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Hydraulic parameters estimation from well logging resistivity and geoelectrical measurements

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ABSTRACT

In this paper, a methodology is suggested for deriving hydraulic parameters, such as hydraulic conductivity or transmissivity combining classical hydrogeological data with geophysical measurements. Estimates values of transmissivity and conductivity, with this approach, can reduce uncertainties in numerical model calibration and improve data coverage, reducing time and cost of a hydrogeological investigation at a regional scale. The conventional estimation of hydrogeological parameters needs to be done by analyzing wells data or laboratory measurements. Furthermore, to make a regional survey many wells should be considered, and the location of each one plays an important role in the interpretation stage. For this reason, the use of geoelectrical methods arises as an effective complementary technique, especially in developing countries where it is necessary to optimize resources. By combining hydraulic parameters from pumping tests and electrical resistivity from well logging profiles, it was possible to adjust three empirical laws in a semi-confined alluvial aquifer in the northeast of the province of Buenos Aires (Argentina). These relations were also tested to be used with surficial geoelectrical data. The hydraulic conductivity and transmissivity estimated in porous material were according to expected values for the region (20 m/day; 457 m^2/day), and are very consistent with previous results from other authors (25 m/day and 500 m^2/day). The methodology described could be used with similar data sets and applied to other areas with similar hydrogeological conditions.

1. Introduction

In developed countries there are lots of resources and funds allocated to hydrogeological researches. This situation enables to have well distributed data and to conduct very specific tests, with the aim of having complete raw data and with the best quality. In this sense, it is possible to fulfill in practice many of the requirements considered from a theoretical point of view.

On the contrary, in developing countries this is not generally the case and researchers usually deal with limited funds and poorly distributed information. Economic and social situation lead to generate expedited data to solve a very specific problem: the provision of water.

In this context, this paper describes the methodology used in order to maximize the amount of data and overcome the lack of specific tests.

Isolated geophysical measurements can be used to locate with certain ambiguousness the depth and thickness of an aquifer. However, in combination with classical hydrogeological data it is possible to obtain quantitative estimates of hydraulic parameters where pumping tests cannot be performed or to improve the location of wells reducing the chance of failure or unexpected low performance in pumping rates.

Among the standard techniques to determine hydraulic parameters as conductivity (K) and transmissivity ($T = Kh$, h is the saturated thickness), the pumping test is the most precise direct method, which provides locally representative information of these parameters. This technique usually constitutes a high cost in hydrogeological studies and some of the procedures used may depend on constructive characteristics of the well (Fetter, 2001). Other methods involve sediment sampling, granulometry and permeability analysis to estimate the K at laboratory scale, but the use of their results in the field scale is not always satisfactory, mainly due to difficulties in upscaling the results.

Despite representing an indirect technique, surface geoelectric methods can provide estimates for T and K, constituting valuable information, especially in areas where there is a lack of subsurface information, reducing the time and costs of a hydrogeological investigation.

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This study has been performed in an alluvial aquifer in the northeast of the province of Buenos Aires. Here T and K were obtained from steady state pumping test. T was also derived from specific capacity (Qe) from other 29 wells. The bulk resistivity and clay content of the sediments were determined with well logging profiles, and three types of fitting curves were proposed between hydraulic and electrical parameters. The applicability of using the resistivity from Vertical Electrical Sounding with these laws was also tested.

The methodology described here is used to provide local and regional hydraulic estimates combining data from well efficiency tests, steady state pumping tests and geophysical measurements, optimizing the significance of non-specific measurements.

1.1. Background setting

The governing equations of electrical and fluid flow (Ohm and Darcy's law) in a conductive medium have similar expressions; therefore, they are a widely accepted mathematical analogy (Fitts, 2002; Freeze and Cherry, 1979; Milsch et al., 2008; Singh, 2005)

$$\mathrm{J} = -\sigma * \mathrm{dV/dr} \tag{1}$$

$$\mathrm{Q} = -\mathrm{K} * \mathrm{dh/dr}; \mathrm{K} = \mathrm{k} * \gamma/\mu. \tag{2}$$

Where *J* is the current density, σ is the electrical conductivity (reciprocal of electrical resistivity ρ), V is the electric potential measure at a certain point at distance *r*. In Eq. (2) *Q* is the flow rate, *h* is the height of the water level, permeability (k), viscosity (μ) and specific weight (γ) (Custodio and Llamas, 1983).

The first attempt to try to find a physical relationship between these rock parameters began with the laws proposed by Archie (1942) for clay free sands.

$$\mathrm{FF} = \rho_r/\rho_w \tag{3}$$

$$\rho_r = \mathrm{a} * \rho_w \phi^{-\mathrm{m}} \mathrm{S_w}^{-\mathrm{n}} \tag{4}$$

where *FF* is the formation factor, bulk and fluid resistivities (ρ_r and ρ_w) porosity (ϕ), tortuosity (a) and S_w is the degree of saturation in Eq. (4). The cementation and saturation exponents are m and n respectively.

Even though a single universal law linking electrical and hydraulic phenomena for saturated sediments does not exist yet, it is valid to assume that the greater the effective porosity, the better the current and fluid flow will be.

Laboratory studies have shown the relations between FF and the intrinsic k of some graded sand samples (Jones and Buford, 1951; Worthington, 1975). Departing from this, Croft (1971) developed a relationship between K and FF for different porosity ranges of an aquifer.

Milsch et al. (2008) presented a theoretical relation between electrical conductivity and k, by direct application of Ohm's and Darcy's laws. Analyzing both properties experimentally, the authors noticed that none of the models was able to predict k within the experimental accuracy.

The same phenomenon had been studied on a macroscopic scale in porous media of alluvial aquifers. T, FF and K were estimated using empirical or semi-empirical correlations. Some authors proposed simple linear equations (Chen et al., 2001; Kelly, 1977; Kosinski and Kelly, 1981; Mazac et al., 1985; Schimschal, 1981; Urish, 1981; Yadav and Abolfazli, 1998) and others non-linear ones, such as potential or exponential equations (Dassargues, 1997; Dhakate and Singh, 2005; Heigold et al., 1979; Purvance and Andricevic, 2000; Shevnin et al., 2006; Singh, 2005; Sinha et al., 2009; Soupios et al., 2007).

Authors such as Niwas and Singhal (1981, 1985) investigated analytical relations between T and Dar-Zarrouk parameters from Vertical Electrical Sounding (VES) by adjusting a ratio of conductivities (K-σ). This approach was applied by Massoud et al. (2010); Tizro Taheri et al. (2010) and Niwas et al. (2011).

The analysis of these previous publications showed that through the application of geophysical methods to hydrogeological studies, empirical laws could be established. However, the use of VES data increase the ambiguity in resistivity determination and reduces the chances of clay interbedded identification.

2. The study area

The area consider for this study lies between latitude 34° 50′ S to 35° 02′ S and longitude 58° 10′ W to 57° 50′ W. It is located in the northeastern part of the province of Buenos Aires at the Río de La Plata estuary (Fig. 1).

2.1. Geological settings

The area is situated in the Río de La Plata Craton, on the northern border of the Salado Basin. In this region the basement is relatively high (300–500 m depth) and the stratigraphy of the Quaternary sediments is subhorizontal.

The terrain is a wide plain with gently slopes and well-defined hydrographic basins. Topographically, it is possible to identify two features: a low coastal land and a high plain. The low coastal land is a flat band parallel to the Río de La Plata estuary and has a width of 6 to 10 km. It is poorly drained causing an increment in the groundwater salinity. The high plain is a rectangular area oriented NW to SE with a gently sloped towards the river (~1.2 m/km). The surface is softly undulated by fluvial erosion. The streams, creeks and canals in this area are intermittent whether in the low coastal land are permanent.

2.2. Hydrogeology

The stratigraphic and hydrogeological characteristics of the sediments (Fig. 2) were widely described by Auge and Hernández (1984), Auge (2005), Auge et al. (2004) and Gonzalez (2005). Although, there are four aquifers units, only the semi-confined aquifer constitutes the major freshwater reserve of the region, called Puleche.

At the top of the stratigraphic sequence, the non-saturated zone has a variable thickness of a few centimeters to 10 m. The Pampean sediments, composed of silts or sandy to clayey silt, are an unconfined aquifer of 25 to 45 m thick. This aquifer is subjected to contamination from urban wastes and agrochemicals, prohibiting its use for human consumption in some areas.

These sediments become more clayey at its base, just on top of a sequence of fine to medium grain size sands of fluvial origin. They constitute the Puelche semi-confined aquifer, containing good quality water and being the main source for human consumption. Puelche aquifer has a thickness ranging from 15 to 30 m.

The base of the aquifer consists of a series of clays from Paraná and Olivos Formation. The first one is composed of marine sediments while the second one has continental origin. In both formations it is possible to find fine grain size sands with saline water. The hard rock basement is composed of granites and gneiss at 490 m depth.

The groundwater of the Puelche aquifer has a very low salinity in the high plain, resulting in values of electrical conductivity ranging from 500 to 2000 uS/cm, and a mean value 970 uS/cm (Auge et al., 2004). In the low coastal land it becomes slightly salty.

3. Methodology

All the data analyzed in this study was spatially distributed over an area of 250 km^2. For this reason, a regional scale analysis was proposed for the hydraulic parameters. The wells used are from the high plain area, where the water chemistry could be considered constant. Representative

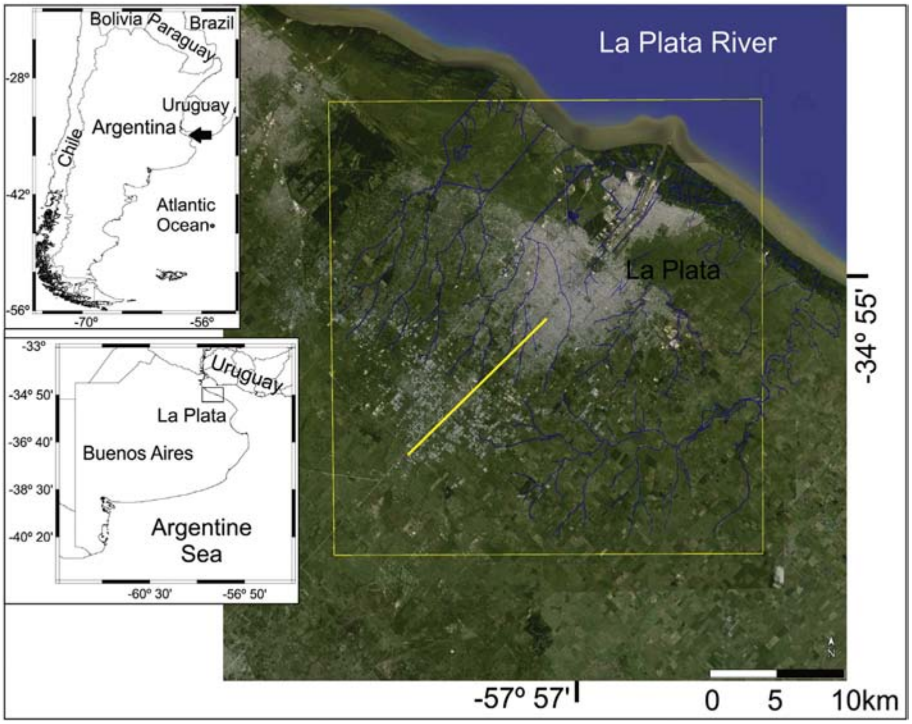

Fig. 1. Map of the studied area in the province of Buenos Aires (Argentina), near to Río de La Plata estuary. The straight line is showing the geological cross section. (Image: Google Maps).

sites with both types of data, well log and hydraulic, were needed. This requirement limited significantly the amount of suitable data and many attempts will be made in order to optimize the available information.

Thus the methodology followed here includes an analysis and interpretation of hydraulic data from steady state tests and step drawdown tests; resistivity determinations from well logging profiles and Vertical

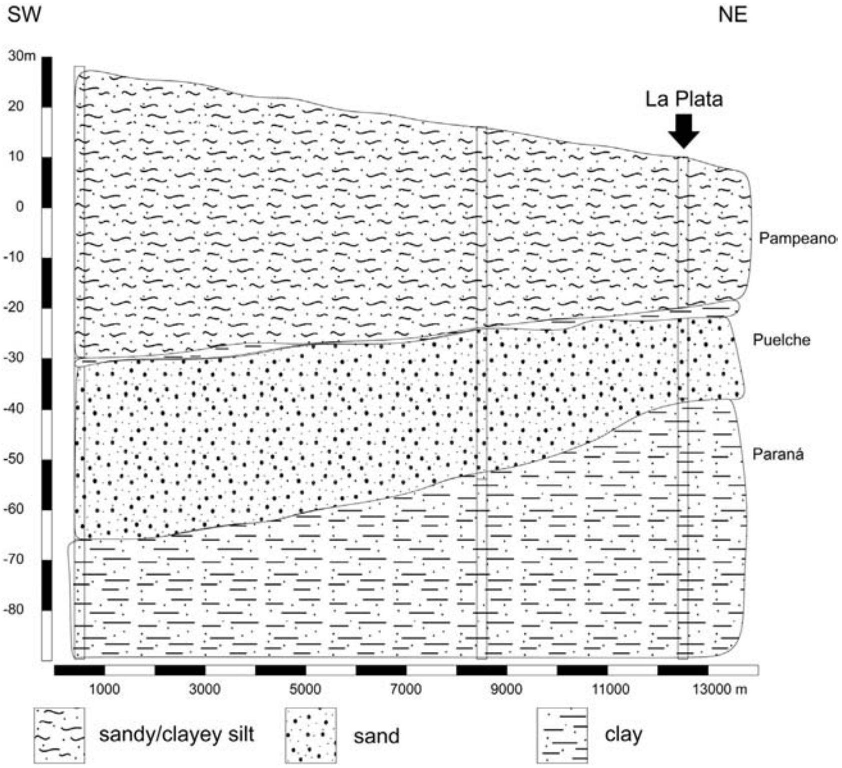

Fig. 2. Geological cross section of the studied site. Line of section shown in Fig. 1.

Electrical Soundings (VESs) and the integration of these data to set empirical laws.

3.1. Estimation of T from pumping test

Constant rate pumping tests were used to determine the transmissivity and hydraulic conductivity of the aquifer in 8 wells by applying the Jacob approximation (Fetter, 2001), using the pumping rate (Q), the drawdown (s), and the aquifer thickness (h):

$$T = 0.183 * Q/s \tag{5}$$

$$K = T/h. \tag{6}$$

All the wells were fully penetrating and screened only in the semi-confined aquifer. The drawdown was measured in the pumping well (no observation well) and the well diameter could be considered negligible.

3.2. Well efficiency tests

In the previous wells, the specific discharge (Qe) was derived from step drawdown tests. These kinds of tests were developed to assess the well performance by increasing the pumping rates in the well and measuring the drawdown produced (Fetter, 2001). By combining the specific discharge and transmissivity an experimental linear relation was proposed:

$$T = a * Q_e + b. \tag{7}$$

Constants were adjusted for this study area ($a = 37.6$; $b = -50$).

Using the Q_e estimated in other 29 wells, where only well efficiency tests were performed, and using this regression line the number of estimates of T was significantly increased. In order to accurately estimate the specific capacity (Q/s) of each well, the effect of partial penetration in the aquifer was taken into account, following the equation proposed by Kozeny (1933).

3.3. Well logging

A total number of 48 well logs were measured with a continuous registration probe and a 2 cm. sampling rate before the plastic casing was installed. Resistivity was measured with Long Normal (64 in), Short Normal (16 in) and lateral arrays. Spontaneous potential (SP) and natural gamma radiation (GR) was also registered. The analysis of GR profiles allows interpreters to infer the presence of clay in the stratigraphic sequence, and the three resistivity measurements are indicative of the electrical behavior of each portion of the formation and the invaded zone (Schlumberger Well Surveying Corp., 1958).

Based on GR data, an estimator for maximum volume of clay (V_c) expected in the formation was calculated using the following relation (Sallam, 2006):

$$V \le (V_c)_{GR} = (GR - GR_{min})/(GR_{max} - GR_{min}). \tag{8}$$

As there may be influence of other radioactive sources, the estimated value is considered an upper bound for the amount of clay present in the formations.

By the combined interpretation of these curves it is possible to accurately differentiate the aquifer zone and the presence of clay banks. Following Eq. (3), FF was then calculated with the resistivity values from Long Normal only in sediments of clean sand.

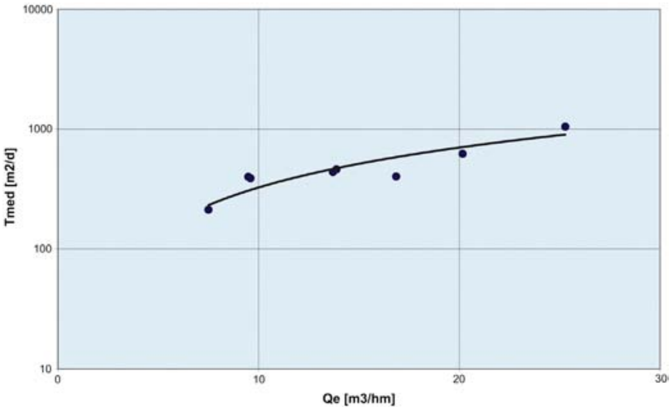

Fig. 3. Regression line fitting specific discharge (Qe) and transmissivity (T) data from long-term pumping tests.

3.4. VES data and interpretation

Additionally to the well logging resistivity, VES data was also analyzed. All 8 VES performed in the area had a 1000 m of maximum electrode distance. Whereas measurements with a well logging tool are a "direct" determination of the resistivity, the VES method shows the vertical distribution of resistivity from surface "indirect" measurements using a Schlumberger array. During the field work an apparent resistivity curve is obtained after circulating a direct current I through the emission circuit and measuring the potential difference ΔV that is generated between the receiver electrodes.

$$\rho_a = G\Delta V/I \tag{9}$$

G is a geometric constant which takes into account the distances between all electrodes. The apparent resistivity represents a weighted average of the true resistivity, which it is obtained after inversion (Revil et al., 2012).

The inversion scheme followed here was proposed by Zohdy (1989). This algorithm provides a very good initial model with a very accurate fit to the observed data. The model has as many layers as observation points in the curve. The number of layers is then reduced using the Dar Zarrouk parameters and the response curve is calculated with a linear filter (Johansen, 1975).

Additional information can be added to constrain the model, specially the thickness or depth of certain layers, improving the resistivity determination.

Dar Zarrouk parameters defined by Maillet (1947) are also very useful in order to overcome the ambiguous determination of thickness and resistivity determination. The transversal resistance (TR) and the longitudinal conductance (S) can be calculated taking into account the

Table 1
Observed values of specific discharge [m^3/hm] and transmissivity [m^2/day]. Qe values were corrected for partial penetration in the aquifer (Kozeny, 1933) and T ded values were inferred using Eq. (12).

ID	Qe	Qe corr	T	Tded
PW2	9.6	9.5	400	307
PW3	10.1	9.6	389	311
PW15	16.9	20.2	623	708
PW16	10.8	13.7	439	465
PW25	10.7	13.9	462	472
PW26	6.6	7.5	213	232
PW27	12.1	16.9	403	584
PW28	18.5	25.3	1049	901

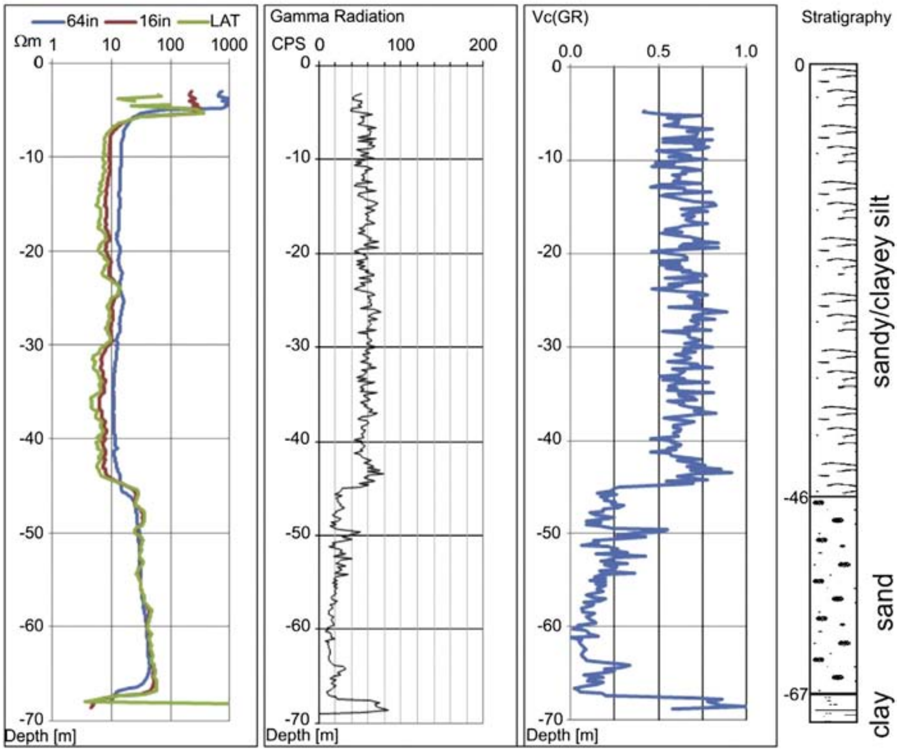

Fig. 4. Geophysical profile and stratigraphy of the well. Resistivity curves (left), natural gamma radiation (middle) and the calculated curve for clay content (right). The aquifer is located below the 45 m depth, showing high resistivity contrast and low CPS. Also the clay content curve shows a high contrast with the upper and lower layers.

relation between thickness and conductivity, for a layer with thickness h and $\sigma = \sigma'$.

$$TR = h/\sigma' \tag{10}$$

$$S = h/\sigma' \tag{11}$$

4. Results

4.1. Estimating transmissivity from specific capacity

Due to the requirement of having wells with T and K data and geophysical logging, information from well efficiency tests was used. A regression line between Qe and T, as proposed in Eq. (7) was adjusted

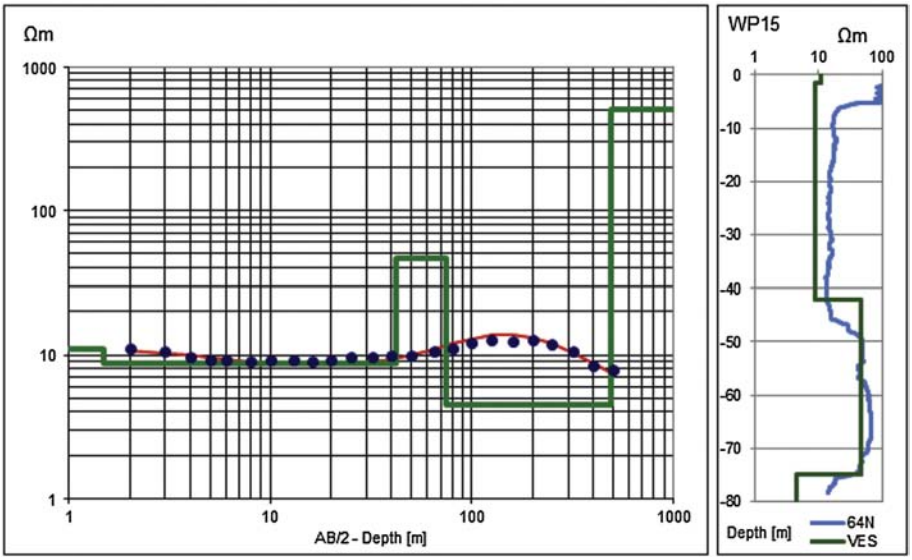

Fig. 5. Vertical Electrical Sounding. Observed and calculated resistivity curves for the suggested model (left) Long Normal resistivity log (blue) and final suggested model are superimposed (right). The model accurately shows the thickness of the aquifer below the 45 m depth.

in a semi-log plot ($R^2 = 0.85$ see Fig. 3) and the results are shown in Table 1. Values of T from 232 to 901 m^2/day were obtained.

Previous results, published by Auge (2005), showed that T ranges from 225 to 1034 m^2/day for the aquifer in the study area, with an average of 500 m^2/day. The minimum and maximum values for K were 8 and 41 m/day, with an average of 20 m/day.

The estimated results using this experimental relation are considered valid because they are similar to those mentioned above, which were obtained through specific tests in other places in the semi-confined aquifer, and are also in agreement with the general literature.

4.2. Well logging data

The well logging profiles analyzed allowed us to accurately estimate the base and top of the semi-confined aquifer, its electrical response and the aquitard that separates it from the upper aquifer. In order to make a correct interpretation of each well, it is necessary to conduct an integral analysis of all geophysical logs (Ainchil et al., 2006, 2007).

Fig. 4 shows a standard curve similar to those measured in the 48 wells profiled. The natural GR curve is plotted in the middle and resistivity measurements are plotted superimposed on the left side. Furthermore, a calculated curve with the maximum expectable clay percentage is shown along the entire borehole.

From Long Normal resistivity log (64 in) it is possible to see that until 45 m deep resistivity remains close to 10 Ωm, below and down to 65 m has a value of 50 Ωm, ending with a sharp decline in the resistivity.

Moreover, the natural GR counting indicates a value oscillating value between 50 and 60 CPS as deep as 42 m, and below 45 m the value increases slightly. In the interval 45–65 m the counting drops down to a mean value of 20 CPS and finally increases significantly.

When analyzing the calculated curve for the clay percentage some features are similar to those observed in the GR curve. However, a peak at 50 m was observed. At this depth, sediments with up to 50% clay content could be expected. As this feature could be showing a clay bank of nearly 2 m thick, it was deleted from the effective calculation of aquifer thickness and of the FF.

4.3. Geoelectrical data field survey (VES)

After processing each of the apparent resistivity curves and achieving a "true" resistivity distribution, the models were compared directly with the corresponding well logging profile.

In Fig. 5a measured field curve, the final model and its calculated curve for a typical VES are plotted. Next to them, the Long Normal resistivity curve and the final model are shown to compare the "true" resistivities obtained with each method.

4.3.1. VES-AS1

In the proposed model (Table 2), the first layers reached a depth of 45 m showing low resistivity values. The next layer had an approximate thickness of 30 m and a resistivity of 50 Ωm and the lowest layer showed a significant contrast with lower resistivity.

The comparison between the VES final model and the well log measured in the vicinity showed a great similarity, identifying the major electrical characteristics of the entire sedimentary package over the clays from Paraná Formation.

The estimated thickness and depth of the electric layer assignable to the semi-confined aquifer seemed to be adequate. Although resistivity was slightly lower than the maximum recorded by the well logging tool, the electric contrast was clearly defined.

Despite the VES had a lower resolution than the well logging, it was possible to make very accurate interpretation because of the strong resistivity contrast present in the area. A difference less than 5 m in the determination of the top and base of the aquifer could be achieved between both methods.

Table 2
VES–AS1 parameters: depth and resistivity of the final model. RMS = 3.13%.

Z [m]	ρ [Ωm]
1.5	11
42	8.8
75	47
490	4.5
INF	500

4.4. Analysis of the relation between hydraulic and geoelectric parameters

In the description of backgrounds, many authors agreed on the need to seek and set new laws in different areas, with different geological conditions, in order to describe the problem in general terms. This paper suggests and analyzes three types of fitting using information from pumping tests and geophysical loggings.

Table 3
Comparison of hydraulic conductivity and transmissivity measured and estimated from well logging. Columns are well profiling identification (ID), mean formation factor (FFm), aquifer thickness in meters, resistivity in ohm, transverse resistance and longitudinal conductance. Also, T measurements are expressed in [m^2/day] and K in [m/day] and estimated values. Colored lines indicate wells with VES data.

ID	FFm	Thick	ρ	TR	S	T	K	Ke	Te (exp)	Te (pot)
WP1	3.6	14	42	586	0.33			19	286	253
WP2	5.3	26	61	1562	0.42			24	836	631
WP3	2.2	22.4	26	573	0.88			11	282	248
WP4	4.1	14	48	677	0.30	389	27	19	316	289
WP5	3.2	24	37	893	0.64			15	401	375
WP6	3.1	13	35	457	0.37			15	248	200
WP7	2.8	20	33	651	0.61	266	13	14	307	279
WP8	4.4	6	51	297	0.11			21	208	134
WP9	8.0	22	92	2024	0.24			36	1391	805
WP10	5.6	19	64	1207	0.29			26	566	496
WP11	2.8	7	43	289	0.16			13	206	131
WP12	4.3	21	49	1019	0.42			20	460	424
WP13	5.0	23	58	1338	0.40			23	654	546
WP14	5.6	26	65	1686	0.40			26	959	678
WP15	4.8	23	55	1243	0.41			22	589	510
WP16	3.9	19	45	851	0.42			18	383	358
WP17	5.0	27	58	1565	0.47			23	839	633
WP18	3.9	19	45	872	0.43			18	392	366
WP19	4.7	20	54	1077	0.37	412	21	22	491	446
WP20	5.1	23	59	1360	0.39			24	670	555
WP21	3.6	18	41	729	0.42	400	23	17	335	310
WP22	5.3	18	61	1098	0.30			24	502	454
WP23	2.6	26	30	796	0.88			13	360	336
WP24	3.7	17	43	729	0.40			18	335	310
WP25	4.3	23	49	1132	0.47			20	521	467
WP26	3.4	20	39	784	0.51	424	21	16	355	332
WP27	5.8	25	67	1655	0.37	901	35	27	927	667
WP28	5.8	28	67	1882	0.42	1180	42	27	1189	752
WP29	4.4	19	50	953	0.38	472	20	20	428	398
WP30	5.3	8.4	62	517	0.14			25	265	225
WP31	2.1	21.5	24	520	0.89	291	12	10	266	226
WP32	3.6	21	41	864	0.51	584	17	17	388	363
WP33	3.2	16	37	591	0.43	215	13	15	288	255
WP34	1.3	14.2	15	215	0.94	189	9	7	190	99
WP35	3.1	7	35	247	0.20			15	197	113
WP36	2.8	20	33	657	0.61	226	13	14	309	281
WP37	4.0	29	47	1353	0.62			24	664	552
WP38	2.8	27	32	859	0.85			18	386	361
WP39	3.9	15	45	671	0.34			22	314	287
WP40	2.4	19	27	517	0.70	264	14	14	265	225
WP41	2.7	9.6	32	303	0.30			15	209	136
WP42	3.2	16	37	588	0.44			18	287	254
WP43	5.2	26.3	60	1586	0.44	623	24	26	859	641
WP44	5.2	23	60	1374	0.38			29	681	560
WP45	2.4	10.5	28	292	0.38	151	14	13	207	132
WP46	2.8	8	33	261	0.25			15	200	119
WP47	2.3	12	27	322	0.45			14	214	144
WP48	2.6	22	30	669	0.72	363	17	14	313	286
Mean		19	45	883	0.45	432	20	19	457	367
Max		29	92	2024	0.94	1180	42	36	1391	805
Min		6	15	215	0.11	151	9	7	190	99
Std		6	15	471	0.20	268	9	6	273	184

The first one links FF with K by a potential relation as in Dhakate and Singh (2005). The regression line was fitted with these parameters:

$$K = 4.29 * FF^{1.10}; R^2 = 0.93. \tag{12}$$

The second fitting is made following an exponential expression as proposed by Singh (2005) between the TR, calculated from the average value of the resistivity log and T.

$$T = 145 * \exp(0.0011 * TR); R^2 = 0.85 \tag{13}$$

Finally, with the same data, a power law used by Soupios et al. (2007) was fitted between TR and T.

$$T = 0.53 * TR^{0.98}; R^2 = 0.98 \tag{14}$$

Subsequently, these relations were extended to other wells with electric logging (see Table 3) to verify that the estimated values by each expression were within the expected range for the semiconfined aquifer (Auge, 2002; Laurencena et al., 2010). The fit of the three curves was satisfactory according to the correlation factors (Fig. 6). The relation between FF-K and TR-T (potential) showed the highest agreements.

Table 4
VES Results. ID is the identification of the nearest well. Depth, thickness and resistivity modeled for the semi-confined aquifer, and the calculated transverse resistance.

VES	ID	Depth [m]	Thick [m]	Res [Ωm]	TR [Ωm^2]
LH1	WP7	48	17	34	578
LH2	WP12	50	20	52	1040
LH3	WP25	47	33	52	1716
AS1	WP15	42	33	47	1551
AS2	WP13	45	30	50	1500
HZ1	WP11	50	15	40	600
HZ2	WP6	25	25	36	900
GT2	WP48	29	35	28	980

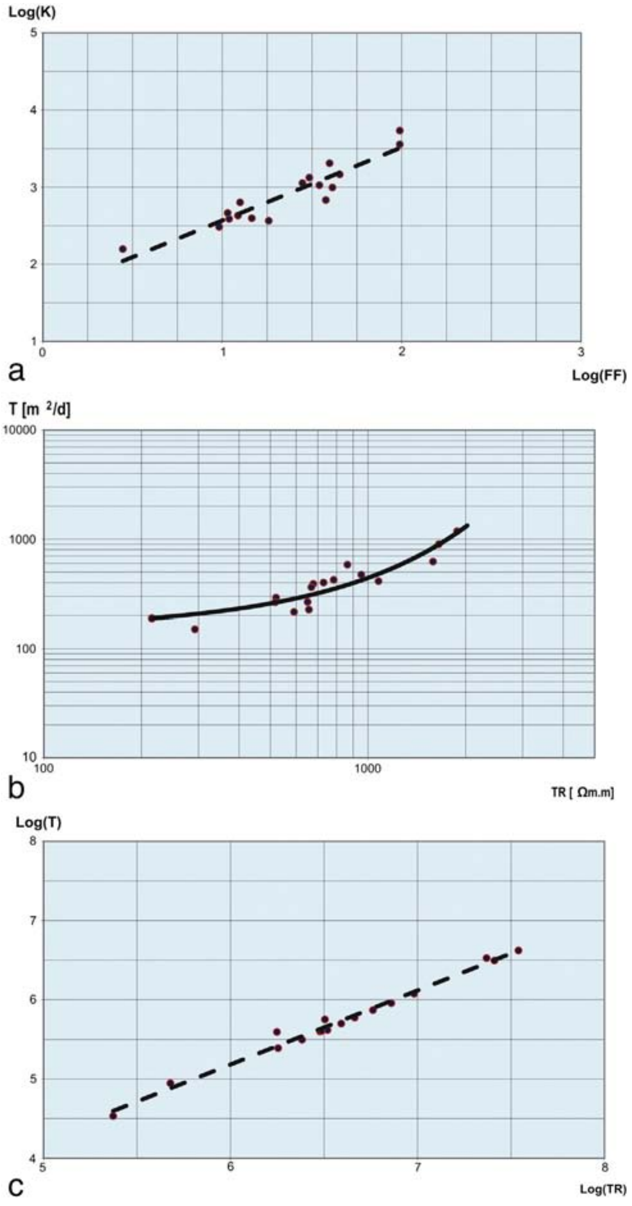

Fig. 6. Empirical laws derived for the same data set. (a) Regression line from hydraulic conductivity (K) and Formation Factor (FF). (b) Exponential fitting between transverse resistance (TR) and transmissivity (T). (c) Power fitting of TR and T.

4.5. Comparison of results with VES and well logging

The methodology previously applied relates “direct” determinations of resistivity with hydraulic parameters, but this paper was also sought to verify the applicability of the empirical laws using indirect geoelectrical data. In this regard, K and T values were calculated using the FF and RT from each VES in the same locations of a borehole with resistivity log (Table 4).

4.5.1. Empirical FF vs K law

Eq. (3) is used for the FF calculation taking an average water resistivity value of 11.5 Ωm (970 uS/cm) and the “true” resistivity of the best proposed model.

The values obtained from both methods were very similar (see Table 5), but the ones obtained with VES were slightly higher. A percentage error was calculated by taking logarithms of K, and it can be seen that it presents low values (0.4, 1.7; 3.1%) achieving similar estimators in most cases (LH1, LH2, LH3, and HZ2).

4.5.2. Empirical RT vs T exponential law

The estimates of T using VES method and electrical well logging are comparable, since the order of magnitude was very similar (300–900 m^2/day). Errors are slightly higher (5.3, 6.4, 8.8%) than those obtained with the FF vs K empirical law. It must be pointed out that this relation is the one with the worst correlation factor ($R^2 = 0.85$).

4.5.3. Empiral RT vs T power law

Even though this law has the best correlation factor, the estimates of T are similar to the preceding laws. The highest errors (12% and 13.9%) are from the lowest values of T (130 and 200 m^2/day) but, in general, both methods gave estimates of the same order of magnitude.

Table 5
Comparison between well profiling (wp) and VES estimates using the proposed relations.

	Potential Relation			Exponential Relation			Potential Relation		
VES	Kves	Kwp	Err %	Tves	Twp	Err %	Tves	Twp	Err %
LH1	14	13	3.1	283	307	1.4	249	279	2.0
LH2	21	20	1.7	471	460	0.4	432	424	0.3
LH3	21	20	1.7	991	521	10.3	690	467	6.3
AS1	19	22	4.5	827	589	5.3	627	510	3.3
AS2	20	23	4.0	782	654	2.7	608	546	1.7
HZ1	16	13	9.1	290	206	6.4	258	131	13.9
HZ2	15	15	0.4	404	248	8.8	377	200	12.0
GT2	12	14	6.8	441	313	6.0	409	286	6.3

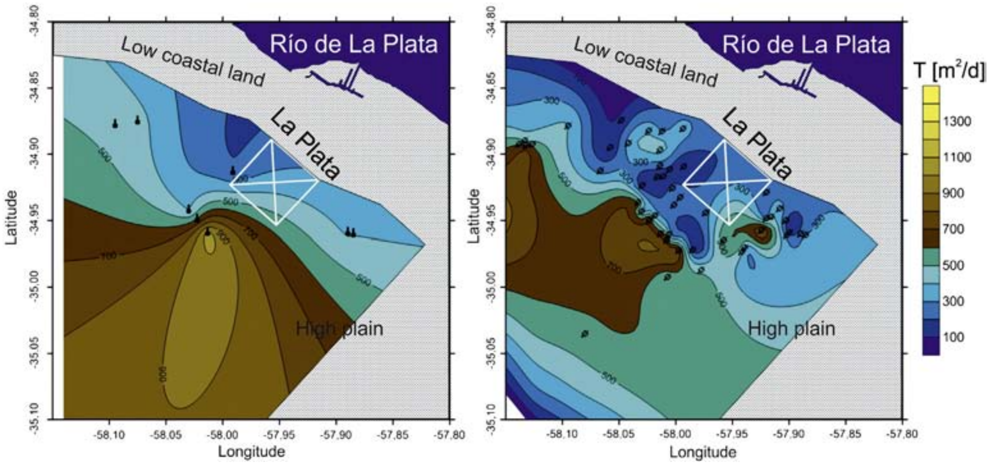

Fig. 7. Hydraulic transmissivity distribution maps. (a) T measured from steady state pumping tests. (b) T derived from well logging data using the exponential relation.

4.6. Data coverage improvement

In the previous sections, it was shown how to obtain estimates of T from different sources. In this way, it was increased the number of locations with aquifer information. Thus, an improvement in the area covered by secondary data was obtained. At the beginning, there were only 8 wells with T estimates and by including well efficiency tests and geophysical data, the number was increased to 48 sites.

As an example in Fig. 7 there is a comparison showing the 2D transmissivity distribution in the study area, according only to the pumping tests and then how it was refined with geophysical data.

The most significant feature is that the area with the maximum value of T was reduced, and another area with values over 700 m^2/day appeared at the southeast corner of the city.

This map also shows that, besides the Puelche aquifer appears to be geologically homogenous, there are important differences in the spatial distribution of its hydraulic properties (T, in this case). For example, in the southwestern area of the city, there are low values of T (~300 m^2/day) close to a very high area with values over 700 m^2/day.

5. Conclusions

In this work a methodology sequence for the correlation between electrical and hydraulic properties was described and applied to a semi-confined aquifer in alluvial sediments in the area of La Plata, of Buenos Aires province (Argentina). Transmissivity was obtained from steady state pumping tests and also derived from specific capacity. Geophysical loggings were used to identify clay free sands and measure bulk resistivity. Although the determination of these parameters is related to different scales, as electrical logs could be considered as point measurements and pumping tests reflects local-regional measurements, the sedimentological conditions of the aquifer and the narrow range of each parameter, sustain the applicability of this methodology.

Three experimental laws were adjusted; the first one using the formation factor and hydraulic conductivity, following a power relation. The other two were an exponential and potential relation, using the transverse resistance and transmissivity data from well logging and pumping tests, respectively.

Since electrical logs in boreholes can be considered a direct determination of the resistivity of the sediments, the laws achieved had no bias compared to those proposed by other authors that used interpreted indirect data.

Additionally, an estimator of the volume of clay was calculated using Natural Gamma counting, which made possible an adequate estimate of “true” thickness of the aquifer and the identification of clay banks in the sand. In this way, the Formation Factor was calculated in clay-free sectors within the aquifer sands, eliminating the need to apply corrections to this parameter.

The estimated values acquired by the three expressions were within the expected range for the semi-confined aquifer, confirming that the methodology was feasible and that the estimates were equally valid. According to the proposed laws, the mean hydraulic conductivity for the aquifer was 19 m/day, and an average transmissivity of 370 to 450 m^2/day was obtained.

Since the major advantage of indirect electrical methods (VES) is that they reduce time and economic costs, their application for the determination of hydraulic estimators was quantitatively evaluated. By applying the proposed relations, it was possible to achieve comparable transmissivity estimates with borehole logging and VES models.

As the determination of the “true” resistivity, using VES method, depends directly on the accuracy of the thickness determination, an overestimation of the thickness is translated into an underestimation in resistivity and hence, in hydraulic conductivity, if using FF vs K law. It is recommended to apply RT vs T laws, since transverse resistance is a more representative property in VES interpretation.

The results obtained, confirm the possibility of obtaining equally satisfactory estimates using resistivity determination with VES or well logging. For this reason, both techniques are propitious for the quantification of the hydraulic parameters.

The application of VES method to provide transmissivity estimates in the region, can improve existing models of the semiconfined aquifer system, resulting in valuable information. It would also allow improving strategies for reducing the number of drilling wells and finding more productive locations, with the consequent cost reduction of hydrogeological studies.

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