Chapter 5

Estimation of Hydrological Parameters from Geoelectrical Measurements

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Abstract

In the coastal aquifer of the lowlands on the right side of the river Sinaloa there is need for fresh water for agricultural development since, around 15% of the water used in agricultural irrigation, is from underground sources. This situation is exacerbated in periods of drought, which promotes drilling with the risk of finding brackish water in them; besides, there is the risk of not meeting water demand due to low hydraulic transmissivity (*T*) of the aquifer, putting at risk the drilling costs that this implies. In this sense, the determination of *T* and *K* (hydraulic conductivity) is important for the development and management of groundwater exploitation of the study area. Generally by means of pumping tests in wells, *T* is obtained, with high costs, so there are few values of *T*. *K* is generally obtained by wells and laboratory test. The aim of this chapter is to establish an empirical relationship between *T* and *K* with Dar-Zarrouk parameter in porous media, transverse resistance (T_R), in addition to a characterization of the water quality through the electrical resistivity. This parameter is estimated from surface resistivity measurements, which are more economical in relation to the pumping tests; thus, *T* was characterized in the study area. The coefficient of correlation of the exponential adjustment is 0.79 and the relation is $T = 137185.7\ T_R^{0.020758} - 156691$ and $K = 367.21^{0.0548} - 518.813$ with coefficient of correlation of 0.678.

Keywords: electrical resistivity, water quality, transverse resistance, hydraulic transmissivity, hydraulic conductivity

1. Introduction

Groundwater of the coastal aquifer in the lowlands of the right side of the Sinaloa River constitutes an important support element for the development of agricultural activity in the region, especially during periods of drought. In order to extract groundwater, it is necessary to perform perforations, whose costs are high. In addition to the high cost is the uncertainty of finding fresh water, so it is desirable to have a preliminary characterization of the quality of groundwater, as well as the hydraulic property, which defines the aquifer water production. Hydraulic transmissivity (T) determines the flow of groundwater that is transmitted through a vertical strip of aquifer-wide unit under a hydraulic gradient unit. This parameter is required in numerical flow modeling processes [1, 2]; recharge tests; and in the determination of the radius of influence of a well for the determination of the perimeters of protection to the contamination of well water, among others. It is useful to estimate the resource groundwater and its integral management [3] through pumping tests, which generally are scarce due to high costs; therefore, the power to determine it through geoelectric parameters such as the resistivity of the aquifer formation, obtained through a vertical electrical sounding [4] is of interest, since this is a non-destructive, economical method and no drilling is required for its realization. The hydraulic limitations presented by the aquifers are directly related to the permeability and thickness that each sequence of the sedimentary cover can develop [5]. The physical analogy between hydraulic and electric flow has been a motivation to study for several authors [2, 3, 6–12] who present relations between electrical and hydraulic parameters of an aquifer. Nourbehect [13] presents a general theoretical approach on the coupling between various flows of fluids of nature through a functional relation, which allows to establish that there are relations between electrical and hydraulic parameters. In this work, we are experimenting in the search for exponential relations between R_o and R_w; T and K with the electric transverse resistance. The transverse resistance is one of the Dar-Zarrouk parameters and has been proved to be useful in the evaluation of hydraulic conductivity and transmissivity [14–20]. In a flat and stratified earth model, each geoelectric layer is characterized by a thickness h and an electrical resistivity ρ. These parameters allow obtaining the parameter of Dar-Zarrouk, the electric transversal resistance (T_R), which, for a layered medium of n layers, in each layer is defined as:

$$T_R = h\rho \tag{1}$$

Niwas and Singhal [21] found analytic relationship between the parameters of Dar-Zarrouk and T as:

$T = (K\sigma)T_R$ and assuming that the product $K\sigma$ remains unchanged in areas with similar geological setting and water quality $T = CT_R$. By knowing the value of this constant C, the T and K can be calculated by knowing T_R.

Ponzini et al. [8] found an empirical function between the transversal electrical resistance of an aquifer with its T. The shape of the relation between aquifer properties and geophysical parameters can be linear or non-linear [16]. The empirical function found is of the potential type of the form $TR = AT^M + B$, where T_R is transversal resistance, T the hydraulic transmissivity, and

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the terms *A, M*, and *B* are constant. Soupios et al. [22] found relations between electrical cross-resistance and hydraulic transmissivity with an expression of the form proposed by Ponzini et al. [8]. Perdomo et al. [23] established a relation of the form $T = A.TR^{M}$. On the other hand, Kazakis et al. [12] obtained linear relations between the K and the resistivity of the aquifer. Some authors have found a linear relationship between *T* and T_R [16–19]. The works of these authors suggest that there is a relation between the transmissivity of an aquifer and the parameter of Dar-Zarouk, also that this relation is influenced by the geo-hydrological conditions of the place and maintains an exponential relation. Under these circumstances and taking into account that *T*, T_R, and electrical resistivity can be obtained from surface measurements of electrical resistivity in combination with pumping tests, it is possible to find relations for the study area.

2. Materials and methods

2.1. Description of the study area

The study area is located between the coordinates 25°16′50″ and 25°41′13″ north latitude and 108°24′51″ to 108°41′22″ west longitude (see **Figure 1**). The climate is dry, very warm, and warm with rains in summer. The average annual precipitation is 300–400 mm (1986–2013) [24]. The average annual temperature is 22–24°C for the 1986–2013 series [24]. Soils are of alluvial origin,

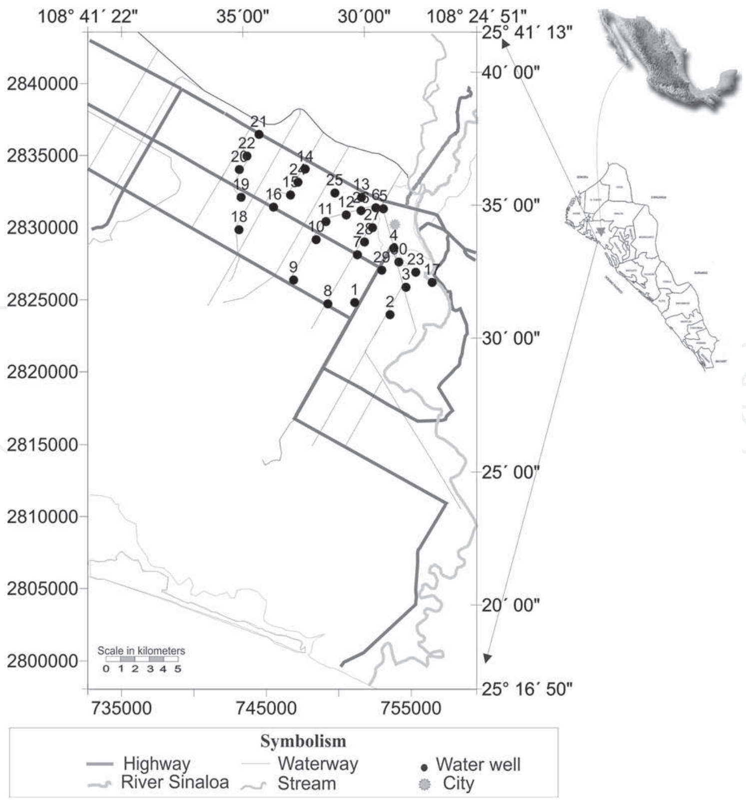

Figure 1. Localization of the study area.

Cenozoic era, quaternary period, predominating soils Vertisol (62.55%), Solonchak (21.72%), Cambisol (3.17%), Kastañozem (2.58%), Regosol (2.13%), Phaeozem (1.52%), Arenosol (1.24%), Fluvisol (0.92%), and Leptosol (0.56%) [25].

The topographical relief is smooth, has a gradient that goes from 0.5 to 1 m per kilometer in a northeasterly direction (**Figure 2**). This was obtained from the heights of the ledge of the wells.

2.2. Wells information

Thirty wells were analyzed with a depth between 100 and 150 m, which were built by the National Water Commission. The wells are geotagged with a portable GPS brand Magellans. Water samples were obtained from each well; for this the wells in operation were sought, and groundwater electrical conductivity was measured *in situ*. Each of the wells counts with information of pumping tests at constant flow rate and steady state in recovery, lithologic columns, and well construction design. With the information of the pumping tests, *T* was obtained by the Theis method [26].

The interpretation of the pumping tests indicated that 3.3% of the *T* values are comprised in medium high, 6.7% in high, and 90% in very high according to the classification of Villanueva and Iglesias [26].

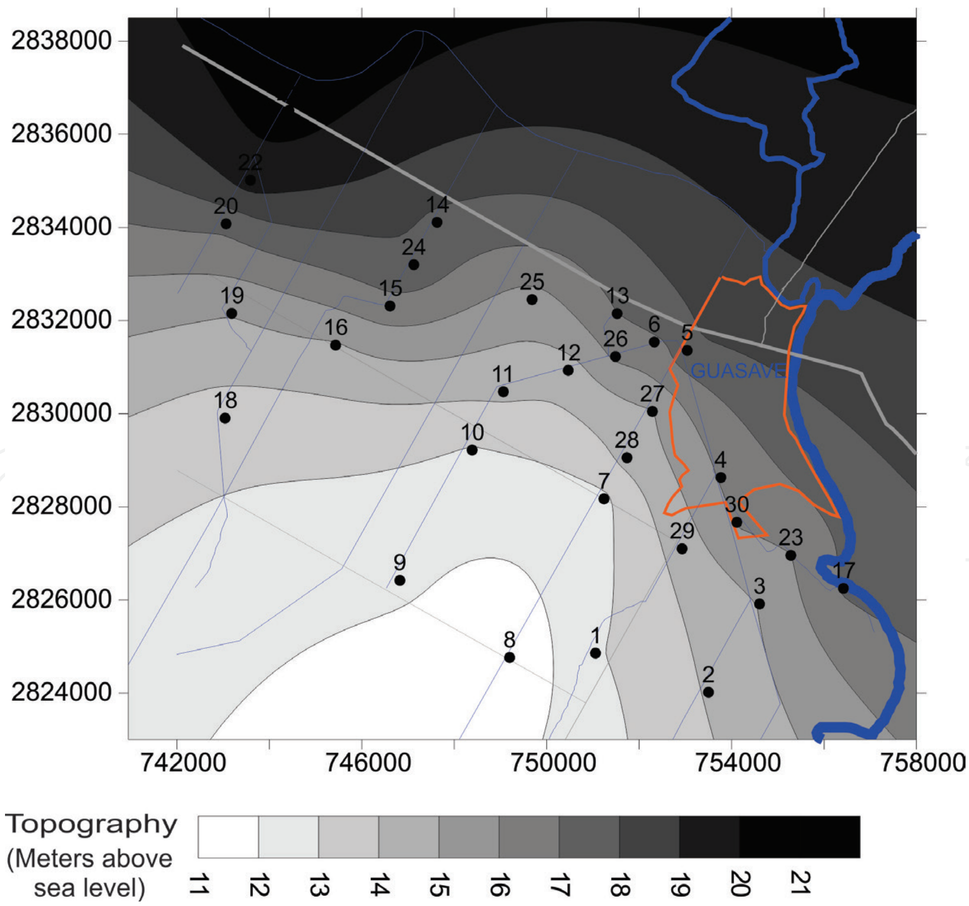

Figure 2. Topographic relief of the study area.

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The Theis method presupposes that the well crosses the whole aquifer. In this case, the correction was not made, because at the moment, neither with geophysics nor with the columns of the wells, the total thickness of the aquifer is known. On the other hand, the impact of the lack of correction is insignificant, since the observed descents are less than 15% of the total saturated thickness, that is, the thickness is greater than 150 m and the observed descent is less than 10 m; thus, according to [26] it is not necessary to make the correction to Dupuit when the descents are inferior to 15 by 100 of the initial saturated thickness, H_0.

2.3. Aquifer geometry

With the information of the 30 lithological columns of wells, the geometry of the aquifer of the study area was determined. **Figure 3** shows a section with the sequence of materials where an abundance of gravel with silty clay matrix, standing out in the presence of a body of gravel is seen. The lithological columns of the wells that have depths between 100 and 150 m do not show a geological or hydrogeological basement.

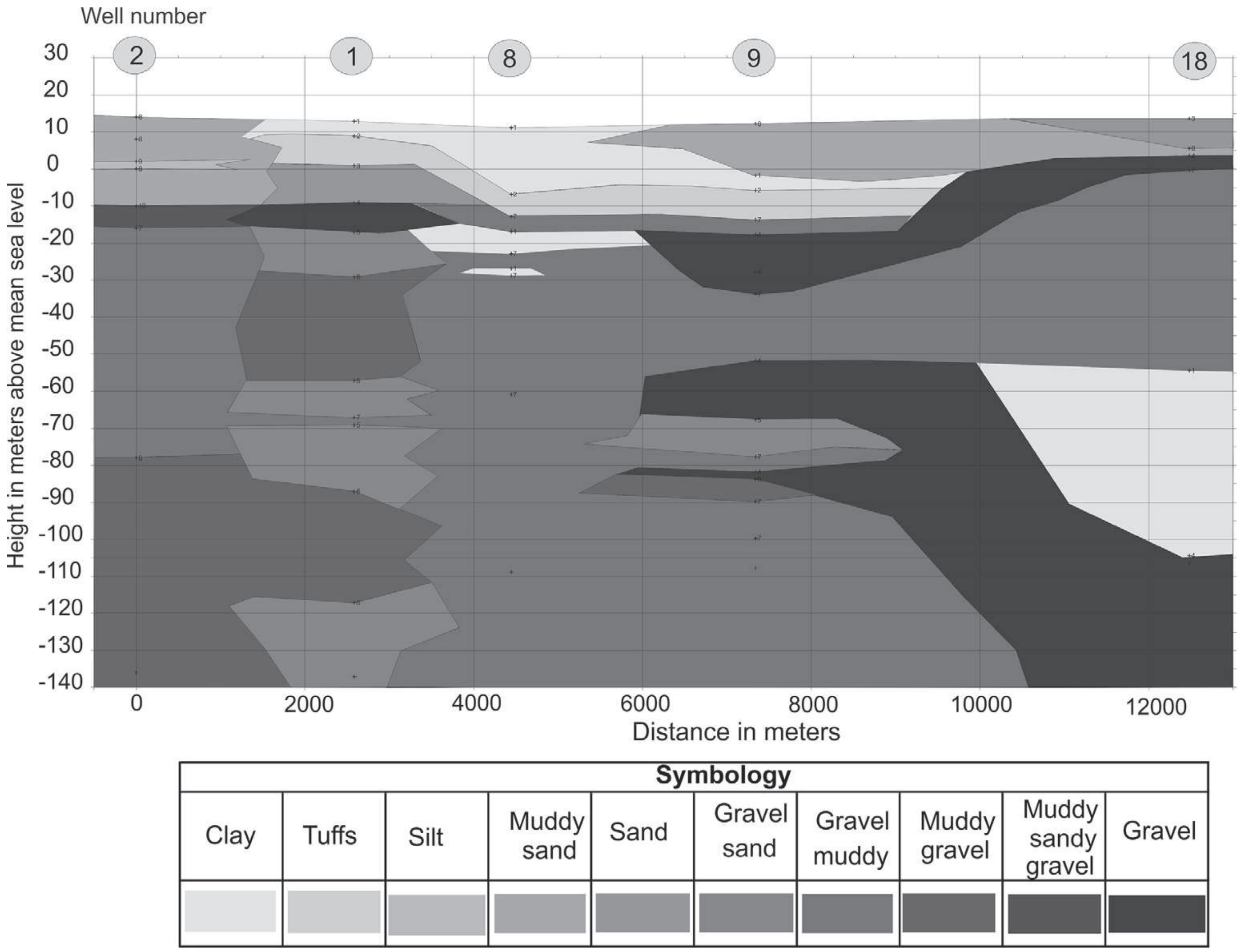

Figure 3. Section perpendicular to the Sinaloa River.

2.4. Vertical electrical soundings

Fourteen wells were selected from 30 wells. In these, a vertical electrical survey was carried out, having them as the center of the sounding. The Schlumberger array was used with a maximum current electrode separation of 500 m the soundings were interpreted by direct modeling using the Guptasarma algorithm [27].

2.5. Relation between R_w and R_o

With the modeling of the vertical electrical sounding, the resistivity (R_o) of the saturated thickness of the formation is obtained. R_w value is obtained from the field measurement of well water samples in pumping. From the different values of R_o and R_w by minimum squares adjustments, the constants A and B of the linear relation are obtained:

$$R_W = A\,R_O + B \tag{2}$$

3. List of hydrological parameters (T and K) with geoelectric measurements and pumping tests

With information from true resistivity (R_o) of each layer and its thickness (h) T_R was obtained, which was related to T and K from the exponential expressions of the form:

$$T = A\,.\,T\,R^M + B \tag{3}$$

$$K = A\,.\,T\,R^M + B \tag{4}$$

Where T is the hydraulic transmissivity, K is the hydraulic conductivity, T_R is the transverse resistance, and A, M and B are constants obtained by minimum squares adjustment.

4. Results and discussion

4.1. Geoelectric sounding

Figure 4 shows the result of the VES performed in wells 1 and 10. For the modeling of the VES data, the available information of the lithological columns, static level of the water, and its salinity was considered. Experimental data and their corresponding models, as well as the root-mean-square (RMS) error of each adjustment are presented. The lithological relationship with electric resistivity allows delimiting the aquifer area, characterized by predominantly low clayey materials. In the case of well 1, the electrical resistivity was 13.04 Ω-m, and in the case of well 10, it varied from 9 to 29 Ω-m. The presence of materials with clay wells favors the $T - T_R$ ratio [10].

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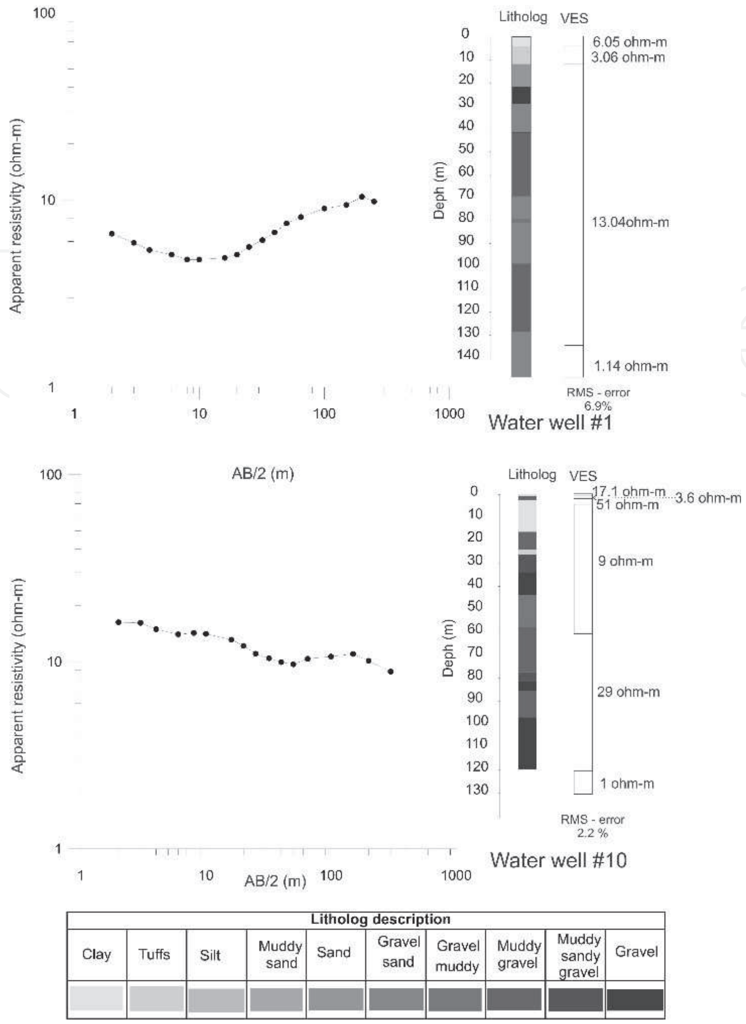

Figure 4. VES experimental data with their respective interpreted model compared with lithological column.

4.2. Water quality

Some authors [11, 28–30] have successfully applied the Archie's law to hydrogeology studies. **Figure 5** shows the fit for 14 pairs of $R_w - R_o$ values that illustrate a linear function directly proportional connecting the groundwater resistivity (R_w) and the saturated layer resistivity (R_o); as the pore water resistivity increases, the formation resistivity increases as well. The constants A and B are 1.014091 and −2.316, respectively. The correlation factor resulting from the adjustment is 0.90, therefore

$$R_w = 1.014\, R_o - 2.316 \qquad (5)$$

The practical meaning of this relation is that, if it is desired to perform a perforation in the study area, it is possible to perform a vertical electrical sounding prior to drilling; its interpretation can be determined by R_o, which when placed in the above expression enables a priori

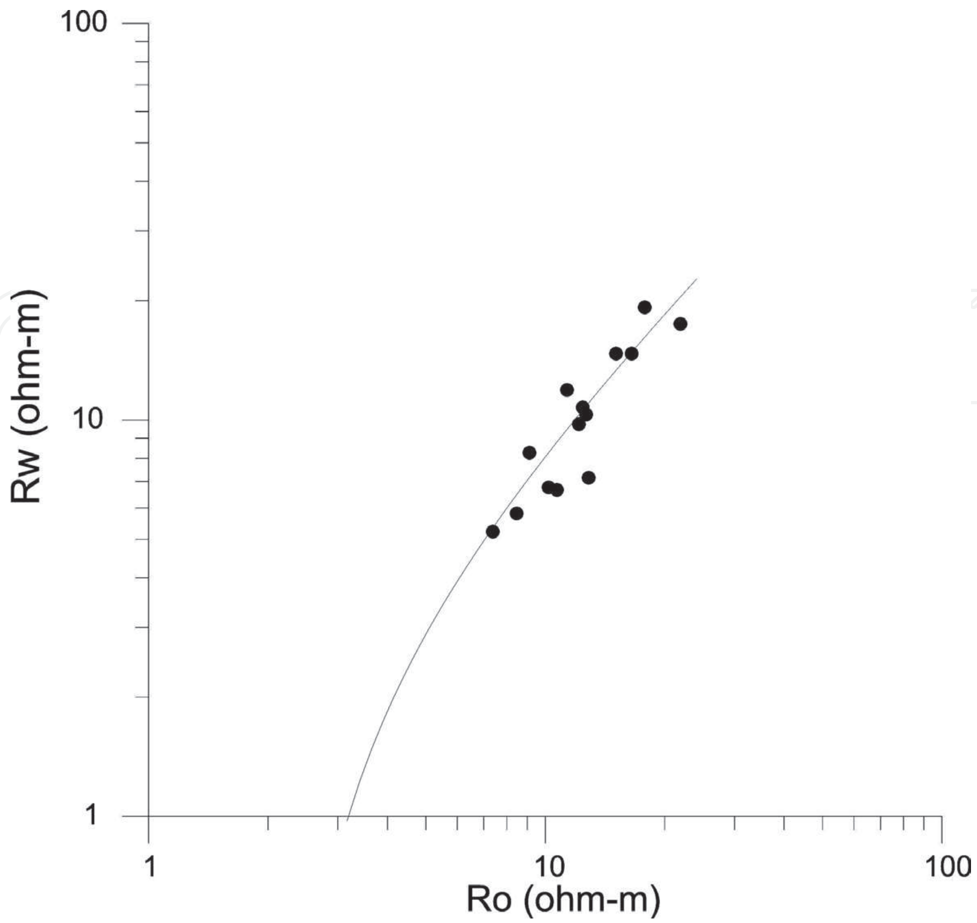

Figure 5. Bulk resistivity versus aquifer resistivity.

value, R_w. Electrical conductivity (EC) of water is inversely proportional to the electrical resistivity and is determined by the expression

$$EC = \frac{10}{R_w} \tag{6}$$

With the value of the EC and considering the relationship between EC and total dissolved solids (TDS), salinity can be obtained by the expression [31]

$$TDS = \frac{1000EC}{1.65} \tag{7}$$

With the value of TDS, the type of water expected can already be determined [32]. From the interpretation of the VESs, it was found that the resistivity of the aquifer formation R_o varies between 7.4 and 21.9 Ω-m, for its part, the water of the formation presented a resistivity that oscillated between 5.2 and 19.2 Ω-m (see **Table 1**). Value of R_o is 10 Ω-m and R_w is 7.825 Ω-m. This value corresponds to 774 ppm of TDS (salinity); thus, it is fresh water according to the classification of Heath [32]

4.3. The relationship between T and T_R

From R_o and aquifer thickness (h) values, T_R was determined. **Table 1** shows the T_R values for 14 wells and their respective T and K values. **Figure 6** shows that T_R and T have a relationship

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Well number	Well depth	Porewater resistivity (R_w, Ω-m)	Hydraulic transmissivity (m^2/day)	Hydraulic conductivity (m/day)	Computed parameters—VES interpretation		
					h (m)	R_o resistivity (Ω-m)	*TR* transverse resistance (Ω m^2)
1	150	10.3	3410.3	25.8	132.2	12.7	1676.3
2	150	14.7	2925.4	22.5	130.3	15.1	1965.2
3	120	19.2	1588.2	22.7	70.0	17.8	1246.6
6	150	10.8	3157.8	35.3	89.5	12.4	1111.3
7	134	6.7	3116.2	31.3	99.7	10.7	1066.8
10	120	17.5	4294.6	47.8	89.8	21.9	1968.1
11	121	14.7	2354.1	30.7	76.7	16.5	1266.3
13	120	11.9	1694.8	17.7	95.9	11.3	1088.1
19	120	8.3	452.4	4.8	94.9	9.1	865.0
20	150	5.8	1675.7	14.7	113.6	8.5	962.0
21	150	5.2	987.4	7.8	126.5	7.4	932.4
22	120	6.8	715.5	8.3	86.0	10.2	876.0
28	122	7.2	3139.2	31.9	98.4	12.9	1265.5
29	120	9.8	2063.2	21.5	95.8	12.2	1164.4

Table 1. Data used and interpreted parameters.

as those found in Refs. [8, 11, 23]. The adjustment to the graph is of exponential type with values of the coefficients *A*, *M*, and *B* of 137185.7, 0.020758, and −156691, respectively. The coefficient of correlation of the exponential adjustment is 0.79.

$$T = 137185.7\ T_R^{\ 0.020758} - 156691 \tag{8}$$

The values of the coefficients depend on the geological conditions, so Ebong et al. [11] found $T = 0.2319 T_R^{0.7246}$, Perdomo et al. [23] $T = 0.53\ T_R^{0.98}$, Ponzini et al. [8] $T_R = 4.022 \times 10^3 T^{0.577} + 17.2$.

Other authors have found direct linear relationship: Niwas and Celik [10] assumed that the product $K\sigma$ remains unchanged in areas with similar geological setting and water quality; Frohlich and Kelly [33], for a constant water resistivity value of 100 Ω-m, obtained a linear relationship between T_R and T; and Kosinsky and Kelly [34] in glacial outwash material.

Since $K\sigma$ is not constant, then according to [10], the expected relation between T and T_R is not linear but exponential. This is due to the geological nature of the study area, which is expressed through the distribution of T and the EC of the aquifer. The values of T are high and vary from 452.4 to 4294.6 m^2/day. The EC varies between 0.45 and 1.35 mS/cm.

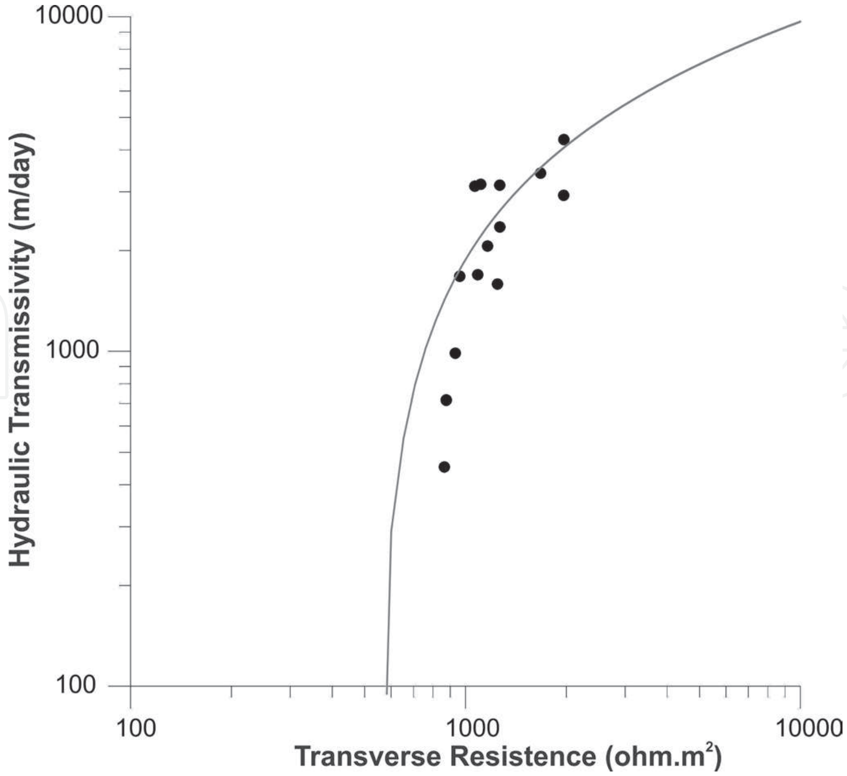

Figure 6. Relation between hydraulic transmissivity and transverse resistance.

4.4. The relationship between K and T_R

Hydraulic conductivity K was obtained from the relation $T = Kb$, finding that this varies from 4.77 m/day to 47.83 m/day. It is an essential parameter to describe water movement under saturated conditions [35]. With the T_R and K values of each well, **Figure 6** was constructed, which in an analogous way to $T - T_R$. The values of the coefficients of the exponential adjustment A, M, and B were 367.21, 0.0548, and −518.813, respectively. The coefficient of correlation of the exponential adjustment is 0.678.

$$K = 367.21^{0.0548} - 518.813 \tag{9}$$

Measurements of aquifer resistivity are useful to estimate the aquifer hydraulic conductivity due to the fundamental relation between K and electrical conductivity [36]. Kelly [37] worked with glacial outwash materials and obtained a linear connection between resistivity and K in relatively uniform water quality. The exponential relation allows to correlate K with T_R, in an area where T and σ already indicated are not uniform.

5. Conclusions

Exponential relations between geohydrologic parameters (T, K) and geoelectric parameter (T_R) have been found with a good statistical adjustment. These relations allow to characterize the water quality and the transmission capacity of the aquifer; therefore, for placements between the wells with which the empirical relations were obtained, there is a characterization so that from the realization of VES a geoelectric section of the subsoil, which includes the value of R_o, thus obtaining T_R. When T_R is obtained, relations with T and K can be found. With these relations, scenarios can be proposed on descents in future wells to be performed. Thus, the relations found guide the planning and use of groundwater.

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References

[1] Painter SL, Woodbury AD, Jiang Y. Transmissivity estimation for highly heterogeneous aquifers: comparison of three methods applied to the Edwards Aquifer, Texas, USA. Hydrogeology Journal. 2007; **15**(2): 315–331. doi:10.1007/s10040-006-0071-y

[2] Asfahani J. Hydraulic parameters estimation by using an approach based on vertical electrical soundings (VES) in the semi-arid Khanasser valley region, Syria. Journal of African Earth Sciences. 2016; **117**: 196–206. doi:10.1016/j.jafrearsci.2016.01.018

[3] Tizro AT, Voudouris K, Basami Y. Estimation of porosity and specific yield by application of geoelectrical method–a case study in western Iran. Journal of Hydrology. 2012; **454**: 160–172. doi:10.1016/j.jhydrol.2012.06.009

[4] Orellana E. Geoelectric prospecting in direct current (2nd ed.). Madrid: Paraninfo; 1982, 578 p. [In Spanish]

[5] Silva Busso AS, Amato SD. Hydrogeological aspects of the periserrana region of Tandilia (Buenos Aires, Argentina). Boletín geológico y minero. 2012; **123**(1): 27–40. [In Spanish]

[6] Archie GE. The electrical resistivity log as an aid in determining some reservoir characteristics. Transactions AIMME. 1942; **46**: 54. doi:10.2118/942054-G

[7] Croft MG. A method of calculating permeability from electric logs. Geological Survey Research. 1971; **750-B**, 265–269

[8] Ponzini G, Ostroman A, Molinari M. Empirical relations between electrical transverse resistance and hydraulic transmissivity. Geoexploration. 1984; **22**(1): 1–15. doi:10.1016/0016-7142(84)90002-4

[9] Chandra S, Ahmed S, Ram A, Dewandel B. Estimation of hard rock aquifers hydraulic conductivity from geoelectrical measurements: a theoretical development with field application. Journal of Hydrology. 2008; **357**(3): 218–227. doi:10.1016/j.jhydrol.2008.05.023

[10] Niwas S, Celik M. Equation estimation of porosity and hydraulic conductivity of Ruhrtal aquifer in Germany using near surface geophysics. Journal of Applied Geophysics. 2012; **84**: 77–85. doi:10.1016/j.jappgeo.2012.06.001

[11] Ebong ED, Akpan AE, Onwuegbuche AA. Estimation of geohydraulic parameters from fractured shales and sandstone aquifers of Abi (Nigeria) using electrical resistivity and hydrogeologic measurements. Journal of African Earth Sciences. 2014; **96**: 99–109. doi:10.1016/j.jafrearsci.2014.03.026

[12] Kazakis N, Vargemezis G, Voudouris KS. Estimation of hydraulic parameters in a complex porous aquifer system using geoelectrical methods. Science of the Total Environment. 2016; **550**: 742–750. doi:10.1016/j.scitotenv.2016.01.133

[13] Nourbehect B. Irreversible thermodynamic effects in inhomogeneous media and their applications in certain geoelectric problems (No. 9017-4). Massachusetts Institute of Technology Cambridge Geophysics Laboratory; 1963, 149 p

[14] Joel ES, Olasehinde PI, De DK, Omeje M, Adewoyin OO. Estimation of aquifer transmissivity from geo-physical data. A case study of Covenant University and Environs, southwestern Nigeria. Science International (Lahore). 2016; **28**(4): 3379–3385

[15] Aizebeokhai AP, Oyebanjo OA. Application of vertical electrical soundings to characterize aquifer potential in Ota, Southwestern Nigeria. International Journal of Physical Sciences. 2013; **8**(46): 2077–2085

[16] Sattar GS, Keramat M, Shahid S. Deciphering transmissivity and hydraulic conductivity of the aquifer by vertical electrical sounding (VES) experiments in Northwest Bangladesh. Applied Water Science. 2016; **6**(1): 35–45. doi:10.1007/s13201-014-0203-9

[17] Teikeu WA, Njandjock PN, Bisso D, Atangana QY, Nlomgan JPS. Hydrogeophysical parameters estimation for aquifer characterisation in hard rock environment: a case study from Yaounde, Cameroon. Journal of Water Resource and Protection. 2012; **4**(11): 944–953. doi:10.4236/jwarp.2012.411110

[18] Utom AU, Odoh BI, Okoro AU. Estimation of aquifer transmissivity using Dar Zarrouk parameters derived from surface resistivity measurements: a case history from parts of Enugu Town (Nigeria). Journal of Water Resource and Protection. 2012; **4**(12): 993–1000. doi:10.4236/jwarp.2012.412115

[19] Oborie E, Udom GJ. Determination of aquifer transmissivity using geoelectrical sounding and pumping test in parts of Bayelsa State, Nigeria. Journal of Physical and Environmental Science Research. 2014; **2**(2): 32–40

[20] Singh S, Singh VS. Estimation of hydraulic characteristics from electrical resistivity data in coastal aquifers of southern India. Journal of the Geological Society of India. 2016; **88**(1): 77-86. DOI: 10.1007/s12594-016-0460-3

[21] Niwas S, Singhal DC. Estimation of aquifer transmissivity from Dar-Zarrouk parameters in porous media. Journal of Hydrology. 1981; **50**: 393–399. doi:10.1016/0022-1694(81)90082-2

[22] Soupios PM, Kouli M, Vallianatos F, Vafidis A, Stavroulakis G. Estimation of aquifer hydraulic parameters from surficial geophysical methods: a case study of Keritis Basin in Chania (Crete–Greece). Journal of Hydrology. 2007; **338**(1): 122–131. doi:10.1016/j.jhydrol.2007.02.028

[23] Perdomo S, Ainchil JE, Kruse E. Hydraulic parameters estimation from well logging resistivity and geoelectrical measurements. Journal of Applied Geophysics. 2014; **105**: 50–58. doi:10.1016/j.jappgeo.2014.02.020

[24] INEGI (National Institute of Statistic and Geography). Statistical and geographical directory of Sinaloa, Mexico. 2014; 53 p. [In Spanish]

[25] INEGI (National Institute of Statistic and Geography). Geographical Information of the United Mexican States, municipality of Guasave, Sinaloa, Mexico. Geostatistical key 25011. México; 2009, 9 p. [In Spanish]

[26] Villanueva M, Iglesias L. Wells and aquifers evaluation techniques through pumping tests. Madrid: Ibergesa; 1984, 426 p. [In Spanish]

[27] Guptasarma D. Optimization of short digital linear filters for increased accuracy. Geophysical Prospecting, 1982; **30**: 501–514. doi:10.1111/j.1365-2478.1982.tb01320.x

[28] Peinado-Guevara H, Green-Ruíz C, Herrera-Barrientos J, Escolero-Fuentes O, Delgado-Rodríguez O, Belmonte-Jiménez S, Ladrón De Guevara M. Relationship between chloride concentration and electrical conductivity in groundwater and its estimation from

vertical electrical soundings (VESs) in Guasave, Sinaloa, Mexico. Ciencia e investigación agraria. 2012; **39**(1): 229–239. doi:10.4067/S0718-16202012000100020

[29] Norzagaray-Campos M, Herrera-Barrientos J, Herrera-Barrientos F, Muñoz-Sevilla P, Yuri-Mendoza E. Capurro-Filigrasso: Simulación bidimensional del transporte de solutos en la costa del acuífero Santo Domingo, Ensenada; B. C. México. Revista Geologica America Central. 2002; **27:** 153–163

[30] Grellier S, Reddy KR, Gangathulasi J, Adib R, Peters CC. Correlation between electrical resistivity and moisture content of municipal solid waste in bioreactor landfill. Geotechnical Special Publication. 2007; **163**: 1–14

[31] Peinado GHJ, Green RCR, Herrera BJ, Escolero FÓA, Delgado RO, Belmonte JSI, Ladrón De Guevara MDLÁ. Quality and suitability for agricultural and domestic use of water from the Sinaloa river aquifer, coastal portion. Hidrobiológica. 2011; **21**(1): 63–76

[32] Heath RC. Basic ground-water hydrology. U.S. Geological Survey Water-Supply paper 2220. U.S. Geological Survey, Reston, Virginia, ISBN 0-607-68973-0. 1983; 86 p.

[33] Frohlich RK, Kelly WE. The relation between hydraulic transmissivity and transverse resistance in a complicated aquifer of glacial outwash deposits. Journal of Hydrology. 1985; **79**: 215–229. doi:10.1016/0022-1694(85)90056-3

[34] Kosinsky WK, Kelly WE. Geoelectric sounding for predicting aquifer properties. Ground Water. 1981; **19**(2): 163–171. doi:10.1111/j.1745-6584.1981.tb03455.x

[35] Jadczyszyn J, Niedzwiecki J. Relation of saturated hydraulic conductivity to soil losses. Polish Journal of Environmental Studies. 2005; **14**(4): 431–435

[36] Kaleris VK, Ziogas AI. Estimating hydraulic conductivity profiles using borehole resistivity logs. Procedia Environmental Sciences. 2015; **25:** 135–141. doi:10.1016/j.proenv.2015.04.019

[37] Kelly WE. Geoelectric sounding for estimating aquifer hydraulic conductivity. Ground Water. 1978; **15**(6): 420–425. doi:10.1111/j.1745-6584.1977.tb03189.x