Viability of detecting fresh water on the coastline using EM methods

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Abstract: The present work focuses on the application of frequency domain electromagnetic induction methods (FDEM) to profile conductivities at Platja dels Gossos in Mataró, aiming to study the potential of this technique. To do so, data was obtained using the CMD Mini Explorer, then processed and interpolated with Python programmes, inverted with the EMagPy software, and graphically represented with Surfer™ to further analyse it.
On the one hand, results indicate an intrusion of saltwater into the sand, disregarding, though, any contributions of underground fresh water. On the other, the FDEM technique has proven to be a useful and reliable tool for a first surveying of the ground, as it is quick, non-intrusive, economical and practical.

I. INTRODUCTION

An increasing concern for localising, analysing and protecting sources of fresh water can be observed during recent years. For instance, the UN Sustainable Development Agenda aims to "eradicate poverty in all its forms" by 2030, and this includes, according to said organism, securing a safe access to water for the world's population [1]. In the same vain, as for October 2022, the EU Water Framework Directive requires the study and management of groundwater bodies, recognising them as a valuable resource upon which many European ecosystems and economic sectors depend.

Electromagnetic methods have been widely used in soil exploration since the 1970s and there exists a plethora of techniques. Particularly, some precedents in groundwater profiling include mapping resistive freshwater channels and saltwater intrusions, profiling the confluence of freshwater and saltwater in coastal aquifers and monitoring temporal soil water content [2] [3] and references therein.

Focusing on electromagnetic induction methods or EMI for short, a time varying magnetic field is used to induce eddy currents in the studied terrain; its properties can be evaluated through measuring a secondary magnetic field, sum of the primary one and the ground response. EMI methods can be categorised into time domain (TDEM) and frequency domain (FDEM). In the former case, changes in the primary magnetic field are made by turning on and off a steady current, whereas in the latter case it is an a.c. current the one producing the variations. Disregarded from mineral exploration because of lower performance, nowadays FDEM still find interesting applications in shallow investigations such as groundwater research [2]. For it does not need contact with the ground, surveys are carried out faster. Moreover, only one operator is needed, reducing costs. Hence, it is thought that EMI profiling will be useful in contexts when it is wanted a first evaluation of an area. The present work aims to analyse this potential via the application of FDEM methods and its inversion techniques in the profiling of Platja dels Gossos in Mataró. This study is encompassed within a larger investigation, the TERRAMAR project supported by the Agència Catalana de l'Aigua, focused on evaluating the underground water resources along the Catalan coast.

II. THEORY

Let the transmitter be a coil trough which an a.c. current flows. This creates a magnetic field that changes amplitude and direction with time, the primary magnetic field or HP. Following Faraday's law, if HP intersects a conductor body it induces eddy currents, which, in turn, create a secondary magnetic field, HS. By recording the response -sum of HP and HS- in a receiver coil, conductive properties of the ground can be inferred.

When using frequencies below 50 Hz, as the distance between the receiver and the transmitter coil is orders of magnitude smaller than the electromagnetic wavelength, wave properties and effects can be neglected; this is called the quasi-static scenario [3]. Nevertheless, obtaining the ratio between HS and HP is still an arduous mathematical exercise. Furthermore, it depends on specific parameters such as instrument frequency, coil positioning and subsurface conditions. Commonly -and it is the case for the CMD Mini Explorer-, coplanar coil orientations in which loops are situated horizontal or vertical to the ground are used. Respectively for this cases and in homogeneous ground, the electrical conductivity (EC) σ will be described by

$$\left(\frac{\mathrm{HS}}{\mathrm{HP}}\right)_{\mathrm{H}} = \frac{2}{\gamma^2 \mathrm{s}^2}\left[-3+\gamma^2\mathrm{s}^2+(3+3\gamma\mathrm{s}+\gamma^2\mathrm{s}^2)e^{-\gamma\mathrm{s}}\right], \quad (1)$$

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$$\left(\frac{\text{HS}}{\text{HP}}\right)_{\text{V}} = \frac{2}{\gamma^2 \text{s}^2}\left[9 - (9 + 9\gamma\text{s} + 4\gamma^2\text{s}^2 + \gamma^3\text{s}^3)e^{-\gamma\text{s}}\right], \quad (2)$$

where $\gamma = \sqrt{i\omega\mu_0\sigma}$ and $\omega = 2\pi$f, being f the frequency, μ_0 the permeability of free space and s, the coils' spacing [4] [5].
Both ratios are complex numbers composed of an in-phase part, determined by magnetic properties, and a quadrature part, proportional to the ground conductivity [6]. But working with low frequencies allows a further approximation. Focusing on the quadrature part, let

$$\text{d} = \frac{\sqrt{2i}}{\gamma} \quad (3)$$

be the skin depth. It informs about the depth at which the magnetic field attenuates e^{-1} (37 %) [2]. Rearranging (3) a dimensionless number β, called the induction number, emerges:

$$\gamma\text{s} = \sqrt{2i}\beta, \quad (4)$$

$$\beta = s\sqrt{\frac{\omega\mu_0\sigma}{2}}. \quad (5)$$

McNeill pointed out that if $\beta \ll 1$ (low induction number or LIN approximation) a Taylor expansion of (1) and (2) can be performed, thus arriving to the simplified McNeill's formula [4]

$$\left(\frac{\text{HS}}{\text{HP}}\right)_{\text{q}} \approx \frac{i\omega\mu_0\sigma\text{s}^2}{4} \quad (6)$$

which allows finding σ. In a non-homogeneous ground, the above conductivity is called apparent conductivity, ECa [4], and it is the data used for interpretation.

III. METHODOLOGY

A. DATA ACQUISITION

The conductivity profiling was conducted at Platja dels Gossos in Mataró (Fig. 1), one of the several locations chosen in the project TERRAMAR. The reason is its potential to harbour ground freshwater intrusions into the sea water. During that day, the beach was also surveyed by the electrical resistivity tomography method (ERT), and the salinity of water samples at various points along the coast and the sea was measured too.

FIG. 1: Google Earth photo of Platja dels Gossos, with the surveyed area framed in red.

The instrument used for data acquisition was the CMD Mini Explorer, from GF Instruments. Briefly, it is composed of a control unit, a probe where the coils are situated, and its holder (Fig. 2). The probe has two connection configurations, high and low, corresponding respectively to the horizontal (HCP) and vertical (VCP) coupling plane loop orientations [6]. Additionally to the transmitter coil, the probe is equipped with three receiver coils, hence, allowing six depth ranges (Table I). Data can be taken in two modes: manual, when the operator selects the points where to measure, or continuous, when the instruments measure conductivity as an average of its values during a chosen period of time. CMD Mini Explorer has a maximum sampling rate of 10 Hz [6], situating the data not only in the quasi-static but also in the LIN approximation.

TABLE I: Coil separations and their respective depth range for high and low configurations.

Dipole centre (m)	Effective high depth range (m)	Effective low depth range (m)
0.32	0.5	0.25
0.71	1.0	0.5
1.18	1.8	0.9

Before going to Mataró, a test was conducted in the gardens of Facultat de Biologia (UB), to become acquainted with the device and the way it provides data. Once the survey is completed, the dataset includes: x and y positions (because the incorporated GPS was not available, they had to be input manually), date, time, conductivities measured by the three receiver coils (mS/m), their respective standard deviations and a 1D inversion model (depth at which each conductivity may be found).

In the Mataró survey a GPS was also provided. Thus, by collecting data simultaneously with the CMD Mini Explorer the coordinates of each conductivity could be determined. Data was taken in a continuous mode every 1s. Thanks to a measuring tape, a grid, which served as

FIG. 2: Photography during the surveying of Platja dels Gossos, with the CMD Mini Explorer device.

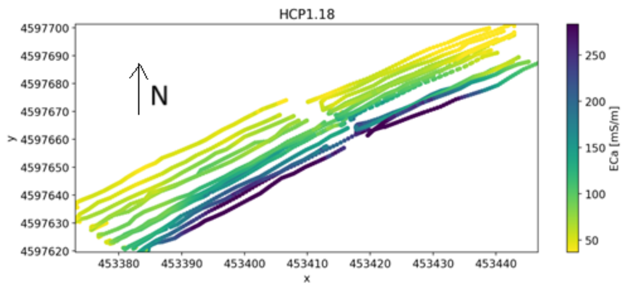

FIG. 3: Map of conductivities in each position (x and y axis are in UTM coordinates) measured in high configuration by the coil separated 1.18m.

a reference to maintain the constant speed and to follow straight and equidistant paths along the beach, was created. In total, 13 lines parallel to the coast were made, separated near the sea by 1m and then by 1.5m, for the interest area was the hypothetical interface between fresh and salt water. To avoid interfering with the ERT survey, the beach was divided in two sections, separated by the line of the ERT device. The trails, each saved in a different file, were always followed in the same direction, first in high and then in low configuration.

B. DATA PROCESSING

In order to process the raw data and make models, a Python program was developed with the assistance of Chat GTP3.5. Previously, using g7towin.exe, the GPS latitudes and longitudes were converted into a readable format, in UTM coordinates. The program firstly unites the high/low data files from the CMD in one. Then, it converts each time data into seconds and calculates their difference relative to the smallest value. CMD conductivities and GPS locations with the same time difference are joined. Lastly, since the GPS records values every 5s while the CMD measurements were acquired every 1s, the program conducts a linear interpolation to obtain the in-between position data -a constant speed between each point was assumed, a quite reasonable approach considering they were 5s intervals. Finally, a revision and a subsequent removal of the outlier points was performed. An example of the results is presented in Fig. 3.

C. INVERSION

Geophysical inversion is a non-unique problem due to the fact that different combinations of variables might end up reproducing the same ground characteristics. To deal with this, some constraints can be applied, for instance, previously known information or multiple source data [2]. For the present analysis, a three layer conceptual model of dry sand, moist sand and saltwater saturated sand is expected. The models were developed on the bases of these assumptions.

For the inversion, EMagPy software, specialised in processing FDEM data, was employed [7]. It features a Python programming interface and a GUI, which was the one used. In addition to displaying the data in different formats, the GUI allows to invert it through a wide range of minimisation methods, both in the LIN approximation and using the full solution of Maxwell's equations. The quality of the inversion can be evaluated by its RMSPE, that is, the percentage of the model-to-data ratio

$$\mathrm{RMSPE} = 100\sqrt{\frac{1}{\mathrm{n}}\sum_{i=1}^{\mathrm{n}}\left(\frac{\mathrm{d_i}-\mathrm{r_i}}{\mathrm{d_i}}\right)^2}. \qquad (7)$$

The total inverted points is n, $\mathrm{d_i}$ is each observed value and $\mathrm{r_i}$ is the simulated one. The smaller the RMSPE, the best the data fits the model.

Then, the high and low separated datasets were inverted and represented via the Software Surfer™. After different tests it was found that the minimisation of RMSPE (Fig. 5) is optimal when the first layer is set between 0 m and 0.6 m of depth, the second layer between 0.6 m and 1.8 m and the third one from 1.8 m forward (Fig. 4). For the analogous models in low configuration see Appendix A.

In addition, a joined file with high and low configuration values was inverted. For doing so, EMagPy requires the measurements to be taken in the same points, so a second interpolation was needed. In this case, the high configuration values -as they were more numerous-were interpolated into the low ones via a second Python program. Some trial showed that the best results were obtained with a five layer model; still, the RMSPE was notoriously higher than that with the separated datasets, indicating a worse adjust to the model (see Appendix B).

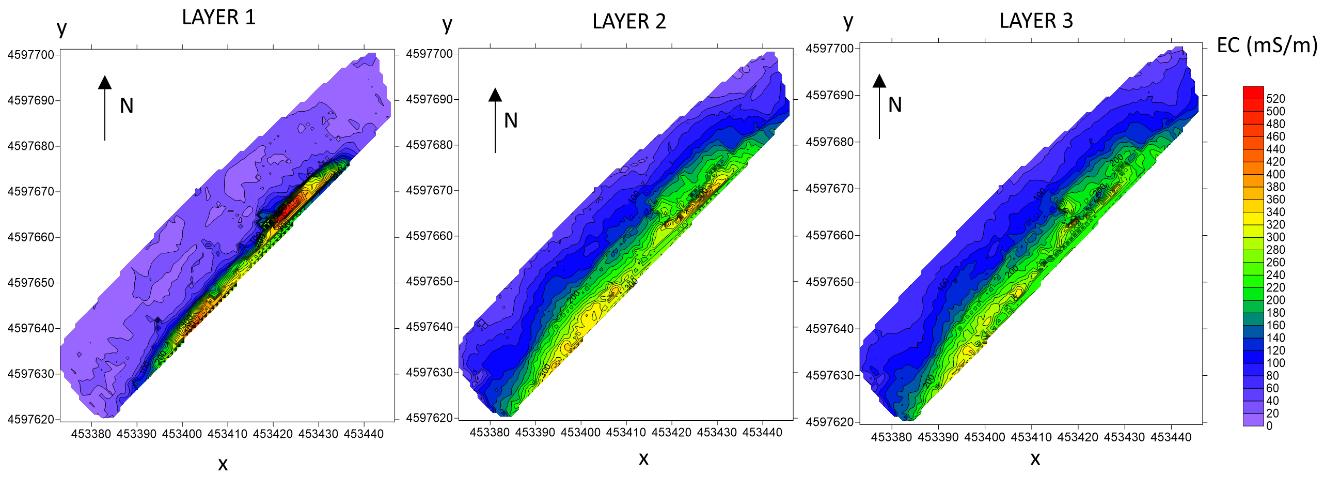

FIG. 4: Models of conductivities σ (mS/m) for the high configuration. From left to right: first layer (0 m-0.6 m), second layer (0.6 m-1.8 m) and third layer (1.8 m -).

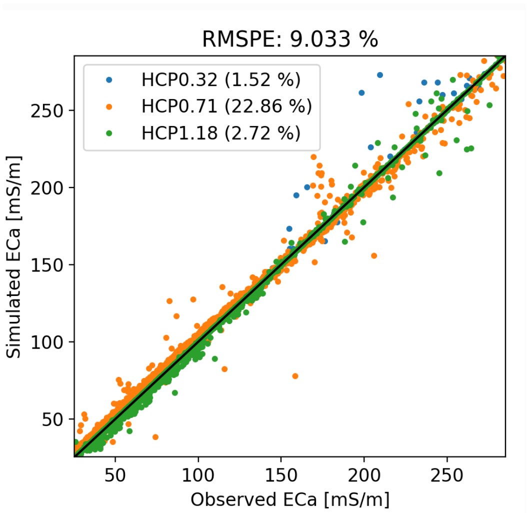

FIG. 5: Modelled to observed ECa for the high configuration data, with layers at 0.6 m and 1.8 m.

D. INTERPRETATION

From Fig. 4, it is noticeable a tendency of decaying conductivity as the data moves away from the seashore. Far from the sea, it keeps approximately constant, with low values between $\sim$0 mS/m and 120 mS/m, whereas higher conductivities can be observed near the sea, with some points reaching up to 520 mS/m in the first layer.

Another interesting feature is the overall behaviour of the conductivity by the sea and how it evolves with depth: the deeper the slice, the larger becomes an area of medium-high conductivities (180 mS/m-300 mS/m). This trend can also be appreciated for the low and the merged datasets (see Appendix A and Appendix B).

IV. DISCUSSION OF THE RESULTS

In terms of inversions and their quality, for the studied case, arguably the separated datasets present better fittings. The reliability of having double measurements might be lost with the second interpolation. Furthermore, it adds difficulty not only per se but because the modelling of more data is needed. The FDEM technique's main strength is its rapidness and easy usage, and has high potential if employed to do preliminary surveys. Hence is more advisable to analyse the datasets separately, bearing in mind that low configuration provides maximum sensitivity in shallower depths while the high one has lower resolution but reaches deeper.

On the other hand, the conductive area increasing with depth might be a saltwater intrusion into the sand. Regarding underground fresh water, even though higher conductivities are expected for naturally fresh water due to impurities, no sings of it are visible.

Lastly, via Archie's law [8], a relationship between physical and electrical properties can be established. Wanting to know how moisture is distributed along the beach, the saturation index $\mathrm{S_w}$

$$\mathrm{S_w^n} = \frac{\mathrm{a}\sigma_{rock}}{\phi^{\mathrm{m}}\sigma_{seawater}} \tag{8}$$

can be calculated. Because Platja dels Gossos is roughly composed by coarse sand grains, porosity is $\phi = 38,6\%$, saturation exponent n = 2, cementation exponent m = 1.37 and a = 0.88 [8] [2]. The sea water conductivity was obtained in-situ $\sigma_{seawater} = 0.18\,\Omega$m, whereas σ_{rock} is the conductivity proportioned by the models. Results in Fig. 5 led to the conclusion that sand has more water content with depth, indicating once more the existence of a sea water intrusion.

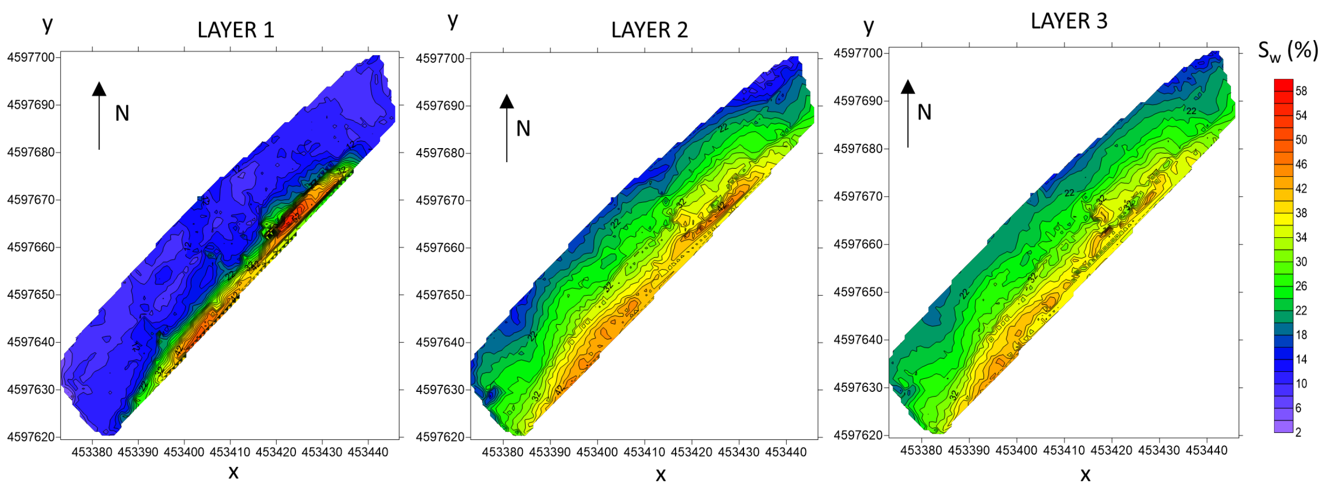

FIG. 6: Distribution of the saturation index (%) along the beach for the conductivities modelled in high configuration. From left to right: first layer (0 m-0.6 m), second layer (0.6 m-1.8 m) and third layer (1.8 m -).

V. CONCLUSIONS

FDEM technique to study the conductivity patterns has proven to be a practical and reliable tool. In addition, the EMagPy software allows a quick and intuitive interpretation of the results, positioning this method as a very valid framework for further investigations and for an initial reconnaissance of the terrain, particularly in large areas with complex orography.

In terms of Platja dels Gossos, whilst conductivity and moist distributions point out towards a salt water intrusion, underground fresh water can be discarded.

A substantial improvement would be the incorporation of the GPS to the CMD device. Not only the data will become more trustworthy by eliminating the first interpolation, but also all the process will turn quicker.

Acknowledgments

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[1] United Nations, [Online]. Available: https://sdgs.un.org/2030agenda. [Last access: 02 06 2024].
[2] Dentith, M., Mudge, S. T.. *Geophysics for the mineral exploration geoscientist.* Cambridge: Cambridge University Press, 2014.
[3] Nabighian, Misac N. (ed.). *Electromagnetic methods in applied geophysics, Volume 2, Application, Part A.* Oklahoma: Society of Exploration Geophysicists, 1991.
[4] McNeill, J.D.. *Electromagnetic terrain conductivity measurement at low induction numbers.* Geonic technical note TN-6, 1980.
[5] INSTRUMENTS, G. F. *Short Guide for electromagnetic conductivity mapping and tomography.* 2016.
[6] INSTRUMENTS, G. F. *CMD Electromagnetic conductivity meter user manual V. 2.0.* Geophysical Equipment and Services, Czech Republic, 2011.
[7] McLachlan, Paul, Guillaume Blanchy, and Andrew Binley. 2020. *EMagPy: Open-Source Standalone Software for Processing, Forward Modeling and Inversion of Electromagnetic Induction Data'.* Computers & Geosciences, August, 104561. https://doi.org/10.1016/j.cageo.2020.104561
[8] Schön, Jürgen H. *Physical properties of rocks: fundamentals and principles of petrophysics.* Oxford: Elsevier, 2015.

VI. APPENDIX

In Appendix A the models for the low configuration and its RMSPE are displayed. In Appendix B two models with their RMSPE are shown: a shallower model with layers at depths at 0.1 m, 0.2 m, 0.5 m and 1 m and a deeper one with layers at 0.2 m, 0.6 m, 1.2 m and 1.6 m.

Appendix A: Models and RMSPE for the low configuration

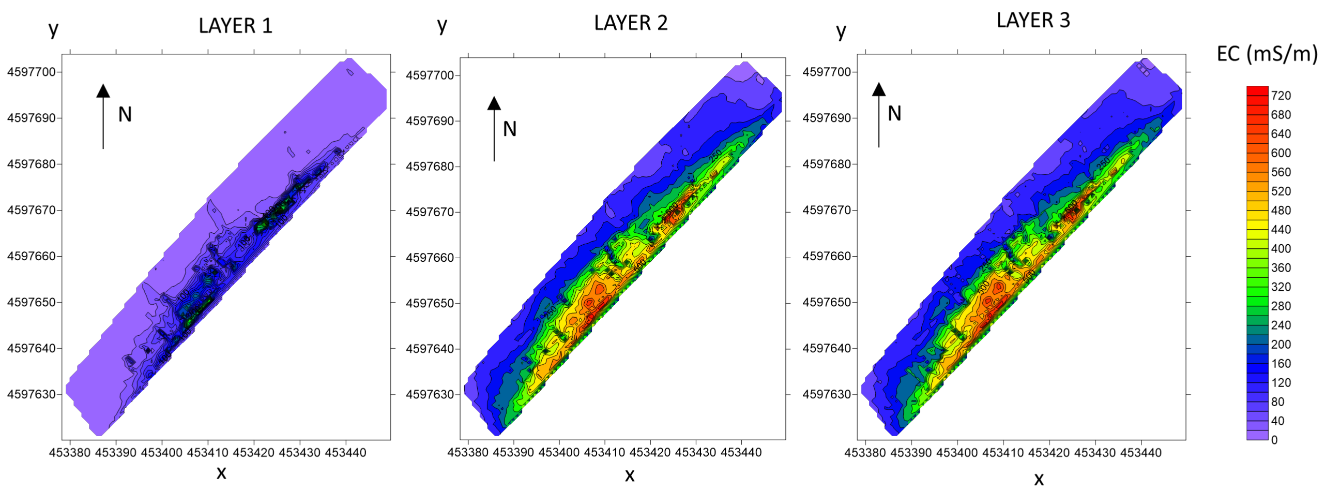

FIG. A1: Models of conductivities (mS/m) for the low configuration. From left to right: first layer (0 m-0.6 m), second layer (0.6 m-1.8 m) and third layer (1.8 m -).

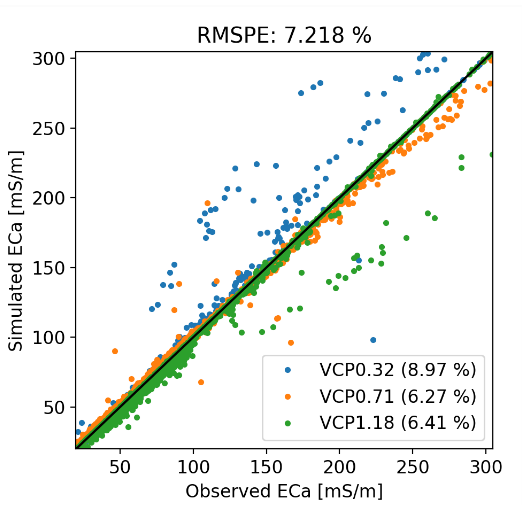

FIG. A2: RMSPE for the low configuration with three layers at depths 0.6 m and 1.8 m.

Appendix B: Models for the merged data

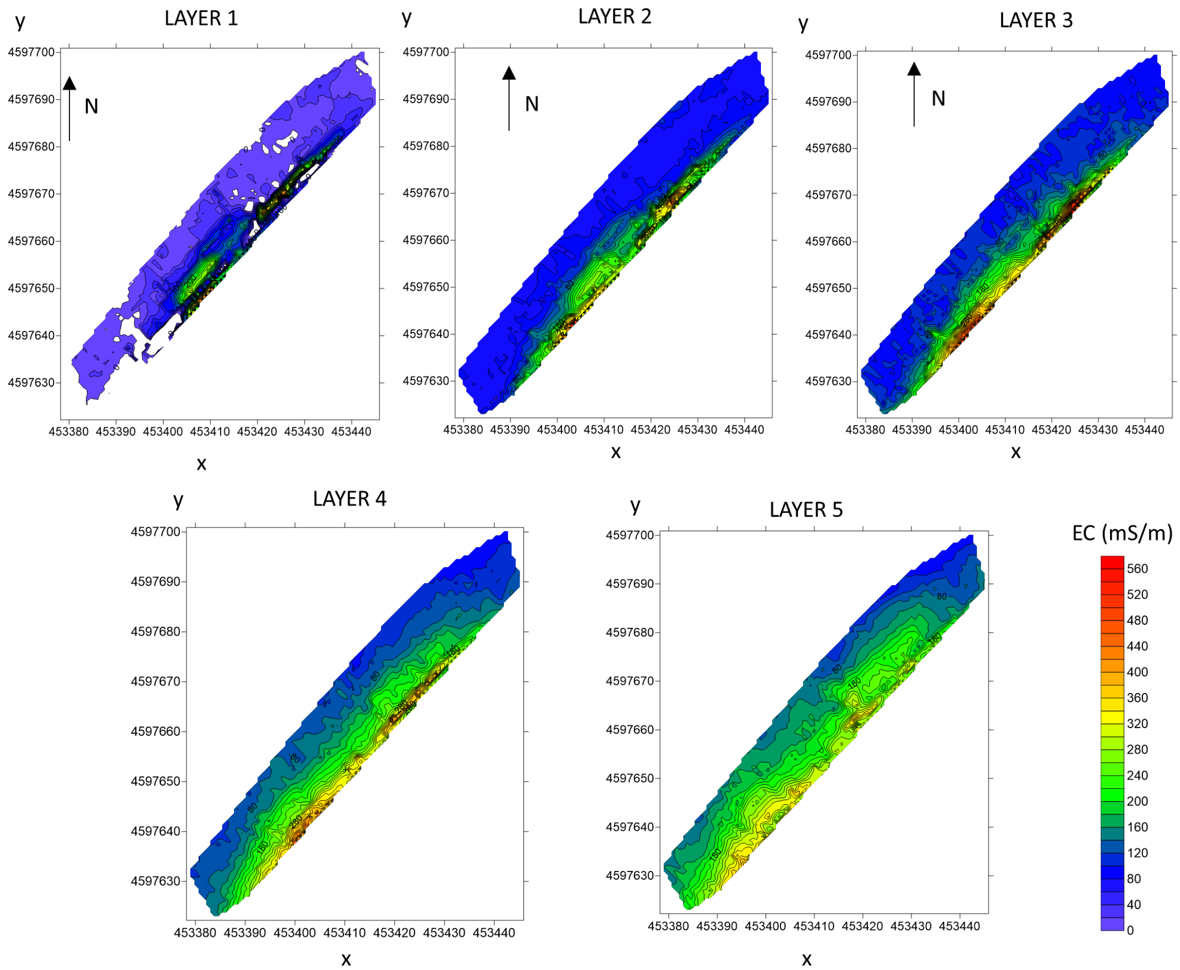

FIG. B1: Models for the merged data. From left to right and top to bottom: first (0 m-0.1 m), second (0.1 m-0.2 m), third (0.2 m -0.5), forth (0.5 m-1 m) and fifth layer (1 m -). The blank spaces at the first layer correspond to artefacts, areas with negative conductivity, which does not have physical meaning.

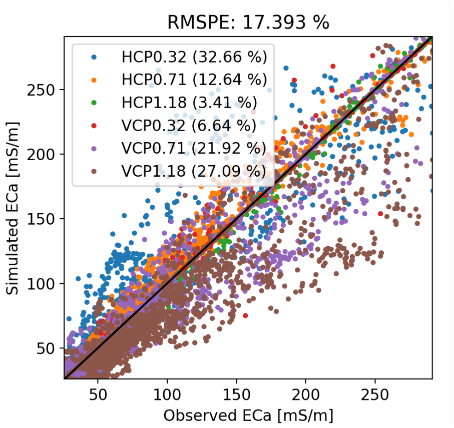

FIG. B2: RMSPE for the merged dataset with five layers at 0.1 m, 0.2 m, 0.5 and 1 m.

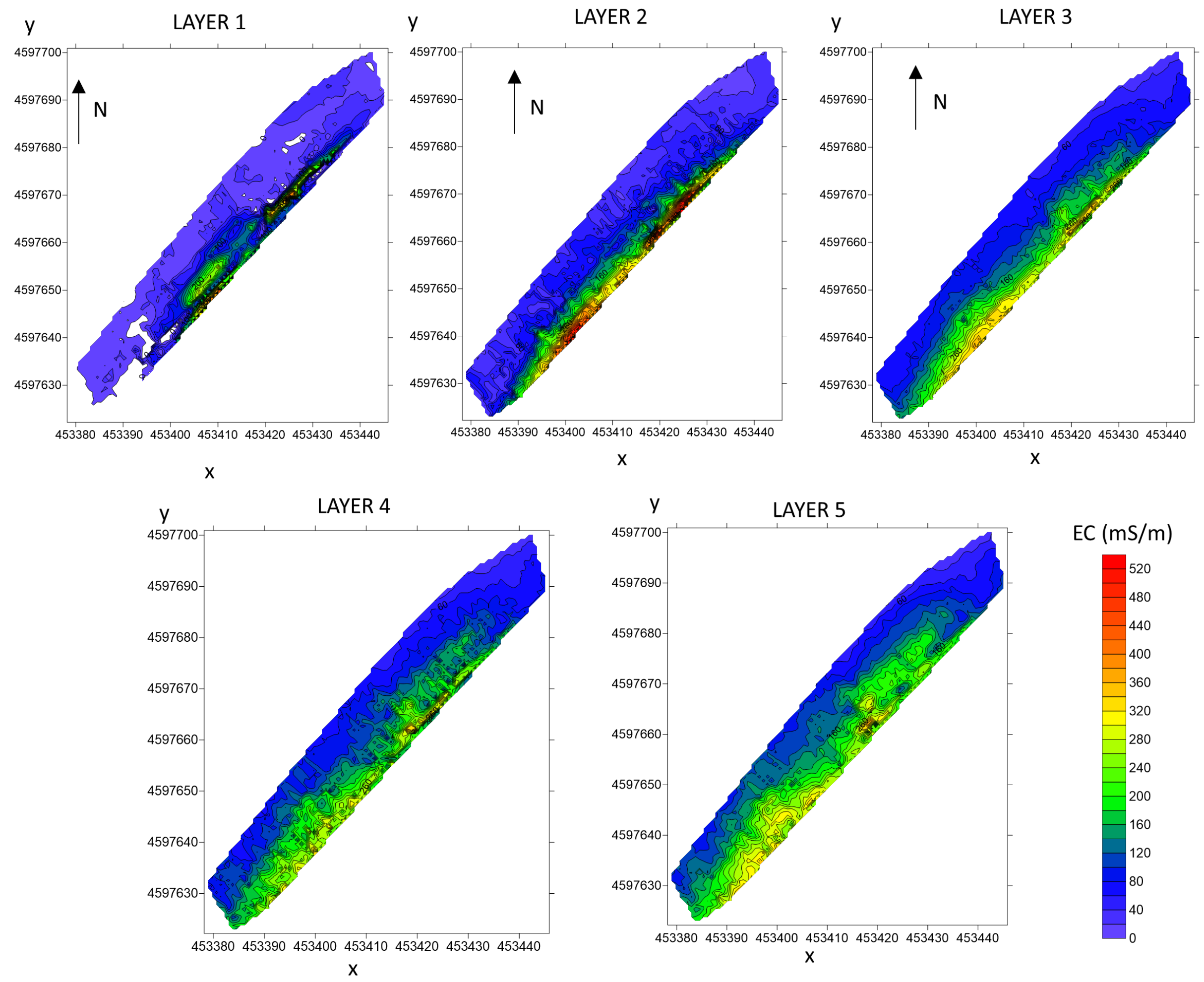

FIG. B3: Models for the merged data. From left to right and top to bottom: first layer (0 m-0.2 m), second layer (0.2 m-0.6 m), third layer (0.6 m -1.2), forth layer (1.2 m -1.6 m) and fifth layer (1.6 m -). The blank spaces at the first layer correspond to artefacts, areas with negative conductivity, which does not have physical meaning.

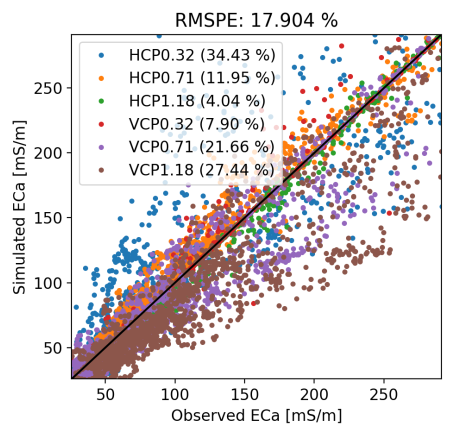

FIG. B4: RMSPE for the merged dataset with five layers at 0.2 m, 0.6 m, 1.2 and 1.6 m.