



Estimation of geohydraulic parameters in coastal aquifers based on VES transformed to ERT profiles

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Received: 3 March 2023 / Accepted: 5 August 2023 / Published online: 16 August 2023
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Abstract

In this study, the geohydraulic parameters of aquifers in the Sahel Doukkala region, western Morocco were estimated using a geostatistical method to transform vertical electrical soundings (VES) data into electrical resistivity tomography (ERT) profiles. The resulting ERT profiles covered a larger area than the original VES data, allowing for a more comprehensive analysis. The obtained results indicated that the apparent and inverted resistivities range from 16 to 1558 Ohm.m and from 4 to 6980 Ohm.m, respectively, with a low inversion error (RMS) of 6.1–13.1%, demonstrating the reliability of the proposed approach. Using the inverted resistivities, the estimated hydraulic conductivity, effective porosity, and transmissivity ranged from 0.2 to > 103.7 m/day, 11.6% to > 45.8%, and 1.7 to > 2028.6 m²/day, respectively. These values reflect the sand, clayey sand, and limestone lithology prevalent in the study area, with medium to high aquifer potential. The validation of our results with pumping test data showed that the estimated geohydraulic parameters are representative of the geological formations in the study area. In addition to providing a rapid interpretation of the data, the present study offers fundamental insights for future research, contributing to better planning and management of groundwater resources.

Keywords Hydraulic conductivity · Effective porosity · Transmissivity · Sahel Doukkala · Morocco

Introduction

Groundwater is a natural resource that plays a critical role in supporting human life. However, the overexploitation of this resource has led to a continuous decline in groundwater levels, especially in arid and semi-arid areas (Hasan et al. 2018; Agbasi et al. 2019; Abdullah et al. 2019; Abdulrazzaq

et al. 2020). This situation has been exacerbated by population growth, urbanization, and industrialization, which have resulted in an increased demand for water. Unfortunately, the exploitation of groundwater resources has been found to be unsustainable according to multiple studies (George et al. 2015; Obiora et al. 2016; Aleke et al. 2018), which have demonstrated that the practices are frequently arbitrary and do not promote the long-term viability of resources. To address this issue, the search for sustainable methods to manage groundwater resources has gained increasing attention.

Geohydraulic parameters, such as hydraulic conductivity, transmissivity, and porosity, are often overlooked when drilling wells (Gemail et al. 2011; Akpan et al. 2013; Ebong et al. 2014; Aleke et al. 2018). These parameters are essential in several hydrogeological areas, including aquifer characterization, modeling, protection, and management (Ebond et al. 2014), emphasizing their significance in good groundwater resource management. They can be determined by analyzing pumping test data, but this method is often costly, and time-consuming, with limited coverage in areas, where boreholes are widely dispersed. Moreover, it can be challenging to interpolate aquifer properties between pumping test wells

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due to the heterogeneous geological formations (Muldoon and Bradbury 2005; Ebong et al. 2014). In addition, this method is less effective in coastal aquifers due to the potential seawater intrusion it may generate (Jha et al. 2008).

Geohydraulic parameters of coastal aquifers have been estimated using several indirect methods. For instance, Dai and Samper 2006 used derived models from hydrogeochemical data to provide optimal estimation of geohydraulic parameters in coastal aquifers. Saaltink et al. (2003) and Coulon et al. (2021) have successfully developed models to assess various chemical and hydrological parameters, including aquifer hydraulic conductivity. In this regard, recent studies have provided geohydraulic parameter estimation for coastal aquifers using indirect modelling approach (Meyer et al. 2019; Siarkos and Latinopoulos 2016). On the other hand, El-Rayes et al. 2020 proposed to estimate the aquifer hydraulic conductivity by applying an unconventional approach entirely based on the data obtained by remote sensing. Besides, numerous research works have been conducted based on the investigation of tidal wave propagation to deduce the hydraulic parameters of coastal aquifers (Fadili et al. 2018; Zhang et al. 2021).

The indirect geophysical acquisition has proven to be a cost-effective and non-invasive alternative to pumping tests in estimating the geohydraulic parameters of aquifers. The correlation between geoelectric and geohydraulic characteristics within geological formations has been suggested as an effective means of overcoming the limitations of pumping tests (Ebong et al. 2014; Asfahani 2016; Aleke et al. 2018; de Almeida et al. 2021; Akhter et al. 2022; Abdulrazzaq et al. 2020). Therefore, it is considered as a more economical and efficient method for obtaining geohydraulic properties of several locations, where pumping tests may not be feasible or applicable.

One of the most promising geophysical methods for investigating groundwater in various geological settings is geoelectrical prospecting using vertical electrical soundings (VES), which enables the mapping of geological variations in the subsurface in a simple and inexpensive way. Several studies have shown a strong correlation between the geohydraulic and electrical properties of the underground aquifer, which are mainly based on the porosity, the degree of saturation, and the geoelectric properties of the geological formation (Noorellimia et al. 2019; Abdulrazzaq et al. 2020; Ezema et al. 2020; Urom et al. 2021; de Almeida et al. 2021; Akhter et al. 2022; Archie 1942; Slater 2007). Equations and correlations between aquifer resistivity, hydraulic conductivity, effective porosity, and formation factor have been proposed by various researchers (Marotz 1968; Heigold et al. 1979; Salem 2001), and these have been widely used in porous and fractured aquifer investigations (Ebong et al. 2014; Asfahani 2016; Aleke et al. 2018; Oguama et al. 2020; de Almeida et al. 2021; Urom et al. 2021; Akhter et al. 2022). Moreover, some researchers

suggested equations and correlations between geoelectric and geohydraulic parameters, and they have highlighted the relative constancy of the geological nature and the aquifer, which allows the establishment of these correlations (Asfahani 2012; Kazakis et al. 2016; Aleke et al. 2018; Choudhury et al. 2017; Abdulrazzaq et al. 2020).

The Sahel Doukkala region is an important agricultural area, where groundwater is the only available water resource (Fig. 1). However, intensive agriculture, especially in the coastal fringe, has led to the deterioration of groundwater quality due to increased marine water intrusion (Fadili et al. 2015, 2016, 2017). Understanding the geohydraulic properties of the aquifer is crucial in mitigating this degradation and formulating suitable management strategies. To the best of our knowledge, there have been limited studies conducted in this region to establish the geohydraulic properties of the aquifer. For instance, some previous studies have utilized pumping tests to determine the hydrodynamic characteristics of the aquifer, including hydraulic conductivity, transmissivity, and storage coefficient (Ferré and Ruhard 1975; Chtaini 1987; DRHT 1994). Meanwhile, Fakir and Razack (2003) and Fadili et al. (2018) have investigated the interaction between oceanic tides and groundwater level variations to establish the hydraulic diffusivity of the aquifer. However, due to the heterogeneity of the geological formations and limited measurement locations, a comprehensive overview of the hydrodynamic behavior of the entire geological formations is not available.

To address this gap, this study aims to estimate the geohydraulic parameters of the coastal aquifers in Sahel Doukkala using subsurface electrical resistivity measurements. The originality of this work lies in the transformation of VES (1D) into ERT profiles (2D) to estimate geohydraulic parameters. Moreover, the adopted method of estimating geohydraulic parameters has been applied for the first time in the study area. This geoelectrical approach offers the possibility of covering a large area and providing an overview of the hydrodynamic behavior of the entire geological formations. Besides, it offers rapid interpretation and prevents the ambiguities associated with VES. The results of this study will serve as a reference for good groundwater exploration in Sahel Doukkala and could also be applied to other geological formations with a similar background. By properly characterizing the geohydraulic properties of the aquifer, suitable management strategies can be formulated and necessary interventions can be applied to mitigate the degradation of groundwater quality.

Materials and methods

Overview of the study area

The Sahel Doukkala area is located in the Western Moroccan Meseta and is bordered by the Atlantic Ocean to the

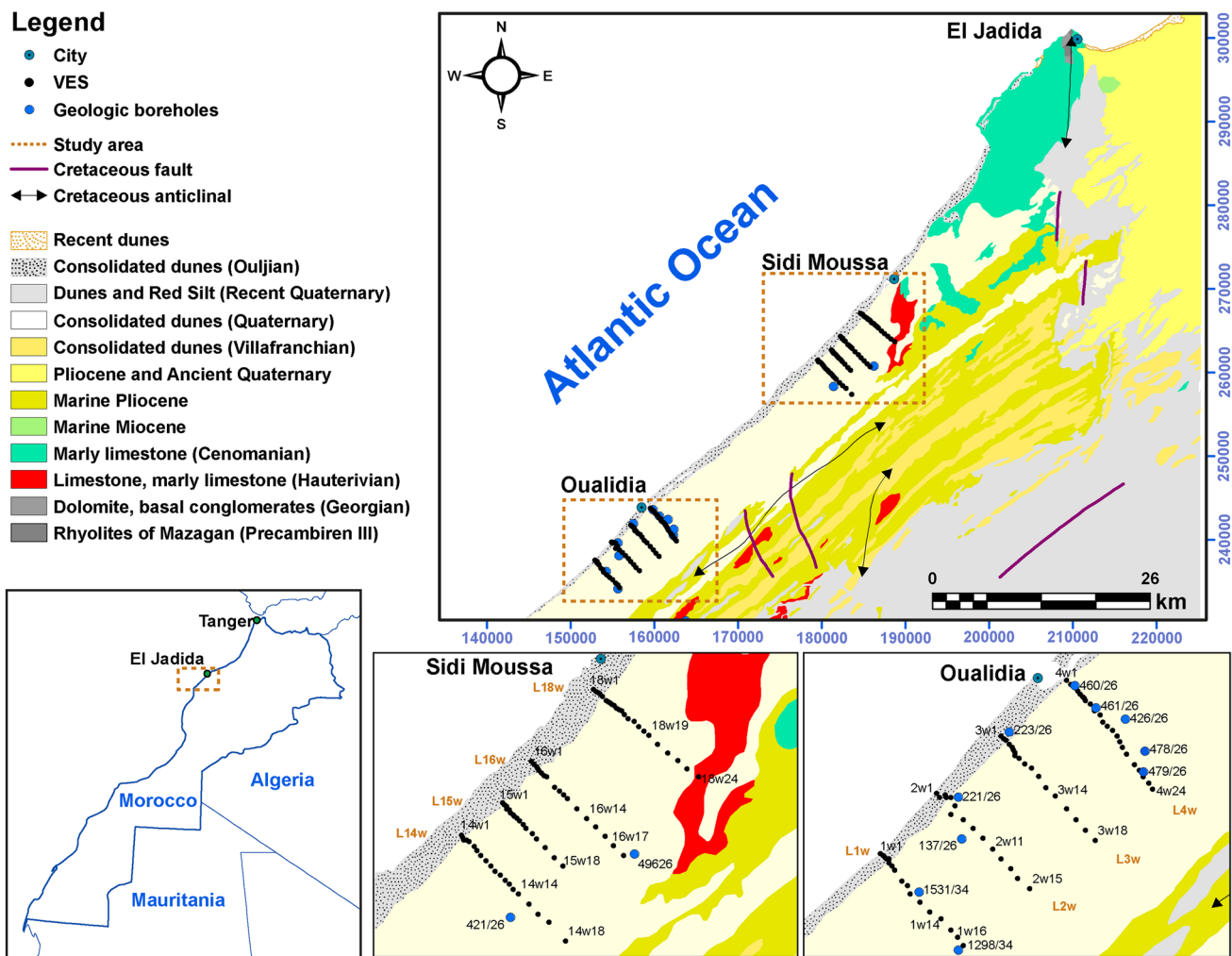


Fig. 1 Geological map of the study area

west and the cities of El Jadida and Oualidia to the north and southwest, respectively (Fig. 1). The climate in Sahel Doukkala area is semi-arid. Temperatures are moderate in areas close to the ocean and more contrasted inland. The hottest months are July and August, and the coldest ones are December and January. Rain falls in autumn and winter, with an average of 355.75 mm (Fadili 2014). A long dry season extends from spring to summer, with December, January and February frequently being the wettest months. Winter crops are grown during these months. However, from the beginning of April, rainfall usually stops and crops are only grown in the irrigated perimeter or on farms using private pumping (Fadili 2014).

The geological formations in this area consist of tabular sedimentary formations of Tertiary, Secondary, and Quaternary ages overlying a folded primary basement (Hafid et al. 2008). The consolidated dunes from the Plioquaternary age are the predominant outcrops (Ferré 1969), overlying a layer of red sandy clay from the Upper Hauterivian

age that forms the roof of the Hauterivian marly limestone and the wall of the Plioquaternary. The wall of the Hauterivian is constituted by Blue Clay of the Upper Valanginian–Lower Hauterivian ages, which in turn overlies the deep Jurassic deposits containing gypsum beds.

The Plioquaternary and Hauterivian aquifers are the only water sources of groundwater in this region, and they are heavily used for all socio-economic activities, especially agriculture, which consumes the largest quantity of water. However, uncontrolled activities such as continuous pumping have resulted in groundwater mineralization, primarily through marine water intrusion (Fadili et al. 2015; 2016; 2017). These two aquifers are separated locally by the Upper Hauterivian red sandy clays. In addition, the Upper Valanginian–Lower Hauterivian marls separate the Plioquaternary and Hauterivian aquifers from the deep Jurassic deposits containing gypsiferous saltwater. The Sahel Doukkala aquifers exhibit also evidence

of karstification and heterogeneity processes (Fakir and Razack 2003; Boualla et al. 2021).

Geoelectrical Data

In this study, we used an archival database of 154 VES collected by the directorate for research and water planning (DRPE 1992). The VESs were divided into 8 profiles perpendicular to the coastline, with profile lengths ranging from 3350 to 5710 m and a total number of VES ranging from 15 to 24 (Fig. 1). The AB/2 distance for each VES ranged from 1 to 500 m, providing a maximum depth of investigation of approximately 200 m (Table 1).

While VES is an efficient method for determining the hydrogeological properties of the aquifer, it only measures vertical electrical resistivities in one dimension (1D) and cannot detect lateral changes in subsurface resistivity (Abdulrazzaq et al. 2020; Ezema et al. 2020; Urom et al. 2021; de Almeida et al. 2021; Akhter et al. 2022; Kazakis et al. 2016). Besides, analyzing numerous VESs or wide areas using this method can be complicated and time-consuming. To compensate for the absence of data in certain areas, we transformed the 1D VES into 2D ERT models following the detailed and approved procedure of Riss et al. (2011). The four-step process involves geostatistical interpolation of the apparent resistivity data obtained by VES, resampling the kriging apparent resistivities using the mesh size a , converting the sampled data into Wenner–Schlumberger configuration supported by Res2DInv software (Loke 2004), taking into account the minimum distance, a , needed to reach the desired depth, and finally, 2D inversion of the obtained ERT pseudo-sections. To focus on the main objective of this study, we will not delve into the geostatistical procedure used for the transformation of VES data into ERT profiles, since it is well-detailed in Riss et al. (2011).

To ensure complete depth coverage of the study area aquifers, a mesh grid with a spacing of $a = 20$ m was used for the VES to ERT transformation across all profiles. This grid spacing provides high resolution to depths of around 200 m (Loke 2004; Riss et al. 2011), using a number of virtual

electrodes comprised between 221 and 339 (Table 1). The resulting number of data points after sampling ranges from 4250 to 7200 (Table 1), leading to more accurate inversion results.

The 2D apparent resistivity pseudo-sections resulting from the VES to ERT transformation were inverted using the Res2DInv software (Loke 2004). For the inversion process, the least squares optimization method with a smoothness constraint was selected. Due to the importance of the profile lengths and the number of data, inversions were performed using the smoothness-constrained incomplete Gauss–Newton option (Loke and Barker 1996). A total of six inversions were carried out, and the final relative root mean square (RMS) error was found to be between 6.1% and 13.1% (Table 1), which can be considered as acceptable for the current study. To further calibrate the geophysical results, geological boreholes of the Sahel Doukkala were used.

Estimation of geohydraulic parameters

According to Archie (1942), the water resistivity of a saturated aquifer could be determined by the following equation:

$$\rho_a = a \cdot \rho_w \cdot \Phi^{-m} \cdot S^n, \quad (1)$$

where ρ_a is the apparent resistivity of the aquifer and ρ_w is the resistivity of water in Ohm, which are directly measured in a borehole. Φ is the porosity of the rock, while a and m are empirical constants that are dependent on the geological formation being studied and are, respectively, called tortuosity and cementing index. The exponent of the saturation S is represented by n .

On the other hand, hydraulic conductivity is a fundamental parameter that describes the dynamic behavior of the aquifer and its response to contaminant migration. This parameter is typically used to establish the performance of the well. While pumping tests are usually used to determine hydraulic conductivity, Heigold et al. (1979) developed Eq. 2 to estimate this parameter based on its electrical resistivity:

Table 1 Characteristics of the geoelectric profiles used in this study

Profile	Number of VES	Number of virtual electrodes	Length of inverted profiles	Data points number	Iteration number	RMS (%)
L 1W	17	273	4390	5550	6	9.5
L 2W	15	290	4730	5975	6	8.2
L 3W	18	303	4990	6300	6	7.9
L 4W	24	300	4930	6225	6	12.6
L 14W	20	339	5710	7200	6	10.1
L 15W	18	221	3350	4250	6	8.4
L 16W	18	307	5070	6400	6	13.6
L 18W	24	316	5250	6625	6	6.1

$$K = 386.40 \cdot R_w^{-0.93283} \tag{2}$$

Here, K is the hydraulic conductivity (m/day), and R_w is the aquifer resistivity (Ohm.m) obtained from the inversion of ERT data.

The formula proposed by Heigold et al. (1979) has been extensively used for estimating the hydraulic conductivity of porous and fractured geological formations in various studies (Aleke et al. 2018; Ezema et al. 2020; Oguama et al. 2020; Urom et al. 2021; de Almeida et al. 2021). Given the similarities between these areas and the Sahel Doukkala region, this equation was used to estimate the hydraulic conductivity for the Sahel Doukkala aquifers, and it has been considered reliable for similar areas.

Effective porosity is also an important parameter as it gives an insight into the drainable pore space. Marotz (1968) established Eq. 3 to determine effective porosity as a function of hydraulic conductivity:

$$\Phi_{\text{eff}} = 25.5 + 4.5 \cdot \ln K, \tag{3}$$

where K is the hydraulic conductivity (m/day) and Φ_{eff} is the effective porosity of the aquifer (%).

Transmissivity is another important hydraulic parameter that defines groundwater potential as shown in Table 2 (Krásný 1993). This parameter can be correlated with geoelectric properties and aquifer thickness using the following equation:

$$T = K \cdot h, \tag{4}$$

where T is the transmissivity (m²/day), K is the hydraulic conductivity (m/day), and h is the aquifer thickness (m).

The obtained thicknesses by VES inversion can sometimes be ambiguous due to the equivalence and suppression principles, and the study area boreholes do not cover all the geological formations. Therefore, it was assumed that the inverted resistivities correspond to a specific depth and thickness.

Considering all the above parameters, the proposed approach to estimate the geohydraulic parameters of each formation involves four steps. The first step is to calculate the hydraulic conductivity (K) using Heigold et al. (1979)

formula, which is suitable for investigating areas with porous and fractured geological formations. The second step is to calculate the porosity of the formations, which gives an insight into the drainable pore space, using Marotz (1968) formula. The third step is to calculate the thickness of the geoelectric formations using the depth corresponding to each resistivity after inversion (Fig. 2). Finally, the transmissivity of the aquifer is calculated knowing K and h using the formula $T=K \cdot h$, which is a significant parameter for aquifer surveys as it defines the groundwater potential.

Results

Resistivity profiles

The present study first involved the transformation of VES data into ERT profiles using the geostatistical approach previously employed by Riss et al. (2011). Thus, the kriging method was used to estimate the logarithmically transformed apparent resistivities along the profiles. The obtained results showed apparent resistivities ranging from 16 to 1558 Ohm.m, whereas the inverted resistivities were between 4 and 6980 Ohm.m (Figs. 3 and 4). These resistivity ranges can be divided into three distinctive layers, reflecting the typical geology of the study area. This distribution of resistivities is consistent with that observed in previous ERT profiles established in the Sahel Doukkala region (Fadili 2014; Fadili et al. 2017). The low inversion error (RMS) between 6.1% and 13.1% indicates that the transformation process from VES data to ERT profiles is accurate and reliable.

The derived apparent resistivity sections from the kriging of the VES data showed three geoelectric levels (Fig. 3) that are more homogeneous throughout all profiles. The correlation with geological boreholes in the study area suggests that the resistive level corresponds to the Plioquaternary layer consisting of consolidated sands, sandstone, calcareous marl, and sandy marl. The medium resistivity level was associated with the Hauterivian and Jurassic marly limestone. Occasionally, the red clays exhibited intermediate resistivities between the two average resistivity levels and the resistant

Table 2 Groundwater potential classification using transmissivity values (Krásný 1993)

Transmissivity (m ² /day)	Specifications	Groundwater supply potential
> 1000	Very high	Withdrawal of great regional importance
100–1000	High	Withdrawal of lesser regional importance
10–100	Intermediate	Withdrawal of local water supply (Small community, plant, etc.)
1–10	Low	Smaller withdrawal for local water supply (Private consumption)
0.1–1	Very low	Withdrawal for local water supply (Private consumption)
< 0.1	Impermeable	Sources for local water supply are difficult

Fig. 2 Schematic graph displaying geohydraulic parameters (T and K) as a function of thickness (h), mesh size a and resistivity (ρ) along ERT profiles (Colors illustrate an example of resistivity variation)

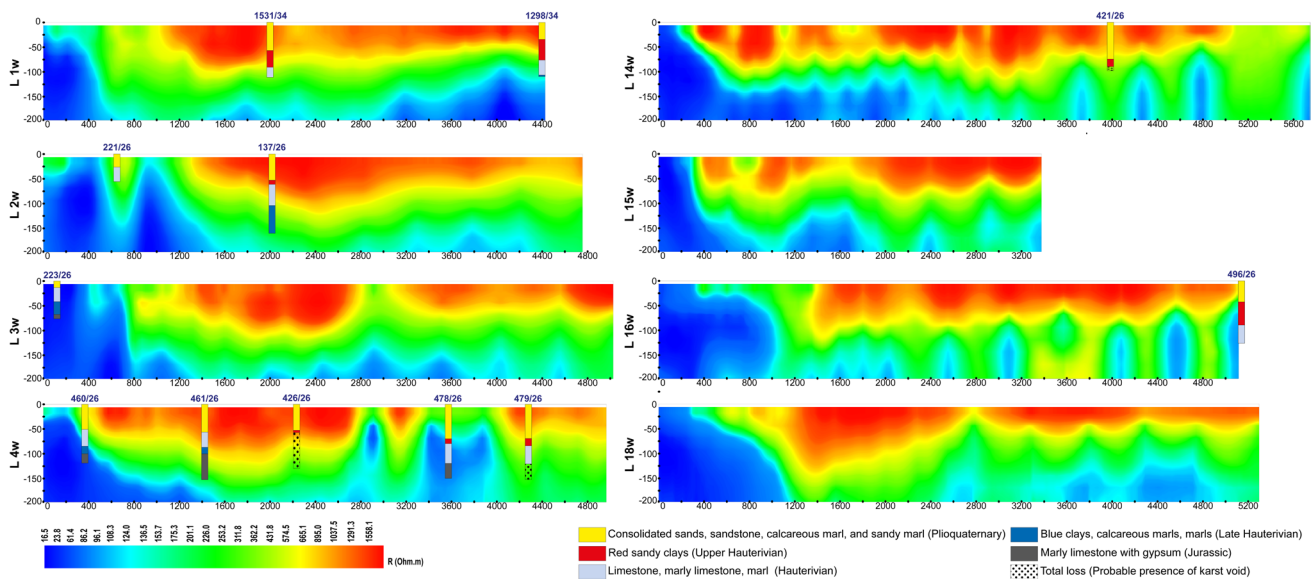
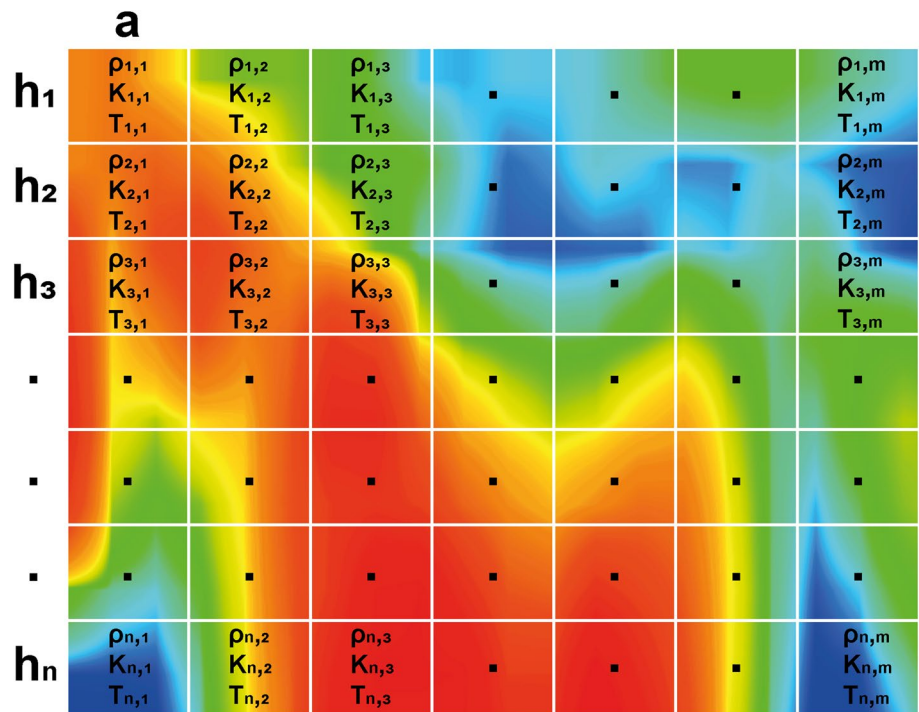


Fig. 3 Profiles of apparent resistivities obtained from VES data kriging (Ohm.m)

level. This may be due to the suppression of this conductive layer, which appears as resistive, since its thickness is often less than that of the other layers, or may be caused by the local disappearance of this formation.

Furthermore, by inverting the apparent resistivity results with an inter-electrode spacing of 20 m, 2D models of the subsurface real resistivity were generated (Fig. 4). The obtained models showed three distinct heterogeneous formations. This time, the resistivity distribution ranged from low

values (4–140 Ohm.m) to high values (1460–6980 Ohm.m), with medium values (199–1244 Ohm.m) in between. Based on geological calibration, the first conductive level, observed in the coastal fringe, was attributed to seawater intrusion. The presence of this level on the surface is reflected in the marshes that can be observed on-site. This conductive level becomes deeper inland to reach a second conductive layer, which corresponds, in this part of the area, to Jurassic gypsum formations. These findings are consistent with those

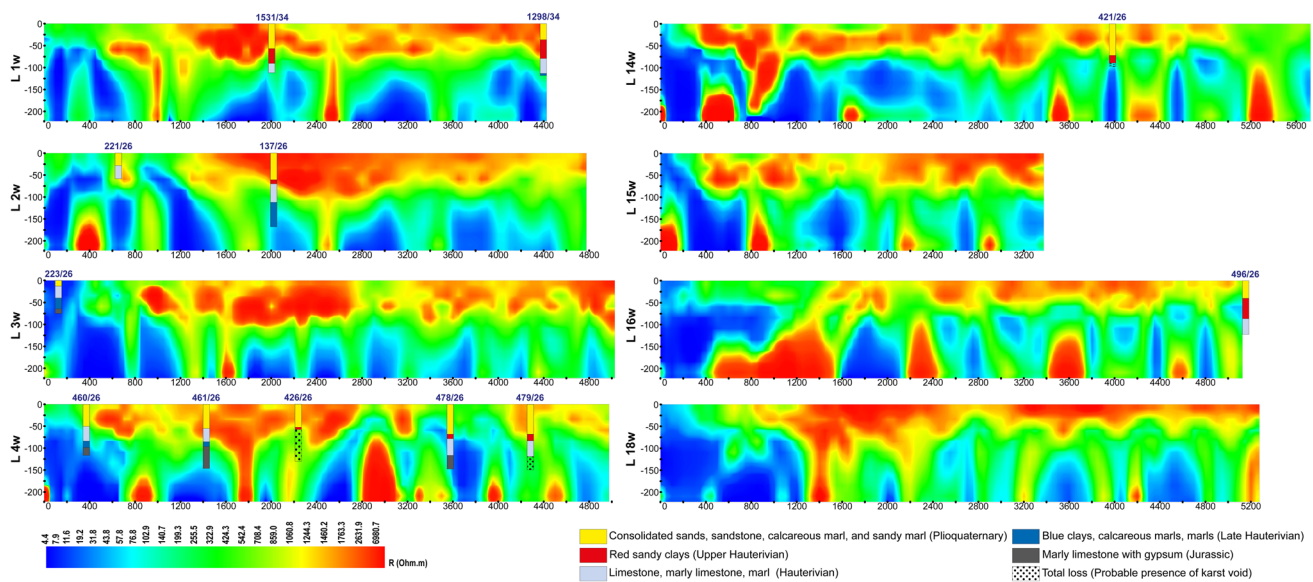


Fig. 4 Profiles of inverted resistivities (Ohm.m)

obtained by Fadili (2014) and Fadili et al. (2015). The Plioquaternary consolidated sands, sandstone, calcareous marl, and sandy marl, as well as the Hauterivian marly limestone formations, displayed resistivities varying between 199 and 6980 Ohm.m. These values are heterogeneously distributed throughout the profiles, with high resistivities at the surface and low resistivities at depth. These changes are mainly due to the lithological variations of the formation and the presence or absence of water. The appearance of red clays, which is discontinuous in the Sahel Doukkala, influenced the resistivity changes with depth. Resistivities between 199 and 1244 Ohm.m reflect the heterogeneity of the Hauterivian and Jurassic layers, which include marly limestone, marl, and marlstone. The punctual resistive anomalies observed at depth may reveal the presence of karstic voids already noted in the region by previous studies (Boualla et al. 2021).

Geohydraulic parameters

The obtained resistivity models provide valuable information about the depth and thickness of each geological formation, including the aquifers in the region. This information is crucial in estimating the geohydraulic parameters of these formations through geoelectrical data analysis. Specifically, the research focuses on hydraulic conductivity (K), effective porosity (Φ_{eff}), and transmissivity (T), which are calculated using Eqs. 2, 3, and 4 for the different formations identified in the study area. To address potential ambiguities resulting from geoelectric suppression and equivalence, thickness changes, and heterogeneities in geological formations, the geohydraulic parameters were calculated for a model with n layers, each with thickness h_1, h_2, \dots, h_n and real resistivity

values $\rho_1, \rho_2, \dots, \rho_n$ as shown in Fig. 2. Furthermore, the results were validated by comparing them to pumping test data from previous studies conducted in the study area.

The estimated K values for different geological formations in the study area vary widely, ranging from 0.2 to > 103.7 m/day (Fig. 5). These values are primarily influenced by lithology, which is dominated by silty sand, clean sand, and limestone (Fitts 2002). The Plioquaternary consolidated sands, sandstone, calcareous marl, and sandy marl exhibited low K values (0.2–0.6 m/day) at the surface due to the presence of clays and low water saturation. However, in some parts of this formation, high K values (1.2–9 m/day) were observed, as in profile Lw4, indicating lithological variation and heterogeneity. The Hauterivian marly limestone and the Jurassic marly limestone with gypsum formations were globally correlated with high K values (between 12 and > 103.7 m/day), making them the main aquifers of the region. Locally, the Hauterivian layer exhibited moderate K values (1.4–9.4 m/day) due to the presence of clays and fracturing. The coastal area showed high K values (ranging from 15.9 to > 103.7 m/day), and it is considered conductive due to marine intrusion. This outcome suggests that the high hydraulic conductivity in this part facilitates the inland penetration of marine waters.

The effective porosity of the geological formations in the study area was estimated using the calculated hydraulic conductivity, as shown in Fig. 6. The obtained values ranged from 11.6% to > 45.8%, indicating the prevalence of sandy and clayey lithology, consistent with the known lithology of the region (Moss and Moss 1990). The higher values suggest the presence of fine sand or fine granulometry, while the lower values are indicative of coarse

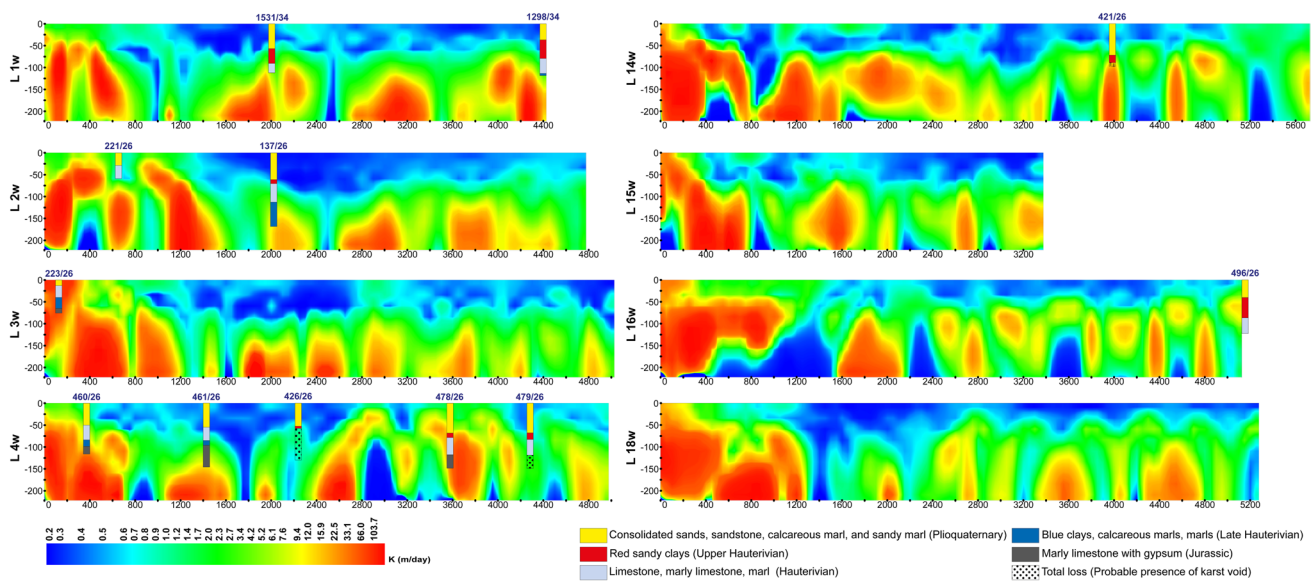


Fig. 5 Section of estimated hydraulic conductivity (m/day)

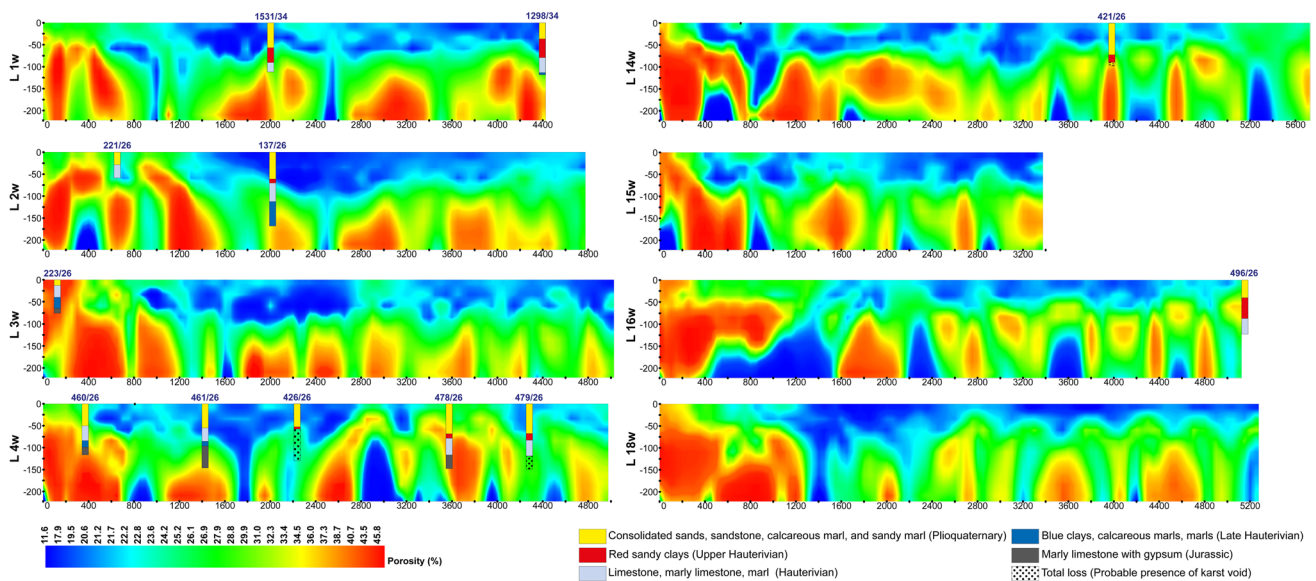


Fig. 6 Section of estimated effective porosity (%)

sand (Akhter et al. 2022). On the surface, the Plioquaternary formation (consolidated sands, sandstone, calcareous marl, and sandy marl) showed overall Φ_{eff} values between 11.6% and 23.6% on most profiles, with local values ranging between 25% and > 45.8%. The variation in porosity was related to the variation in granulometry, the clay content, and the karstification characteristic of the region (Boualla et al. 2021). On the other hand, the Hauterivian and Jurassic marly limestone exhibited high Φ_{eff} values between 25.2% and > 45.8%, thus justifying their potential as aquifers, which is linked to fracturing

and karstification. Conversely, low Φ_{eff} values were associated with reduced water volume in the pores, resulting in higher aquifer resistivity and lower hydraulic conductivity (de Almeida et al. 2021). This is particularly evident at the surface of the profiles, where resistivities are high, while K and Φ_{eff} values are low, likely due to unsaturation or low water content with a clay bedrock of the Upper Hauterivian. As for the coastal part of the study area, high Φ_{eff} values exceeding 45.8% were observed, supporting excellent hydraulic conductivity and promoting marine intrusion penetration. This outcome indicates

a potentially productive aquifer or a probable karst region with high hydraulic conductivity.

The estimated values of hydraulic conductivity and transmissivity are mutually proportional, with increasing K values corresponding to higher transmissivity. This correlation can be assigned to various factors, including hydraulic and electrical anisotropies, lithological variations, grain size, and pore connectivity (Salem 1999; Ebong et al. 2014). In this study, the estimated T values vary between 1.7 and > 2028.6 m²/day, as shown in Fig. 7. This result highlights the significant lithology contrast within the study area. Low T values of 1.7 to 13.5 m²/day were mainly observed on the surface of the Plioquaternary formation, with local areas reaching values close to 205 m²/day, particularly in the coastal fringe. Overall, the Hauterivian and Jurassic formations were characterized by high T values ranging from 20.6 to > 2028.6 m²/day, indicating their aquifer potential. According to Krásný (1993) classification, T values of > 1000 , 100–1000, and 10–100 m²/day indicate very high, high, and medium aquifer potential, respectively. Therefore, the study area aquifers have a medium to very high groundwater potential, making them suitable for supporting regional water projects. Higher T values, between 148.2 and > 2028.6 m²/day, were mainly observed at depth and in the coastal area, indicating high vulnerability to marine water penetration due to the area’s high hydraulic conductivity.

Discussion

The aquifers in the study area are significantly affected by oceanic tides, resulting in large fluctuations in the piezometric level (Fakir and Razack 2003; Fadili et al. 2018). These fluctuations can influence and perturb the results of pumping tests with an increased risk of marine intrusion, particularly in the coastal fringe. Therefore, this study aimed to indirectly estimate geohydraulic parameters by transforming VES data into ERT profiles. This approach not only reduces interpretation time but also avoids ambiguities associated with VES inversion.

The distribution of apparent and inverted resistivities obtained through this approach reflects the typical geological variation of the study area (Figs. 3 and 4). Similar resistivity distributions have been reported by previous studies using ERT profiles (Fadili 2014; Fadili et al. 2015). Moreover, the low value of the inversion error RMS for all obtained models confirms the reliability and usefulness of this method in estimating geohydraulic parameters of geological layers.

Using the inverted resistivities, the hydraulic conductivity was calculated according to Heigold et al. (1979) formula, which is the most suitable for the geological context of the study area. The obtained results indicated that the hydraulic conductivity could be estimated accurately using surface geoelectrical measurements. The obtained values of hydraulic conductivity indicated mainly the dominance of silty sand, clean sand, and limestone formations that characterize the study area (Fitts 2002). According to Ebong et al. (2014), high K values are typically associated with strongly fractured and porous water-bearing horizons, which are

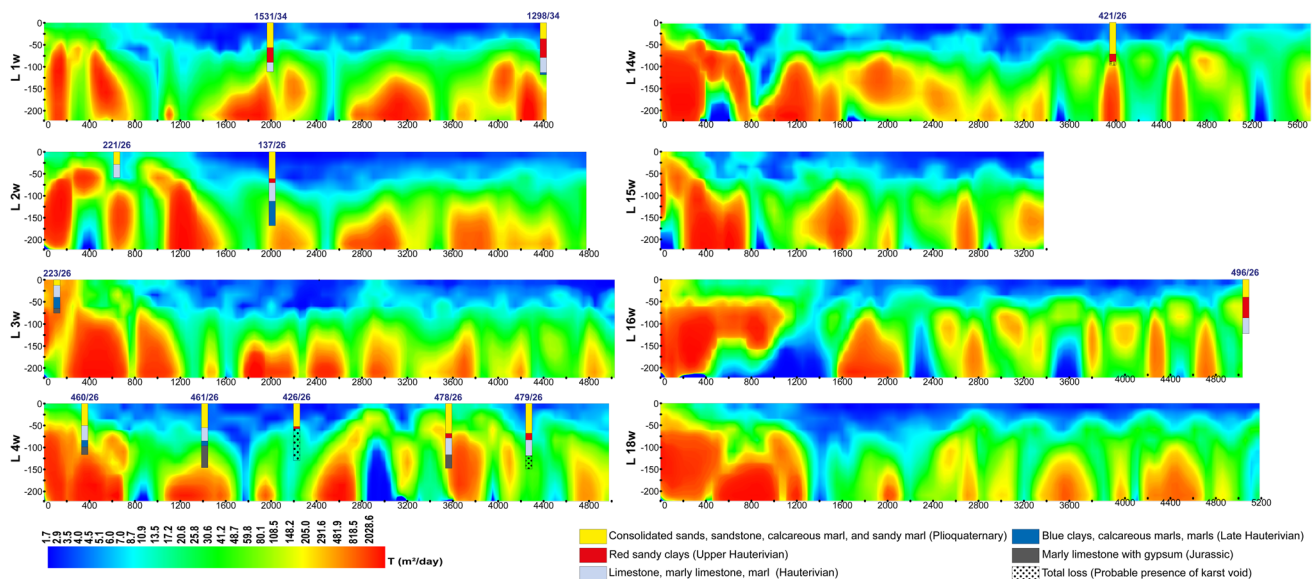


Fig. 7 Section of estimated transmissivity (m²/day)

mainly formed by marly limestone layers from the Hauterivian and Jurassic ages. However, locally observed low values may be explained by the presence of clayey minerals in the rock materials or by the influence of clay formations, such as Red Clay and Blue Clay (Heigold et al. 1979; Ebong et al. 2014). Another possible explanation for the low values could be the effect of reduced pore geometry, which can influence groundwater flow in the study area (Aleke et al. 2018; Oguama et al. 2020). Akhter et al. (2022) claim that low T and K values may be associated with fine-grained sediments composed mostly of sand and clay. In addition, de Almeida et al. (2021) suggest that a decrease in effective porosity leads to a lower water volume in the pores and, as a result, a decrease in K values. Therefore, the effective porosity is proportional to the hydraulic conductivity of the geological formation.

The range of the estimated Φ_{eff} values reflect the predominance of formations with variable grain sizes. According to Oguama et al. (2020), this range of values suggests that consolidated materials such as sand and clay dominate the geology of the study area. The results also show a positive correlation between the variation of effective porosity and hydraulic conductivity, indicating that K values increase with increasing effective porosity size. This positive correlation is supported by several studies, which reported a high correlation coefficient between K and Φ_{eff} (Aleke et al. 2018; de Almeida et al. 2021; Akhter et al. 2022).

According to Offodile (1983), high T values indicate a moderate to high aquifer potential and suggest the possible presence of fractured units that may contribute to groundwater occurrence. The geological calibration shows that the Hauterivian and Jurassic marly limestone formations are correlated with the highest T values. Consequently, areas with high T values are likely to have productive aquifers, while low values may indicate the absence of an aquifer or impermeable clay zones (Oguama et al. 2020).

Furthermore, the obtained results show an inverse relationship between the estimated geohydraulic parameters and the resistivity of the studied geological formations, which is consistent with estimated models found in the scientific literature (Ebone et al. 2014; Kazakis et al. 2016; De Almeida et al. 2021). This correlation can be attributed to the higher resistivity of the aquifer, owing to the decrease in hydraulic conductivity and transmissivity (Ammar and Kamal 2019; De Almeida et al. 2021). Saturation percentage, clay concentration, and grain size have also been shown to affect this inverse relationship (Urish 1981; Díaz-Curiel et al. 2016; Choo et al. 2016; Díaz-Curiel et al. 2016; George et al. 2017). In the present study, the decrease in T and K values within the study area occurs in conjunction with a decrease in grain size and an increase in clay content in the geological formations. On the other hand, homogeneous granular structures can lead to an increase in hydraulic

conductivity, as observed in coarse-grained aquifers (Choo et al. 2016; Pincus et al. 2017). The Sahel Doukkala area exhibits higher K and T values towards the coastal fringe, where the clay layer is absent. This finding further supports the idea that clay content plays a significant role in controlling the hydraulic properties of geological formations, and can thus have a considerable impact on aquifer potential.

To validate the findings of this study, the estimated K and T values from geoelectrical measurements were compared to values obtained from pumping tests conducted at different sites along the Sahel Doukkala. Ferré and Ruhard (1975) reported an average K value of 701 m/day for the recent Quaternary and a range between 2.59 and 52 m/day for the Plioquaternary. For the Hauterivian limestones, they reported an average K value of 432 m/day, while the fractured Cenomanian of marly limestones had low values ranging between 0.4 and 4 m/day. Overall, the range of K values reported by Ferré and Ruhard (1975) for the geological formations of Sahel Doukkala (0.4–701 m/day) is comparable to that estimated in the present study, which ranged between 0.2 and > 103.7 m/day. Moreover, the geological calibration carried out in this study resulted in low K values between 0.2 and 0.6 m/day for the Plioquaternary and values ranging between 12 and > 103 m/day for the Hauterivian and Jurassic marly limestone. Notably, the geological formations of the coastal area had high K values ranging between 15.9 and > 103.7 m/day.

According to the DRHT report (DRHT 1994), the T values in Sahel Doukkala are highly variable, typically ranging from 69 to 864 m²/day. In the coastal fringe, particularly from the south of Oualidia to Sidi Moussa, they were found to be higher than 864 m²/day. In the inland, T values are generally comprised between 9 and 86 m²/day, which was explained by the decrease in aquifer thickness and the increase in clay content. Pumping tests revealed T values ranging from 0.4 to 4 m²/day for the Cenomanian layer and from 86 to 8640 m²/day for the Jurassic layer (DRHT 1994). Meanwhile, Chatini (1987) used four different methods and obtained T values ranging from 28 to 778 m²/day (with an average of 259 m²/day) for the Plioquaternary layer and from 4 to 32 m²/day (with an average of 15 m²/day) for the Hauterivian, with a T value of 199 m²/day for the Jurassic layer. All these studies reported a range of T values (0.4–8640 m²/day) that is not significantly different from the findings of this study (1.7 → 2028.6 m²/day). The geological calibration conducted in the present study attributed low T values (1.7–13.5 m²/day) to the superficial part of the Plioquaternary, but they could reach values close to 205 m²/day in the coastal fringe. On the other hand, high T values (20.6 → 2028.6 m²/day) were associated with the Hauterivian and Jurassic layers. Moreover, the results of Chatini (1987) and DRHT FAO (1994) revealed higher T values in the coastal area, which aligns with the findings of the present work.

Overall, the geohydraulic parameters estimated from geoelectric data in this study can be considered representative of the geological formations in the study area when compared to data from previous studies. However, the observed differences may be primarily attributed to variations in lithology and heterogeneity within the geological formations as well as the dispersion of measurement points and the effects of oceanic tide on pumping test results. Nonetheless, the proposed approach provides a valuable tool for estimating geohydraulic parameters in areas, where pumping tests are not available or feasible while reducing the time required for the interpretation and determination of these parameters.

Despite the various constraints such as the collection and analysis of VES data and the absence of actual pumping test results, this study successfully estimated the geohydraulic parameters using the proposed approach. However, it is important to note that this approach was applied to a coastal porous aquifer, and its effectiveness in other types of aquifers should be evaluated. Furthermore, geohydraulic parameter estimation was based on only one equation type (Marotz 1968; Heigold et al. 1979), so it would be beneficial to compare the obtained results with alternative equations using ERT profile data for the same aquifer to increase the reliability of this approach. Despite these limitations, the findings of this study have significantly improved the understanding of the geohydraulic properties of the Sahel Doukkala aquifer. Therefore, addressing these limitations should be a focus of future research to ensure better planning and management of groundwater resources.

Conclusion

The present study aimed to indirectly estimate the geohydraulic parameters (K , T , and Φ_{eff}) of the coastal aquifers in Sahel Doukkala using subsurface electrical resistivity measurements. This study utilized an approach of transforming 1D VES data into 2D electrical resistivity tomography (ERT) models, which yielded more accurate results. Based on the resistivities obtained from the ERT profiles, the estimated values for K , T , and Φ_{eff} ranged from 0.2 to > 103.7 m/day, 11.6% to > 45.8%, and 1.7 to > 2028.6 m²/day, respectively. These values reflect the lithology of the study area, which is dominated by silty sand, clean sand, and limestone. Moreover, Inverse correlations were found between the geohydraulic parameters and aquifer resistivity, consistent with previous reports in the literature. This relationship is linked to the decrease in hydraulic conductivity and transmissivity, increase in clay concentration, and decrease in grain size and saturation percentage. These findings further support the lithologic contrast in the study area.

Pumping test data obtained from the literature of the study area gives k values ranging from 0.4 to 701 m/

day, while estimated ones range from 0.2 to > 103.7 m/day, whereas the T values obtained by pumping tests are between 0.4 and 8640 m²/day and the estimated values in this study are between 1.7 and > 2028.6 m²/day. Comparing the ranges of estimated K and T values with pumping test results revealed no significant differences. This suggests that the geohydraulic parameters estimated from geoelectric data are representative of the geological formations in the study area, with observed differences likely due to heterogeneous aquifers and dispersion of pumping test measurement points. Despite certain limitations, including the collection of geophysical data, the absence of recent pumping tests, the focus on a single type of aquifer, and the reliance on a single estimation equation, this study substantially increases the understanding of the geohydraulic properties of the Sahel Doukkala aquifers. The proposed approach offers a valuable alternative for estimating geohydraulic parameters from geoelectric data in areas, where pumping tests are not available or feasible. However, future research is needed to evaluate the effectiveness of this method in other types of aquifers to improve groundwater resource planning and management.

Author contributions Study conception and design, Acquisition of data, Drafting of manuscript, Analysis and interpretation Ahmed FADILI, Saliha NAJIB, Othmane BOUALLA Critical revision, Analysis and interpretation Abdelhadi MAKAN, Khalid MEHDI, Abdel-Ali KHARIS

Funding No financial resources have been assigned to support this study.

Data availability The data that support the findings of this study are available from the corresponding author, [Ahmed FADILI], upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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