Fault-block Transmissibility Estimation using Injection and Production data
A simplified Approach

By

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15772

Dissertation Report submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Petroleum)

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(Truong Van Phuc)

CERTIFICATION OF APPROVAL

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Approved by

____

(Dr. Mohammed Abdalla Ayoub)

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Abstract

It is common in industry to analyze reservoir characterization using geological data and early geophysics evaluation. However, there are limited studies about utilizing offshore instrumentation and monitoring data to effectively characterize reservoir description. These under-utilized dynamic data are usually used for evaluating reservoir production yet to be used for better understanding reservoir characterization for reservoir optimization purposes. This study proposes a semi-analytical approach to utilize reservoir pressure, production and injection data to ultimately estimate and monitor the transmissibility of a leaking fault. A history of average reservoir pressure and production rate is matched to determine fault status. The reservoir pressure and production/injection history in different reservoir compartments are evaluated to estimate flux rate across leaking fault. An offshore case study consists of two reservoir compartments separated by a fault with unknown connectivity and supported by large active aquifer and water injection was implemented. The history match honored the reservoir pressure and the re-allocated production/injection data in each compartment. A material balance simulator was used to build a static 1-D simulation model to execute the methodology of the proposed technique. The flexibility of sensitivity of simulator enables the estimation of water injection contribution to each reservoir compartment, as well as estimating and monitoring the transmissibility of the leaking fault along with history matching of pressure and production data using analytical approach. This approach is not a replacement of complex reservoir simulation models in estimating transmissibility of a leaking fault but a quick win in terms of time and cost, especially in brown fields with adequate data to build comprehensive static and dynamic simulation models.

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Nomenclature:

PV = produced pore volume (ac.ft)
N_p = cumulative oil produced (mmbbls)
B_{oi} = initial oil formation volume factor (rb/stb)
Φ = porosity (fraction)
S_{wi} = initial water saturation (fraction)
S_{oi} = residual oil saturation (fraction
G_{gc} = gas cap volume at current pressure (mmscf)
S_{gbt} = gas saturation at breakthrough (fraction)
B_{ga} = gas formation volume factor at current pressure (cf/scf)
G_{rec} = recoverable gas volume (mmscf)
S_{gr} = residual gas saturation (fraction)
B_g = gas formation volume factor (cf/scf)
i_g = gas injection rate (mmscf/d)
B_o = oil formation volume factor (rb/stb)
q_o = oil production rate (mmbpd)
R_p = productive gas oil ratio (scf/stb)
R_s = solution gas oil ratio (scf/stb)
B_w = water formation volume factor (rb/stb)
q_w = water production rate (mmbpd)
STOIIP = stock tank oil initially in place (mmbbls)
GIIP = gas initially in place (Bcf)
f_w = fraction of water (water cut), bbl/bbl
k_o = effective permeability of oil, md
k_w = effective permeability of water, md
ρ = water–oil density differences, g/cm3
Δρ = difference in densities between oil and water, g/cm3
q_t = total flow rate, bbl/day
μ_o = oil viscosity, cp
μ_w = water viscosity, cp
A = cross-sectional area, ft2

Abbreviation:

Rel. perm: Relative permeability

1. INTRODUCTION

1.1 Project Background

With the development of new technology, there have been numerous methods being studied to estimate the transmissibility of leaking fault. Tracer test and well test analysis were first introduced in previous studies to characterize the fault qualitatively and quantitatively. However, it is common in brownfields that these methods had not generated close match due to limited information about the oil reservoirs, especially in offshore environment. Apart from that, by not accounting for investigation of injection and production data, the aforementioned methods did not provide a systematic evidence and estimation of transmissibility of reservoir in the same hydraulic unit. This study introduced a workflow to investigate thoroughly from geological data, well events, reservoir pressure data, and effectiveness of injectivity, injection and production data. Various engineering analyses were carried out in details aim to propose a more practical method with available data of most oil reservoirs.

A pilot reservoir in PM3 CAA in Malaysia basin with two reservoir compartments sealed by a fault with unknown connectivity was being investigated. A material balance model was built to estimate the transmissibility between two tanks by generating a decent match between reservoir pressure and cumulative oil production. Comparing to more robust numerical simulators, this method offer a quick observation about the fault especially in a common event that full field modeling is too far costly.

These study focuses on water drive reservoirs with strong aquifer. The dynamic transmissibility between waterflooded reservoir yields correspondent behaviors of water cut, average reservoir pressure and production history. Understanding the communication between reservoirs is crucial in estimating initial reserve as well as in future field development plan.

1.2 Problem Statement

It is crucial in investigating the transmissibility of leaking fault that abundant reservoir data available result in better understanding about the fault. The available data will be taken into account as input for various engineering analyses. However, problem usually arises in brown fields in offshore environment with the unreliable reservoir pressure. In North America, there is no oil field being developed with commingle wells. The picture is so much different in South East Asia that commingle wells are being developed widely to save development cost. It usually leads to uncertainties in injection and production back allocation data. The main proposed tool in this study is multi-tank Material Balance (MB) model. Apart from PVT data, the one-cell tank model requires reservoir pressure, production and injection input data. Similar to other techniques, the first step in building a valid material balance model is to examine and validate all initial inputted data. The aforementioned uncertainties in reservoir static and dynamic data cause difficulties in building a representative MB model.

In order to obtain a deep understanding about the transmissibility, we do not rely solely on the result of MB model. It is challenging to collect, organize and analyze a large amount of data consist of available geological model, intermittent reservoir pressure and production data.

The other main factor is often considered to evaluate the effectiveness of a simulation approach is simulation time. If the offshore dynamic data such as production and injection data were not stored and allocated accordingly with precise back-allocate algorithm, the obtain of a decent history match is extremely time consuming yet impossible.

1.3 Objectives and Scope of Study

The objective of this project is mainly to estimate the transmissibility flux rate by modeling of hydraulically connected reservoirs in a single system. The matching parameters are hydrocarbon in place and transmissibility constant between two tanks. The obtained oil and gas initial in place will be compared to reserves estimated in PETREL to check validation of the methodology.

The pilot reservoir of this study is the Mega I-90 oil reservoir in PM3 CAA. The West I-90 is one of the major reservoirs and the only undersaturated reservoir (initially) in PM-3. The reservoir has the benefit of strong aquifer support supplemented by water injection. Production from this reservoir started in July 1997. The North West I-90 reservoir was discovered in 1997 which has small initial gas cap and strong aquifer drive supplemented by water injection. Reservoir management for these two reservoirs needs to be done together with an overall water injection strategy. This leads to high injection into North West I-90 to compensate for lack of injection in West I-90 which gives an increase in oil production. Based on current seismic and geological interpretation, the North West I-90 reservoirs could also be connected to the East I-90 reservoir, however, the effect of aquifer/injection support from North West I-90 has not been observed from the dynamic data possibly due to more complex tortuosity and stratigraphic features.

The proposed workflow is applicable for reservoir with water drive mechanism. However, with some minor changes in pseudo-production history, this approach can be used for reservoir with others drive mechanism. The limitation of material balance based simulator makes it not practical to predict the production rate due to transmissibility.

2. LITERATURE REVIEW

A question frequently arises in field development plan of matured fields is to what extent the transmissibility across a leaking fault between reservoirs in the same hydraulic unit is connected. Answering this question is not only important to understand reservoir dynamic characterization but also a major indicator to plan for future infilled wells.

The fault status in a hydrocarbon bearing can be either sealing or leaking fault. The sealing fault completely blocks the accumulation of fluid flow between two strata which results in no connectivity between two sides of the fault. The trapping mechanism prevents any further transmissibility and the throw of the fault implied that, if there are no further geological activities or artificial fracture to eventually create a hydraulic channel across the fault, the permeable and impermeable strata are juxtaposed sealed against each other.

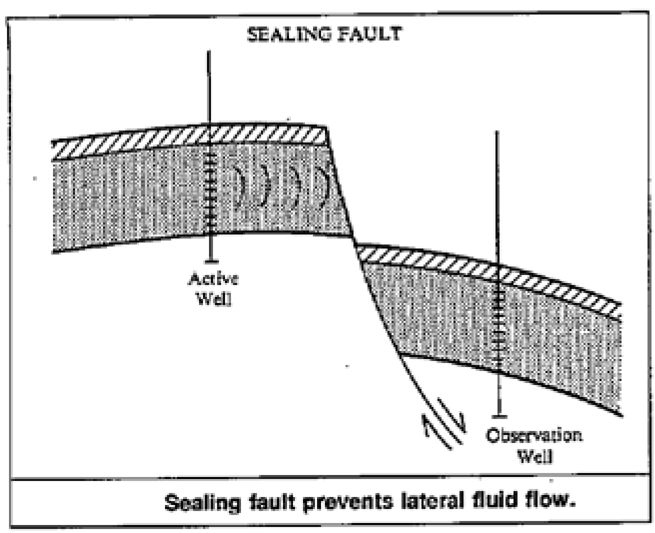


Figure 1: Schematic diagram of sealing fault

On the other hand, the leaking/non-sealing faults usually have insufficient throw to completely form a no-flow barrier. The hydraulic channel allows lateral fluid flow in two opposites of the fault. Due to various geological mechanisms which created the connectivity, the transmissibility of these faults are always much lower than a virgin undisturbed strata. This is usually categorized as partially leaking faults.

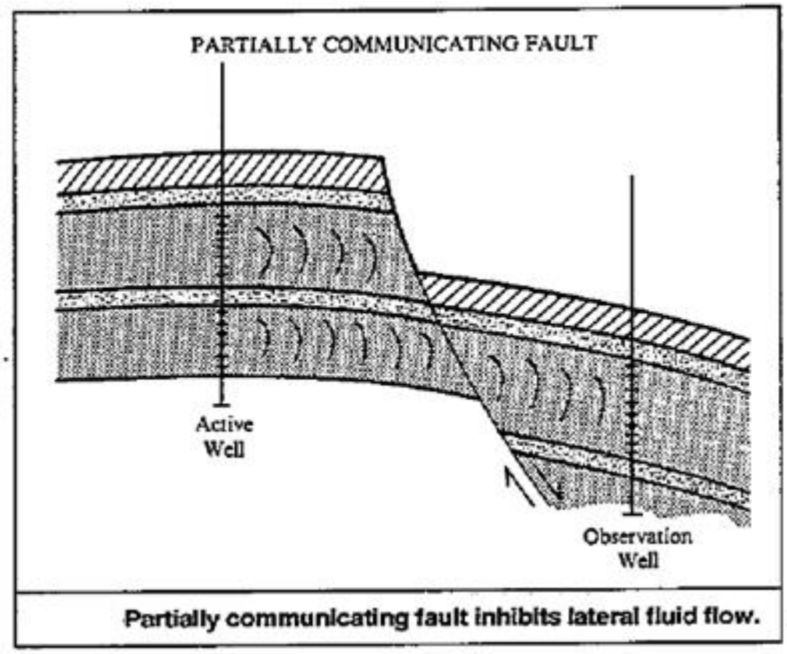


Figure 2: Schematic diagram of leaking-fault

Commonly in industry, petro-physical data has been widely used to find and evaluate the evidence of partially leaking faults. Geological studies were first introduced by using log data, dip-meter and seismic data (Stewart, et al.1984). However, the obtained result was not abundant to process a high-resolution data (Stewart, et al.1984). Low-resolution data gathered caused difficulty in estimating transmissibility information of the fault. Numerous techniques have been employed to enhance the estimation by increasing the resolution of data gathered since then such as by tracer test (Lange, et al. 2005), Smear Gauge Ratio (Archarya, et al. 1997) and time-lapse (4D) seismic (Edris et al. 2008). Beside, various studies have been conducted to estimate average communication across the fault. These studies focused on experimenting traditional well test such as interference test, pulse test, pressure transient behavior (Yaxley 1987) to provide information about transmissibility between well-connected reservoirs. In order to get a close estimation of transmissibility of the leaking fault, not only the aforementioned techniques need to be applied, but also complex geological models are required. This method yields an extremely data extensive process in order to get matching parameters.

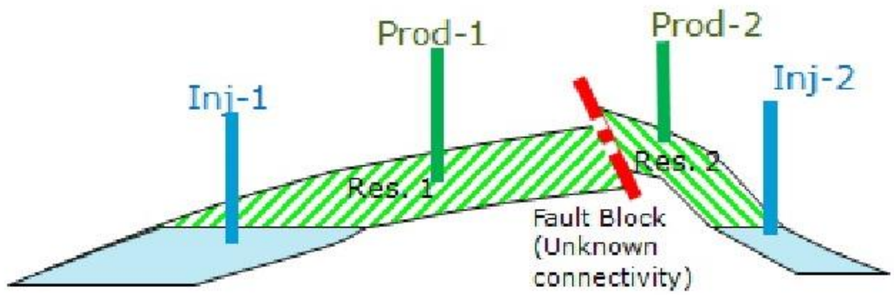


Figure 3: Two reservoirs separated by a fault of an unknown connectivity

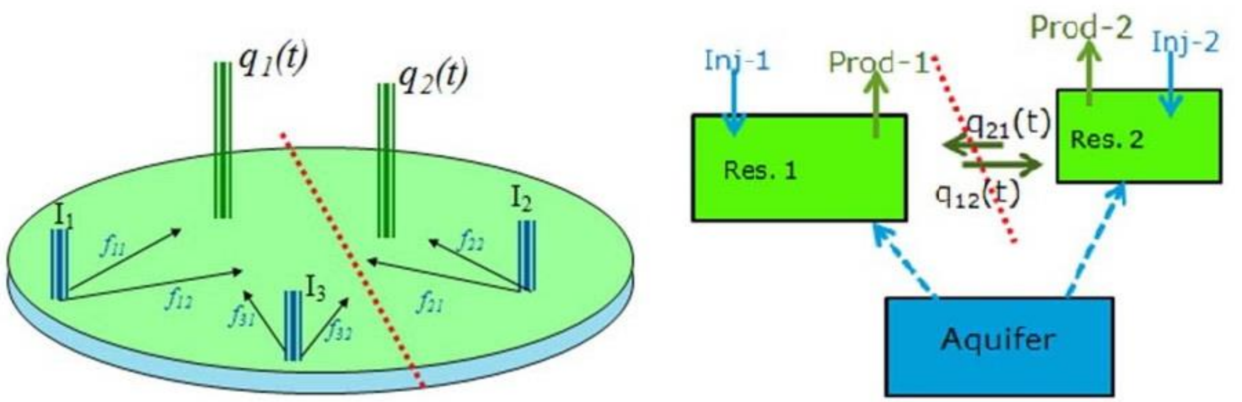
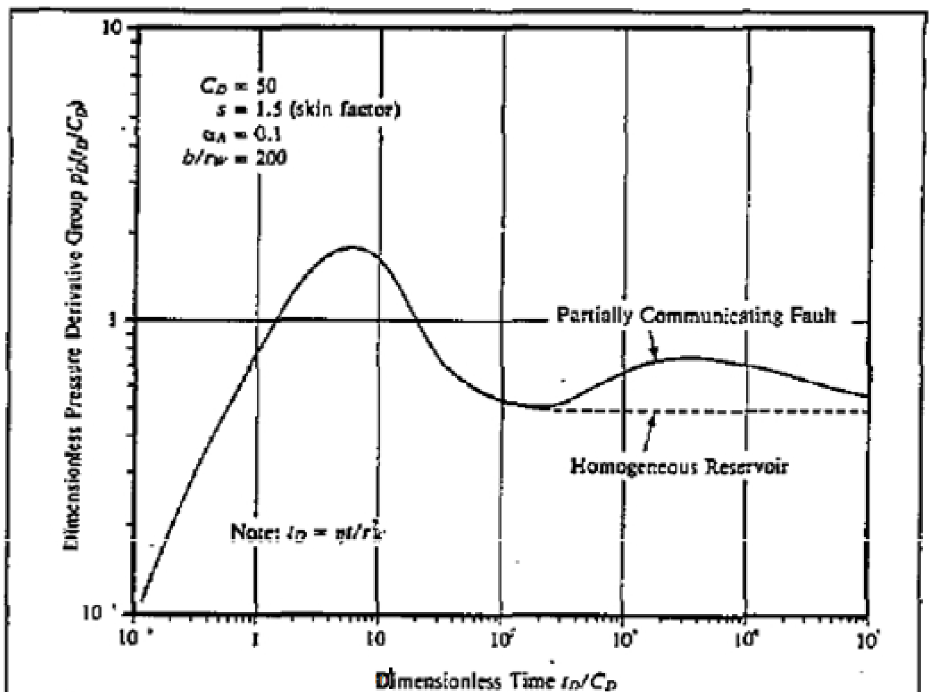


Figure 4: Reservoir model description and approximation

Before the advances of simulation in hardware and software in the late 1990s, the transmissibility estimation mainly depends on interference and pulse tests. Yaxley (1997) presented his technique on interpretation of low-resolution data obtained from these tests. Yaxley studied an infinite reservoir that contained a linear, vertical semipermeable barrier under a drawdown test. The drawdown distribution caused by constant production rate was interpreted to find the evidence of non-sealing fault. The test based on homogeneous reservoir model assumption which was inadequate. It may give an average transmissibility but were not able to evaluate separately the transmissibility of the fault and the transmissibility of the continuous reservoir. Moreover, the assumptions which the mathematical model relied on were not practical. In fact, it is not possible to maintain a constant flow rate and the reservoir is not homogeneous in all rock properties and non-isotropic with respect to permeability.



Pressure derivative drawdown example for an active well with wellbore storage and skin.

Figure 5: Pressure derivative drawdown example for active well with WBS and skin

While pressure test gives access to the reservoir anisotropy within the well drainage area, tracer tests give a signature of the main flow paths that are responsible for this anisotropy. In his study, Lange (2005) simulated tracer-test on discrete fracture network models for the characterization of fractured reservoir. Additional information about the reservoir heterogeneity is the main advantage of using tracer test over pressure test.

In another approach, Acharya et al. (1997) proposed another method to evaluate reservoir juxtaposition and potential cross-fault communication pathways using Sear Gouge Ratio (SGR). Given data from E-logs were used to calculate SGR. It then was used to estimate the composition of fault-gouge materials between the juxtaposed reservoirs. The relationship between fault transmissibility and fault composition were qualified using history matching of utilized field data of reservoir pressure, production and injection data. The below figure shows how SGRs is calculated.

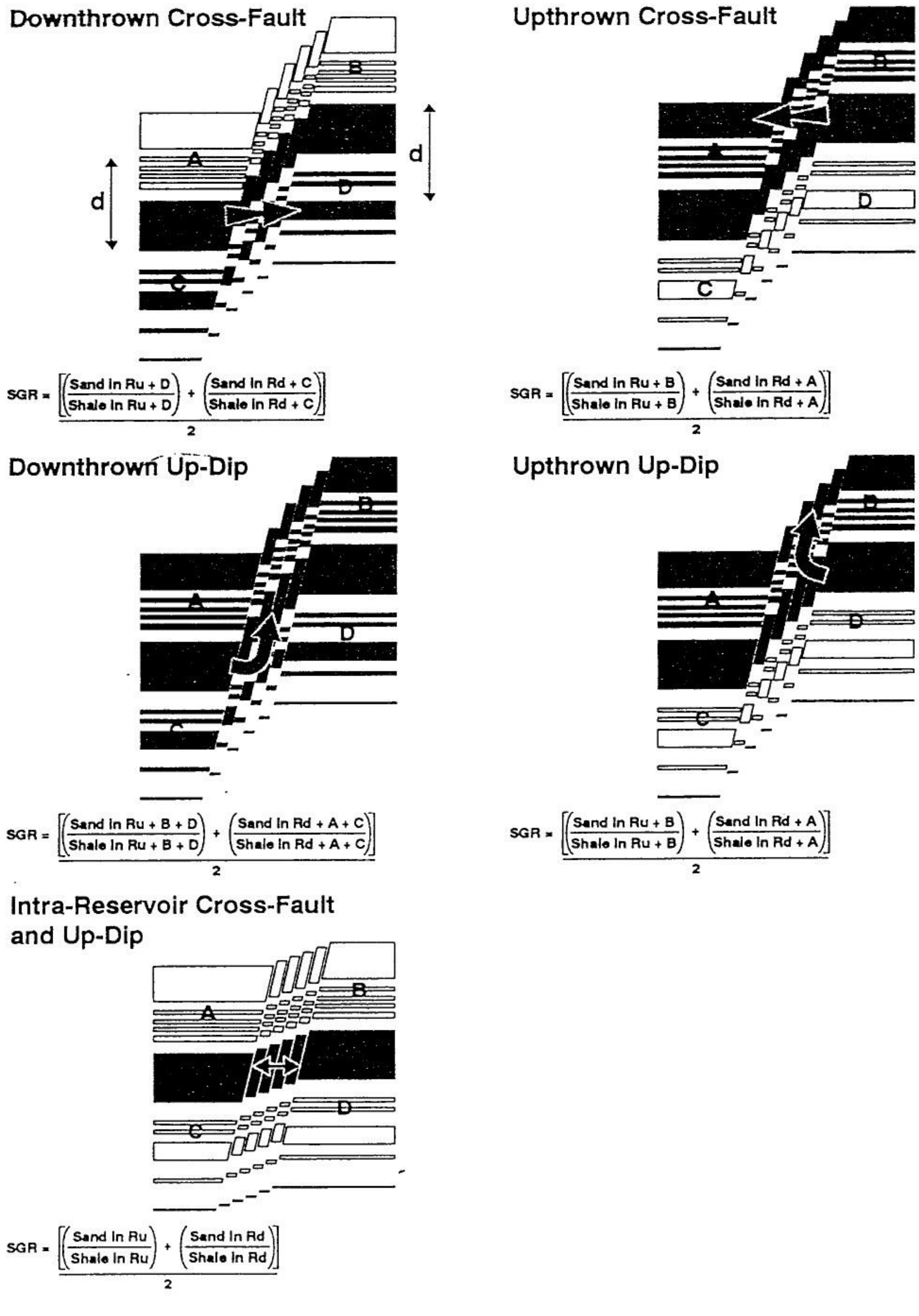


Figure 6: Calculation of SGRs

The previous approaches have shown the advances in qualifying the properties of leaking fault connectivity. In most case, the interpretation is either giving low-resolution data which yields uncertainties or required extensive well test and data acquisition. Moreover, injection and production data have not been used extensively to estimate the connectivity of the leaking fault. This proposed workflow calculates the communication parameters by unitizing both pressure data and production data simultaneously.

The theory behinds this techniques is the utilization of material balance equation, transmissibility equation and Voidage replacement ratio equation.

Material Balance Equation for Oil Reservoir

Material balance equation is one of the most important equations developed for petroleum engineering studies.

$$NB_{oil} = (N - N_p)B_o + \left[\frac{NB_o}{1 - S_w}\right] c_f(p_i - p) + \left[\frac{NB_o}{1 - S_w}\right] C_w S_w(p_i - p) + W_e - W_p B_w + W_i B_w + G_i B_g$$

W_e : *water influx*
$W_p B_w$: *water production*
$W_i B_w$: *water injection*
$G_i B_g$: *Gas injection*

Transmissibility Equation

$$Q_t = C * \sum_{i=0}^{i=n} (K_n/m_i * \Delta p)$$

With:
Q_t = *total downhole flow rate*
C = *transmissibility constant*
K_n = *relative permeability of phase i*
m_i = *viscosity of phase i*
Δp = *pressure difference*
Q_t *is then split into* Q_o, Q_g *and* Q_w *using the relative permeability curves.*

If the two reservoir compartments are having different initial reservoir pressure, it is assumed due to difference in depth and hydrostatic pressure. At initial state, there is no change in pressure difference. As long as pressure difference starts to change, the transmissibility starts to affect the production of two compartments.

Voidage Replacement Ratio

$$VOIDAGE\ REPLACEMENT\ RATIO\ (VRR) = \frac{injected\ reservoir\ volume}{produced\ reservoir\ volumes}$$

$$VRR = \frac{B_w(i_w)}{B_o q_o + B_w q_w + q_o(GOR - R_{s)B_g}}$$

Generating the VRR plot is not only a tool to monitor the effectiveness of injection activity but also an indicator for transmissibility between reservoirs. Depending on objectives of VRR analysis to choose to generate whether instantaneous or cumulative VRR as shown below:

$$Instanaeous\ VRR = \frac{q_{winj}B_{winj} + g_{ginj}B_{ginj}}{q_o B_o + q_o(R_p - R_{s)B_g} + q_w B_w}$$

$$Cumulative\ VRR = \frac{W_{winj}B_{winj} + G_{ginj}B_{ginj}}{N_p B_o + N_p(R_p - R_{s)B_g} + W_p B_w}$$

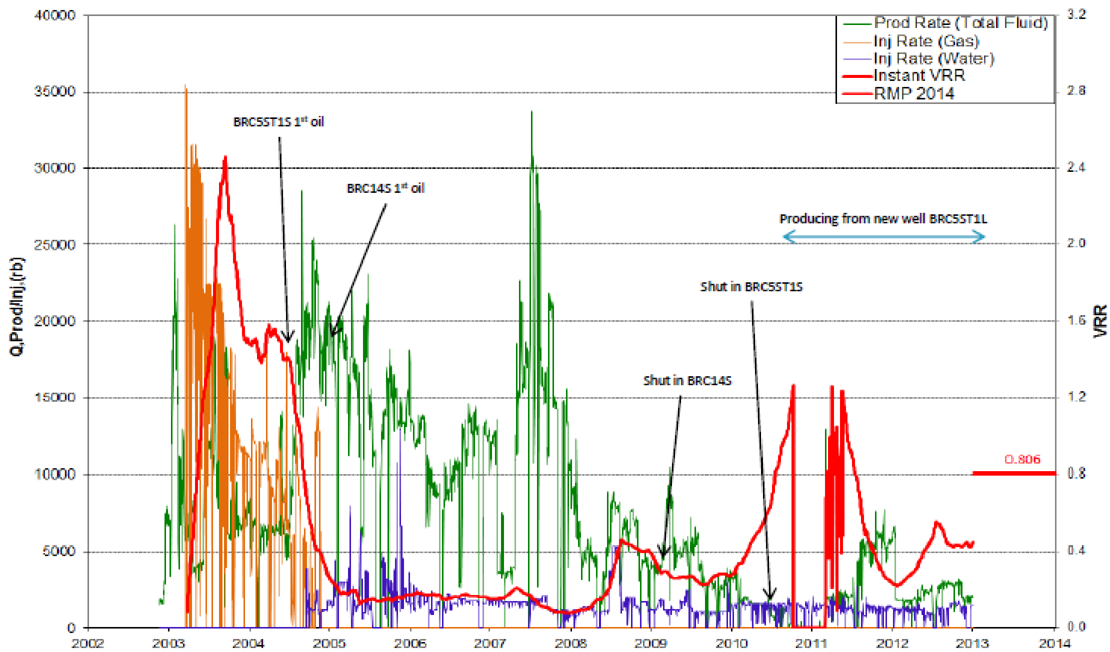


Figure 7: Example of 6-month rolling instantaneous VRR plot

Fractional Flow Equation

$$f = \frac{1}{1 + \frac{k_o}{k_w}\frac{\mu_o}{\mu_w}} + \frac{\frac{1.127 k_o}{\mu_o}\frac{A}{q_t}\left[\frac{\partial P_c}{x} + 0.433(\rho_o - \rho_{g)} g sin\alpha\right]}{1 + \frac{k_o}{k_w}\frac{\mu_o}{\mu_w}}$$

f_w = fraction of water (water cut), bbl/bbl

k_o = effective permeability of oil, md

k_w = effective permeability of water, md

ρ = water–oil density differences, g/cm3

Δρ = difference in densities between oil and water, g/cm3

q_t = total flow rate, bbl/day

μ_o = oil viscosity, cp

μ_w = water viscosity, cp

A = cross-sectional area, ft2

Usage of Fractional Flow Equation in this study, is to match it with current water saturation. It is another matching criteria in history matching.

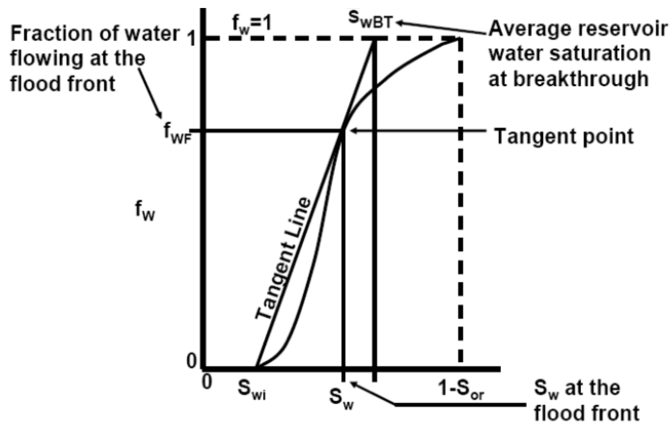


Figure 8: Usage of Fractional Flow Equation

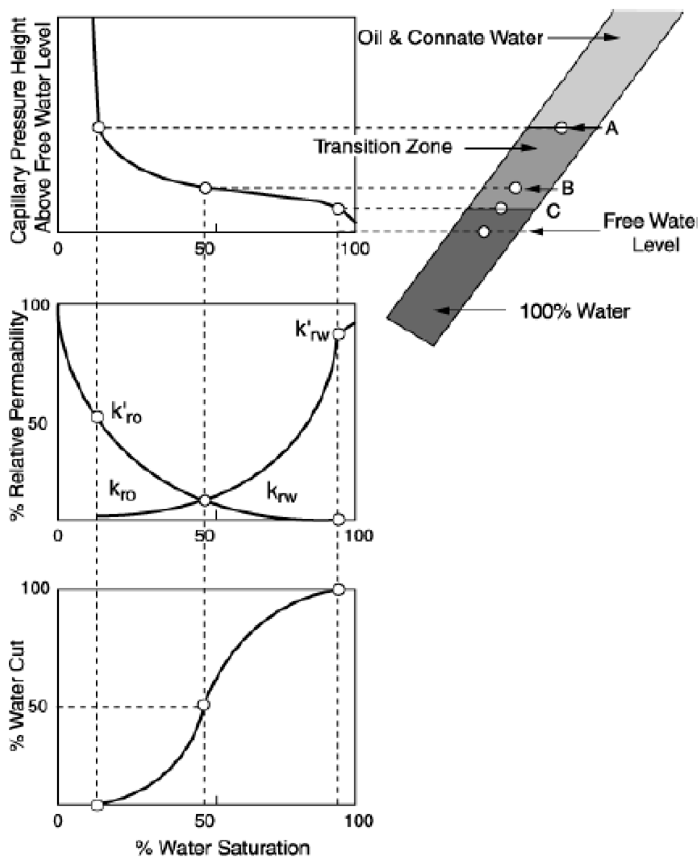


Figure 9: Relationship between capillary pressure, relative permeability and fractional flow

For example in this reservoir:

At A the well only produces oil

At B, 45%saturation both oil & water produced with water cut of 50%.

At C advancing water isolated irreducible oil saturation

3. METHODOLOGY

There are three main steps in order to make the conclusion to the feasibility of this study. First step is data gathering and validation, follow by data analysis to find evidence of connectivity and lastly is simulating transmissibility.

Geological maps are first come into review of the location of reservoirs, producing and injection wells as well as the direction of the fault. Pressure data are then collected and corrected to the same datum. Production and injection data will be carefully back-allocated to ensure the behavior of production trend line is consistent with the pressure trend line.

Pressure trend line of two reservoirs is plotted in the same time scale with history events such as first oil production and introduction of water injection/new production well. The pressure trend is the first evidence of the connectivity between two reservoirs.

After PVT data are collected and validated, the acquired data will be sufficient to build a one-tank material model. In this section, we shall discus the methodology we applied in building the well predictive MBE models. The workflow to build a MB model is shown below:

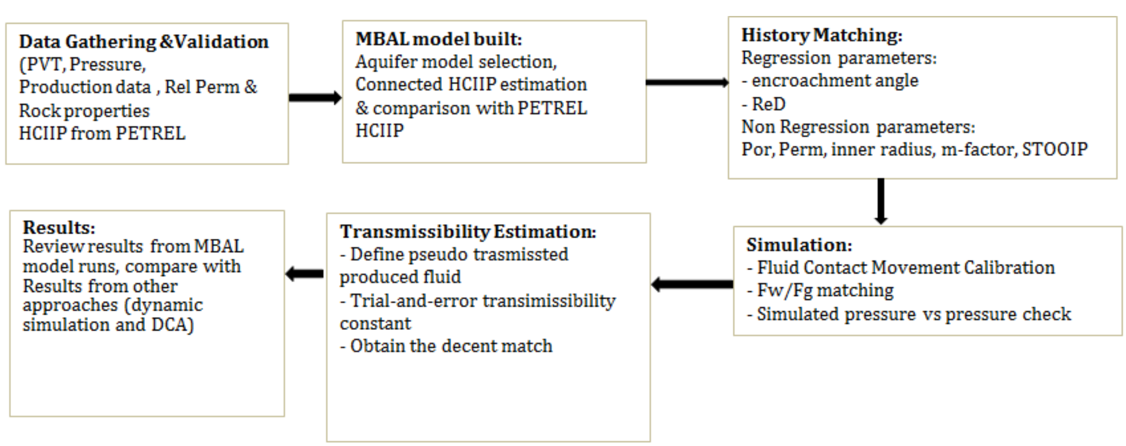


Table 1**:** Workflow for material balance analysis

Along with building and analyzing result from MBAL, reservoir pressure behaviors due to water injection is also another tool for gathering information about transmissibility. Voidage Replacement Ratio is plotted to analyze the effectiveness of water injection activity which is another indicator for dynamic communication between two reservoirs.

In this study, transmissibility estimation is applied instead of prediction. The simulator used is MBAL in PETEX package. The workflow below shows steps to set up an MBAL model:

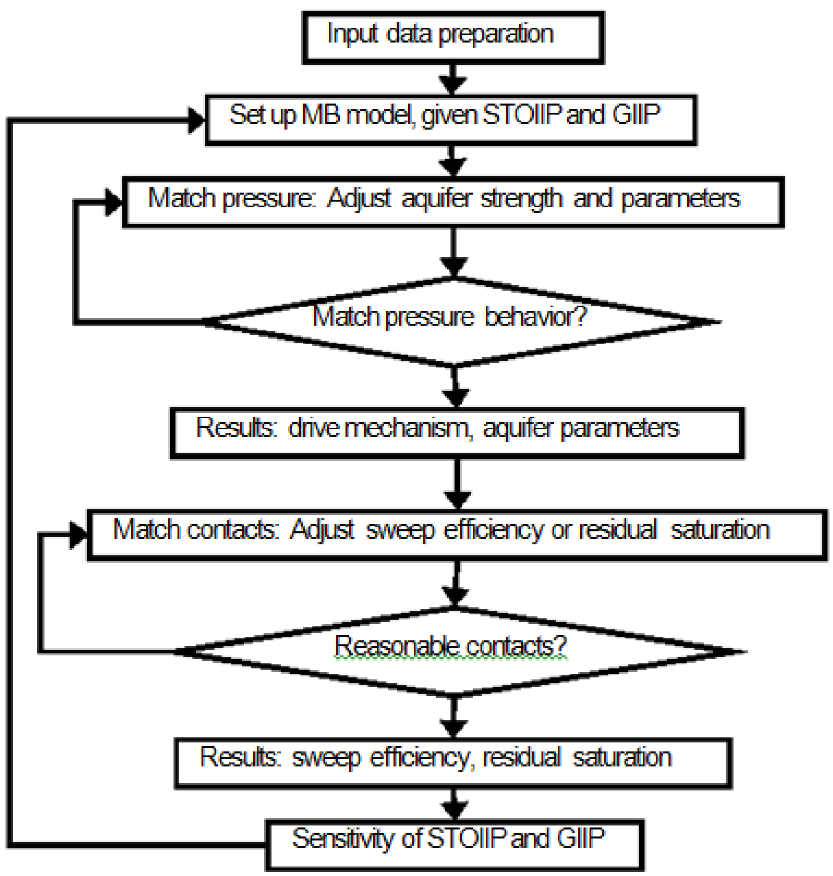


Figure 10: MBAL model set up

Nowadays, most of operating companies are using OFM (Oil Field Manager) to manage their production data. However, the back-allocation algorithm simply relies on vertical permeability k_h which usually results in uncertainties in production history, especially in matured fields with the number of commingle wells are majority. In order to fix that disadvantage, production and injection data is thoroughly allocated manually using EXCEL. This gives us the flexibility in controlling the allocation data in events of commingled production and intermittent well status.

After *"input data"* is completed, a set of relative permeability is tuned with respect to the latest changes in fluid phase behavior. Honoring a fixed set of rock and fluid properties (PVT), the tuning process of relative permeability has a major impact in obtaining a good history match.

The figure below was an example from MBAL Manual describing the analytical method to match reservoir pressure with cumulative oil production.

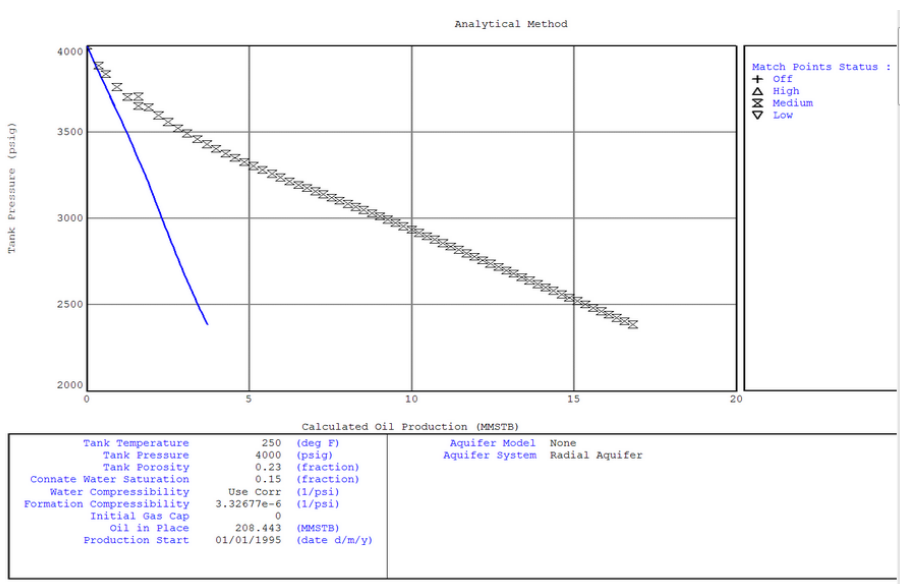


Figure 11: Example of history match using analytical method

To ensure the validation of a history match, all of the matching techniques need to be employed. This figure shows the different history matching approaches in MBAL:

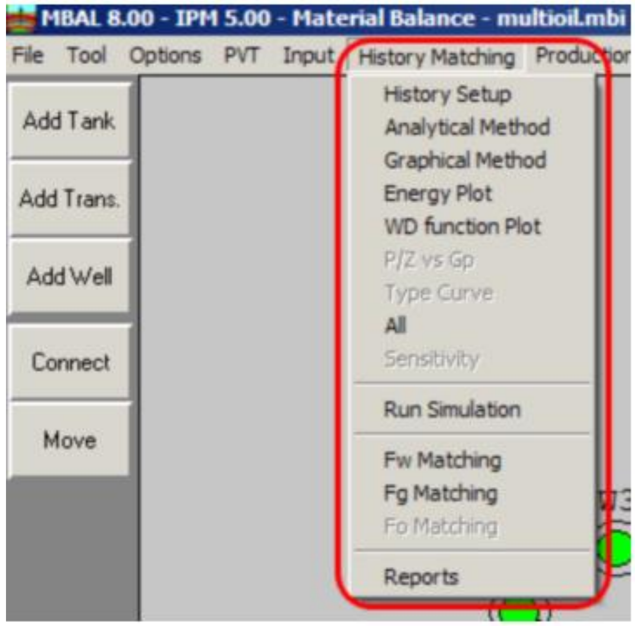


Figure 12: History matching techniques in MBAL

It is not possible to obtain a decent match in the first simulation running. The regression process can be run with the unknown parameters such as the size of aquifer and hydrocarbon in place.

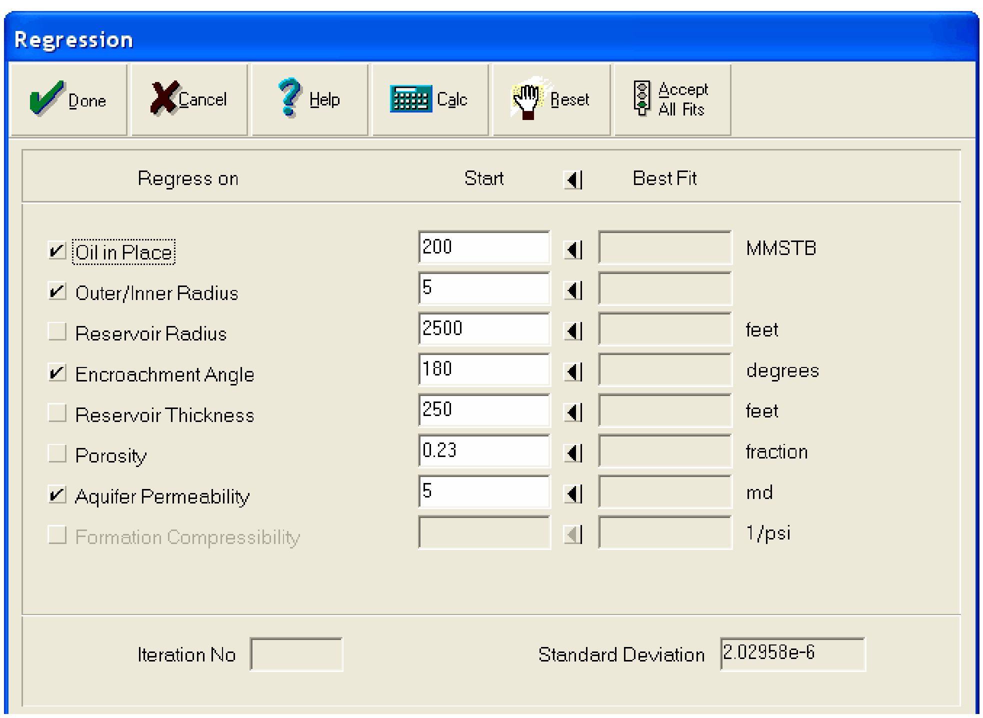


Figure 13: Regression parameters in MBAL

In this case study, a multi-tank model is set up with a trans (transmissibility), therefore, a decent match cannot be reached until the transmissibility data are utilized. The aforementioned pressure data analysis has determined the direction of the fluid flow across leaking fault. The transmissibility input require the tank direction, breakthrough constrains and permeability correction of transmissibility and transmissibility constant. In most cases, transmissibility constant is the parameter being trial-and-error experimented until getting a good match.

Certain phases can be prevented from flow by using the Breakthrough Constraints. The relative permeability curves can be corrected to maintain their shape while starting from the breakthrough saturation.

Production history through *trans* is not a mandatory key input. However, a deep understanding of reservoir description allows us to simulate pseudo-production history. In this case, water injection is supplemented in aquifer. The stick diagram indicated that most of the transmissible production is contributed by aquifer, which is *water production.* Therefore, it is applicable for this water drive mechanism reservoir. In cases of different drive mechanisms, the pseudo-production data will be changed accordingly.

Production – Injection Reallocation

Nowadays, most of the operating companies are using an integrated live-time system to record and store the production and injection rate. Reservoir fluid rate was recorded at the platform using transmitters before sending those data to a control center. With the aid of satellite transmission, these data are sent to onshore live-time and can be viewed instantaneously by operation/ reservoir engineer. However, since these transmitters working under hazardous and highly corrosive environment, they often need to be repaired or replaced. Under many circumstances, these operations are delayed for days/ months. The data are sent to onshore are carry-forwarded, therefore, highly incorrect. This is the most common reason makes the inputted data for history matching unreliable.

On the other hand, there is always a manually report made by offshore technician to record the injected/ produced fluid daily and the working condition of transmitters. These are the only reliable data for reservoir engineer to re-allocate. According to operational report and well events, a better allocation of different produced/ injected fluid can be done.

Reservoir Pressures Correlation

Often the reservoir pressures are reliable. However, due to different pressure tests were conducted in different depth, the average reservoir pressure need to be corrected to the same datum depth. Moreover, there are events when pressure tests in some particular wells are not following the reservoir pressure trend, for example, in virgin well or commingle well. Those pressure data need to be removed from history matching process.

The following steps are representing the 'history match' process:

WD Function Plot

The WD plot shows the dimensionless aquifer function versus dimensionless time type curves. This plot also indicates the location of the history data points in dimensionless co-ordinates. Linear and logarithmic axes are available.

A typical WD plot will look like this:

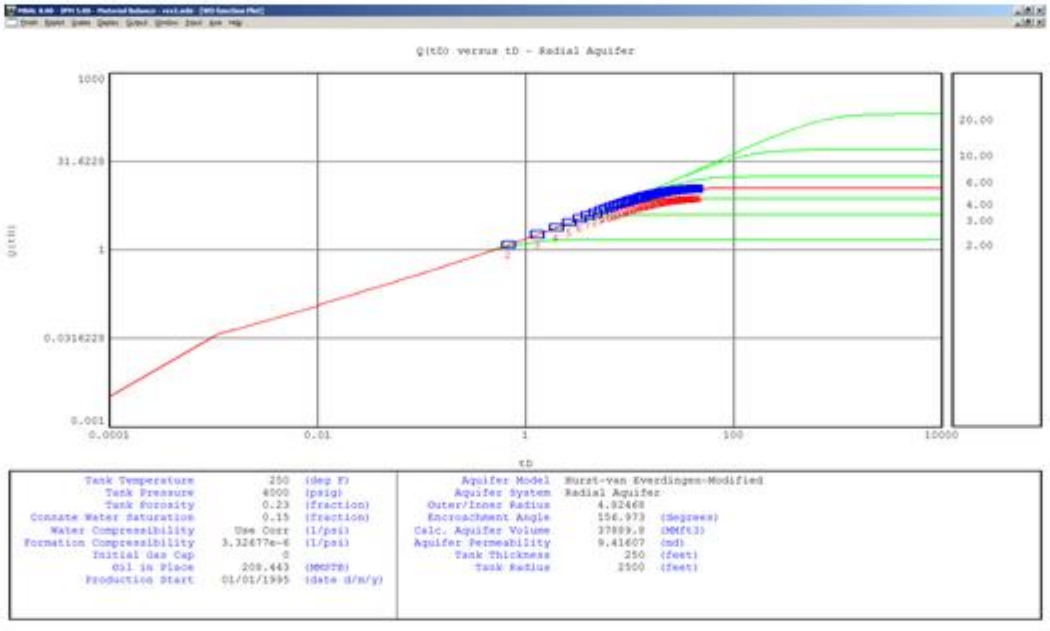


Figure 14: Typical WD Function Plot

For radial aquifers, the rD parameters (ratio of outer aquifer radius to inner aquifer radius) can be changed on the plot. The program immediately runs a short regression on the rD to find the type curve passing through the selected point.

The program will not calculate rD parameters for points selected below the minimum displayed rD value. An infinite WD solution curve will be calculated for points selected above the maximum displayed rD value.

Energy Plot

This plot shows the relative contributions of the main source of energy in the reservoir and aquifer system. It does not in itself provide the user with detailed information, but indicates very clearly which parameters and properties should be focused on (i.e. PVT, Formation Compressibility, and Water Influx). For example, if the 'Water Influx' area (normally red) is very small then the aquifer properties could be ignored to focus on other areas

Consider the following plot:

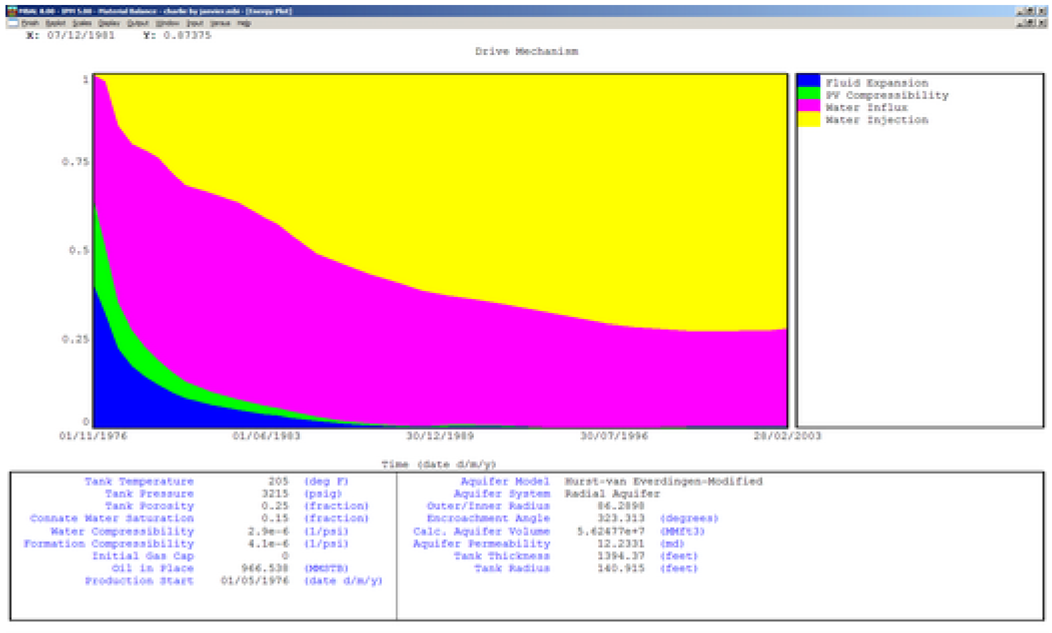


Figure 15: Typical Energy Plot

At the beginning of history, some energy comes from the expansion of the fluid in place, whereas towards the end of history, a negligible drive comes from the hydrocarbon expansion. Therefore, when trying to history match and get the OOIP the initial production points should be focused on, not the points at the end of history. Reservoir, transmissibility and aquifer parameters can be changed without exiting the plot.

Graphical Method

This graphical method plot is used to visually determine the different reservoir and aquifer parameters. The following different methods are available:

For Oil reservoirs	·Havlena - Odeh ·F/E versus We/Et ·$(F - We)/Et$ versus F (Campbell) ·$F - We$ versus Et ·$(F - We)/(Eo + Efw)$ vs $Eg/(Eo + Efw)$ ·F/Et versus F (Campbell - No Aquifer)
For Gas/ Condensate reservoirs	·P/Z ·P/Z (over pressured) ·Havlena - Odeh (over -pressured) ·Havlena - Odeh (water drive) ·$(F - We)/Et\ (Cole)$ ·Roach (unknown compressibility) ·F/Et (Cole - No Aquifer)

Table 2: List of graphical methods

The aim of most graphical methods is to align all the data points on a straight line. The intersection of this straight line with one of the axes (and, in some cases the slope of the straight line) gives some information about the hydrocarbons in place.

For this purpose, a 'straight line tool' is provided to attain this information. This line 'tool' can be moved or placed anywhere on the plot. Depending on the method selected, the slope of the line (when relevant) and its intersection with either the X axis or Y axis is displayed at the bottom part of the screen

F_w / F_g Matching

One of the main difficulties when running a ‘Production Simulation’ and 'Production Prediction' is to find a set of relative permeability curves which will result in a GOR, WC or WGR similar to those observed during the production history. The purpose behind this tool is to generate a set of Corey function parameters that will reproduce the fractional flows observed in the production history.

The relative permeabilities can be generated for the tank, individual wells or transmissibilities. In order to generate the relative permeabilities for a well, the production history for this well must be entered. In order to generate the relative permeabilities for a transmissibility, the production history for it must be entered in the ‘Transmissibility Data' Input. The history simulation has to be run after this input data has been entered. If this is not done, the history simulation uses the rel perms of the source tank so any F_w / F_g match will simply generate the entered relative permeability curves. Choose the item to regress on by selecting the tank, transmissibility or the well in the item menu option.

This fractional flow matching tool can only be used if a simulation has been run. It is also important to re-run a simulation each time input parameters are changed as they will probability affect the saturations and/or the PVT properties. A plot showing the fractional flow versus saturation will be displayed. No data points will be displayed if the simulation has not been run or there is no water/gas production. Most of the time, particularly after a long production history, the late WC do not really represent the original fractional flows. They usually take into account the water breakthroughs and also show the different work-overs done to reduce water production.

These late data point can be hidden from the regression by double clicking on the point to remove. The breakthrough for the saturation that is displayed on the X axis is marked on the plot by a vertical green line. This will be taken into account by the regression. The breakthrough value can be changed on the plot by simply double-clicking on the new position - the breakthrough should be redrawn at the new position.

These parameters represent the best mathematical fit for the input data, insuring a continuity in the WC, GOR and WGR between history and forecast. This set of Corey function parameters will make sure that the fractional flow equations used in the

'Production Prediction' tool will reproduce as close as possible the fractional flow observed during the history. These parameters have to be considered as a group and the individual value of each parameter does not have a real meaning as, most of the time, the solution is not unique.

The theory behind reproducing a set value of Fw or Fo is in Corey function in order to determine a representative set of relative permeability. In a Corey function, the relative permeability for the phase x is expressed as:

$$K_{rx} = E_x * \left(\frac{S_x - S_{rx}}{S_{mx} - S_{rx}} \right)^{nx}$$

where:

E_x is the end point for the phase x,

Nx is the Corey Exponent,

S_x is the phase saturation,

S_{rx} is the phase residual saturation

and

S_{mx} is the phase maximum saturation.

The phase absolute permeability can then be expressed as:

$$K_x = K * K_{rx}$$

where:

K is the reservoir absolute permeability and

K_{rx} the relative permeability of phase x.

For the purpose of clarity, the following detailed explanation describes the matching of the water fractional flow in an oil tank.

The first step is to calculate the points from the input production history which are shown as points on the plot. For each production history point the Sw value is the one calculated in the production history. The Fw value is calculated using the rates from the production history and the PVT properties. Now accounting for the capillary pressures and the gravities, the water fractional flow can be expressed as:

$$F_w = \frac{Q_w * B_w}{Q_o * B_o + Q_w * B_w}$$

where :

Qx is the flow rate and

Bx is the Formation volume factor of phase x.

The second step is to calculate the theoretical values – these are displayed as the solid line on the plot. As for the date points, the water saturations are taken from simulation. The Fw is calculated from the PVT properties and the current relative permeability curves using:

$$F_w = \frac{\frac{K_w}{\mu_w}}{\frac{K_w}{\mu_w} + \frac{K_o}{\mu_o}}$$

When a regression is performed, the Corey terms are adjusted with respect to the relative permeability curves to best match the Fw from the data points and the Fw from the theoretical curves.

Transmissibility

After the production and injection rate back-allocation was completed, a set of data which will be used to estimate the trans flux rate will be prepare. Assuming that the two reservoirs only connected in the shared aquifer, the difference in produced fluid between two tanks are considered as produced water.

4. RESULT AND DISCUSSION

4.1 Result

The first evidence of transmissibility is gained by analyzing reservoir pressure.

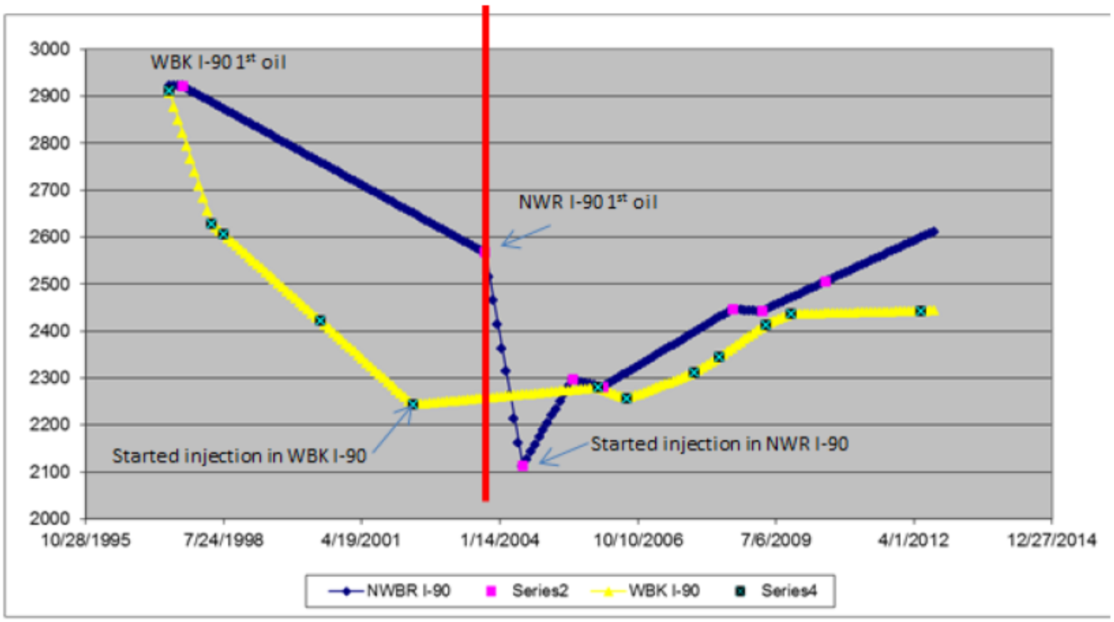


Figure 16**:** Reservoir pressure behavior due to transmissibility and water injection

The blue line indicates pressure trend of tank 1 and the yellow line indicates the pressure trend of tank 2. Fist oil of tank 1 was in 1995 while tank 2 had its first oil in 2004 at the same time with water injection was introduced in both tanks. Although tank 1 only started production 9 years after tank 2, the pressure in tank 1 had reduced 300psi without production. This can be explained by these two tanks sharing the same aquifer. The reducing in the mutual aquifer size resulted in pressure decline in both tanks. The stepper pressure decline trend in tank 2 is due to high production rate in the early life of reservoir.

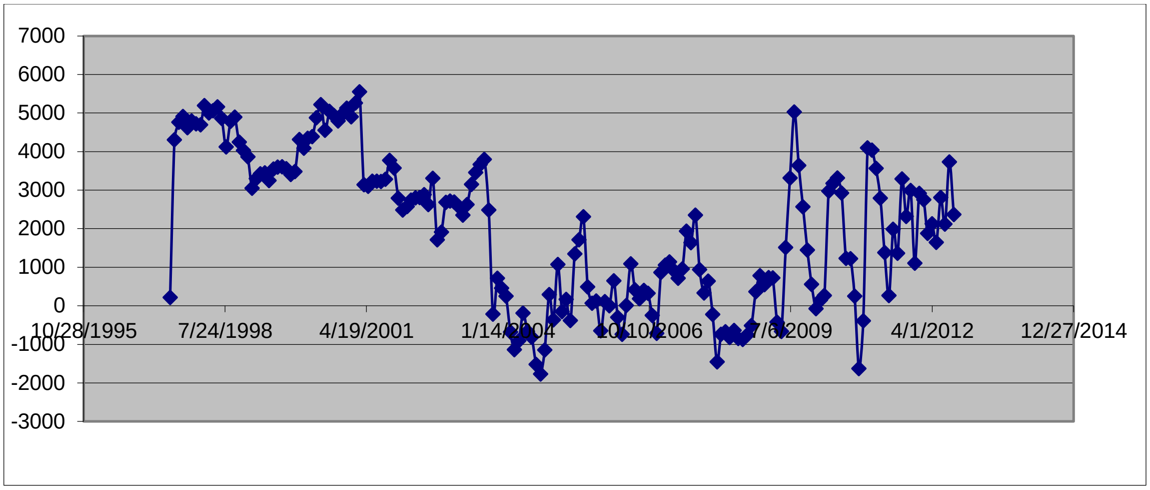


Figure 17: Produced liquid rate difference between two tanks

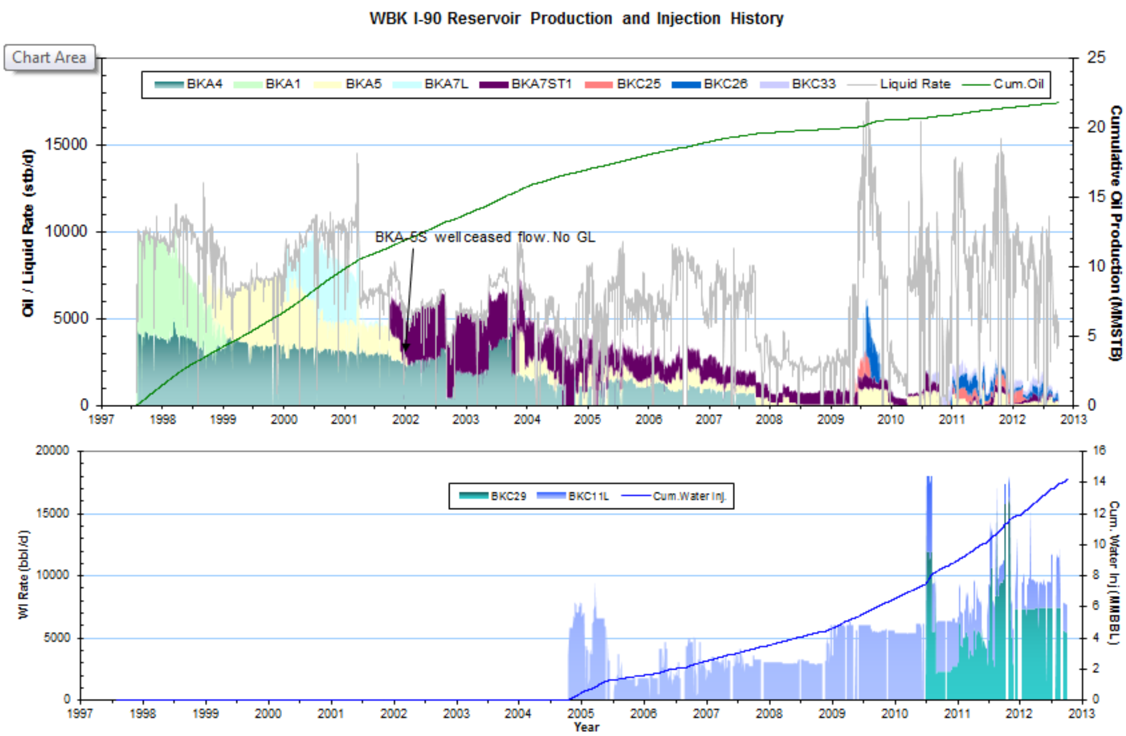


Figure 18: WBK I-90 Reservoir Production and Injection History

The back-allocation process was carefully carried on. Figure 18 is the plot showing the injection and production history of reservoir. Figure 18 shows the pressure difference between two tanks. If the difference is positive means the flow direction from tank 1 to tank 2 and vice versa. Generally, fluid flowed from tank 1 to tank 2 before it started production. It took 4 years of production support by water injection to stabilize both reservoir pressure and transmissible flow. When the pressure started to increase in both tanks, it established its initial fluid flow direction from tank 1 to tank 2. Up to this point, the prepared data are ready for history matching process.

The VRR plots are also constructed:

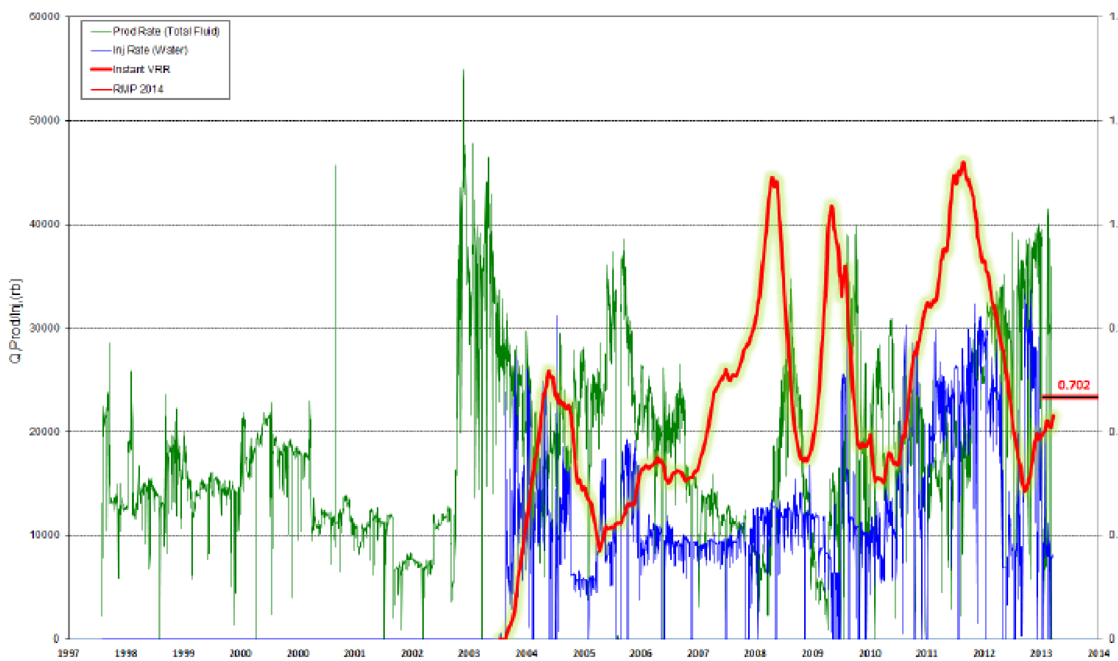


Figure 19: 6 months rolling VRR of Mega I-90 Reservoir

By considering figure 19 to 21, it is clearly shown that the effectiveness of water injection in both reservoir compartments was interfered by the connection in aquifer between them. Since NW I-90 shows a much greater VRR ratio than in WBK I-90, it can be explained that not every barrel of water injected in WBK I-90 are supporting its own production, but being shared with NW I-90.

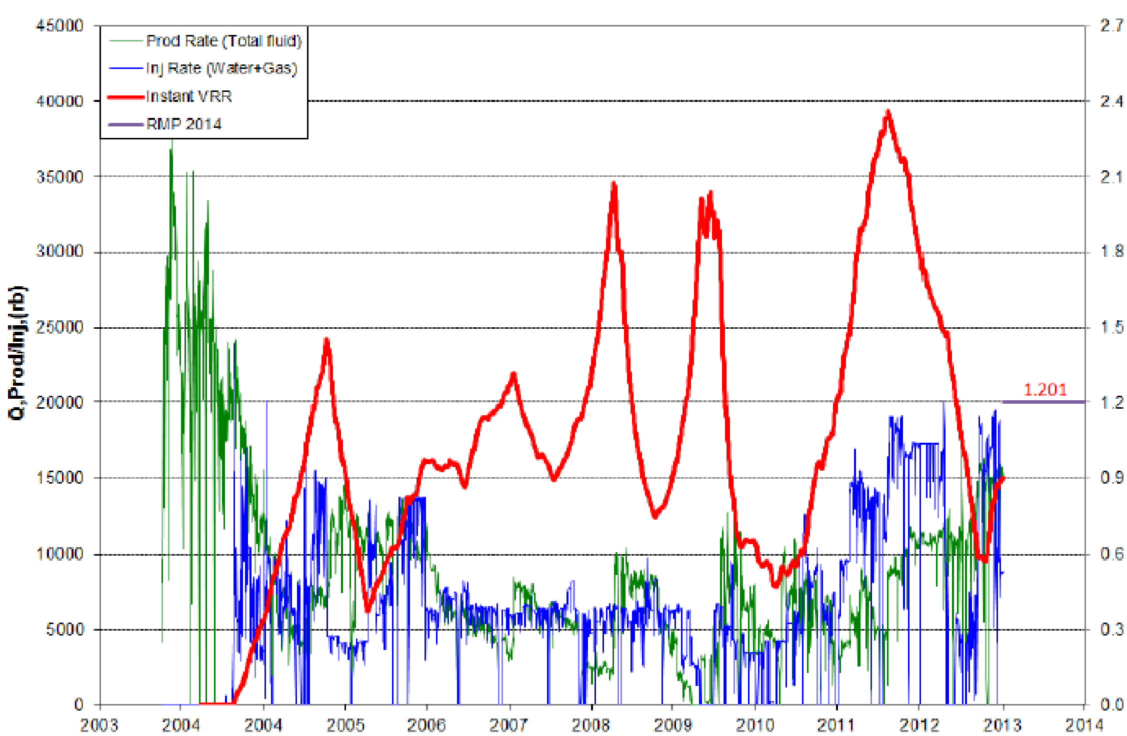


Figure 20: 6 months rolling VRR of NW I-90

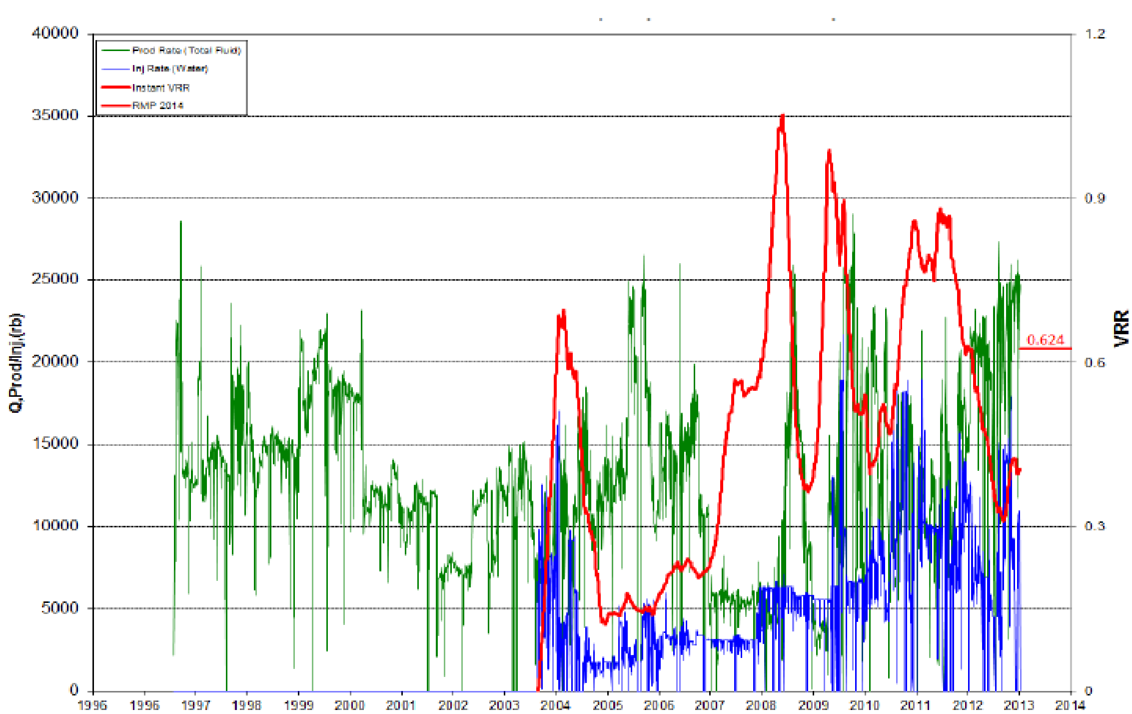


Figure 21: 6 months rolling VRR of WBK I-90

Reservoir pressure in different wells and different pressure tests are corrected to the same datum:

NWBR I-90 datum = 6749ftss

Well	Reservoir	Date	Pressures at Gauge Depth			Gauge Depth		Datum Depth		Pressures at Datum Depth		
			Pwf	P*	Pi	MD	TVDSS	TVDSS	diff.	Pwf	P*	Pi
			psia	*psia*	*psia*	*ft*	*ft*	*ft*	*ft*	*psia*	*psia*	*psia*
		29/Jul/97			2,866		6,596	6,749	153			2,911.6
A1-S	I-90	28/May/98	2,214	2,429	2,419	6,709	6,224	**6,749**	525	2,372	2,587	2,587.0
BKA4-S	I-90	31/May/98	1,725	2,602	2,553	7,243	6,514	**6,749**	235	1,796	2,673	2,628.2
BKA4-S	I-90	3/Aug/98	1,709	2,559	2,530	7,243	6,514	**6,749**	235	1,780	2,630	2,605.2
BKA4-S	I-90	4/Jul/00	1,522	2,344	2,294	7,237	6,509	**6,749**	240	1,594	2,421	2,420.8
BKA4-S	I-90	30/Jul/01			1,907	7,237	6,509	**6,749**	240			1,983.8
BKA4-S	I-90	30/Jan/06	1,950	2,191	2,202	7,237	6,509	**6,749**	240	2,022	2,263	2,278.8
BKA4-S	I-90	17/Aug/06	1,969	2,175	2,183	7,254	6,523	**6,749**	226	2,037	2,243	2,255.3
BKA4-S	I-90	21/Dec/07			2,240	7,261	6,529	**6,749**	220			2,310.4
BKA5-S	I-90	23/Feb/99	2,188	2,358	2,354	6,644	6,414	**6,749**	335	2,289	2,459	2,461.2
BKA5-S	I-90	2/Nov/99	2,029	2,268	2,262	6,641	6,411	**6,749**	338	2,122	2,361	2,370.2
BKA5-S	I-90	21/Jul/00	1,945	2,234	2,231	6,641	6,411	**6,749**	338	2,046	2,335	2,339.2
BKA5-S	I-90	24/Mar/02			2,230	6,640	6,410	**6,749**	339			2,338.5
BKA5-S	I-90	16/Apr/03			2,253	6,640	6,410	**6,749**	339			2,361.5
A7-L	I-90	13/Jan/00	2,468	2,501	2,499	9,619	6,580	**6,749**	169	2,510	2,552	2,553.1
A7-L	I-90	24/Jul/00	2,200	2,317	2,325	9,465	6,472	**6,749**	277	2,283	2,400	2,413.6
A7-L	I-90	29/Oct/00	2,171	2,296	2,298	9,465	6,472	**6,749**	277	2,254	2,379	2,386.6
A7ST1S	I-90	8/May/02	1,712		2,069	8,123	6,504	**6,749**	245	1,786	74	2,147.4
A7ST1S	I-90	26/Oct/02			2,054	8,123	6,504	**6,749**	245	74	74	2,132.4
BKC-11L	I-90	1/Aug/05	3,560		2,338	11,923	6,666	**6,749**	83	3,585	25	2,364.3
BKA-05L	I-90	29/Jun/08			2,278	6,428	6,543	**6,749**	206			2,344.1
BKA-05L	I-90	11/May/09			2,354	6,752	6,633	**6,749**	116			2,390.9
BKA-05L	I-90	15/Jun/12			2,349	6,664	6,437	**6,749**	312			2,442.2
BKC-25	I-80/90U	6/Apr/09						**6,749**				2,435.3
BKC-29	I-80	16/Nov/09						**6,749**				2,423.6
BKC-29	I-90	16/Nov/09						**6,749**				2,447.3
BKC-29	I-90	5/Nov/10			2,847		6632.137	**6,749**	117			2,898

Table 3: Reservoir pressure corrected to the same datum depth

PVT Matching

Rock and Fluid data were acquired from DST Test. Below are the PVT input for two tanks:

For WBK I-90

Input parameters	Unit	
Formation GOR	scf/STB	552
Oil Gravity	API	36
Gas Gravity	sp. Gravity	1.118
Gas Remixing	%/year	0
Mole Percent H2S	%	0
Mole Percent CO2	%	36
Mole Percent N2	%	0.77
Water Salinity	ppm	15000

Separator	Single -Stage
Correlations Pb, Rs, Bo	Vazquez-Beggs
Oil Viscosity	Beggs et al

Temperature	def F	245
Initial Pressure	psia	2905
Porosity	%	18
Swi	%	19
STOOIP	MMSTB	60

Table 4: PVT data for WBK I90

For NWBR I-90

Input parameters	Unit	
Formation GOR	scf/STB	612
Oil Gravity	API	32.8
Gas Gravity	sp. Gravity	1.16
Gas Remixing	%/year	0
Mole Percent H2S	%	0
Mole Percent CO2	%	34.83
Mole Percent N2	%	0.43
Water Salinity	ppm	15000

Separator	Single -Stage
Correlations Pb, Rs, Bo	Vazquez-Beggs
Oil Viscosity	Beal et al

Temperature	def F	252
Initial Pressure	psia	2921.7
Porosity	%	18
Swi	%	19
Gas cap *	fraction	0.1262
STOOIP	MMSTB	25.91

*‘m’ ratio

Table 5: PVT data for NWBR I90

Simulation

After revising PVT and reservoir rock data, the re-allocated production and injection data are inputted. The reservoir model is now ready to be simulated. A simulation will be run and simulated result will be compared with history data to evaluate the feasibility of simulation attempt. For this model, reservoir pressure is the match parameter.

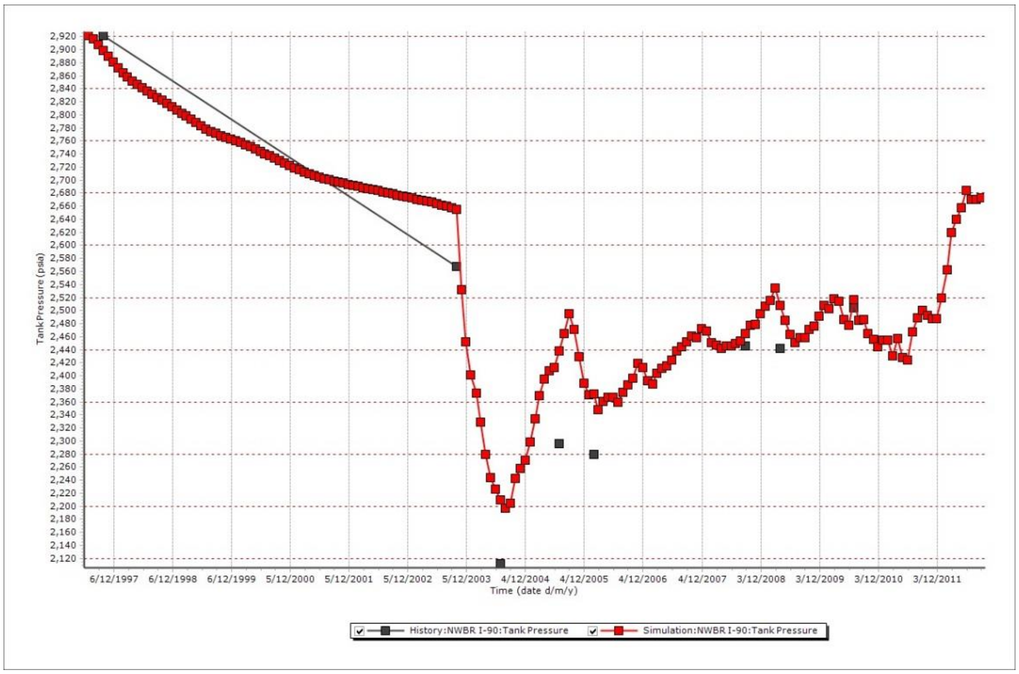


Figure 22: Pressure Match NWBR I90

As observed from the above plot, the simulated pressure data follow the trend of history data. The average difference between simulated data and history data is less than 10%, which is consider a good match. Moreover, as mentioned earlier, after the simulation is run, a Fw match will be establish in order to generate a set of representation relative permeability data. The below plots are Fw match for two tanks:

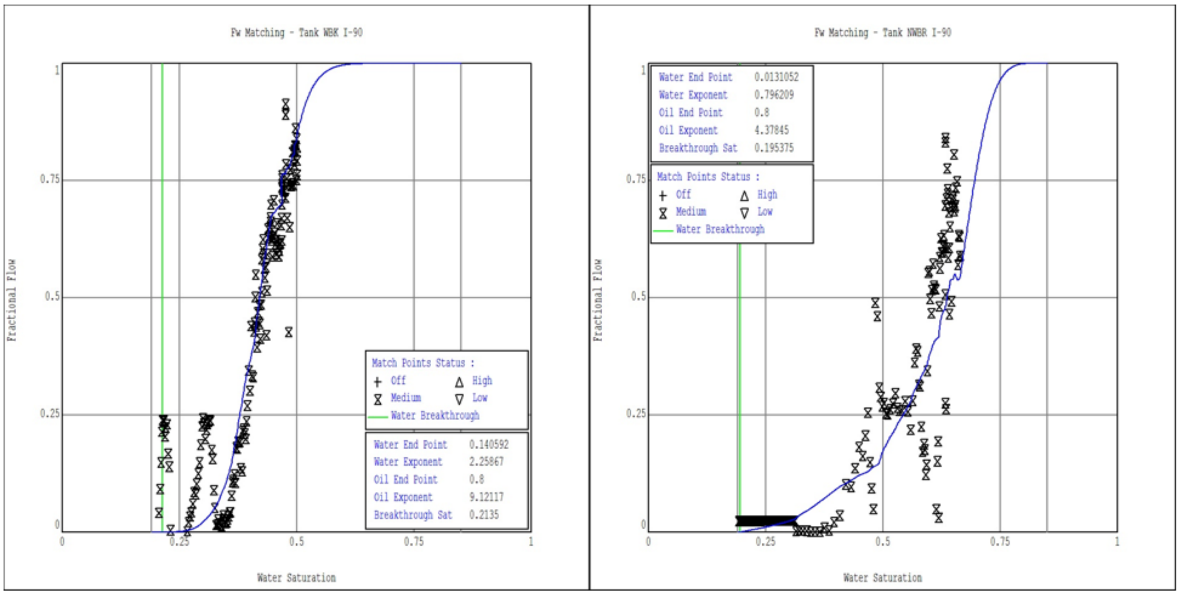


Figure 23: Fw Matching NWBR I90 & WBK I90

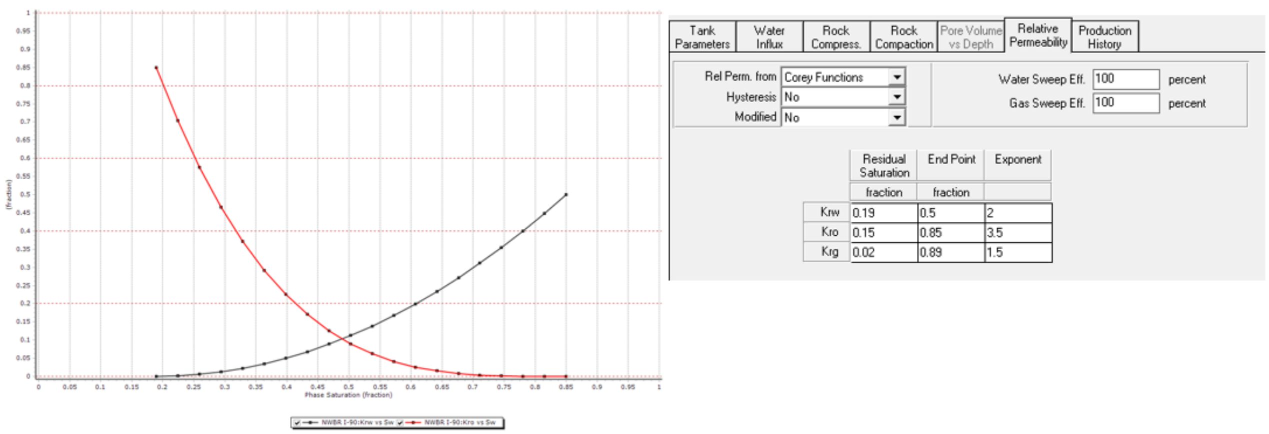


Figure 24: Rel perm curve for NWBR I-90

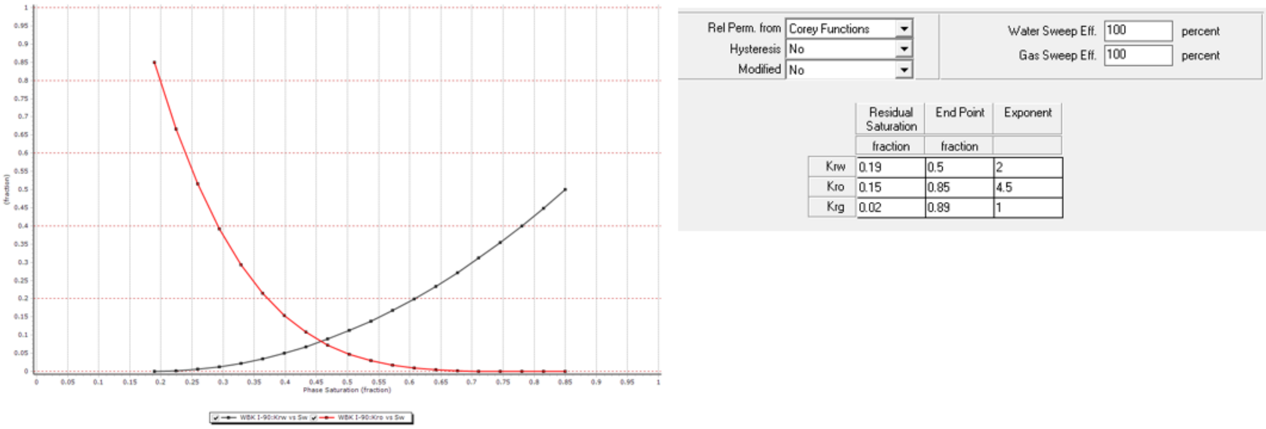


Figure 25: Rel perm curve for WBK I-90

Up to this step, a history match can be obtained by doing regression and running sensitivity on particular parameters such as aquifer strength, gas cap size and transmissibility constant. The non-regression parameters are hydrocarbon in place and properties such as porosity and permeability. As a result of tuning the model, relative permeability is the most sensitive parameter for matching process.

After regression with aquifer strength, a decent match was obtained with transmissibility constant of 7 RB/day*cp/psi and aquifer size was determined by these parameters:

Model	Hurst-van Everdingen-Modified
System	Radial Aquifer
Reservoir Thickness	65 ft
Reservoir Radius	6000 ft
Outer/ Inner Radius Ratio	5.8
Encroachment Angel	180 degree
Aquifer Permeability	50 md

Table 6: Aquifer model for NWBR I90

Model	Hurst-van Everdingen-Modified
System	Radial Aquifer
Reservoir Thickness	65
Reservoir Radius	5250
Outer/ Inner Radius Ratio	9.35
Encroachment Angle	180
Aquifer Permeability	50

Table 7: Aquifer Model for WBK I-90

These two reservoirs sharing the same aquifer which is divided into two large aquifer tanks. The energy plot below shows a great contribution of water influx in drive mechanisms.

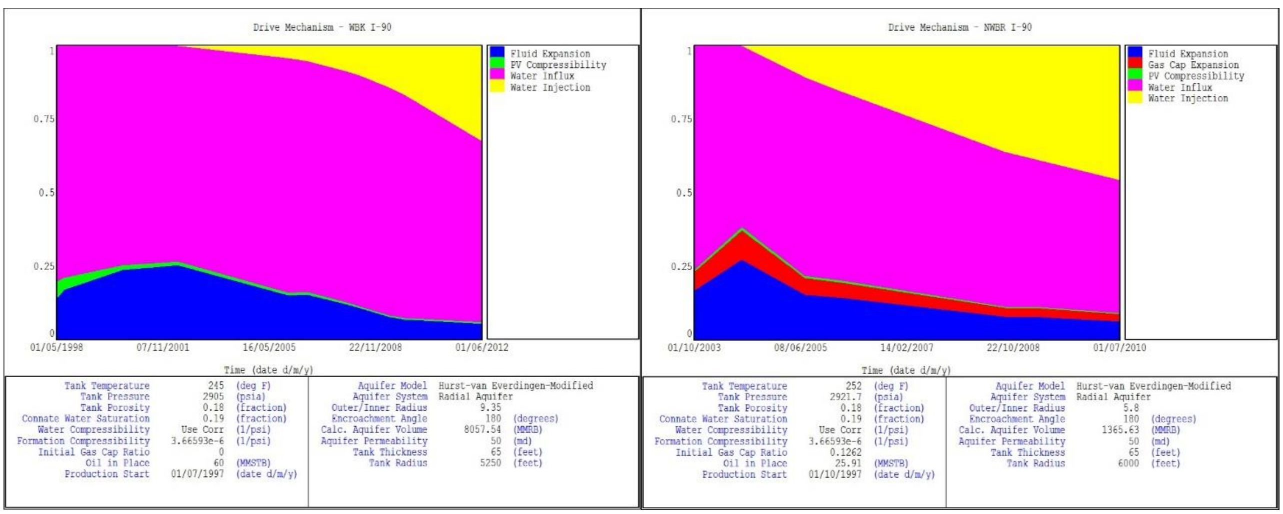


Figure 26: Energy plot for both tanks

The pink portion indicates the energy contribution of water influx to drive mechanism while the portion in yellow and red indicate water injection and gas cap expansion respectively.

The most important match is using analytical approach to match reservoir pressure versus cumulative oil production using three sensitivity cases

- Without aquifer influx and transmissibility
- With aquifer influx and without transmissibility
- With aquifer influx and transmissibility

While using the same static data with more robust simulators such as hydrocarbon in place, rock and fluid properties, the 1-D simulator using material balance approach still yields a very close match. This implies that reservoir can be consider almost homogeneous and anisotropic. The final match below also leads to conclusion that the flux flow only from NWBR I90 to WBK I90.

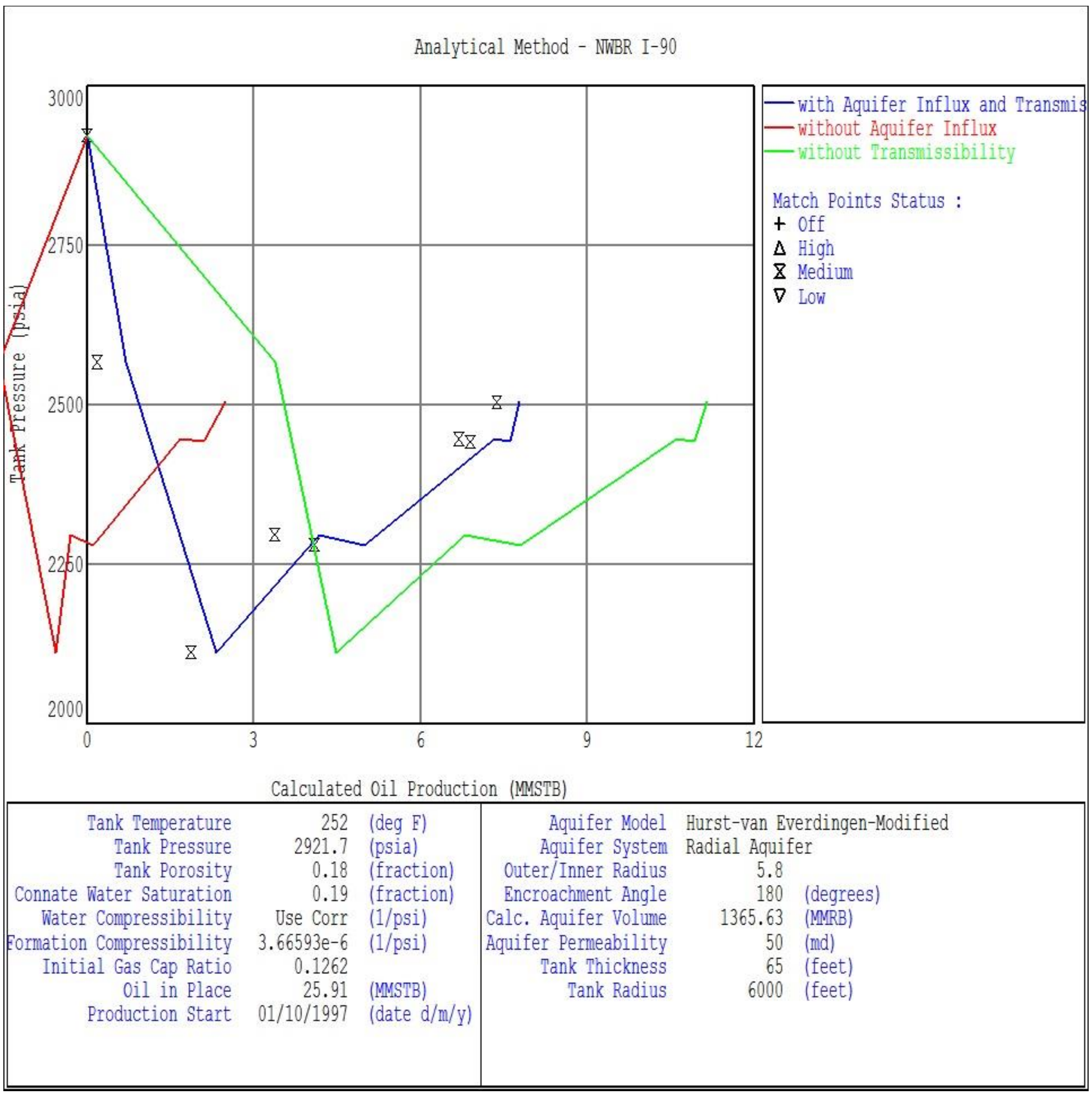


Figure 27: Analytical History Matching NWBR I90

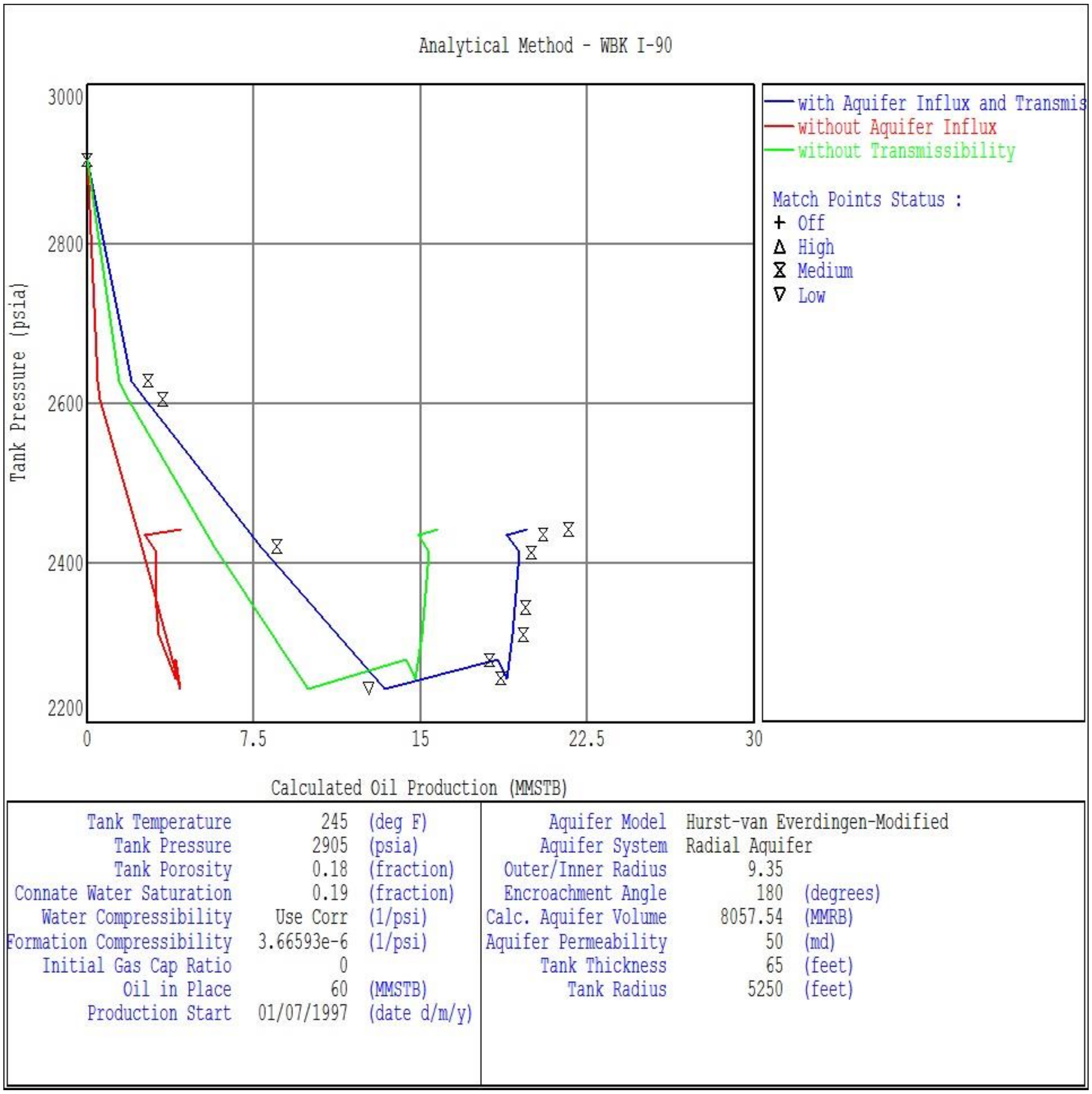


Figure 28: Analytical History Matching WBK I90

4.2 Discussion

The reservoir pressure analysis has provided with the first evidence of transmissibility in pilot reservoir. With the collected production and injection data, the application of manual back-allocation need to be carried out in order to utilize these data for history matching.

A set if iteration and regression were run in the material balance based simulator to generate a decent match of production history versus corresponding reservoir pressure.

The result provided from simulator were used to validate with geological data and reservoir description to ensure the feasibility of proposed method.

The same approach can be done every year with the updated production and injection data from offshore to monitor the influx rate of transmissibility between reservoir compartments across leaking faults. The integrated workflow is the combination of reservoir surveillance, data inspection & QC and reservoir simulation.

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

1. Transmissibility is the major modeling component in a multi-tank MBAL model to estimate the rate of reservoir fluid movement across the leaking fault.
2. A transmissibility rate was estimated at 7rb/day*cp/psi. The parameters that are most sensitive with regression to obtain a decent match are relative permeability, aquifer strength and influx rate.
3. In order to build a representative MB model, data inspection and validation need to be carried out in details of reservoir pressure, injection and production data.
4. Along with MB model to estimate the transmissibility, reservoir pressure and Voidage Replacement Ratio Analysis are minor tools to indicate the fluid movement.

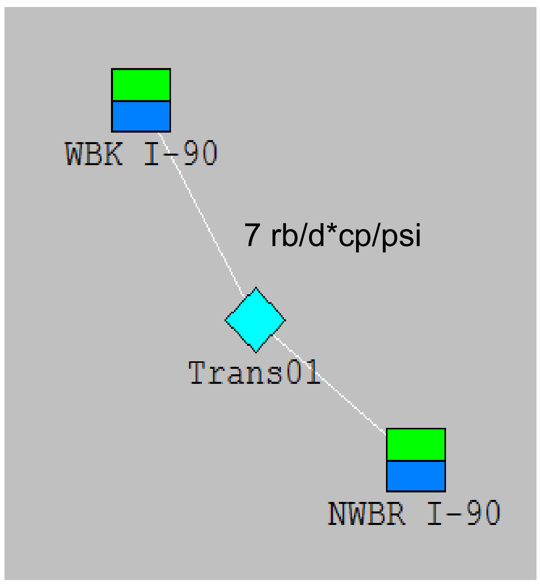


Figure 29: Model setup philosophy and result

5.2 Recommendation

1. Existing wells having adequate data to generate a reliable model is required.
2. Appropriate data acquisition campaign need to be carried out to acquire good surveillance data.
3. Data acquisition needs to cover both surface and subsurface data.
4. This tool is a quick check for dynamic communication between waterflooded reservoirs and not applicable in predicting reservoir performance due to water injection.

REFERENCES

1. Blaskovich, F. T.: "Historical Problems with Old Field Rejuvenation," paper SPE 59471 presented at the 2000 SPE Asia Pacific Conference on Integrated Modeling for Asset Management, Yokohama, Japan, April 25-26.

2. Craft, B.C. and Hawkins, M.F.: "Applied Petroleum Reservoir Engineering," second edition, Prentice- Hall Inc. Englewood Cliffs, N.J. (1991).

3. Bui, T., Bandal, M., and Hutamin, M.: "Material Balance Analysis in Complex Mature Reservoirs - Experience in Samarang Field, Malaysia," paper SPE 101138 presented at the 2006 SPE Asia Pacific Oil & Gas Conference and Exhibition held in Adelaide, Australia, 11-13 September 2006.

4. Havlena, D. and Odeh, A. S.: "The Material Balance as the Equation of a Straight Line," JPT (August 1963).

5. Dake L.P.: "Fundamentals of Reservoir Engineering", Elsevier, Amsterdam (1977) 443.

6. MBAL Technical Manual, ver. 8.1, Petroleum Experts, 2013.

7. Chukwuemeka N., I.: "Material Balance Modeling of Hydraulically Connected Reservoirs in a Single System: Case Studies," paper SPE 167561 presented at the Nigeria Annual International Conference and Exhibition held in Lagos, Nigeria, July 29 –August 2 2013.

8. Chukwuemeka E. N., I. U.: "Well Predictive Material Balance Evaluation: A Quick Tool for Reservoir Performance Analysis," paper SPE 162988 presented at the 2012 SPE Nigerian Annual International Conference and Exhibition held in Abuja, Nigeria, 6-8 August 2012.

9. Abu, E.E.: "Reservoir Characterization from Material Balance Result Analysis," paper SPE 108548 presented at the 2007 International Oil Conference and Exhibition in Mexico held in Veracruz, Mexico, 27-30 June 2007.

10. Abdelaziz, Bensadok, and Djebbar Tiab. "Pressure behaviour of a well between two intersecting leaky fault." Annual SPE International Technical Conference and Exhibition. Abuja Nigeria: SPE, 2004.

11. Acharya, U.K., R.A. Eisenberg, R.J. Brenneman, and A.A. Adeogba. "Integrated Fault Seal Characterization for Reservoir Management." Asia Pacific Oil & Gas Conference and Exhibition. Kuala Lumpur: SPE, 1997.

12. Edris, N.R., K.D. Stephen, A. Shams, and C. MacBeth. "Updating Fault Transmissibilies in Simulations by Successively Adding Data to an Automated Seismic History Matching Processes: A Case Study." SPE Europe/EAGE Annual Conference and Exhibition. Rome, Italy: SPE, 2008. 9.

13. Lange, A., J. Bouzian, and B. Bourbiaux. "Tracer-Test Simulation on Discrete Fracture Network Models for the Characterization of Fractured Reservoirs." SPE Europec/EAGE Avvual Conference. Madrid, Spain: SPE, 2005.10

14. Stewart, G., A. Gupta, and P. Westaway. "The interpretation of Interference Tests in a Reservoir with Sealing and Partially Communicating Faults." European Petroleum Conference. London, England: SPEDAL, 1984. 17.

15. Yaxley, L.M. "Effect of a Partially Communicating Fault on Transient Pressure Behavior." SPE Formation Evaluation, 1987: 590-598.

APPENDICES

Appendix A: West I-90 Reservoir Pressure

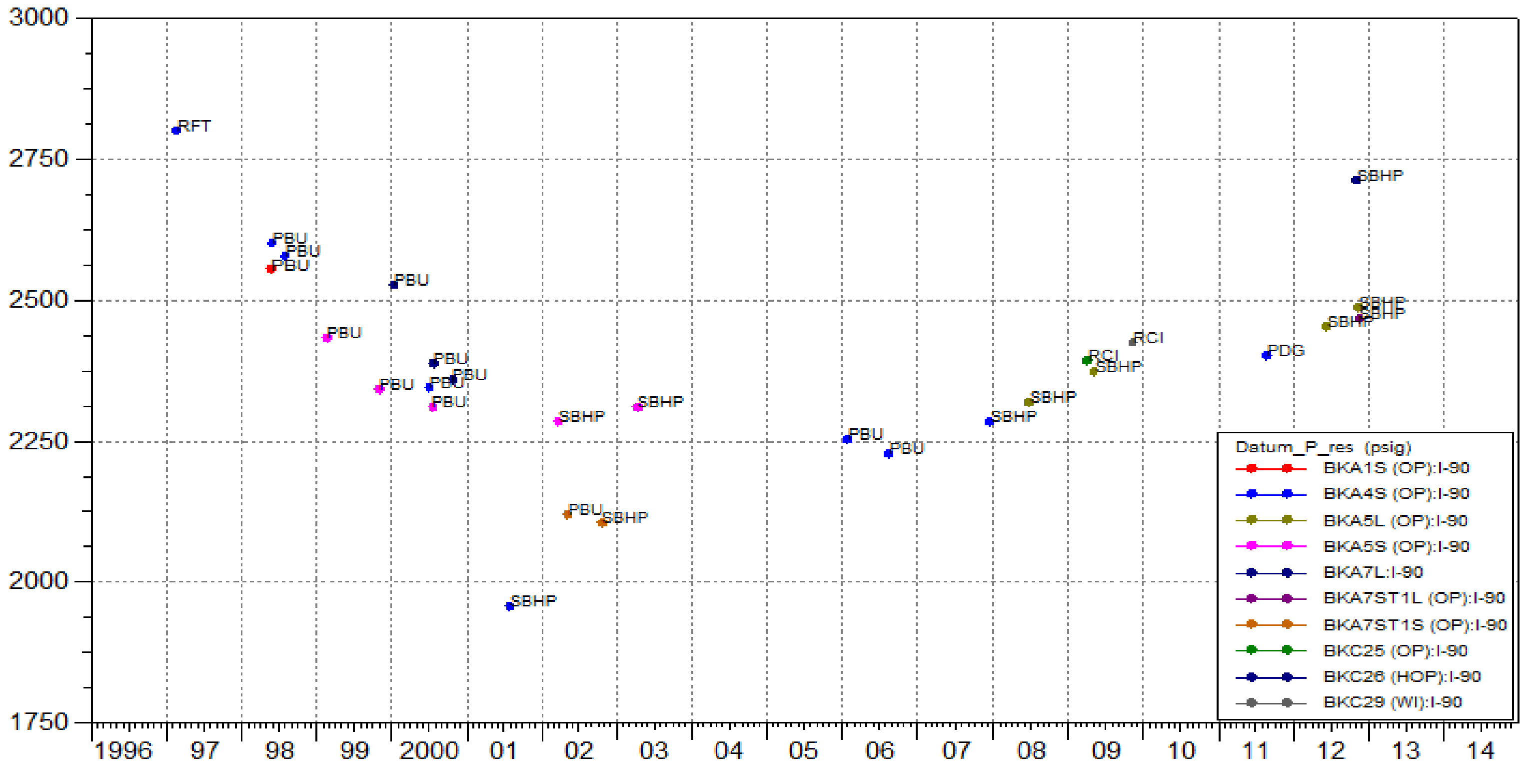
Appendix B: West I-90 stick diagram

Appendix C: North West I-90 Reservoir Pressure

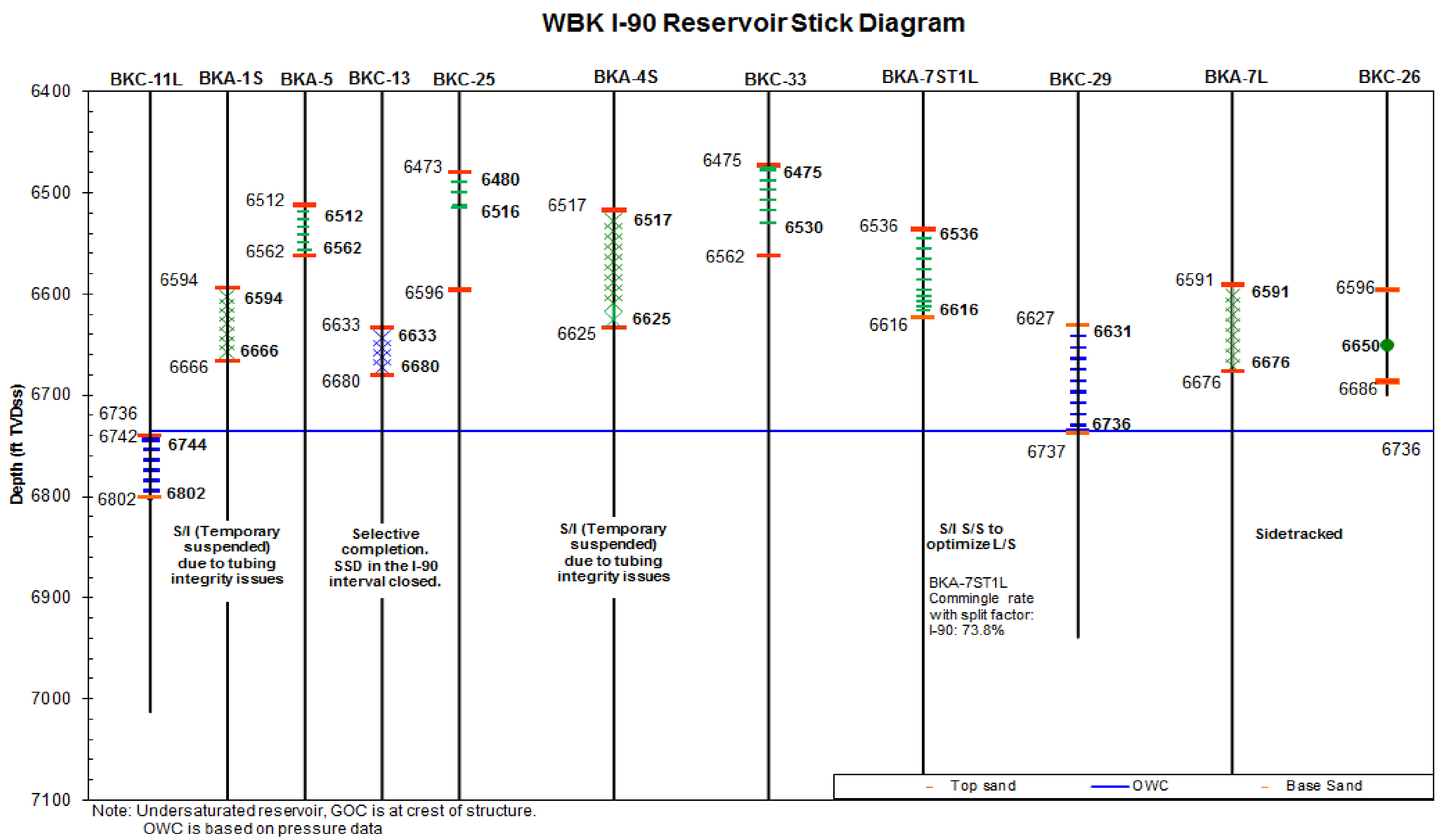
Appendix D: North West I-90 stick diagram

Appendix E: North West Bunga Raya – I90L AI and Depth map

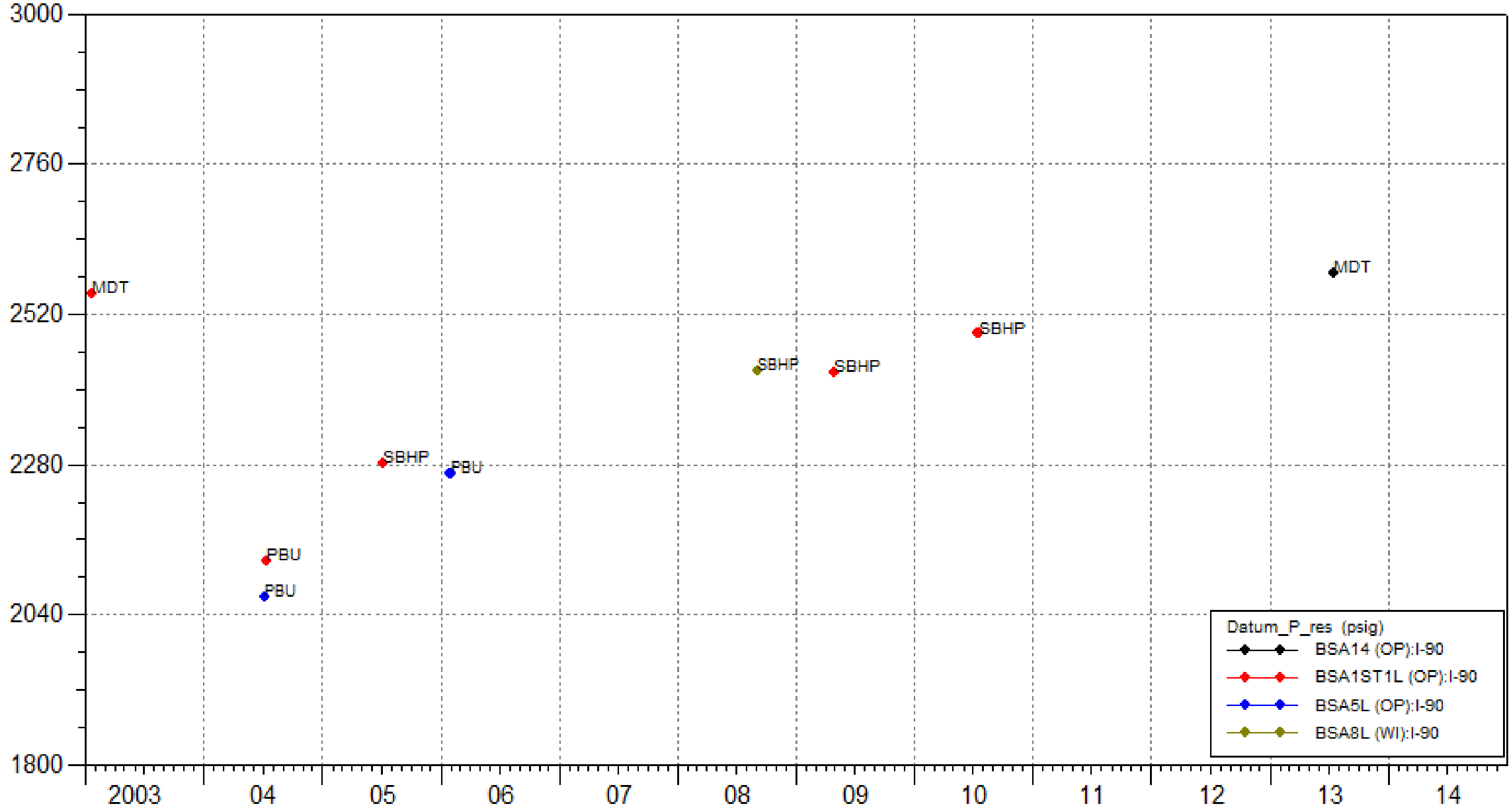
Appendix F: West Bunga Kekwa – I90U AI and Depth map



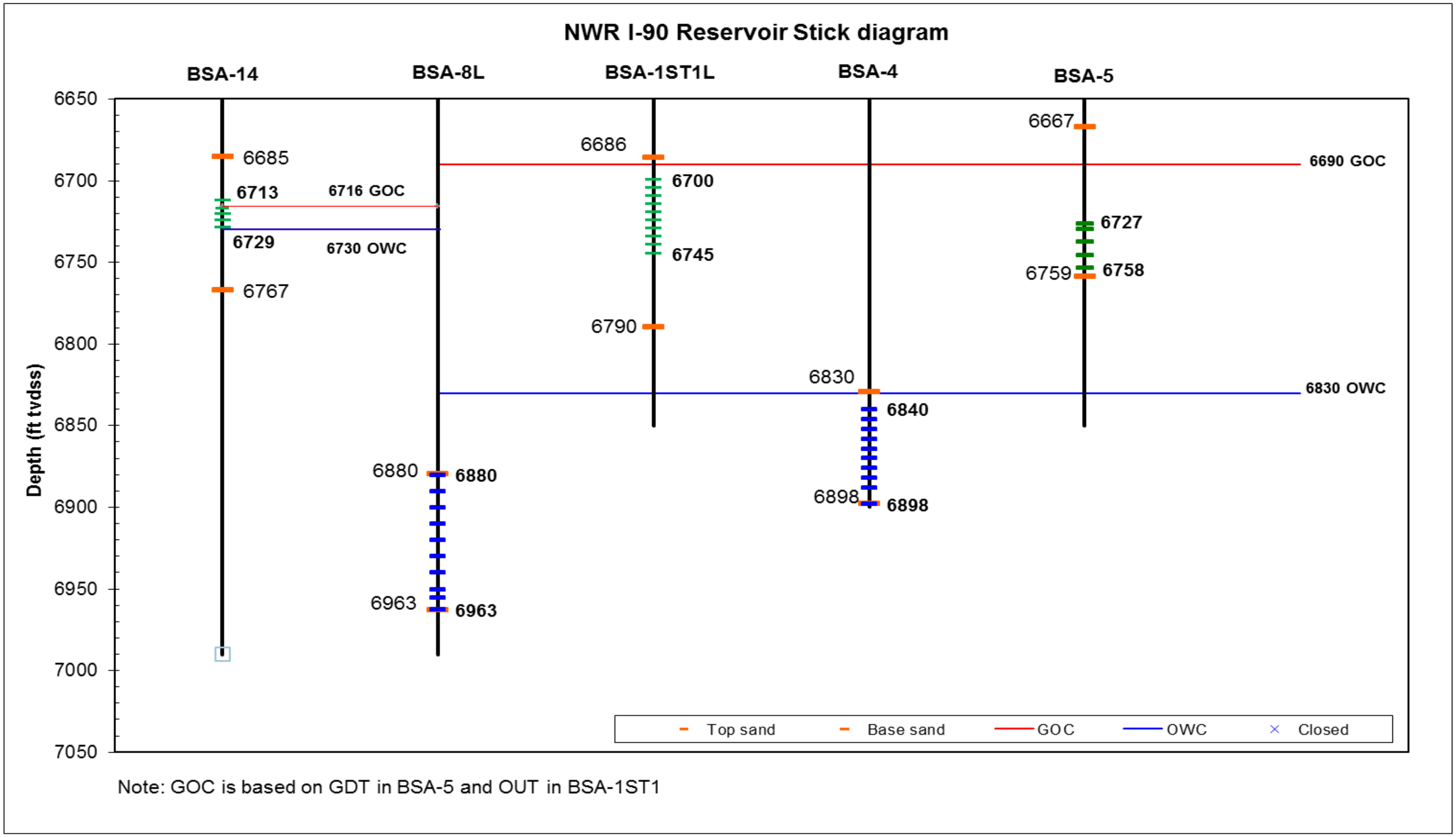
Appendix A: West I-90 Reservoir Pressure



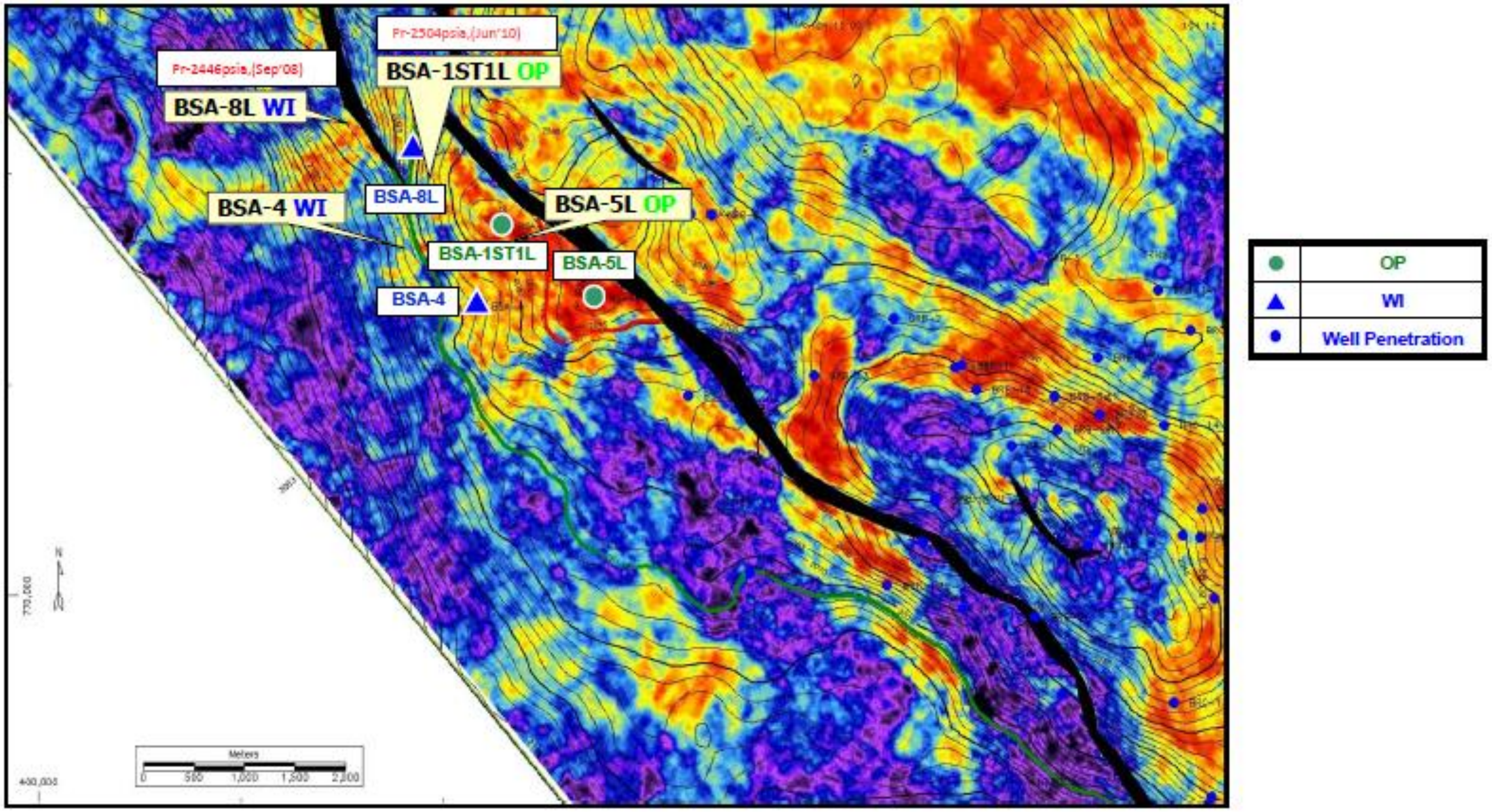
Appendix B: West I-90 stick diagram



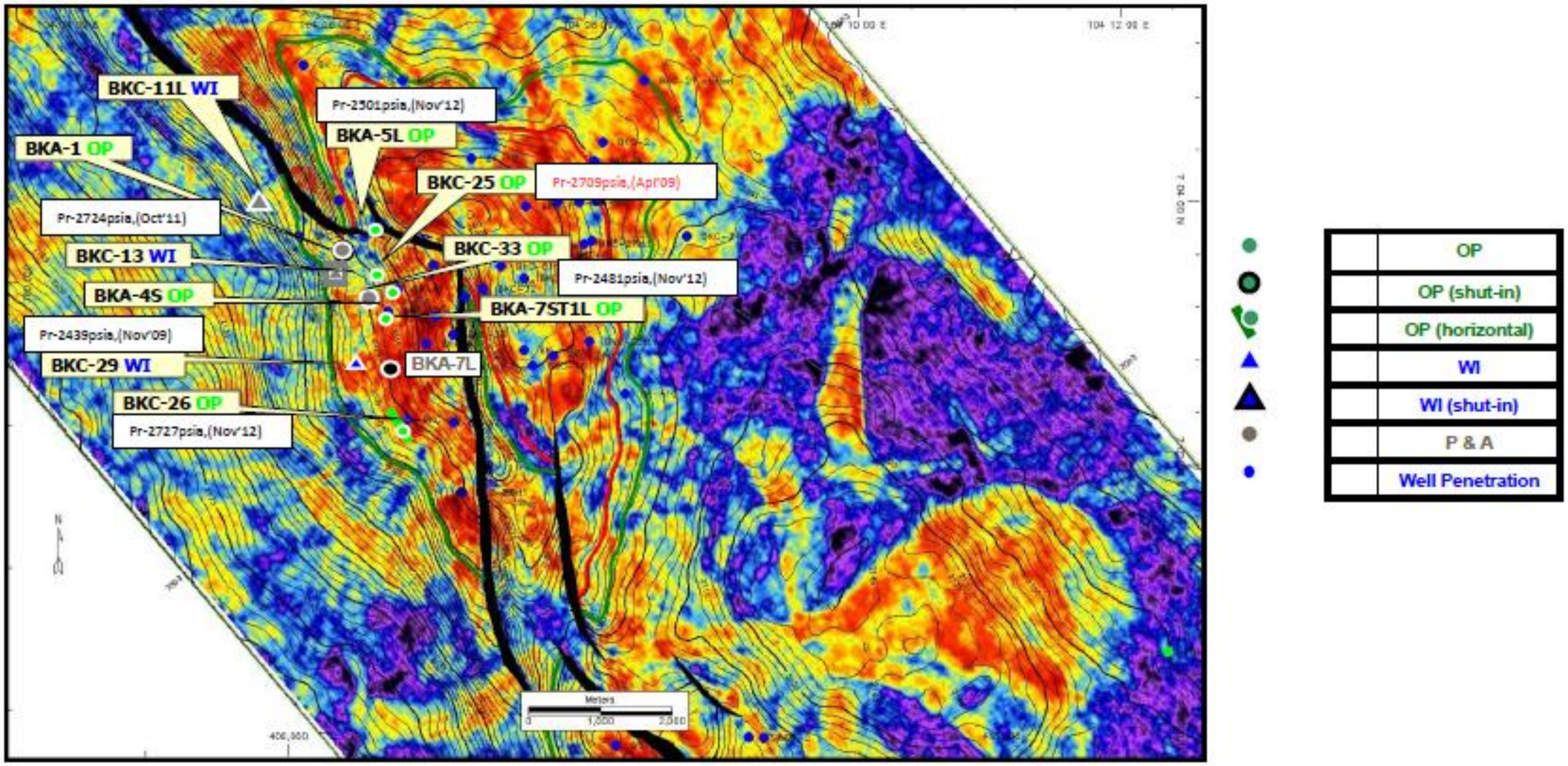
Appendix C: North West I-90 Reservoir Pressure



Appendix D: North West I-90 stick diagram



Appendix E: North West Bunga Raya – I90L AI and Depth map



Appendix F: West Bunga Kekwa – I90U AI and Depth map