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Analytical and Statistical Interwell Connectivity Analysis in Tight and Complex Reservoir

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Abstract
One of the most important parameters governing waterflood performance is connectivity between producer(s) and injector(s). Several methods have been established to infer interwell connectivity but as all methods have their own limitations, the best practice is always to perform an integrated analysis by applying several methods and comparing their results. This is especially important for tight and complex reservoirs like the TK reservoir highlighted in this study. The methodology implemented in this study was organized into four parts. First, the reservoir of interest was segmented into two and five regions by considering their statics and dynamics characteristics. Next, statistical method with Spearman's correlation was applied to determine the connection between injection and production in each region. Subsequently, streamline simulations were performed to obtain a quick determination of producer/injector connectivity in each region. After inferring the connectivity between producer(s) and injector(s), their actual interactions were validated using production/injection analysis. The input data needed are production/injection data as well as simple geological characteristics. The workflow was performed successfully. Spearman correlation with a time gap quantified the degree of interaction between production and injection both for the entire reservoir as well as for each region. The streamline simulation enabled quick production/injection correlation between several producers and injectors at once. Results from these tools were then compared to results obtained from well-by-well production/injection analysis. Good agreement between the three methods were obtained thereby increasing confidence regarding the reservoir heterogeneity and interwell communication. This methodology provides rapid and easy techniques to obtain a more reliable reservoir heterogeneity characterization and quick identification of interwell connectivity which will be very important input for reservoir management and waterflood optimization. The proposed workflow can be deployed to other complex reservoirs.

Introduction
Interwell connectivity analysis, both qualitatively and quantitatively, is a very important aspect of waterflood evaluation to characterize reservoir heterogeneity and understand how and which injector(s) influence the producer(s), and with that knowledge, formulate the strategy to improve waterflood efficiency. Waterflood optimization strategies here can include water shutoffs, either at producer or injector side, gross production rates adjustments, and/or injection rates optimization.

There are numerous techniques for analyzing interwell connectivity. Conventional methods include interference test, tracer injection, and finite-difference reservoir simulation. Both interference test and tracer test can accurately capture connectivity between producers and injectors. Interference test, however, requires long-term well shut-in which will affect normal field production, whereas tracer injection project is considered expensive and challenging in its execution. The finite-difference reservoir simulation can quantitatively evaluate interwell communication and its dynamic nature, but it is time intensive, tedious, and less reliable for heterogeneous reservoirs.

Due to the disadvantages of these traditional methods, more and more novel techniques are developed to provide quick interpretations of interwell connectivity with only a small amount of data, and for some methods, only production and injection data which is normally available. Refunjol (1996) and Heffer et al. (1997) performed Spearman's rank correlation to quantitatively assess the communication of injector-producer pairs and preferential flow across a reservoir. Soeriawinata and Kelkar (1999) also leveraged Spearman's approach to analyze interwell connectivity, and proposed the constructive and destructive interference of the injected signals using superposition technique. Another statistical method besides Spearman's correlation is Pearson's correlation. Tian and Horne (2016) developed a modified Pearson's correlation coefficient (MPCC) to quantify interwell connection. Albertoni and Lake (2003) performed multivariate analysis to infer interaction between injectors and producers only from the well-rate fluctuations. Yousef et al. (2005, 2006) developed Capacitance-Resistance Model (CRM) which incorporated both flow rate and bottomhole pressure data to provide a more robust evaluation of the correlations between injectors and producers. This method becomes growingly popular and is currently one of the go-to methods for interwell connectivity interpretation. Many researchers modified the CRM to further improve the applicability of this method (Sayarpour, et al., 2009; Nguyen, et al., 2011; Prakasa, et al., 2017; Holanda, et al., 2018). The latest methods developed to interpret interwell communication are machine learning-based (Demiryurek, 2008; Liu, 2019; Ujjwal, 2019).

Despite the advantages to its powerfulness and growing popularity, machine learning is not perfect. Machine learning still has a lot of drawbacks one of which is the need of massive data sets to train on, and these data should be inclusive or unbiased, and of good quality. Machine learning requires enough time to allow the algorithms learn and develop enough to fulfill their objectives with a considerable amount of accuracy and relevancy. This method is also highly susceptible to error, and last but not least, it still has few success stories of applications.

Field Overview
The reservoir of interest in this study is the TK, which is currently operated by PT. Medco E&P Indonesia. This reservoir is located onshore Sumatra, approximately 70 km northwest of Palembang City. TK reservoir can be described as a saturated, low permeability, shaly sandstone reservoir with high heterogeneity. Table 1 summarizes the key properties of this reservoir. Due to the relatively low reservoir permeability, all TLS wells are hydraulically fractured to enable production. After fast production build-

up in the early stage of the production, the reservoir pressure dropped significantly.

Table 1. TK reservoir properties summary

Parameters	Value
Lithology	Sandstone
Depth (ft-TVD)	2,000 – 3,000
Initial Pressure (psia)	1,230
Current Pressure (psia)	500 – 1,230
Initial Temperature (°F)	175
Porosity (%)	10 – 20
Permeability (mD)	5 – 50
Average Net Pay (ft)	29
Initial Water Saturation (%)	40 – 65
Drive Mechanism	Solution-gas Drive
Production Commencement	Year 2002
Injection Commencement	Year 2009

Considering the weak pressure support from the natural solution-gas drive mechanism, water injection was then established to provide pressure maintenance. However, water injection in TK reservoir is challenging due to the following reasons:

1. low permeability,
2. high reservoir permeability (laterally and vertically),
3. high initial water saturation, and
4. complicated subsurface flow paths due to numerous fractures as the results of hydraulic fracturing in most wells (70+ wells).

Water injection surveillance and performance monitoring is therefore of paramount significance to characterize, manage, and optimize the water injection operation. The surveillance best practice applied in TK reservoir has been reported by Arnold and Asrul (2020). One critical aspect that governs the performance of water injection is interwell connectivity, which is the core subject of this study.

This paper summarizes the interwell connectivity analysis techniques implemented to characterize TK reservoir heterogeneity and determine the connection between injectors and producers. The methodology includes three methods, namely Spearman's rank correlation as the statistical approach, 2D streamline simulation as the semi-analytical approach, and actual production-injection analysis as the observational approach.

Data and Method

Reservoir Segmentation

Prior to evaluating waterflood performance in a heterogeneous reservoir, it is advisable to divide the reservoir into several segments or regions. Reservoir segmentation is important to make the analysis more detailed, accurate, and representative by honoring the reservoir heterogeneity, both laterally and vertically. The segmentation can be done by simple geographic delineation, for example by grouping the regions into: north, south, east, and west. The best practice, however, is to always consider the statics and dynamics characteristics of the reservoir.

Spearman's Rank Correlation

The first interwell connectivity analysis performed in this study is Spearman's correlation. This method is a non-parametric statistical approach that does not require assumptions about the distribution shape of the data (Alabri, 2020). Non-parametric method was applied in this study due to the fluctuative nature of the production and injection rates that make the data to be of unknown distribution. In this method, ordinal data is used, which means the orders or ranks of the data are used rather than the actual values.

Mathematically, Spearman's rank correlation can be expressed as (Hollander, 2013):

$$r_s = 1 - \frac{6\sum_{i=1}^{n} D_i^2}{n(n^2-1)}$$

$$D_i = rank(X_i) - rank(Y_i)$$

where

r_s = Spearman's rank correlation coefficient
Di = difference between the two ranks (*i.e. X* and *Y*) of each observation
n = number of observations.

The correlation degree between X_i and Y_i can be used according to the standards of r_s shown in Table 2.

Table 2. Spearman's correlation coefficient and degree

Correlation Coefficients	Correlation Degree
$r_s = 0$	no correlation
$0 < \lvert r_s \rvert \leq 0.19$	very weak
$0.20 \leq \lvert r_s \rvert \leq 0.39$	weak
$0.40 \leq \lvert r_s \rvert \leq 0.59$	moderate
$0.60 \leq \lvert r_s \rvert \leq 0.79$	strong
$0.80 \leq \lvert r_s \rvert \leq 1.00$	very strong
1.00	monotonic correlation

The advantages of Spearman's analysis are that it only requires production and injection rates data that are readily available and that, as a statistical tool, it encompasses a massive amount of data and it is not idealistic. It accounts for all the fluctuation of flow rates in one single number which indicates the strength of the well pair connectivity. The weakness of this method, however, is that it does not honor geology and other physical attributes.

2D Streamline Simulation

To validate the results from Spearman's method, we need to compare it with streamline simulation. 2D streamline technique using MBAL software was leveraged in this study. This approach provides a quick and relatively simple method of determining the sweep efficiencies and the interwell connectivity without the need to build complex 3D numerical simulation models.

The simulator models a rectangular reservoir with a combination of no-flow and/or constant pressure boundaries. It assumes that the PVT is constant and the calculated streamlines do not change position with time. The working principles of this method are as follows:

1. the simulator generates image wells to model reservoir boundaries (no flow or constant pressure),
2. calculates the velocity field by time simulation,
3. the resulting streamlines then progress from the injector(s) to the producer(s) over time thereby developing connectivity between the well pairs,
4. once a streamline reaches a producer the water cut will increase, and the more streamlines reaching the producers, the higher the water cuts will become, and
5. track the progression of water along the stream tubes with time.

This method requires the following data:

- well locations,
- reservoir boundaries (no flow or constant pressure),
- well injection and production volumes,
- fluid properties, and
- simple reservoir geological description.

It is worth noting that both Spearman's analysis and streamline simulation are best applied when producers and injectors are kept in constant rate.

Production/Injection Analysis

Production/injection analysis is a traditional approach to infer interwell connectivity. Connectivity between producer(s) and injector(s) is interpreted qualitatively by focusing on the production and injection profiles of the well pairs under investigation. If injection rate increase from a particular injector is followed by liquid production increase from the studied producer(s), then the injector is considered connected to the producer(s) constructively. If changes in injection rates do not change the production rate, even in the slightest, then it will be inferred that the injector is not connected with the producer(s).

Result and Discussion

Reservoir Segmentation

Considering the reservoir heterogeneity, reservoir segmentation strategy is implemented. The reservoir is segmented into two and five regions based on: (1) reservoir characteristics, (2) reservoir pressure, (3) well performance, and (4) well population. In this study, the reservoir is grouped into two regions for Spearman's method and five regions for streamline analysis. Figure 1 and 2 show the areal segmentation of the reservoir for two regions and five regions, respectively.

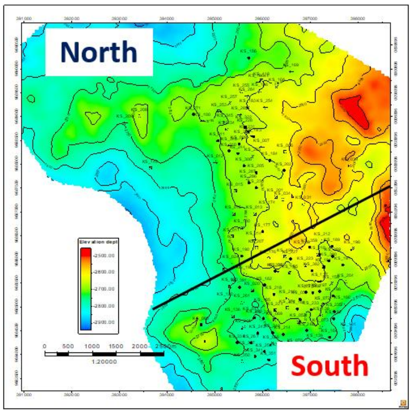

Figure 1: Reservoir north-south segmentation for Spearman's analysis

Spearman's Correlation

Spearman's correlation was performed at both field and regional level. The correlation coefficients were calculated based on the entire injection period of about twelve years. Considering the time required for the injected water to sweep and pressurize the reservoir and ultimately affect the production, time lag was invoked in the calculation process. The results of the field-scale Spearman's analysis is shown in Table 3.

Table 3. Spearman's coefficients for field-scale analysis with time lag invoked

Time Lag (months)	Spearman's Coefficient
0	0.690
1	0.721
2	0.710
3	0.690
4	0.669
6	0.682

From Table 3, two key points can be concluded. Firstly, Spearman's value of approximately 0.70 for all the time lags invoked indicated that the production responded positively and strongly to the injection. It means that, although well-by-well analysis has not been performed, we can safely conclude that there was strong connectivity between the injectors and the producers. The second important observation is that time lag of one month results in the highest Spearman's coefficient which means that it took one month for the injection to finally influence the production strongly.

It is important to note that field-scale analysis results should be refined with regional-scale or pattern-scale analysis. This method therefore was also applied at regional level. The results from the north and south regions are tabulated in Table 4.

Table 4. Spearman's coefficients for regional-level analysis with time lag invoked

Time Lag (month)	Spearman's Value (North)	Spearman's Value (South)
0	0.149	0.676
1	0.145	0.704
2	0.147	0.721
3	0.128	0.730
4	0.117	0.738
5	0.127	0.730
6	0.137	0.755
7	0.148	0.747
8	0.084	0.739
9	0.059	0.717

The results presented in Table 4 show that the performance of northern region differed significantly from that of the southern region. Southern region exhibited a strong, positive relationship between the injection and the production. The time lag required to achieve the highest Spearman's value for the southern region is six months. On the other hand, northern region showed very weak, positive correlation between the injection and the production with no time lag giving the highest Spearman's value. The weak Spearman's correlation at the northern region was predictable due to the following reasons:

- northern region was significantly more depleted than then southern region which necessitated a significantly longer fill-up period for the northern region,
- injection at the northern region was 15 months late from the injection at the southern region,
- injection at the northern region was four times lower than that of the southern region making the sweeping and pressurization less effective, and
- northern region has a large gas cap and area with low permeability which complicated the injection streamline.

Spearman's correlation can also be applied for oil production rate but considering the declining nature of oil flow rate, even at constant injection rate, this analysis was not performed.

Besides quantifying the injection/production connectivity, Spearman's analysis reaffirmed the importance of segmentation in this heterogeneous reservoir. Clearly, field-scale analysis alone was not sufficient to fully describe the reservoir performance and characteristics; regional and pattern-level analysis are required. Also, the northern regions should be further divided into smaller segments to obtain a more robust Spearman's analysis.

2D Streamline Simulation

2D streamline simulation was performed to infer interwell communication after it had been indicated from the Spearman's correlation that the field injection influenced the field production strongly and positively. Streamline analysis was done with 5-regions scheme (A, B, C, D, and E), rather than 2-regions as in Spearman's analysis, to obtain a more accurate evaluation. The streamline results for the whole reservoir and for Region C are depicted in Figure 2 and 3, respectively.

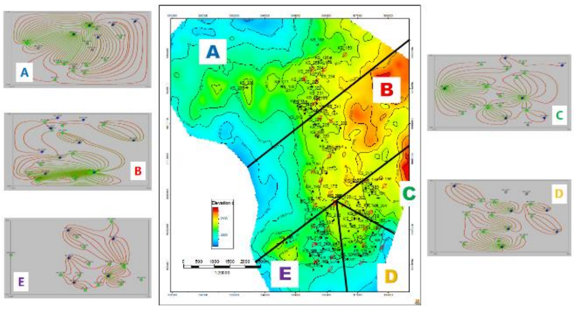

Figure 2: Reservoir segmentation for 2D streamline simulation

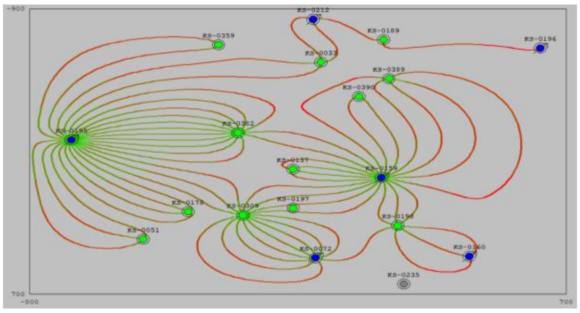

Figure 3: 2D streamline simulation results for Region C

Streamline analysis provides a quick interwell connectivity interpretation but it is important to note that this method takes only a snapshot of the entire production-injection history and uses that for analysis. Due to this limitation, at the time of this writing, this method was applied for semi-qualitative purpose to interpret interwell interaction, rather than deeply quantitative.

Production-Injection Analysis

To validate the results of the Spearman's correlation and the streamline simulation, actual well-to-well production-injection (P/I) analysis was performed. The P/I analysis validated the other methods as illustrated in Figure 4 and 5.

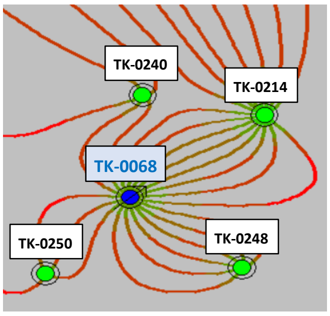

Figure 4: Streamline simulation results showing interwell connectivity between the injector TK-0068 and the four adjacent producers

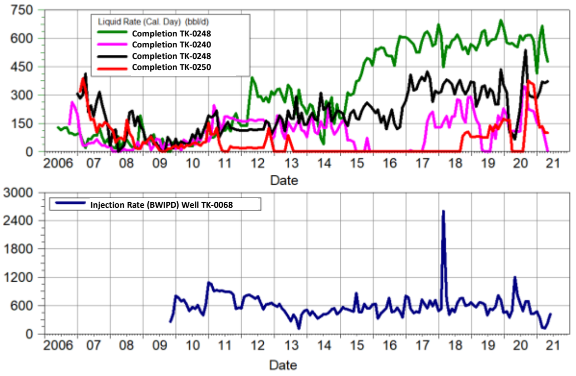

Figure 5: Production-injection profiles indicating strong influence of TK-0068 injection to the production of the adjacent producers

TK-0068 is an injector located at the center of the five-spot pattern with the other four producers, namely TK-0214, TK-0240, TK-0248, and TK-0250. Streamline analysis indicated the communication between the injector with the adjacent producers and this is confirmed by P/I analysis. All the surrounding producers were producing prior to the start of TK-0068 injection. Due to the lack of pressure support, the production of these four producers dropped significantly in 2009. However, after TK-0068 was put to injection, it can be clearly seen that production decline of the four producers were arrested and even reversed. The sweeping effect and pressurization provided by TK-0068 was effectively received by TK-0214 and TK-0248 enabling the two producers to increase production by ESP operation without significant production declines. Unfortunately, TK-0240 and TK-0250 should be produced only intermittently due to high water cut. This high water cut was in part caused by water injection from TK-0068. From this investigation, it can be concluded that water injection can constructively support the production through efficient sweep and pressurization, as in the case of TK-0214 and TK-0248, but it can also destructively impact the production through water breakthrough and/or water channeling, as in the case of TK-0240 and TK-0250. This further emphasizes the importance of interconnectivity analysis as it can be the main input for water injection optimization so that the positive impact of injection can be exploited while avoiding the negative effect of it.

Future Work

Interwell connectivity analysis performed in the TK reservoir is not perfect as it is still on the early stage of maturity. The nearest future works are to conduct the following analyses to enrich and validate the current interpretation of interwell communication:

- reservoir segmentation at a smaller scale,
- 3D streamline simulation,
- 3D reservoir (finite difference simulation),
- capacitance-resistance model (CRM),
- interwell Spearman's correlation, and
- water injection optimization.

Conclusions

In this work, we performed interwell connectivity analysis using production and injection data. The reservoir segmentation is important to make the analysis focused, detailed, and more accurate considering the high heterogeneity of the reservoir under study. Spearman's correlation with a time gap quantified the degree of communication between production and injection rates both for the entire reservoir as well as for each region. This analysis captured a strong correlation between the field-wide injection and production. At regional level, it is shown that the injection influenced the production strongly and positively in the southern region, while injection's effect on production in the northern region was weak. The 2D streamline simulation enabled a quick semi-qualitative assessment of the interwell connectivity between producers and injectors. Results from the two methods were then validated by well-by-well production/injection analysis. Good agreement between the three methods were obtained thereby increasing certainty regarding reservoir heterogeneity and interwell interactions. This methodology provides rapid and easy techniques to obtain a more reliable reservoir heterogeneity characterization and quick identification of interwell connectivity which will be very important inputs for reservoir management and water injection optimization.

References

Refunjol, B. T. (1996). Reservoir characterization of North Buck Draw field based on tracer response and production/injection analysis (Doctoral dissertation).

Heffer, K.J., Fox, R.J., McGill, C.A., and N.C. Koutsabeloulis. "Novel Techniques Show Links between Reservoir Flow Directionality, Earth Stress, Fault Structure and Geomechanical Changes in Mature Waterfloods." SPE J. 2 (1997): 91–98.

Soeriawinata, T., and M. Kelkar. "Reservoir Management Using Production Data." Paper presented at the SPE Mid-Continent Operations Symposium, Oklahoma City, Oklahoma, March 1999.

Tian, Chuan , and Roland N. Horne. "Inferring Interwell Connectivity Using Production Data." Paper presented at the SPE Annual Technical Conference and Exhibition, Dubai, UAE, September 2016.

Albertoni, Alejandro, and Larry W. Lake. "Inferring Interwell Connectivity Only From Well-Rate Fluctuations in Waterfloods." SPE Res Eval & Eng 6 (2003): 6–16.

Yousef, Ali A., Gentil, Pablo H., Jensen, Jerry L., and Larry W. Lake. "A Capacitance Model To Infer Interwell Connectivity From Production and Injection Rate Fluctuations." SPE Res Eval & Eng 9 (2006): 630–646.

Yousef, Ali A., Lake, Larry Wayne, and Jerry L. Jensen. "Analysis and Interpretation of Interwell Connectivity From Production and Injection Rate Fluctuations Using a Capacitance Model." Paper presented at the SPE/DOE Symposium on Improved Oil Recovery, Tulsa, Oklahoma, USA, April 2006.

Arnold, R. and Asrul, F. 2020. Waterflood Surveillance Best Practice in a Tight, Heterogeneous, Water-Sensitive, and Massively Fractured Reservoir. Paper IATMI20-87. Presented at IATMI Simposium 2020, 24 – 25 October 2020

Alabri, S., Ghafram, H., & AlKalbani, M. (2020, November). A Method to Correlate Interactions Between Injectors and Producers. In Abu Dhabi

International Petroleum Exhibition & Conference. OnePetro.

Hollander, M., Wolfe, D. A., & Chicken, E. (2013). Nonparametric statistical methods (Vol. 751). John Wiley & Sons.

Sayarpour, M., Zuluaga, E., Kabir, C. S., Lake, L. W., 2009. The use of capacitance–resistance models for rapid estimation of water flood performance and optimization. Journal of Petroleum Science and Engineering, 69(3-4), 227-238.

Nguyen, Anh P., Kim, Jong S., Lake, Larry W., Edgar, Thomas F., and Byron Haynes. "Integrated Capacitance Resistive Model for Reservoir Characterization in Primary and Secondary Recovery." Paper presented at the SPE Annual Technical Conference and Exhibition, Denver, Colorado, USA, October 2011.

Prakasa, Bona , Shi, Xiang , Muradov, Khafiz , and David Davies. "Novel Application of Capacitance-Resistance Model for Reservoir Characterisation and Zonal, Intelligent Well Control." Paper presented at the SPE/IATMI Asia Pacific Oil & Gas Conference and Exhibition, Jakarta, Indonesia, October 2017.

Holanda, R. W. D., Gildin, E., Jensen, J. L., Lake, L. W., & Kabir, C. S. (2018). A state-of-the-art literature review on capacitance resistance models for reservoir characterization and performance forecasting. Energies, 11(12), 3368.

Demiryurek, Ugur, Banaei-Kashani, Farnoush, Shahabi, Cyrus, and Frank G. Wilkinson. "Neural-Network based Sensitivity Analysis for Injector-Producer Relationship Identification." Paper presented at the Intelligent Energy Conference and Exhibition, Amsterdam, The Netherlands, February 2008.

Ujjwal, Manu , Tummala, Pradeep , Kumar, Viren , Singhal, Manu , and Andrew James. "Rapid Insights into Waterflood Management Using Advanced Analytics and Machine Learning." Paper presented at the SPE/IATMI Asia Pacific Oil & Gas Conference and Exhibition, Bali, Indonesia, October 2019.

Liu, Wei, Liu, Wei David, and Jianwei Gu. "Reservoir Inter-Well Connectivity Analysis Based on a Data Driven Method." Paper presented at the Abu Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, UAE, November 2019.

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