AEM survey of the Neretva Delta (Croatia): a case study for hydrogeology

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SUMMARY

Groundwater salinisation is a serious problem affecting numerous areas of the world, and Neretva's delta in Croatia is one of them. Airborne electromagnetics is already widely used to feed data-driven decision and management processes with accurate (hydro)geomodels and, by doing so, to mitigate the detrimental effects of salinisation.

In this perspective, in 2021, an airborne electromagnetic survey was flown over about 100 km^2. The overall goal of the survey was to better understand the hydrogeology of the plain leading to a more quantitative assessment of the saltwater intrusion and possible preferential paths.
Here, we present the results of data processing and inversion. We built a (pseudo-)3D resistivity model based on 1D forward approximation. And we compare it against ground-based electrical measurements. According to the available boreholes, freshwater is related to a relatively resistive unit.

Key words: inversion, saltwater intrusion, airborne electromagnetics, frequency-domain, time-domain.

INTRODUCTION

Over the past years, airborne electromagnetics (AEM) has become a key tool to tackle hydrogeological problems (Christiansen et al., 2006; Viezzoli et al., 2010; Ageev et al., 2022; Knight 2022). Specifically, numerous works have been devoted to investigating groundwater salinisation problems (Palamara et al., 2010; Ball et al. 2020; Tosi et al., 2022; Billy et al., 2022). Generally, during coastal surveys, it is reasonable to expect quite low resistivity values: in the order of 0.2-0.3 Ω·m for the seawater, and about 0.3-0.8 Ω·m for the seafloor. In our case, the task was to detect and characterise a relatively resistive layer supposedly at around 100-m depth. The target was quite challenging because of such a conductive overburden. The area under investigation was the Neretva Delta in Croatia (Figure 1). Originally, there were swamps, but now, the area is actively used for agricultural purposes. While the river itself is significantly affected by seawater encroachment, aquifers are less impacted by saltwater.

In terms of AEM measurements, in addition to the problems connected with the reduced signal penetration due to the electrically conductive environment, issues are due to the presence of sources of anthropic noise. In fact, together with several power lines crossing the investigated area, the northern portion of the survey is characterised by the presence of a DC-powered railway.

The AEM system used to perform the survey is EQUATOR (Figure 2). EQUATOR has been developed by Geotechnologies LLC as a tool providing EM data both in frequency and time domains (Moilanen et al., 2013; Karshakov et al. 2017; Moilanen 2022). Such a system was necessary to meet the goals of the project: high productivity (it can fly at 150 km/h), high vertical and lateral resolution (due to the capability to measure on-time and its 77 Hz base frequency) to infer the presence and characteristics of thin/shallow sand and clay lenses. On the other hand, to cope with the anthropic noise, instead of the commonly used spatial filtering (Kang et al. 2022), we managed to effectively remove the industrial noise in the frequency-domain by suppressing uniquely the disturbed frequencies. At the same time, the combination of the high base frequency and the conductive environment could have prevented reaching investigation depths of 100-150 m but, as shown in the following, this did not happen.

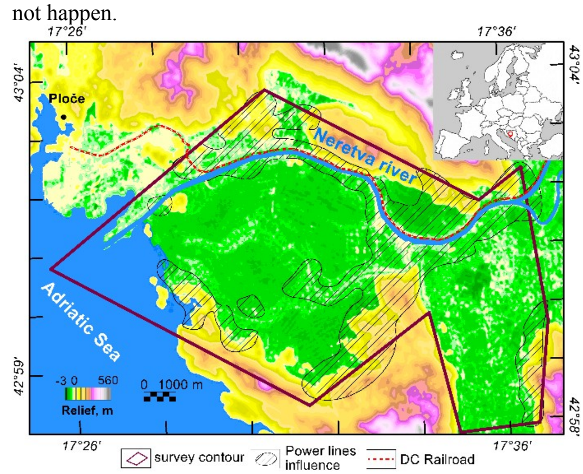

Figure 1. Overview of the survey area in Croatia.

DATA PROCESSING AND NOISE REMOVAL

Sometimes, industrial noise contaminates specific frequencies, close to harmonics of 50 Hz. In the Neretva survey, the most significant interference was found in the channels: 848 Hz (near the 17th harmonic of 50 Hz) and 540 Hz (near the 11th harmonic). In case of considerable amplitude of the industrial noise, also other harmonics were distorted. Clearly, from a time-domain perspective, noise components with low amplitude can impact merely the (low amplitude) late-time channels, whereas noise components with larger amplitudes might be able to significantly distort also earlier time gates (Figure 3). As an indicator of the presence of significant electromagnetic coupling, the 2nd-order variation of the un-normalized adjacent Im(B_z(f)) values (at 848 Hz) has been used: when such a variation was larger than a predefined threshold, distortions were expected in all time-domain channels. The hatching area in Figure 1 shows where the noise level is higher than the selected threshold; hence it is clear that almost half of the entire survey area is potentially heavily affected by anthropic noise and, without the proper data conditioning, the inversion of the measurements would lead to artifacts and possible misinterpretations.

Figure 2. The AEM system EQUATOR during the Neretva survey in Croatia.

METHOD AND RESULTS

Generally, AEM data are inverted via 1D forward modelling approximations assuming that the subsurface can be reasonably represented locally by a 1D resistivity parametrisation (Guillemoteau et al, 2011). In this framework, in order to enforce spatial coherence to the results and provide (quasi-)3D resistivity reconstruction of the investigated volume, several schemes have been implemented (e.g.: Viezzoli et al., 2009; Bai et al., 2021; Klose et al., 2022). An alternative, and extremely efficient, approach to ensure both vertical and lateral spatial consistency of the retrieved resistivity model (while, clearly, fitting the data equally well) is based on the iterated extended Kalman filter (Karshakov, 2020). Indeed, this is the approach used for the inversion of Neretva's dataset. In particular, the used parametrisation consisted of 20 layers, and we inverted the observed data uniquely to retrieve the layers' resistivity. The initial model was a homogeneous half-space with resistivity equivalent to apparent resistivity at 77 Hz. One additional advantage of the approach based on the Kalman filter is that it naturally provides the variances of the estimation error, which can be used for the calculation of the stochastic estimability of each layer (Golovan and Parusnikov, 1998). In this way, each layer can be also characterised in terms of estimation quality and, consequently, the local penetration depth for each measurement location across the survey area can be effectively assessed.

In the case of the Neretva Delta, saltwater intrusion is occurring due to several factors, including climate change and human activities: rising sea levels are causing seawater to encroach in the river and the surrounding aquifers (Lovrinović et al., 2021; Lovrinović et al., 2022). This is exacerbated by the overuse of groundwater for irrigation, which leads to a depletion of freshwater resources and an increase in the amount of saltwater entering the aquifers. In addition, the possible wrong siting of wells might endanger the quality of different aquifers by inadvertently connecting them. In this respect, it is worth noticing how the ground-based geophysical investigation - in particular, the performed electrical surveys - could not detect the deep conductor. On this matter, Figure 4 shows an example of electrical tomography not capable to properly reconstruct the deep low resistive anomaly.

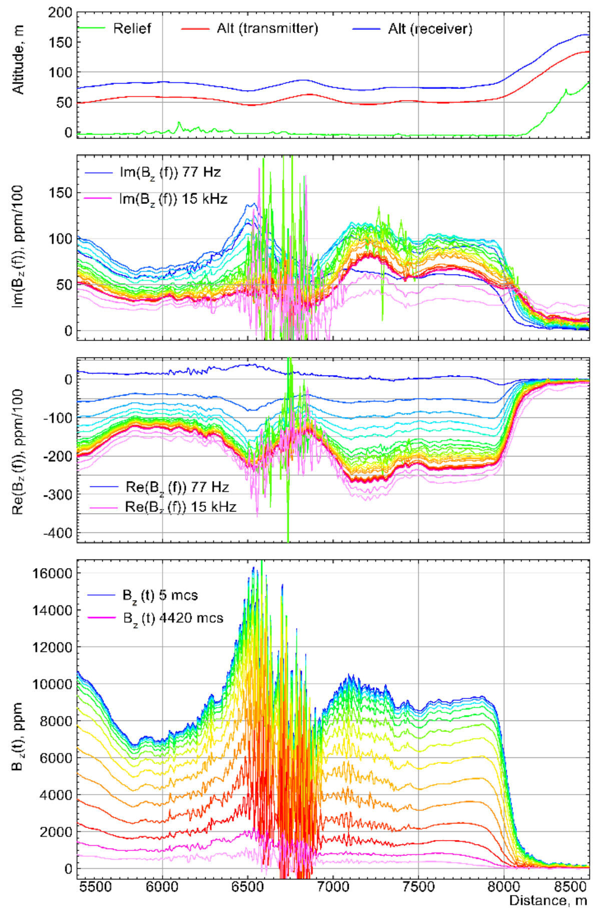

Figure 3. Industrial noise distortion on AEM data. Upper chart – the geometry of the system; central charts – imaginary and in-phase components of frequency domain data; bottom chart – time-domain data.

Similarly, in Figure 5, the bottom layer, as retrieved from the AEM data inversion, is characterised by a resistivity of 0.5. Ω·m and unknown thickness. In this context, such a low resistivity is a clear indication of saltwater presence, and in these cases, particular care should be put in siting the wells. In this respect, drilling should avoid areas in which the saltwater level could be particularly shallow (e.g.: the left side on Figure 5) and/or depths for which the pumping well could intersect unit saturated with saltwater (e.g.: the right part on Figure 5, in which the Drillhole 1 stops at the top of the last resistive unit). In Figure 6, we compare the stratigraphy deduced from Drillhole 1 against the electrical resistivity profile retrieved from the AEM data. To verify the survey proposals several drillholes were drilled (Figure 7). No freshwater has been found beneath the clay confining unit.

CONCLUSIONS

Groundwater resources need to be investigated and characterised to allow their most effective protection and management. This is particularly true in case of coastal aquifers endangered by climate changes, subsidence, sea level rising, or, more often, overexploitation concurrently causing saltwater intrusion.

In our specific case, we make use of the large coverage and dense sampling typical of AEM data to retrieve a (quasi-) 3D reconstruction of the subsurface resistivity distribution and, in turn, of the complex geology of the Neretva Delta in Croatia.

In particular, the characteristics of the AEM system EQUATOR allowed us to meet the requirements of high spatial resolution and to naturally perform an anthropic noise removal in the frequency domain (preserving almost all the collected soundings). Despite the conductive environment, the investigation depth could reach the remarkable depth of 225 m.

The AEM results have been corroborated by the numerous ground-based measurements and the information from boreholes. In the near future, the hydrogeological model based on the geological interpretation of the AEM results will be used for scenario analyses and to undertake the most effective initiatives to counteract the salinisation of the area.

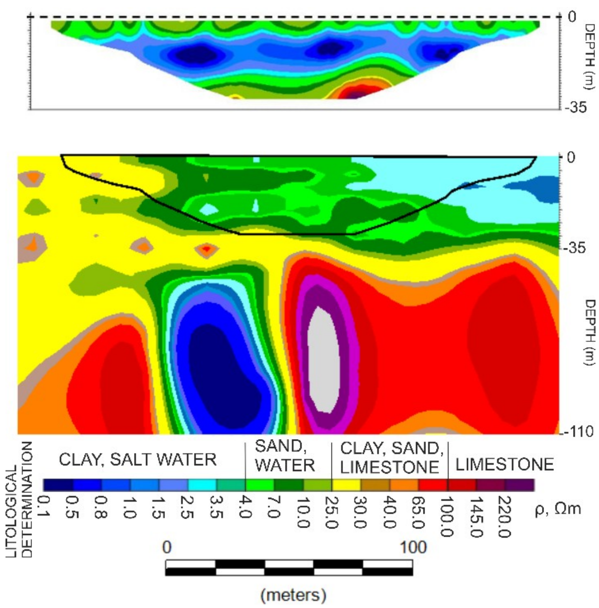

Figure 4. A geoelectrical cross-section retrieved by ground-based measurements (upper chart) compared with the AEM result.

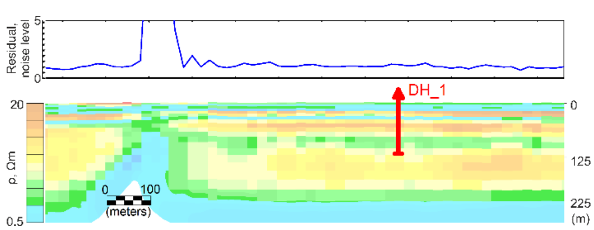

Figure 5. Resistivity section as retrieved by the AEM data (lower chart) with the corresponding data misfit (upper chart) and the location of Drillhole 1 (in red; See Figure 6).

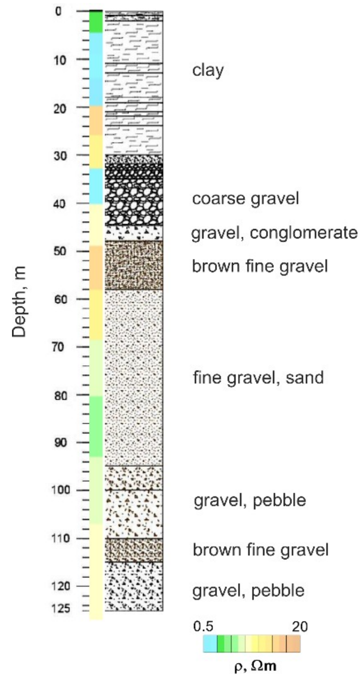

Figure 6. Stratigraphy of Drillhole 1 compared against the corresponding resistivity vertical profile as inferred from the inversion of the AEM data.

Figure 7. Drillhole B2 performed in February 2022.

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