Integration of geophysical and groundwater electrical conductivity data in a coastal aquifer for monitoring saltwater intrusion dynamics

Lorenzo De Carlo[1], Maria Clementina Caputo[1], Rita Masciale[1], Antonietta Celeste Turturro[1], Ivan Portoghese[1], Giuseppe Passarella[1]

[1] National Research Council of Italy – Water Research Institute, Via F. De Blasio 5 70132 Bari, Italy
lorenzo.decarlo@cnr.it

Abstract.

This research focuses on monitoring saltwater intrusion dynamics in a coastal aquifer in Southern Italy.

In the Torre Guaceto area, a multidisciplinary approach, based on the geophysical Electromagnetic Induction (EMI) technique and groundwater electrical conductivity (EC) data was applied. The EMI survey was carried out, between November 2022 and January 2024, along a 2.5 km transect, perpendicular to the coastline covering both agricultural and wetland landscapes. The data were collected over time to assess the space-time variation of the bulk EC. Likewise, the groundwater's EC was monitored using probes installed in two wells and a coastal pond at varying distances from the sea along the transect. The geophysical model helped identify a highly conductive plume potentially associated with saltwater intrusion, determine the plume's extent, and monitor coastal dynamics by tracking its evolution over time. The continuous EC groundwater values recorded at the monitoring points, situated at increasing distances from the coastline, confirmed the findings of the geophysical model. This integrated approach has proven reliable for monitoring saltwater intrusion dynamics in coastal aquifers at different spatial scales.

Keywords: coastal aquifer dynamics, saltwater intrusion, integrated monitoring, Electromagnetic Induction data, groundwater electrical conductivity.

1 Introduction

The saltwater intrusion process strongly affects groundwater quality in Mediterranean coastal areas, significantly reducing fresh water for drinking and irrigation over time.

In the past decade, an integrated approach based on geophysical techniques combined with traditional measurements in wells has been successfully employed to investigate coastal aquifer dynamics. In particular, noninvasive geophysical methods have been widely used due to their ability to detect soil moisture and salinity (De Carlo et al. 2024; McLachlan et al. 2021; von Hebel et al., 2014). Additionally, conventional hydrogeological measurements from wells are usually used to gain direct information about groundwater quality (Frollini et al., 2022; Hanafy & Benaafi, 2024).

This integrated approach was applied to the Torre Guaceto study area (Fig.1), a Natural State Reserve hosting a coastal wetland surrounded by an intensive agricultural landscape in the southeastern part of the Apulia region (Southern Italy). In its agricultural portion, this transect passes through rainfed crops (olive groves and winter wheat) and irrigated vineyards supplied by saline groundwater wells. The approach aimed to define the area’s hydrogeological characteristics, identify a highly conductive plume associated with saltwater intrusion, determine the extent of the plume, and monitor coastal dynamics by tracking the plume's evolution over time.

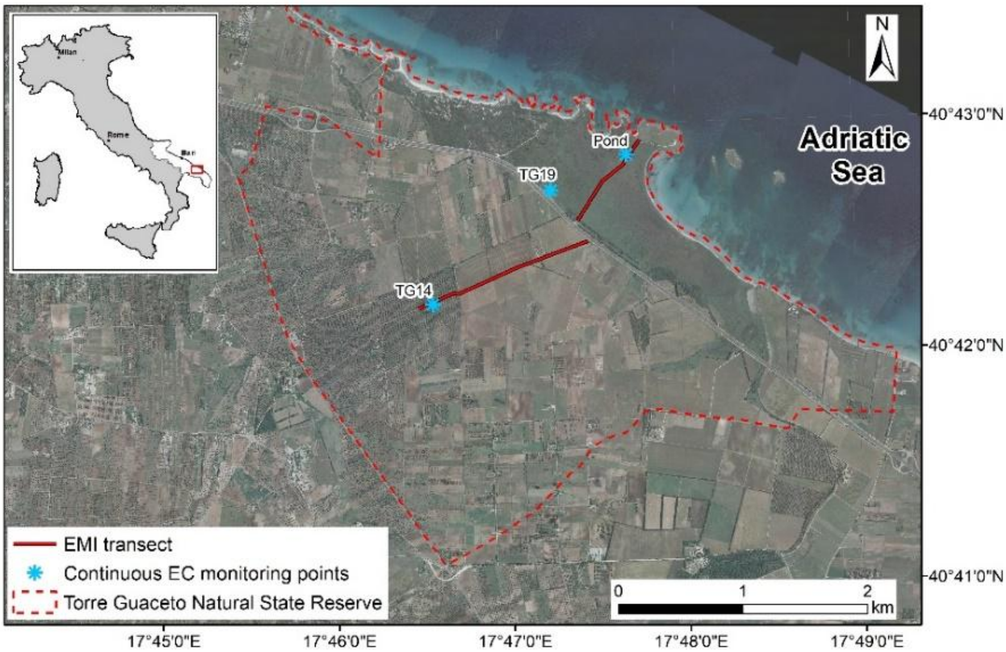
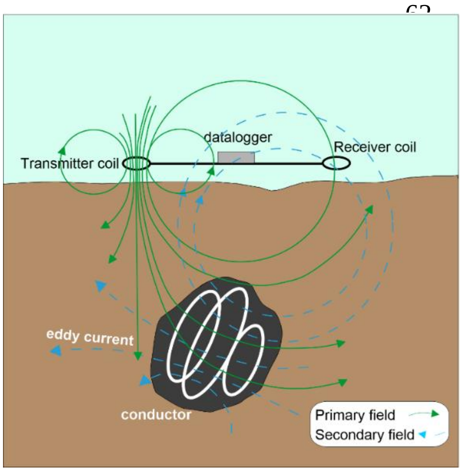


Fig. 1. Location of the experimental site.

2 Materials and Methods

The electromagnetic Induction (EMI) technique, also called Frequency Domain Electromagnetics (FDEM), is based on the induction of electrical currents in the conductive subsurface through electromagnetic waves generated on the surface. Fig. 2 shows a simple description of the basics. EMI measurements do not require any galvanic contact between the sensor and the conductive medium.



In addition, EMI data are on-the-go field measurements, allowing the gathering of a large amount of spatial data in a relatively short time. A transmitter coil generates an alternate current that spreads into the subsurface. As the electromagnetic (EM) waves travel through different materials, eddy currents induce secondary EM fields. At the surface, a receiver coil records a signal that is the sum of the primary and secondary fields.

Fig. 2. Basics of EMI technique

The components of the secondary field that are in phase with the primary transmitted field and that portion that is 90 degrees out of phase (the quadrature component), are measured by a data logger. Under normal subsurface conditions, the in-phase component is strongly affected by buried metallic objects, while the quadrature component is directly related to the subsurface conductivity (McNeill, 1980).

In the experimental site, the EMI campaigns were performed between November 2022 and June 2024 along the same transect 2.5 Km long, located about perpendicular to the coastline (Fig. 1). The CMD DUO sensor (GF Instruments s.r.o., Czech Republic) collected electromagnetic data. The sensor consists of two independent coils, a transmitter, and a receiver connected by a flexible cable. The transmitter coil is energized with an alternating current at 925 Hz, the receiver can be used at various inter-coil distances from the transmitter, one at a time. In this study, a combination of three different cables (10 m, 20 m, and 40 m long) and coils configuration (VCP and HCP) was used to deepen the investigation to the maximum depth.

Since the data collected in the field are apparent electrical conductivity (ECa) they were processed through an inversion procedure to obtain an accurate distribution of the true electrical conductivity. The EM4SOIL code (EMTOMO) uses a nonlinear smoothness-constrained inversion algorithm for producing quasi-2D conductivity imaging. A forward modeling subroutine, based on the cumulative function, is used for solving the EM fields and calculating the theoretical ECa responses at the nodes of a tridimensional mesh of hexahedral blocks, distributed according to the locations of the measurement points.

The data were collected at three different time points to evaluate the changes in electrical conductivity over time. Along such transect, the EC of the groundwater was monitored using a submersible data logger for long-term monitoring (CTD-Diver®, Van Essen Instruments B.V.) installed at different distances from the sea: in two wells (TG14, TG19) and the pond (PND00) (Fig. 1).

3 Results and discussion

Figure 3 shows the EMI cross-sections taken from November 2022 to January 2024. On November 22 (Figure 3a), a layered model was observed upstream of the cross-section, consisting of an upper resistive body (EC < 20 mS/m) overlaying a lower conductive layer (20 < EC < 70 mS/m) below the rein-fed olive grove. A sloping discontinuity surface (black dotted line) marks the transition between the resistive unsaturated zone and the conductive groundwater. Moving downstream, the upper resistive layer thins and eventually disappears at approximately 1800 m from the start of the cross-section. Meanwhile, the electrical conductivity of the bottom layer increases as we move towards the sea, about 1250 m from the start of the section, due to groundwater salinity rising (EC>10 mS/m up to 200 mS/m).

Approximately a year later, in September 2023, the highly conductive body, associated with the salt wedge, intruded about 200-250 m inland (Figure 3b). Moreover, significant variations in EC were observed in the area closest to the sea. In particular, the EC increased by about 30% near the pond in September 2023 compared to November 2022. In January 2024, the trend observed in September 2023 was confirmed, indicating negligible movement of the salt wedge (Figure 3c). Meanwhile, the EC in the area towards the sea had returned to levels comparable to November 2022. In addition, on top of the profile, the alternation between higher and lower resistive bodies is preserved thus underlining a possible correlation between saline water irrigation and the 2D patterns of EC in the unsaturated zone.

Direct EC measurements in groundwater along the transect closely reflect the trend identified by geophysical techniques (Figure 4) showing a progressive salinity influence from inland to the coast.

The EC values in well TG14 remain almost constant throughout the monitoring period, well TG19 shows a consistent EC increase during the irrigation period, while the EC measured in the pond is extremely variable in time being affected by precipitation during the Winter (decrease) and withdrawals and evaporation phenomena during the Summer (increase).

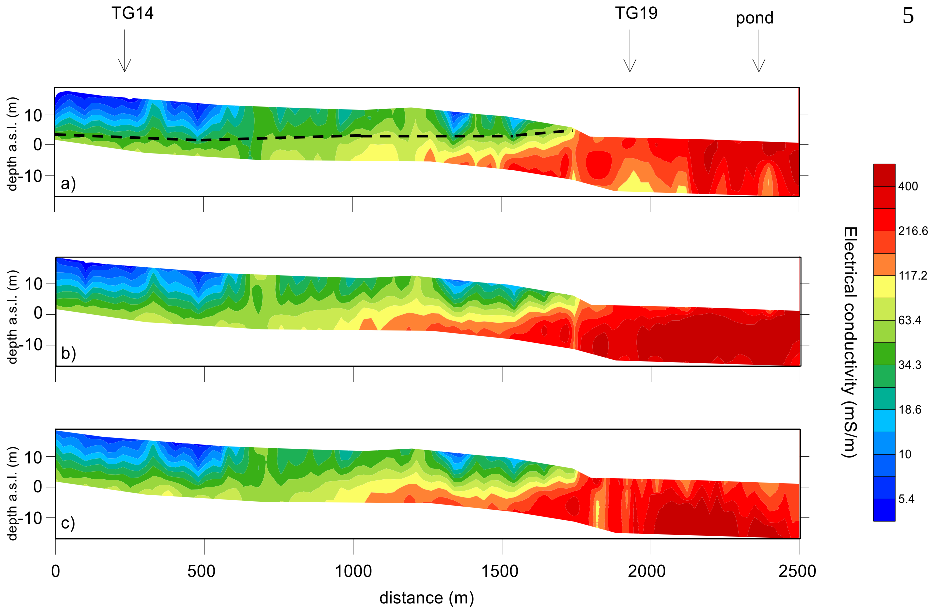


Fig. 3. Inverted EMI cross-sections referred to: a) November 2022; b) September 2023; c) January 2024

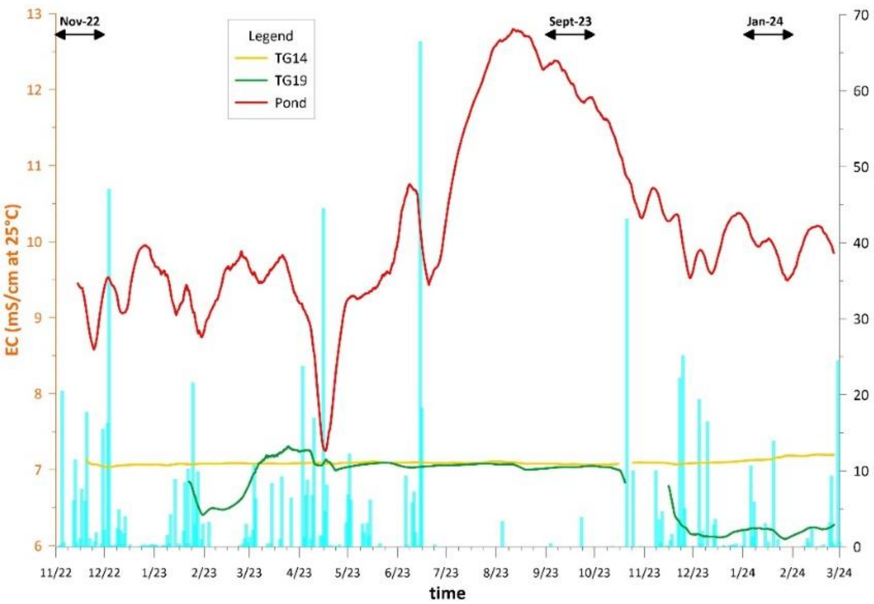


Fig. 4. Continuous monitoring of EC values (running average-window width 1 week) recorded in the monitoring points TG14, TG19 and pond. The periods of geophysical surveys are also indicated.

4 Conclusions

The integrated approach has proven to be an effective tool for monitoring saltwater intrusion dynamics at various spatial scales. The comparison between direct EC measurements in groundwater and EMI outputs confirmed the latter's strong potential for revealing details about subsurface structures that would otherwise remain unpredictable without widespread point measurements. The adopted approach seems also promising for investigating salinization in the unsaturated zone caused by irrigation with saline waters.

Funding

This research was partially funded by the NextGenerationEU, within PRIN PNRR FU.CO.KA Project - Future scenarios in coastal karst: saltwater intrusion, loss of water resources and sinkhole development as effects of climate changes, P2022JZHKM.

References

1. De Carlo, L., Turturro, A.C., Caputo, M.C., Sapiano M., Mamo, J., Balzan, O., Galea, L., Schembri, M.: Mapping saltwater intrusion via Electromagnetic Induction (EMI) for planning a Managed Aquifer Recharge (MAR) facility in Maltese Island Acque Sotterranee - Italian Journal of Groundwater 13(1), 07–15 (2024).
2. Frollini, E., Parrone, D., Ghergo, S., Masciale, R., Passarella, G., Pennisi, M., Salvadori, M., Preziosi, E.: An integrated approach for investigating the salinity evolution in a Mediterranean coastal karst aquifer. Water 14 (11), 1725 (2022).
3. Hanafy, S., Benaafi, M.: Investigating seawater intrusion and salinization using the integration of hydrochemical and geoelectrical techniques. Geophysics 89(5), B329-B338 (2024).
4. McLachlan, P., Blanchy, G., Chambers, J., Sorensen, J., Uhlemann, S., Wilkinson, P., Binley, A.: The application of electromagnetic induction methods to reveal the hydrogeological structure of a riparian wetland. Water Resources Research, 57(6) 1–20 (2021).
5. McNeill JD. Electromagnetic terrain conductivity measurement at low induction numbers: Geonics, Technical Note TN-6 (1980). Available at: http://www.geonics.com/ pdfs/technicalnotes/tn6.pdf
6. von Hebel, C., Rudolph, S., Mester, A., Huisman, J.A., Kumbhar, P., Vereecken, H., van der Kruk, J.: Three-dimensional imaging of subsurface structural patterns using quantitative large scale multiconfiguration electromagnetic induction data. Water Resources Research 50(3), 2732–2748 (2014).