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Application of Nonparametric Regression on Well Histories of Geothermal Production Fields in the Philippines

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ABSTRACT

The nonparametric regression ACE (Alternating Conditional Expectation) method was applied to the different production fields of Energy Development Corporation (EDC) in the Philippines. Production chloride chemistry well histories were correlated to injection rate histories based on nonparametric regression to establish well-to-well connectivity. The method of inferring well connectivity by this approach can be conducted with routinely measured production and geochemical data which does not require operational disruption that would be needed with the typical tracer test. Attaining an understanding of the connections between wells is very useful in designing a strategy for brine injection, and predicting where thermal breakthroughs are likely to occur. The comprehensive field wide application of the forecasting method shows that applicability and usefulness of the technique should be calibrated with actual tracer tests data. The equation derived for well connection indices was found to be applicable only to Palinpinon-1 in Southern Negros Geothermal Production Field.

1. INTRODUCTION

Injection strategy is one of the important tasks in geothermal reservoir management. A primary objective is to eliminate detrimental effects due to possible thermal breakthrough. Different methods have been applied to estimate connections between wells, as an aid in designing and managing reinjection schemes. One traditional means of determining well connectivity is through tracer testing. Though proven to be effective, injection and monitoring of artificial tracer poses some economic disadvantages. An alternative that has become popular is to analyze movement of fluids using regularly monitored production parameters such as chloride concentration.

The analytical approach has been presented in numerous works and in different mathematical forms. This can be seen in the classic paper of Harper and Jordan (1985) who quantified the rate of return of injection water at Palinpinon in the Southern Negros Geothermal Production Field (SNGPF) based on chloride histories. Later mathematical analysis of Palinpinon's chloride histories was carried out by Urbino and Horne (1991) using a correlation method, and by Sullera and Horne (2001) who used wavelet decomposition. All three studies analyzed chloride histories of production wells of Palinpinon-1 field to infer well connectivities that were verified qualitatively by comparison with tracer tests results. However, these methods have shown a weakness in that an assumption of the mathematical form of the connection model is required. This could mean imposing reservoir relationships that may not be extrapolated validly into the future.

In 2007, in an attempt to address the limitation of the previous works, Horne and Szucs investigated the use of nonparametric regression. The approach aims to match the given data without making any assumptions about the underlying reservoir model. The method known as ACE (alternating conditional expectation) was chosen by Horne and Szucs (2007) for the purpose.

ACE is a nonparametric method developed and presented by Breiman and Friedman (1985) for transformation/regression. The method provides nonlinear transformations which minimizes error in both response and predictors. This method assumes that the optimal transform of a function is the sum of the optimal transforms of the independent variables. This means that ACE works by decomposing the signal of each variable in the following form:

$$g^{*}(y) = \sum_{i=1}^{p} f^{*}(x_i) + e^{*} \qquad (1)$$

ACE can be used for multivariate problems such as the case of chloride concentration of a specific production well with injection rates of multiple injection wells.

Using the ACE algorithm, Palinpinon-1 chloride data and injection histories were reexamined. The magnitude of the connectivity indices computed was remarkably consistent with the tracer test results.

The sections that will follow will present a review of the Palinpinon-1 results, and further application of ACE to data from two other fields, Mindanao Geothermal Production Field (MGPF) and Palinpinon-2 in SNGPF

2. REVIEW OF PALINPINON-1 CHLORIDE DATA RESULTS

With the introduction of the ACE approach, the set of Palinpinon-1 data used in previous "parametric" approach was reexamined. This covers the period of 1983 to 1989. Typical results show that the magnitude of the positive values of the transform function indicate the connection between the wells. An example is depicted in Figure 1 which is the transform functions for all the injection wells in relation to production well OK7.

The indices are illustrated graphically in Figure 2. These connection strengths may be used to infer the likelihood of a thermal breakthrough, based on the length of each of the segments.

The computed indices were compared with actual tracer results. The connectivity estimated based on the PN1RD tracer test were very consistent with those computed using the ACE method. Connectivities based on PN9RD tracer test results also showed consistency although not as good as in the case of PN1RD.

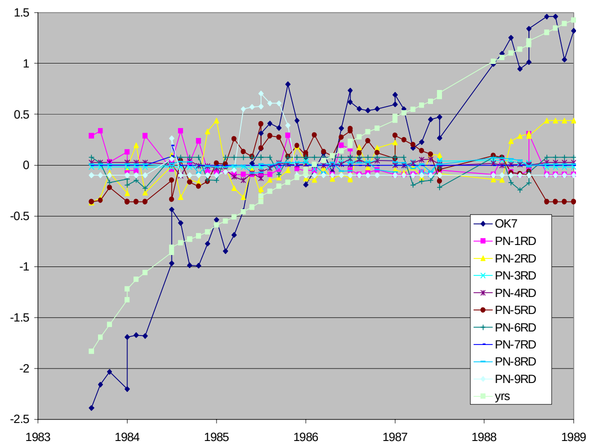

Figure 1: Extracted model function from OK7 data showing dependence on time and injection wells

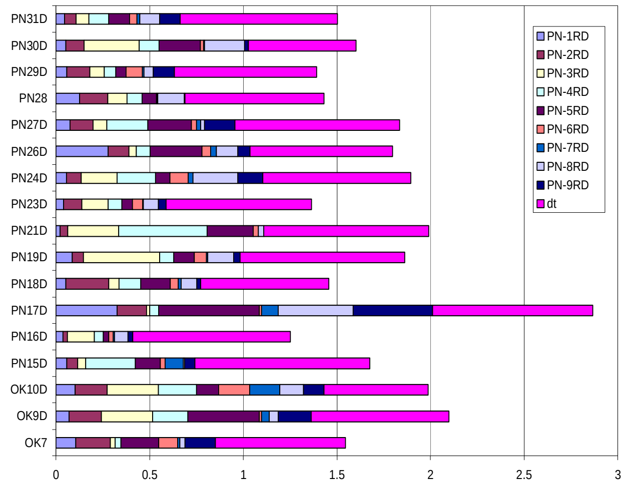

Figure 2: Summary of 'connection indices' based on ACE function magnitudes

3. APPLICATION TO MGPF CHLORIDE DATA

The Mindanao Geothermal Production Field (MGPF) is located on the northwest flank of Mt. Apo, Cotabato in the island of Mindanao. The field began commercial operation in 1997 with the commissioning of Mindanao 1 power plant with an installed capacity of 52MWe. It was followed by the commissioning of Mindanao 2, another 52 MWe power plant, in 1999. MGPF's steam come from the Marbel and Sandawa sectors while injection areas are located at Kullay-Matingao and Kanlas sectors.

After a year of exploitation, suspected injection breakthrough from the Marbel sector was manifested from the geochemical parameters being monitored. Several tracer tests were conducted to investigate the phenomenon. Two tests were performed in 1998 which used sodium flourescein and radioactive I-131. Findings of this testing were presented in the works of Delfin and Pioquinto (1999) and Delfin et al. (1999). With the marked changes of geochemical parameters in well discharges, another tracer test was conducted in 2003. The 2003 test utilized the compound Napthalene Disulfonate (NDS) in two injection wells, MT2RD and KL1RD. Results have been evaluated and highlights were documented in reports by Nogara and Sambrano (2004) and Aragon et al. (2005).

Another tracer test was conducted in 2006, using three injection wells, MT1RD, KL4RD, and KN2RD. Initial results have been presented in EDC internal technical meetings since 2008. Complete evaluation and reports about the test have not been released since some tracer samples have not been analyzed yet due to the breakdown of the HPLC liquid chromatograph unit.

With the introduction of the ACE approach and its initial successful application to Palinpinon-1 data, the same program was applied to the injection rate histories and chloride concentration of MGPF. This investigation further evaluated the applicability of the method in predicting well-to-well connectivity. The period covered by the study is from the commissioning of the power plant in 1997 up to 2007.

Results for Well APO1D and for SK2D are presented in Figures 3 and 4. As been pointed by the work of Horne and Szucs (2007), time dependence of the response variable need not have linear functional form, which was a common assumption in the earlier 'parametric' modeling approaches. The relative magnitude of the positive values of the model function coefficients were used to represent connectivity with the production well.

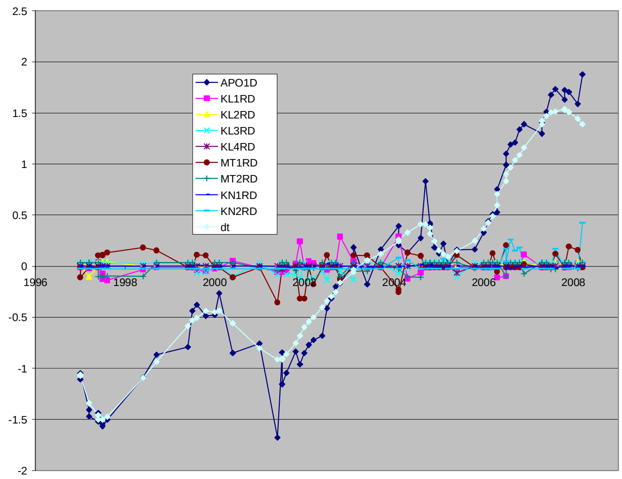

Figure 3: Extracted model function from APO1D data showing dependence on time and injection wells

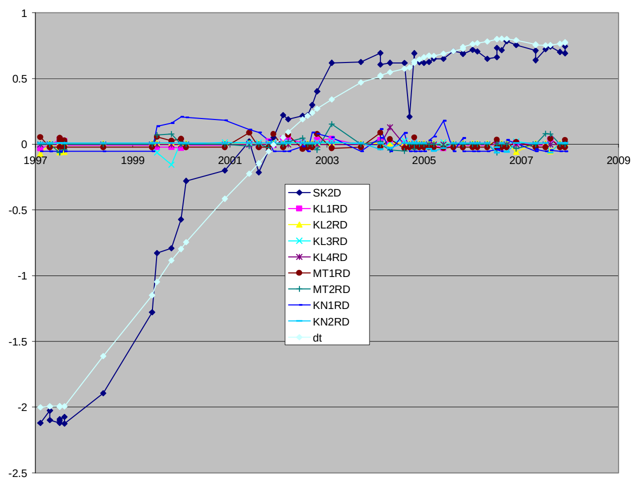

Figure 4: Extracted model function from SK2D data showing dependence on time and injection wells

The well-to-well connectivity was measured through the "connection index" computed based on the transform functions. The index is defined as:

$$I_i = \frac{1}{n}\sum_{j=1}^{n}\left| f_i(x_i(t_j)\right| \qquad (2)$$

which is the same form that was used previously for Palinpinon-1 data by Horne and Szucs (2007). These indices are tabulated in Table 1 and presented in individual bar segments for easy visualization in Figure 5. The bar segment's length shows the connection strength. The longer the bar, the more likely it is that injection breakthrough will occur between the wells.

Table 1. Connection indices at MGPF based on the average absolute magnitude of the ACE functions shown in Figure 5.

	KL1RD	KL2RD	KL3RD	KL4RD	MT1RD	MT2RD	KN1RD	KN2RD	dt
APO1D	0.04	0.01	0.04	0.00	0.07	0.04	0.01	0.05	0.76
APO2D	0.10	0.04	0.08	0.01	0.18	0.21	0.09	0.06	0.72
APO3D	0.06	0.08	0.03	0.01	0.13	0.06	0.11	0.04	0.74
KN2D	0.28	0.04	0.25	0.00	0.07	0.13	0.10	0.01	0.17
KN3D	0.15	0.26	0.18	0.02	0.09	0.14	0.09	0.24	0.71
MD1D	0.11	0.06	0.30	0.11	0.40	0.20	0.13	0.04	0.56
SK1D	0.23	0.01	0.26	0.03	0.33	0.09	0.11	0.05	0.67
SK2D	0.01	0.01	0.01	0.00	0.03	0.02	0.07	0.01	0.81
SK3D	0.30	0.28	0.03	0.04	0.05	0.09	0.02	0.07	0.55
SK4D	0.18	0.20	0.06	0.01	0.46	0.28	0.04	0.01	0.69
SK5D	0.06	0.18	0.10	0.00	0.14	0.05	0.02	0.13	0.66
SK6D	0.12	0.04	0.01	0.03	0.15	0.16	0.06	0.19	0.71
SP4D	0.08	0.02	0.14	0.00	0.20	0.10	0.27	0.04	0.72

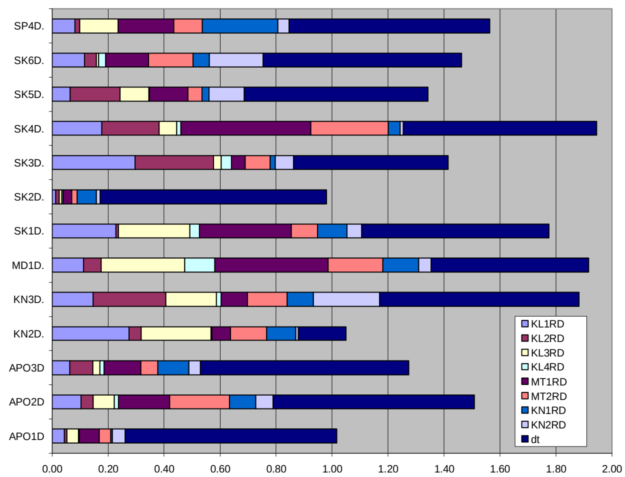

Figure 5: Summary of 'connection indices' based on ACE function magnitudes for MGPF wells

4. APPLICATION TO PALINPINON-2 CHLORIDE DATA

Another set of data was examined using the ACE approach, namely the injection rate histories and chloride concentrations of Palinpinon-2 production wells. This is the second sector of Southern Negros Geothermal Production field (SNGPF) which has three modular plants. These three plants are located in Nasuji, Sogongon, and Balasbalas and were commissioned in 1993 to 1995 with a total installed capacity of 80 MWe.

Injection returns in this sector have been manifested through the slight yet distinct decline in temperature in its production wells. In 2005, tracer testing was conducted using injection wells NJ2RD and SG2RD. This activity aimed to aid in developing an effective injection strategy for the upcoming increase in mass extraction due to a proposed additional 20MWe power plant in the Nasuji area. Detailed results and procedures have been discussed in the report by Maturgo et al. (2006).

The same ACE program applied to Palinpinon-1 and MGPF data was also used to produce the transform functions. Only liquid-dominated wells in Palinpinon-2 sectors have been included in this study. No tracer chemical was recovered in production wells in the Palinpinon-1 area, hence Palinpinon-1 wells were not considered in the analysis. Available data for these production wells was from 1999 to 2008 and so this was the period covered in the study.

Results for wells SG1 and NJ3D are shown in Figures 6 and 7. These again show that time dependence is not a linear function. In addition, it can be seen that relatively high positive values for SG2RD and NJ2RD, reflect connection with NJ3D while positive values for NJ1RD and NJ2RD transform functions show association with NJ5D.

'Connection indices' for each well were also calculated using the form defined and used for Palinpinon-1 data. Computed values were tabulated and can be seen in Table 2. The values are also illustrated as bar segments in Figure 8. Both show the connection strength and likelihood of an injection breakthrough.

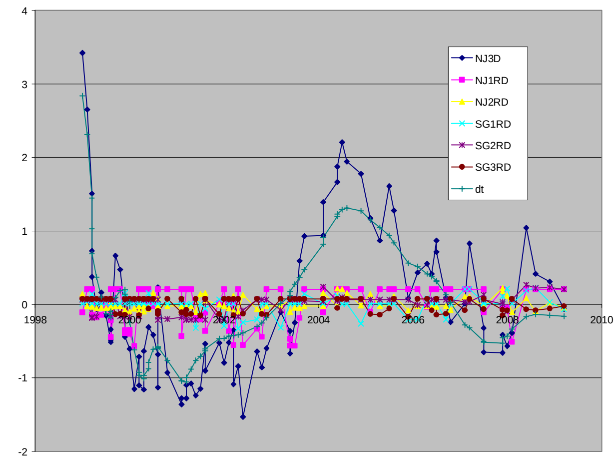

Figure 6: Extracted model function from NJ3D data showing dependence on time and injection wells

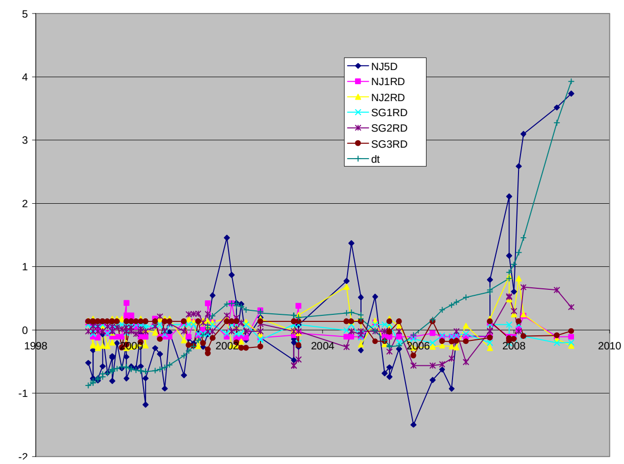

Figure 7: Extracted model function from NJ5D data showing dependence on time and injection wells

Table 2: Connection indices based on the average absolute magnitude of the ACE functions shown shown in Figure 8.

	NJ1RD	NJ2RD	SG1RD	SG2RD	SG3RD	dt
NJ3D	0.23	0.07	0.07	0.10	0.09	0.60
NJ4D	0.39	0.40	0.21	0.35	0.25	0.51
NJ5D	0.12	0.21	0.09	0.15	0.16	0.57
NJ6D	0.00	0.12	0.16	0.22	0.26	0.69
NJ7D	0.18	0.13	0.25	0.12	0.42	0.38
NJ8D	0.22	0.06	0.09	0.19	0.08	0.60
OK5D	0.10	0.16	0.22	0.07	0.08	0.87
OK6D	0.41	0.26	0.29	0.43	0.24	0.27
SG1	0.09	0.12	0.11	0.12	0.08	0.78

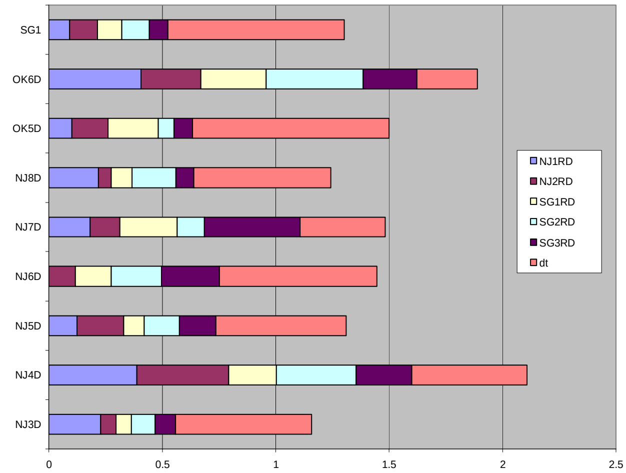

Figure 8: Summary of 'connection indices' based on ACE function magnitudes for Palinpinon-2 wells

5. COMPARISON TO TRACER RESULTS

The computed connection indices using the ACE approach were compared to the respective tracer testing results of MGPF and Palinpinon-2 to examine their physical significance.

As mentioned earlier, there have been four tracer tests conducted in MGPF. The third test that was conducted in 2003 will be used as reference for the purpose of comparison of the indices or degree of strength of well connection. For MT2RD tracer injection, positive responses were manifested with the following wells, SK2D, SK4B, SP4D, APO3D, APO1D, SK1D, SK5D, SK6D, SK7D, SK3D and APO2D. These wells were arranged in increasing amount of tracer concentration recovered. The results showed that the most affected well is SK2D. However, based on the connectivity indices calculated by ACE; SK2D is one of the least affected. APO2D, which should have the least effect experienced among these wells, appeared to have the strongest connection as illustrated in Figure 5. This can be further seen in Figure 9 which shows the comparison of the ACE connection indices from injection well MT2RD and the tracer result indices (inverse of peak time arrival).

This was similar to the comparison with the result of the tracer test in the case of well KL1RD. The production well that yield the most positive tracer response was APO1D. Unfortunately, it is the one with the least connection strength suggested by ACE.

As for the case of Palinpinon-2 wells, chemical injected in SG2RD was recovered from NJ3D while arrival of chemical from NJ2RD was noted at NJ5D and OK5D. The ACE transform functions for these respective wells seem to be roughly consistent with the tracer result. However, the overall connection indices showed different relationships. Arrival time for peak concentrations were not completely monitored for all the production wells hence inverse of these values are not available for comparison.

6. DISCUSSION

The initial demonstration of the ACE approach and its successful application to Palinpinon-1 data lead us to further investigate the usefulness and limitation of the method by using new data from other geothermal fields in the Philippines. The well-to-well connectivity form that was defined for the Palinpinon-1 data seems to be very consistent with the results obtained by the tracer testing. This provided advantages in predicting injection breakthrough and development of reservoir management schemes without sacrificing normal field operation to perform tracer tests.

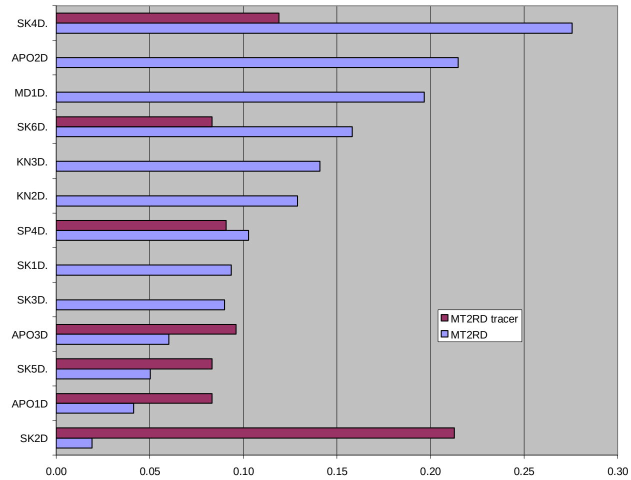

Figure 9: Comparison of indices for injector MT2RD, compared to tracer test results into MT2RD

On the other hand, the method fell short in foreseeing that the defined form of well-to-well 'connectivity index' may only be applicable for a certain set of data. The form of the connectivity index used for the Palinpinon-1 data did not work as well for the MGPF or Palinpinon-2 data. This would imply that different data may require a different equation to define the connection indices. In addition, actual tracer testing should be done to calibrate the results generated by the ACE method. Upon calibration, this equation could then be used in predicting long-term fluid movement within the reservoir, perhaps without further tracer testing.

CONCLUSION

The ACE nonparametric method shows promise to make a good estimate of well-to-well connectivity. This has been verified by its successful application at Palinpinon-1 field. However application to MGPF and Palinpinon-2 field data showed less success. The inference from this lack of success is that the form of the connection index should be defined for a specific data set.

The approach would need to be calibrated with actual tracer test results before application to the development of a long-term injection strategy.

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