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Determination of hydraulic transmissivity in coastal aquifer by optimal estimation of the Qe-T relationship using Kalman filter

Determinación de la transmisibilidad hidráulica en un acuífero costero mediante estimación óptima de la relación Qe-T usando el filtro de Kalman

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ABSTRACT

Background: The knowledge on the management of water as a vital resource to develop agriculture allows having greater effectiveness in its use. **Goals**: The agricultural activity in the lower part of the Sinaloa River depends on the fresh water of the regional dams and the aquifer. **Methods**: The use of groundwater represents approximately 15% of the total water used. In the presence of prolonged periods of drought, new wells are drilled without the use of an appropriate guide for farmers on the location of aquifer areas with a greater hydraulic transmissivity with the purpose of exploiting them more rationally. The National Water Commission has registered more than 680 wells on both banks of the Sinaloa River. **Results**: The information of 205 of these pumping wells for agricultural or domestic use and the specific capacity information was analyzed. Then, 79 out of 205 wells have pumping tests. It is then determined that the objective of this research work was to find the relationship between the specific capacity (Qe) and hydraulic transmissivity (T) data of the study area using the Thiem formula, considering a fixed value of the radius of influence. This hypothetical consideration and the heterogeneities of the aquifer environment add to the T-Qe relationship an additional component, it is determined that it has a normal behavior. Using the Kalman filter it is possible to eliminate or reduce such a component, thus improving the determination of the T-Qe relation of an R-value of 0.95 (without filter) to 0.97 (with filter), for a linear and exponential relationship. **Conclusions**: The application of a T-Qe estimate allows characterizing the aquifer area, with this procedure a map was obtained on the distribution of T, which will serve as a guide for future exploitations of groundwater in the study area.

Keywords: groundwater, hydraulic parameters, Kalman filter, Thiem formula

RESUMEN

Antecedentes: El conocimiento sobre el manejo del agua como recurso indispensable para desarrollar la agricultura permite tener mayor efectividad en su uso. **Objetivos**: La actividad agrícola en la parte baja del río Sinaloa depende del agua dulce de las presas regionales y del acuífero. **Métodos**: El uso del agua subterránea, representa aproximadamente el 15% del agua total usada. Ante la aparición de periodos de sequía prolongados, se perforan nuevos pozos sin el uso de una guía apropiada que oriente a los agricultores sobre la ubicación de las zonas acuíferas que tienen una mayor transmisividad hidráulica con el propósito de explotarlos de manera más racional. **Resultados**: La Comisión Nacional del agua tiene registrados más de 680 pozos en ambas márgenes del Río Sinaloa. Se analizó la información de 205 de estos pozos de bombeo para uso agrícola o doméstico y la información de capacidad específica. De este número, 79 pozos tienen pruebas de bombeo. Se determina entonces que el objetivo de este trabajo de investigación fue encontrar la relación entre los datos de capacidad especifica (Q_e) y transmisividad hidráulica (T) de la zona de estudio usando la fórmula de Thiem, considerando un valor fijo del radio de influencia. **Conclusiones**: Esta consideración hipotética y las heterogeneidades del medio acuífero suman a la relación T-Q_e una componente adicional, se determina que tiene un comportamiento normal. Mediante el filtro de Kalman es posible eliminar o reducir tal componente, mejorando así la determinación de la relación T-Q_e de un valor r de 0.95 (sin filtro) a 0.97 (con filtro), para una relación lineal y exponencial. La aplicación de una estimación T-Q_e permite caracterizar la zona acuífera, con este procedimiento se obtuvo un mapa sobre la distribución de T, que servirá de guía para futuras explotaciones del agua subterránea en la zona de estudio.

Palabras claves: agua subterránea, filtro de Kalman, fómula de Thiem, parámetros hidráulicos

INTRODUCTION

Hydraulic conductivity and transmissivity of an aquifer constitutes essential data for groundwater exploitation management and planning (Kazakis *et al.*, 2016). Measurements of aquifer hydraulic parameters can be measured by laboratory experiments or *in situ* tests; however, the former are inaccurate, and the latter is expensive and difficult (Bateni *et al.*, 2015).

Hydraulic transmissivity (T) determines the flow of groundwater that is transmitted through a vertical strip of aquifer unit width under a hydraulic gradient unit (Palafox-Avila, 2008). This parameter is required in numerical flow modeling processes (Painter *et al.*, 2007; Asfahani, 2016); horizontal recharge of fresh water (Cruz-Falcón *et al.*, 2013); in the determination of the radius of influence of the descent cone of the well (Vargas, 2016) in order to determine the perimeters for the protection from contamination of the well water, and water management, among others. It is useful to estimate the groundwater resource and its integral management (Tizro *et al.*, 2012). Its determination can be from the specific well capacities (Q_e), which is obtained from the pumping flow Q, static and dynamic level in a pump well once it is stabilized.

Through the Thiem's formula, assuming a fixed influence radius and that there are no load losses in the wells, using a relation between transmissivity values obtained from pumping tests and their corresponding specific capacity, dependency relations are obtained between both parameters, which can be linear or exponential (Al Farrah *et al.*, 2013).

Determinations of T in the manner indicated above have been made successfully in different geological environments (Chandra *et al.*, 2008; Perdomo *et al.,* 2014; Malík *et al.*, 2015; Sanz *et al.,* 2005; Sánchez *et al.*, 2013). WRI Report 87-4034 (2008) states that estimates of transmissivity from specific capabilities provide values that are used to characterize transmissivity in certain local areas and may reveal trends or patterns. However, there are cases where this relation is not met due to the heterogeneity present in the aquifer, and erroneous transmissivities that do not correspond to the aquifer are obtained.

The groundwater of the coastal aquifer of the lower right and left bank of the Sinaloa River constitutes an important element of support for the development of agricultural activity in the region, since the water from local dams is insufficient to irrigate the Guasave valley, that is why the extraction of groundwater is required through wells and bored wells. Of the total water used in agriculture, groundwater accounts for 15% and surface water 85% (Peinado-Guevara *et al.*, 2017).

The bed of the Sinaloa River is regulated by the Gustavo Díaz Ordaz Dam. In 2005, with the water from the dam, the left and right banks of the Sinaloa River were irrigated, 54,134 ha and 45,105 ha, respectively, corresponding to the Irrigation District No.63. Guillermo Blake Aguilar is another dam in the region, with this, 21,820 ha are cultivated. CONAGUA (2000), using the piezometric fluctuations method, determined an overexploitation of 97.3 million m³ for October 1997 and October 1998 periods.

The National Water Commission has registered more than 680 pumping wells distributed on both banks of the Sinaloa River, of the which, 79 pumping tests are analyzed with their respective information of specific capacity Q_e and hydraulic transitivity T. The Kalman filter is applied to the Q_e-T relation which is widely used to estimate the state of dynamic systems, as an optimization method, as an optimizer that eliminates or reduces the normal random component that is the use that will be given in this work to remove the Gaussian noise component produced naturally by assuming that the radius of influence of the wells is constant as well as by the influence of the heterogeneities of the aquifer, which deviate from the theoretical considerations of the Thiem formula which assumes that the aquifer is confined, homogeneous, isotropic, horizontal, among other considerations.

MATERIALS AND METHODS

Description of the study area. The study area lies between the coordinates 25°25´8.36" and 25°48'30.04" north latitude and 108°13'32.64" to 108 °35'38.65" west longitude (Fig. 1). The climate is very hot and warm dry with rain in summer. The average annual precipitation for the period 1986-2013 fluctuated from 300 to 400 mm (INEGI, 2014). The average annual temperature is of 22 to 24° for the serie1986-2013 (INEGI, 2014). The soils are of alluvial origin, Cenozoic era, Quaternary period, Vertisol soils predominate (62.55% of the surface of the municipality) (INEGI, 2009).

Wells information. 205 pumping wells for agricultural or domestic use that have specific capacity information were analyzed. Of these, 79 wells have pumping tests carried out by the National Water Commission using different techniques.

Of the wells with pumping test it was obtained that 11.4% of the T values are between medium to high ($100 < T < 500$ m^2/day), 8.9% in high ($500 < T < 1000$ m^2/day) and 79.7% in very high ($T > 1000$ m^2/day) according to the classification of Villanueva & Iglesias (1984). Those values indicate that this is a coastal aquifer with high capacity to transmit water that, in the face of a scenario of overexploitation due to its high potential to be contaminated by saline intrusion or contamination by dissolution due to the presence of evaporite bodies in the study zone.

There is information of 30 lithological columns with depths ranging between 100 and 150 meters, with four lithological sections being constructed that show the heterogeneous distribution (horizontal and vertical variations) of the aquifer materials. The wells were geolocated with a portable GPS Magallanes brand.

Qe-T relation. Al Farrah *et al.* 2013 uses the Thiem equation which, by setting a value of R and substituting that of r_w according to the radius of the well in question, Thiem's formula can be written as

$$T = \frac{1}{2\pi} \ln\left(\frac{R}{r_w}\right)(Q/s)$$

$$T = C(Q/s)$$

$$T = CQe$$

Where: T is hydraulic transmissibility (m^2/day), R is the radius of influence of the pumping well (m) and r_w (m) is the radius of the well, s (m) is the depression in the well. For a given R value and the corresponding radius of the well r_w, the term $\frac{1}{2\pi}\ln\left(\frac{R}{r_w}\right)$ is a constant, C.

Hamm *et al*. (2005) and Galvão *et al*. (2016) have established relations of the form:

$$T = C(Q/s)^n$$

The range of the exponential coefficient is in a range of 0.6 to 1.4 and is related to the lithology and the aquifer (Al Farrah *et al*., 2013).

With 79 pairs of Q_e values, T obtained from the National Water Commission, the Q_e - T ratio was found without using the Kalman filter and using the filter. From the filtered T-Q_e ratio, a map of equal hydraulic transmissibility was obtained, which is a guide for future drilling.

Uncertainties of Qe and T. The values of Qe and T present uncertainties due to the following: un aquifer tends to present heterogeneities and anisotropy, the well does not always cross the entire aquifer formation, part of the water pumped from the well reaches reincorporated into the aquifer, the pumping flow Q tends to present variations due to fluctuations in the electric current of the pumping system, the diameter of the well is finite and there is usually a head drop in the well due to the screen pipe or well face, the radius of influence is often unknown, among others factors. All these variables add uncertainties to the relationship between Qe and T expressed by Thiem equation, which establishes that it is that of a straight line that passes through the origin and that, due to the aforementioned uncertainties, it undergoes variations, so that the Kalman filter eliminates additive contributions whose behavior has a normal distribution (white noise uncertainty), thus achieving a better relationship between Qe and T given by the correlation coefficient.

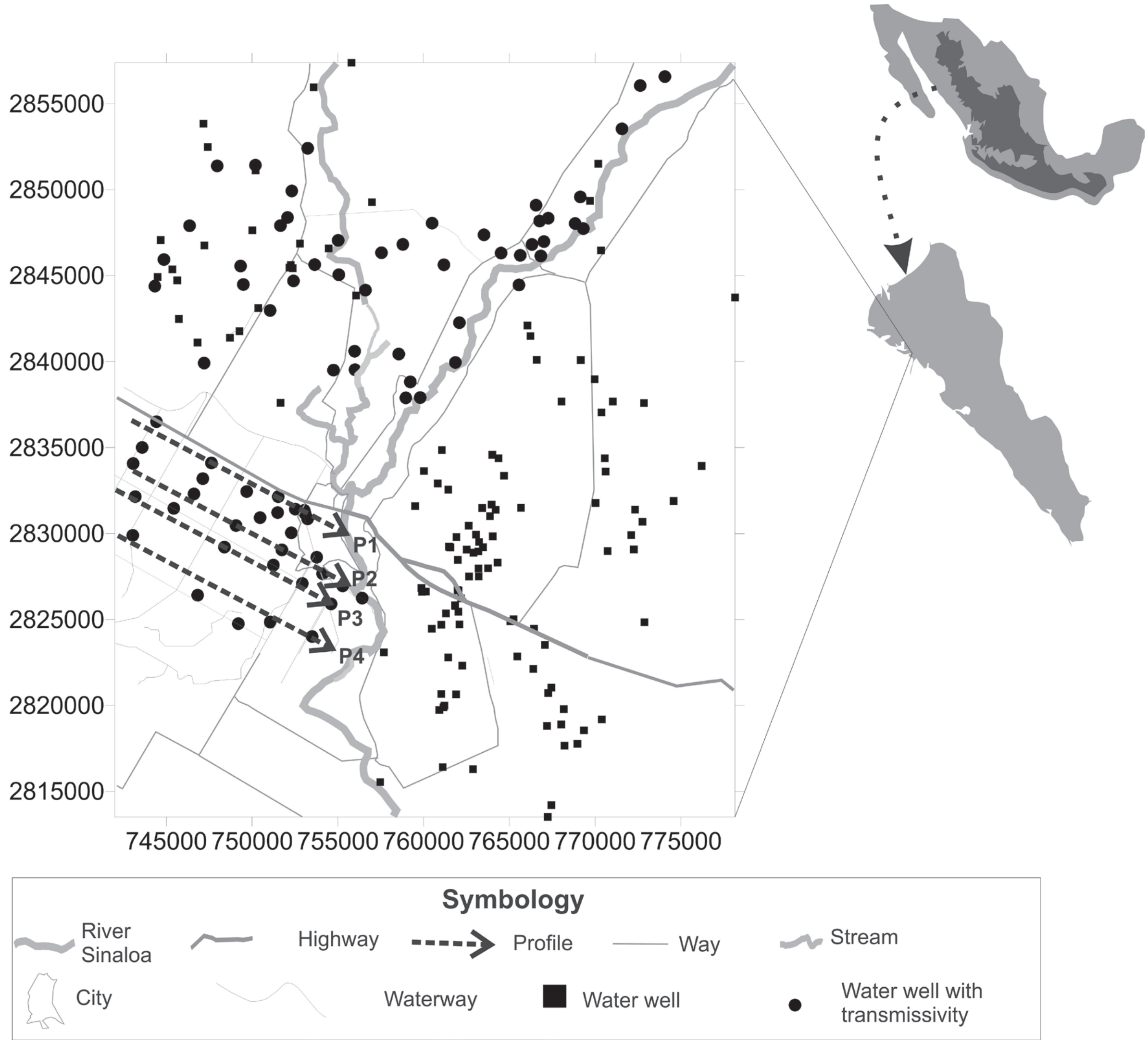


Figure 1. Location of the study area. With black circles are indicated wells with information of pumping tests and with black squares the wells with specific capacity information.

Kalman Filter. The Kalman Filter (KF) is an optimal estimator (Kim, 2011). Faragher, 2012, indicates that it has extensive use as a noisy data smoother. Following Grewal-Mohinder & Andrews, 1995, the discrete-time model is established for a linear stochastical system which takes the form:

$$x_k = A_{k-1} + u_{k-1} \tag{1}$$

$$y_k = C_k x_k + {}_k \tag{2}$$

The zero mean uncorrelated Gaussian random processes $\{u_{k-1}\}$ and $\{v_k\}$ have matrices of variances Q_{k-1} and R_k, respectively, at time t_k; x_k describe the unknown signal; y_k is the measurement with white gaussian noise and the matrices A_{k-1} and C_k are constants. The KF as a data softener has the form:

$$\hat{x}_k^- = A_{k-1}\, \hat{x}_{k-1}^+$$

$$P_k^- = A_{k-1}\, P_{k-1}^+ A_{k-1}^T + Q_{k-1}$$

$$K_k = P_k^-\, C_k^T\, (C_k P_k^- C_k^T + R_k)^{-1}$$

$$\hat{x}_k^+ = \hat{x}_k^- + K_k\, (y_k - C_k \hat{x}_k^-)$$

$$P_k^+ = P_k^- - K_k C_k P_k^-$$

Where $\hat{x}_k^-$ is the estimate signal of x_k before processing the measurement y_k in the instant t_k ; P_k^- is the variance of the estimation error $\hat{x}_k^-$; K_k is the optimization factor, usually named Kalman gain; $\hat{x}_k^+$ describes the estimate signal of x_k after processing the measurement v_k y_k in the instant t_k; and P_k^+ is the variance of the estimation error $\hat{x}_k^+$.

For the particular case of this work, that correspond to the filtering of signals, the system (1) and (2) as well as the KF are specified with the matrices:

$$A_{k-1} = I_{2*2}$$

$C_k = I_{2*2}$, $Q_{(k-1)}=0.1\, I_{2*2}$ $R_k = 0.01\, I_{2*2}$ and initial conditions

$\hat{x}_0^+ = [173,7.5]^T$ and $P_0 = I_{2*2}$

RESULTS

Geometry of the aquifer. With the information available from 30 lithological columns, the aquifer's geometry was determined, as well as the distribution of the aquifer materials, which, as can be seen, has significant lateral and vertical heterogeneities. Figure 2 shows four profiles with the sequence of materials showing the abundance of gravel with clay-silt matrix, highlighting the presence of a gravel body, which

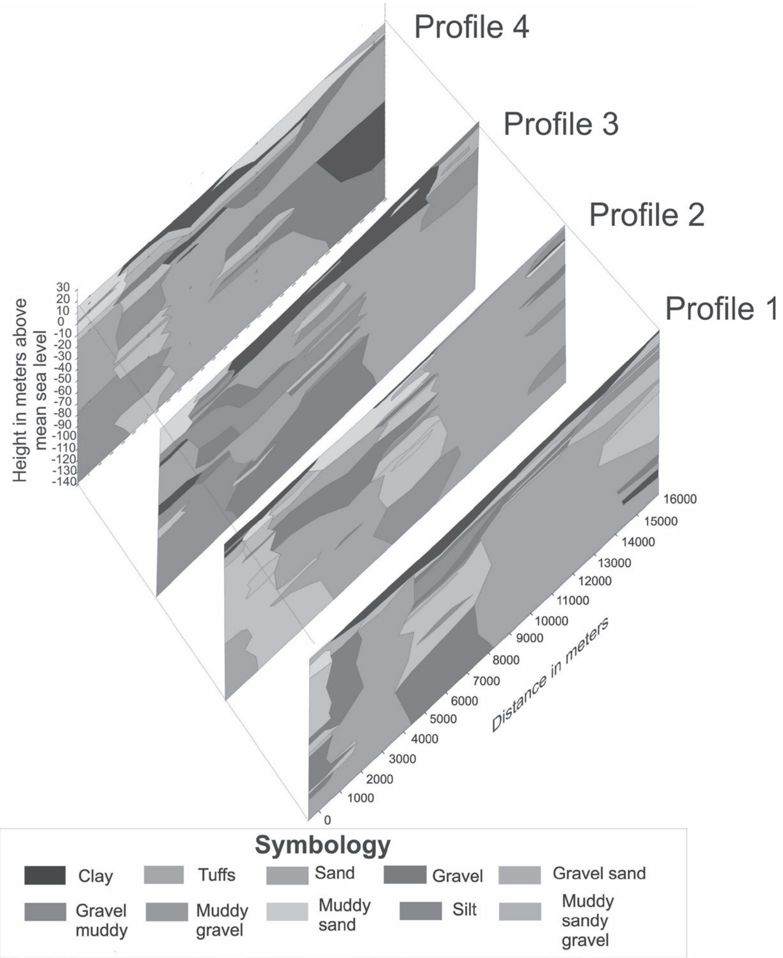


Figure 2. Perpendicular section to the Sinaloa River.

are indicators of the ability of materials to yield water. The wells of 100 to 150 m partially penetrate the aquifer, since it cannot touch the geological or hydrological basement.

Relation between specific capacity and hydraulic transmissivity. The empirical approach is based on determining the empirical relations between T and Q_e, which are regarded as aquifer and area-specific (El-Naqa, 1994; Al Farrah *et al.*, 2013). Table 1 shows the values of hydraulic transmissivity, and specific capacity Q_e. Figure 5 shows the relation between transmissivity and specific flow rate with an adjustment of 0.989, so it is possible to estimate the transmissivity in function of its specific capacity. T is directly proportional to the specific flow, such as those obtained by Bosch, 2014, Chandra *et al.*, 2008, Ebong *et al.*, 2014 and Perdomo *et al.*, 2014.

Table 1. Wells data from pumping tests and specific well capacities.

Coordinates		**Hydraulic transmissivity**	**Specific well capacities (Q_e)**	**Coordinates**		**Hydraulic transmissivity**	**Specific well capacities (Q_e)**
X	Y	m/day	lps/m	X	Y	m/day	lps/m
749489	2844495	173	7.5	767015	2846992	3629	30.6
750195	2851435	207	3.2	767267	2848352	3646	29.4
758551	2840450	242	3.5	766837	2846157	4441	47
749330	2845569	251	2.9	752315	2849936	4454	37
744860	2845948	276	3.9	758790	2846828	4687	34.5
759225	2838831	302	3.8	756001	2839538	4700	34.6
747965	2851393	354	4.8	766321	2846824	5435	37.2
766554	2849107	492	4.2	768835	2848045	6834	75.9
763521	2847384	570	5	755058	2845062	8208	57.5
761184	2845644	829	6.9	751056	2824860	3410	27.506
751656	2847922	864	10.2	753500	2824020	2925	26.051
752414	2844704	924	20.8	754605	2825918	1588	13.136
769138	2849591	924	8	753768	2828632	1909	16.313
764518	2846326	1020	8.7	753040	2831360	2888	27.334
761854	2839960	1054	11.6	752519	2831428	3158	27.425
759801	2837919	1210	14.5	751240	2828174	3116	25.799
755019	2847063	1253	11.2	749198	2824766	4078	35.123
744330	2844398	1305	11.1	746824	2826422	4569	40.408
765560	2844468	1339	12.9	748387	2829222	4295	37.584
762087	2842274	1382	12	749063	2830475	2354	17.067
758964	2837902	1469	15.7	750466	2830934	2039	16.423
760495	2848063	1529	14.2	751524	2832152	1695	14.293
746357	2847915	1555	20.3	747628	2834115	1369	11.574
755981	2840616	1555	17.2	746611	2832315	1050	10.214
751052	2842985	1564	16.3	745434	2831474	2401	21.481
754746	2839514	1620	14.2	756419	2826252	1721	14.786
753243	2852417	1728	16.8	743042	2829906	2117	19.524
756610	2844169	1771	18	743186	2832156	452	3.908
753091	2831170	1901	21.5	743064	2834081	1676	14.466
753236	2830864	1901	21.6	744423	2836516	987	10.424
757544	2846342	2125	19	743590	2835017	715	5.937
774069	2856590	2195	21	755282	2826961	1725	16.063
772631	2856067	2316	22.4	747126	2833203	2319	19.399
769315	2847747	2411	25.9	749683	2832454	2325	21.208
765637	2846194	2635	28.1	751488	2831230	1254	11.335
747203	2839926	2730	23.2	752286	2830051	2685	25.924
766768	2848188	2981	29.4	751737	2829058	3139	29.707
753652	2845651	3041	27.3	752929	2827102	2063	17.914
752065	2848392	3283	37.4	754113	2827671	2207	18.492
771567	2853551	3473	37.3				

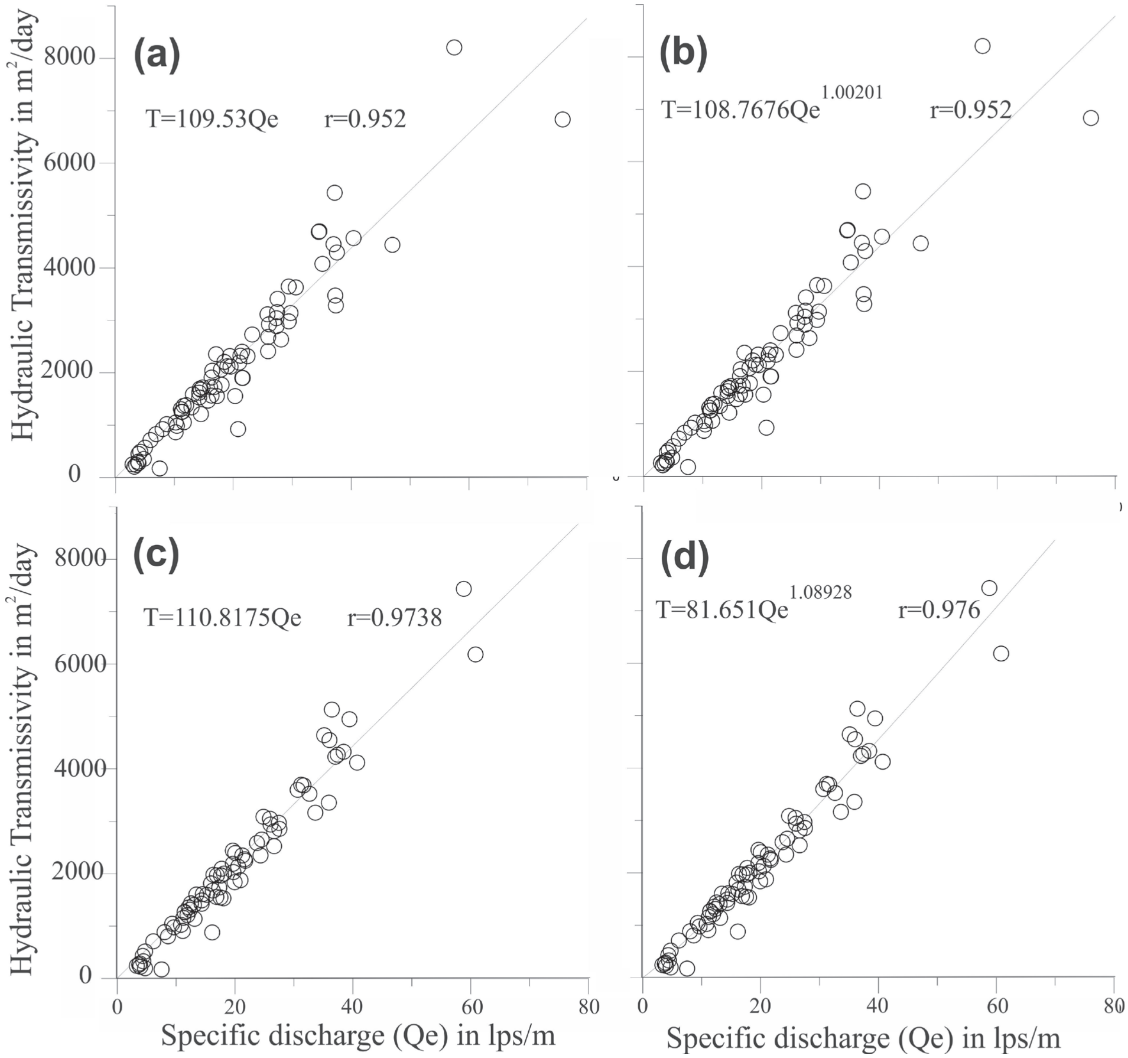
Relation is given by:

$$T = 109.533Q_e$$

Bosch (2014) states that the factor that relates to T with Q_e oscillates from a range between 100 to 500, so the relation obtained is consistent with that obtained in other aquifers by other authors.

Figure 3 shows that it is possible to estimate the hydraulic transmissivity in function of specific capacity. The application of the Kalman filter to the $T\text{-}Q_e$ relation improved the correlation coefficient going from 0.95 to 0.97. Figure 3c shows how applying the Kalman filter reduces the dispersion of the data and therefore increases r, as is the case.

Practical application. In 126 pumping wells Q_e was calculated by knowing the expense, static and dynamic level of the water in each well, estimating T from a relation $T = 109.533Q_e$. The map of equal values of hydraulic transmissivity shows that it is lower on the left bank of the Sinaloa River, which is consistent with that established by Norzagaray-Campos (2003), who built four profiles parallel to the river, indicating that the lithological changes are explained by the migration of the Sinaloa River from East to West.



Figures 3a-d. Regression line fitting specific discharge (Q_e) and transmissivity (T) data from pumping tests in 79 wells: a) linear regression; b) exponential relation; c) linear regression with Kalman filter; d) exponential relation with Kalman filter.

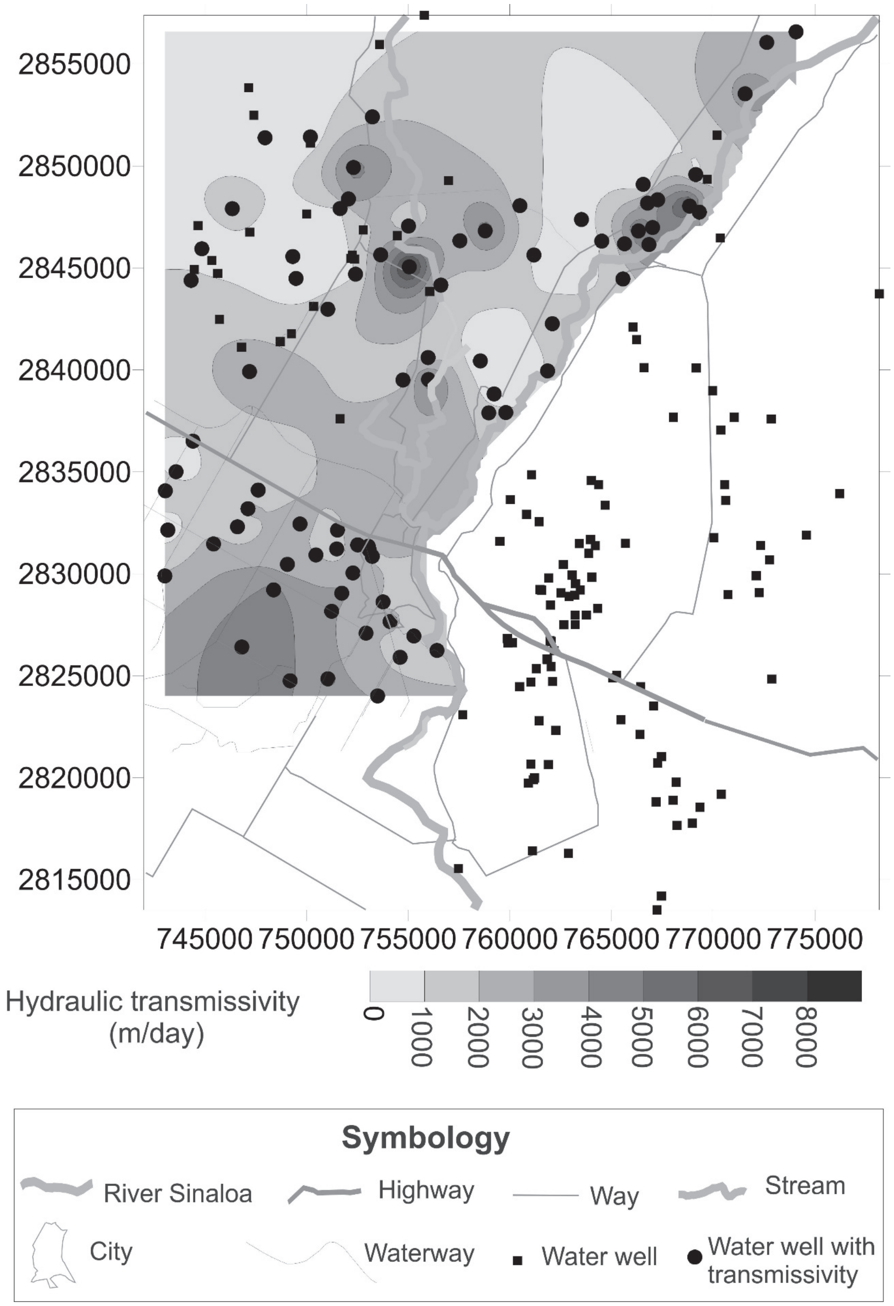
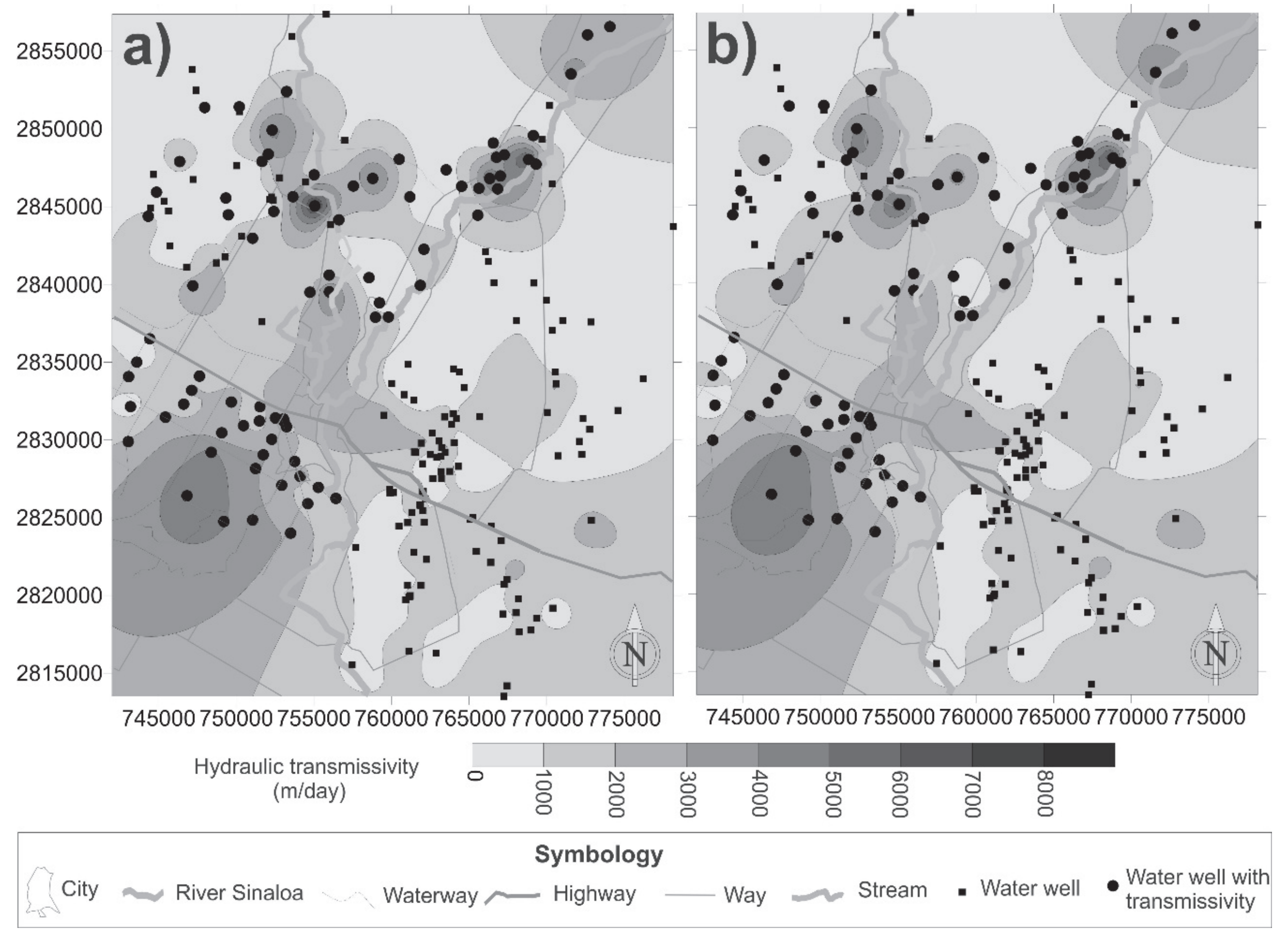


Figure 4. Transmissivity Isocontorms in m^2/day.

DISCUSSION

Specific capacity is directly proportional to T, such as those obtained by [Ebong *et al.*, 2014; Perdomo *et al.*, 2014, Bosch, 2014, Zeferino *et al.*, 2016, Hamm *et al.*, 2005 y Galvão *et al.*, 2016]. The relation $T/Q_e = 109.533$ is in the range proposed by Bosch (2014) who established that the factor that relates T with Q_e oscillates in a range between 100 and 500, reason why the relation obtained is consistent with that obtained in other aquifers, as reported by Perdomo *et al.* (2014) $T = 135.36Q_e - 50$ and Zeferino *et al.* (2016) of $T = 100.23\ Q_e - 7.126$ in different geological environments. In other studies, this relation has been of the exponential form as reported by Hamm *et al.* (2005) $T=0.99\ Q_e^{0.89}$ where T and Q_e are in m^2/day. Galvão *et al.* (2016) also proposes an empirical relationship in karst systems in Sete Lagoas, MG, Brazil. $T=330\ Q_e^{0.21}$ where T and Q_e are in m^2/day, the coefficient of determination R^2 was 0.55.



Figures 5a-b. Hydraulic transmissivity behavior (m^2/day) in the study area: a) from the linear relation; b) from the Kalman filter application.

It has been found that the Kalman filter is a useful tool in the determination of the relation T-Q_e, since it improved the relation between both parameters by increasing the correlation coefficient. The Thiem formula has a practical application that, although it is a relation for a homogeneous and isotropic medium, works in areas that present heterogeneities as is the present case.

Heterogeneities that are considered to have an effect with normal behavior in the T-Qe relation, which can be reduced by the Kalman filter, as indicated, the correlation increased from 0.95 to 0.97.

The T-Q_e relation has practical application since it allows to characterize the aquifer environment concerning T.

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