Analytical Methods for Establishing Interwell Connectivity in a North Sea Field

By

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A report submitted in partial fulfilment of the requirements for the MSc and/or the DIC

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DECLARATION OF OWN WORK

I declare that this thesis

*Analytical Methods for Establishing Interwell Connectivity in a North Sea Field*

is entirely my own work and that where any material could be construed as the work of others, it is fully cited and referenced, and/or with appropriate acknowledgement given.

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ABSTRACT

This study evaluates several techniques for establishing and quantifying interwell connectivity from production historical data, without requiring any disruption in field operations. The field studied has permanent downhole gauges and flow meters available for 35 wells. The 3.5 years of production history is rich in interference information, because the current stage of the development of the field implies constantly changing well alignments and production optimisation operations, to keep production in plateau.

Production data is, in general, not suitable for interference and pulse test analysis, because the requirements on duration of the flow periods, sharp rate changes, cycling and constant rates are not honoured throughout most of the production history. This is mainly because well management operations are done to maximise production, and are not intended for reservoir characterisation.

This study uses two different methodologies for characterising connectivity from production data. The Capacitance-Resistive Model (Yousef et al. 2006; Sayarpour et al. 2009) was used to investigate longer time scale behaviour, occurring in days, and a Time Window Analysis technique was developed for short time scale behaviour, occurring in hours.

The long time scale method allowed establishing connectivity for a limited number of well pairs. The applicability and reliability of this technique was discussed for the reservoir in study, as this is the first time this model was used for a field in production plateau, with Darcy permeability, and under peripheral waterflooding.

This study focused mainly on the design and implementation of the short time scale approach. A data mining system was built to scan the production history of the field, for every well, to find time windows in which a region of the reservoir is in constant rate, stabilised flow, and one well changes rate. This enables capturing the interference effects generated following rate change events. Connectivity was quantified by cross-correlation between pressure time derivatives (Ramakrishnan and Raghuraman 2004). The results were processed using statistics, and used to compute interwell diffusivities. Finally, it was possible to map the history of the interwell diffusivity for several well pairs in the field.
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Abstract
This study evaluates several techniques for establishing and quantifying interwell connectivity from production historical data, without requiring any disruption in field operations. The field studied has permanent downhole gauges and flow meters available for 35 wells. The 3.5 years of production history is rich in interference information, because the current stage of the development of the field implies constantly changing well alignments and production optimisation operations, to keep production in plateau.

Production data is, in general, not suitable for interference and pulse test analysis, because the requirements on duration of the flow periods, sharp rate changes, cycling and constant rates are not honoured throughout most of the production history. This is mainly because well management operations are done to maximise production, and are not intended for reservoir characterisation.

This study uses two different methodologies for characterising connectivity from production data. The Capacitance-Resistive Model (Yousef et al. 2006; Sayarpour et al. 2009) was used to investigate longer time scale behaviour, occurring in days, and a Time Window Analysis technique was developed for short time scale behaviour, occurring in hours.

The long time scale method allowed establishing connectivity for a limited number of well pairs. The applicability and reliability of this technique was discussed for the reservoir in study, as this is the first time this model was used for a field in production plateau, with Darcy permeability, and under peripheral waterflooding.

This study focused mainly on the design and implementation of the short time scale approach. A data mining system was built to scan the production history of the field, for every well, to find time windows in which a region of the reservoir is in constant rate, stabilised flow, and one well changes rate. This enables capturing the interference effects generated following rate change events. Connectivity was quantified by cross-correlation between pressure time derivatives (Ramakrishnan and Raghuraman 2004). The results were processed using statistics, and used to compute interwell diffusivities. Finally, it was possible to map the history of the interwell diffusivity for several well pairs in the field.

Introduction
The main goal of this study is to present a tool for analysing the interference effects that occur in the reservoir every time a well rate is changed for operational purposes. It is possible to extract reservoir characterisation information from everyday production data, provided suitable time periods of surveillance data are found. The goal is to scan the production history, to find time windows where pressure transient analysis can be executed. The proposed technique relaxes the constraints of test duration, and reduces the necessary data for analysis. The reduced volume of inputs, and shorter time scale, imply a reduction of information that is obtainable. The reservoir parameters are obtained in a lumped form, as interwell diffusivity. It was found possible to reliably extract the interwell diffusivity from several well pairs, and establish its historical trends.

The reservoir comprises a large Upper Jurassic, deep marine, stacked turbidite system. The STOIIP is over 1 billion STB. Major W-E faults divide the reservoir in multiple panels. There is pressure communication across several zones and panels. Permeability is in the Darcy range, in some zones reaching tens of Darcies. Average porosity is 25%.

The reservoir has no gas cap and the GOR is 220 scf/STB. Oil viscosity is 1.19cP. Well test analysis has shown that the effect of wellbore storage lasts for only seconds for the producer wells, in part due to the low solution gas. Production wells are commingled with different layers perforated. These are equipped with downhole pressure gauges and downhole multiphase flow meters. Injector wells have flow meters and tubing head gauges. The field is produced using peripheral waterflooding. Producer wells are all tied in directly to the platform. Injector wells are connected to the facilities using subsea tiebacks.

The field management is based on water and H2S handling constraints. There is a limit on export BS&W and H2S, so well line-ups are constantly changing to keep production levels at installed capacity, without exceeding export limits. Additionally, new wells are being drilled, further changing the reservoir drainage patterns. These dynamically changing reservoir conditions have impeded the execution of interference and pulse tests for reservoir characterisation.

The sections in this paper are organised as follows.
1. Field observations: A set of conclusions from field observations on well pressure behaviour are drawn, resulting in the selection of two different methodologies for establishing and quantifying connectivity for the field.
2. Analytical techniques followed: A short description is given about the application of a method to analyse long time scale reservoir behaviour, along with a discussion of results after implementation for the field in study. The technical basis of the second, shorter time scale approach is described later. The technique merges a data mining system, to find time windows of data, and a cross-correlation method, to enable quantification of reservoir properties. From this point onwards the focus of the paper is on the second approach.

3. Validation with synthetic data: The time window and cross-correlation methods are evaluated using simulation to analyse problems that are expected to occur when real field data is used, and find solutions for these.

4. Implementation to the actual field: The steps for the implementation of the integrated system for the field are explained. The effects that the facilities and well management strategies produce on the dataset are also evaluated.

5. Results: The system was field tested successfully. Two examples are shown, explaining how the interwell diffusivity history was extracted.

Field observations

The characteristics of the field imply that pressure responses are transmitted quickly, and pressure trends are identifiable. The example in Fig. 1a shows a well pair that exhibits high connectivity. P10 has constant rate and P12 has changing rate. One buildup and two drawdown periods are identified in well P12 pressure signal. P10 responds to the perturbations by showing a deflection in its drawdown pressure trend.

It is interesting to see that if the time derivatives of the pressures are computed, as shown in Fig. 1b, the signature of interference becomes a series of characteristic spike and hump pairs. The humps correspond to an impulse response function, as described by Johnson et al. (1966). More on this is explained later in the paper. For this field, when the flow is stabilised, the time derivatives fluctuate around +50 psi, so it was thought easier to examine interference effects by plotting pressure time derivatives within this range, as opposed to plotting pressures in plots with multiple axis, converting to datum, etc. This study uses the derivatives to extract reservoir properties. Analysis with pressures also works, but was not covered in the study.

![Fig. 1- Wells P10 and P12 interference (a) Bottomhole pressure (b) Bottomhole pressure time derivative](image)

It was found that a good quality assurance on the connectivity established by examining pressure time derivatives can be done, by looking for repeatability in the interference signatures. This is illustrated in Fig. 2. The conditions to follow for validation are:

- Well A rate change produces a spike in the pressure derivative of Well A, and a hump in Well B.
- The hump in Well B has a characteristic time lag signature that is repeatable.
- The amplitude of the hump is variable, and related to the magnitude of the rate change.
- If Well A vs. Well B is showing the spike/hump pattern, Well B vs. Well A must show the same behaviour.

![Fig. 2- Schematic of interference effects between two wells](image)

For the particular field analysed, these interference patterns are clearly visible for several well pairs, but for others, the magnitude of the humps is too low to reliably establish connectivity. This may be because wells are not connected, the signal
is dampened when travelling long distances, barriers to flow, among other reasons. This rationale led to the application of two different approaches for quantifying connectivity:

- **Long time scale**: Establish and quantify connectivity between wells that are receiving pressure support, but do not clearly show from PDG data which injectors are connected with them. The Capacitance-Resistive Model (Yousef et al. 2006; Sayarpour et al. 2009) is designed for injector-producer pairs, and is based on material balance, so it appears suitable for these cases. One time period was selected for analysis, and the results are discussed.

- **Short time scale**: Extract the time lags observed on the pressure derivatives, to calculate reservoir parameters, and their variations throughout the production history. A system was implemented to scan the production history and find time windows where pressure trends are stable enough so that interference effects are identifiable. The lags were retrieved via cross-correlation (Ramakrishnan and Raghuraman 2004), and used to estimate interwell diffusivity.

**Analytical techniques followed**

**Long time scale approach**

**Description.** The Capacitance-Resistive Model (CRM) is based on performing a material balance over a control volume within the reservoir. This control volume can be the entire reservoir, an injector-producer volume, or a producer drainage volume. The technique was developed for quantifying injector-producer connectivity, and has been field-tested on several pattern water flood reservoirs with vertical wells. The time scale of the analyzed data is large, and calculations are based on rate and pressure histories. For a control volume, the diffusivity equation can be presented as (Yousef et al. 2006):

\[
c_i V_p \frac{dP}{dt} = i(t) - q(t)\]

(1)

Where \( c_i \) is the total compressibility, \( V_p \) is the drainage pore volume, \( P \) is the average pressure within the pore volume, \( i(t) \) is the injection rate, and \( q(t) \) the production rate. Generalising for a field with several producer and injector wells, the differential equation can be solved with superposition in time, as follows (Sayarpour et al. 2009):

\[
q_j(t_k) = q_j(t_{k-1})e^{-\frac{\Delta t}{\tau_j}} + (1-e^{-\frac{\Delta t}{\tau_j}}) \sum_{i=1}^{N_w}[f_{iq_j}^{(k)}] - J_j \tau_j \frac{\Delta p_{iw_{fj}}^{(k)}}{\Delta t}\]

(2)

\[
\tau_j = \left( \frac{c_i V_p}{J_j} \right)\]

(3)

Where \( f_{ij} \) is the fraction of the injected volume from injector \( i \) that is directed to producer \( j \), \( I_i^{(k)} \) is the \( k \)th interval injection rate for injector \( i \), \( \Delta p_{iw_{fj}}^{(k)} \) is the variation in the bottomhole pressure of the producer \( j \) in the \( k \)th interval, \( J_j \) is the productivity index of the producer \( j \), and \( \tau_j \) is a time constant for the producer \( j \) drainage volume. These results are applicable to a time period when the following assumptions are honoured (Yousef et al. 2006):

- Little variation in flow streamlines: The streamlines of the liquid flow within the reservoir should exhibit low variations, i.e., no new producers added, and no extended shut in periods. Injector-producer connectivity factors obtained through CRM can be considered a time average of well allocation factors (WAFs) obtained via streamline-based simulations (Izgic et al. 2009; Thiele and Batycky 2006).

- No well stimulation/workovers: These would change the inflow performance curves of the producers, which are assumed constant by this method.

- Low fluid compressibility.

The reservoir in this study meets the requirements for the application of the method. The parameters \( q_j(t_k), f_{ij}, \tau_j \), and \( J_j \) are found by minimising the sum of squared differences between the measured values of producer well liquid rates, and those estimated from equation 2. For this approach, the total number of variables to regress would be \( N_{prod} \times (N_{waf} + 2) \). The best regression has to follow the following constraints (Sayarpour et al. 2009):

- \( \sum_{i=1}^{N_w} f_{ij} \leq 1 \)

- All parameters are positive.

The stability of the results from the regression is affected by the degree of correlation between injection rates. This relates to the statistical phenomena of collinearity, where high correlation in a set of predictor variables in a multivariate regression model produces unstable estimation of the regression coefficients. If there are minor changes in the input data or in the model, the resulting coefficients may vary widely. Yousef et al. (2006) suggested using a statistical tool, the Variance Inflation Factor...
(VIF), as a measure of collinearity of the injection rates. The VIFs of each injection well regression coefficient, $f_{ij}$, are determined as the $i$th element in the diagonal of the inverse of the injection rate correlation matrix. For this study, a cutoff of VIF=10 was used for validation of the injection rate input.

The CRM assumes an immediate pressure response at the producer from an injection event (Sayarpoour et al. 2009). This may not be true for all injector-producer pairs from the field in this study, because the peripheral waterflood configuration implies the injector wells may be far from the producers. However, the permeability in this field is higher than those of previous studies, so the application of the method may return interesting results.

**Application.** Well P8 is known to be stratigraphically isolated from nearby producers. It is receiving pressure support from the Southern panel injection system, but it has not been possible to establish which injectors are supporting its pressure. A CRM analysis was applied to determine the injectors providing support.

The injection and production rate history for the Southern panel was examined, to find periods where the set of producers closer to the injectors are all producing; with a minimal amount of shut-ins. A high level of collinearity in injection rates was detected, because all injectors in the Southern panel are mainly controlled via subsea tie-backs, all at the same time. Individual injector well control is possible, but it is done with less frequency.

It was possible to extract a time period of 44 days that honours most of the constraints mentioned above. The regression was done using this period, with hourly sampled data. This provided enough resolution to capture all the relevant changes in flow patterns. Fig. 3a and Fig. 3b show the injection rates for all wells in the Southern panel during the time period analysed.

![Fig. 3- Injection rates on 44 day period. (a) Per injector (b) Total for Southern panel](image)

<table>
<thead>
<tr>
<th>Injector</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1B4L</td>
<td>30.64</td>
</tr>
<tr>
<td>S1B4U</td>
<td>30.87</td>
</tr>
<tr>
<td>S2</td>
<td>1.44</td>
</tr>
<tr>
<td>S3</td>
<td>2.05</td>
</tr>
<tr>
<td>S4</td>
<td>1.23</td>
</tr>
</tbody>
</table>

The VIFs for this group of wells is shown in **Table 1**. Wells S1B4L and S1B4U exhibit collinearity. It is known that these two wells are injecting in two large separate sand units, so the regression coefficients, $f_{ij}$, for well pairs that are less likely to be connected, such as P8 vs. S1B4U, were initially fixed as zero. The initial values for the rest of the $f_{ij}$ were determined by distance criteria, with higher values for closer wells. The initial values of productivity indexes, $J_{ij}$, were taken from available well test data. The time constants, $\tau_{ij}$, were set with initial values of 15 days.

The active wells for this panel during the period are P8, P2, P17, P10 and P12. Well P12 has an extended shut in of 12 days. This violates one of the constraints, but this time period still represents the best case for CRM analysis found for this field. Furthermore, well P12 is far away from injectors, which should reduce the distortion on the streamlines along the more close-by wells, such as P8.

The regression was performed using the MS Excel Solver, as it was shown in previous studies (Sayarpoour et al. 2009) that its algorithm is capable of performing the regression properly. Results are shown in **Table 2**. Regression indicates a strong connection of producer P8 with injector S1B4L. The productivity indexes for wells P8, P2 and P17 are close to the initial ones,
but for well P10 and P12 they are considerably below the expected ranges. This may be due to difficulties found by the regression algorithm to match the points of highly changing rates, soon after short well shut-ins.

The history match obtained using the regression parameters from Table 2 is depicted in Fig. 4. The quality of the match is compromised when there are many variations in BHP. Additionally, when rates are above or below the operating envelope of the flow meters, measurements are not reliable.

The matches in Fig. 4 are of good quality, but validation of the results is difficult. There are not enough valid time periods in the production history to verify the coefficients obtained. Further use of this method for the field was discarded, and the focus of the rest of the paper will be on the short time scale approach.

**Fig. 4- Capacitance-Resistive Model: History match**

**Short time scale approach**

**Description.** The derivation of the equations to characterise the pressure responses at observation wells, as presented by Ramakrishnan and Raghuraman (2004) is as follows:

Solve the diffusivity equation:

\[ \frac{\partial p}{\partial t} = \frac{k}{\phi \mu c_i} \frac{1}{r} \left[ \frac{\partial}{\partial r} \left( \frac{\partial p}{\partial r} \right) \right] \]

\[ \eta = \frac{k}{\phi \mu c_i} \]

Following these constraints:

- Line source well (no wellbore storage, no skin)
- Infinite reservoir
- Low compressibility

Using a volume impulse as boundary condition on a virgin reservoir:

\[ -2\pi h \frac{k}{\mu} \left( \frac{\partial p}{\partial r} \right) = Q \delta(t) \Rightarrow \Delta p_o(t) = \frac{Q \mu}{4zkh} \int \frac{1}{t} \left( -\frac{r_o^2}{4\eta} t \right) e^{-\frac{r_o^2}{4\eta t}} H(t) \]

Using a finite pulse as a boundary condition on a virgin reservoir:

\[ -2\pi h \frac{k}{\mu} \left( \frac{\partial p}{\partial r} \right) = \frac{Q}{\nu} \left[ H(t) - H(t - \nu) \right] \Rightarrow \Delta p_o(t) = \frac{Q \mu}{4zkh} \int \frac{1}{t} \left( -\frac{r_o^2}{4\eta} t \right) e^{-\frac{r_o^2}{4\eta t}} H(t) - \frac{Q \mu}{4zkh} \int \frac{1}{t - \nu} \left( -\frac{r_o^2}{4\eta (t - \nu)} \right) e^{-\frac{r_o^2}{4\eta (t - \nu)}} H(t - \nu) \]

The consequences of this are more clearly visible in Fig. 5(a) and Fig. 5(b). The derivative of the finite width pulse response tracks the shape of the impulse response, hence its maximum, corresponding to \( t = \frac{r_o^2}{4\eta} \), can be computed. This is true only...
if the pulse duration is long enough. The implications are that it is possible to estimate the interwell diffusivity by finding the time lags between a rate change in one well, and the peak in the derivative in another connected well. This discussion is present in Johnson et al. (1966) paper on pulse testing. In a producing field this gets complicated, as the bottomhole pressure measured in the wells is the result of superposition in time and space through the production history. Moreover, the finite resolution of the pressure gauges adds special requirements for the differentiation of the data. How these problems were addressed is explained in the next sections.

![Figure 5](image)

**Fig. 5** (a) Pulse width too short, and its derivative response (b) Pulse width of proper duration

The novelty introduced by Ramakrishnan et al. (2006) is the suggestion that a good approximation of the time lag (time to reach the peak of the derivative) can be reliably extracted from pressure trends by computing the cross correlation between the observation well and active well pressure derivatives, as specified in equation 9. This cross correlation can be calculated efficiently via Fast Fourier Transform, as shown in equation 10. The `xcorr` function in Matlab Signal Processing Toolbox was used for this purpose.

\[
C(\hat{p}_1, \hat{p}_2)(t) = \int_{-\infty}^{\infty} \hat{p}_1(t+\tau)\hat{p}_2(\tau)d\tau 
\]

(9)

\[
FFT\{C(\hat{p}_1, \hat{p}_2)(t)\} = (FFT\{\hat{p}_1(t)\})^* \cdot FFT\{\hat{p}_2(t)\} 
\]

(10)

* Complex conjugation

The conversion of the pressure correlation results to diffusivity are affected by:
- Wellbore Storage.
- Well Distance.
- Duration of step change in rate for the active well. See [Fig. 5a](image) and [Fig. 5b](image).

This can be circumvented as follows:

\[
t_{\text{real}} = \frac{\text{Corr}_{\text{distance}}}{\text{Corr}_{\text{wellboreStorage}}} \text{Corr}_{\text{interference}} 
\]

(11)

These correction factors have been computed for different well configurations (Ramakrishnan and Raghuraman 2004). For this field there are no correction factors for distance required. The time scale of wellbore storage effects was found to be small compared to the correlation time scale, so no wellbore storage correction factor was required either.

The present study applied the cross-correlation technique to a producing field for the first time. In order to define the proper pressure differentiation methodology, the effects of gauge resolution and pressure variability in a drawdown were analysed. From the analysis of correlation times, however, the effects from superposition in time were not clear. To address this, a simulated data set was built and correlation functions determined to identify the influence of the preceding well history on the output.

**Validation with synthetic data**

An analytical model was built for a well pair, to examine the process of extracting the time lags from interference effects in pressure data. The interferences were simulated using superposition in time with the exponential integral solution, as follows (Johnson et al. 1966):
\[
\Delta p = \frac{70.6B}{T} \sum_{i=1}^{n} (q_i - q_{i-1}) E_i \left( -\frac{948S_c^2}{T(t - \sum_{j=1}^{\infty} \Delta_t)} \right)
\]  \hspace{1cm} (12)

Where \( T = kh/\mu \) (transmissibility) and \( S = \phi k_h \) (storativity).

The well pressure response to a change in rates was modelled as a vertical well with wellbore storage and skin in an infinite acting reservoir. This model was superimposed with the interference response depicted above, by adding:

\[
\Delta p = -\frac{141.2B}{T} \sum_{i=1}^{n} (q_i - q_{i-1}) p_{D} [(t - \sum_{j=1}^{\infty} \Delta t)]
\]  \hspace{1cm} (13)

Where \( p_0 \) corresponds to the drawdown type curve for wellbore storage and skin (Agarwal et al. 1970).

Quartz gauge resolution is typically 0.02 psi, but the small natural fluctuations in rate under a stable drawdown amplify the variability in the PDG readings. Filtering is therefore necessary to compute pressure derivative and the cross-correlations. Gaussian noise with mean=0 psi and \( \sigma = 0.1 \) psi was added to the simulated pressure signals to model the PDG behaviour.

**Fig. 6b** shows the effect of the differentiation of the observer well pressure signal using simple central derivatives. A trend is hardly recognisable within the cloud of points. For this reason, an adaptive polynomial interpolation, ranging from order 1 to 2 was used for calculating the derivative. An algorithm called ELS (De Levie 2008), for Equidistant Least Squares, is based on fitting a polynomial through a moving window of data. The resulting trend using a 15 point moving window, with 5 minute sampling, yields the pink points, which match the actual derivative, in black.

For the active well pressure signal, it was found that the cross correlation is better when ELS with low smoothing is used, as this represents better the magnitudes and shapes of the derivative spikes when the pressure variation is large, and filters outliers that may produce fake spikes. The black line on **Fig. 6a** shows the derivative for an active well.

![Active Well Response](image1)

**Observation Well Response**

![Observation Well Response](image2)

**Fig. 6-** (a) Simulated response for active well (b) Effect of noise in pressure derivative for observer well.

A more complex rate history for both wells was simulated, to examine the shapes of the cross correlation function, and analyse the effects of noise and superposition. **Fig. 7a** and **Fig. 7b** illustrate a sample noiseless production history, where five time windows with interference effects exist. The time windows were extracted, defining well B as the active well for every window, except the fourth one, where well A is the active one.

![Rates vs. Pressures](image3)

**Rates vs. Pressures**

![Rates vs. Pressure Derivatives](image4)

**Fig. 7-** Simulated response for well pair. (a) Rates vs. Pressures (b) Rates vs. Pressure Derivatives
Noise was then added on the pressure signals. The active well pressure derivative was re-calculated with central differences, and the observer response was obtained using ELS order 1 to 2. Fig. 8a and Fig. 8b illustrates the effects of noise in the signal for 5 minute frequency data. The plot on the left uses a 61 point moving polynomial vs. 15 points on the right. It was found that the cross correlation function is sensitive to the noise, to a point in which the correlation peak is not clearly distinguishable for some time windows. Stable drawdown periods exhibit more variability than buildup periods, but are also much more frequent. The system developed is able to find patterns in both buildup and drawdown periods. This increased the chances of finding enough valid time windows to be able to establish a historical trend of time lags and reservoir properties.

![Fig. 8- Cross correlation results for Fig. 7. (a) Smooth derivative (b) Noisy derivative](image1)

The effects of superposition can be seen on Fig. 8a and Fig. 8b. Each one of the evaluated time periods has a different pressure derivative trend when interference effects occur. The cross-correlation is unable to extract the exact time lags from the humps formed over these trends, because they are not periodical events that the FFT can capture and separate. This is a deconvolution problem, which for this study has been circumvented by statistical analysis. Depending on the underlying pressure derivative trend, the time lag may be slightly shifted to the right, or to the left. The trend can be decreasing or increasing. It was found that if there are enough time lag samples, it should be possible to obtain the most likely value ranges by plotting results in a histogram. The shape of the histogram is affected by the well management in the field regarding sand, water and H2S control, well tests, workovers, and changes in reservoir properties.

**Implementation to the actual field**

**Data management**

Data from PI Osisoft® is available for all pressure gauges and flow meters. Compressed data archived in this system was retrieved with an equidistant 5 minute sampling rate. Periods of missing data, i.e., due to communications failure, were filled via linear interpolation, for pressure data, and fixed to last valid value, for rates. The effect of this interpolation in the pressure is that constant values can be seen when plotting the derivative in some time windows.

A relational database was designed to streamline the search for time window candidates for analysis. Fig. 9 shows the structure used to handle the project data. This structure allows adding validation variables, such as multipliers and cut-offs for tags, and differentiation variables for every well. It allows keeping track of any data manipulation performed.

![Fig. 9- Relational structure for data handling](image2)
The identification of time windows is a multi-step process. The first step was to define the set of periods with stabilised flow for every well. To accomplish this, the pressure history for each well, with hourly sampling, was differentiated via ELS, to reveal large spikes, corresponding to changes in rate. A moving band was fixed, to slice the history into several stable periods, as shown in Fig. 10. Pressures within the band imply stabilised flow in the producer/injector. These stable periods were stored in the tblWellStatus database table shown in Fig. 9.

The profiles in Fig. 2 where used to identify flow periods as drawdown or buildup. A minimum stable period duration threshold was set, to ensure there is enough data in every period to be useful for analysis. The resulting stable periods should exhibit pressure trends where interference effects are identifiable. Humps in the derivatives due to interference should be detectable, despite being superimposed on the pressure derivative trends.

The rationale behind this approach is to harness the capability of a relational database system for information lookup. Once the stable periods are defined, there is no need to read the entire history to search for a time window. It is only necessary to execute a procedure to define these. This was done as follows:

1. Define a cluster of wells close to well A that are suspected to be connected, as shown in Fig. 11b within a dotted line. In this example, the effect of well P12 over P10 can be evaluated.

2. Intersect the stable periods of the wells within the cluster, to find time windows where all wells are in constant rate; by following the process depicted in Fig. 11a.

The resulting time windows, where all wells in the cluster are in constant rate, are then intersected with the stable periods of a well chosen to be changing state. For the example in Fig. 11b, this would be well P12. Fig. 12 below shows the procedure followed to intersect these time windows.
Fig. 12- Time window intersection

This process was fully automated for the field, and it is possible to identify these periods for a specified stable well cluster vs. a changing well in a fraction of a second. The pressure data for these time windows is later retrieved and processed to extract derivative spike/hump pairs for computing cross-correlation. The process is explained in the next section. Fig. 13 shows a good time window found for the field. Analysing a single time window, however, is not enough for drawing any conclusion about connectivity. The suggested quality assurance may help, as it enables establishing connectivity in a qualitative fashion. The resulting time windows depend on how the well clusters are defined.

Fig. 13- Sample time window - drawdowns. Derivatives calculated using backward differences. (Peaks shifted to the right)

Operational considerations

The facilities have a single separator train. Changes in the separator parameters will have effects on every producer well at the same time. Any well group where all wells are opened or closed simultaneously will generate pressure transients in the reservoir that are hard to decouple. Field-wide and group-wide effects were circumvented in several cases by inputting prior knowledge of connectivity on the selection of the well clusters. The optimal inputs for the time window analysis comes from scheduled single well events, such as workovers, shut-ins, well tests, etc, as these events are independent from what occurs in neighbouring wells, and provide sharp rate changes that act as good inputs for the correlations.

Most of the inputs used come from production optimisation operations, such as choking some wells to keep the BSW or H2S below limits. Many of these events produce changes in rate that are not strong enough to generate detectable pressure transients in neighbouring wells. Furthermore, most of the changes in rate for wells are done gradually. This seriously affects the correlation output of the system, as the interference signals are dampened and deformed.

To address these issues, a filter on the shape of the derivative spikes was implemented. The peaks were considered valid for cross-correlation if their height is above a threshold value. Additionally, a fixed size for the spike/hump pair windows was defined, to ensure time is long enough for the maximum in the derivative responses to be reached. Fig. 14 shows one time window with several spikes and humps. Only three valid spike/hump pairs could be extracted from it.

The entire process up to this point requires the adjustment of several thresholds and parameters to filter the history and find relevant data for reservoir characterisation. Higher filtering ensures higher quality of the data, but reduces its quantity. This leads to a trial and error process till the optimal combination of parameters is found, and the data can be extracted. Reducing the filtering will introduce spurious results, that vary randomly, following a uniform distribution.
Definition of well clusters

Well clusters were defined and ranked for analysis, based on distances, operational considerations and prior qualitative understanding of geology and connectivity. More time windows can be extracted when the number of wells in a constant rate cluster is smaller, so it is important to keep the cluster size to a minimum.

Well perforations were classified by zones and panels, and the number of shared zones within the same panels for every well pair was determined. Wells that share more zones are more likely to be connected and show a pressure response. Especially those that are perforated in higher permeability units.

One example for definition of well clusters can be well P8 in Fig. 15. This well is known to be isolated from other producers, although it is receiving pressure support from the injectors. A good cluster for this well could be {P8,S4,S2}, if the connectivity of wells P8 vs. S1B4L is to be quantified.

Distance is the most important factor in the definition on well clusters. Interference effects from close by wells will have a higher amplitude than wells that are far away, if the diffusivities are similar.

<table>
<thead>
<tr>
<th>Producers</th>
<th>Injectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>S5</td>
<td>2 1 1 1 1</td>
</tr>
<tr>
<td>S4</td>
<td>2 2 1 1 1</td>
</tr>
<tr>
<td>S3</td>
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<tr>
<td>S2</td>
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<td>S1B4U</td>
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<td>2 2 1 1 1</td>
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<td>C4</td>
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<td>P11</td>
<td>1 1 1 1 1</td>
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Fig. 15- Selection of well clusters based on geology
Results

Producer/Producer case: Wells P10 & P2 connectivity

From the validation steps described before, if well A vs. well B shows connectivity, well B vs. well A should also show it. Therefore, the algorithm was run twice for each well pair.

Well P2 was defined to be the well changing rate, with well P10 being at constant rate. The constant rate cluster for well P10 was set as \{P10, P12, P22, P3\}. All the time windows in which all the wells listed have constant rate were found, and intersected with periods of rate changes in well P2. Once the spike/hump pairs were extracted, cross-correlation was computed, returning the 25+ curves shown in Fig. 16a. It is possible to see that most of the peaks are around 6 hours. This can be seen more clearly in the contour in Fig. 17a, which acts as a quick quality check on the results. A block of peaks around a specific time range indicates there is a high degree of connectivity. The same process was followed for well P10 as the well with changing rate. The constant rate cluster for well P2 was set as \{P2, P17, P12, P3\}. Results are shown in Fig. 16b and Fig. 17b. Both P10 vs. P2 and P2 vs. P10 show the same ranges of time lags. This means that the well clusters may have been selected correctly, the wells are connected, and the data is of good quality and has been processed properly.

![Fig. 16- Wells P10 & P2 correlation functions (a) P10 vs. P2 (b) P2 vs. P10](image1)

![Fig. 17- Wells P10 & P2 correlation contours (a) P10 vs. P2 (b) P2 vs. P10](image2)

To extract the time lag/diffusivity history, a histogram was plotted for all the time lag results, as shown in Fig. 18a. A Gaussian like distribution is visible, providing clues on the true ranges for the time lags. Fig. 18b shows a series of bad data peaks that may be caused by the reasons discussed in the previous sections. A cutoff of 10 hours was fixed for this well pair, after visual examination of individual cases confirmed the time windows above this threshold were invalid.

![Fig. 18- Wells P10 & P2 statistical analysis (a) Time lag histogram (b) Gross time lag history](image3)
The time windows were then converted into history by assigning the middle date between the start and end dates for every valid time window. Time lags were converted into diffusivity using $\eta = r_0^2 / 4t$. Results are shown in Fig. 19.

The diffusivity trend for this well pair is approximately constant. P2 has been cutting water for one year, while well P10 is not, however, there is not enough data to see the effects of this in the diffusivity though the last year. Due to the distance between wells and ranges of permeability for this field, well P10 should be cutting water as of now. It is possible that water is entering well P2 from one zone that is not shared with P10.

Injector/Producer case: Wells P1 & C2 connectivity
Interwell connectivity could also be quantified for injector/producer pairs. P1 is an observation well, so the analysis is done only for P1 vs. C2. The constant rate cluster for P1 was defined as $\{P1,P6,P5,C5,C1\}$. The time windows found were intersected with periods of rate changes in well C2, and further processed to extract the spike/hump pairs. Wells are relatively far apart, at a distance of 6800ft, so longer time lags are expected. A correlation window size of 30 hours was selected, to properly capture these times. Fig. 20a and Fig. 20b show a pattern in the correlation peaks for 40 spike/hump pairs found. Fig. 14 shows one of the time windows for this well pair that were used for extracting some of these results.

The histogram of time lags for this well pair, is shown in Fig. 21a. After visual examination of several invalid time windows in the peaks of Fig. 21b, it was found that good cut-offs for the distribution are between 12 and 24 hours. The resulting interwell diffusivity history for wells P1 & C2 is shown in Fig. 22.
The interwell diffusivity for well pair P1 & C2 is approximately 7.5 times larger than for well pair P10 & P2. The ranges are consistent with results from well test analysis. Permeability around P10 and P2 range around 1 – 1.5 Darcy, while P1 and C2 are both perforated in a 10 Darcy zone. This indicates that this high permeability zone is continuous in the reservoir around these wells.

**Conclusions**

The Capacitance-Resistive Model was found not to be applicable in the current stage of the field production, because of difficulties in finding time periods where all the constraints required are honoured. The results obtained for one period could not be validated. However, the method may be more useful at later stages, when well settings are changed less frequently.

Data mining on historical production data proved a useful technique to aid in reservoir characterisation. It was found possible to extract relevant well interference information and process it automatically to find historical trends in reservoir behaviour. The system developed is scalable and can be deployed quickly for other highly instrumented fields. A similar, more advanced windowing algorithm would add value if implemented in a reservoir surveillance software, as it can help the production engineers to optimise the operations, so that more valuable reservoir characterisation data becomes available, at no extra cost.

The time lags obtained from the spike/hump pairs are affected by the duration of the rate pulses, superposition, noise, and small changes in rate during drawdown. These problems were circumvented by setting a series of thresholds and smoothing parameters, that filtered the production history. Additionally, the histogram technique allowed a quick quality control on the results obtained, the removal of spurious data, and the visualization of the ranges of the time lags and interwell diffusivities throughout history.

**Recommendations for further study**

A study on how time lags and the diffusivity changes as the flood front moves between two wells would enable engineers to track the position of the water front within the reservoir using the methodology presented. A work similar to this, applied to pulse testing, was presented by Orangi and Ershaghi (2008).

The present study did not consider the interpretation of results for a layered reservoir with crossflow. How are the time lags affected by the presence of different layers with crossflow? A study on this, with validation through simulation may show interesting insights. The work of Uk Kim et al (2009) integrates pressure derivative analysis with reservoir simulation.

More advanced data manipulation techniques can be applied for the time window algorithm, to remove outliers from pressure responses, and better determine the time windows (Horne 2007). Time windows can be better defined with the application of wavelet theory (Athichanagorn 2002), because wavelets are ideal for locating breakpoints in pressure data, to find periods with stabilised flow. It also provides a more efficient data smoothing mechanism, such as the one implemented by Kappa (Houzé et al. 2008). Change Point Analysis (Taylor Enterprises 2010) may also work for this purpose, because it allows splitting the history into stable trends.

**Acknowledgements**

I would like to thank Nexen Petroleum Inc. for providing the opportunity to carry on this project, and the permission to publish results. I am grateful for the guidance given by my supervisors Jon Wardell (Nexen Inc.) and Prof. Alain Gringarten (Imperial College London). My appreciation also goes to Santander Bank, for providing me with a scholarship to pursue my MSc.
Nomenclature

Capacitance Resistive Model:

\[ f_j \] = Fraction of volume of water from one injector that goes to one producer

\[ J_j \] = Productivity index of producer

\[ \tau_i \] = Time constant of capacitance-resistive model

\[ f_i^{(k)} \] = Injection rate during time step k

\[ q_j \] = Producer rate

\[ \Delta p_{ij}^{(k)} \] = BHP variation during time step k

\[ N_{mi} \] = Number of injectors giving supporting a producer

\[ \Delta t_k \] = Time step for superposition in Capacitance Resistive model

\[ c_r \] = Total compressibility

\[ V_p \] = Drainage pore volume

\[ CRM \] = Capacitance-Resistive Model

Time windowing and correlation techniques:

\[ \eta \] = Diffusivity

\[ \delta(t) \] = Dirac delta: \[ \delta(t) = \left\{ \begin{array}{ll} +\infty, & t = 0 \\ 0, & t \neq 0 \end{array} \right. \]

\[ H(t) \] = Heaviside function: \[ H(t) = \left\{ \begin{array}{ll} 0, & t > 0 \\ 1, & t \geq 0 \end{array} \right. \]

\[ V \] = Pulse duration

\[ FFT \] = Fast Fourier Transform

References


### Appendix A: Literature Review

<table>
<thead>
<tr>
<th>SPE Paper n°</th>
<th>Year</th>
<th>Title</th>
<th>Authors</th>
<th>Contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1517</td>
<td>1966</td>
<td>Pulse-Testing: A New Method for Describing Reservoir Flow Properties Between Wells</td>
<td>C.R. Johnson R.A. Greenkorn E.G. Woods</td>
<td>Introduced the pulse testing technique for reservoir characterisation, a methodology that enables the extraction of interwell mobility and storativity by performing a series of controlled pulses in an active well, and measuring the pressure response in an observer well.</td>
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<tr>
<td>90910</td>
<td>2004</td>
<td>A Method for Continuous Interpretation of Permanent Monitoring Pressure Data</td>
<td>T.S. Ramakrishnan B. Raghuraman</td>
<td>Presented a new technique to extract the interwell diffusivity from pressure data, by computing cross correlation of the derivative of the pressures. Analyses the cross correlation technique for impulse responses and finite width pulse response and finds a series of correction factors for distance and wellbore storage.</td>
</tr>
<tr>
<td>95322</td>
<td>2006</td>
<td>A Capacitance Model to Infer Interwell Connectivity from Production- and Injection- Rate Fluctuations</td>
<td>A.A. Yousef P. Gentil J.L. Jensen L.W. Lake</td>
<td>Introduced the Capacitance-Resistive Model, a non-linear constrained multivariate regression, to establish injector-producer connectivity in a waterflooded reservoir.</td>
</tr>
<tr>
<td>114233</td>
<td>2008</td>
<td>Flood Front Tracking and Pulse Test Time Lags</td>
<td>A. Orangi I. Ershaghi</td>
<td>Presents an analytical study with synthetic data about the use of frequently gathered pulse test data for tracking the movement of the flood front within a waterflooded reservoir.</td>
</tr>
<tr>
<td>114983</td>
<td>2009</td>
<td>Field Applications of Capacitance-Resistive Models in Waterfloods</td>
<td>M. Sayarpour C.S. Kabir L.W. Lake</td>
<td>Expanded the Capacitance-Resistive method by presenting analytical solutions to all the differential equations used. Tested the model in several pattern waterflood fields, with good results overall.</td>
</tr>
<tr>
<td>121203</td>
<td>2009</td>
<td>Establishing Injector/Producer Connectivity Before Breakthrough During Fluid Injection</td>
<td>O. Izgec C.S. Kabir</td>
<td>First to discuss the applicability of the Capacitance Resistive Methods for estimating interwell connectivity before breakthrough. Established its use is valid for fields with zero or low water cut.</td>
</tr>
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**SPE 1517 (1966)**

Pulse-Testing: A New Method for Describing Reservoir Flow Properties Between Wells

**Authors:** Johnson, C.R., Greenkorn, R.A., Woods, E.G.

**Contribution the analysis of interwell connectivity from production data:**
High. This paper introduces the pulse testing technique. Several studies have been done on the potential application of frequent pulse testing data. Other studies have worked on different techniques using the same technical basis as pulse testing, such as the present work.

**Objective of the paper:**
Pulse testing is developed to determine interwell mobility and storativity by characterising the time lags and amplitudes of pressure responses from a series of rate pulses at an active well, under a fixed pulsation frequency.
Methodology used:
Pulse Testing

Conclusion reached:
1. By characterizing both the time lag, and the amplitude of the pressure responses, it is possible to get two reservoir parameters, mobility and storativity.
2. If only the time lag is characterized, it is possible to get one reservoir parameter, diffusivity.

Comments:
This paper presents part of the technical background used for the simulation of interference effects for the present project.

SPE 90910 (2004)
A Method for Continuous Interpretation of Permanent Monitoring Pressure Data
Authors: Ramakrishnan, T.S. and Raghuraman, B.

Contribution to the analysis of interwell connectivity from production data:
First paper to suggest the use of cross-correlation for analysis of pressure data. This technique allows easy extraction of time lags between a status change in an active well and the response in an observer well. It can be implemented easily in a data mining system to get reservoir properties with minimal number of assumptions or prior knowledge of the reservoir.

Objective of the paper:
To present a cross-correlation technique for analysis of pressure data. The paper proposes using this technique for extracting the time lag between a rate change in an active well, and the peak in the pressure derivative at an observer well. To achieve this, rate-pressure, pressure-pressure, and pressure derivative-pressure derivative cross correlations are suggested, and correction factors for distance and wellbore storage are presented.

Methodology used:
Pressure cross-correlation. The technical basis of the method is a comparison between finite pulse and impulse pressure responses. The technique is similar to pulse testing, but it uses the derivatives of the pressures instead.

Comments:
1. The paper focuses on the ability of the method to obtain permeability, even though the only reservoir property obtained through their technique is diffusivity.
2. No mention is done to the effects on the correlation due to superposition.
3. No mention on how time windows found.
4. Technique has the advantage of easy implementation, as there are several routines for cross correlation and FFT freely available.
5. No demonstration that the technique works reliably, as only one correlation example is shown for each well pair.

SPE 95322 (2006)
A Capacitance Model to Infer Interwell Connectivity from Production – and Injection-Rate Fluctuations
Authors: Yousef, A.A., Gentil, P., Jensen, J.L., Lake, L.W.

Contribution to the analysis of interwell connectivity from production data:
Proposes a new method for modelling interwell interactions that considers small compressibility effects within the reservoir. The method is based on performing material balance around several control volumes within the reservoir. It is a good candidate for long time scale interwell connectivity analysis, for fields undergoing pattern waterflooding.

Objective of the paper:
Introduce the basis and assumptions of the Capacitance-Resistive Model (CRM), and its mathematical derivation. Illustrate its applicability on real fields, and a discussion on the quality of the regression results.
Methodology used:
Capacitance–Resistive Model: Defines a control volume for each well pair, and formulates a differential equation based on material balance for it. The differential equation comprises several parameters, which can be calculated via constrained nonlinear multivariate optimisation. This method accounts for compressibility within the reservoir, and adds the producer BHP to the analysis.

Conclusion reached:
The interwell interactions can be modelled using the Capacitance-Resistive model for a real field. The differential equation parameters are used to describe the connectivity between the input signals from the injectors (rate) and the output signals at the producers (rate, BHP).

Comments:
1. Care must be taken, as there are many constraints and considerations for the application of the method. Its reliability depends on honouring all constraints.
2. Works over longer periods of data, weeks, months, and years.
3. Is very sensitive to collinearity on injection signals

SPE 114233 (2008)
Flood Front Tracking and Pulse Test Time Lags
Authors: Orangi, A., Ershaghi, I.

Contribution to the analysis of interwell connectivity from production data:
First study that correlates the movement of the flood front with the time lags estimated from pulse tests. Discovers that it is possible to track the position of the flood front from the history of the time lags.

Objective of the paper:
To study the relation between the movement of the flood front in a reservoir and the time lags from multiple rate pulses, that can be pre-scheduled or unsupervised. This study was done with synthetic data.

Methodology used:
Pulse Testing.

Conclusion reached:
It should be possible to track the position of the flood front from the history of the time lags.

Comments:

SPE 114983 (2009)
Field Applications of Capacitance-Resistive Models in Waterfloods
Authors: Sayarpour, M., Kabir, C.S., Lake, L.W.

Contribution to the analysis of interwell connectivity from production data:
Expanded the Capacitance-Resistive Model (CRM) by presenting analytical solutions to all the differential equations used. Tested the model in several real fields, with good results overall.

Objective of the paper:
Present the use of the CRMs to model the interwell connectivity for several real fields. Clearly presents the analytic solution for all the CRM differential equations, and outlines a procedure for their application.

Methodology used:
Capacitance-Resistive Model (See SPE 95322)
Conclusion reached:
Study shows that the calibrated CRMs are capable of modelling the reservoir and generate solutions comparable to those obtained from 3d numerical flow simulation, provided there are no extended shutins, workovers, etc, included in the analysis.

Comments:
1. The paper presents several field applications of the CRMs, and presents simpler formulas for its implementation.
2. Method has only been tested in pattern waterflood fields, with low to medium range permeability.
3. Little mention of effect of multiple wells with changes in BHP on the regression results.
4. Analytical solutions can be programmed quickly, but constrained nonlinear multivariate optimisation requires good initial iteration seed, to avoid finding multiple minima.

SPE 121203 (2009)

Establishing Injector/Producer Connectivity Before Breakthrough During Field Injection

Authors: Izgec, O., Kabir, C.S.

Contribution to the analysis of interwell connectivity from production data:
First study analysing the applicability of the Capacitance-Resistive Model (CRM) for a field before water breakthrough.

Objective of the paper:
Perform CRM analysis and compare with numerical simulation, to estimate sensitivities on reservoir parameters that change with the saturation. The sensitivities were applied to CRM model, and the technique was found robust also for reservoirs before water breakthrough.

Methodology used:
Capacitance-Resistive Model (See SPE 95322)

Conclusion reached:
The CRM is applicable to fields with zero or very low water cut

Comments:

SPE 124834 (2009)

Calibration of High-Resolution Reservoir Models Using Transient Pressure Data

Authors: Uk Kim, J., Datta-Gupta, A., Brouwer, R., Haynes Jr., B.

Contribution to the analysis of interwell connectivity from production data:
This paper presents an advanced technique to integrate the pressure derivative data into reservoir models, without the computational expense of performing sensitivity analysis on pressures using grid based simulators. The simulator is configured to solve the diffusivity equation with a high frequency asymptotic solution.

Objective of the paper:
To present a set of techniques for calibration of high resolution reservoir models by integrating them with production data. Through streamline-based and ray-based simulation, the permeability fields of the model can be modified, honouring the constraints imposed by geostatistics, to match the high frequency pressure responses. This is done by comparing the simulated pressure derivatives with the real pressure derivatives

Methodology used:
High frequency asymptotic solution of the diffusivity equation

Conclusion reached:
It is possible to enhance the quality of the reservoir models by integrating the simulation with the observed short time scale pressure responses in the reservoir.

Comments:
Appendix B: Other Results

Wells P2 & P17

Clusters: \{P2, P10, P12, P16\} vs. P17 and \{P17, P13, P7, P10\} vs. P2

Fig. B-1 Wells P2 & P17 correlation functions (a) P2 vs. P17 (b) P17 vs. P2

Fig. B-2 Wells P2 & P17 correlation contours (a) P2 vs. P17 (b) P17 vs. P2

Fig. B-3 Wells P2 & P17 statistical analysis (a) Time lag histogram (b) Gross time lag history

Fig. B-4 Wells P2 & P17 interwell diffusivity history. Valid time lags < 20hr and > 8 hr
## Appendix C: Computer Program Description

### Table C-1 – List of functions in data mining and cross correlation analysis application

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<th>Module</th>
<th>Code</th>
<th>Type</th>
<th>Use</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Db</td>
<td>getFromDb</td>
<td>Function</td>
<td>Internal</td>
<td>Get data from database. Executes a SELECT query and returns array</td>
</tr>
<tr>
<td></td>
<td>getPIFromDb</td>
<td>Function</td>
<td>Interface</td>
<td>Get the PI Tag from tblPITag, given the well name and data type name</td>
</tr>
<tr>
<td></td>
<td>updateOnDb</td>
<td>Function</td>
<td>Internal</td>
<td>Update data on database. Executes an UPDATE query</td>
</tr>
<tr>
<td></td>
<td>updateStartEndDates</td>
<td>Macro</td>
<td>Internal</td>
<td>Get start and end dates of history for every variable and every well, and updates tblWellData</td>
</tr>
<tr>
<td></td>
<td>updateHistory</td>
<td>Macro</td>
<td>Internal</td>
<td>Deletes previous and inserts new well data history in the tblWellHistory</td>
</tr>
<tr>
<td></td>
<td>updateStatusTable</td>
<td>Macro</td>
<td>Internal</td>
<td>Deletes previous and inserts new well stable periods in tblWellStatus</td>
</tr>
<tr>
<td>Numeric</td>
<td>fixOrderDiff</td>
<td>Function</td>
<td>Internal</td>
<td>ELS Derivative, fixed order (much faster)</td>
</tr>
<tr>
<td></td>
<td>variableOrderDiff</td>
<td>Function</td>
<td>Internal</td>
<td>ELS Derivative, variable order (slow)</td>
</tr>
<tr>
<td></td>
<td>convertFileToArray</td>
<td>Function</td>
<td>Internal</td>
<td>Converts file to VBA array</td>
</tr>
<tr>
<td></td>
<td>writeToFile</td>
<td>Function</td>
<td>Internal</td>
<td>Converts VBA array to file</td>
</tr>
<tr>
<td>FileIO</td>
<td>fillDataGaps</td>
<td>Function</td>
<td>Internal</td>
<td>Fills out gaps in surveillance data. Pressures are interpolated; rates fixed to last valid value</td>
</tr>
<tr>
<td></td>
<td>getPIData</td>
<td>Macro</td>
<td>Interface</td>
<td>Call PI DataLink functions in spreadsheet, process and input to database</td>
</tr>
<tr>
<td></td>
<td>interpolate</td>
<td>Function</td>
<td>Internal</td>
<td>Linear interpolation function</td>
</tr>
<tr>
<td>Scanner</td>
<td>fixTheWellRange</td>
<td>Function</td>
<td>Internal</td>
<td>Convert an Excel range with GAPS into a VBA array</td>
</tr>
<tr>
<td></td>
<td>generateTimeWindowArray</td>
<td>Function</td>
<td>Internal</td>
<td>Prepare the historical list of stable time periods for intersection</td>
</tr>
<tr>
<td></td>
<td>getStablePeriods</td>
<td>Macro</td>
<td>Interface</td>
<td>Get the complete PI history with hourly timestamps for one well, differentiate and slice. StablePeriods</td>
</tr>
<tr>
<td></td>
<td>getTimeWindows</td>
<td>Function</td>
<td>Both</td>
<td>Get time windows for well A cluster of constant rate vs. well B with changing rate</td>
</tr>
<tr>
<td></td>
<td>getWellStatuses</td>
<td>Function</td>
<td>Interface</td>
<td>Intersects stable periods of all the wells with a specified range in the interface</td>
</tr>
<tr>
<td></td>
<td>intersectStableWithOffender</td>
<td>Function</td>
<td>Internal</td>
<td>Once stable cluster time windows of well A are found, intersect with rate change periods of well B</td>
</tr>
<tr>
<td></td>
<td>intersectTimeWindows</td>
<td>Function</td>
<td>Internal</td>
<td>Intersect stable periods of selected cluster, to find time windows where all wells have constant rate</td>
</tr>
<tr>
<td></td>
<td>rangeIntersect</td>
<td>Function</td>
<td>Internal</td>
<td>Auxiliary function for intersectTimeWindows</td>
</tr>
<tr>
<td>Results</td>
<td>setupPlot</td>
<td>Macro</td>
<td>Interface</td>
<td>Launches getTimeLagHistory for selected well pairs, with the required input parameters</td>
</tr>
<tr>
<td>Analysis</td>
<td>getNeighboors</td>
<td>Function</td>
<td>Internal</td>
<td>Gets well clusters defined in a table, when exploring the data for a selected constant rate well</td>
</tr>
<tr>
<td></td>
<td>getTimeLagHistory</td>
<td>Macro</td>
<td>Internal</td>
<td>Get time windows for well A cluster vs. Well B. Splits into spike/hump patterns, launches GetCorrelation; get time lag results, put in worksheet cell placeholders</td>
</tr>
<tr>
<td></td>
<td>getHistoryFromStrings</td>
<td>Function</td>
<td>Internal</td>
<td>Gets converts one string output from EXPLOREDATA into array for plotting histogram</td>
</tr>
<tr>
<td></td>
<td>simpleDiff</td>
<td>Function</td>
<td>Internal</td>
<td>Calculates central derivatives, for differentiation of active well pressure history for cross-correlation</td>
</tr>
</tbody>
</table>

### Table C-2 – List of functions in GetCorrelation.exe Matlab Executable

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>getCorrelation</td>
<td>Read spike/hump pressure derivative data, compute cross-correlation, generate plot, generate contour, validate correlation functions, get all valid correlation peaks</td>
</tr>
<tr>
<td>savePPT</td>
<td>Save plot into a powerpoint file</td>
</tr>
</tbody>
</table>