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Editorial

Application of Geophysical Methods for Hydrogeology

Alex Sendrós [1,2,*], María del Carmen Cabrera [3] and Albert Casas-Ponsatí [1,2]

[1] Department of Mineralogy, Petrology and Applied Geology, Universitat de Barcelona, 08028 Barcelona, Spain; albert.casas@ub.edu
[2] Water Research Institute, Universitat de Barcelona, 08001 Barcelona, Spain
[3] Instituto Universitario de Estudios Ambientales y Recursos Naturales (i-UNAT), Universidad de Las Palmas de Gran Canaria, 35017 Las Palmas de Gran Canaria, Spain; mcarmen.cabrera@ulpgc.es
* Correspondence: alex.sendros@ub.edu

1. Introduction

Groundwater is considered essential in the world's current water supply. Subsurface water also supports ecosystems and is more resilient than surface watercourses to the negative effects of climate change and human activity. In many places, aquifers are the only source of water. However, there has been an increase in the intensive use of groundwater and a growing number of reports of degradation [1–3].

The characterization of the subsurface and its hydraulic properties is essential for an appropriate groundwater and surface water management [4], but they are often difficult to evaluate from traditional borehole drilling, water well and piezometer pumping tests, or soil sampling techniques [5,6]. Traditional soil sampling methods and the use of devices to obtain hydraulic properties in the field, such as permeameters or humidity sensors, typically only provide localized data from the upper layers, and borehole drilling is a destructive and expensive technique which requires accessible areas to place heavy machinery and only delivers spotted information [7]. The integration of geophysical data into direct hydrogeological measurements is a challenging issue that could be used to characterize, monitor, and investigate hydrological parameters and processes in the vadose zone and aquifers at different resolutions and over many spatial scales in a minimally invasive manner [8,9].

For the purpose of characterizing groundwater, electrical, electromagnetic, and seismic geophysical techniques are frequently employed [10]. While the latter is primarily used to deduce aquifer geometry and certain steady aquifer hydraulic parameters, the first two are usually used to infer aquifer geometry and certain transient groundwater features like the piezometric level, freshwater–saltwater interface, characterization of groundwater flow, and pore water conductivity [8,11]. The interpretations become clearer when several methodologies are combined and used on conductive structures and pore-filling fluids (both natural and man-made) that are subjected to the temporal dynamics of dissolved ions and water content. Integration can also include utilizing direct data (such as physical parameters, geochemical tracers, and lithological logs) to enhance and/or validate the geophysical models. There are several scientific software systems available with user-friendly interfaces, robust data inversion techniques, and tools for dealing with uncertainty analysis [12].

In this broad hydro-geophysical framework, this Special Issue aimed to attract specialized researchers using geophysical prospecting techniques for groundwater research and for gathering the advances and challenges associated with the use of geophysical methods. The special focus of this Special Issue is on case studies demonstrating the

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potential to improve our understanding of hydrogeological parameters in vadose and non-vadose zones used to modelize groundwater flow, study the transport of substances, and, therefore, improve our aquifer knowledge and manage many important processes such as contamination and saltwater intrusion. The accepted papers included (i) geophysical prospecting surveys as a part of the holistic strategy for aquifer conceptualization and modeling, (ii) integrated large and detailed scale near-surface geophysical prospecting techniques and time-lapse approaches to reduce the ambiguity of hydrogeological interpretations, (iii) experimental field and numerical operational designs, and (iv) case studies surveying saturated and unsaturated media for methodological and conceptual purposes. Other papers contributed to understanding the state of the art of geophysical techniques through specific study cases covering (i) hydrogeological environments such as polluted sites and urbanized areas in different countries; (ii) aquifer typologies in coastal and inland areas such as Paleogene and Neogene sedimentary rocks and Quaternary detrital sediments; and (iii) climate settings including humid, sub-humid, and semiarid to arid. The used techniques were (i) electrical, such as electrical resistivity tomography (ERT), vertical electrical sounding (VES), resistivity well logs, self-potential (SP) measurements, and induced polarization tomography (IPT); (ii) electromagnetic, such as ground-penetrating radar (GPR), the time-domain electromagnetic method (TDEM), and Global Navigation Satellite Systems reflectometry (GNSS-R); and (iii) seismic, such as Seismic Refraction Tomography (SRT), multichannel analysis of surface waves (MASW) and microtremor recordings elaborated with the horizontal-to-vertical seismic ratio (HVSR) technique.

2. Contributions

Twelve manuscripts have been accepted for publication since the March 2023 announcement of the call for papers. The manuscripts have been accepted for publication following a rigorous review process. To achieve a better insight into the Special Issue, we present brief highlights of the published papers below.

The authors of the paper "Hydrogeophysical Investigation in Parts of the Eastern Dahomey Basin, Southwestern Nigeria: Implications for Sustainable Groundwater Resources Development and Management" conducted geoelectrical resistivity measurements (VES and ERT) in five locations within the eastern portion of the Dahomey Basin (Nigeria). The geophysical results were integrated with the borehole logs to generate the spatial distribution of the subsurface lithologies and to estimate the hydraulic parameters (porosity, hydraulic conductivity, and transmissivity) of two highly productive local aquifers. However, it is crucial to consider the presence of sub-vertical faults in the study site, as these faults can significantly affect water wells' productivity and ultimately influence the overall water availability in the area.

The authors of the paper "Geophysical Constraints to Reconstructing the Geometry of a Shallow Groundwater Body in Caronia (Sicily)" analyzed and reinterpreted geoelectrical data, allowing for the construction of a preliminary 3D resistivity model. This initial modeling was subsequently integrated with a geophysical data campaign to define the depth of the bottom of the shallow Caronia Groundwater Body and the thickness of alluvial deposits. Finally, a preliminary mathematical model flow was generated to reconstruct the dynamics of underground water. The results show that the integration of multidisciplinary data represents an indispensable tool for the characterization of complex physical systems.

The authors of the paper "Coupled Geophysical and Hydrogeochemical Characterization of a Coastal Aquifer as Tool for a More Efficient Management (Torredembarra, Spain)" integrated hydrogeological, hydrogeochemical, and electrical resistivity subsoil data to establish a hydrogeological model of the coastal aquifer of this area. The obtained results could be used as a support tool for the assessment of the most favorable areas for groundwater withdrawal, as well as enabling the control and protection of the most susceptible areas affected by saltwater intrusion.

The authors of the paper "Identification of Breaches in a Regional Confining Unit Using Electrical Resistivity Methods in Southwestern Tennessee, USA" applied electrical resistivity and borehole data to delineate lithostratigraphic boundaries and image the geometry of confining-unit breaches in Eocene coastal-plain deposits to evaluate inter-aquifer exchange pathways. The results underscore the efficacy of the ERT method in identifying sand-rich paleochannel discontinuities in a low-resistivity regional confining unit, which may be a common origin of breaches in coastal-plain confining units.

The authors of the paper "An Integrated Approach for Saturation Modeling Using Hydraulic Flow Units: Examples from the Upper Messinian Reservoir" characterized and predicted the change in reservoir water saturation (SW) with time, while reservoir production life is based on the change in reservoir capillary pressure. The study introduced an integrated approach, including the evaluation of core measurements, well-log analysis covering cored and non-cored intervals, neural analysis techniques, and permeability prediction in non-cored intervals. The empirical formula was predicted for direct calculation of dynamic SW profiles and predicted within the reservoir above the fluid contact and free water level based on the change in reservoir pressure.

The authors of the paper "Geometry, Extent, and Chemistry of Fermentative Hot Spots in Municipal Waste Souk Sebt Landfill, Ouled Nemma, Beni Mellal, Morocco" aimed to detect and characterize fermentative hotspots in municipal waste dumps as well as the leachates that form within them using SP measurements. Despite the small size of the hotspots generating the leachates, the accumulation of leachates in ponds and the low soil permeability limits the percolation rate, resulting in moderate but permanent groundwater pollution.

The authors of the paper "A Real-Time Prediction Approach to Deep Soil Moisture Combining GNSS-R Data and a Water Movement Model in Unsaturated Soil" proposed a real-time prediction approach to deep soil moisture combining GNSS-R data and a water movement model in unsaturated soil. The approach was validated in a study area in Goodwell, Texas County, Oklahoma, USA, and validates the feasibility of the proposed procedure, which has the potential to play a crucial role in agricultural production, geological disaster management, engineering construction, and heritage site preservation.

The authors of the paper "Environmental Monitoring of Pig Slurry Ponds Using Geochemical and Geoelectrical Techniques" evaluated the relationship between electrical values and geochemical parameters and the risk of lateral contamination of pig slurry stored in a pond using ERT and geochemical analysis. The infrastructures dedicated to managing pig farm by-products are necessary to prevent environmental pollution and eutrophication of groundwater, and this non-invasive method provides detailed information on the distribution and characteristics of the fluids.

The authors of the paper "Coastal Groundwater Bodies Modelling Using Geophysical Surveys: The Reconstruction of the Geometry of Alluvial Plains in the North-Eastern Sicily (Italy)" reconstructed the pattern and extent of two groundwater bodies, located in populated and industrialized coastal sectors of north-eastern Sicily, through the integrated analysis and interpretation of several geoelectrical (VES, ERT, and IPT), seismic (active and passive seismic), and geological data. The procedure followed allowed them to recognize the areal extension and thickness of the various lithotypes and define the depth and the morphology of the base of the groundwater bodies and the thickness of the filling deposits.

The authors of the paper "Assessing and Improving the Robustness of Bayesian Evidential Learning in One Dimension for Inverting Time-Domain Electromagnetic Data: Introducing a New Threshold Procedure" applied Bayesian evidential learning in one dimension for stochastic TDEM inversion with a threshold approach on field data collected in the Luy River catchment (Vietnam) to delineate saltwater intrusions. Their results show that the proper selection of time and space discretization is essential for limiting the computational cost while maintaining the accuracy of the posterior estimation. Moreover, the selection of the prior distribution has a direct impact on fitting the observed data and is crucial for realistic uncertainty quantification.

The authors of the paper "Characterization of a Contaminated Site Using Hydro-Geophysical Methods: From Large-Scale ERT Surface Investigations to Detailed ERT and GPR Cross-Hole Monitoring" presented the results of an advanced geophysical characterization of a contaminated site, where a correct understanding of the dynamics in the unsaturated zone is fundamental to evaluate the effective management of the remediation strategies. Large-scale surface ERT was used to perform a preliminary assessment of the structure in a thick unsaturated zone and to detect the presence of a thin layer of clay supporting an overlying thin perched aquifer. Therefore, a deep trench was dug upstream of the site and a forced infiltration experiment was carried out and monitored using ERT and GPR measurements in a cross-hole time-lapse configuration. The results emphasize the contribution of hydro-geophysical methods to the general understanding of subsurface water dynamics.

The authors of the paper "Dynamics of Saltwater Intrusion in a Heterogeneous Coastal Environment: Experimental, DC Resistivity, and Numerical Modeling Approaches" conducted experimental, numerical, and geophysical field campaigns to assess the saltwater intrusion phenomena in coastal aquifers. Direct Current (DC) resistivity sounding data were collected using a laboratory physical model to determine the depth of the freshwater–saltwater interface, a finite element analysis was employed to generate numerical models based on experimental feedback and for validation purposes, and ERT data were acquired from the seacoast and an aquaculture area. The alignment of the experimental, numerical, and geophysical data suggests that this integrated approach could be valuable for studying saltwater intrusion and can be applied to different geological settings, including tidal flats and alluvial plains.

3. Future Prospects

The Guest Editors envision that practitioners and scholars will find the published papers in this Special Issue interesting and useful in identifying areas for further research in the use of geophysical techniques applied to groundwater. Applications such as obtaining reliable three-dimensional and time-lapse hydro-geophysical models, working with uncertainty reductions at greater depths, improving the uncertainty quantification, obtaining more robust correlation among hydro-geophysical and hydrochemical parameters, transitioning from homogeneous to heterogeneous subsurface models, and dealing with the integration of geophysical information with routine environmental matrices monitoring as defined by community regulations can benefit from the papers included in this issue. Additionally, we hope that readers will find this Special Issue's contents to be both educational and motivating as they investigate geophysical techniques for hydrogeology. The methods and conclusions offered in this compilation of publications add to the growing interest in the application of geophysical methods in groundwater studies.

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List of Contributions

1. Oyeyemi, K.D.; Aizebeokhai, A.P.; Olaojo, A.A.; Okon, E.E.; Kalu, D. V; Metwaly, M. Hydrogeophysical Investigation in Parts of the Eastern Dahomey Basin, Southwestern Nigeria: Implications for Sustainable Groundwater Resources Development and Management. *Water* **2023**, *15*.
2. Canzoneri, A.; Capizzi, P.; Martorana, R.; Albano, L.; Bonfardeci, A.; Costa, N.; Favara, R. Geophysical Constraints to Reconstructing the Geometry of a Shallow Groundwater Body in Caronia (Sicily). *Water* **2023**, *15*, 3206, doi:10.3390/w15183206.
3. Pavoni, M.; Boaga, J.; Peruzzo, L.; Barone, I.; Mary, B.; Cassiani, G. Characterization of a Contaminated Site Using Hydro-Geophysical Methods: From Large-Scale ERT Surface Investigations to Detailed ERT and GPR Cross-Hole Monitoring. *Water* **2024**, *16*.
4. Sendrós, A.; Cubides, I.J.; Himi, M.; Lovera, R.; Urruela, A.; Tapias, J.C.; Rivero, L.; Garcia-Artigas, R.; Casas, A. Coupled Geophysical and Hydrogeochemical Characterization of a Coastal Aquifer as Tool for a More Efficient Management (Torredembarra, Spain). *Water* **2023**, *15*.
5. Hasan, M.R.; Larsen, D.; Schoefernacker, S.; Waldron, B. Identification of Breaches in a Regional Confining Unit Using Electrical Resistivity Methods in Southwestern Tennessee, USA. *Water* **2023**, *15*.
6. El-Gendy, N.H.; Mabrouk, W.M.; Waziry, M.A.; Dodd, T.J.; Abdalla, F.A.; Alexakis, D.E.; Barakat, M.K. An Integrated Approach for Saturation Modeling Using Hydraulic Flow Units: Examples from the Upper Messinian Reservoir. *Water* **2023**, *15*.
7. El Mouine, Y.; El Hamdi, A.; Bousouis, A.; El Jarjini, Y.; Touzani, M.; Valles, V.; Barbiero, L.; Morarech, M. Geometry, Extent, and Chemistry of Fermentative Hot Spots in Municipal Waste Souk Sebt Landfill, Ouled Nemma, Beni Mellal, Morocco. *Water* **2024**, *16*.
8. Luo, X.; Yin, C.; Sun, Y.; Bai, W.; Li, W.; Song, H. A Real-Time Prediction Approach to Deep Soil Moisture Combining GNSS-R Data and a Water Movement Model in Unsaturated Soil. *Water* **2024**, *16*.
9. Capa-Camacho, X.; Martínez-Pagán, P.; Acosta, J.A.; Martínez-Segura, M.A.; Vásconez-Maza, M.; Faz, Á. Environmental Monitoring of Pig Slurry Ponds Using Geochemical and Geoelectrical Techniques. *Water* **2024**, *16*.
10. Capizzi, P.; Martorana, R.; Canzoneri, A.; Bonfardeci, A.; Favara, R. Coastal Groundwater Bodies Modelling Using Geophysical Surveys: The Reconstruction of the Geometry of Alluvial Plains in the North-Eastern Sicily (Italy). *Water* **2024**, 16.
11. Ahmed, A.; Aigner, L.; Michel, H.; Deleersnyder, W.; Dudal, D.; Flores Orozco, A.; Hermans, T. Assessing and Improving the Robustness of Bayesian Evidential Learning in One Dimension for Inverting Time-Domain Electromagnetic Data: Introducing a New Threshold Procedure. *Water* **2024**, *16*.
12. Tiwari, P.; Rupesh, R.; Sharma, S.P.; Ciazela, J. Dynamics of Saltwater Intrusion in a Heterogeneous Coastal Environment: Experimental, DC Resistivity, and Numerical Modeling Approaches. *Water* **2024**, *16*, doi:10.3390/w16141950.

References

1. Dao, P.U.; Heuzard, A.G.; Le, T.X.H.; Zhao, J.; Yin, R.; Shang, C.; Fan, C. The impacts of climate change on groundwater quality: A review. *Sci. Total Environ.* **2024**, *912*, 169241. [CrossRef]
2. Custodio, E. Education and science to safeguard the human right to water: The role of groundwater. *Boletín Geológico Min.* **2020**, *131*, 745–755. [CrossRef]
3. Fernández-Ortega, J.; Ulloa-Cedamanos, F.; Barberá, J.A.; Batiot-Guilhe, C.; Jourde, H.; Andreo, B. A common framework for the development of spring water contamination early warning system in western Mediterranean karst areas: Spanish and French sites. *Sci. Total Environ.* **2024**, *956*, 177294. [CrossRef] [PubMed]

4. Duque, C.; Nilsson, B.; Engesgaard, P. Groundwater–surface water interaction in Denmark. *WIREs Water* **2023**, *10*, e1664. [CrossRef]
5. Ronayne, M.J.; Gorelick, S.M.; Zheng, C. Geological modeling of submeter scale heterogeneity and its influence on tracer transport in a fluvial aquifer. *Water Resour. Res.* **2010**, *46*, W10519. [CrossRef]
6. Sendrós, A.; Himi, M.; Estévez, E.; Lovera, R.; Palacios-Diaz, M.P.; Tapias, J.C.; Cabrera, M.C.; Pérez-Torrado, F.J.; Casas, A. Hydrogeophysical Assessment of the Critical Zone below a Golf Course Irrigated with Reclaimed Water close to Volcanic Caldera. *Water* **2021**, *13*, 2400. [CrossRef]
7. McLachlan, P.J.; Chambers, J.E.; Uhlemann, S.S.; Binley, A. Geophysical characterisation of the groundwater–surface water interface. *Adv. Water Resour.* **2017**, *109*, 302–319. [CrossRef]
8. Binley, A.; Hubbard, S.S.; Huisman, J.A.; Revil, A.; Robinson, D.A.; Singha, K.; Slater, L.D. The emergence of hydrogeophysics for improved understanding of subsurface processes over multiple scales. *Water Resour. Res.* **2015**, *51*, 3837–3866. [CrossRef]
9. Capizzi, P.; Cellura, D.; Cosentino, P.; Fiandaca, G.; Martorana, R.; Messina, P.; Schiavone, S.; Valenza, M. Integrated hydrogeochemical and geophysical surveys for a study of sea-water intrusion. *Boll. Geofis. Teor. Appl.* **2010**, *51*, 285–300.
10. Vereecken, H.; Binley, A.; Cassiani, G.; Revil, A.; Titov, K. (Eds.) *Applied Hydrogeophysics*; Springer: Amsterdam, The Netherlands, 2006; p. 383.
11. Flores Orozco, A.; Steiner, M.; Katona, T.; Roser, N.; Moser, C.; Stumvoll, M.J.; Glade, T. Application of induced polarization imaging across different scales to understand surface and groundwater flow at the Hofermuehle landslide. *CATENA* **2022**, *219*, 106612. [CrossRef]
12. Alcalá, F.J.; Paz, M.C.; Martínez-Pagán, P.; Monteiro Santos, F. Integrated Geophysical Methods for Shallow Aquifers Characterization and Modelling. *Appl. Sci.* **2022**, *12*, 2271. [CrossRef]