DOI 10.7343/as-2024-743

ACQUE SOTTERRANEE
Italian Journal of Groundwater
journal homepage: https://www.acquesotterranee.net/

2024-AS48-743: 07 - 15

Mapping saltwater intrusion via Electromagnetic Induction (EMI) for planning a Managed Aquifer Recharge (MAR) facility in Maltese Island

Mappatura dell'intrusione dell'acqua salata con la tecnica ad induzione elettromagnetica nell'isola di Malta per progettare un impianto di Ricarica dell'Acquifero Gestita (MAR)

Lorenzo DE CARLO[a], **Antonietta Celeste TURTURRO**[a] , **Maria Clementina CAPUTO**[a], **Manuel SAPIANO**[b], **Julian MAMO**[b], **Oriana BALZAN**[b], **Luke GALEA**[b], **Michael SCHEMBRI**[b]

[a] National Research Council (CNR), Water Research Institute (IRSA), Bari, Italy - email : *celeste.turturro@ba.irsa.cnr.it* - *lorenzo.decarlo@ba.irsa.cnr.it; maria.caputo@ba.irsa.cnr.it*

[b] Energy and Water Agency (EWA), Malta - email: *manuel.sapiano@gov.mt; julian.a.mamo@um.edu.mt; oriana.balzan@gov.mt; luke.j.galea@gov.mt; michael.schembri@gov.mt*

ARTICLE INFO

Ricevuto/*Received*: 15 December 2023
Accettato/*Accepted*: 4 March 2024
Pubblicato online/*Published online*: 27 March 2024

Handling Editor:
Antonio Menghini

Citation:
De Carlo, L., Turturro, A.C., Caputo, M.C., Sapiano M., Mamo, J., Balzan, O., Galea, L., Schembri, M. (2024). 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
https://doi.org/10.7343/as-2024-743

Correspondence to:
Turturro Antonietta Celeste
celeste.turturro@ba.irsa.cnr.it

Keywords: *: Electromagnetic Induction (EMI) technique; saltwater intrusion; Managed Aquifer Recharge (MAR).*

Parole chiave: Tecnica ad Induzione Elettromagnetica; intrusione salina; Ricarica dell'acquifero gestita (MAR).

Riassunto

Nelle zone costiere, l'intrusione di acqua salata causa un esaurimento della risorsa riducendo l'approvvigionamento di acqua dolce potabile e di irrigazione e causando un grave deterioramento della qualità delle risorse idriche sotterranee.

Questo trend è osservato nella valle di Pwales (Isola di Malta), dove la gestione della risorsa idrica svolge un ruolo cruciale per la sostenibilità ambientale della zona, considerata la sua forte vocazione agricola. Al fine di contrastare questo fenomeno, così come altri effetti dei cambiamenti climatici, azioni o misure di adattamento ai cambiamenti climatici sono fortemente richieste. Per esempio, il Managed Aquifer Recharge è una tecnica di gestione idrica in grande sviluppo perchè in grado di mantenere, e garantire la salvaguardia di sistemi idrici sotto stress e, al tempo stesso, di proteggere e migliorare la qualità dell'acqua.

Per pianificare in maniera accurata un impianto Managed Aquifer Recharge è fondamentale definire un modello idrogeologico dell'area studiata, integrando sia misure idrogeologiche tradizionali che innovative tecniche non convenzionali.

Negli ultimi anni, le misure a induzione elettromagnetica, basate sui dati di conducibilità elettrica del sottosuolo, sono state sempre più utilizzate per studiare le dinamiche di intrusione salina in ambito costiero a causa della loro elevata sensibilità alla salinità.

Nell'isola di Malta un impianto pilota Managed Aquifer Recharge è stato progettato nel piccolo bacino della Pwales Valley. A supporto di tale progetto, è stata effettuata un'indagine a induzione elettromagnetica per caratterizzare l'idrogeologia dell'area. In pochi giorni sono stati acquisiti complessivamente più di 20.000 dati di conducibilità elettrica apparente (ECa) in modo da generare un modello quasi 3D ad alta risoluzione di conducibilità elettrica della Pwales Valley. I risultati hanno evidenziato l'estensione spaziale dell'intrusione di acqua salata a forma di lingua da Est a Ovest lungo la valle, nonché alcune peculiarità geologico-idrogeologiche come lo spessore del cuneo salino e la superficie superiore irregolare dello strato inferiore impermeabile, non rilevabile con altre tecniche di investigazione comunemente utilizzate. Questo approccio si conferma uno strumento utile per un'efficace caratterizzazione idrogeologica, essenziale per la pianificazione delle azioni di mitigazione e per affrontare i cambiamenti climatici o le misure di adattamento, come ad esempio impianti di ricarica artificiale Managed Aquifer Recharge.

Abstract

In coastal areas, saltwater intrusion causes a depletion of the resource by reducing potable and irrigation freshwater supplies and causing severe deterioration of groundwater quality.

This trend is observed in Pwales Valley, in the North part of Malta where the management of water resources plays a crucial role for the environmental sustainability of the area, given the importance of intensive agricultural activity along this valley. In order to tackle such phenomenon, actions or adaptation measures against climate change are strongly required. For example, Managed Aquifer Recharge (MAR) is an increasingly important water management strategy to maintain, enhance and secure stressed groundwater systems and to protect and improve water quality.

To accurately plan a Managed Aquifer Recharge scheme, it is crucial to define a hydrogeological model of the studied area, with the use of traditional hydrogeological measurements and innovative unconventional techniques. In recent years, Electromagnetic Induction measurements, based on induction of em fields, have been increasingly used for investigating the saltwater intrusion dynamics due to their high sensitivity to the salinity.

In the study area of Pwales Valley, a Managed Aquifer Recharge scheme is being planned and, for this aim, a hydrogeological model has been developed through an Electromagnetic Induction survey.

More than 20,000 apparent electrical conductivity (ECa) data were collected to generate a quasi 3D high-resolution model of electrical conductivity of the Pwales Valley. The results highlighted the spatial extension of the tongue-shape salt water intrusion from east to west along the valley, as well as some geological-hydrogeological peculiarities such as the thickness of the salt wedge and the irregular top surface of the bottom impermeable layer, otherwise undetectable with other direct techniques at the field scale resolution. The approach was confirmed to be a useful tool for an effective hydrogeological characterisation, essential for planning adaptation measures to a changing climate, such as the implementation of a Managed Aquifer Recharge scheme.

Introduction

In many coastal areas of the Mediterranean area, groundwater remains one of the main sources of potable and agricultural water. In the last decades, the high rates of population growth, coupled with uncontrolled water consumption, is causing increased water needs and, consequently, stress on the groundwater resource. For this reasons, coastal aquifers are extremely vulnerable to the impact of human activities (Aslam et al., 2018; Ferguson et al., 2012; Frollini et al., 2022; Iyalomhe et al., 2015; Lu et al., 2022; Post & Werner, 2017; Qin et al. 2013).

Coastal zones face many hydrogeological problems mainly due to the seawater intrusion into coastal aquifers (Alfarrah et al., 2018; Bellafiore et al., 2021; Colombani et al., 2016; Costall, et al., 2020; Masciale et al., 2021; Moore & Joye, 2021). In addition, climate changes effects, such as sea level rise, amplify saltwater intrusion leading to groundwater quality degradation and quantitative depletion (Ketabchi et al., 2016; Masciopinto & Liso, 2016; Werner & Simmons, 2009). At the same time, the use of salty groundwater for irrigation can cause severe salinization of soils by reducing its quality and increasing land degradation (Tarolli et al., 2023; Tully et al., 2019; Zaccaria et al., 2016).

Since the negative effects of saltwater intrusion are expected to increase over time affected by climate change, a better understanding of the phenomenon and its origin, dynamics, evolution, and impacts is needed for planning effective actions to optimize water management practices. Among these, Managed Aquifer Recharge (MAR) is an increasingly important water management strategy, alongside demand management, to maintain, enhance and secure stressed groundwater systems and to protect and improve water quality (Dillon et al., 2019; Masciopinto, 2013; Page et al., 2018; Ringleb et al., 2016;).

MAR is the intentional groundwater replenishment through wells, ditches and trenches in order to increase groundwater storage.

In order to plan a MAR facility, it's crucial to define an accurate hydrogeological model of the studied area. Traditional techniques based on measurements in existing groundwater sources are not always able to accurately provide detailed information due to the poor distribution of wells, as well as the limited capability to collect synchronous data at different depths.

Recently, geophysical techniques are widely used to investigate coastal area dynamics because they can gather a large amount of data in relatively short time.

Among geophysical techniques, Electromagnetic Induction (EMI) is sensitive to soil moisture and salinity because the electrical conductivity, or its inverse electrical resistivity, mainly depends on both water, that moves into the rock/soil, and dissolved salts. EMI is a geophysical technique widely used for several issues such as: hydrological characterization (Boaga et al., 2018; Brosten et al., 2011; Cassiani et al. 2012; McLachlan et al. 2021; Revil et al., 2012; Robinson et al., 2008; von Hebel et al., 2014), characterization and monitoring of landfills (Buselli et al., 1992; Deidda et al., 2022; Jansen et al., 1992; Martinelli et al. 2008; Tezkan, 1999), archeological applications (Christiansen et al., 2016; De Smedt et al., 2014; Guillemoteau et al., 2023; Lascano et al., 2006; Osella et al., 2005) and precision agriculture (Brogi et al. 2019; De Carlo et al. 2022; Dragonetti et al., 2018; Yao et al., 2010; Kaufmann et al., 2020; Minsley et al., 2012; von Hebel et al., 2021; Jadoon et al., 2015).

An EMI survey has been carried out in the study area of Pwales Valley on the island of Malta where a MAR scheme is being design for the storage and recovery of highly treated wastewater, locally known as New Water.

The aim of the geophysical survey was to define the hydrogeological setting of the valley, with particular regard (i) to recognize the highly conductive plume associated to the saltwater intrusion, (ii) define the extension of the plume and (iii) identify the top of the Blue Clay Formation, which represents the bottom of the aquifer.

Material and methods

Study area

The study area is Pwales Valley, located in the Northern part of the Maltese Island (3977319 N – 443018 E WGS UTM84), with an extension of about 2 Km^2 (Fig. 1). The area has a strong agricultural vocation and, at the same time, tourist attractions in the outermost parts of the valley (Golden Bay Beach in the West and Simar Natural Reserve in the East). From a geological point of view, Pwales Valley is a graben

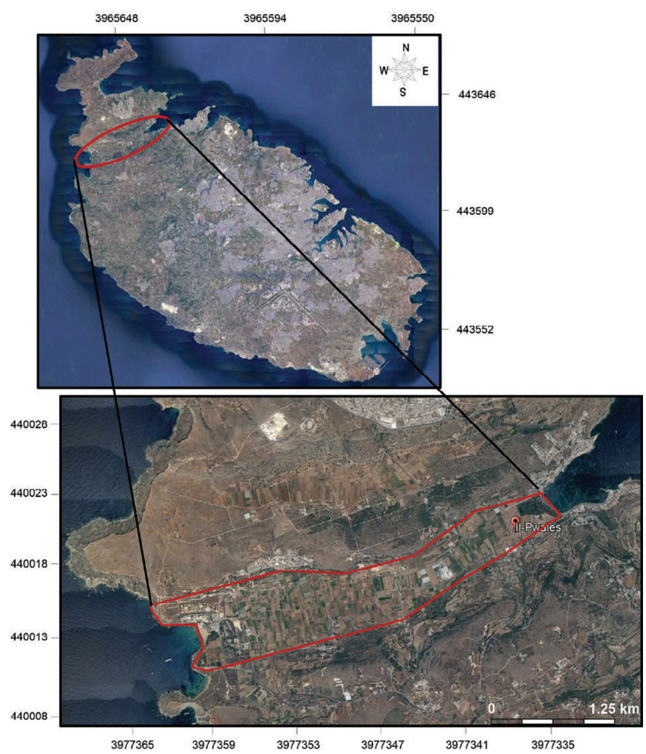

Fig. 1 - Location of the study area.

Fig. 1 - Ubicazione dell'area di studio.

DOI 10.7343/as-2024-743

resulting from bounding faults dipping towards each other (Fig. 2). From the oldest to the newest formation, the stratigraphic sequence is made of: 1) Oligocene Lower Coralline Limestone; 2) Miocene Globigerina Limestone; 3) Miocene Blue Clay Formation 4) Miocene Upper Coralline Limestone. The geological formation outcropping in the study area is the Upper Coralline Limestone, highly porous and poorly crystalline, that is the main formation bearing freshwater.

This aquifer is also named Mean Sea Level aquifer (Demichele et al., 2023) since the water table level is controlled by the sea level and, on its boundaries, is in direct contact with the sea water, giving rise to the seawater ingression (Lotti et al., 2021; Polemio et al., 2019). Lateral seawater intrusion occurred in the Pwales aquifer because of the low depth of the aquifer bottom, corresponding to the top of the impermeable Blue Clay Formation (Fig. 3).

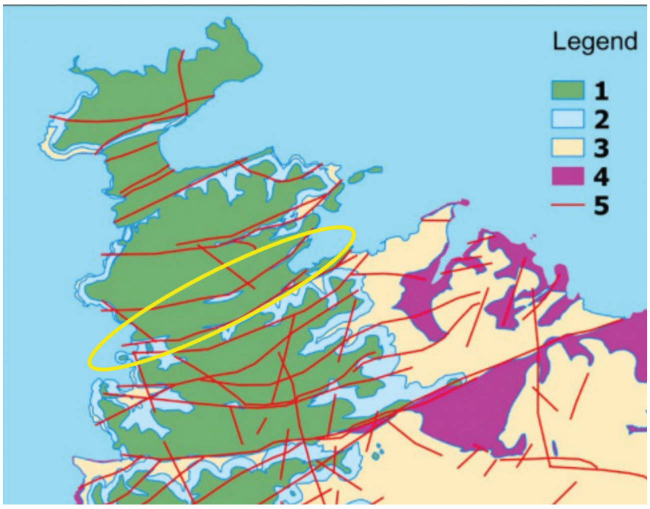

Fig. 2 - Geological sketch of the Pwales Valley area (yellow rounded part): 1) Upper Coralline Limestone (Miocene); 2) Blue Clay (Miocene); 3) Globigerina Limestone (Miocene); 4) Lower Coralline Limestone (Oligocene); 5) Faults.

Fig. 2 - Disegno della geologia dell'area di Pwales Valley (linea gialla): 1) Calcare Corallino Superiore (Miocene); 2) Argille Blu (Miocene); 3) Calcare Globigerina (Miocene); 4) Calcare Corallino Inferiore (Oligocene); 5) Faglie.

Basics of Electromagnetic Induction (EMI)

EMI technique is based on the induction of electrical currents generated on the surface and spread in subsurface conductors for diffusion. It is also named Frequency Domain Electromagnetics (FDEM) because it operates in the frequency domain. A short description of the basics is described in Figure 4. The technique used 2 coils, a transmitter and a receiver. A transmitter loop generates an alternate current that, according to the electromagnetic induction principle, produces a variable magnetic primary field (Hp) that, in turn, induces a flow current propagating into the subsurface (McNeill, 1980). In presence of a conductor, eddy currents are induced and a secondary EM field (Hs) is generated. Compared to the primary field, the secondary field is distorted in direction and phase and its magnitude is much lower. The total field, i.e. the sum of the primary and the secondary components, is then recorded at the surface by the receiver coil.

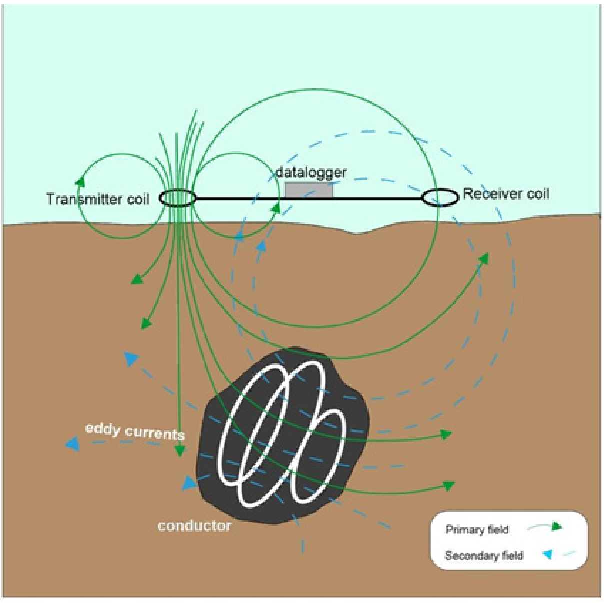

Fig. 4 - Principles of the EMI survey.

Fig. 4 - Principi di un'indagine EMI.

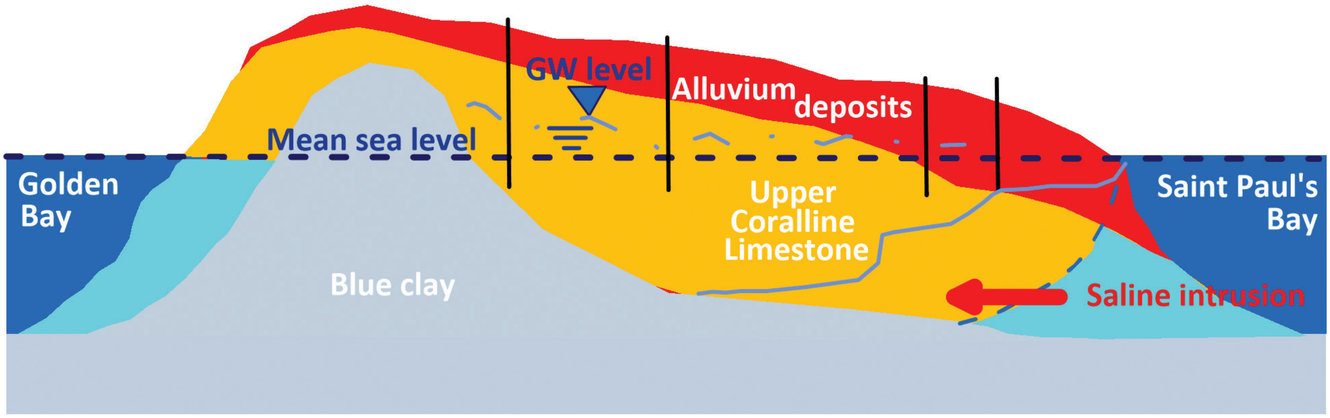

Fig. 3 - Conceptual model (not to scale) of Pwales Valley aquifer system.

Fig. 3 - Modello concettuale (non in scala) del sistema dell'aquifero di Pwales Valley.

Principles of the EMI survey

The secondary magnetic field is characterized by a real and an imaginary component. The real part, which has the same phase as the primary magnetic field, is called in-phase component, while the imaginary part (the quadrature component) is 90° out of phase with the primary field.

More generally, the secondary magnetic field is a complex nonlinear function depending on several parameters, such as the electrical conductivity, the magnetic permeability, the distance between the coils and the frequency of the primary field. For a non-magnetic half space, when the coils are grounded and the operating frequency is small, these complex relationships can be formulated in a simplified relationship as a function of the β, induction number (Mc Neill, 1980)

This parameter, expressed in Equation 1 is the ratio between the inter-spacing coils and the skin depth, i.e. the depth of penetration of the electromagnetic signal or the depth at which an electromagnetic signal attenuates by a value equal to 37% with respect to the initial value.

$$\beta = \frac{r}{\delta} = \frac{r}{\sqrt{\frac{2}{\varpi\sigma\mu_0}}} \tag{1}$$

The skin depth is a parameter closely linked to the electromagnetic properties of the medium such as magnetic permeability of the free space, the electrical conductivity of the half-space and the operating frequency of the electromagnetic wave.

The penetration depth of the signal depends not only on the electromagnetic properties of the investigated medium, but also on the orientation of the coils. When they are oriented perpendicular to the ground, the vertical coplanar position (VCP) allows the investigation of more superficial portions of the subsurface. By rotating both coils by 90°, the horizontal coplanar position (HCP) increases the depth of investigation.

McNeill (1980) showed that, when the induction number is very small (low induction number defined as LIN) and the coils operate on the surface of a non-magnetic half-space, the imaginary part of the ratio between the secondary and primary magnetic field, or quadrature component, is linearly proportional to the electrical conductivity of the half-space, according to the Equation 2:

$$\sigma_a = \frac{4}{\mu\varpi r^2}\,\mathrm{Im}\left(\frac{H_S}{H_P}\right) \tag{2}$$

The measured conductivity, or ECa, is the apparent electrical conductivity, i.e. the equivalent electrical conductivity of a homogeneous half-space that produces the same measured response to the instrument in a single configuration (coil distance, coil orientation, frequency). The ECa parameter is commonly used for a qualitative visualization of the electrical properties because it provides an average value of the electrical conductivity for materials at different depths, giving no information about the variation of the true electrical conductivity with depth.

Similarly, the real part, or in-phase component, of the measured signal is mainly affected by the magnetic permeability.

It seems to be clear that in coastal aquifers subjected to salt water intrusion, the LIN condition is not satisfied due to the highly conductive subsurface, causing a non-linear instrument response. In fact, using the procedure described in Beamish (2011), for the CMD DUO probe, the LIN condition is met for half-space conductivities less than 6 mS/m for 10 m coil spacing (VCP configuration), 8 mS/m for 20 m coil spacing (VCP configuration), and 5 mS/m for 40 m coil spacing (HCP configuration), respectively. In these cases, in order to image the subsurface hydrogeological structures, an inversion procedure of the geophysical data has been required.

Geophysical inversion refers to the mathematical techniques for recovering information on subsurface physical properties from observed geophysical data.

Field activity: EMI data collection

The EMI campaign has been performed between the end of May and half of June 2022. In total, twenty-two transects were oriented about along North-South direction, as shown in Figure 5

The CMD DUO sensor (GF Instruments s.r.o., Czech Republic) was used for collecting electromagnetic data. The sensor consists of two independent coils, a transmitter and a receiver, 65 cm in diameter and 5 Kg in weight, which are connected to each other 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 each transect was repeated 6 times, as a combination of three different cables (10 m, 20 m and 40 m long) and coils configuration (VCP and HCP).

For data collection, a continuous measurements mode, based on the movement with quasi-constant speed along the measured line, and a frequency of 2 seconds were set. Overall, more than 20,000 data measurements were collected and about 42 km were walked.

Results

The EMI data have been processed in different steps: 1) merging data collected at each transect; 2) pre-processing based on data treatment and filtering; 3) inversion of the EMI data along each transect; 4) building a 3D conductivity model of the Pwales Valley.

The first step was to georeference all the data collected along the same transect with different coil configuration and cables.

The filtering aimed to remove bad measurements affected by electromagnetic noise. This step has been performed with a specific tool included in the EM4SOIL code, i.e. the code used for the data inversion process. In particular, the data measured along transects p4 and p11 were completely removed because of the high noise due to the presence of the

Fig. 5 - Location of the EMI transects.

Fig. 5 - Ubicazione dei profili EMI.

nearby high voltage line. For the other transects, negative values or spikes due to local noise were removed.

Finally, the last step of the processing consisted in the inversion of the data. The inversion provides a reliable electromagnetic model of the investigated subsurface. Inversion refers to the mathematical and statistical techniques for recovering information on subsurface physical properties (magnetic susceptibility, density, electrical conductivity, seismic velocity, dielectric permittivity, gamma radiation, gravity, thermal radiation) from observed geophysical data.

The inversion procedure used is a 1-dimensional laterally constrained technique (Monteiro Santos, 2004), also known as Quasi-2D (Q2D) inversion. The forward modelling of the EM4Soil software is based on the cumulative function (McNeil, 1980) or on the full solution of EM fields in a layered earth (Keller and Frischknecht, 1996). The inversion algorithm is based on the Occam regularization method (e.g. DeGroot and Constable 1990; Sasaki 1989).

Figure 6a-e shows the most representative 2D cross sections obtained through inversion.

In order to clearly compare the EMI findings, the cross sections have been scaled with the same conductivity range, that is 5-500 mS/m.

From a geophysical point of view, the cross-sections located in the central and eastern part of the valley (from transects p12 to p10) show a clear layered electromagnetic model. Particularly, three layers have been identified: a) upper conductive layer (EC<80 mS/m); b) middle highly conductive layer (80 to 458 mS/m); c) lower conductive layer (EC<80 mS/m).

The three-layer model is well detected in some transects (Figure 6b corresponding to p8), while close to the coastline the upper layer is not clearly visualized (Fig. 6a corresponding to p12) due to its small thickness.

Conversely, the cross-sections located in the western part of the valley (from p22 to p21) do not always show a clear layered model. In fact, the highly conductive layer, clearly detected in the eastern part of the investigated area, is no longer continuous (Figure 6c-d corresponding to p10-p14), until it disappears completely (Figure 6e corresponding to p19).

Discussion

In order to accurately provide hydrogeological interpretation from geophysical findings, a priori direct observations are strongly required. Such observations, usually drillings, core sampling, stratigraphy, water level and electrical conductivity of the aquifer, can provide a calibration of the EMI sections to properly assign each geophysical layer to hydrogeological structure and avoid misinterpretations of the geophysical outcomes.

Few drillings, whose depth varies from 18 m to 30 m below ground surface (bsg) and located in the easternmost part of the investigated area along EMI transect p12 and very close to the EMI transect p8, provide information about the geological structures, which can be correlated with EMI transect p12 and p8.

The lithology is mainly constituted from sandy clay, red clay and Quaternary limestone. As the Blue Clay Formation has not been detected in the drillings, the lower conductive layer recognized in every EMI transect should not refer to this Formation.

Along the remaining part of the valley, the lack of drillings does not allow to clearly associate the lower conductive layer to the Blue Clay Formation. This evidence, together with the assumption that the Blue Clay Formation can lie below the Upper Coralline Limestone at higher depths than those reached with the geophysical survey, as inferred in Lotti et al. (2021), still leaves a doubt to be fully solved.

No information has been recorded about water level in the boreholes but, given the short distance from the coastline, it can be assumed that the upper conductive layer, when detected, can be associated to a thin unsaturated layer and the highly conductive middle layer is clearly associated to the saline water which intrudes from the eastern to the western part of the valley.

This could be explained by the geological setting of Pwales which causes a quasi-horizontal tongue of seawater spreading from east to west, as confirmed by geological studies performed in this area (Lotti et al., 2021).

Moving to the central and western part of the valley, the

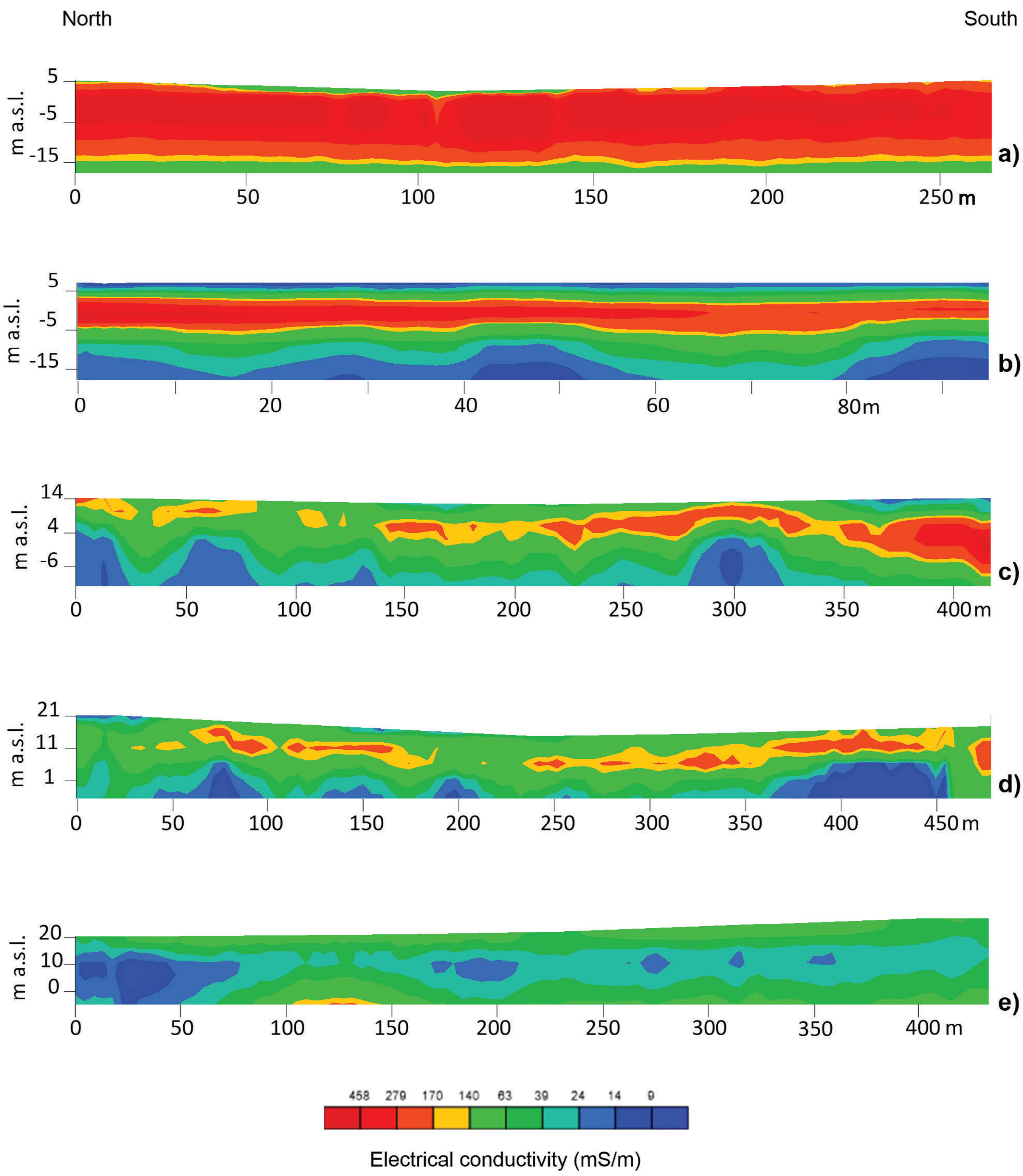

Fig. 6 - 2D inverted EMI cross-sections related to: a) transect p12; b) transect p8; c) transect p10; d) transect p14; e) transect p19. The orientation of the profiles is from North to South.

Fig. 6 - Sezioni trasversali EMI invertite 2D relative a: a) profilo p12; b) profilo p8; c) profilo p10; d) profilo p14; e) profilo p19. L'orientazione dei profili è da Nord verso Sud.

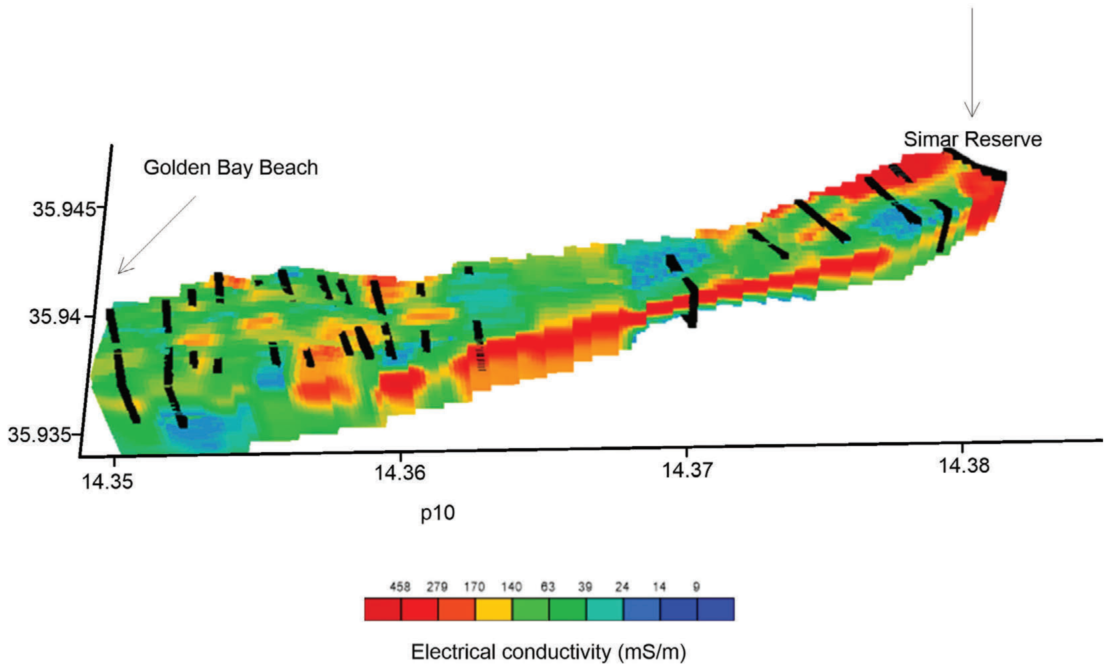

Fig. 7 - 3D electrical conductivity model of Pwales Valley.

Fig. 7 - Modello di condcibilità elettrica 3D di Pwales Valley.

thinning of the highly conductive middle layer shows a reduction in saline intrusion.

The quasi 3D model of Pwales Valley (Fig. 7) developed through Voxler code (Golden Software) corroborates such hypothesis. The model has been built by merging all outputs for each EMI transect. The higher values are mainly located in the central and eastern areas of the valley, with orientation from the East to the West along the main alignment of the valley and extension up to about transect p10.

The information inferred from the geophysical findings can be strategically used in the planning stage of a MAR scheme. They can drive both the location of the injection points and the technical solution to be adopted: a) injection through wells or trenches drilled in the unsaturated zone or b) wells deepening in the saturated zone. Since one of the objectives of the MAR scheme is to improve the quality of groundwater, the injection points must be located upstream of the transept p10, that is where the salt wedge extends. The definition of the top of the Blue Clay Formation is crucial for the comprehension of the volumes of water potentially storable, as well as the hydraulic parametrization of the filtering unsaturated medium, if the first technical solution is chosen. At this regard, the uncertainty in the identification of the top of the Blue Clay Formation along the whole area leaves an unsolved doubt.

Conclusion

We presented a study case in Maltese Island where an EMI survey was carried out to define the hydrogeological setting of the Pwales Valley, heavily affected by saltwater intrusion.

The capability of the EMI technique to investigate wide areas allowed to define a quasi 3D electrical conductivity model with a good resolution.

The geophysical tool was able to recognize a highly conductive plume associated to the ingression of the seawater in the eastern part of the valley. The plume extends up to the central part of the investigated area while in the western region the highly conductive signal gradually diminishes until it vanishes.

The EC model of the subsurface was developed for about 20 m bgs allowing for providing accurate information in terms of thickness of the salinized aquifer and geological peculiarities, otherwise undetectable with traditional direct techniques.

At the same time, the uncertainty in the attribution of the lower conductive layer to the Blue Clay Formation, due to lack of direct information (stratigraphic data) in the investigated area, suggests additional surveys in order to improve the geophysical modeling and its interpretation.

The results suggest that the geophysical approach can be used as an effective supporting tool for the hydrogeological characterization in order to plan facilities for mitigation and adaptation measures, such as MAR schemes, by driving both the location of the injection points and the technical solution to be adopted.

Acknowledgments
The authors are grateful to Ivan Portoghese, Francesco Demichele and Christa Pisani for their support in field activity..

Funding source
This work was supported by the Energy and Water Agency, an agency of Malta Government [grant numbers EWA 94/2020, prot. 5485_15.10.2020].

Competing interest
All authors, declare no competing interests.

Author contributions
Collection of data, Lorenzo De Carlo, Maria C. Ca puto, Antonietta Celeste Turturro, Julian Mamo, Luke Galea, Oriana Balzan; data processing, Lorenzo De Carlo, Maria C.Caputo, Antonietta Celeste Turturro; interpretation of results, Lorenzo De Carlo; writing-original draft preparation, Lorenzo De Carlo; writing-review and editing, Maria C. Ca puto, Antonietta Celeste; visualization, Lorenzo De Carlo and Maria C.Caputo; supervision, Manuel Sapiano; project administration, Manuel Sapiano. All authors have read and agreed to the final version of the manuscript.

Additional information
DOI: https://doi.org/10.7343/as-2024-743
Reprint and permission information are available writing to acquesotterranee@anipapozzi.it
Publisher's note Associazione Acque Sotterranee remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

REFERENCES

Alfarrah, N., & Walraevens, K. (2018). Groundwater overexploitation and seawater intrusion in coastal areas of arid and semi-arid regions. Water, 10, 143. https://doi.org/10.3390/w10020143

Aslam, R.A., Shrestha, S., & Pandey, V.P. (2018). Groundwater vulnerability to climate change: A review of the assessment methodology. Science of the Total Environment, 612, 853-875. https://doi.org/10.1016/j.scitotenv.2017.08.237

Bellafiore, D., Ferrarin, C., Maicu, F., Manfè, G., Lorenzetti, G., Umgiesser, G., Zaggia, L., & Valle Levinson A. (2021). Saltwater intrusion in a Mediterranean Delta under a changing climate. Joutnal of Geophysical Research: Oceans, 126, e2020JC016437. https://doi.org/10.1029/2020JC016437

Boaga, J., Ghinassi, M., D'Alpaos, A., Deidda, G. P., Rodriguez, G., & Cassiani, G. (2018). Geophysical investigations unravel the vestiges of ancient meandering channels and their dynamics in tidal landscapes. Scientific Reports, 8, 1708. https://doi.org/10.1038/s41598-018-20061-5

Brosten, T.R., Day-Lewis, F.D., Schultz, G.M., Curtis, G.P. and Lane Jr, J.W. (2011). Inversion of multi-frequency electromagnetic induction data for 3D characterization of hydraulic conductivity. Journal of Applied Geophysics, 73(4), pp.323-335.

Buselli, G., Davis, G.B., Barber, C., Height, M.I. and Howard, S.H.D., (1992). The application of electromagnetic and electrical methods to groundwater problems in urban environments. Exploration Geophysics, 23(4), pp.543-555.

Brogi, C., Huisman, J.A., Pätzold, S., Von Hebel, C., Weihermüller, L., Kaufmann, M.S., Van Der Kruk, J. and Vereecken, H., 2019. Large-scale soil mapping using multi-configuration EMI and supervised image classification. Geoderma, 335, pp.133-148.

Cassiani, G., Ursino, N., Deiana, R., Vignoli, G., Boaga, J., Rossi, M., Perri, M. T., Blaschek, M., Duttmann, R., Meyer, S., Ludwig, R., Soddu, A., Dietrich, P., & Werban, U. (2012). Noninvasive monitoring of soil static characteristics and dynamic states: a case study highlighting vegetation effects on agricultural land. Vadose Zone Journal, 11(13). https://doi.org/10.2136/vzj2011.0195

Christiansen, A.V., Pedersen, J.B., Auken, E., Søe, N.E., Holst, M.K. and Kristiansen, S.M. (2016). Improved geoarchaeological mapping with electromagnetic induction instruments from dedicated processing and inversion. Remote Sensing, 8(12), p.1022.

Colombani, N., Osti, A., Volta, G., & Mastrocicco, M. (2016). Impact of climate change on salinization of coastal water resources. Water Resources Management, 30, 2483–2496. https://doi.org/10.1007/s11269-016-1292-z

Costall, A. R., Harris, B. D., Teo, B., Schaa, R., Wagner, F. M. & Pigois, J. P. (2020). Groundwater throughflow and seawater intrusion in high quality coastal Aquifers. Scientific Reports, 10, 9866. https://doi.org/10.1038/s41598-020-66516-6

De Carlo, L., Vivaldi, G.A., & Caputo, M.C. (2022). Electromagnetic Induction measurements for investigating soil salinization caused by saline reclaimed water. Atmosphere, 13, 73. https://doi.org/10.3390/ atmos13010073

DeGroot-Hedlin C. & Constable S. C. (1990). Occam's inversion to generate smooth, two-dimensional models from magnetotelluric data. Geophysics, 55, 1613-1624. https://doi.org/10.1190/1.1442813

Deidda, G. P., De Carlo, L., Caputo, M. C., & Cassiani, G. (2022). Frequency domain electromagnetic induction imaging: An effective method to see inside a capped landfill. Waste Management, 144, 29-40. https://doi.org/10.1016/j.wasman.2022.03.007

Demichele, F., Micallef, F., Portoghese, I., Mamo, J. A., Sapiano, M., Schembri, M., Schüth, C. (2023). Determining aquifer hydrogeological parameters in coastal aquifers from tidal attenuation analysis, case Study: the Malta Mean Sea Level Aquifer system. Water, 15, 177. https:// doi.org/10.3390/w15010177

De Smedt, P., Van Meirvenne, M., Saey, T., Baldwin, E., Gaffney, C. and Gaffney, V., (2014). Unveiling the prehistoric landscape at Stonehenge through multi-receiver EMI. Journal of Archaeological Science, 50, pp.16-23.

Dillon, P., Stuyfzand, P., Grischek, T., Lluria, M., Pyne, R. D. G., Jain, R. C., Bear, J., Schwarz, J., Wang, W., Fernandez, E., Stefan, C., Pettenati, M., van der Gun, J., Sprenger, C., Massmann, G., Scanlon, B. R., Xanke, J., Jokela, P., Zheng, Y., Rossetto, R., Shamrukh, M., Pavelic, P., Murray, E., Ross, A., Bonilla Valverde, J. P., Palma Nava, A., Ansems, N., Posavec, K., Ha, K., Martin, R. & Sapiano, M. (2019). Sixty years of global progress in managed aquifer recharge. Hydrogeological Journal, 27, 1–30. https://doi.org/10.1007/s10040-018-1841-z

Dragonetti, G., Comegna, A., Ajeel, A., Deidda, G. P., Lamaddalena, N., Rodriguez, G., Vignoli, G., & Coppola, A. (2018). Calibrating electromagnetic induction conductivities with time-domain reflectometry measurements. Hydrology and Earth System Sciences, 22, 1509-1523. https://doi.org/10.5194/hess-2017-288

EMTOMO LDA (2023). EM4Soil-v4.5 – Guide. A program for 1D Laterally Constrained Inversion. 55 pp

Ferguson, G., & Gleeson, T. (2012). Vulnerability of coastal aquifers to groundwater use and climate change. Nature Climate Change, 2, 342-345. https://doi.org/10.1038/nclimate1413

Frollini, E., Parrone, D., Ghergo, S., Masciale, R., Passarella, G., Pennisi, M., Salvadori, M., & Preziosi, E. (2022). An integrated approach for investigating the salinity evolution in a Mediterranean coastal karst aquifer. Water, 14, 1725. https://doi.org/10.3390/w14111725

Guillemoteau, J., Dousteyssier, B., Heinig, L., Tchana, S.G.N. and Tronicke, J., 2023. Evaluation of the 3-D Multichannel Deconvolution Method for the Case of Low S/N Inphase Data Collected With Loop–Loop FD-EMI Sensors. IEEE Transactions on Geoscience and Remote Sensing, 61, pp.1-9.

Iyalomhe, F., Rizzi, J., Pasini, S., Torresan, S., Critto, A., & Marcomini, A. (2015) Regional risk assessment for climate change impacts on coastal aquifers. Science of The Total Environment, 537, 100-114. https://doi.org/10.1016/j.scitotenv.2015.06.111

Jadoon, K.Z., Moghadas, D., Jadoon, A., Missimer, T.M., Al-Mashharawi, S.K. and McCabe, M.F. (2015). Estimation of soil salinity in a drip irrigation system by using joint inversion of multicoil electromagnetic induction measurements. Water Resources Research, 51(5), pp.3490-3504.

Jansen, J., Haddad, B., Fassbender, W. and Jurcek, P. (1992). Frequency domain electromagnetic induction sounding surveys for landfill site characterization studies. Groundwater Monitoring & Remediation, 12(4), pp.103-109.

Kaufmann, M.S., von Hebel, C., Weihermüller, L., Baumecker, M., Döring, T., Schweitzer, K., Hobley, E., Bauke, S.L., Amelung, W., Vereecken, H. and van der Kruk, J., (2020). Effect of fertilizers and irrigation on multi-configuration electromagnetic induction measurements. Soil use and management, 36(1), pp.104-116.

Keller, G. V. & Frischknecht, F. C. (1996). Electrical methods in geophysical prospecting. Pergamon Press, Inc., 513 pp.

Ketabchi, H., Mahmoodzadeh, D., Ataie-Ashtiani, B., & Simmons, C. T. (2016). Sea-level rise impacts on sea water intrusion in coastal aquifers: Review and integration. Journal of Hydrology, 535, 235–255. https://doi.org/10.1016/j.jhydrol.2016.01.083

Lascano, E., Martinelli, P., & Osella, A. (2006). EMI data from an archaeological resistive target revisited. Near Surface Geophysics, 4(6), 395-400. https://doi.org/10.3997/1873-0604.2006013

Lotti, F., Borsi, I., Guastaldi, E., Barbagli, A., Basile, P., Favaro, L., Mallia, A., Xuereb, R., Schembri, M., Mamo, J. A., & Sapiano, M. (2021). Numerically enhanced conceptual modelling (NECoM) applied to the Malta Mean Sea Level Aquifer. Hydrogeology Journal, 29, 1517-1537. https://doi.org/10.1007/s10040-021-02330-2

Lu, J., Zhang, Y., Shi, H., & Lv, X. (2022). Coastal vulnerability modelling and social vulnerability assessment under anthropogenic impacts. Frontiers in Marine Science, 9, 1015781. https://doi.org/10.3389/fmars.2022.1015781

Martinelli, P., & Duplaa, M. C. (2008). Laterally filtered 1D inversions of small-loop, frequency domain EMI data from a chemical waste site. Geophysics, 73(4), F143–F149. https://doi.org/10.1190/1.2917197

Masciale, R., Amalfitano, S., Frollini, E., Ghergo, S., Melita, M., Parrone, D., Preziosi, E., Vurro, M., Zoppini, A., & Passarella, G. (2021). Assessing natural background levels in the groundwater bodies of the Apulia Region (Southern Italy). Water, 13, 958. https://doi.org/10.3390/w13070958

Masciopinto, C. (2013). Management of aquifer recharge in Lebanon by removing seawater intrusion from coastal aquifers. Journal of Environmental Management, 130, 306-312. https://doi: 10.1016/j.jenvman.2013.08.021

Masciopinto, C., & Liso, I. S. (2016). Assessment of the impact of sea-level rise due to climate change on coastal groundwater discharge. Science of The Total Environment, 569, 672-680. doi: 10.1016/j.scitotenv.2016.06.183

McLachlan, P., Blanchy, G., Chambers, J., Sorensen, J., Uhlemann, S., Wilkinson, P. and Binley, A., (2021). The application of electromagnetic induction methods to reveal the hydrogeological structure of a riparian wetland. Water Resources Research, 57(6), p.e2020WR029221.

McNeill, J.D. (1980). Electromagnetic terrain conductivity measurement at low induction numbers: Geonics, Technical Note TN-6. Available at http://www.geonics.com/pdfs/technicalnotes/tn6.pdf

Minsley, B.J., Smith, B.D., Hammack, R., Sams, J.I. and Veloski, G., 2012. Calibration and filtering strategies for frequency domain electromagnetic data. Journal of Applied Geophysics, 80, pp.56-66.

Monteiro Santos, F.A., (2004). 1-D laterally constrained inversion of EM34 profiling data. Journal of Applied Geophysics, 56, 123-134. https://doi:10.1016/j.jappgeo.2004.04.005

Moore, W. S., & Joye S. B. (2021). Saltwater intrusion and submarine groundwater discharge: acceleration of biogeochemical reactions in changing coastal aquifers. Frontiers in Earth Science, 9, 600710. https://doi: 10.3389/feart.2021.600710

Osella, A., de la Vega, M., & Lascano, E. (2005). 3D electrical imaging of an archaeological site using electrical and electromagnetic methods. Geophysics, 70(4), G101–G107. https://doi.org/10.1190/1.1993727

Page, D., Bekele, E., Vanderzalm, J., & Sidhu, J. (2018). Managed Aquifer Recharge (MAR) in sustainable urban water management. Water, 10, 239. https://doi.org/10.3390/w10030239

Polemio, M., Sapiano, M., Santaloia, F., Basso, A., Dragone, V, De Giorgio, G., Limoni, P., Zuffianò, L. E., Mangion, J., & Schembri, M. (2019). A hydrogeological study to support the optimized management of the main sea level aquifer of the island of Malta. Rendiconti Online della Società Geologica Italiana, 47, 85-89. https://doi.org/10.3301/ROL.2019.16

Post, V.E.A., & Werner A. D. (2017). Coastal aquifers: Scientific advances in the face of global environmental challenges. Journal of Hydrology, 551, 1-3. https://doi.org/10.1016/j.jhydrol.2017.04.046

Qin, R., Wu, Y., Xu, Z., Xie, D., & Zhang, C. (2013). Assessing the impact of natural and anthropogenic activities on groundwater quality in coastal alluvial aquifers of the lower Liaohe River Plain, NE China. Applied Geochemistry, 31, 142-158. https://doi.org/10.1016/j.apgeochem.2013.01.001

Revil, A., Karaoulis, M., Johnson, T. and Kemna, A. (2012). Some low-frequency electrical methods for subsurface characterization and monitoring in hydrogeology. Hydrogeology Journal, 20(4), p.617.

Ringleb, J., Sallwey, J., & Stefan, C. (2016). Assessment of Managed Aquifer Recharge through Modeling-A Review. Water, 8, 579. https://doi.org/10.3390/w8120579

Robinson, D.A., Binley, A., Crook, N., Day-Lewis, F.D., Ferré, T.P.A., Grauch, V.J.S., Knight, R., Knoll, M., Lakshmi, V., Miller, R. and Nyquist, J. (2008). Advancing process-based watershed hydrological research using near-surface geophysics: A vision for, and review of, electrical and magnetic geophysical methods. Hydrological Processes: An International Journal, 22(18), pp.3604-3635.

Sasaki, Y. (1989). Two-dimensional joint inversion of magnetotelluric and dipole-dipole resistivity data. Geophysics, 54, 254-262. https://doi.org/10.1190/1.1442649

Tarolli, P., Luo, J., Straffelini, E., Liou, Y. A., Nguyen, K. A., Laurenti R., Masin, R., & D'Agostino, V. (2023). Saltwater intrusion and climate change impact on coastal agriculture. PLOS Water, 2(4), e0000121. https://doi.org/10.1371/journal.pwat.0000121

Tezkan, B. (1999). A review of environmental applications of quasi-stationary electromagnetic techniques. Surveys in Geophysics, 20, pp.279-308.

Tully, K. L., Weissman, D., Jesse Wyner, W., Miller, J., & Jordan, T. (2019). Soils in transition: saltwater intrusion alters soil chemistry in agricultural fields. Biogeochemistry, 142, 339-56. https://www.jstor.org/stable/48701385

von Hebel, C., Rudolph, S., Mester, A., Huisman, J.A., Kumbhar, P., Vereecken, H. and van der Kruk, J. (2014). Three-dimensional imaging of subsurface structural patterns using quantitative large-scale multiconfiguration electromagnetic induction data. Water Resources Research, 50(3), pp.2732-2748.

von Hebel, C., Reynaert, S., Pauly, K., Janssens, P., Piccard, I., Vanderborght, J., van der Kruk, J., Vereecken, H. and Garré, S. (2021). Toward high-resolution agronomic soil information and management zones delineated by ground-based electromagnetic induction and aerial drone data. Vadose zone journal, 20(4), p.e20099.

Werner, A. D., & Simmons C. T. (2009). Impact of sea-level rise on sea water intrusion in coastal aquifers. Groundwater, 47, 197-204. https://doi.org/10.1111/j.1745-6584.2008.00535.x

Yao, R., & Yang, J. (2010). Quantitative evaluation of soil salinity and its spatial distribution using electromagnetic induction method. Agricultural Water Management, 97(12), 1961-1970. https://doi.org/10.1016/j.agwat.2010.02.001

Zaccaria, D., Passarella, G., D'Agostino, D., Giordano, R., & Solis, S. S. (2016). Risk assessment of aquifer salinization in a large-scale coastal irrigation scheme, Italy. CLEAN–Soil, Air, Water, 44(4), 371-382. https://doi.org/10.1002/clen.201400396