Modeling of groundwater yield by the electrical method case of the Triassic sandstone aquifer (Tataouine South-Eastern Tunisia)
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ABSTRACT
The method of electrical resistivity has proven very effective in the evaluation of groundwater. This specialized technique uses Dar-Zarrouk (D-Z) parameters in the estimation of longitudinal unit conductance, transverse unit resistance, and longitudinal resistivity to examine the groundwater level, to distinguish the fresh, brackish, and saline water interface, and to assess the storage capacity of groundwater in the Triassic sandstone aquifer system in the Tataouine region (South-Eastern Tunisia). In this context, 23 vertical electrical soundings (VESs) were carried out in the Tataouine region using the Schlumberger configuration with a current electrode with a maximum spacing of the current electrodes (AB) of 500–600 m. The results indicate that the study area consists of three types of aquifers: (i) silt/clay saline water (<20 Ωm), (ii) a mixture of sand and clay freshwater (20–40 Ωm), and (iii) sand freshwater (40–200 Ωm). These sand freshwater aquifers are characterized by low longitudinal unit conductance (0–2.8 S), high values of transverse unit resistance (more than 9,000 Ωm²), and longitudinal resistivity (more than 35 Ωm) and are mainly concentrated in the north, south, and south-west regions of the study area. It should also be noted that the coefficient of anisotropy (λ) overlaps and does not clearly differentiate the characteristics of the aquifers of fresh, brackish, and saline water. An interpretation of VESs can also determine the storage capacity of groundwater by determining yield index values. Groundwater supply for the entire study area was classified as low yield, with a percentage of 13% and a maximum of 31% of the study area and 56% of moderate yield. Lastly, the real data from the drilling confirm all these results presented previously. The findings suggest that D-Z parameters are useful for making a distinction of various aquifer zones.

Key words | Dar-Zarrouk parameters, groundwater yield, sandstone aquifer, Tataouine, vertical electrical sounding

HIGHLIGHTS
• The geophysical method by electrical prospecting was used in this study.
• To evaluate the groundwater of the Triassic sandstone aquifer system in the Tataouine region (South-Eastern Tunisia).
• To delimit fresh, brackish, and saline water.
• To assess the storage capacity of groundwater in this aquifer level.

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INTRODUCTION

In the Tataouine region, the sandstone aquifer of Triassic at the below-to-medium level constituted the most precious resources in terms of quantity and quality, giving a rich inventory of drinking water to the principal urban communities of the locale and providing an abundant supply of drinking water to the main cities of the region (Smar, Kirchaou, Tataouine city, Ghomrassen, and Bir Lahmer). Therefore, it becomes highly important to improve and preserve these resources. Geographically, the study area is located in the Tataouine region in the extreme south of Tunisia. It lies within longitude 3,645,147 to 3,679,870 m and latitude 630,747 to 674,014 m (Figure 1), and the location map of the study area was produced using a Geographic Information System (GIS) by assembling topographic, geological, and DEM (Digital Elevation Model) maps. The municipality shares boundaries with the outcrop of the Triassic series at Djebel Rehech to the south, the outcrop of the Jurassic series to the West, Sahel Abebsa to the North, and the Djeffera plain to the East. It occupies a land area of approximately 1,278.3 km². The study area is characterized by arid climatic conditions and the annual rainfall was 159.7 mm during the 2019 season. In 2019, the annual average temperature ranged between 13 and 31 °C, and August was the hottest month. The important crops cultivated are vegetables, some fruitful trees, and wheat. Triassic deposits are widespread in the Tataouine region, especially in Djebel Rehech, (Burollet 1965; Busson 1970, 1972; Ben Ismail 1991; Bouazziz 1993); the lower to middle Triassic is filled with the sandstones of Sidi Stout (Scythian-Anisian) and Kirchaou sandstones (Ladinian) and the Upper Triassic is filled with Mekraneb dolomites (lower Carnian), Touareg sandstone (Middle Carnian), and Rehech dolomites (upper Carnian) (Figure 2). The hydrographic networks (Fessi Oued) and the outcrop of the sandstone sequence along Jebel Rehech (Figure 1) toward the Mzar

![Location map of the study area.](https://iwaponline.com/aqua/article-pdf/70/4/600/898943/jws0700600.pdf)
region favor direct infiltration of runoff water into these sandstone units, thus forming an aquifer unit with freshwater. On the other hand, in the Bir Lahmer area, the lower aquifer is covered by a thick series of more or less waterproof monk clay, which delimits the runoff direct supply. Logs from wells entering the test holes indicate that the middle of the study area occupied by a thick series of clays is considered an area with no aquifer potential. Figure 3 shows a hydrograph of the fluctuation of the Triassic sandstone water table in the Tataouine area, clearly indicating a gradual decrease in the static level of around 27.94 m during high water in 1996 until it reaches 30.15 m in low water in 2019. This loss can be explained by the increase in the exploitation of groundwater (increase in the number of boreholes) (Duan 2019a, 2019b, 2020) accompanied by a succession of periods of drought.

Extreme climatic conditions (high temperature and extremely low precipitation) and increased water demand in arid zones could significantly affect water supply availability and water demand patterns (Duan & Kaoru 2020). Therefore, it became necessary to evaluate these groundwater resources. The evaluation of the quality and quantity of hydraulic resources in the arid zone is carried out by several methods such as the statistic method of chemical analyses, the use of meteorological data (Kansoh et al. 2020), and salt concentrations (Obianyo 2019), but these methods are a bit expensive and time-consuming. In the same context, in an effort to provide more drinking water to the various regions, competent departments concentrated on digging many wells (but they were an expensive and time-consuming exercise). Apart from these disadvantages, the water in these wells is sometimes highly saline, making it unfit for both consumption and agricultural use. We, therefore, adopted an alternative method, which is a new geophysical method by electrical prospecting of D-Z parameters. This allows us first to assess the groundwater, then to determine the interface between fresh, brackish, and saline water, and finally to evaluate the storage capacity of groundwater in the Triassic sandstone aquifer system in the Tataouine region (South-Eastern Tunisia). The scope of this work was to assist the government agencies plan, develop, and manage groundwater resources in the Tataouine region in collaboration with the Tataouine Regional Agricultural Development Commissioner (RADC).

Our work is subdivided into five parts: First, from the apparent resistivities, a pseudo section is built, which provides a fairly clear picture of the variation in the apparent resistivities both laterally (depending on the profile) and vertically (in-depth). It highlights, especially by the contrasts of resistivities, the risks involved as well as the changes of facies. Then, we determine the ranges of resistivities of the resistance and conductor soils and identify the aquifer levels. This is done by a comparison of vertical electrical sounding (VES) interpretation and lithology, since it is considered a necessity for efficient use of electrical data in hydrogeological research (George et al. 2011). The changes in the resistivity of the grounds are
linked to geological parameters such as the type of rock, porosity, and degree of saturation. Indeed, dry sand or gravel usually yields high resistivity, since their pore spaces lack water content for such materials. Usually, water aquifers of high resistivity are found in sand or gravel. On the other hand, the aquifers constitute altered rocks and the clayey materials present an average-to-low resistivity. Then, we use the parameters D-Z, that is, the longitudinal unitary conductance ($S_c$), the transverse unit resistance ($T_r$), and the longitudinal resistivity ($\rho_l$), to differentiate the zones of fresh, brackish, and saline water in the first step and to subsequently evaluate the groundwater yield index. Finally, we will confirm all these results by the real data of drilling (Figure 4).

Several studies were carried out within this study area, most of them focusing on the determination of the hydrogeological characteristics (thickness, salinity, piezometric level, flow, transmissivity, etc.), geochemistry and geometric configuration, and the geographical delineation of each level, but none of them considered the aspect of determination of the interface between fresh and saltwater and then the evaluation of the storage capacity of groundwater. These two important aspects are our main focus.

MATERIALS AND METHODS

VESs were performed at the Tataouine region with Schlumberger configuration, as shown in Figure 1. The maximum current spacing of the electrodes (AB) was maintained between 400 and 500 m ($AB/2 = 200$–$250 \text{ m}$). The unit measured is the apparent resistivity, and $\rho$ is plotted on the bilogarithmic paper as a function of $AB/2$ in meters, resulting in a VES curve, using IpI2Win software (IpI2Win v.2.1 Usersguide 2001).

Both a qualitative and a quantitative interpretation of the VES curve was done, and the qualitative analysis involved a visual examination of the pseudo sections and the sounding curves. Although the soundings were also quantitatively interpreted, the findings were interpreted in terms of geoelectric parameters (i.e., resistivity and thickness of the layer). Subsequently, the geoelectric parameters were combined into single variables, in other words, known as the Dar-Zarrouk (D-Z) parameters (Mailet 1974). However, in the present study, based on the parameters of D-Z (longitudinal unit conductance $S_c$, transverse unit resistance $T_r$, and longitudinal resistivity $\rho_l$) we delineated the interface of fresh, brackish, and saline waters; in the
second stage, we relied on the coefficient of anisotropy ($\lambda$) and total transverse resistance ($Tr$), i.e., ($\lambda*Tr$) to calculate the groundwater supply index value, which proved very useful for determining and assessing groundwater supply. The groundwater yield index was used for validating the groundwater supply throughout the study area.

RESULTS AND DISCUSSION

Pseudo section

The pseudo section is a qualitative approach that shows the lateral and vertical variance of the apparent resistivity. The locations of the profiles are shown in Figure 1.

The pseudo section following profile 1 (Figure 5) shows the presence of four highly resistant anomalies over 100 $\Omega$m. The first is at the base of VES 13, and the second is semideep (+50 m deep) located below SEV 9. These two anomalies reflect the sandstone unity of Inferior Trias. The third anomaly is located below SEV 2, 21, and 18 and is rooted in depth, while the fourth anomaly is superficial and is located at the level of SEV 6, 12, and 1 and does not attack the 50 m depth. These two last anomalies are stuck to the sandstone unit of the Middle Triassic.

Note also that a conductive anomaly located in the middle of the profile shows that the terrain is dominated by clay. The rest of the profile is occupied by average resistivity attributed to clay-sandy or sand-clay soil.
We note a slight discontinuity in the lithology accompanied by two fairly contrasting resistivities which reflect that the area is affected by three faults, the first located between VES 9 and VES 14, the second between VES 2 and VES 21, and the third located between VES 21 and VES 18.

The pseudo section following profiles II and III (Figure 6(a) and 6(b)) are of direction E-W that shows the same pace; a resistant anomaly extends almost over the entire profile; it shows the sandstone terrain. There are also clayey-sandstone lenses whose resistivities do not exceed 70 Ωm for profile II and 40 Ωm for profile III.

**Analyses of D-Z parameters**

A qualitative and a quantitative interpretation of the VES curve was done, and the result of the qualitative...
interpretation is apparent resistivity and geoelectric pseudo sections, while the quantitative interpretation employed the technique of 1-D inversion using EPI2Win-2001 software with an average adjustment error of around 2.5%. The quantitatively interpreted sounding curves gave results interpreted as geoelectric layer parameters (i.e., resistivity and thickness). For various sedimentary formations, the resistivity ranges for freshwater clay (7–15 Ωm) show similar values for saltwater clay (3–6 Ωm) and for the clay with sand (8–25 Ωm). Similar values for freshwater sandstones (30–150 Ωm) interfere with sandstones with clay (20–40 Ωm). This similarity of the resistivity range in different layers, therefore, causes some ambiguity in the differentiation of the boundary between geological units.

Regarding our study area, Table 1 shows the resistivity ranges of the various formations after interpreting the layer parameters and then comparing them with the lithological logs. A remarkable difference is revealed for the resistivity value range of the study area (Table 1) and that of Table 2: for clay with saline water and clay with freshwater sand. A slight variation in sand, clay, and salinity can alter the values of resistivity, causing uncertainty in interpretation. This uncertainty will make differentiating between fresh and saline aquifers a difficult task. In such a case, an effective method for analyzing and interpreting the data is required to obtain a viable solution for delineating the aquifers of fresh, brackish, and saline water. An analysis of the D-Z parameters (Sc, Tr, and ρl) provides a simple and useful method for understanding the geophysical character of the fresh, brackish, and saline aquifers. These parameters are validated in Table 3.

### D-Z Parameters (methods of estimation)

For a horizontal, homogeneous, and isotropic layer, two basic parameters are defined: the layer resistivity (ρi) and the layer thickness (hi) for its h layer (i = 1 for the surface layer). The integration of this parameter into single variables, in other words, is known as Dar-Zarrouk parameters. Mailet in 1974 was the first to introduce the concept of these parameters, which is used as the basis for determining aquifer properties (Niwas & Singhal 1987). Other parameters such as Sc, Tr, ρl (Singh et al. 2004), and anisotropy (λ) can be derived for each layer from the respective resistivities and thicknesses.

For a given layer (Figure 7),

Longitudinal conductance Sc

\[ Sc = h / \rho \]

The Sc is measured in Siemens (S) or mho. (1)

Transverse resistance \( Tr = h \bullet \rho \) The unit of Tr is Ohm meter square (Ω-m²).

(2)

For \( n \) layers,

\[ Sc = \sum_{i=1}^{n} \left( h_i / \rho_i \right) = h_1 / \rho_1 + h_2 / \rho_2 + h_3 / \rho_3 + \cdots + h_n / \rho_n \]

(3)

\[ Tr = \sum_{i=1}^{n} \left( h_i \bullet \rho_i \right) = h_1 \bullet \rho_1 + h_2 \bullet \rho_2 + h_3 \bullet \rho_3 + \cdots + h_n \bullet \rho_n \]

(4)

where \( \rho \) is the resistivity calculated in ohm meters (Ωm), \( h \) is the thickness consecrated in meters (m), and \( I \) is the number of layers.

\[ \rho_l = H / Sc \]

(5)

\[ \rho_t = Tr / H \]

(6)
The application of the D-Z parameters received a great deal of attention by several authors, especially for the characterization of groundwater (Henriët 1997; Singh et al. 2004; Singh 2005; Oliveira Braga et al. 2006; Nwankwo et al. 2011; Srinivasa et al. 2012; Utom et al. 2012; Batayneh 2013; Hasan et al. 2017).

Longitudinal unit conductance (Sc)

Typically, longitudinal conductance (Sc; Equation (3)) is used to define the potential target areas of groundwater. Based on resistivity data from 23 sounding stations, the contour map of the Sc value was established with a contour

\[
\lambda = \frac{\sqrt{\frac{S_c \times T_r}{H}}} = \sqrt{\frac{\rho_t}{\rho_l}}.
\]  

(7)

where \( H \) is the depth of the bottom-most geoelectric layer.

| Values of Dar-Zarrouk (D-Z) parameters, namely, the total longitudinal unit conductance (Sc), total transverse unit resistance (Tr), and longitudinal resistivity (\( \rho_l \)) for all the 23 sounding locations with depth (\( H \)), average transverse resistivity (\( \rho_t \)), and anisotropy (\( \lambda \)) |

| Sounding station | \( h \) (m) | Sc (S) | Tr (\( \Omega \)m²) | \( \rho_l \) (\( \Omega \)m) | \( \rho_t \) (\( \Omega \)m) | \( \lambda \) |
|------------------|-------------|--------|------------------|----------------|----------------|-------|
| 1                | 73.46       | 2.66540211 | 3,853.7466 | 27.5605695 | 52.4604764 | 1.37965 |
| 2                | 150         | 2.02779282 | 16,586.7   | 73.9720541 | 110.578     | 1.22264 |
| 3                | 150         | 1.84602877 | 16,815.8   | 81.2555051 | 112.105333  | 1.174591 |
| 4                | 118         | 7.55710375 | 3,542.025  | 15.6144475 | 30.017161   | 1.3865051 |
| 5                | 111         | 1.8686535  | 15,397     | 59.4010608 | 138.711712  | 1.528127 |
| 6                | 90          | 10.9775611 | 3,763      | 8.19854264 | 41.8111111  | 2.2582 |
| 7                | 117         | 0.7749502  | 36,912.57  | 150.977444 | 315.492051  | 1.4455 |
| 8                | 175         | 34.8884942 | 5,317.6    | 5.01598032 | 30.3862857  | 2.46127 |
| 9                | 105         | 2.8525334  | 19,405.12  | 41.6778545 | 163.068235  | 1.978026 |
| 10               | 130         | 34.8884942 | 5,317.6    | 5.01598032 | 30.3862857  | 2.46127 |
| 11               | 130         | 5.482979   | 22,072.817 | 23.7097388 | 169.7909    | 2.676 |
| 12               | 93          | 3.25513168 | 6,356      | 28.5702728 | 68.344086   | 1.5466 |
| 13               | 137         | 1.55200343 | 14,286.06  | 88.273001  | 104.27781   | 1.08688 |
| 14               | 131         | 14.0403808 | 7,264.7526 | 9.33023129 | 55.4561267  | 2.437971 |
| 15               | 119         | 2.8525334  | 19,405.12  | 41.6778545 | 163.068235  | 1.978026 |
| 16               | 200         | 5.64866594 | 7,947.3    | 35.4065901 | 39.7365     | 1.0593 |
| 17               | 62.4        | 1.99816986 | 2,969.64   | 31.2285763 | 47.5903846  | 1.23447 |
| 18               | 83          | 4.63746041 | 10,572.74  | 17.8977269 | 127.38241   | 2.66781 |
| 19               | 154.9       | 5.49965254 | 10,025.12  | 28.1654157 | 64.7199484  | 1.5158666 |
| 20               | 100         | 12.6703929 | 3,584.4    | 7.89241507 | 35.844      | 2.13109729 |
| 21               | 130         | 2.08809007 | 12,241.03  | 62.2578508 | 94.1617692  | 1.229816 |
| 22               | 82          | 0.87021032 | 11,375.43  | 94.2300933 | 138.724756  | 1.21333 |
| 23               | 138         | 0.50991747 | 47,746.3   | 270.63203  | 345.987681  | 1.1306826 |

Figure 7 | Three-dimensional electrostratigraphic model showing the total longitudinal conductance (Sc) and total transverse resistance (Tr) (modified from Reynolds (1997)).

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interval of 2 Sc (Table 3; Figure 8). The Sc values for the 23 stations range from 0.5 to 34.88 S. The map clearly and without overlap indicates three aquifer zones, namely, fresh, brackish, and saline water:

1. Sc values <2.8 S, indicated by the dark blue color on the map, indicate that the fresh groundwater is mainly concentrated in the north and south of the study area.
2. 2.8–7.5 S, with the azure color on the map, shows brackish water between saline water and freshwater that is in the center of the study area along the NW-SE line.
3. Sc values >7.5 S, colored azure to red on the map, shows the northwest, south, and east of the study area of the saline aquifer.

Usually, high Sc values are typical of low transmissivity in aquifers.

For a greater classification of Sc, 23 soundings are classified into three groups: freshwater group with VES 2, 3, 5, 7, 9, 10, 13, 15, 17, 21, 22, and 23; brackish water group with VES 1, 11, 12, 16, 18, and 19; and saline water group with VES 4, 6, 8, 14, and 20. For these groups, a graphical plot of Sc values is proved in Figure 9, which indicates that a marked variation in the variety of Sc values also shows large differences in the magnitudes of saline, brackish, and fresh groundwater. The range of Sc values for saline water in the graph is 7.5–34.88 S, the range for brackish water is 3–7.5 S, and the range for freshwater is 0.5–2.8 S.
So, the categorization of the three zones becomes uncomplicated.

**Transverse unit resistance (Tr)**

Figure 10 presents the transverse unit resistance map, Tr, in 23 sounding stations with an interval of 3,000 Ωm². Once again, it furnishes a remarkable distinction between the three regions of the saline, brackish, and fresh aquifers.

1. For 1,000 < Tr values < 5,000 Ωm², the saline aquifers can be identified.
2. Tr values from 5,000 to 9,000 Ωm² indicate the brackish water aquifers.
3. For 9,000 < Tr < 44,000 Ωm², the freshwater aquifers can be identified.

It can also be noticed from the map that the contours of saltwater brackish and those of freshwater have a distinct region and are not similar.

Figure 11 displays a better distinction in the behavior of the saline, brackish, and freshwater aquifers. The area of saline water aquifers is defined with the VES 1, 4, 6, 8, 17, and 20. The brackish water aquifer region is represented by the sounding numbers of VES 12, 14, and 16. The freshwater region is shown by the sounding numbers, VES 2, 3, 5, 7, 9, 10, 11, 13, 15, 18, 19, 21, 22, and 23, which clearly indicate a noticeable difference in the behavior of these aquifers.

The same figure exposes a range of values for the transverse longitudinal (Tr) of saline water, oscillating between 3,000 and 5,317.6 Ωm² and between 6,356 and 7,947.3 Ωm² and those for brackish water and freshwater aquifers extending from 10,025.12 to 47,746.3 Ωm².

**Longitudinal resistivity (ρl)**

The ρl has also been used to distinguish between saline, brackish, and freshwater. The 10 m contour interval map is plotted for all values, as shown in Figure 12. These represent very simple, visible, and widely differing ranges in three different regions for the saline, brackish, and freshwater aquifers based on the widths that these have achieved. For the saline water aquifer, the ρl is <15 Ωm;
for the brackish water aquifer, it is from 15 to 35 Ωm; and for the freshwater aquifer, it is up to 35 Ωm. A graph of ρl values for the soundings belonging to the saline (VES 4, 6, 8, 14, and 20), brackish (VES 1, 11, 12, 16, 17, 18, and 19), and freshwater (VES 2, 3, 5, 7, 9, 10, 13, 15, 21, 22, and 23) groups is shown in Figure 13. The graph clearly shows all three types of aquifers, as well as a clear contrast and distinction between the fresh, brackish, and saline water aquifers. The chart also explains that the values of ρl for

the saline water aquifer range from 5.01 to 15.61 Ωm, for brackish water from 17.89 to 35.40 Ωm, and for freshwater from 41.76 to 270.63 Ωm.

Coefficient of anisotropy ($\lambda$)

Anisotropy is the result of alternating layers of clay and fine sand, according to Flathe (1955), while Frohlich (1974) indicates that anisotropy is the impact of the intercalation of
Figure 11 | Graphical plot of transverse unit resistance (Tr) for fresh, brackish, and saline water aquifers.

Figure 12 | Contour map of longitudinal resistivity (10 m contour interval).
various grains within the equivalent layers. Singh & Singh (1970) noted that lower values of anisotropy correspond to areas of high aquifer capacity. Keller & Frischknecht (1966) indicate that the anisotropy coefficient ($\lambda$) increases with increasing compaction and the durability of rocks.

Unlike other parameters such as Sc, Tr, and $\rho_l$, the anisotropy contour map (Figure 14) is not able to distinguish between the three water groups. Figure 15 shows great overlap and does not easily distinguish between the saline, brackish, and freshwater characteristics. The ambiguity of these characteristics can be explained by the irregularity in the proportion of clay and sand. So, we should infer that it is not possible to distinguish the three groups of water aquifers based on anisotropy ($\lambda$).

**Significance and use of D-Z parameters**

Through the research mentioned above, the behavior of Sc, Tr, and $\rho_l$ with respect to the saline, brackish, and freshwater aquifers was evidently proved. Table 2 illustrates the different resistance levels for understanding subsurface layers in groundwater aquifer systems. With the exception of the ranges of 30–150 $\Omega$m for freshwater areas, which also overlap with sandstone ranges with clay layers (20–40 $\Omega$m), we find that the ranges for different geoelectric layers are very similar and display no wide variation and have overlapping characteristics. Therefore, they establish an ambiguous and speculative condition. In fact, it is difficult to set specific resistance values for fresh, brackish, and saline groundwater because they depend on various factors that are beyond the scope of this article, but the present uncertainties in the demonstration of resistance data can be greatly reduced if the geophysical parameter is clear and easy to identify, supporting the interpretation. This reduction in uncertainty is based on the D-Z parameters as they provide very good accuracy. They indicate obvious, clear, and widely large ranges for the saline, brackish, and freshwater aquifers, as summarized in Table 4. In addition, it can be noted that the graphic presentations (Figures 9, 11, and 13) and the contour maps of Sc, Tr, and $\rho_l$ (Figures 8, 10, and 12) agree with the distinction between the three types of aquifers, brackish, saline, and freshwater, for the entire study area. If these parameters are implemented consistently and correctly, the ambiguity generated by the interpretation of the resistivity data may be minimized. Therefore, in any virgin area, the above-illustrated techniques must be performed and useful and applicable ranges of Sc, Tr, and $\rho_l$ must be defined for that area. This helps regional authorities to select

![Graphical plot of longitudinal resistivity ($\rho_l$) for fresh, brackish, and saline water aquifers.](image-url)
**Figure 14** | Contour map of anisotropy (0.15 contour interval).

**Figure 15** | Graphical plot of anisotropy ($\lambda$) for fresh, brackish, and saline water aquifers.
areas with freshwater to dig new wells that may contribute to reducing the acute shortage of water for irrigation and drinking water.

**Modeling of groundwater yield capacity**

Depending on the previous studies for each of Okonkwo & Ugwu (2015) and Olubusola et al. (2018). It became possible to determine and evaluate the groundwater yield index values by using the D-Z parameters. Moreover, these parameters were further defined in this study by applying the combination of two parameters of anisotropy coefficient ($\lambda$) and the total transverse resistance ($Tr$), i.e., ($\lambda^*Tr$). The groundwater yield capacity map (Figure 16) shows values between 3,703.41 and 53,985.9106. The special distribution of these values over the entire study area can help classify the categories into three main areas (Figure 17):

1. The area with low to extremely low yields presents groundwater yield capacity values between 3,703.41 and 13,088.0494 G.W.Y.I., dominating 13% of the studied area, and were observed in the extreme southern part.
2. The second zone reflects a high efficiency where the efficiency values are greater than 30,000 G.W.Y.I., with about 31% of the studied area being mainly concentrated in the northeast part, part of the south, and the northwest.
3. The zone of moderate yield of groundwater presents yield values oscillating between 15,196.7446 and 28,206.0615 G.W.Y.I., with a percentage of about 56%, and occupies the rest of the study.

**Validation of the groundwater yield map**

To verify the accuracy of the groundwater crop map and hence the proposed methodology, pumping test results were used from the fixed and stationary water-level wells in the total field of research. To ensure the success of the groundwater yield capacity method, it suffices to superimpose the two groundwater yield maps (Figure 15) and the actual yields map (Figure 1) and deduce the degree of compatibility between the two. This is done by comparing the actual yield of each borehole and the estimated yield of its position (Olubusola et al. 2018). Tables 5 and 6 provide a table indicating the correlation (agreement) between the present and the predicted yields. Based on this table, the prediction’s success rate is estimated as follows.

Tables 5 and 6 show the correlation (concordance) between actual and expected returns. The following are founded on this table:

1. Success percentage (precision) of the groundwater potential map is shown in Table 5 = (20 boreholes coincide/24 boreholes do not coincide) × 100 = 83.33%.
2. The success percentage (precision) of the groundwater potential map is presented in Table 6 = (10 wells coincide/12 wells do not coincide) × 100 = 83.33%.

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**Table 4** | Dar-Zarrouk parameters applicable for saline, brackish, and freshwater in the Triassic sandstone aquifer system

| Parameter                          | Freshwater aquifers | Brackish water aquifers | Saline water aquifers |
|------------------------------------|---------------------|-------------------------|-----------------------|
| Longitudinal unit conductance ($Sc$) | 0–2.8 S             | 2.8–7.5 S               | More than 7.5 S       |
| Transverse unit resistance ($Tr$)   | Freshwater aquifers | More than 9,000 Ωm²     | 5,000–9,000 Ωm²       |
| Longitudinal resistivity ($\rho_l$) | Freshwater aquifers | More than 35 Ωm         | 15–35 Ωm              |
| Coefficient of anisotropy ($\lambda$)| Freshwater aquifers | The contours and graphs are overlapping and do not clearly differentiate the characteristics of fresh brackish and saline water aquifers. |
| Saline water aquifers               | More than 5,000 Ωm² | <5,000 Ωm²              |<15 Ωm |

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Finally, this study is of vital importance for this aquifer, as it helps reduce the margin of error when researching and exploring areas of high yield and good quality. It also reduces the uncertainty resulting from the interpretation of the resistivity data. Therefore, researchers like us can apply this study to other regions whose groundwater experiences ambiguities in the distribution of fresh, brackish, and saline water. However, the limitation of this study is its unsuitability to areas with complex geological settings.

CONCLUSION

In order to obtain a knowledge of the geoelectric characteristics of the subsurface sequence, aquifer geometry, and fresh, brackish, and saline water, a geoelectric investigation of groundwater potential was performed around Tataouine and Bir Lahmer, South-Eastern Tunisia. We also suggested a detailed method of combining all parameters that are significant for determining groundwater potential. This article confirms some of the results of the previous study and exposes...
further details and a clear demonstration of the distinction of the three groups of aquifers from evaluations of the parameters of D-Z, i.e., Sc, Tr, and $\rho_l$. We concluded the following from this study: one can deduce that the North and South-East parts of the study region are characterized by a low value of Sc < 2.8 S, and values of Tr range between 9,000 and 44,000 $\Omega$ m$^2$ and $\rho_l > 35 \Omega$m, and this zone reflects fresh groundwater. The rest of the study area is occupied by brackish to saline water. Thus, the D-Z parameter allows an easy distinction between the three groups of aquifers (fresh, brackish, and saline water). In addition, the value of the groundwater production capacity index less than 13,088 G.W.Y.I. implies a low or extremely low yield, that between 15,196 and 28,206 G.W.Y.I. implies a moderate yield, while a value of 30,000 G.W.Y.I. and above represents a high yield. These yield values are validated by the drilling data. The interpretation of these parameters is considered to be

Table 5 | Validation borehole for the groundwater yield map

| Well numbers | Expected yield description from the groundwater yield map | Actual yield from the drilled borehole (l/s) | Actual description | Remarks |
|--------------|--------------------------------------------------------|--------------------------------------------|--------------------|---------|
| A            | Low                                                    | 0.27                                       | Low                | Coincide|
| B            |                                                        | 4                                          |                    | Coincide|
| C            |                                                        | 1                                          |                    | Coincide|
| D            | High                                                   | 6                                          | Not coincide       |         |
| E            |                                                        | 10                                         |                    | Coincide|
| F            |                                                        | 3                                          |                    | Coincide|
| G            | Low                                                    | 4                                          | Low                | Coincide|
| H            | Moderate                                               | 11.5                                       | Moderate           | Coincide|
| I            |                                                        | 11.75                                      |                    | Coincide|
| J            |                                                        | 15.3                                       |                    | Coincide|
| K            |                                                        | 12.2                                       |                    | Coincide|
| L, M, and N |                                                        | 11.6, 13.5, and 20                         |                    | Coincide|
| W            | Low                                                    | 14.7 (TDS = 15.64 g/l)                     | Low                | Coincide|
| O            | High                                                   | 33.8                                       | High               | Coincide|
| P            |                                                        | 36                                         |                    | Coincide|
| Q            |                                                        | 27.8                                       |                    | Coincide|
| R            |                                                        | 23.5                                       |                    | Coincide|
| S            |                                                        | 22                                         |                    | Coincide|
| T            |                                                        | 30.5                                       |                    | Coincide|
| U            | Moderate                                               | 24.4                                       | High               | Not coincide|
| K            | Moderate                                               | 24.5                                       | High               | Not coincide|
| V            | High                                                   | 0.32                                       | Low                | Not coincide|
an easy task, can be efficiently done, and is not a time-consuming affair. It also helps the competent departments to choose less salty areas for drilling wells in order to augment water resources in the region.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or in its Supplementary Information.

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