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Determination of hydraulic conductivity and fines content in soils near an unlined irrigation canal in Guasave, Sinaloa, Mexico

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Abstract

The determination of hydraulic conductivity is essential for the assessment of fluid migration rates in the subsurface. Geoelectric methods are often used in hydrogeological studies as quick and inexpensive tools. The relation between saturated soil hydraulic conductivity (K), clay content and soil resistivity allows an estimation of clay content and K from electrical measurements made in the field or laboratory. In this work, a methodology for estimating fines (silt + clay) content and K from electrical measurements in silt-loam soils is presented. A textural analysis was performed in 73 soil samples collected from 21 boreholes located in the municipality of Guasave, Sinaloa, Mexico, to determine the sections with a greater infiltration of water from the Valle del Fuerte irrigation canal to the local aquifer. The calculated values of texture and *K* were used to develop a new empirical equation, $K = 0.101176 * FINES^{-1.62}$, which achieved a new relation to properly estimate the *K* values from the percentage of fines content. Electrical measurements were performed in the laboratory for each soil sample to determine the fines content. The *K* values, which were determined by a new empirical equation, showed an acceptable correlation with the values obtained by traditional techniques for silt and silt loam soils with a clay content < 35%. Water resistivity measurements were performed for samples collected from wells and flumes, showing that the water salinity of the canal is significantly lower than the groundwater. Due to the location of the Valle del Fuerte canal and soil K values, the water infiltrated from the flume into the subsoil creates a barrier preventing or slowing down the advance of the saltwater intrusion from the Sea of Cortez. Short Electrical Resistivity Tomography (ERT) profiles were carried out to determine the surface stratigraphy. The results achieved by the application of ERT and the groundwater salinity values allowed the recalculation of the geoelectrical sections in the fines content and K sections, resulting in a new, faster and less expensive procedure for the determination of hydraulic and petrophysical parameters.

Keywords: petrophysical parameters, fines content, hydraulic conductivity, saltwater intrusion.

1. Introduction

The coastal zone of the state of Sinaloa is classified as one of the areas with the highest presence of saline groundwater in Mexico (Marin, 2002). The advance of saltwater intrusion in coastal aquifers depend on factors such as the pumping rate of fresh water compared with the aquifer recharge as well as the thickness and hydraulic properties of the aquifer (Barlow and Reichard, 2009). Most aquifers in northwestern Sinaloa, including the Sinaloa River aquifer, are subject to exploitation. The Sinaloa River aquifer is composed of regional northwest-southeast and intermediate southwest-northeast groundwater flows. The regional flow receives water from the Valle del Fuerte canal on its passage toward the Sea of Cortez, while the intermediate flow provides water to the Sinaloa River. Both flows have prevented the inland advance of saline intrusion into the Valle del Fuerte plain (Norzagaray *et al.*, 2009). However, there is a gradual decrease of static water level in the wells located at the east of the Sinaloa River, thus favouring the movement of the saline intrusion. At the west of the Sinaloa River, the advance of saltwater intrusion is lower than in the eastern portion due to the existence of large irrigated areas supplied by the Valle del Fuerte canal. In general, the groundwater in the Sinaloa River aquifer has a high content of calcium-magnesium-sulphate associated with sodium chloride and carbonic acid, both in coastal and inland zones (CONAGUA, 2002).

The Valle del Fuerte unlined canal and lateral drains play an important role in the irrigation of farmland in the municipality of Guasave, Sinaloa, Mexico. Government officials have proposed lining some sections of the Valley del Fuerte canal with concrete (having lined, to date, some lateral drains) to prevent water seepage from the canal to the subsoil (CONAGUA, 2007). However, the canal's strategic location in relation to the coastline makes it a supply system of fresh water to the local (coastal) aquifer, preventing or slowing down the saltwater intrusion from the Sea of Cortez. Therefore, lining the canal with concrete will have social and ecological impacts by breaking the canal-aquifer balance. In unlined canals, the amount of water leakage by infiltration depends on hydraulic conductivity (K).

The saturated soil K depends on the characteristics of the soil matrix and the fluid present in the soil. Thus, understanding this parameter in relation to the clay content is a key element for widespread knowledge of a geological background, both in the flow process and of the transportation of contaminants in porous media; such knowledge is needed, for example, in the management and development of environmental policies for the protection of ecosystems. It is important to take into account the soil K in the solution of problems related to irrigation and the drainage of farm soils. The value of K is also one of the key factors defining the performance of a well.

There are different indirect procedures for estimating K, such as electrical methods. Several authors (Kelly, 1977; Kosinski and Kelly, 1981; Ponzini *et al.,* 1984; Peinado-Guevara *et al.,* 2009) have found a relationship between the apparent formation factor (F) and K. Archie (1942) defined F by the relation between brine-saturated sand resistivity and brine resistivity. In case of the formation of non-clean sands (i.e., sand containing silt and clay), the above relation is called the apparent formation factor:

$$F_a = \rho_b / \rho_w \quad (1)$$

where F_a is the apparent formation factor, ρ_b is the bulk electrical resistivity (Ohm.m), and ρ_w is the pore fluid resistivity (Ohm.m).

F_a can be related to K as follows:

$$K = c\, F_a^{\,m} \qquad (2)$$

where K is given in cm.sec^{-1}, c is a constant (m.sec^{-1}) and m is a constant (unitless) ranging between 6.5 and 21. Equation (2) is valid only for the limited geologic environment for which it was derived and for nearly constant fluid salinity (Huntley, 1986).

Shevnin et al. (2006) found a relationship between *K* and clay content using electrical methods. They compared the relationship between *K* and clay content published by various authors (Ogilvi, 1990; Slater and Lesmes, 2002). Although the relationships expressed are similar, they vary among the different geological environments from where they originated, suggesting a new relationship with greater statistical reliability based on experimental data with successful results in sandy-clay soils. Laboratory measurements of soil resistivity and the petrophysical algorithm of Ryjov (software *PetroWin;* Ryjov and Shevnin, 2002) are used to estimate clay content, porosity, CEC and *K* (Shevnin *et al*., 2007, 2008). This technology has been successfully applied for years in environmental impact surveys in Mexico, specifically in the characterisation of sandy-clay soils contaminated by hydrocarbons (Shevnin *et al*., 2005, Delgado-Rodriguez *et al*., 2006).

An analysis of soil *K* on both sides of the canal was performed in this work, with the objective of determining sections with a greater infiltration of fresh water underground. We propose a new methodology to estimate fines (silt + clay) content and *K* from electrical measurements from the field and laboratory. To comply with these objectives, seven sites were selected and soil samples were collected from different depths at three wells from each site. A total of 73 samples were collected and analysed by traditional and electrical lab methods. The achieved results allow the establishment of relationships between *K* and fines content for the soils of the region.

The interpreted geoelectrical sections of the application of the ERT verify the existence of a local sandy aquifer between two layers of soil with high silt content, where the values of K can be increased up to 7 m day^{-1}. In addition, the recalculation of geoelectrical sections obtained from the ERT method into fines content and *K* sections represents a new procedure for the determination of hydraulic and petrophysical parameters that are faster and less expensive than traditional methods.

1.1. Description of the study area

The study area is located in the municipality of Guasave, Sinaloa, Mexico, between latitude 25° 34’ 43” and 25° 38’ 34” north latitude and 108° 26’ 31” and 108° 34’ 14” west longitude (see Figure 1). This area lies in a sedimentary coastal aquifer consisting mainly of gravel, sand, silt and clay sediments, products of erosion on the western side of the Sierra Madre Occidental (CONAGUA, 2002). The alluvial soils are Quaternary, with a dry and warm climate, and the average annual temperature is 25.4 °C. The average annual rainfall at Guasave station was 449.0 mm during 1986-2005 (INEGI, 2007). Regarding the topography, the terrain is gentle with a slope of approximately 1 m km^{-1}.

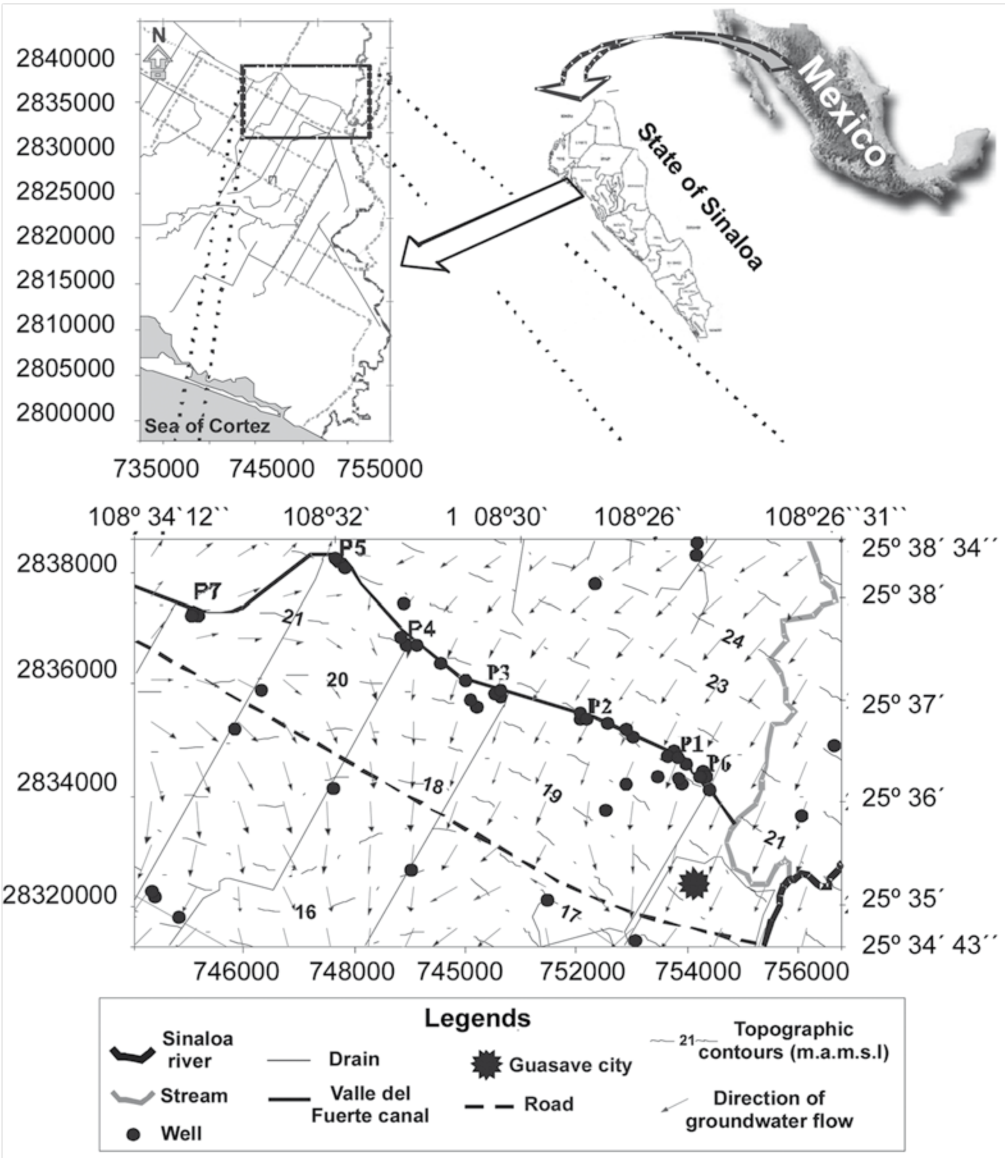

Figure 1. Location of the study area.

The Valle del Fuerte canal is supplied with water from the "Miguel Hidalgo" dam, which is located near the Fuerte River. The canal has an operating supply of 140 m^3 sec^{-1} with an irrigated area of 86.7 hectares (CONAGUA, 2002). In the technical dossier supporting the Sinaloa River aquifer (CONAGUA, 2002), it was considered that on the East side of the Sinaloa River, the advance of saline intrusion is harder than that on the West side. The Valle de Fuerte canal crosses the central part of Guasave, parallel to the coastline, with a series of lateral canals (drains) that originate from it. These canals irrigate the valley of Guasave, causing infiltration to the aquifer. Therefore, it is of utmost importance to understand the behaviour of *K* over this canal and to determine the role it plays in providing fresh water to an aquifer at high salinization risk.

2. Materials and methods

Several locations along the Valle del Fuerte canal were selected for drilling and soil sample collection (P1 to P7, Figure 1). Three boreholes were installed at these locations to a maximum depth of 4 m, where 73 soil samples were collected (3-4 samples per well) to determine the petrophysical and textural characteristics in the laboratory. A representative groundwater sample was obtained for each well. Furthermore, 31 water samples were collected from additional wells located in the study area. The salinity and electrical conductivity were determined all of the wells.

2.1. Determination of Texture and K by traditional techniques

The soil samples collected in the field were subjected to a drying and homogenising process. The texture was determined in each sample by the Bouyoucos procedure (Bouyoucos, 1936) for quantifying the content of sand, silt and clay. The soils in the study area are predominantly silt-loam (clay (14%), silt (46%) and sand (40%)). The *K* was determined using a variable head permeameter proposed by Juarez-Badillo and Rico-Rodriguez (1999). The *K* and texture values determined by the traditional methods mentioned above are presented in Table 1.

Table 1. Texture determined by Bouyoucos, K values (using head permeameter), soil classification and percentage of fines for 73 soil samples collected in the study area.

Shallow well	depth (m)	Texture by Bouyoucos			Pemeameter	% Fines	
		% Sand	% Silt	% Clay	K(m day^{-1})	Classification	(Clay+Silt)
P1	0 - 1.8	18.00	30.00	52.00	0.0850	Clay	82.00
P1	1.8 - 4	73.00	24.00	3.00	0.9700	Sand	27.00
P1B	0 – 1	30.92	20.00	49.08	0.3784	Clay	69.08
P1B	1 - 1.9	25.64	29.28	45.08	0.1506	Clay	74.36
P1B	1.9 - 4	83.64	13.28	3.08	3.0790	Sandy	16.36
P1C	0 – 1	41.64	33.28	25.08	0.7516	Silt Loam	58.36
P1C	1 - 1.4	58.92	40.00	1.08	0.6026	Sandy Loam	41.08
P1C	1.4 - 4	82.92	11.28	5.80	0.6668	Loamy Sand	17.08
P2	0 - 0.8	28.00	58.00	14.00	0.1390	Silt Loam	72.00
P2	0.8 - 1.4	84.00	9.00	7.00	1.4260	Sand	16.00

Continued...

Shallow well	depth (m)	Texture by Bouyoucos			Pemeameter	% Fines	
		% Sand	% Silt	% Clay	K(m day^{-1})	Classification	(Clay+Silt)
P2	1.4 - 2.4	25.00	67.00	8.00	0.1503	Silt Loam	75.00
P2	2.4 - 4	78.00	17.00	5.00	0.7332	Loamy Sand	22.00
P2B	0 - 1.4	46.00	48.00	5.80	0.1182	Sandy Loam	53.80
P2B	1.4 - 4	42.92	53.28	3.80	0.1278	Silt Loam	57.08
P2C	0 - 1.8	34.92	55.28	9.80	0.0071	Silt Loam	65.08
P2C	1.8 - 4	38.92	43.28	17.80	0.0154	Loam	61.08
P3	0 - 1.1	59.00	27.00	14.00	0.8856	Sand	41.00
P3	1.1 - 2	48.00	45.00	7.00	0.3186	Sandy Loam	52.00
P3	2 - 2.4	42.00	51.00	7.00	0.1766	Silt Loam	58.00
P3	2.6 - 4	86.00	7.00	7.00	2.0281	Sand	14.00
P3B	0 - 1.1	34.92	54.56	10.52	0.9519	Silt Loam	65.08
P3B	1.1 - 2.6	16.92	63.28	19.80	0.1268	Silt Loam	83.08
P3B	2.6 - 2.8	38.20	59.28	2.52	0.1156	Silt Loam	61.80
P3B	2.8 - 3.2	42.20	55.28	2.52	0.1555	Silt Loam	57.80
P3B	3.2 - 4	56.20	37.28	6.52	0.4482	Sandy Loam	43.80
P3C	0 - 1.4	34.20	43.28	22.52	0.0016	Silt Loam	65.80
P3C	1.4 - 3.1	32.20	56.00	11.80	0.0098	Silt Loam	67.80
P3C	3.1 - 4	40.20	57.28	2.52	0.2527	Silt Loam	59.80
P4	0 - 0.9	17.00	53.00	30.00	0.1284	Silty Clay	83.00
P4	0.9 - 1.5	55.00	34.00	11.00	0.5741	Sandy Loam	45.00
P4	1.5 - 2.6	8.00	16.00	76.00	0.1149	Clay	92.00
P4	2.6 - 5.5	6.00	34.00	60.00	0.0988	Clay	94.00
P4B	0 – 1	20.92	75.28	3.80	0.1022	Silt Loam	79.08
P4B	1 - 2.1	20.92	75.28	3.80	0.1008	Silt Loam	79.08
P4B	2.1 - 2.9	20.92	65.28	13.80	0.0997	Silt Loam	79.08
P4B	2.9 - 3.7	30.92	67.28	1.80	0.1284	Silt Loam	69.08
P4C	0 - 0.7	30.20	59.28	10.52	0.1779	Silt Loam	69.8
P4C	0.7 - 1.8	13.48	79.28	7.24	0.1065	Silt Loam	86.52
P4C	1.8 - 2.1	39.48	57.28	3.24	0.1777	Silt Loam	60.52
P4C	2.1 - 2.9	21.48	55.28	23.24	0.0718	Silt Loam	78.52
P4C	2.9 - 4	31.48	61.28	7.24	0.1765	Silt Loam	68.52
P5	0 - 2.2	26.00	28.00	46.00	0.0099	Clay	74.00
P5	2.2 - 4	39.00	55.00	6.00	0.0233	Silt Loam	61.00

Continued...

Shallow well	depth (m)	Texture by Bouyoucos			Pemeameter	% Fines	
		% Sand	% Silt	% Clay	K(m day^{-1})	Classification	(Clay+Silt)
P5B	0 - 1.2	24.76	72.72	2.52	0.0631	Silt Loam	75.24
P5B	1.2 - 1.8	22.76	40.72	36.52	0.0078	Clay Loam	77.24
P5B	1.8 - 2.6	32.76	62.72	4.52	0.0010	Silt Loam	67.24
P5C	0 - 0.7	27.48	70.00	2.52	0.0598	Silt Loam	72.52
P5C	0.7 - 1.6	9.00	80.00	11.00	0.0731	Silt Loam	91.00
P5C	1.6 - 2.2	19.08	74.92	6.00	0.0037	Silt Loam	80.92
P5C	2.2 - 4	25.08	54.92	20.00	0.0134	Silt Loam	74.92
P6	0 - 1	48.00	46.00	6.00	1.1507	Sandy Loam	52.00
P6	1 - 2.2	7.00	55.00	38.00	0.1614	Silty Clay	93.00
P6	2.2 - 4	93.00	1.00	6.00	7.7129	Sand	7.00
P6B	0 - 1.2	45.64	51.12	3.24	0.3855	Silt Loam	54.36
P6B	1.2 - 1.7	54.92	41.84	3.24	0.4716	Sandy Loam	45.08
P6B	1.7 - 2.7	89.48	7.28	3.24	4.0416	Sand	10.52
P6C	0 - 0.8	45.00	42.00	13.00	0.3987	Loam	55.00
P6C	0.8 - 1.3	35.48	59.28	5.24	0.2363	Silt Loam	64.52
P6C	1.3 - 2	38.76	54.00	7.24	0.4302	Silt Loam	61.24
P6C	2 - 3.4	78.76	16.00	5.24	2.3819	Loamy Sand	21.24
P7	0 - 2	31.00	33.00	36.00	0.3418	Clay	69.00
P7	2 - 2.8	44.00	50.00	6.00	0.1449	Silt Loam	56.00
P7	2.9 - 3.3	57.00	37.00	6.00	0.2927	Sandy Loam	43.00
P7	3.3 - 4.1	77.00	17.00	6.00	0.8631	Loamy Sand	23.00
P7B	0 – 1	12.76	22.00	65.24	0.1345	Clay	87.24
P7B	1 - 2.4	28.76	67.28	3.96	0.2044	Silt Loam	71.24
P7B	2.4 - 3.2	41.32	54.72	3.96	0.2859	Silt Loam	58.68
P7B	3.2 - 3.8	49.32	46.72	3.96	0.2977	Sandy Loam	50.68
P7B	3.8 - 4	66.04	30.00	3.96	1.0107	Sandy Loam	33.96
P7C	0 – 2	36.04	60.00	3.96	0.4879	Silt Loam	63.96
P7C	2 – 3	24.04	72.00	3.96	0.1928	Silt Loam	75.96
P7C	3 - 3.8	16.76	79.28	3.96	0.1508	Silt Loam	83.24
P7C	3.8 - 4	75.32	20.72	3.96	0.9760	Sandy Loam	24.68
Typical soil sample		40	46	14		Silt-Loam	

2.2. Electrical Measurements in the Lab

Each of the soil samples, after being dried and homogenised, were divided over five similar soil boxes, adding water with a certain salinity (different for each soil box, ranging between 0.1 and 80 g l^{-1}) so that the sample was 100% saturated.

The soil box was a rectangular plastic container. An electrode (electrodes A and B) was placed on each smaller side of the container to inject into soil current *I* from the resistivity equipment (e.g., Saris and Syscal). Two potential measuring electrodes (M and N) were placed on the larger side of the container to obtain measurements of the potential difference (ΔU). The measurements were recorded by the resistivity meter. The soil resistivity (ρ) value in each soil box was determined by the expression:

$$\rho = A * \Delta U / I \quad (3)$$

where *A* is a calibration factor that includes the shape of the soil box and the position of the electrodes. To obtain reliable measurements, the value of *A* was determined in each soil box using water samples with known salinity and temperature. At the end of the measuring process, there were five pairs of values (one for each soil box) of soil resistivity and water salinity, resulting in a soil resistivity vs. pore water salinity curve corresponding to each soil sample.

The resistivity vs. salinity curve was subjected to a process of interpretation based on the theoretical model developed by Ryjov (Shevnin *et al.*, 2007) using the Petrowin software. Ryjov developed this software to calculate the different geological parameters and soil resistivity as a solution to forward and inverse petrophysical problems, and its applicability was verified in loamy soils (Shevnin *et al.*, 2007). Different parameters are used for petrophysical modelling, including the following: water salinity (including types of anions and cations with their valence, hydration number, sorption constant and mobility); porosity; capillary radii; humidity; cementation exponent *m*; the cation exchange capacity for each component of soil, including sand and clay; and the temperature of the soil. The result of the modelling is the soil resistivity as a function of water salinity. We need to estimate three soil parameters: clay content, porosity and cation exchange capacity. This theory and field methodology was applied for several years in Mexico, mainly on oil-contaminated soils, and its efficiency was demonstrated (Shevnin *et al.*, 2005; 2006). The theoretical model proposed by Ryjov takes into account soil composed of clay and sand, not considering the presence of silt, which, by its electrical characteristics, can be considered low CEC clay. The final result is the determination of the clay content for each soil sample (Shevnin *et al.*, 2007). The *K* was calculated based on the clay content using the empirical formula proposed by Shevnin *et al*. (2006):

$$K_f = C^{-2}.7.2.10^{-4} \quad (4)$$

where K_f is the saturated soil hydraulic conductivity (m day^{-1}), and *C* is the clay content. The restrictions are the following: the clay content cannot be zero, and it is only valid for unconsolidated formations.

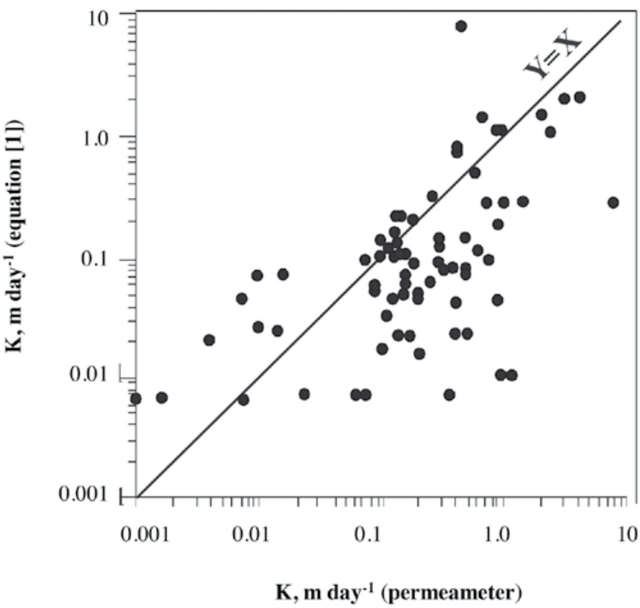

Figure 2. Correlation between K values determined by permeameter and K values determined by equation (4).

The values of K_f determined by equation (4) were correlated to those determined by the permeameter, showing a considerable dispersion about the expected identity, $Y = X$ (Figure 2). Most of the dispersion corresponds to samples of silt-loam soil, so the K_f is less than the K determined by the permeameter (Figure 2). Consequently, we must find a new empirical equation to calculate K considering clay and silt contents that are suitable for assessing silt-loam soils.

2.3. Electrical Measurements in the field

Application of the Electrical Resistivity Tomography (ERT) method

Electrical Resistivity Tomography (ERT) is performed using small regular intervals of measurements along profiles for the 2D study of inhomogeneous media, and a great number of electrodes are reconnected both manually and automatically. The objectives of applying the ERT method in the site were to determine the stratigraphy up to 7 meters of depth from the geoelectrical sections and to recalculate the geoelectrical sections into sections of petrophysical parameters of interest in our study.

The use of the ERT method for determining petrophysical parameters in the Ryjov theory is explained above. The Ryjov algorithm allows the recalculation of soil resistivity received from the ERT interpretation into petrophysical parameters. If we know the soil resistivity (cross-sections after interpretation with Res2DInV software, Loker and Barker, 1996) and the water salinity (from groundwater resistivity measurements), we can solve the inverse problem. The inverse problem consists of the estimation petrophysical parameters on the basis of soil resistivity and pore water salinity, taking into account an initial soil model that includes the mean petrophysical properties of the soils in the studied site.

The initial soil model is defined using the obtained results of the soil electrical measurements performed in the lab.

Seven key areas near the canal were selected, and short ERT profiles were measured in each area. Each ERT profile included electrodes with a linear step of 2 m to perform 11 Vertical Electrical Soundings (VESs) with an AB/2 from 3 to 21 m with a step between VES points of 4 m. An interpretation process of the ERT data was performed using Res2DInv software (Loke and Barker, 1996), resulting in a geoelectrical section for each profile.

Water resistivity measurements

Water resistivity measurements were made in the field as follows: in each well or flume, a cylindrical container fitted with a valve at its lower end (bailer) was used, and a water sample (no less than 250 ml) was collected and placed in a thoroughly cleansed plastic or glass (not metal) bottle. Then, a pocket HI98130 resistivimeter was placed inside the bottle, and the water conductivity was measured. The water conductivity (σ_w) measurements were given in mS/cm and corrected to a reference temperature of 18°C. The values of σ_w were recalculated in the water resistivity (ρ_w, Ohm.m) according to ρ_w, Ohm.m = 10 / σ_w, mS/cm.

3. Results and Discussion

3.1. Relation of K with fraction of clay, fines and sand

For each of the 73 samples, the correlation between *K* (determined by the permeameter) and clay content and the correlation between *K* and fines (clay + silt, see Table 1) is considered.

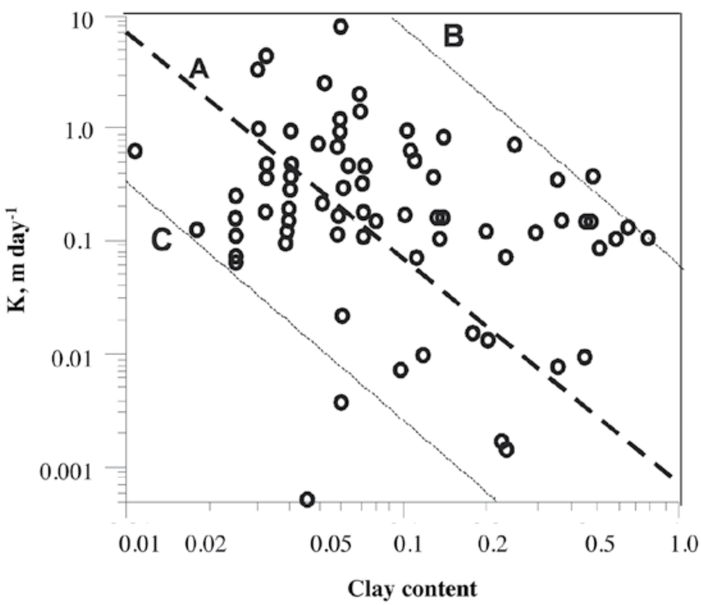

Figure 3. Relation between K (determined by permeameter) and clay content (determined by the Bouyoucos technique). Clay content values are given in the 0 (0%) and 1 (100%) interval. Line A represents the function of equation (4). Lines B and C represent the main dispersion limits.

Figure 3 shows a correlation analysis of the values of *K* (permeameter) and clay content determined by the Bouyoucos technique for the 73 samples, showing a high dispersion around the dashed line, which represents the function A corresponding to equation (4) proposed by Shevnin *et al*. (2006). The analysed soils are predominantly silt-loam (Table 1); the *K* values are significantly affected by silt, resulting in the high dispersion (mainly between lines B and C) shown in the correlation graph in Figure 3.

When considering the content of fines (clay + silt, Table 1) a better adjustment (line D, Figure 4) is obtained, allowing an adequate correlation between both parameters, showing an exponential relationship by:

$$K = 0.101176 * FINES^{-1.62} \quad (5)$$

where *K* - is the filtration coefficient, and FINES is the percentage of silt and clay. The coefficient of determination is R^2 = 0954.

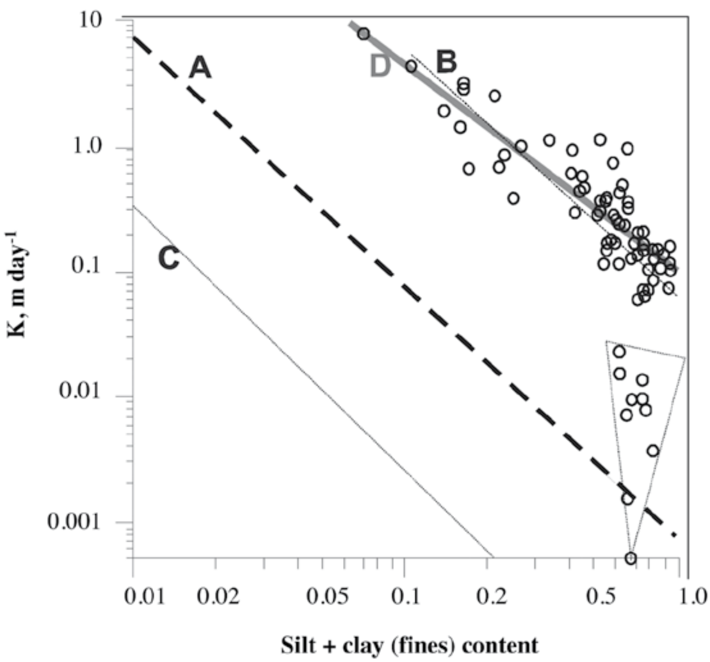

Figure 4. Relation between K (determined by permeameter) and silt + clay (fines) content (determined by the Bouyoucos technique). The fines content values are given in the 0 (0%) and 1 (100%) interval. Line A represents the function of equation (4). Lines B and C represent the main dispersion limits determined in Figure 4. Grey line D represents the function of equation (5).

Based on equation (4), a function marked as line A was obtained (Figure 4). Letters B and C were marked the above and below the limits, respectively, of the cloud data, published by different authors and used in Shevnin *et al*. (2006). The exponent equal to -2 in the clay content in equation (4) (line A, Figure 4) corresponds to the theoretical relationship between *K* and the grain diameters established by Kobranova (1989). The exponent equal to -1.62 in equation (5) (line D, Figure 4) was obtained empirically by the regression approach. In Figure 4, it can be noted that line D does not fit the 10 soil samples with fines content ~ 0.7.

From this analysis, it follows that equation (4), proposed by Shevnin (Shevnin *et al*., 2006), was established on the basis of studies of sandy and clay soils. The soils studied in this work are predominantly silt-loam, so a better estimate of *K* could be made by taking into account the amount of clay and silt as the fines component; therefore, equation (5) would be statistically more reliable.

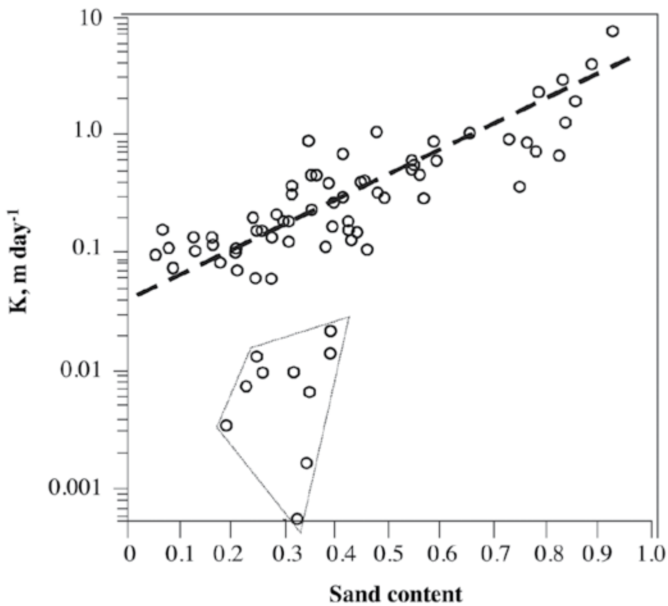

Figure 5. Relation between K (determined by permeameter) and sand content.

Figure 5 shows the data distribution of *K* as a function of sand content. A good correlation between *K* and the content of sand is shown for the 63 soil samples. The *K* and sand content values are directly proportional. There is a small cloud of data separated from the main distribution with minimum values of *K* with a sand content of approximately 0.3. This minimum value of *K* in Figure 5 corresponds to the minimum *K* observed in Figure 4 (fines content equal to 0.7). Starting from the fines mean fraction of silt and clay, in this minimum of *K*, the fines + sand content is equal to 1 (100%). These 10 samples had more than 35% clay (see grey rows in Table 1).

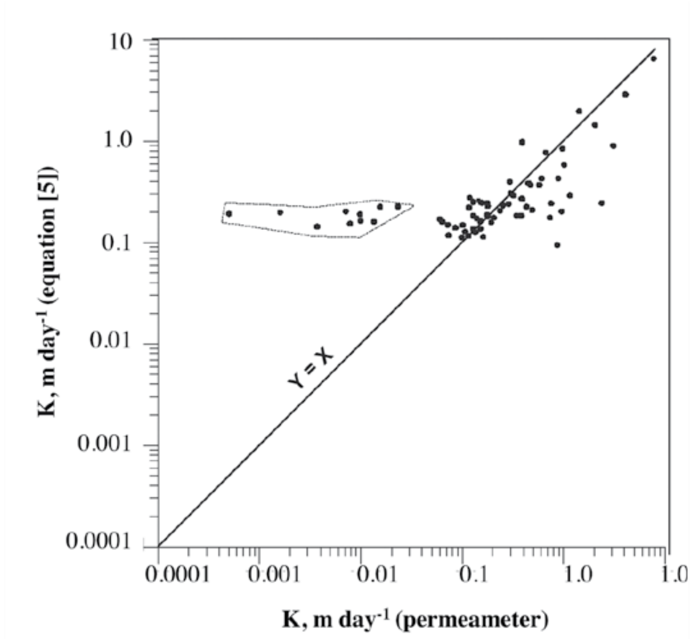

Figure 6. Relation between K (determined by permeameter) and K (determined by equation (5)).

Figure 6 shows a correlation analysis between the *K* values determined by the head permeameter and those determined by equation (5). We can observe that some of the 63 soil samples scatter around the identity function $Y = X$; again, the 10 samples with clay content ≥ 35% are separated from the line $Y = X$ (cloud of data), with the *K* values determined by equation (5) higher than those determined by the head permeameter. Therefore, we conclude that in soils with clay content ≥ 35%, it is reliable to use equation (4) to estimate the soil *K*. Otherwise, if the silt content is ≥ 30% and the clay content < 35%, it is more reliable to use equation (5) to estimate the soil *K*. In sandy soil, both equations give similar results to the head permeameter, and they produce no dispersion in Figures 2 to 6.

3.2. Influence of the Valle del Fuerte canal in the recharges of the local aquifer

Figure 7 shows the *K* histogram, where the three groups are observed according to their statistical hydraulic conductivity. Group 1 (*K* values < 0.04 m day^{-1}) has a relative maximum of 0.02, corresponding to 5% of the samples and indicating the presence of clay in the soil at sampling points farther from the Sinaloa River, mainly between P4 and P7 (northwest portion of the study area). Group 2 has an absolute maximum of 0.2 m day^{-1}, corresponding to 35% of the soil samples (less permeable loamy soils). Group 3 corresponds to *K* values higher than 0.5 m day^{-1}, being the most permeable samples collected at points P1, P2 and P6 (sampling points nearest to the Sinaloa River).

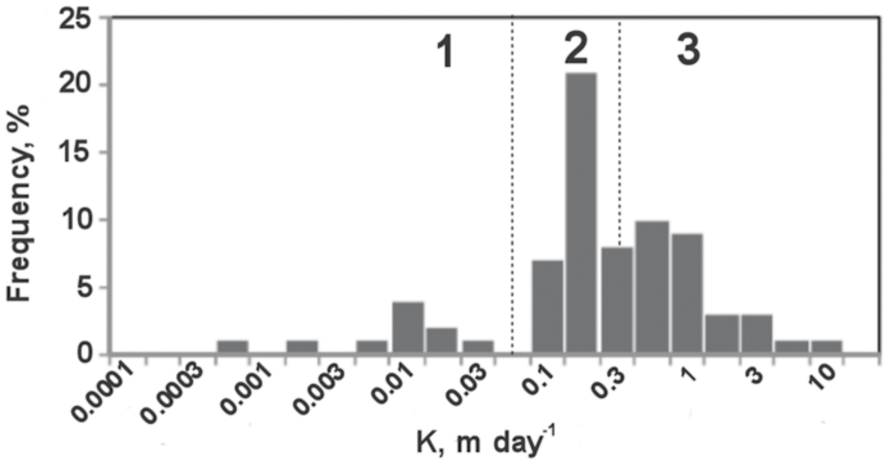

Figure 7. Histogram of K values for the 73 soil samples.

This result indicates that the clay content decreases towards the Sinaloa River (Figure 8), increasing soil permeability and, thereby, the system of surface water infiltration. This behaviour gives way to a possible vulnerability to salinization, but it also facilitates water infiltration from the canal to the local aquifer. Consequently, the Valle del Fuerte canal is considered an important factor in the fresh water recharge to the aquifer. In some collected soil samples related with P5 (Wells P5, P5B, P5C, Table 1), the clay content is more than 25%, thus decreasing the *K* value (Figure 8).

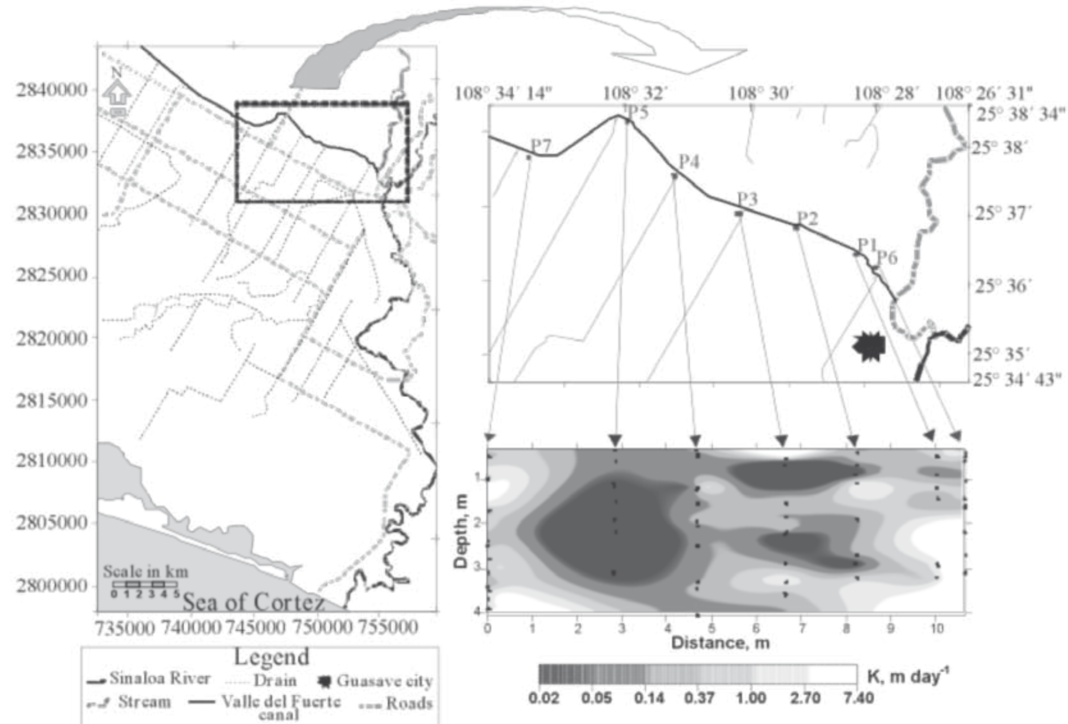

Figure 8. Vertical distribution of K along the Valle del Fuerte irrigation canal.

Figure 9A shows that the resistivity background of the groundwater is approximately 5 Ohm.m. However, the values increase (ρ_w > 20 Ohm.m) near the canal, except for point P5 due to the effect of a small salty-water lagoon located to the north (~ one km) of point P5. Thus, the Valle del Fuerte canal is a source of fresh water, with ρ_w = 76.9 Ohm.m. Based on the *K* values and the direction of groundwater flow, fresh water is supplied to the aquifer, improving the water quality and forming a protective barrier against saltwater intrusion. Again, low resistivity values were determined in P5 due to the low soil permeability in this zone (Figure 7), preventing the infiltration of fresh water from the canal.

Figure 9B shows four groundwater resistivity profiles where the highest values are found in the canal; thus, the resistivity values decreased in a gradient influenced by the values of soil *K* near the canal. As the values of *K* (Figure 8) increase, fresh water infiltrates more easily, and the gradient is softer (in 1B and 2B, the water resistivity typically ranges from 6 to 7 Ohm.m) and vice versa (in 3B and 4B, the water resistivity typically ranges from 9.5 to 11 Ohm.m). Therefore, the infiltration of fresh water is a favourable factor for preventing the advance of saltwater intrusion from the Sea of Cortez.

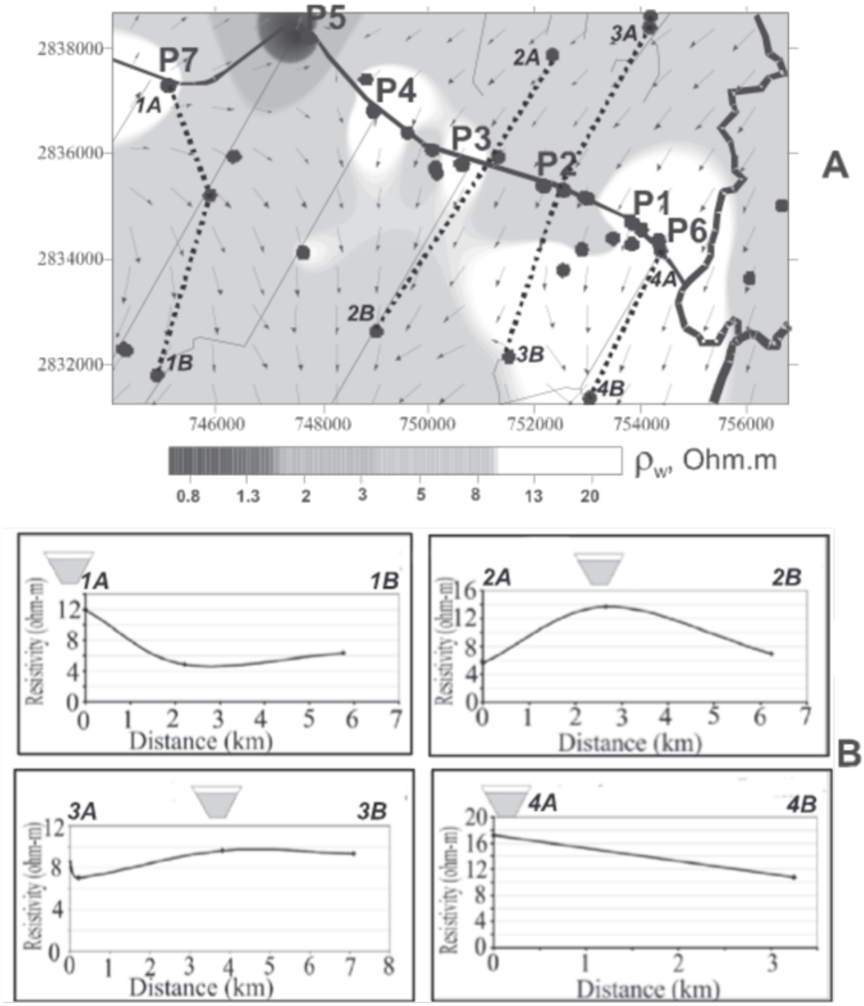

Figure 9. (A) groundwater electrical resistivity in the vicinity of the Valle del Fuerte irrigation canal and (B) four groundwater resistivity profiles. Black dots show the locations of the wells. Dashed lines represent the locations of groundwater resistivity profiles. ▽ - Location of the canal in the profiles. Note that the groundwater resistivities typically range from 0.5 to 30 Omh.m (canal water resistivity is typically 70 Ohm.m).

3.3. Application of electrical resistivity tomography (ERT)

Seven ERT profiles were processed using Res2DInv software (Loke and Barker, 1996). Considering profile P1 as an example to present the typical stratigraphy of the site and the results of the recalculation of the geoelectrical sections into the clay content and *K* sections, then, using equations (4) and (5) (if the clay content is more or less than 35%, respectively), a cross-section with three horizontal layering can be obtained, as shown in Figure 10. The resistivity section (Figure 10A) presents a model type K ($\rho_1 < \rho_2 > \rho_3$) where the second layer corresponds to a sandy layer (clay content $\leq$ 6%, Figure 10B). By equations (4) and (5) (if the clay content is more or less than 35%, respectively), a soil *K* section is determined (Figure 10C). The sandy layer, with high hydraulic conductivity ($K \geq 6$ m day^{-1}, Figure 10C), is a shallow aquifer, which easily permeates the fresh water from the irrigation canal. The overlying and underlying strata are primarily loam or silt-loam soils, with the exception of the third layer in the 36 m to 40 m interval, where the clay content is more than 45% (clay soil).

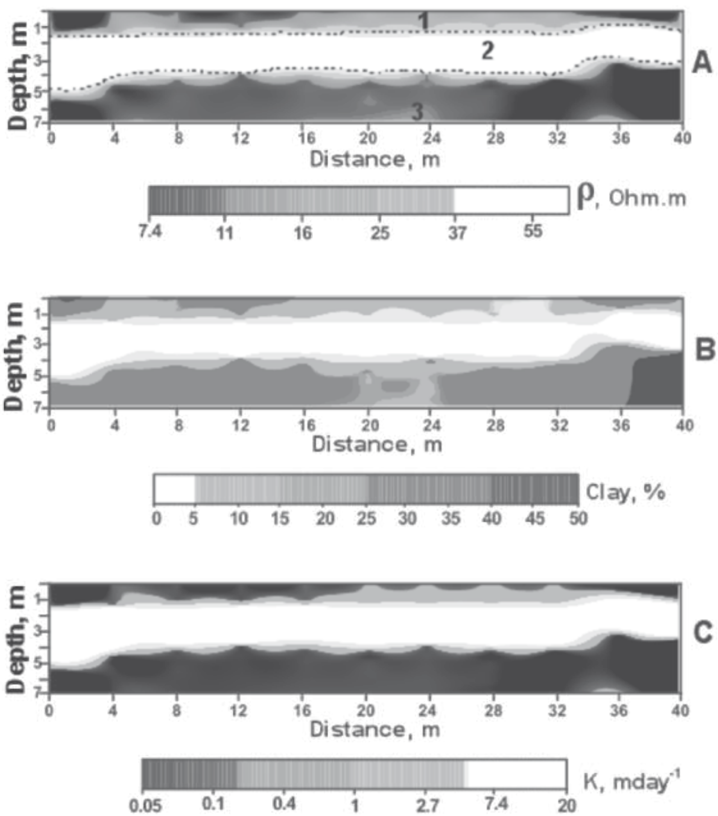

Figure 10. (A) resistivity, (B) clay content and (C) K cross-sections with three horizontal layers obtained from the application of the ERT method.

Any traditional method for determining clay (or fines) content and K requires the completion of drilling and the collection and analysis of soil samples in the laboratory. The application of the ERT method combined with knowledge of the groundwater salinity results in a fast and inexpensive procedure to study soils. The future inclusion of EM induction equipment (e.g., EM-38; Geonics Limited, 2010) may further increase the efficiency of this procedure, making it an effective technique for studies of large areas of agricultural soils.

4. Conclusions

The groundwater salinity from the Valle del Fuerte canal, approximately 0.09 gl^{-1} (ρ_w = 76.9 Ohm.m), contrasts sharply with that of the water samples from the wells (mean groundwater salinity is 0.6 gl^{-1}, $\rho_{w\ mean}$ = 10.2 Ohm.m). The K values obtained using the head permeameter from the 73 soil samples and the direction of the groundwater flow show that the Valle del Fuerte canal is a supply of fresh water to the local aquifer, improving water quality and preventing the advance of saltwater intrusion from the Sea of Cortez. For these reasons, we recommend disallowing the concrete lining of the Valle del Fuerte irrigation canal.

The procedure to determine fines content and K in silt-loam soils is based on laboratory electrical measurements, which have been shown to be appropriate if we consider the sum of the silt and clay contents as fines. Based on the K values and fines (clay + silt) content identified in the studied site, a new empirical equation arises, $K = 0.101176 * FINES^{-1.62}$, which allows a good estimation of K in silt and silt-loam soils. However, in soils with a clay content ≥ 35%, it is more reliable to use the equation $K_f = C^{-2} \cdot 7.2 \cdot 10^{-4}$ to estimate the soil K. We recommend verifying the reliability of both equations at other sites with different soil characteristics.

Traditional laboratory methods are accurate, but expensive, and their results are confined to scattered soil samples collected in the study site. The recalculation process of the geoelectrical sections obtained from the ERT method into fines content and K sections results in a new, faster and inexpensive procedure for the determination of hydraulic and petrophysical parameters. This procedure promises to be effective for the evaluation of large tracts of agricultural land using EM induction equipment to obtain the soil resistivity values.

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