models to local ground-based and in-situ EC and chloride measurements proved to be sufficiently high.

For the Province of Zeeland, the availability of a detailed groundwater salinity model will help to sustainably manage the scarce freshwater resource.

Acknowledgements

FRESHEM was funded by Province of Zeeland, Deltafonds, Evides, Rijkswaterstaat, municipalities of Zeeland, VNSC, Waterboard Scheldestromen, and ZLTO.

The results are publicly available for professionals and other interested people:

http://www.arcgis.com/apps/webappviewer/index.html?id=f91742fc9a114b6e925dbb330c2eb98c.

Translation of Bulk EC to Chloride Concentration

The chloride concentration of the groundwater was derived from bulk EC values applying several steps:

- Information on lithology was provided by the GeoTOP geological model (Stafleu et al. 2011) – an example is shown in Figure 5a;
- Soil samples were analysed to derive formation factors and surface conductivities for typical lithology classes (Revil et al. 2017);
- Taking into account the information from the first two steps, the water EC values were obtained;
- The water EC values were transformed from 11 °C to 25 °C assuming a linear increase of 2 % per 1 °C;
- The chloride values were calculated from water EC applying an empirical formula (de Louw et al. 2011).

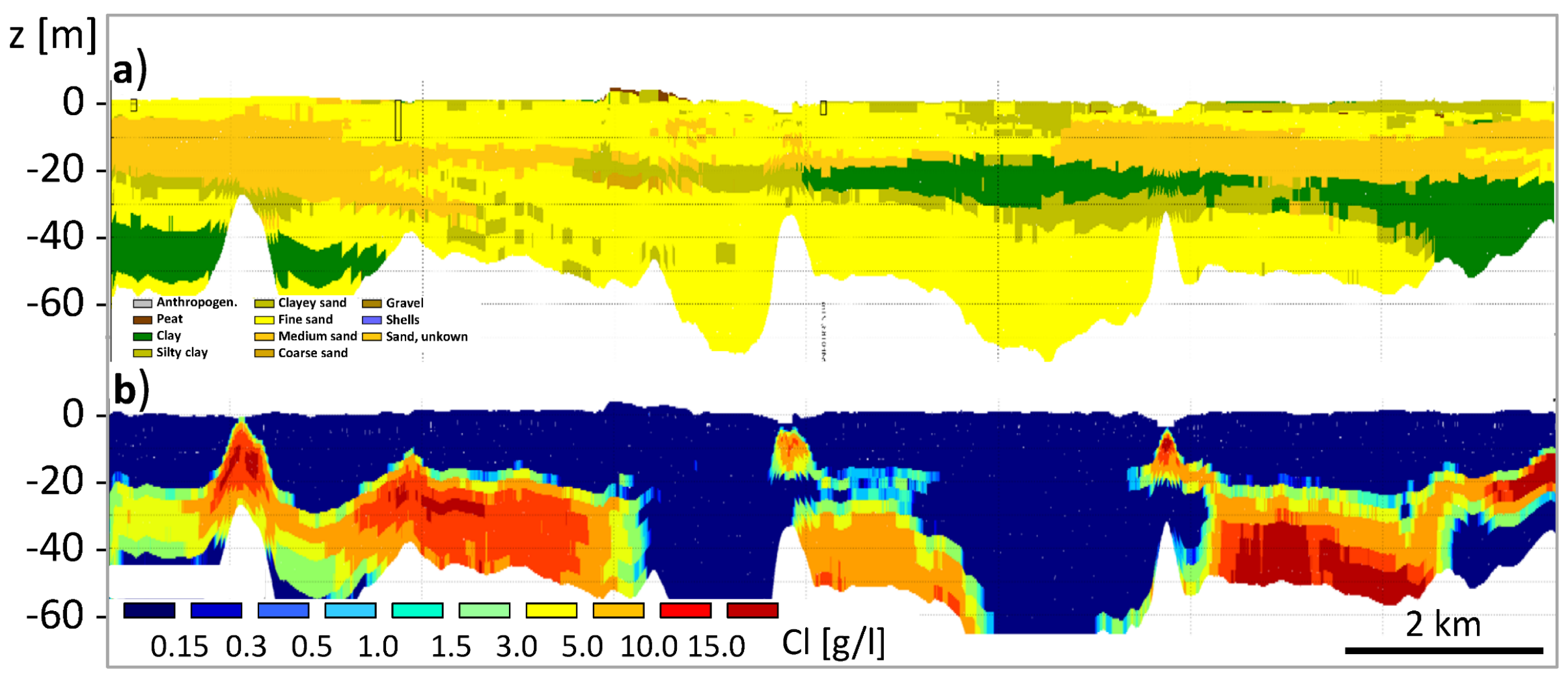

Figure 5. Example of a S–N cross-section (cf. Figure 3) showing a) the most probable lithology (GeoTop), b) the derived chloride concentration.

3D Voxel Model of Chloride Concentration

Calculation of the chloride concentration was performed with a Monte Carlo approach, taking into account the uncertainty in the following parameters: bulk EC, lithology, formation factor and surface conductivity, and the translation from water conductivity to chloride concentration. This approach resulted in chloride classes assigned to each FDHEM model layer along each flight line.

A full 3D mapping of the chloride concentration was requested by the stakeholders including the areas in between the flight lines. Therefore, a 3D voxel model (50 m × 50 m × 0.5 m) was derived using indicator kriging (Bleines et al. 2004). The 3D model enables stakeholders to draw random profiles in areas of interest and to directly implement the chloride concentration in groundwater models.

Fresh water in Zeeland is often constricted to elongated lenses. The direction and magnitude of this anisotropy has been deduced from the calculated chloride concentrations along the flight lines. Imposing anisotropy to the interpolation increases the importance of data points located in specific directions, reducing the uncertainty of the model in between flight lines.

Figure 6 shows an example map for the depth to the upper bound of the chloride class of 1.5 g/l. The green and blue coloured areas, where the freshwater is thicker than 15 m, are most interesting.

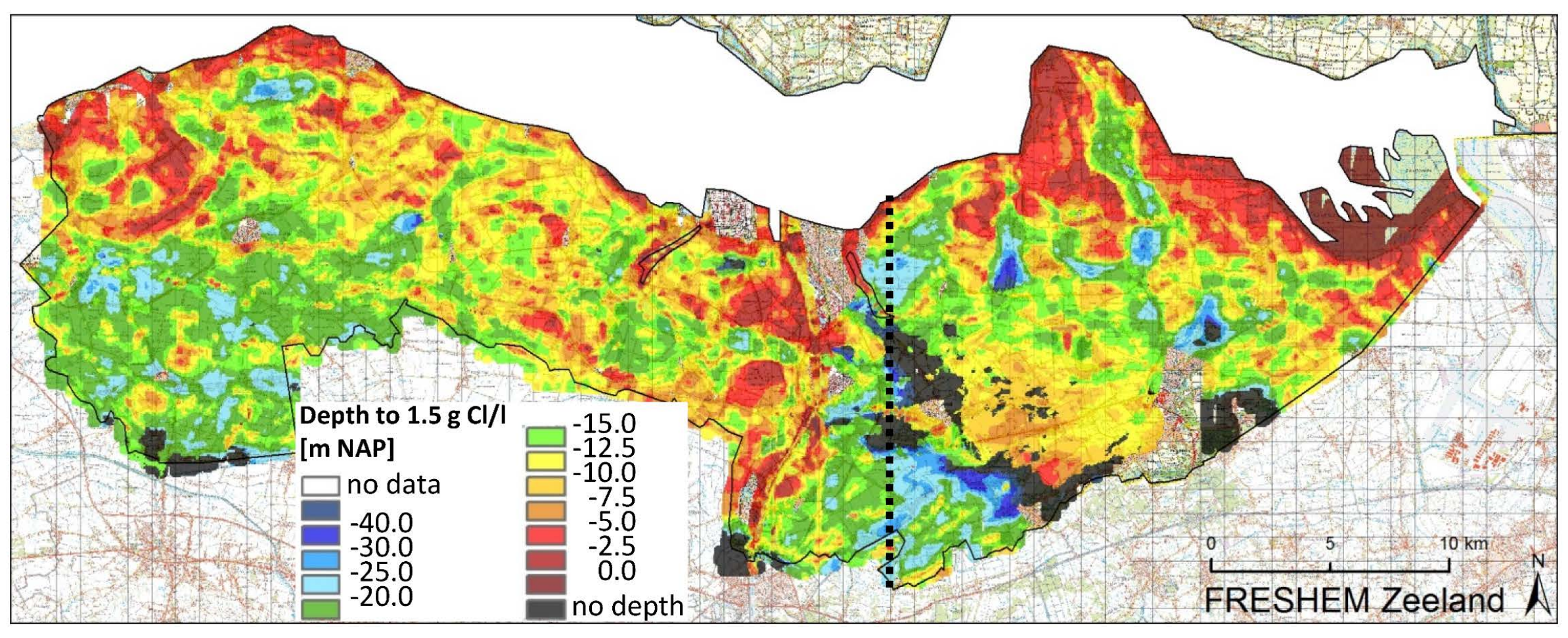

Figure 6. Depth (in m NAP) to chloride concentration class of 1.5 g/l for the southern part of Zeeland (Zeeuws-Vlaanderen).

References

Bleines, C., Perseval, S., Renard, D. and Toulffait, Y. [2004] ISATIS software manual, 5th ed., Geovariances & Ecole Des Mines, Paris.

van Baaren, E., Oude Essink, G., Delsman, J., Pauw, P., Karaoulis, M., de Louw, P., Siemon, B., Steuer, A., Dabekaussen, W. and Gunnink, J. [2016] FRESHEM: characterization of the fresh-saline groundwater distribution in the Province of Zeeland, The Netherlands. *24th Salt Water Intrusion Meeting and 4th Asia-Pacific Coastal Aquifer Management Meeting*, Extended Abstracts, Cairns, Queensland, Australia.

de Louw, P.G.B., Eeman, S., Siemon, B., Voortman, B.R., Gunnink, J.L., van Baaren, E.S. and Oude Essink, G.H.P. [2011] Shallow rainwater lenses in deltaic areas with saline seepage. *Hydrol. Earth Syst. Sci.,* **15**, 3659–3678.

de Louw, P., Oude Essink, G., Eeman, S., van Baaren, E., Vermue, E., Delsman, J., Pauw, P., Siemon, B., Gunnink, J. and Post, V. [2015] Dunne regenwaterlenzen in zoute kwelgebieden. *Landschap*, **2015**(1), 5–15.

Revil, A., Coperey, A., Shao, Z., Florsch, N., Fabricius, I.L., Deng, Y., Delsman, J.R., Pauw, P.S., Karaoulis, M., de Louw, P.G.B, van Baaren, E.S., Dabekaussen, W., Menkovic, A. and Gunnink, J.L. [2017] Complex conductivity of soils. *Water Resources Research*, **53**, doi:10.1002/2017WR020655.

Siemon, B., Christiansen, A.V. and Auken, E. [2009] A review of helicopter-borne electromagnetic methods for groundwater exploration. Near Surface *Geophysics*, 7, 629-646.

Siemon, B., Steuer, A., Ullmann, A., Vasterling, M. and Voß, W. [2011] Application of frequency-domain helicopter-borne electromagnetics for groundwater exploration in urban areas. *Journal of Physics and Chemistry of the Earth*, **36**(16), 1373-1385.

Stafleu, J., Maljers, D., Gunnink, J.L., Menkovic, A. and Busschers, F.S. [2011] 3D modelling of the shallow subsurface of Zeeland, the Netherlands. *Netherlands Journal of Geosciences – Geologie en Mijnbouw,* **90**(4), 293-310.

Contact:

Bernhard Siemon
Bundesanstalt für Geowissenschaften und Rohstoffe
Stilleweg 2, D-30655 Hannover, Germany
Tel.: +49 (0)511-643 3488 Bernhard.Siemon@bgr.de

Esther van Baaren
Stichting Deltares
Princetonlaan 6, 3584 CB Utrecht, The Netherlands
Tel.: +31 (0)88 335 7775 Esther.vanBaaren@deltares.nl

Willem Dabekaussen
Geological Survey of the Netherlands
Princetonlaan 6, 3584 CB Utrecht, The Netherlands
Tel.: +31 (0)88 866 2789 Willem.Dabekaussen@tno.nl