Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

A Study of Reinjection and Connectivity between Wells in the Los Azufres (Mexico) Geothermal Field

Abel F. Hernández[1], Víctor M. Arellano[1], Rosa M. Barragán[1], Emigdio C. Espinoza[2], Lisette Reyes[2], and Alfredo Mendoza[2]

[1]Instituto de Investigaciones Eléctricas, Gerencia de Geotermia, Reforma 113, Col. Palmira, 62490, Cuernavaca, Mor. México

[2]Comisión Federal de Electricidad, Residencia Los Azufres, Campamento Agua Fría, Michoacán, México.

afho@iie.org.mx

Keywords: connectivity, nonparametric regression, reinjection, Mexico

ABSTRACT

Historical records of production and reservoir-monitoring data gathered in the Los Azufres geothermal field were studied to assess the effect of geothermal reinjection and the connectivity among geothermal wells. The former data correspond to wells producing vapor or a liquid-vapor mixture. To estimate the connectivity between pairs of injection-production wells, the known nonparametric regression ACE (Alternating Conditional Expectation) method was used to correlate injection rate histories to either chloride concentration histories for liquid/mixture production wells or to bottom-hole pressure histories for vapor production wells. The statistical results were analyzed in light of earlier field studies based on tracer tests as well as on histories of both chemical species and isotope concentrations. Our study assessed the relative effect of reinjection through monitoring chloride concentration and, for the first time, bottom-hole pressure histories measured at production wells of both southern and northern Los Azufres geothermal field. Our analysis suggests that the connectivity indices yielded by the ACE method for some well pairs are in agreement with earlier reservoir data. Further comparison with other types of reservoir data is required to evaluate or calibrate our estimations.

1. INTRODUCTION

The Los Azufres geothermal field is located in the state of Michoacán, central Mexico (Fig. 1); it is owned and operated by the Comisión Federal de Electricidad (CFE). The geothermal field has two areas of production: Marítaro in the northern zone and Tejamaniles in the southern region (Fig. 1). The total installed electrical generating capacity of the entire field is currently 188 MWe. The first production wells started operating in 1982. As of 2008, 39 production wells were in operation, which produced 14.6 million tons (Mt) of steam. The former led to 4.53 Mt of brine that was fully injected into the reservoir through six injection wells (Gutiérrez-Negrín et al. 2010; Arellano et al. 2012). Previous studies (Barragán et al., 2005, 2010, 2011, 2013; Arellano et al. 2005, 2012; Iglesias et al., 2011) have observed and analyzed the effect of reinjected brine on produced fluids through chemical and isotope production-well data as well as through tracer tests.

The aim of our study is to explore the applicability of the nonparametric-regression "Alternating Conditional Expectation" (ACE) method (Breiman and Friedman, 1985) for estimating the degree of connectivity between pairs of injection-production wells of the Los Azufres field. The ACE method was introduced into the geothermal reservoir engineering field by Horne and Szucs (2007). It is in general suitable for correlating variables having a non-linearly relationship, as it is often the case between state variables of geothermal fluid flow and mass transport. This method has been applied previously in other geothermal fields to correlate production chloride chemistry well histories to injection rate histories so as to establish well-to-well connectivity (Horne and Szucs, 2007; Villacorte et al., 2010; Korkmaz Basel et al., 2011). Unlike the former studies, our application of the ACE algorithm considers also bottom-hole pressure histories for vapor production wells in addition to chloride concentration data measured at liquid/mixture production wells.

2. METHODOLOGY

We consider using the non-parametric statistical ACE method developed by Breiman and Friedman (1985) to infer the degree of connectivity between a pair of wells: one injecting a fluid mixture of condensed vapor and/or separated water, the other producing reservoir fluids. Due to its non-parametric nature, the ACE algorithm assumes an underlying model is unknown a priori and seeks to estimate it from data.

Here we only present a brief description of the ACE method; for further details please refer to Breiman and Friedman (1985) and to Horne and Szucs (2007). Let $X_1, X_2, \ldots, X_p$ represent our (random) input variables (e.g., mass flow rates at p injection wells) and Y our (random) output variable (e.g., chloride concentration measured at a production well). $T_1(X_1)$, $T_2(X_2), \ldots, T_p(X_p)$, and $T_y(Y)$ represent zero-mean arbitrary transformations of the input and output variables X_i and Y, respectively. One can show that (Breiman and Friedman, 1985)

$$T_y^*(Y) = \sum_{i=1}^{p} T_i^*(X_i) + e^* \tag{1}$$

where $T_1^*(X_1)$, $T_2^*(X_2), \ldots, T_p^*(X_p)$, and $T_y^*(Y)$ are optimum estimations of the input (X_i) and output (Y) variable transformations, and e* is an error with a zero-mean, normal distribution. It is known (Horne and Szucs, 2007) that including time as the (p+1)th variable in Equation 1 improves the regression in the transformed space. Although both $T_i^*(X_i)$ and $T_y^*(Y)$ are unknown a priori, the ACE algorithm determines their functional forms at the end of the numerical process. The quality of the results depends on the information contained in the available data.

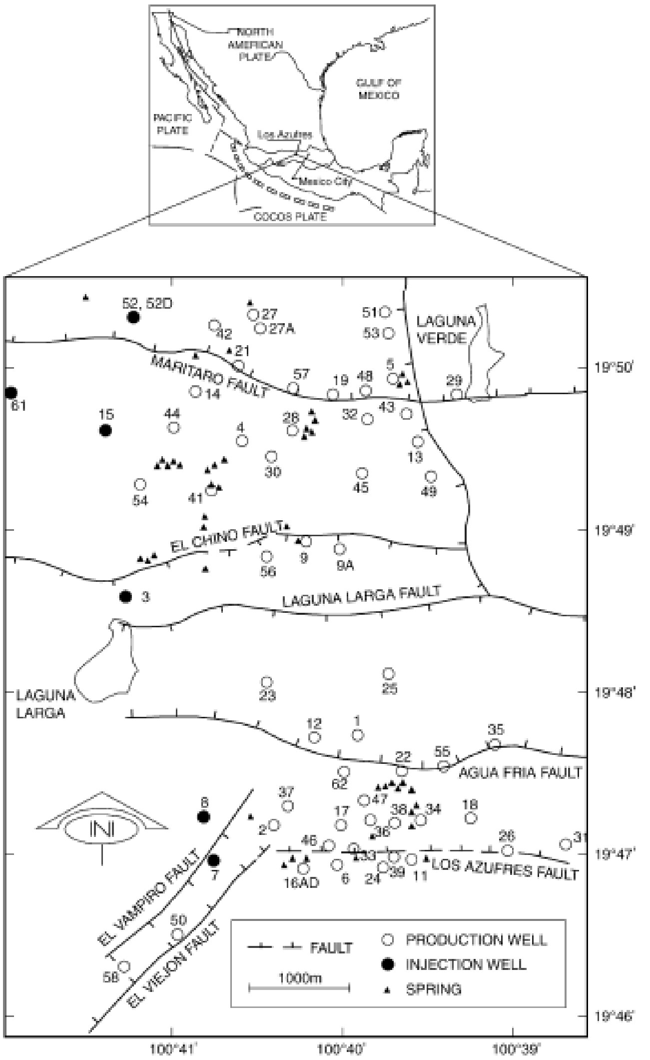

Figure. 1. Location of the Los Azufres geothermal field. Wells (without the prefix "Az-") are denoted by numbers (after Barragán et al. (2005)).

Additionally, the ACE algorithm allows estimating a measure of connectivity or connection index, between an injector i and a given production well by means of the following formula (Horne and Szucs, 2007):

$$I_i = \frac{1}{n}\sum_{j=1}^{n} \left| T_i^* \left(X_i(t_j) \right) \right| \quad (2)$$

where i is the injection well index, n is the total number of times (dates) on which injection and production data were measured simultaneously, and t_j is the jth time or date on which simultaneous measurements were recorded. Hence, I_i (i = 1, 2,..., p+1) represents the time-average magnitude of the transformed variable $T_i^*(X_i)$, where $T_{p+1}^*(X_{p+1})$ corresponds to the time variable. A large (small) value of I_i suggests a relatively high (low) connectivity between the injector well i and the production well.

The ACE method works for one output variable and several input variables. The algorithm requires that data for all input/output variables be measured simultaneously. If a well could not be measured at a given date, that fact would render all data for that date useless for the ACE analysis. This in turn would shorten the useful time series to be employed by the ACE method. In our case examples, we consider only injection-well rates as input variables but other measured quantities such as chemical-species or isotope concentrations can be deemed as well. On the other hand, in our work we used only total discharge chloride concentrations at production wells as output variables (one at a time); although another measured chemical-species/isotope or production-well outflow rate can be employed too. The advantage of working with chloride concentrations is that Cl is a conservative solute that generally does not react with the host rocks.

Previous geothermal engineering applications (Horne and Szucs, 2007; Villacorte et al., 2010; Korkmaz Basel et al., 2011) of the ACE method have focused on correlating chloride production histories and injected mass flow rates. In the next section, we apply this method to similar data as well as to bottom-hole pressure time series of vapor production wells from the Los Azufres geothermal field.

3. CASE RESULTS

3.1 Southern Los Azufres Geothermal Field – Liquid/Mixture Production Wells

Here we considered injection rate histories of the three injection wells in the southern section of the Los Azufres field: Az-7, Az-8, and Az-7A (Figure 1). The Az-7 injector closed operations in 2003 and it was replaced with the Az-07A well in 2005; these two injectors are physically located a few meters apart of each other. Chloride concentrations were measured at 13 liquid/vapor-mixture production wells located in southern Los Azufres field (Figure 1) and the data was included in the ACE regression with the injection measurements. In Figure 2 we present the results of the calculated connection indices.

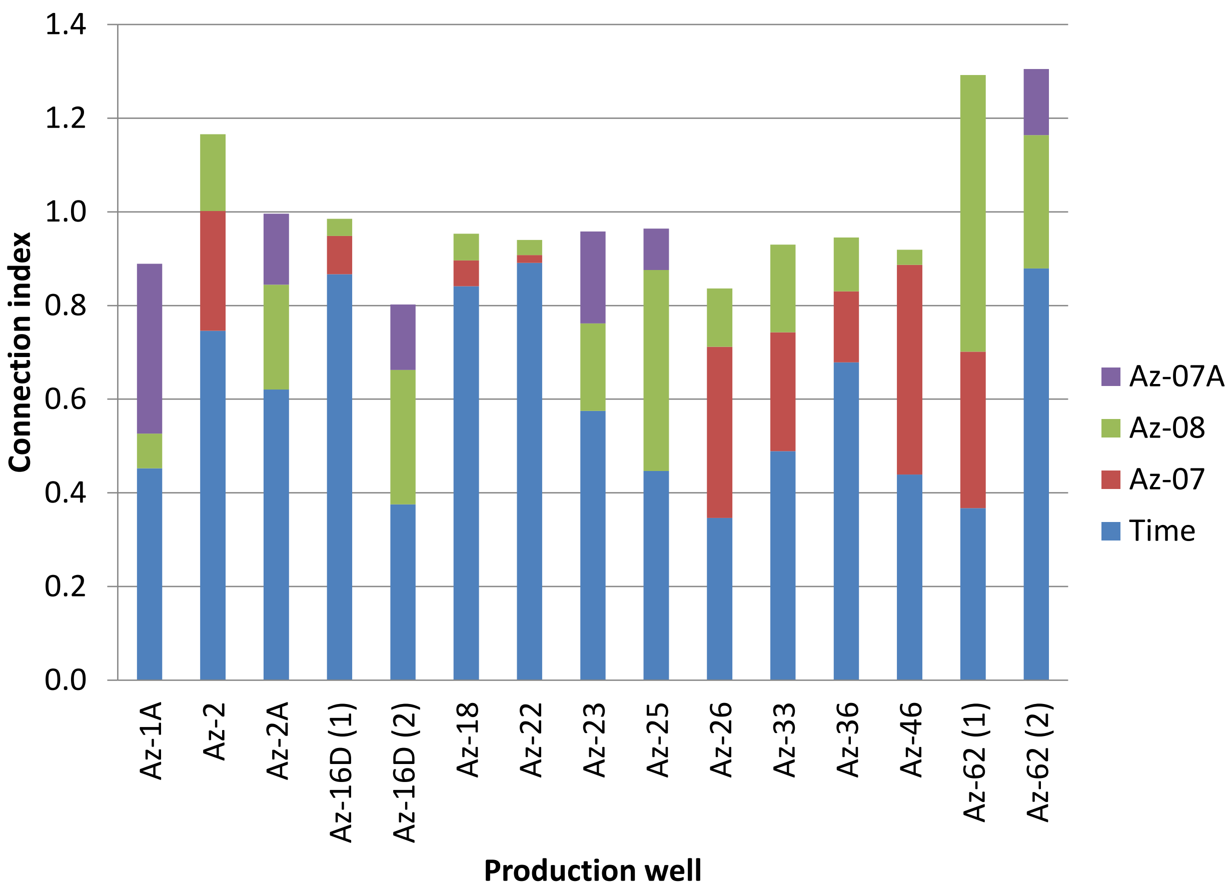

Figure 2. Connection indices between injection and liquid/mixture production wells in the southern Los Azufres field as calculated by the ACE algorithm using injection rates and production chloride concentrations.

Note that results for wells Az-16D and Az-62 are split into two periods due to the substitution of injector Az-7 by well Az-7A. One can see that the time variable shows the largest connection index values for most of the well pairs in Figure 2. When in operation, injection well Az-7 yielded better connection indices for the southern production wells than injector Az-8 did, with the exception of wells Az-22 and Az-62; this is supported by the decline in mass flow rate of some production wells (e.g., Az-26) during the period in which the well Az-8 was the only injector (Arellano et al. 2012). On the other hand, injection well Az-7A presented smaller connection indices for the southern production wells than injector Az-8 did, except for well Az-1A.

Iglesias et al. (2011) conducted a tracer test in the southern Los Azufres field, injecting the liquid-phase tracer in well Az-8. The investigators concluded that at the time of writing their conclusions (407 days after the tracer was injected), the test was not complete as the tracer was still arriving to the wells. Due to this, we could not make a comparison between the tracer test results and ours.

3.2 Northern Los Azufres Geothermal Field - Liquid/Mixture Production Wells

In the northern Los Azufres field there are four injection wells: Az-3, Az-15, Az-52, and Az-61 (Figure 1). We considered chloride concentration data from 17 liquid/vapor-mixture production wells of this field zone and correlated them with the injection rate histories from the same zone. The connection indices yielded by the ACE algorithm are presented in Figure 3.

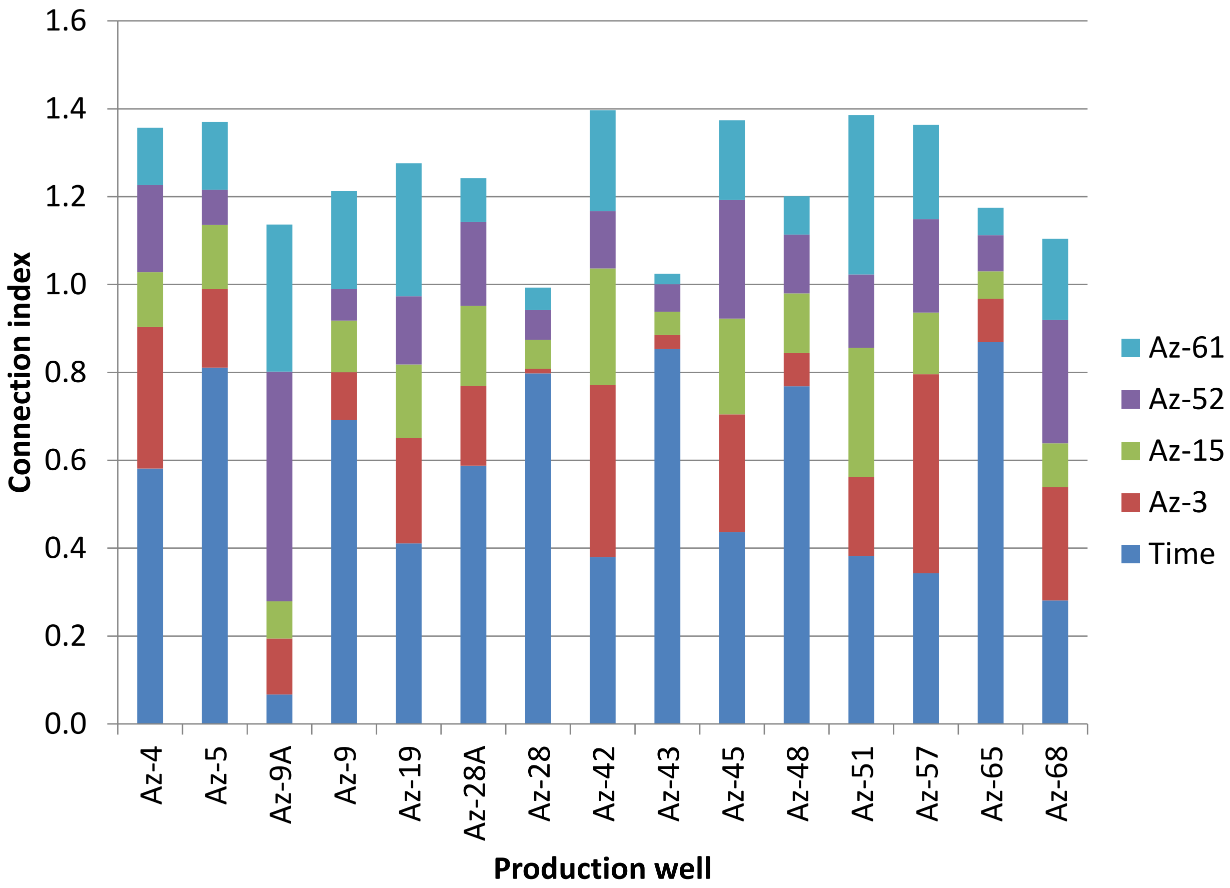

Figure 3. Connection indices between injection and liquid/mixture production wells in the northern Los Azufres field as calculated by the ACE algorithm using injection rates and production chloride concentrations.

The advantage of using chloride data is that one may be able to discriminate between reinjection fluids coming directly from the injection wells and fluids whose origin is reinjected-fluid vapor condensate that is more diluted in salts. The latter was observed recently (Arellano et al. 2012), through analysis of gases, in the northern field and also in some wells of the southern field.

The time variable holds the largest connection indices for most of the production wells (Figure 3). Injectors Az-3 and Az-52 shows the largest connectivity on the majority of the northern production wells; although, injection well Az-61 has the largest index values with production wells Az-9, Az-19, and Az-51.

3.3 Southern Los Azufres Geothermal Field - Vapor Production Wells

For this case, we used bottom-hole pressure time series from nine vapor production wells jointly with the mass flow rates histories of the three injection wells of the southern Los Azufres field (Figure 1); to our knowledge, this is the first time an ACE analysis using vapor production data is reported in the literature.

As in the first case example, the replacement of injector Az-7 by well Az-7A led to the division of the ACE analysis into two parts for each injection-production well pair. The ACE algorithm results are presented in Figure 4. The wells Az-33, Az-36, and Az-46 were considered as liquid-phase wells (Section 3.1) and also as vapor-phase wells because at their initial production stages mostly liquid was tapped from them. At later stages, these wells shifted to producing only vapor. The results in Figure 4 show that time is by far the variable with the largest connection indices, in average, in a greater degree than displayed in the case of the liquid/mixture wells of the southern field. Only the injector Az-7 shows a larger index than the time variable when the former is correlated with well Az-6. On the other hand, the indices of injector Az-8 are overall greater than those of injectors Az-7 and Az-7A. Nevertheless, well Az-7 exhibits larger indices than production wells Az-6, Az-34, and Az-37; whereas injector Az-7A does similarly when correlated with wells Az-6, Az-33, Az-35, and Az-37.

In their field study, Iglesias et al. (2011) also injected a vapor-phase tracer in well Az-8. They considered this test complete upon reporting their results. Their greater recoveries were recorded in wells Az-2A (0.018 %), Az-46 (0.002 %), Az-16AD (8.6×10^{-4} %), Az-37 (3.3×10^{-4}), and Az-6 (2.9×10^{-4}). We can note that our results show a relatively large connection index for well Az-46, in agreement with the tracer test. However, it is difficult to establish a firmer comparison as this field study did not include injecting another tracer in well Az-7A.

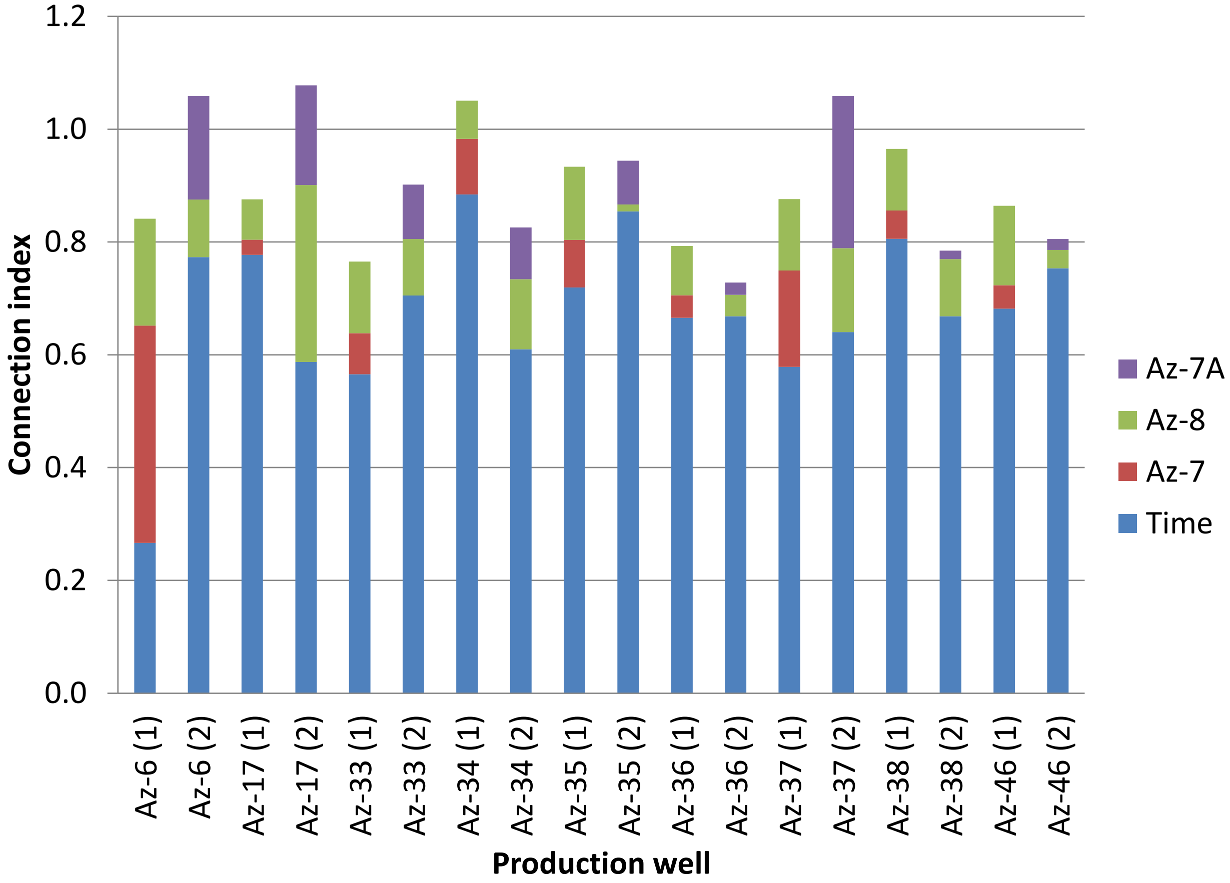

Figure 4. Connection indices between injection and vapor production wells in the southern Los Azufres field as calculated by the ACE algorithm using injection rates and bottom-hole pressure histories.

4. CONCLUSION

Our study assessed the relative effect of reinjection through monitoring chloride concentration and, for the first time, bottom-hole pressure histories measured at production wells of both southern and northern Los Azufres geothermal field. Our analysis suggests that the connectivity indices yielded by the ACE method for some well pairs are in agreement with earlier reservoir data. Further comparison with other types of reservoir data is required to evaluate or calibrate our estimations.

ACKNOWLEDGEMENT

The authors wish to thank the authorities of the Gerencia de Proyectos Geotermoeléctricos (CFE) for granting permission to publish this work. We also want to thank Prof. Roland Horne for providing us with a computational copy of his ACE algorithm.

REFERENCES

Arellano, V.M., Torres, M.A., and Barragán, R.M.: Thermodynamic Evolution of the Los Azufres, Mexico, Geothermal Reservoir from 1982 to 2002, *Geothermics*, **34**, (2005), 592–616.

Arellano, V.M., Barragán, R.M., López, S., Paredes, A., and Aragón, A.: Respuesta del Yacimiento de Los Azufres a la Explotación 2003-2011, *Final Report,* IIE/11/14283/02F, Instituto de Investigaciones Eléctricas for the Comisión Federal de Electricidad, Cuernavaca, Morelos, México, (2012).

Barragán, R.M., Arellano, V.M., Portugal, E., and Sandoval, F.: Isotopic ($\delta^{18}O$, δD) Patterns in Los Azufres (Mexico) Geothermal Fluids Related to Reservoir Exploitation, *Geothermics*, **34**, (2005), 527–547.

Barragán, R.M., Arellano, V.M., Aragón, A., Martínez, J.I., Mendoza, A., and Reyes, L.: Geochemical Data Analysis (2009) of Los Azufres Geothermal Fluids (Mexico). *Water Rock Interaction*, Birkle and Torres –Alvarado (Eds.), Taylor & Francis Group, London, (2010), pp. 137- 140.

Barragán, R.M., Arellano, V.M., Mendoza, A., and Reyes, L.: Effects of Reinjection on The Chemical and Isotopic ($\delta^{18}O$, δD) Behavior of Los Azufres (Mexico) Geothermal Fluids, as Indicated by 2010 Data, *Proceedings,* Geothermal Resources Council 2011 Annual Meeting, San Diego CA, USA, Geothermal Resources Council Transactions, **35**, 603-608, (2011).

Barragán Reyes, R.M., Arellano Gómez, V.M., Hernández, A., Aragón, A., Mendoza, A., and Reyes, L.: Evaluación Preliminar del Proceso de Reinyección en la Zona Sur del Campo Geotérmico Los Azufres, Mich. (1989-2011) con Base en la Concentraciones de Cl de los Fluidos Producidos y de Inyección, *Geotermia*, Revista Mexicana de Geoenergía, **27**, Núm. 1, (2013), 12-23.

Breiman, L., and Friedman, J.H.: Estimating Optimal Transformations for Multiple Regression and Correlation, *Journal of American Statistical Association*, **80**, (1985), 580-619.

Gutiérrez-Negrín, L.C.A., Maya-González, R., and Quijano-León, J.L.: Current Status of Geothermics in Mexico, *Proceedings,* World Geothermal Congress 2010, Bali, Indonesia, (2010).

Horne, R.N., and Szucs, P.: Inferring Well-to-Well Connectivity Using Nonparametric Regression on Well Histories, *Proceedings*, 32nd Workshop on Geothermal Reservoir Engineering, Stanford, CA (2007).

Iglesias, E.R., Flores-Armenta, M., Torres, R.J., Ramírez-Montes, M., Reyes-Picasso, N., and Reyes-Delgado, L.: Estudio con trazadores de líquido y vapor en el área Tejamaniles del campo geotérmico de Los Azufres, Mich., *Geotermia,* **24**, (2011), 38-49.

Korkmaz Basel, E.D., Juliusson, E., and Horne, R.N.: A New Look at Well-to-Well Correlations Using Nonparametric, Nonlinear Regression, *Proceedings*, 36th Workshop on Geothermal Reservoir Engineering, Stanford, CA (2011).

Villacorte, J.D., Malate, R.C.M., and Horne, R.N.: Application of Nonparametric Regression on Well Histories of Geothermal Production Fields in the Philippines, *Proceedings,* World Geothermal Congress 2010, Bali, Indonesia, (2010).