Thematic Block C

Geophysical imaging of the salt content at the soda lakes from the Neusiedler See – Seewinkel National Park

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Abstract

The soda lakes of the National Park Neusiedlersee - Seewinkel harbor rare and endangered waterfowl species and plants adapted to these extreme biotopes only found in this area within Austria. The high salt content at the surface is driven by capillary forces that permit the up-flow transport of salt from the subsurface through a shallow soil layer characterized by low hydraulic permeability. Such a shallow soil layer also hinders the percolation of surface water; whereas while salt transport to the surface is only possible if the low permeable layer remains wet during the summer periods when evaporation reduces the volume of the surface water. Hence, soda lakes are sensitive to climate change because long dry periods or changes in the groundwater levels may degrade the soda lakes, endangering the rich biosphere that depends on them. The design of adequate methods to restore and preserve the soda lakes requires a good understanding of the surface-groundwater interactions that control the salt dynamics. In particular, it is required to understand the spatial variations of the water content, geometry, and hydraulic properties of the shallow soil layer, which ultimately control the salt dynamics in the soda lakes. To date, subsurface investigations in the soda lakes are still based on the analysis of soil and water samples, thus, they rely on the interpolation of discrete data and may be biased by the characteristics of the samples. To overcome this limitation, we propose applying electrical and electromagnetic geophysical methods, which permit to map variations in subsurface electrical conductivity based on non-invasive measurements in an imaging framework. The electrical conductivity is mainly controlled by water content, porosity and salinity, three relevant parameters driving salt dynamics. The combination of different geophysical methods allows for an improved interpretation of the results and permits the estimation of relevant parameters for managing soda lakes. In particular, we apply frequency-domain electromagnetic methods to map variations in the salt content at the lake-scale, while using monitoring measurements with electrical resistivity tomography to resolve temporal changes in water content at different depths. We obtained deeper information, as required to understand the geometry of the aquifers, by combining dc-resistivity measurements and transient electromagnetic soundings. We also deploy a joint inversion strategy combining induced polarization and refraction seismic to directly solve for porosity and the hydraulic conductivity in the soil layer and the aquifer in an imaging framework. Interpretation of the geophysical images is evaluated through the analysis of soil sediments in the laboratory.

Keywords: soda lakes, Seewinkel, Geophysics, salinity, conductivity, remediation, soil moisture, porosity

Introduction

The soda lakes of the Seewinkel sustain flora and fauna which subsist in the extreme biotopes only found in area within Austria. From the total area of lakes available in the XIX century, only 18% are conserved to date, with only five lakes considered to be in good conditions (e.g., Krachler et al., 2000). The degradation of the lakes has been attributed mainly to the rising temperatures and reduced precipitation in summer due to climate change, while groundwater extraction and other anthropogenic activities are also playing an important role. Current efforts to maintain and restore the soda lakes require a precise knowledge on the temporal and spatial variations of salt content, as well as the variability in relevant hydrogeological parameters, such as soil moisture and porosity in the near surface. Such information is critical for the management of the soda lakes in frame of climate change.

To date, the management of the soda lakes is based on subsurface information gained through borehole data, which provides precise measurements on water level, salt content and soil moisture. However, such investigations provide limited spatial information, as the number of boreholes and samples is minimized to reduce costs and the impact of the investigations on the soda lakes. Additionally, analysis of soil samples are not suited for monitoring purposes (e.g., Flores Orozco et al., 2019). Hence, the development of non-invasive methods able to characterize the dynamics of the salt content in the soda lakes is critical.

Electrical and electromagnetic geophysical methods are sensitive to the electrical properties of the subsurface. Hence, they are optimal tools to delineate changes in the salt content, considering that an increase in the salinity is related to higher electrical conductivity. Geophysical methods are non-invasive as the sensors are dragged along the surface, just requiring none-to-minimal contact with the ground. Accordingly, the use of geophysical methods permits to characterize larger areas without drilling or excavations (i.e., without affecting the soda lakes), permitting extensive investigations with higher details than those based on direct methods.

Here we demonstrate that we can use measurements of the electrical conductivity (σ) as a proxy to map variations in the salt content across the soda lakes of the Seewinkel. We propose the combination of induced polarization (IP) imaging - an electrical method - as well as the electromagnetic at low induction number (EMI) and transient electromagnetic (TEM) methods.

Methods

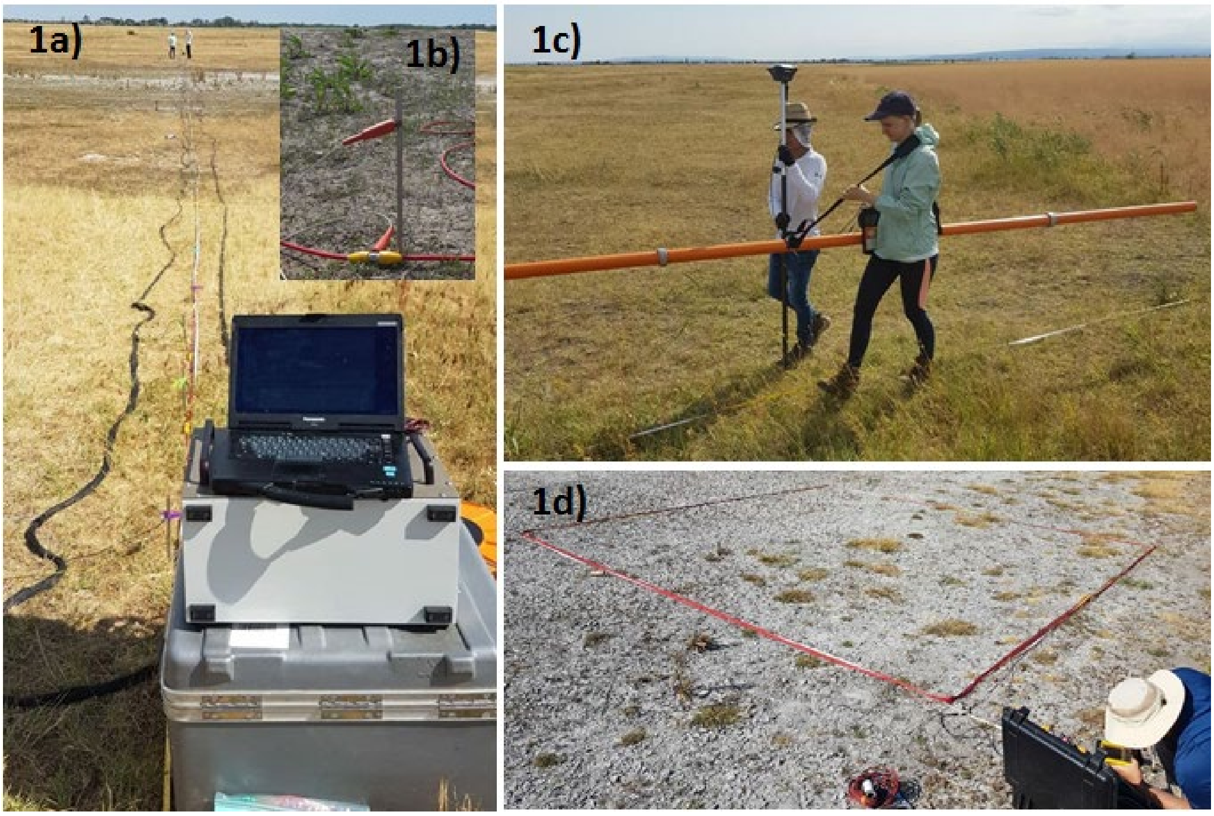

Figure 1: Geophysical methods deployed here: induced polarization, IP (Fig. 1a), requiring galvanic contact with the ground based on electrodes (Fig. 1b), as well as electromagnetic at low induction number, EMI (Fig. 1c) and transient electromagnetic, TEM (Fig. 1d).

The IP method is based on four electrode measurements, where two electrodes are used to inject current and other two permit to measure the resulting electrical impedance (Fig. 1a).

Electrodes are commonly stainless steel rods (with a diameter of 1 - 2 cm) which are hammered 3-4 cm into the ground to have galvanic contact with the measuring device (Fig. 1b). Measurements using tens of electrodes (for a few thousands of 4-electrode readings) together with an inversion algorithm permit to solve for changes in the electrical conductivity and capacitive properties of the subsurface. Here we present 2D imaging results as cross-sections from measurements collected with 72 electrodes (spacing between them either 0.5 or 1 m) using a Syscal Switch72 pro unit (from IRIS instrument), and current injections vary in the range between 10 and 100 miliamperes. The collection of a data set lasted about 30 minutes, and electrodes were removed afterwards; thus, without affecting the soil, flora or fauna.

EMI measurements were collected with the CMD-Explorer and CMD-Mini Explorer (from GF Instruments) to map electrical conductivity of the soil at varying depths between ca. 0.25 and 6.7 m. These instruments provide information about the electrical conductivity in real time, and do not require contact with the ground (Fig. 1c), as they are based on induction of an EM field. Also known as "terrain conductivity meters", the instruments provide measures of σ at the position of the device, which can be attached to one operator. Collection of the data is performed while walking (Fig. 1c), thus, permitting the elaboration of conductivity maps for different depths.

The TEM method provides information about the changes in depth of the electrical conductivity at a given point. As illustrated in Fig. 1d, the transmitter and receiver is a single wire laying on the floor forming a square (i.e., loop), where the circulation of a current and its sudden turn-off generates a primary EM field that propagates in the subsurface. Hence, variations in the secondary EM field over time provide information about changes in the electrical conductivity of the ground without need of galvanic contact. We use a single-loop configuration (the same cable is used as transmitter and receiver), yet conducted measurements with different loop-sizes (12.5 x 12.5, 25 x 25, 50 x 50, and 100 x100 m) to enhance the magnetic momentum and, thus, the depth of investigation. TEM measurements aimed at gaining information about the number of possible aquifers (and their thickness) in depths down to 75 m. Mapping TEM measurements were conducted with a 6 x 6 m loop to gain information about lateral changes in σ in depths between 1 and 10 m.

Results

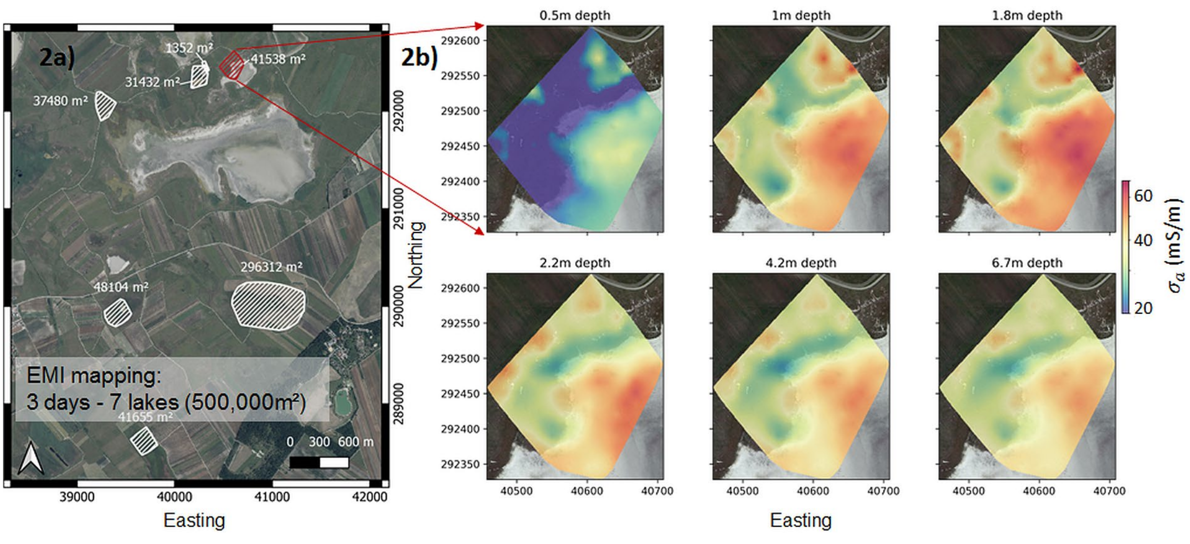

Figure 2: EMI measurements were conducted at different lakes covering a total area of 50 ha (Fig. 2a) to map variations in the apparent electrical conductivity (σ_a). Illustrative results are presented in Fig 2b for a selected lake (red polygon in Fig. 2a) in terms of the lateral changes in σ_a sensed at different depths. The σ_a represents the average conductivity from the surface to the nominal depth of investigation

EMI permits the mapping of large extensions with high spatial resolution in relatively short time. As presented in Fig. 2, we managed to cover an area of 50 ha in three days, corresponding to different soda lakes in the Seewinkel. We will discuss in detail the results obtained in the lake Katschitzl (Fig. 2b), yet similar conclusions can be drawn for the other lakes under investigation. Fig. 2b presents the lateral variations of the apparent conductivity (σ_a) in the same area at different depths. The apparent conductivity as the quantity represents an average value from the surface to the nominal depth of investigation. It can be observed that the lowest values ($\sigma_a < 30$ mS/m) are resolved in the shallower regions (0.5 m depth) to the North of the lake, where the vegetation is already visible on the surface; thus, indicating a degraded lake. In the active part of the Katschitzl lake, the conductivity is much higher (varying between 40 and 60 mS/m), yet clear lateral variations are observed, with some features revealing a main trend NW-SE. The limit between the high and low σ_a is in agreement with the geometry of the white sand in the orthophoto, corresponding to high salt concentrations observed at the surface (Fig. 2b). Such agreement can be consider as a first validation on the ability of the EMI results to delineate a lateral increase in the salt content as an increase in the σ_a values.

Lateral variations in σ_a are helpful to identify the geometry of the soda lakes. Moreover, EMI information reveals a significant decrease in the conductivity values at depths below 1.8 m. The decrease in the conductivity at depths is clearly related to the lower salt concentrations. However, σ_a values at depths below 1.8 m still are influenced by the high salinity in the near-surface. To solve for the actual conductivity at different depths, the inversion of the EMI data is required. After the inversion, it is possible to delineate the extension in depth of the conductivity anomalies. Such results can be found elsewhere (Hettegger, 2022) and will not be presented here, where EMI data is used for the mapping at large extensions.

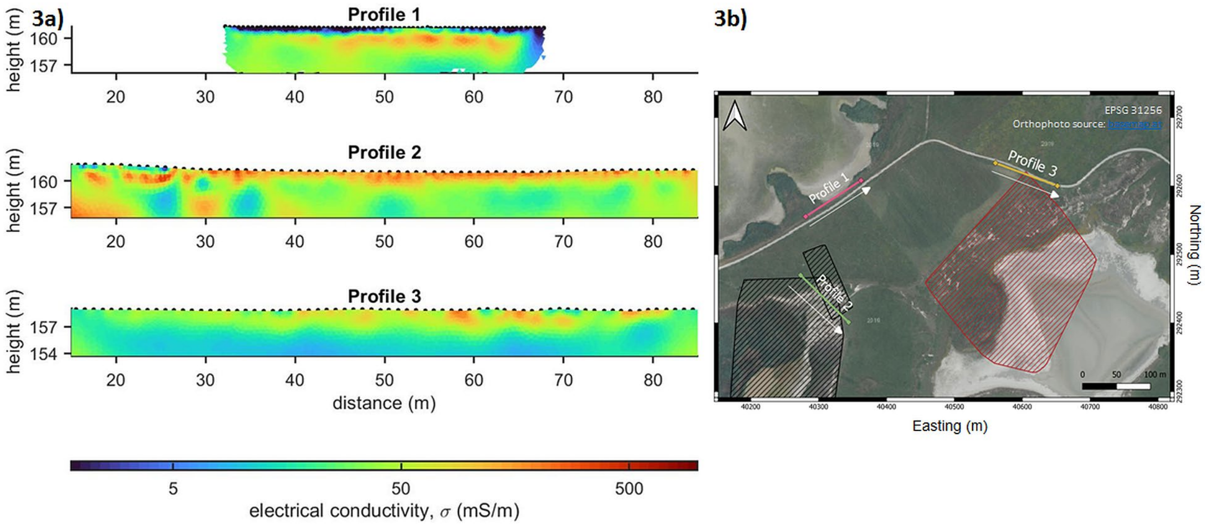

Figure 3: Conductivity (σ) results for data collected along Profiles 1, 2 and 3 (Fig. 3a). The position of the profiles in the soda lakes is presented on the orthophoto (Fig. 3b).

Fig. 3 shows the variations in σ resolved by means of the IP data collected at selected transects. Data were collected in Profile 1 with an electrode spacing of 0.5 m (resolution of 0.125 m), while in Profiles 2 and 3 the electrode spacing was 1 m (resolution 0.25 m). Fig. 2 reveals that the highest values ($\sigma > 60$ mS/m) are resolved in Profiles 1 and 2, corresponding to active lakes, whereas measurements in Profile 3 are related to much lower values ($\sigma < 50$ mS/m) in a degraded lake, in an area that is currently used as farming land. Plots in Fig. 3 also demonstrate that σ values retrieved with EMI and IP methods are comparable.

Imaging results for data collected in Profile 1 reveal three units: (i) a soil layer on the top (ca. 0.2 m thickness and $\sigma < 10$ mS/m), (ii) an intermediate layer corresponding to the salt-rich materials (ca. 0.5 m thickness and $\sigma > 50$ mS/m), and (iii) a bottom layer with moderate conductivity values (average 20 mS/m) corresponding to the aquifer. The high σ values in the second layer are clearly related to the accumulation of salts, which are transported upwards due to capillary forces. The salts act as free ions in the pore water that facilitate current conduction, thus, the increase in the electrical conductivity. However, as revealed in Fig. 2, the salt-rich layer is not continuous across the lake, with variations in the thickness and lateral extension. In particular, Fig. 2 reveals important lateral variations along profile 2, with much lower values in the first third of the profile, evidencing much lower salt content, likely a degraded part of the lake. Lateral changes are also observed along Profile 2, which also show the thicker layer between 45 and 55 m distance, corresponding to the most active part of the lake, where capillary forces result in a larger accumulation of salts.

Capillary forces at the top of the phreatic surface leads the upwards transport of salts, as well as clays. Consequently, an impermeable layer is formed close to the surface due to the clays clogging the pore space (Flores Orozco et al., 2019). The geometry of such impermeable layer is evidenced for the three electrical profiles in Fig.2 associated to the highest σ values. Such impermeable layer hinders the percolation of surface water and permits the formation of lakes following raining events. Likewise, lateral variations in such layer with low conductivity values, for instance in the first 10 m of Profile 1 (Fig 3.) are indications of degrading conditions in a soda lake, i.e., where salts are not being transported upwards anymore. Likewise, images of Profile 3 (Fig. 3) revealing only modest conductivity values, clearly indicate a degraded lake.

The presence of clays limits a direct quantification of salt content from σ values. This is because clay minerals act as a second path for current conduction, due to the accumulation of charges in the so-called electrical double layer (EDL) formed at the interface between clay surface and the pore water (see Flores Orozco et al., 2020). Hence, during current injection, the extra charges accumulated at the EDL form an alternative path for current flow, known as surface conductivity. It has been noticed that surface conductivity might dominate over electrolytic conduction, especially in soils with high clay content and organic matter (e.g., Flores Orozco et al., 2019; 2020; Katona et al., 2021). IP measurements provide information on both the conductive and capacitive properties of the subsurface. The former is controlled by both surface and electrolytic conduction; whereas the latter is only a function of the surface conductivity. Accordingly, images of the capacitive properties (only related to the polarization of the EDL) may help to improve the interpretation of the conductivity images.

In Fig. 4 we present the IP imaging results obtained for Profile 2, yet expressed in terms of the complex-valued electrical conductivity, where the real component (σ') is related to the conduction, while the imaginary component (σ'') to the polarization effect. Such plots reveal that the polarization effect ($\sigma'' < 0.5$ mS/m) is negligible within an active soda such as Profile 2. The high salinity of the active soda lakes is reducing the mobility of the ions in the EDL; thus, hindering surface conduction mechanisms (e.g., Flores Orozco et al., 2019; Katona et al., 2021). Hence, an increase in σ'' may permit a quick identification of areas where the impermeable layer has been washed out, likely related to a degraded part of the soda lake.

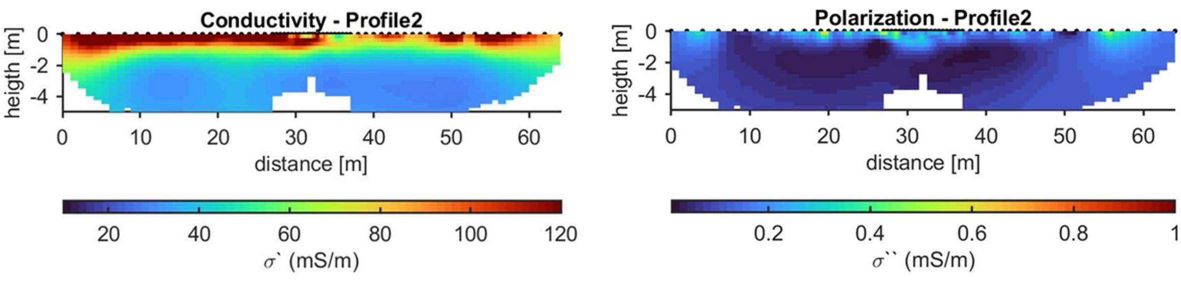

Figure 4: IP imaging results for data collected along Profiles 2 expressed in terms of the conductivity (σ') and polarization (σ''). Blanked areas refer to model parameters of poor sensitivity.

To gain information about the geometry of the aquifer underlying the salt-rich impermeable layer, we conducted TEM soundings in the area between Profiles 2 and 3. Data were processed using the steps described by Aigner et al. (2021), and a 2D section of the study area was elaborated by interpolating the 1D electrical conductivity models obtained. To differentiate these from previous results, we present in Fig. 5 the electrical model obtained by means of TEM soundings in terms of the electrical resistivity (ρ), the inverse of the electrical conductivity ($\rho = \frac{1}{\sigma}$). TEM results presented in Fig. 5 reveal the existence of two aquifers in the area of study: (1) a shallow aquifer between 2 m and 10 m depth, and (ii) a deeper aquifer between 20 m and 30 m depth.

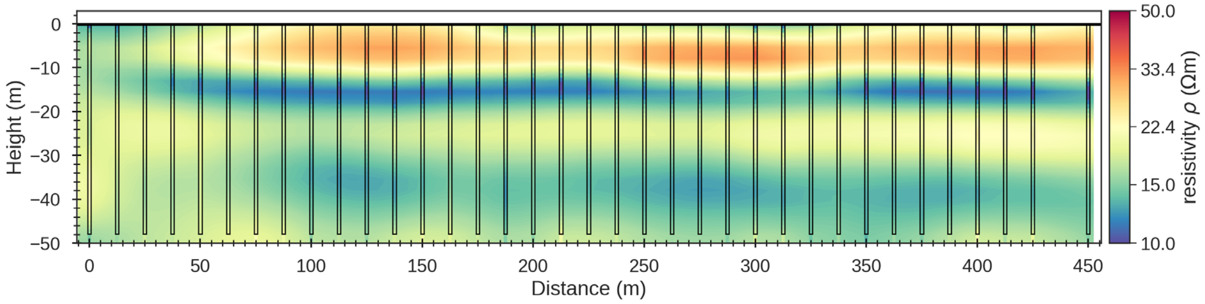

Figure 5: TEM imaging results presented in terms of the electrical resistivity (ρ), the inverse from the conductivity ($\rho = 1/\sigma$), to differentiate those from the EMI and IP. TEM soundings were collected in the area between Profiles 1 and 3.

Conclusions

We demonstrate that EMI permits to map extensive areas with high lateral resolution, as required to identify variations in salt content, as well as preferential flowpaths for surface water; whereas IP permits to gain detailed information at depth, in particular to characterize the geometry of the shallow impermeable layer and well as spatial variations in clay and salt content. TEM measurements permit fast investigations at depth required to delineate the geometry of the aquifer. Ongoing research corresponds to the repetition of geophysical measurements for a non-invasive monitoring of changes in soil moisture, clay and salt content. Additionally, we test the use of joint inversion schemes that simultaneously solve electrical resistivity and refraction seismic datasets to obtain the spatial variations of porosity and soil moisture.

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