IMPERIAL COLLEGE LONDON

Department of Earth Science and Engineering

Centre for Petroleum Studies

Combination of Conventional and Optimisation Techniques for Performance Prediction in Large Waterflood Projects

By

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

September 2011

DECLARATION OF OWN WORK

I declare that this thesis *Combination of Conventional and Analytical Techniques for Performance Prediction in Large Waterflood Projects* 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

Quantification of reservoir and fluid properties in large, highly matured fields with high watercuts is proving to be a main issue in reservoir characterization and engineering due to bad production and reservoir data management. Most of these matured fields, such as a matured field located in Romania that is analysed in this study, have been producing for more than 40 years, and the data available such as production data, pressure data, fluid properties data and Special Core Analysis (SCAL) data for these fields are either sparse or unavailable. The purpose of this study is to develop a methodology to estimate and quantify the reservoir and fluid properties of these fields and reduce the uncertainty in these fields.

The study incorporates the use of linear and one-dimensional Buckley-Leverett Theory (Buckley and Leverett 1942) to analyse the sparse production data for a well located in a matured field in Romania. A real-time producer which was pre-assessed for good connectivity with an injector was used in this analysis to test the methodology. Using the Buckley-Leverett Theory, the parameters of the reservoir and fluids were optimized using a simple algorithm to history match the actual production data with the generated Buckley-Leverett solution. This method resulted in multiple solution sets of the average reservoir and fluid properties and the drainage volumes surrounding the producer well. The properties that could be estimated with this methodology include absolute permeability, Corey exponents, fluid viscosities, porosity, net pay thickness, width of the flood etc. The study finally discusses the development and implementation of an Automated-History Matching tool, called WATERFLOOD, which is based on the methodology discussed in the study.

The paper also discusses the limitations and assumptions of this method. Using simulated production data, the results show that this method can be used for accurate estimation of these properties for horizontal and slightly dipping reservoirs but not for gravity-dominated, largely dipping reservoirs. This is due to the assumption of no change to the fractional flow curve due to gravity when the total liquid rate is varied. This tool would not only be able to estimate reservoir and fluid properties, which can be used as precursors for reservoir model characterization for future dynamic simulations, but would also aid in decision-making of future infill drilling campaigns.

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I would also like to thank my industry supervisor, Mrs Archana Kumar, for her help and advice on Buckley-Leverett Theory and Automated History Matching of production history with Buckley-Leverett Solutions.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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Combination of Conventional and Optimisation Techniques for Performance Prediction in Large Waterflood Projects

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Abstract

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Introduction

Large fields that are characterized by high maturity and high watercuts are proving to be very difficult to implement traditional workflows, such as geocellular modeling and advanced 3D dynamic simulation techniques to provide reliable insights towards future decision making around infill drilling and flood pattern optimization. Due to bad data management in the past, inaccuracy or unavailability in data collection of these reservoir properties for these matured fields are common. These limitations result in the accuracy with which the reservoir properties can be estimated in these matured fields. Due to the very high cost of coring analysis to estimate reservoir parameters, a lot of emphasis is focused on history matching of production data. In this process, the reservoir and fluid parameters are manipulated til the simulated production data matches the data that was measured during production.

In cases of highly matured fields that has been producing for more than 40 years, where the data are sparsely distributed and often are of very bad quality, simulation of production data itself is an arduous process due to the properties selection being spatially three-dimensional (3D) during the history matching. Therefore, for this type of fields, the simplest way forward would be to use one-dimensional (1D) conventional analytical techniques instead of 3D numerical techniques to perform the history matching and estimate the reservoir and fluid properties.

Sitorus *et al*(2006), worked on development of fractional flow curve from historic production. It involved using a commercial optimisation program to historically match the production data by optimizing the parameters of the fractional flow curve. However, this method is only analysed for performance prediction for horizontal wells and in estimating only the relative permeabilities-saturation relationships and the fluid properties, not inclusive of the drainage areas, volumes and porosity.

Van den Bosch *et al* (1977) explained history matching two phase petroleum reservoirs for incompressible flow which would be able to estimate porosity, absolute permeability and relative permeability-saturation relationships. To be able to use this method successfully, significantly good production data and pressure data has to be present for the accurate estimation of these properties.

The 1D history matching is developed from the Buckley-Leverett theory (Buckley *and Leverett* 1942) assuming a post-breakthrough saturation profile in this study. This paper describes a methodology based on 1D Buckley-Leverett Theory for estimation of reservoir and fluid properties by history matching only production and injection data and analysis on the constraints and assumptions that are made for this methodology are discussed.

Theory

Oil displacement by waterflooding is assumed to take place under diffuse flow condition where the fluid saturations at any point are uniformly distributed with respect to thickness. Therefore, the displacement can be described in one dimension and provides the simplest possible model of the oil displacement by waterflooding (Buckley *and Leverett* 1942). The fractional flow of water, f_W, can be described from one-dimensional equations of simultaneous flow of oil and water by applying Darcy's Law. By simple derivation, the fractional flow of water in one dimension can be expressed as follows:

$$f_w = \frac{1+\frac{k k_{ro} A}{q_t \mu_o}\left(\frac{\partial P_c}{\partial x}-\Delta\rho g \sin\theta\right)}{1+\frac{\mu_w}{k_{rw}}\cdot\frac{k_{ro}}{\mu_o}} \tag{1}$$

Neglecting capillary pressure effects on fractional flow of water,

$$f_w = \frac{1-\frac{k k_{ro} A}{q_t \mu_o}(\Delta\rho g \sin\theta)}{1+\frac{\mu_w}{k_{rw}}\cdot\frac{k_{ro}}{\mu_o}} \tag{2}$$

Where k_{ro} and k_{rw} are the relative permeabilities of oil and water respectively, k is the average absolute permeability of the formation, A is the cross sectional area of the flow (product of the net pay thickness, h, and the width of the flood area, w), q_t is the total flow rate of the liquid, θ is the dip angle of the reservoir, Δ ρ is the density difference between oil and water and μ_o and μ_w are the viscosities of oil and water respectively.

For the analysis based on this paper, k_{ro} and k_{rw} can be approximated by the Corey Correlation:

$$k_{ro} = k_{roe}\left[\frac{(1-S_w-S_{or})}{1-S_{wc}-S_{or}}\right]^{N_o} \tag{3}$$

$$k_{rw} = k_{rwe}\left[\frac{(S_w-S_{wc})}{1-S_{wc}-S_{or}}\right]^{N_w} \tag{4}$$

k_{roe} and k_{rwe} are the respective oil and water relative permeability end points, S_{or} is the irreducible oil saturation, S_{wc} is the connate water saturation and N_o and N_w are the respective Corey oil and water exponents.

Buckley and Leverett (1942) presented the basic equation for describing immiscible displacement in one dimension. For water displacing oil, the equation determines the velocity of a plane of constant water saturation travelling through a linear system.

The equation states that the velocity of a plane of constant water saturation is directly proportional to the derivative of the fractional flow equation evaluated for that saturation as shown in (5).

$$\frac{dx}{dt}|_{S_w} = \frac{q_t}{A\emptyset}\frac{df_w}{dS_w}|_{S_w} \tag{5}$$

Where, ø is the average porosity of the formation.

Integrating (5) for the total time since the start of water flooding (injection),

$$x_{S_w} = \frac{1}{A\emptyset}\frac{df_w}{dS_w}|_{S_w} \int_0^t q_t dt \tag{6}$$

Further simplification of (4) leads to

$$x_{S_w} = \frac{W_i}{A\emptyset}\frac{df_w}{dS_w}|_{S_w} \tag{7}$$

Where W_i is the cumulative water injected and it is assumed that $W_i=0$ when t=0. This equations shows that position of the different water saturation planes can be plotted, using (5) by determining the slope of the fractional flow curve for the particular saturation.

Using (7) as the starting point we could derive oil recovery calculations after breakthrough of water at the production well. (8) and (9) relates the cumulative dimensionless number of pore volumes injected, W_{id}, and the cumulative dimensionless number of pore volumes produced after breakthrough of water, N_{pd}, respectively (Welge 1952).

$$W_{id} = \frac{1}{\frac{df_w}{dS_w}|_{S_{we}}} \tag{8}$$

$$N_{pd} = (S_{we} - S_{wc}) + (1 - f_{we})W_{id} \tag{9}$$

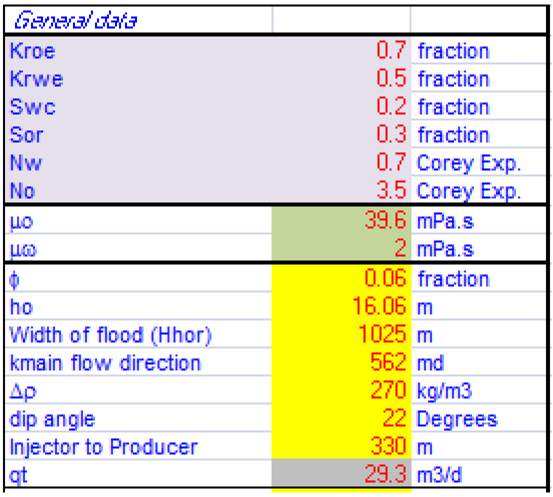
S_{we} and S_{wc} is the water saturation at the position of the producer and the connate water saturation respectively. f_{we} is the fractional flow of water at S_{we}.

Methodology and Analysis

The main idea is to generate an Auto History Match (Auto-HM) tool by a deterministic approach for wells that has been assessed to be well connected to injectors (well-connected injector-producer pairs). The Automated History match is implemented by fitting the generated Buckley-Leverett solution with the production and injection history data of the single well by optimizing the unknown reservoir, fluid and production parameters(such as k_{ro} and k_{rw} by changing the Corey parameters, k, μ_o, μ_w, the drainage area, h, θ, etc.). This is a multiple solution optimization workflow, where there are multiple sets of parameters solutions that can be generated for a history match. A simple optimization algorithm was implemented for the multiple solutions search for the Automated History Matching. The consistency of the matched parameters can be checked by cross plotting against the available data wherever possible. The Auto-HM solutions also provide the drainage area and the associated sweep efficiency (VSE) for each parameters solution set. The matched reservoir, fluid and production parameters can then be utilised as precursors for static and dynamic models characterization in the future.

Construction of BL spreadsheet

The construction of the Buckley-Leverett (BL) spreadsheet is the first step in developing the Auto-HM tool. Real-time production data of a well that has been operating for 54 years in a matured field in Romania was used to test the spreadsheet. The reservoir, fluid and production parameters were manually changed to fit the BL solution to the production data. The parameters that were available with the data were kept unchanged. The parameters that were unavailable with the data were manually changed to fit the BL solution for the Cumulative Oil Production (CumOil) versus Cumulative Water Injection (CumWater) plots and the WaterCut (WC) versus CumOil plots for the time period after breakthrough. This manual match would give one single set of the many plausible parameters solution sets. Figures 1, 2 and 3 illustrate the single matched solution set.



General data		
Kroe	0.7	fraction
Krwe	0.5	fraction
Swc	0.2	fraction
Sor	0.3	fraction
Nw	0.7	Corey Exp.
No	3.5	Corey Exp.
μo	39.6	mPa.s
μω	2	mPa.s
ϕ	0.06	fraction
ho	16.06	m
Width of flood (Hhor)	1025	m
kmain flow direction	562	md
Δρ	270	kg/m3
dip angle	22	Degrees
Injector to Producer	330	m
qt	29.3	m3/d

Figure 1 A single manual match solution set of parameters

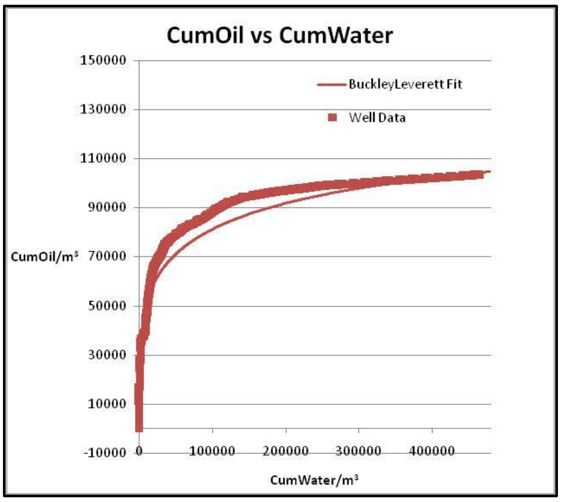


Figure 2 A single manual match for CumOil vs CumWater of a real time producer well.

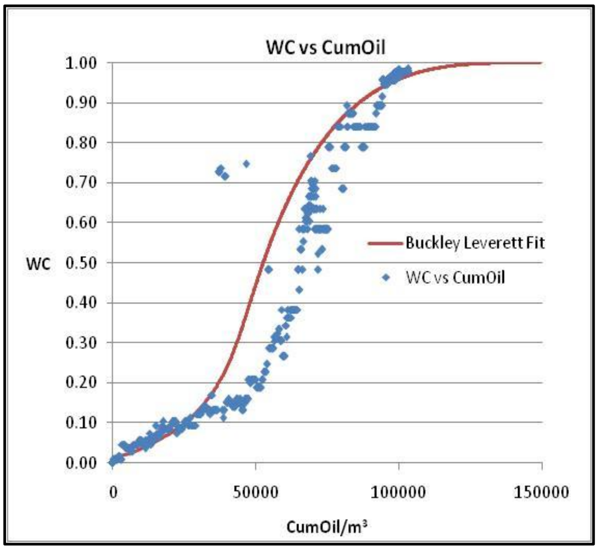


Figure 3 A single manual match for WC vs CumOil of a real time producer well.

Validation of negligible effect of variable q_t on f_w for low N_{gv} reservoirs

The production history data of the producer well shows that the well delivers variable total liquid production rates over time in reservoir volume. This indicates that the total liquid flow rate is not constant as assumed in fractional flow derivation and in the Buckley-Leverett solution derivation. Therefore, it has to be validated that the variable total liquid production rates do not affect the fractional flow curve and therefore do not affect the Buckley-Leverett solution. A new term is introduced in (2) to account for the gravity term, called the Gravity number, N_{gv} (Walsh and Moon 1991).

From (2),

$$f_w = \frac{1 - N_{gv} k_{ro}}{1 + \frac{\mu_w}{k_{rw}} \cdot \frac{k_{ro}}{\mu_o}} \tag{10}$$

Where,

$$N_{gv} = \frac{kA}{\mu_o q_t}(\Delta\rho g \sin\theta) \tag{11}$$

The magnitude of N_{gv} determines the change in fractional flow curve due to variable total liquid rate over the production history of the well. This magnitude is mainly dependent on the reservoir and oil fluid properties such as k, μ_o, θ, net pay thickness and Δρ. The N_{gv} corresponds to how gravity dominant the immiscible flow is in dipping reservoirs. When very high magnitude of k, h, θ, Δρ, is coupled with very low μ_o and q_t, the flow becomes very highly gravity-dominant (N_{gv} is more than 1) in a highly dipping reservoir. This relates to an immiscible flow of very light oil in a highly permeable and dipping reservoir with thick net pay. 2 cases were analysed by simulating data with ECLIPSE, a numerical simulator, and analysing with the BL spreadsheet on slightly gravity dominated reservoir and highly gravity dominated reservoir. These 2 cases were analysed to check how different simulation production data is with using variable rate scenario over time and a single average over time scenario. In addition the parameters solutions set that was obtained from the manual match was validated with the parameters set that were used to simulate the production data in ECLIPSE. The input files to the simulator for both cases 1 and 2 are shown in Appendices D to G.

Case 1

Case 1 is a highly gravity-dominated and dipping reservoir model. The properties of the reservoir are shown in Table 1. The total liquid flow rate in reservoir volume was varied for the simulation between 10 m^3/day and 125 m^3/day. The average permeability was set to be very high at about 25 Darcy (25000mD) to represent case 1 as an extreme case of a highly gravity-dominant reservoir. The net pay thickness is set to be at 10m. The dip angle was also set to be at a high angle of 45^o.

Table 1 Properties of reservoir for highly-gravity dominant and dipping reservoir and the production data for simulation of Case 1

Average K (mD)	25000	**N_o**	2
Φ	0.3	**N_w**	2
Δρ (kg/m^3)	300	**S_{or}**	0.2
μ_o(mPa.s)	17	**S_{wc}**	0.2
μ_w(mPa.s)	1.5	**Θ**	45^o
K_{roe}	1	**q_t range (m^3/d)**	10-125
k_{rwe}	1	**Average q_t (m^3/d)**	65
h	10	**Duration of simulation (days)**	9150

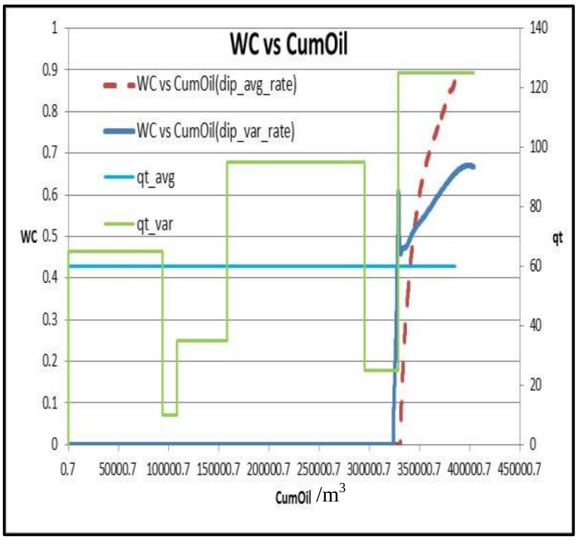


Figure 4 Comparison of WC vs CumOil using variable rate and average rate throughout the production history for Case 1

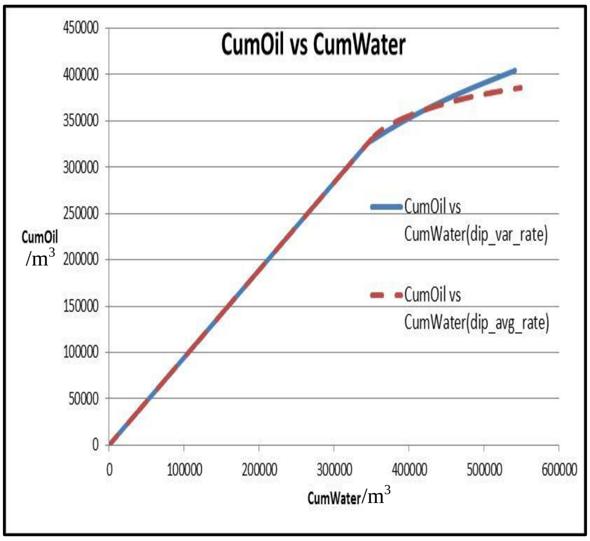


Figure 5 Comparison of CumOil vs CumWater using variable rate and average rate throughout the production history for Case 1

After running the simulation for case 1 reservoir model with 1 injector and 1 producer, the simulation results were compared with the results of a simulation of the same reservoir model but with an average total liquid rate of 65m^3/day. The CumOil versus CumWater plot and WC versus CumOil plot were used for the analysis of the two different scenarios for case 1 reservoir model. Figures 3 and 4 illustrate the comparison of these 2 scenarios. It can be deduced from the plots that for the average total liquid rate scenario, more water needs to be injected than for the variable liquid rate scenario to produce the same volume of oil. Therefore, there is a slight deflection for the average total liquid rate scenario from the variable liquid rate scenario in the CumOil versus CumWater plot after breakthrough. Another difference that can be noted between the 2 scenarios is the start of breakthrough. For Figure 4, it can be deduced that the start of breakthrough is slightly earlier for the variable total liquid rate scenario. This may be caused by the fractional flow curve changes due to the differences in the total rates between the 2 scenarios. The watercut of the average total liquid rate scenario also reaches a high value, increasing sharply even though it has a later breakthrough when compared to the variable liquid rate scenario. These slight differences may be due to the fractional flow curve changes due to rate differences in the highly-gravity dominated and dipping reservoir.

Case 2

Case 2 is a slightly gravity dominated reservoir model. The properties are shown in Table 2. The total rates in reservoir volume were varied for the variable total liquid rates scenario for the same time period as case 1. For this case, the average permeability was set to be lower by a magnitude when compared to case 1 at 2.5 Darcy. The net pay thickness was lowered to 1.5m. This dip angle was also set to be at about 5^o to represent case 2 to be a slightly gravity-dominated and dipping reservoir as it has a comparably lower N_{gv} than case 1.

Table 2 Properties of reservoir for slightly-gravity dominant and dipping reservoir and the production data for simulation of Case 2

Average K (mD)	2500	**N_o**	2
Φ	0.3	**N_w**	2
Δρ (kg/m^3)	300	**S_{or}**	0.2
μ_o(mPa.s)	7	**S_{wc}**	0.2
μ_w(mPa.s)	1.5	**θ**	5^o
K_{roe}	1	**q_t range (m^3/d)**	10-125
k_{rwe}	1	**Average q_t (m^3/d)**	65
h	1.5	**Duration of simulation (days)**	9150

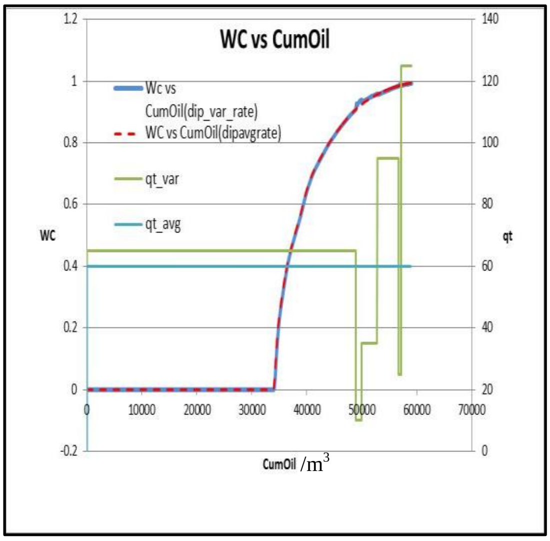


Figure 6 Comparison of WC vs CumOil using variable rate and average rate throughout the production history for Case 1

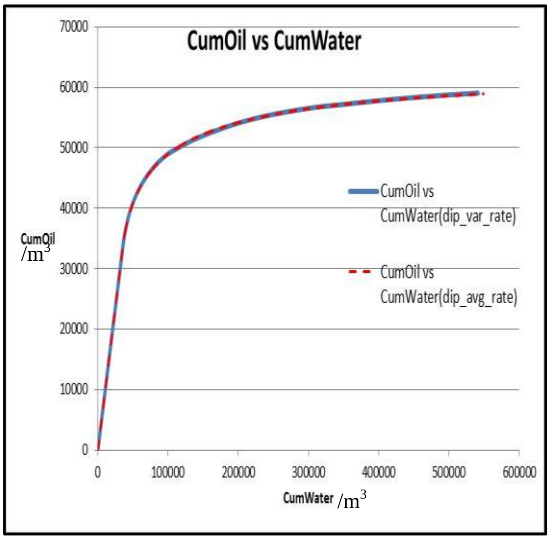


Figure 7 Comparison of CumOil vs CumWater using variable rate and average rate throughout the production history for Case 1

In Case 2, after running the simulation for the same duration as case 1 with one injector and 1 producer for variable total liquid flow rate scenario, it can be seen from Figure 4 that it gives an exact match for the CumOil versus CumWater plot when plotted against the simulated results of the average total liquid flow rate scenario for case 2. This result shows that even if the average permeability is as high as 2.5 Darcy, the fractional flow curve does not change at all for a variable total liquid flow rate scenario when compared to the variable liquid flow rate scenario for a slightly dipping reservoir. The WC versus CumOil plot comparison for the 2 scenarios also gives an exact match, which reiterates our conclusion that there is no change in the fractional flow curve for a variable flow rate scenario as long as the N_{gv} is relatively low.

Therefore, from the analysis of the 2 cases, we can deduce that variable total flow rate do not affect the fractional flow curve for dipping reservoirs as long as the N_{gv} is low enough for the flow to be only slightly gravity dominated. Hence, the Buckley-Leverett solution parameter sets can be deduced from Automated-History Matching the production history data for slightly dipping or horizontal reservoirs.

Since the fractional flow curve is validated to be the same for slightly dipping or horizontal reservoirs, two more plots were constructed from the production data and matched with the BL solutions. The two plots are the oil rate (OilRate) versus time plot and the water rate (WaterRate) versus time plot at reservoir volume. The Buckley-Leverett solutions for these plots are derived by comparing the Cumwater from the production history and the BL solution and picking out the f_w from the BL solution for each time step of the production history. The data points after breakthrough is used for the construction of the rates versus time plots and matching with the BL solution. Using this f_w, the WaterRate at each time step for a BL solution is calculated from,

$$q_w = q_t \times f_w \tag{12}$$

$$q_o = q_t - q_w \tag{13}$$

Where q_w is the WaterRate and q_o is the OilRate

From this workflow, the OilRate versus time plot and the WaterRate versus time plot of the production history can be matched with the BL solution for consistency once the CumOil versus CumWater and WC versus CumOil plots have been matched by manually manipulating the different parameters for a single set of matched parameters set. The plots that have been manually matched for the previous example for the production well with real time production history of 54 years was plotted for the 2 rates versus time plots and checked for consistency as shown in Figures 8 and 9. This workflow for plotting the rates plots were performed by creating a VBA Macro in the same Excel Spreadsheet. A simple workflow for the manual history matching of the simple BL solution with the production history for a single solution set that was implemented in an Excel Spreadsheet is shown in Figure 10.

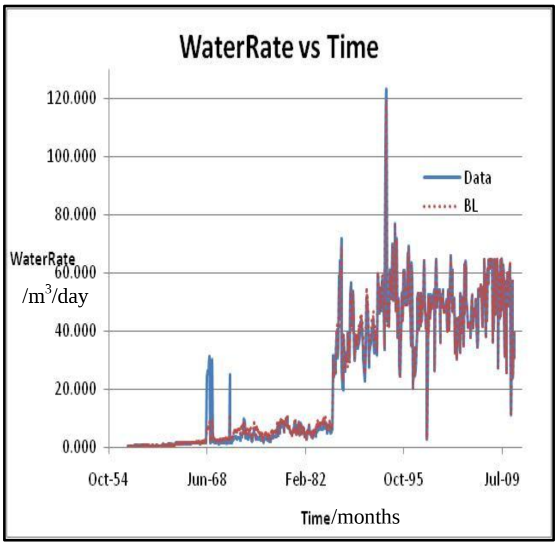


Figure 8 A single manual match for WaterRate vs Time of a real time producer well

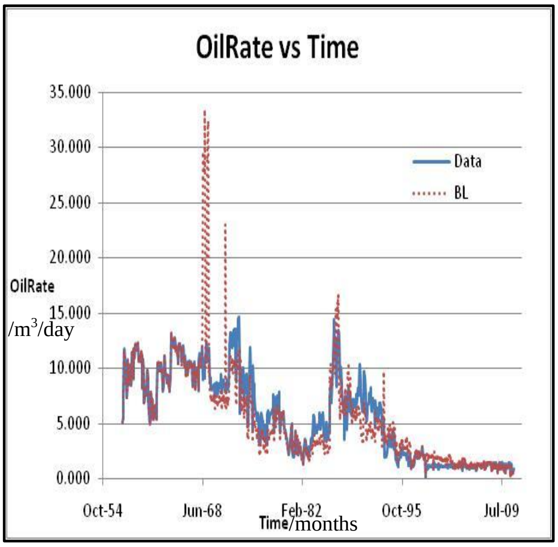


Figure 9 A single manual match for OilRate vs Time of a real time producer well

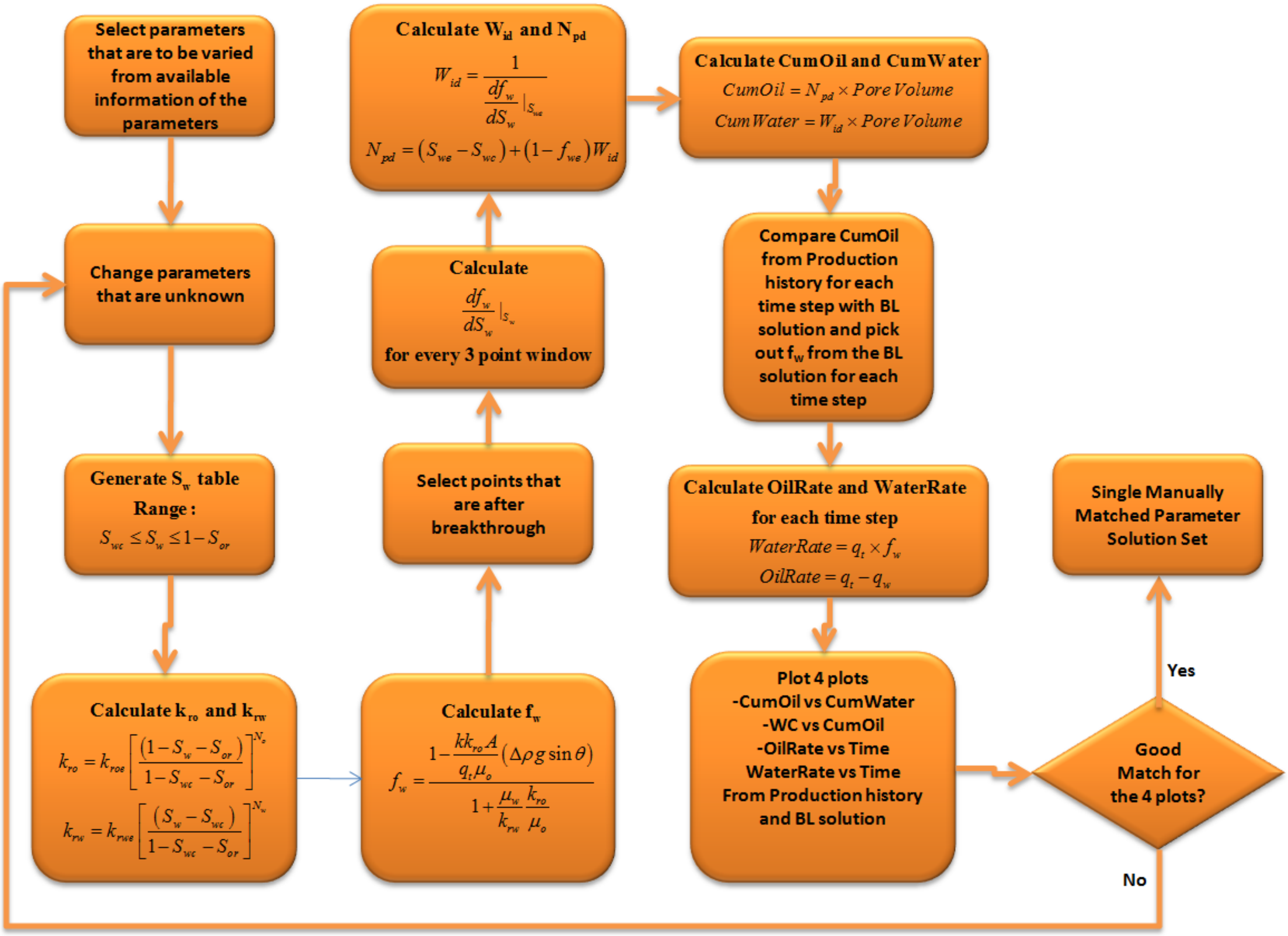


Figure 10 Workflow for manual history matching of a simple BL solution with the production history for a single solution set

Construction of the Automated-HM tool – WATERFLOOD

After construction and validation of production history on the BL spreadsheet for history matching using Buckley-Leverett solution, an Automated-HM tool, named WATERFLOOD, was developed on a C# platform. This tool would use the same principle as the BL spreadsheet. However, the tool is programmed with a simple optimization algorithm that would be able to generate multiple parameters solution sets based on matching the production history with the BL solutions by optimization as long as the tolerance on the error for the match is given by the user as input. The tool also has the option of a manual selection of parameters for a manual match. A workflow for the tool is shown in Figure 11 which is a deterministic approach to Automated-HM using BL solution. The sample code of the calculation of the BL solutions for the tool is shown in Appendix H.

The optimization algorithm is a search optimisation algorithm called Multivariate Binary Search Algorithm. When a range of the variable parameter is given, using Binary Search method, the algorithm searches for the optimised parameter within the range for minimum error. The error, or the objective function is calculated using sum of least squares method. The algorithm is also recursive as we are conducting an optimisation search for multivariable parameters. Therefore, the algorithm is recursive to optimize all variable parameters within their own range and search values of these parameters for the error that is a minimum. This is the workflow for the optimization search algorithm for this Automated-HM tool.

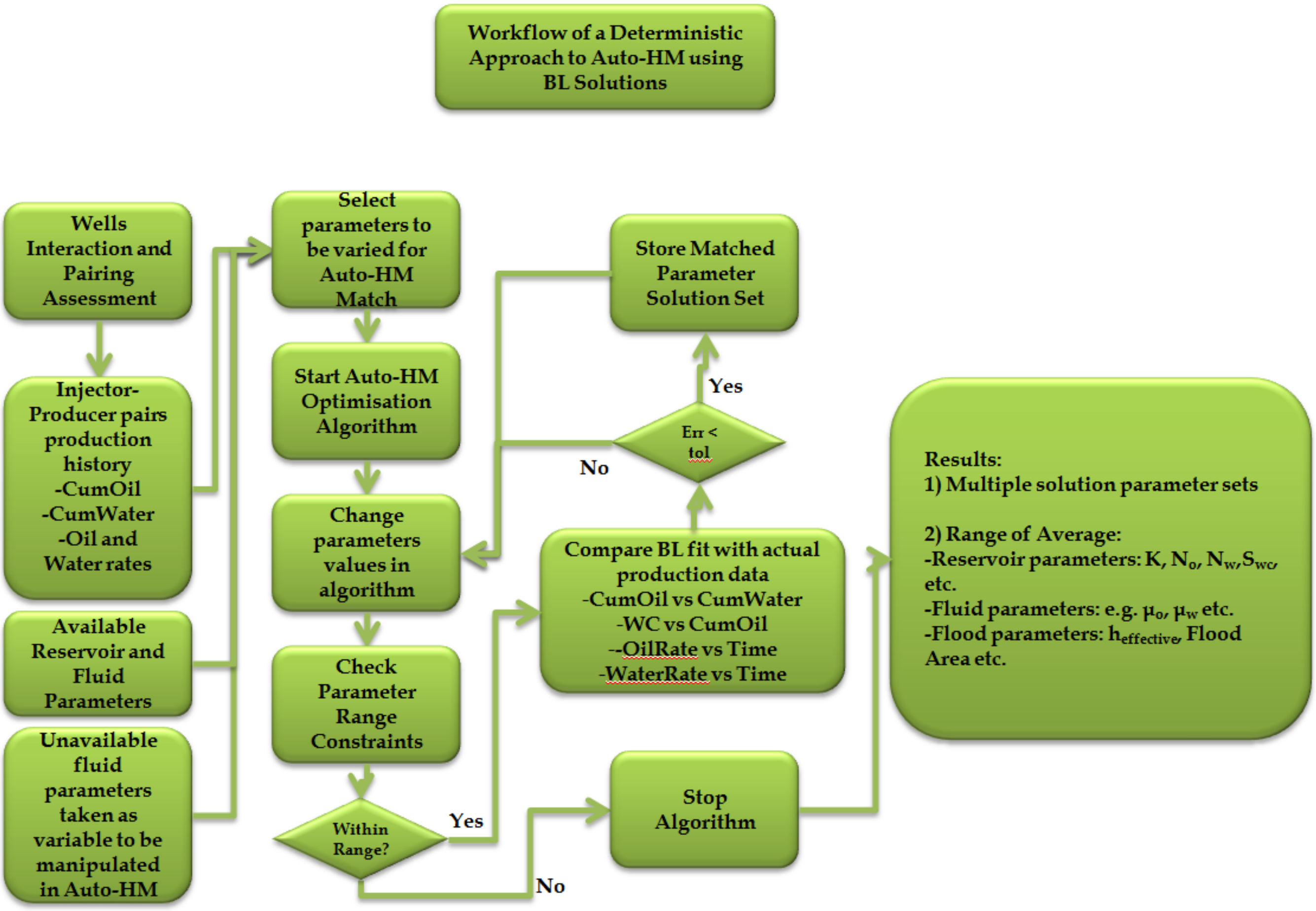
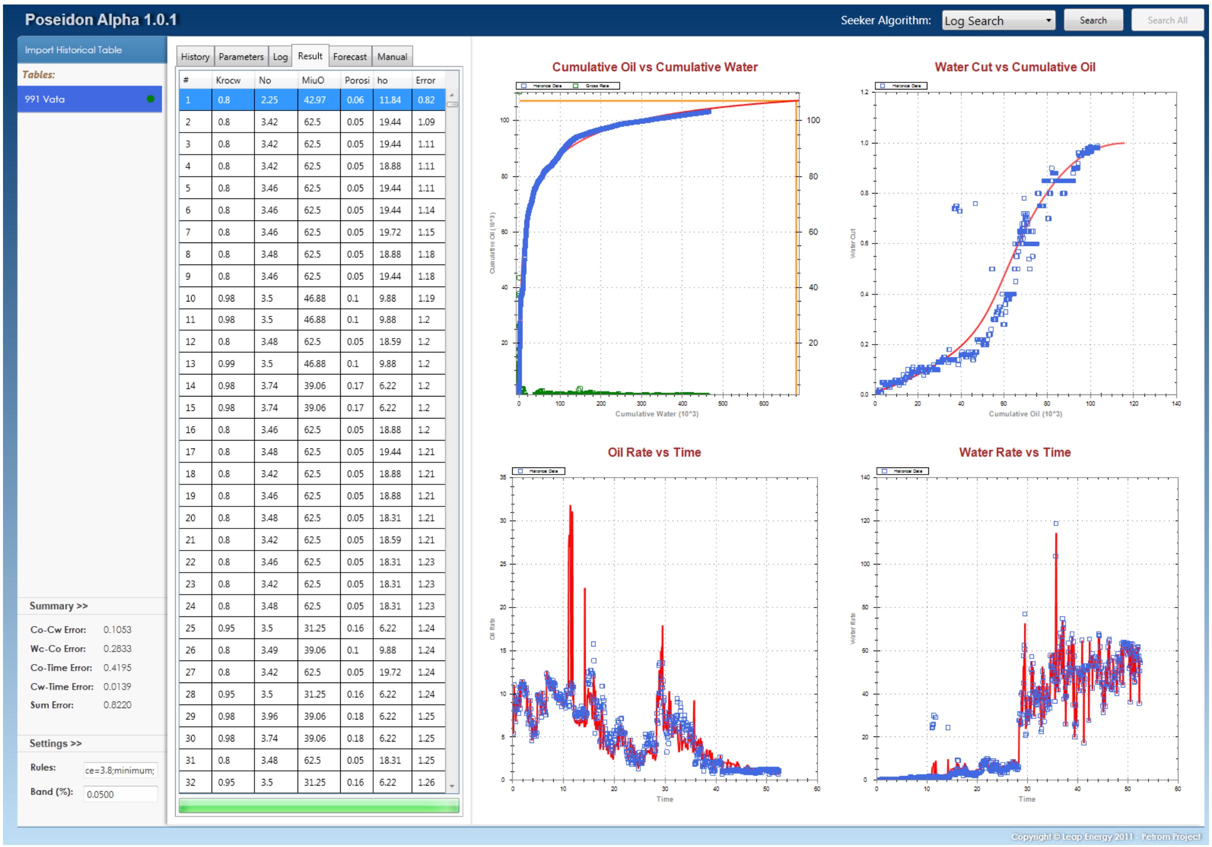


Figure 11 Workflow of a Deterministic Approach to Auto-HM using BL solutions

Once Injector-Producer pairs has been pre-assessed for interaction and connectivity and information about the connectivity for the pairs are known, using the production and injection history for a single producer well, BL solutions are generated for multiple solution parameter sets as shown in the workflow in Figure 11. Ranges of parameters in which the solutions lie are given to the tool as constraints for the optimization algorithm. These ranges are rough estimates that can be log-based estimates or static model-based estimates. Using these multiple parameter solutions sets, a range of average values for each unknown parameter for the well can be obtained by the Auto-HM tool. These results can be used to reduce the uncertainty in the reservoir parameters and fluid parameters. In addition, the flood pattern range can also be assessed, as the results give an explicit range of drainage areas and associated vertical sweep efficiency if the geological net pay thickness is known.

Therefore, based on this workflow that was initially developed in an Excel spreadsheet for a single matched parameter solution set, the Auto-HM multiple-solution searching tool, WATERFLOOD, was developed. Figure 12 to Figure 18 show the features and the interface of this tool.



#	Krocw	No	MiuO	Porosi	ho	Error
1	0.8	2.25	42.97	0.06	11.84	0.82
2	0.8	3.42	62.5	0.05	19.44	1.09
3	0.8	3.42	62.5	0.05	19.44	1.11
4	0.8	3.42	62.5	0.05	18.88	1.11
5	0.8	3.46	62.5	0.05	19.44	1.11
6	0.8	3.46	62.5	0.05	19.44	1.14
7	0.8	3.46	62.5	0.05	19.72	1.15
8	0.8	3.48	62.5	0.05	18.88	1.18
9	0.8	3.46	62.5	0.05	19.44	1.18
10	0.98	3.5	46.88	0.1	9.88	1.19
11	0.98	3.5	46.88	0.1	9.88	1.2
12	0.8	3.48	62.5	0.05	18.59	1.2
13	0.99	3.5	46.88	0.1	9.88	1.2
14	0.98	3.74	39.06	0.17	6.22	1.2
15	0.98	3.74	39.06	0.17	6.22	1.2
16	0.8	3.46	62.5	0.05	18.88	1.2
17	0.8	3.48	62.5	0.05	19.44	1.21
18	0.8	3.42	62.5	0.05	18.88	1.21
19	0.8	3.46	62.5	0.05	18.88	1.21
20	0.8	3.48	62.5	0.05	18.31	1.21
21	0.8	3.42	62.5	0.05	18.59	1.21
22	0.8	3.46	62.5	0.05	18.31	1.23
23	0.8	3.42	62.5	0.05	18.31	1.23
24	0.8	3.48	62.5	0.05	18.31	1.23
25	0.95	3.5	31.25	0.16	6.22	1.24
26	0.8	3.49	39.06	0.1	9.88	1.24
27	0.8	3.42	62.5	0.05	19.72	1.24
28	0.95	3.5	31.25	0.16	6.22	1.24
29	0.98	3.96	39.06	0.18	6.22	1.25
30	0.98	3.74	39.06	0.18	6.22	1.25
31	0.8	3.48	62.5	0.05	18.31	1.25
32	0.95	3.5	31.25	0.16	6.22	1.26

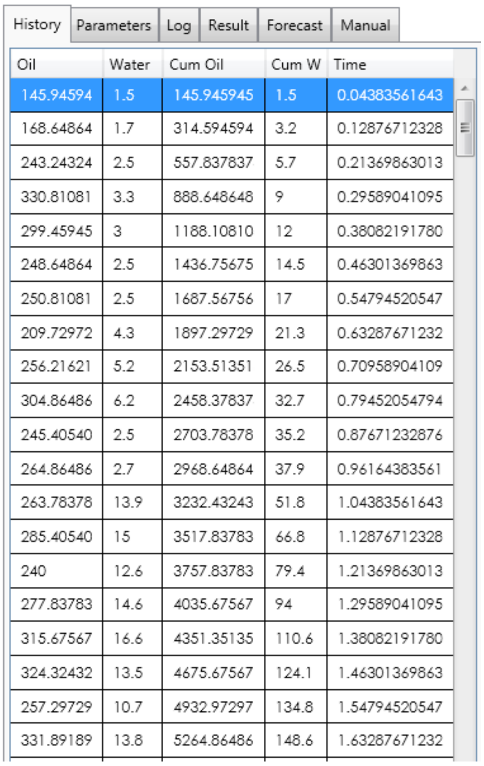
Summary >>

Co-Cw Error: 0.1053
Wc-Co Error: 0.2833
Co-Time Error: 0.4195
Cw-Time Error: 0.0139
Sum Error: 0.8220

Settings >>

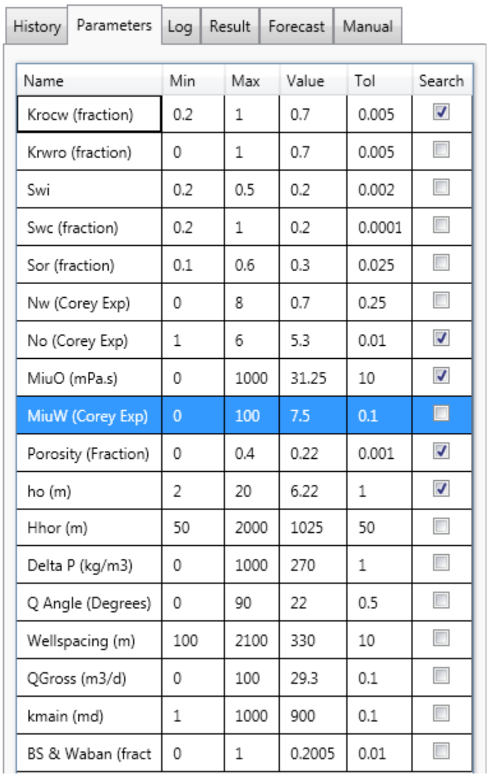
Rules: ce=3.8;minimum;
Band (%): 0.0500

Figure 12 Main Interface of WATERFLOOD Auto-HM tool showing the multiple solutions of the AUTO-HM of the well on the left hand side of the screen



Oil	Water	Cum Oil	Cum W	Time
145.94594	1.5	145.945945	1.5	0.04383561643
168.64864	1.7	314.594594	3.2	0.12876712328
243.24324	2.5	557.837837	5.7	0.21369863013
330.81081	3.3	888.648648	9	0.29589041095
299.45945	3	1188.10810	12	0.38082191780
248.64864	2.5	1436.75675	14.5	0.46301369863
250.81081	2.5	1687.56756	17	0.54794520547
209.72972	4.3	1897.29729	21.3	0.63287671232
256.21621	5.2	2153.51351	26.5	0.70958904109
304.86486	6.2	2458.37837	32.7	0.79452054794
245.40540	2.5	2703.78378	35.2	0.87671232876
264.86486	2.7	2968.64864	37.9	0.96164383561
263.78378	13.9	3232.43243	51.8	1.04383561643
285.40540	15	3517.83783	66.8	1.12876712328
240	12.6	3757.83783	79.4	1.21369863013
277.83783	14.6	4035.67567	94	1.29589041095
315.67567	16.6	4351.35135	110.6	1.38082191780
324.32432	13.5	4675.67567	124.1	1.46301369863
257.29729	10.7	4932.97297	134.8	1.54794520547
331.89189	13.8	5264.86486	148.6	1.63287671232

Figure 13 Production history of well as input



Name	Min	Max	Value	Tol	Search
Krocw (fraction)	0.2	1	0.7	0.005	☑
Krwro (fraction)	0	1	0.7	0.005	☐
Swi	0.2	0.5	0.2	0.002	☐
Swc (fraction)	0.2	1	0.2	0.0001	☐
Sor (fraction)	0.1	0.6	0.3	0.025	☐
Nw (Corey Exp)	0	8	0.7	0.25	☐
No (Corey Exp)	1	6	5.3	0.01	☑
MiuO (mPa.s)	0	1000	31.25	10	☑
MiuW (Corey Exp)	0	100	7.5	0.1	☐
Porosity (Fraction)	0	0.4	0.22	0.001	☑
ho (m)	2	20	6.22	1	☑
Hhor (m)	50	2000	1025	50	☐
Delta P (kg/m3)	0	1000	270	1	☐
Q Angle (Degrees)	0	90	22	0.5	☐
Wellspacing (m)	100	2100	330	10	☐
QGross (m3/d)	0	100	29.3	0.1	☐
kmain (md)	1	1000	900	0.1	☐
BS & Waban (fract	0	1	0.2005	0.01	☐

Figure 14 Choice of parameters to be varied and their ranges as input

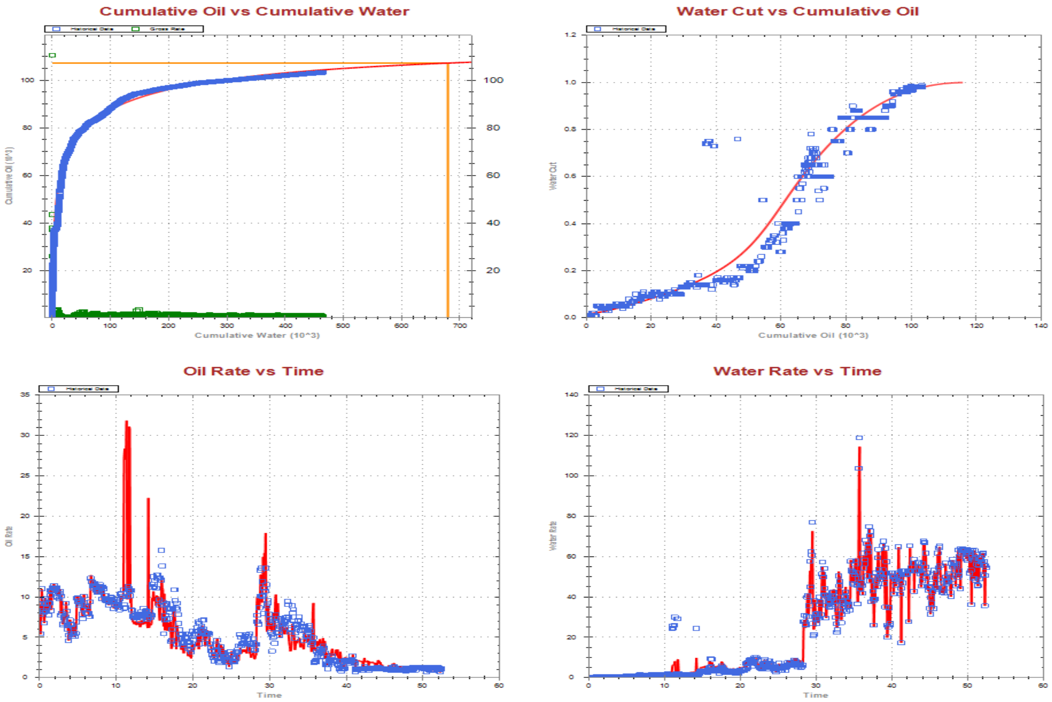
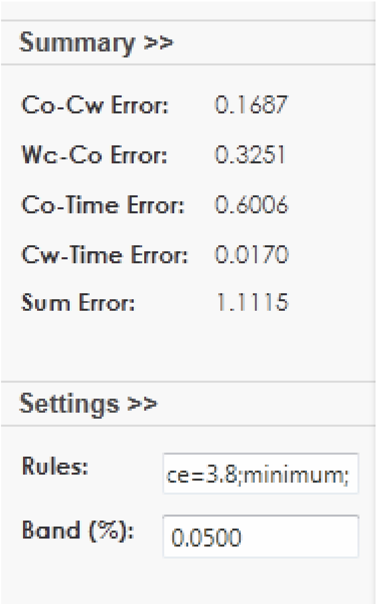


Figure 15 Auto-HM of a well showing the best fit solution for the 4 plots



Summary >>

Co-Cw Error: 0.1687

Wc-Co Error: 0.3251

Co-Time Error: 0.6006

Cw-Time Error: 0.0170

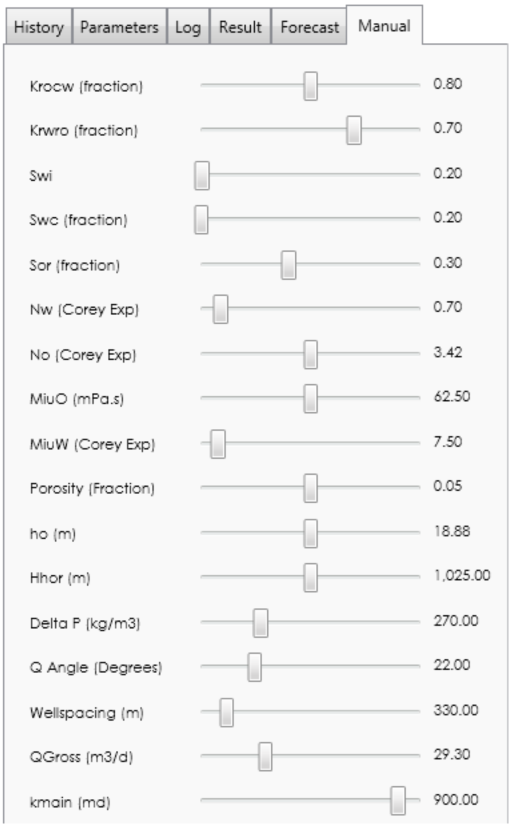
Sum Error: 1.1115

Settings >>

Rules: ce=3.8;minimum;

Band (%): 0.0500

Figure 16 Error Calculation of the 4 plots



Krocw (fraction) 0.80
Krwro (fraction) 0.70
Swi 0.20
Swc (fraction) 0.20
Sor (fraction) 0.30
Nw (Corey Exp) 0.70
No (Corey Exp) 3.42
MiuO (mPa.s) 62.50
MiuW (Corey Exp) 7.50
Porosity (Fraction) 0.05
ho (m) 18.88
Hhor (m) 1,025.00
Delta P (kg/m3) 270.00
Q Angle (Degrees) 22.00
Wellspacing (m) 330.00
QGross (m3/d) 29.30
kmain (md) 900.00

Figure 17 Manual matching of the parameters

In Figure 18, multiple BL solutions that have errors less than the tolerance given by the user is shown and plotted against the actual production history of the well. These solutions give a range of forecasts for the well based on these BL solutions. The results that were obtained from this tool were validated with the BL spreadsheet that was constructed earlier and checked for

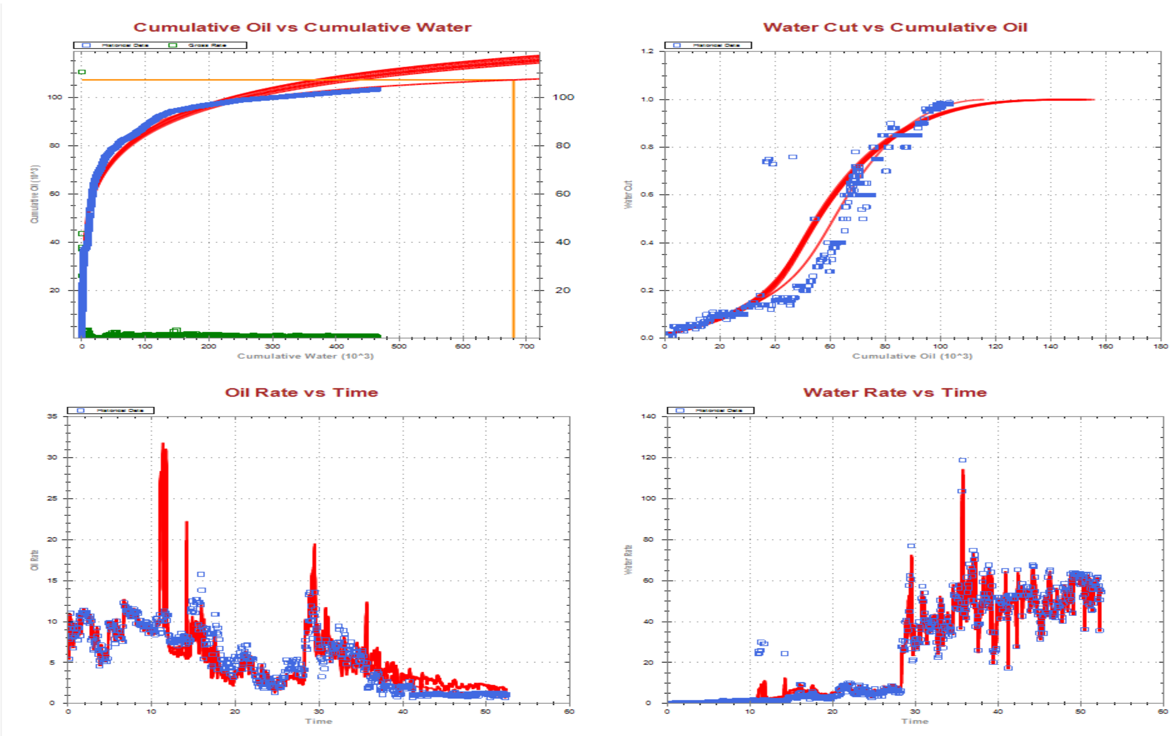


Figure 18 Auto-HM of a well showing multiple parameters solutions sets for the 4 plots

consistency. The parameters solution set that was obtained for the best fit from the Auto-HM tool was used in the spreadsheet and the BL solution was generated and matched with the production history of the well. The 4 plots that were generated in the spreadsheet are shown in Figure 19.

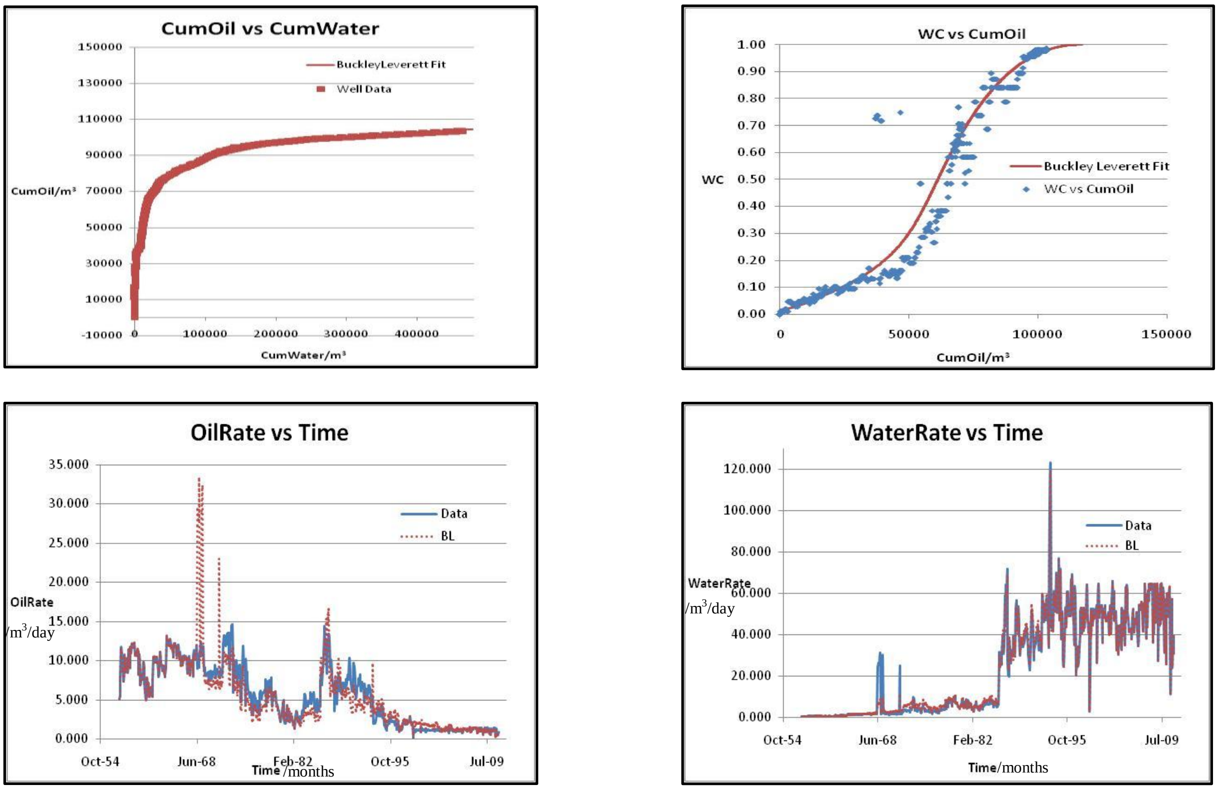


Figure 19 Manual match using BL spreadsheet for best fit parameters solution set from WATERFLOOD tool for validation of the tool

It can be illustrated that the exact same plots are obtained in the spreadsheet for the same parameter solution set as in WATERFLOOD. Therefore, it can be verified that the calculations that are implemented in the tool are validated and the multiple solution sets that are obtained from the tool are reliable.

Discussion and Future Recommendations

WATERFLOOD tool is able to generate multiple parameters solution sets from the optimisation technique implemented in the tool as explained in the previous sections. As shown in the previous section, when the tool was tested for a real time production history of a production well, it generated many plausible parameters solution sets, of about 160 parameters solution sets, for a tolerance level of 3.8 and below on the total error for the matching of the 4 plots. The error ranges from 0.82 to 3.26 for these 160 solution sets. In addition, some of these solution sets had porosity values as high as 0.6, which is not physically possible. Hence, since the fitting solutions are non-unique, the selection of parameters and their ranges based on consistent field specific data is of utmost importance and the reliance on assumed values should be best avoided. As future development, further constraints to the optimisation algorithm can also be implemented such as material balance calculations if pressure data is available. This would reduce the number of plausible solution sets and give more reliable results.

The WATERFLOOD tool has been developed based on a very simple optimisation technique. Therefore, the searching time for the multiple solutions takes about 30 minutes for cases where 6 parameters are used as unknown variables for the Automated-HM. In addition, the searching time increases exponentially when an extra parameter is added as a variable parameter for the Automated-HM. Therefore, it is also equally important to improve the optimisation technique used for the tool to improve the searching time for the solutions. Multiple optimisation techniques that are being used in the current market can be tested and analysed for sensitivity in terms of running time and accuracy. After the analysis of different optimisation techniques, the best optimisation technique can be chosen that gives a good balance on both solutions searching speed and accuracy of the results.

WATERFLOOD also has been developed based on constant fractional flow curve regardless of variable total liquid rates at reservoir volume. Therefore, if the tool is used for analysis of highly-gravity dominating and highly dipping reservoirs, where the N_{gv} is very high, the results of the multiple BL fitting solutions may give highly erroneous results that are not reliable.

Once reliable average parameter ranges are obtained from the tool for those parameters for which very little information is available, their uncertainties are effectively reduced. The ranges of flood areas and volumes that are obtained from WATERFLOOD from analysis of each well, flood pattern assessments can be made from which future decisions can be made on selection of areas for infill-drilling campaigns and identification of producers without support and identification of ineffective injectors. This tool can not only be used on a well basis but also on a sector or field basis to obtain the range of average parameters. The results of this tool can also be used as precursors for dynamic simulation models and characterization of static models in the future as more information about the parameters are known through the analysis of the WATERFLOOD tool.

Conclusion

In conclusion, the Auto-HM tool, WATERFLOOD, which is developed from a simple one dimensional conventional technique called Buckley-Leverett Theory, helps in obtaining additional information on reservoir and fluid properties that are considered relatively unknown based on lack of information at a well, sector or field level. This tool therefore helps in reducing the uncertainties of these properties and helps in future decision-making for infill-drilling campaigns. The tool also serves as precursors to dynamic simulation in the future once more information is known about these properties.

However, there are certain limits on the ability of this tool to obtain reliable information on these properties. The tool can only be used for horizontal and slightly dipping reservoirs where the N_{gv} number is low and therefore there are no changes in the fractional flow curves for variable total liquid flow rates throughout the production history of a well. The range of values that are given as inputs for the properties which are to be varied should also be based on consistent field specific data which can be logs-based or static model-based data. This helps in improving the reliability of the results of this tool.

And as for future recommendations, in addition to the accuracy of the results of this tool, the speed at which the tool searches for the solutions also has to be improved. Therefore, many different optimisation techniques has to be tested to develop and improve WATERFLOOD to be as accurate and fast as possible in searching these parameters solution sets. Further constraints can also be implemented, such as coupling material balance calculations when pressure data is available to reduce the number of plausible solutions. This would mould WATERFLOOD to be a very robust tool in decision-making in very large waterflood projects in highly matured reservoirs.

Nomenclature

1D = one dimensional
3D = 3 dimensional
f_W = fractional flow of water
k_{ro} = relative permeability of oil
k_{rw} = relative permeability of water
k = average absolute permeability of formation
A = cross-sectional of fluid flow
h = net pay thickness
W = width of flood area
q_t = total flow rate of liquid
θ = dip angle of reservoir
$\Delta \rho$ = density difference between oil and water
μ_o = viscosity of oil
μ_w = viscosity of water
k_{roe} = relative permeability end point of oil
k_{rwe} = relative permeability end point of water
S_{or} = irreducible oil saturation
S_{wc} = connate water saturation
N_o = Corey oil exponent
N_w = Corey water exponent
Ø = average porosity of formation
W_i = cumulative water injected
W_{id} = cumulative dimensionless number of pore volumes injected
S_{we} = water saturation at the position of the producer
N_{pd} = cumulative dimensionless number of pore volumes produced after breakthrough
f_{we} = fractional flow of water at S_{we}
N_{gv} = gravity number
q_w = water rate
q_o = oil rate

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3. Havlena, D. and Odeh, A.S. 1963. The Material Balance as an Equation of a Straight Line. *Journal of Petroleum Technology*, **26** (1): 21-51
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Appendices

Appendix A – Critical Milestones

Table A-1 Milestones in the study of "Combination of Conventional and Optimisation Techniques in Performance Prediction of Large Waterflood Projects"

Paper n°	Year	Title	Authors	Contribution
T.P. 1337 PETROLEUM TECHNOLOGY	1942	Mechanism of Fluid Displacement in Sands	Buckley, S.E, Leverett, M.C.	Developed a mechanism by which the production of oil is accomplished by the result of its displacement from the reservoir by water. Also developed the equation of the velocity of the saturation wave front, from which the saturation distribution with distance was evaluated.
T.P. 3309 AIME	1952	A Simplified Method for Computing Oil Recovery by Gas or Water Drive	Welge, H.J.	Development of a useful analytical method for computing the average saturation graphically from fractional flow curve, and hence the oil recovery.
SPE 559	1963	The Material Balance as an Equation of a Straight Line	Havlena, D., Odeh, O.S.	Presented a straight line method of the material balance equation which gives a dynamic meaning to the otherwise static material balance equation.
SPE 6579	1977	History Matching in Two-Phase Petroleum Reservoirs: Incompressible Flow	Van den Bosch, B., Seinfield, J.H.	Presented a method on estimation of porosity, absolute permeability and two-phase relative permeability-saturation relations in a two-phase petroleum reservoir by history matching. It was focused on incompressible flow.
SPE 12579	1984	Identifiability of Estimates of Two-Phase Reservoir Properties in History Matching	Watson, A.T., Gavalas, G.R., Seinfield, J.H.	Developed a study on how accurately can one expect to estimate spatial porosity, absolute permeability and relative permeabilities given typical production and pressure data.
SPE 20064	1990	A Study of the Post-Breakthrough Characteristics of Waterfloods	Lo, K.K., Warner Jr, H.R., Johnson, J.B.	Developed a method of estimating OOIP from log(WOR) versus cumulative oil plot.

SPE 21651	1991	An Analysis of Gravity-Dominated, Immiscible Flows in Dipping Reservoirs	Walsh, M.P., Moon, G.M.	Developed a term, called the Gravity Number, which can be used to quantify the effect of gravity on the fractional flow of water in a two-phase flow system.
SPE 83502	2003	Rate Forecasting of a Mature Waterflood Using Fractional Flow and Decline Curve Analysis, East Wilmington Long Beach, California	Al-Sharif, S., Rael, E.	Developed a method to predict oil and water rates by coupling the hyperbolic curve fitting and fractional flow of water relationships.
SPE 101144	2006	Developing a Fractional Flow Curve from Historic Production to Predict Performance of New Horizontal Wells, Bekasap Field, Indonesia	Sitorus, J., Sofyan, A., Abdulfatah, M.Y.	Developed a method for estimating reservoir parameters by constructing the fractional flow curve from History-matching production data of horizontal wells.

Appendix B – Critical Literature Review

T.P. 1337
Mechanism of Fluid Displacement in Sands, 1942

Authors: Buckley, S.E., Leverett, M.C.

Contribution:
This paper explains the development of a velocity of the saturation wave front equation which is derived from the fractional flow curve of water for a 1 dimensional linear flow of oil by water.

Objective of the paper:
The aim of this work is to describe the mechanism by which water displaces oil in a linear 1 dimensional flow by looking at results of experimental observations of the flow of mixtures of oil and water through sands.

Methodology:
Using a linear 1 dimensional model, an equation is expressed relating velocity of wave front with the derivative of fractional flow curve by using simple material balance assuming incompressible flow.

Conclusion reached:

1) In any reservoir composed of heterogeneous sands, the overall recovery is related to the rate of advance of the water.
2) The magnitude of the effect depends upon the degree and nature of the irregularities of the sand and upon the viscosity of the oil.

Comments
This work shows that for a 1-dimensional, linear, homogeneous and incompressible flow, the rate of water advancement is a function of the fractional flow of water.

T.P. 3309, AIME
A Simplified Method for Computing Oil Recovery by Gas or Water Drive, 1952

Authors: Welge, H.J.

Contribution:
This paper explains the development of a graphical and analytical method using the fundamentals of Buckley-Leverett Theory.

Objective of the paper:
The aim of this work is to derive the average water saturation of the reservoir during oil displacement of water in a linear sand section after which the oil recovery can be calculated.

Methodology:

1) By applying Buckley-Leveret frontal advancement equation at the outlet face of the linear sand body, the average saturation at the outlet face can be evaluated by integration of the saturation distribution between the inlet and outlet of the sand body and dividing it by the length of the sand body.
2) Graphically, this could be achieved by drawing the slope of the fractional flow curve for points after breakthrough, and the average water saturation could be evaluated for that point at the intersection of the tangent line and the line where fractional flow equals to unity.

Conclusion reached:

1) The contribution of gravity is of negligible importance unless the angle of dip is comparatively large or the flow velocity is relatively small, or both.
2) If the gravity term is found to be negligible, there will theoretically be no advantage resulting from injecting all of the water at the base of the structure.

Comments
This work shows that the average water saturation and the oil recovery could be evaluated graphically from the fractional flow curve after breakthrough of water.

SPE 559

The Material Balance as an Equation of a Straight Line, 1963

Authors: Havlena, D., Odeh, O.S.

Contribution:

No Contribution.

Objective of the paper:

The aim of this work is to develop an analytical solution to the material balance equation graphically and interpret different drive mechanisms from the graphical analysis.

Methodology:

The material balance equation is arranged algebraically, resulting in an equation of a straight line and analysed for the drive mechanisms using actual production and pressure history.

Conclusion reached:

1) The straight line method of solving the material balance equation differes fromt he commonly used one as it imparts a dynamic meaning to the individual calculated points.
2) Limited success for saturated reservoirs as when a gas cap is to be solved for, an exceptional accuracy of basic data such as pressure data is required.
3) Early history do not conform with the latter points which may be due to inaccuracy of early average production-pressure-PVT data or pressure-production effect has not been felt by all the active oil-in-place.

SPE 6579
History Matching in Two-Phase Petroleum Reservoirs: Incompressible Flow, 1977

Authors: Van den Bosch, B., Seinfield, J.H.

Contribution:
This paper gives the constraints in estimating reservoir and fluid properties from history matching of production data for incompressible flows.

Objective of the paper:
This paper explains the method of estimating porosity, absolute permeability and relative permeability-saturations by a history matching method in a two phase petroleum reservoir where the flow is incompressible.

Methodology:
Using that data that is available, which includes oil flow rates and pressure at the wells, the porosity can be estimated on the basis of saturation behaviour, absolute permeability on the basis of pressure behaviour and coefficients in the relative permeability on the basis of both saturation and pressure behaviour.

Conclusion reached:
1) In the case of 1-dimensional and incompressible flow, the ability to estimate the unknown parameters depends on the type of flow encountered, specifically whether saturation shocks form.
2) Ill-determined nature of history-matching problems is present in two-phase problems.

SPE 12579

Identifiability of Estimates of Two-Phase Reservoir Properties in History Matching, 1984

Authors: Watson, A.T., Gavalas, G.R., Seinfield, J.H.

Contribution:

No Contribution.

Objective of the paper:

This paper conducts a study to analyse how accurately the reservoir parameters can be estimated from the available data in History Matching as the number of parameters to be estimated in a reservoir history match is quite large.

Methodology:

Analytical solutions for pressure and saturation in a one-dimensional waterflood are used to determine the accuracy with which history matching is conducted to estimate spatial variable porosity, absolute permeability and relative permeabilities.

Conclusion reached:

1) Only the average value of the porosity can be determined on the basis of water/oil flow measurements.
2) The permeability distribution can be determined from pressure drop data with accuracy depending on the mobility ratio.
3) Exponents in a power function representation of the relative permeabilities can be determined from WOR data alone but not nearly as accurate as when pressure drop and flow data are used simultaneously.

Comments

This paper provided a brief idea of the shortcomings of history matching to estimate reservoir parameters in a one-dimensional waterflood example.

SPE 20064
A Study of the Post-Breakthrough Characteristics of Waterfloods, 1990

Authors: Lo, K.K., Warner Jr, H.R., Johnson, J.B.

Contribution:
No Contribution

Objective of the paper:
This paper gives other practical uses of the plot of log (WOR) versus cumulative oil for waterflood analysis after breakthrough which was traditionally used to estimate ultimate oil recovery from waterflooding.

Methodology:
The study, based on one-dimensional Buckley-Leverett Theory, utilizes the dependence of the slope of the log (WOR) versus cumulative oil plot on various reservoir parameters. The effect of this slope caused by different reservoir layering, flood configurationsand operational changes are presented and applied to estimate the original oil in place (OOIP) for two real-time waterflood examples. The OOIP results are then compared with those calculated by volumetric methods.

Conclusion reached:

1) In a fully developed pattern waterflood, a linear relationship exists between the logarithm of the WOR and the cumulative oil produced for individual wells, pattern elements, multiple patter elements and even the entire field. This slope is independent of the oil/water viscosity ratio.
2) The pattern element slope of the log(WOR) cumulative oil straight line is independent of the pattern geometry, the relative production rates of the producers and infill drilling. Well shut-ins lower the watercut and hence affect the slope of the straight line temporarily, although the pattern-element slope is asymptotically approached as production continues.

Comments
These results can be used to diagnose waterflood performance. This paper thereby gives a method of estimating OOIP which in turn can be used in material balance calculations couple with production and injection data to generate pressure data.

SPE 21651

An Analysis of Gravity-Dominated, Immiscible Flows in Dipping Reservoirs, 1991

Authors: Walsh, M.P., Moon, G.M.

Contribution:

This paper illustrates the effects of gravity dominated immiscible flows on fractional flow of water.

Objective of the paper:

This study presents a Buckley-Leverett theory extension, which applies to gravity-dominated immiscible flows to account for countercurrent flow while fluid injection and production is going on.

Methodology:

The analysis characterizes the gravity to viscous force ratio by a dimensionless Gravity Number. New graphical solution methods are also presented to predict displacement performance for arbitrary initial and injected conditions.

Conclusion reached:

1) A dimensionless Gravity Number effectively describes the role of gravity and viscous forces in immiscible displacements. Gravity Numbers with sufficiently low absolute values imply viscous-dominated flow; such flows are characterized by uni-directional flow. Gravity Numbers with sufficiently high absolute values imply gravity-dominated flow; such flows can yield countercurrent flow.
2) Downdip waterfloods or updip waterfloods at sufficiently high Gravity Numbers are characterised by final oil saturations much greater than the measured residual oil saturation. It is mainly controlled by the Gravity Number.
3) An approximation to predict oil recovery from downdip gas floods based on using only oil relative permeability data is valid provided both the gas viscosity and Gravity Number are sufficiently low.

Comments

Sufficiently low Gravity Numbers do not affect the fractional flow of water. Therefore, the gravity term has very little effect on the fractional flow of water.

SPE 83502

Rate Forecasting of a Mature Waterflood Using Fractional Flow and Decline Curve Analysis, East Wilmington Long Beach, California, 2003

Authors: Al-Sharif, S., Rael, E.

Contribution:

No contribution

Objective of the paper:

This paper gives an extension of the traditional theory of predicting oil and water rates over time by using Log(WOR) versus cumulative oil produced relationships, which was based on the assumption of constant liquid rate over time. This extension of the theory involves prediction of rates for variable total liquid rates over time.

Methodology:

This paper illustrates a methodology that uses a combination of predicting oil rates by hyperbolic decline curve fitting and predicting water rates by fractional flow of water relationships.

Conclusion reached:

The methodology of applying fractional flow theory to predict water rates, which was analysed on a real time data in Long Beach Unit, do give valuable insight into future strategic projects and waterhandling plans.

Comments

This paper gives a first understanding of handling variable total liquid rates for analytical analysis.

SPE 101144

Developing a Fractional Flow Curve from Historic Production to Predict Performance of New Horizontal Wells, Bekasap Field, Indonesia, 2006

Authors: Sitorus, J., Sofyan, A., Abdulfatah, M.Y.

Contribution:

This paper gives an understanding of how reservoir parameters can be estimated by history matching and constructing a fractional flow curve.

Objective of the paper:

This paper demonstrates a technique to develop a reservoir scale fractional flow curve from historic production data. The curve becomes the basis for an analogous model that allows the estimation of oil rate production forecasts and reserves for existing or proposed new wells.

Methodology:

A simplified material balance algorithm and the corey equation are solved simultaneously to develop a f_w(fractional flow of water) versus S_w(water saturation) relationship from historical production data. A number of iterations are made until a reasonably good match is achieved.

Conclusion reached:

1) Many plausible solutions may exist, thus information from logs and cores are as important as production data.
2) Curves generated may be different in terms of relative permeability values, however they have similar values with respect to fractional flow of water.
3) The result may offer knowledge of expected drainage volume. The range can be used to further estimate future well reserves and performance.
4) Scoping studies for horizontal wells in Sumatra fields show the applicability of this method as a screening tool prior to simulation.

Comments

This paper develops an idea of multiple plausible solutions from history matching production data for estimation of reservoir parameters.

Appendix C – VBA code for manual matching of rates in BL solution

```
Private Sub CommandButton1_Click()

Dim count As Integer
Dim count2 As Integer
Dim count3 As Integer
Dim count4 As Long
Dim lookup As Double
Dim count5 As Integer
Dim swi As Double

Range("P6").Value = Application.CountIf(Range("F9:F1609"), ">0")
count = Range("P6").Value
Range("R6").Value = Application.CountIf(Range("N9:N1609"), ">0")
count2 = Range("R6").Value
count3 = 0
count4 = 1
swi = Range("N6").Value

ReDim sw(0 To count) As Double




   For i = 0 To count

      If Val(Cells(count3 + 9, 7).Value) = 0 Then

         'Cells(1, 1).Value = Val(Cells(9, 7).Value)
         sw(count3) = Range("O9").Value
         'Cells(count3 + 9, 19).Value = count3
         count3 = count3 + 1

      End If



               If Val(Cells(i + 9, 7).Value) > 0 Then

                  lookup = Val(Cells(i + 9, 8).Value)
                  'Cells(count3 + 9, 12).Value = lookup
                  'Cells(count3 + 9, 23).Value = Cells(count4 + (1609 - count2 - 1), 14).Value
                  'Cells(count3 + 9, 19).Value = lookup

                  For j = 1 To count2


                     If lookup <= (Cells(count4 + (1609 - count2 - 1), 14).Value) Then
```

```
                sw(count3) = Val(Cells(count4 + 1609 - count2 - 1, 15))
                'Cells(count3 + 9, 19).Value = sw(count3)
                count3 = count3 + 1
                Exit For

              End If

                    If lookup > (Cells(count4 + (1609 - count2 - 1), 14).Value) And lookup <= (Cells(count4 + (1609 - count2), 14).Value) Then

                      sw(count3) = Val(Cells(count4 + 1609 - count2, 15))
                      'Cells(count3 + 9, 19).Value = sw(count3)
                      count3 = count3 + 1
                      Exit For

                        Else

                          count4 = count4 + 1
                    End If



            Next j

          End If


      If count3 - 1 = count Then

        Exit For

      End If

  Next i



    For k = 1 To count

      Cells(k + 8, 19).Value = sw(k - 1)

    Next k

End Sub
```

Appendix D – Simulator Input Data File for Case 1 – Variable Rate Scenario

```
RUNSPEC   == memory dimensioning of the run ==============================

TITLE     -- title of the run
PHASE 4: MODEL a: 3D, HOMOGENEOUS, OIL-WATER SYSTEM

DIMENS    -- dimensions of the model
-- NX    NY   NZ
   48    50     50 / --2D Model XY Section

OIL       -- two phase black oil
WATER     -- water is present, but no gas
METRIC    -- unit specification
START     -- starting date for simulation run
  1 'JAN' 1983 /

EQLDIMS   -- equilibration table size
    1  100   10    1   20 /
TABDIMS   -- size of saturation and pvt tables
    1    1   101   40 /
WELLDIMS  -- max numb of WELLS/CONN per WELL/GROUPS/WELLperGROUP
    2    25    1    2 /

UNIFIN
UNIFOUT
MONITOR
-- UNIFOUT
FMTOUT

NSTACK    -- usually 10
    50 /

GRID      == geometry of our model ====================================
EQUALS    -- set top depth, block sizes and rock properties
          -- valid for a given range of blocks: I1 I2   J1 J2   K1 K2
      'DX'     8   /                        -- default box => all blocks
      'DY'     8   /
--      'PORO'   0.3 /
      'DZ'     10  / -- thickness of the layers
--      'PERMX'  50   /
--         'PERMY'  50   /
--         'PERMZ'  50   /

/

INCLUDE
'PORO.DAT'
```

```
/


INCLUDE
'perm.dat'
/
MULTIPLY
PERMX 1000 /
/
COPY
 PERMX PERMY/
 PERMX PERMZ/
/

MULTIPLY
PERMZ 0.1 /
/

BOX
1 48 1 50 1 1/

TOPS
2400*70/

ENDBOX


-- request init and grid file, necessary for post processing of the simulation with floviz
INIT
GRIDFILE
 2 /

PROPS     == pvt and relperm tables =============================


-- Specify properties of water phase
PVTW
-- P_reference  FVF  Compressibility Viscosity@Pref
     295      1.00      0.0000000000000000001           1.5 /

-- Specify properties of rock matrix
ROCK
-- P_reference  Compressibility
     295.0         0 /

-- Specify densities for all phases at surface conditions

DENSITY
-- oil    wat    gas
```

```
  700   1000  100 /

-- Specify properties of dead oil (no dissolved gas)
PVDO
--P_oil   FVF  Viscosity

100      1.071   30
200      1.070   30
300      1.069   30
400      1.068   30
500      1.067   30
600      1.066   30
700      1.065   30
800      1.064   30
900      1.063   30
1000    1.062   30
1100    1.061   30
1200    1.060   30
1300    1.059   30
1400    1.058   30
1500    1.057   30
1600    1.056   30
1700    1.055   30




/

--PVCDO
--100 1.071 0.000000001 20 0.0 /


SWOF     -- Wat-oil Relative Permeabilities and Pcow
--sw     krw       krow    Pc
0.00E+00       0.00E+00       1.00E+00       0
1.00E-02       1.00E-04       9.80E-01       0
2.00E-02       4.00E-04       9.60E-01       0
3.00E-02       9.00E-04       9.41E-01       0
4.00E-02       1.60E-03       9.22E-01       0
5.00E-02       2.50E-03       9.03E-01       0
6.00E-02       3.60E-03       8.84E-01       0
7.00E-02       4.90E-03       8.65E-01       0
8.00E-02       6.40E-03       8.46E-01       0
9.00E-02       8.10E-03       8.28E-01       0
1.00E-01       1.00E-02       8.10E-01       0
1.10E-01       1.21E-02       7.92E-01       0
1.20E-01       1.44E-02       7.74E-01       0
```

1.30E-01	1.69E-02	7.57E-01	0
1.40E-01	1.96E-02	7.40E-01	0
1.50E-01	2.25E-02	7.23E-01	0
1.60E-01	2.56E-02	7.06E-01	0
1.70E-01	2.89E-02	6.89E-01	0
1.80E-01	3.24E-02	6.72E-01	0
1.90E-01	3.61E-02	6.56E-01	0
2.00E-01	4.00E-02	6.40E-01	0
2.10E-01	4.41E-02	6.24E-01	0
2.20E-01	4.84E-02	6.08E-01	0
2.30E-01	5.29E-02	5.93E-01	0
2.40E-01	5.76E-02	5.78E-01	0
2.50E-01	6.25E-02	5.63E-01	0
2.60E-01	6.76E-02	5.48E-01	0
2.70E-01	7.29E-02	5.33E-01	0
2.80E-01	7.84E-02	5.18E-01	0
2.90E-01	8.41E-02	5.04E-01	0
3.00E-01	9.00E-02	4.90E-01	0
3.10E-01	9.61E-02	4.76E-01	0
3.20E-01	1.02E-01	4.62E-01	0
3.30E-01	1.09E-01	4.49E-01	0
3.40E-01	1.16E-01	4.36E-01	0
3.50E-01	1.23E-01	4.23E-01	0
3.60E-01	1.30E-01	4.10E-01	0
3.70E-01	1.37E-01	3.97E-01	0
3.80E-01	1.44E-01	3.84E-01	0
3.90E-01	1.52E-01	3.72E-01	0
4.00E-01	1.60E-01	3.60E-01	0
4.10E-01	1.68E-01	3.48E-01	0
4.20E-01	1.76E-01	3.36E-01	0
4.30E-01	1.85E-01	3.25E-01	0
4.40E-01	1.94E-01	3.14E-01	0
4.50E-01	2.03E-01	3.03E-01	0
4.60E-01	2.12E-01	2.92E-01	0
4.70E-01	2.21E-01	2.81E-01	0
4.80E-01	2.30E-01	2.70E-01	0
4.90E-01	2.40E-01	2.60E-01	0
5.00E-01	2.50E-01	2.50E-01	0
5.10E-01	2.60E-01	2.40E-01	0
5.20E-01	2.70E-01	2.30E-01	0
5.30E-01	2.81E-01	2.21E-01	0
5.40E-01	2.92E-01	2.12E-01	0
5.50E-01	3.03E-01	2.03E-01	0
5.60E-01	3.14E-01	1.94E-01	0
5.70E-01	3.25E-01	1.85E-01	0
5.80E-01	3.36E-01	1.76E-01	0
5.90E-01	3.48E-01	1.68E-01	0
6.00E-01	3.60E-01	1.60E-01	0
6.10E-01	3.72E-01	1.52E-01	0

```
6.20E-01     3.84E-01     1.44E-01     0
6.30E-01     3.97E-01     1.37E-01     0
6.40E-01     4.10E-01     1.30E-01     0
6.50E-01     4.23E-01     1.23E-01     0
6.60E-01     4.36E-01     1.16E-01     0
6.70E-01     4.49E-01     1.09E-01     0
6.80E-01     4.62E-01     1.02E-01     0
6.90E-01     4.76E-01     9.61E-02     0
7.00E-01     4.90E-01     9.00E-02     0
7.10E-01     5.04E-01     8.41E-02     0
7.20E-01     5.18E-01     7.84E-02     0
7.30E-01     5.33E-01     7.29E-02     0
7.40E-01     5.48E-01     6.76E-02     0
7.50E-01     5.63E-01     6.25E-02     0
7.60E-01     5.78E-01     5.76E-02     0
7.70E-01     5.93E-01     5.29E-02     0
7.80E-01     6.08E-01     4.84E-02     0
7.90E-01     6.24E-01     4.41E-02     0
8.00E-01     6.40E-01     4.00E-02     0
8.10E-01     6.56E-01     3.61E-02     0
8.20E-01     6.72E-01     3.24E-02     0
8.30E-01     6.89E-01     2.89E-02     0
8.40E-01     7.06E-01     2.56E-02     0
8.50E-01     7.23E-01     2.25E-02     0
8.60E-01     7.40E-01     1.96E-02     0
8.70E-01     7.57E-01     1.69E-02     0
8.80E-01     7.74E-01     1.44E-02     0
8.90E-01     7.92E-01     1.21E-02     0
9.00E-01     8.10E-01     1.00E-02     0
9.10E-01     8.28E-01     8.10E-03     0
9.20E-01     8.46E-01     6.40E-03     0
9.30E-01     8.65E-01     4.90E-03     0
9.40E-01     8.84E-01     3.60E-03     0
9.50E-01     9.03E-01     2.50E-03     0
9.60E-01     9.22E-01     1.60E-03     0
9.70E-01     9.41E-01     9.00E-04     0
9.80E-01     9.60E-01     4.00E-04     0
9.90E-01     9.80E-01     1.00E-04     0
1.00E+00     1.00E+00     0.00E+00     0
/




------------------------------ Solution Section --------------------------------
-- Implies the beginning of Solution section
SOLUTION
```

```
-- Specify initial state of the reservoir
--EQUIL
--   DATUM  DATUM   OWC    OWC    GOC    GOC
--   depth  press  depth   PcOW  depth   PcOG
--     70.0   1400  80.0  0.0    200.0  0.0 /

PRESSURE
120000*1400 /

SWAT
120000*0 /



---------------------------
RPTSOL
'RESTART=2' /

SUMMARY    == output written to summary *.RSM file ===================
RUNSUM     -- additional table in *.PRT file
SEPARATE   -- write a seperate *.RSM file

WOPR       -- 'W'ell 'O'il 'P'roduction 'R'ate
'P1'
/
WWPR       -- 'W'ell 'W'ater 'P'roduction 'R'ate
'P1'
/
WWIR       -- 'W'ell 'W'ater injection 'R'ate
'P1'
/
WBHP       -- and the bottom hole pressure of 'PROD'
 'P1'
 'I1'
/
FPR        -- Average reservoir pressure
FOPR
FWPR
FWIR
FOPT       -- Cumulative oil production of the field, ('F'ield 'O'il 'P'roduction 'T'otal)
FWPT       -- Cumulative water production of the field, ('F'ield 'O'il 'P'roduction 'T'otal)
FWIT       -- Cumulative water injection of the field
FOE        -- request oil recovery
FOPV       -- field oil pore volume
FWPV       -- field water pore volume

SCHEDULE   == operations to be simulated ==============================
RPTSCHED   -- CONTROLS ON OUTPUT AT EACH REPORT TIME
-- 'WELLS=2' 'WELSPECS'/
```

```
'SWAT' 'PRES'/
--RPTRST
-- 3 0 1 0 0 1 /
--/

DRSDT     -- Free gas is not allowed to re-dissolve within oil
  0 /

RPTRST    -- request restart file
'BASIC=2'
/

-- Sets simulator control parameters
TUNING
1* 1 1* 1* 3/
/
/

WELSPECS   == WELL SPECIFICATION DATA ================================
--   WELL   GROUP LOCATION  BHP   PI
--Name  Group   I     J     Datum     Phase
'P1'      'G'     48    50       555      'OIL'    /
/


-- Specification for completion of oil producing well
COMPDAT
--Name   I    J   K1   K2   Status  Sattab Trfact  Diam  EffKh  Skin
  'P1'   48   50   48   50   'OPEN'    1*     1*   0.1    1*    0.0 /
/

-- Control data for oil producing well
WCONPROD
--Name Status  Mode "o_rate" "w_ rate" "g_rate" "l_rate" "rf_rate"    BHP
  'P1' 'OPEN' 'RESV'   1*      1*       1*       1*      65      200/
/

-- Specification data for injector well on the left
WELSPECS
--Name  Group   I     J    Datum  Phase
  'I1'   'G'    1    1   85  'WATER' /
/

-- Specification for completion of injector well
COMPDAT
--Name   I    J   K1   K2   Status  Sattab Trfact  Diam  EffKh  Skin
  'I1'   1    1   1   1   'OPEN'    1*     1*   0.1    1*    0.0 /
/
```

```
-- Control data for water injecting well
WCONINJE
--Name  Type   Status  Mode "w_rate" "rf_rate"  BHP
  'I1' 'WATER' 'OPEN' 'RATE'    65        1*     1500 /
/

-- Total duration of simulation run / frequency of reports of restart files
TSTEP
50*30.5
 /



WELTARG
'P1' RESV 10 /
'I1' WRATE 10/
/

-- Total duration of simulation run / frequency of reports of restart files
TSTEP
50*30.5
 /

WELTARG
'P1' RESV 35 /
'I1' WRATE 35/
/

-- Total duration of simulation run / frequency of reports of restart files
TSTEP
50*30.5
 /



WELTARG
'P1' RESV 95 /
'I1' WRATE 95/
/

-- Total duration of simulation run / frequency of reports of restart files
TSTEP
50*30.5
 /

WELTARG
'P1' RESV 25 /
'I1' WRATE 25/
/

-- Total duration of simulation run / frequency of reports of restart files
```

```
TSTEP
50*30.5
 /



WELTARG
'P1' RESV 125/
'I1' WRATE 125/
/

-- Total duration of simulation run / frequency of reports of restart files
TSTEP
50*30.5
 /



END
```

Appendix E – Simulator Input Data File for Case 1 – Average Rate Scenario

```
RUNSPEC   == memory dimensioning of the run ============================

TITLE     -- title of the run
PHASE 4: MODEL a: 3D, HOMOGENEOUS, OIL-WATER SYSTEM

DIMENS    -- dimensions of the model
-- NX    NY   NZ
   48    50     50 / --2D Model XY Section

OIL       -- two phase black oil
WATER     -- water is present, but no gas
METRIC    -- unit specification
START     -- starting date for simulation run
  1 'JAN' 1983 /

EQLDIMS   -- equilibration table size
    1  100   10    1   20 /
TABDIMS   -- size of saturation and pvt tables
    1    1   101   40 /
WELLDIMS  -- max numb of WELLS/CONN per WELL/GROUPS/WELLperGROUP
    2    25    1    2 /

UNIFIN
UNIFOUT
MONITOR
-- UNIFOUT
FMTOUT

NSTACK    -- usually 10
    50 /

GRID      == geometry of our model ====================================
EQUALS    -- set top depth, block sizes and rock properties
          -- valid for a given range of blocks: I1 I2   J1 J2   K1 K2
      'DX'     8   /                      -- default box => all blocks
      'DY'     8   /
--     'PORO'   0.3 /
      'DZ'     10  / -- thickness of the layers
--     'PERMX'  50   /
--        'PERMY'  50   /
--        'PERMZ'  50   /

/

INCLUDE
'PORO.DAT'
/
```

```
INCLUDE
'perm.dat'
/
MULTIPLY
PERMX 1000 /
/
COPY
 PERMX PERMY/
 PERMX PERMZ/
/

MULTIPLY
PERMZ 0.1 /
/

BOX
1 48 1 50 1 1/

TOPS
2400*70/

ENDBOX


-- request init and grid file, necessary for post processing of the simulation with floviz
INIT
GRIDFILE
 2 /

PROPS     == pvt and relperm tables =============================


-- Specify properties of water phase
PVTW
-- P_reference  FVF  Compressibility Viscosity@Pref
     295      1.00      0.00000000000000000001          1.5 /

-- Specify properties of rock matrix
ROCK
-- P_reference  Compressibility
     295.0        0 /

-- Specify densities for all phases at surface conditions

DENSITY
-- oil    wat    gas
   700   1000  100 /
```

```
-- Specify properties of dead oil (no dissolved gas)
PVDO
--P_oil   FVF   Viscosity

100     1.071   30
200     1.070   30
300     1.069   30
400     1.068   30
500     1.067   30
600     1.066   30
700     1.065   30
800     1.064   30
900     1.063   30
1000    1.062   30
1100    1.061   30
1200    1.060   30
1300    1.059   30
1400    1.058   30
1500    1.057   30
1600    1.056   30
1700    1.055   30
/

--PVCDO
--100 1.071 0.000000001 20 0.0 /


SWOF     -- Wat-oil Relative Permeabilities and Pcow
--sw      krw      krow    Pc
0.00E+00     0.00E+00     1.00E+00     0
1.00E-02     1.00E-04     9.80E-01     0
2.00E-02     4.00E-04     9.60E-01     0
3.00E-02     9.00E-04     9.41E-01     0
4.00E-02     1.60E-03     9.22E-01     0
5.00E-02     2.50E-03     9.03E-01     0
6.00E-02     3.60E-03     8.84E-01     0
7.00E-02     4.90E-03     8.65E-01     0
8.00E-02     6.40E-03     8.46E-01     0
9.00E-02     8.10E-03     8.28E-01     0
1.00E-01     1.00E-02     8.10E-01     0
1.10E-01     1.21E-02     7.92E-01     0
1.20E-01     1.44E-02     7.74E-01     0
1.30E-01     1.69E-02     7.57E-01     0
1.40E-01     1.96E-02     7.40E-01     0
1.50E-01     2.25E-02     7.23E-01     0
1.60E-01     2.56E-02     7.06E-01     0
1.70E-01     2.89E-02     6.89E-01     0
1.80E-01     3.24E-02     6.72E-01     0
```

1.90E-01	3.61E-02	6.56E-01	0
2.00E-01	4.00E-02	6.40E-01	0
2.10E-01	4.41E-02	6.24E-01	0
2.20E-01	4.84E-02	6.08E-01	0
2.30E-01	5.29E-02	5.93E-01	0
2.40E-01	5.76E-02	5.78E-01	0
2.50E-01	6.25E-02	5.63E-01	0
2.60E-01	6.76E-02	5.48E-01	0
2.70E-01	7.29E-02	5.33E-01	0
2.80E-01	7.84E-02	5.18E-01	0
2.90E-01	8.41E-02	5.04E-01	0
3.00E-01	9.00E-02	4.90E-01	0
3.10E-01	9.61E-02	4.76E-01	0
3.20E-01	1.02E-01	4.62E-01	0
3.30E-01	1.09E-01	4.49E-01	0
3.40E-01	1.16E-01	4.36E-01	0
3.50E-01	1.23E-01	4.23E-01	0
3.60E-01	1.30E-01	4.10E-01	0
3.70E-01	1.37E-01	3.97E-01	0
3.80E-01	1.44E-01	3.84E-01	0
3.90E-01	1.52E-01	3.72E-01	0
4.00E-01	1.60E-01	3.60E-01	0
4.10E-01	1.68E-01	3.48E-01	0
4.20E-01	1.76E-01	3.36E-01	0
4.30E-01	1.85E-01	3.25E-01	0
4.40E-01	1.94E-01	3.14E-01	0
4.50E-01	2.03E-01	3.03E-01	0
4.60E-01	2.12E-01	2.92E-01	0
4.70E-01	2.21E-01	2.81E-01	0
4.80E-01	2.30E-01	2.70E-01	0
4.90E-01	2.40E-01	2.60E-01	0
5.00E-01	2.50E-01	2.50E-01	0
5.10E-01	2.60E-01	2.40E-01	0
5.20E-01	2.70E-01	2.30E-01	0
5.30E-01	2.81E-01	2.21E-01	0
5.40E-01	2.92E-01	2.12E-01	0
5.50E-01	3.03E-01	2.03E-01	0
5.60E-01	3.14E-01	1.94E-01	0
5.70E-01	3.25E-01	1.85E-01	0
5.80E-01	3.36E-01	1.76E-01	0
5.90E-01	3.48E-01	1.68E-01	0
6.00E-01	3.60E-01	1.60E-01	0
6.10E-01	3.72E-01	1.52E-01	0
6.20E-01	3.84E-01	1.44E-01	0
6.30E-01	3.97E-01	1.37E-01	0
6.40E-01	4.10E-01	1.30E-01	0
6.50E-01	4.23E-01	1.23E-01	0
6.60E-01	4.36E-01	1.16E-01	0
6.70E-01	4.49E-01	1.09E-01	0

```
6.80E-01      4.62E-01      1.02E-01      0
6.90E-01      4.76E-01      9.61E-02      0
7.00E-01      4.90E-01      9.00E-02      0
7.10E-01      5.04E-01      8.41E-02      0
7.20E-01      5.18E-01      7.84E-02      0
7.30E-01      5.33E-01      7.29E-02      0
7.40E-01      5.48E-01      6.76E-02      0
7.50E-01      5.63E-01      6.25E-02      0
7.60E-01      5.78E-01      5.76E-02      0
7.70E-01      5.93E-01      5.29E-02      0
7.80E-01      6.08E-01      4.84E-02      0
7.90E-01      6.24E-01      4.41E-02      0
8.00E-01      6.40E-01      4.00E-02      0
8.10E-01      6.56E-01      3.61E-02      0
8.20E-01      6.72E-01      3.24E-02      0
8.30E-01      6.89E-01      2.89E-02      0
8.40E-01      7.06E-01      2.56E-02      0
8.50E-01      7.23E-01      2.25E-02      0
8.60E-01      7.40E-01      1.96E-02      0
8.70E-01      7.57E-01      1.69E-02      0
8.80E-01      7.74E-01      1.44E-02      0
8.90E-01      7.92E-01      1.21E-02      0
9.00E-01      8.10E-01      1.00E-02      0
9.10E-01      8.28E-01      8.10E-03      0
9.20E-01      8.46E-01      6.40E-03      0
9.30E-01      8.65E-01      4.90E-03      0
9.40E-01      8.84E-01      3.60E-03      0
9.50E-01      9.03E-01      2.50E-03      0
9.60E-01      9.22E-01      1.60E-03      0
9.70E-01      9.41E-01      9.00E-04      0
9.80E-01      9.60E-01      4.00E-04      0
9.90E-01      9.80E-01      1.00E-04      0
1.00E+00      1.00E+00      0.00E+00      0
/




------------------------------ Solution Section --------------------------------
-- Implies the beginning of Solution section
SOLUTION

-- Specify initial state of the reservoir
--EQUIL
--   DATUM  DATUM   OWC    OWC    GOC    GOC
--   depth  press  depth   PcOW  depth   PcOG
--     70.0   1400  80.0  0.0    200.0  0.0 /
```

```
PRESSURE
120000*1400 /

SWAT
120000*0 /




---------------------------
RPTSOL
'RESTART=2' /

SUMMARY    == output written to summary *.RSM file ====================
RUNSUM     -- additional table in *.PRT file
SEPARATE   -- write a seperate *.RSM file

WOPR       -- 'W'ell 'O'il 'P'roduction 'R'ate
'P1'
/
WWPR       -- 'W'ell 'W'ater 'P'roduction 'R'ate
'P1'
/
WWIR       -- 'W'ell 'W'ater injection 'R'ate
'P1'
/
WBHP       -- and the bottom hole pressure of 'PROD'
 'P1'
 'I1'
/
FPR        -- Average reservoir pressure
FOPR
FWPR
FWIR
FOPT       -- Cumulative oil production of the field, ('F'ield 'O'il 'P'roduction 'T'otal)
FWPT       -- Cumulative water production of the field, ('F'ield 'O'il 'P'roduction 'T'otal)
FWIT       -- Cumulative water injection of the field
FOE        -- request oil recovery
FOPV       -- field oil pore volume
FWPV       -- field water pore volume

SCHEDULE   == operations to be simulated ==============================
RPTSCHED   -- CONTROLS ON OUTPUT AT EACH REPORT TIME
-- 'WELLS=2' 'WELSPECS'/
'SWAT' 'PRES'/
--RPTRST
-- 3 0 1 0 0 1 /
--/

DRSDT      -- Free gas is not allowed to re-dissolve within oil
```

```
  0 /

RPTRST    -- request restart file
'BASIC=2'
/

-- Sets simulator control parameters
TUNING
1* 1 1* 1* 3/
/
/

WELSPECS   == WELL SPECIFICATION DATA ================================
--   WELL   GROUP LOCATION  BHP   PI
--Name  Group   I     J     Datum     Phase
'P1'      'G'     48    50       555      'OIL'    /
/



-- Specification for completion of oil producing well
COMPDAT
--Name   I    J   K1   K2   Status  Sattab Trfact  Diam  EffKh  Skin
  'P1'   48   50   48   50   'OPEN'    1*     1*   0.1    1*    0.0 /
/

-- Control data for oil producing well
WCONPROD
--Name Status  Mode "o_rate" "w_ rate" "g_rate" "l_rate" "rf_rate"    BHP
  'P1' 'OPEN' 'RESV'   1*      1*       1*       1*      65      200/
/

-- Specification data for injector well on the left
WELSPECS
--Name  Group   I    J    Datum  Phase
  'I1'   'G'    1    1   85  'WATER' /
/

-- Specification for completion of injector well
COMPDAT
--Name   I    J   K1   K2   Status  Sattab Trfact  Diam  EffKh  Skin
  'I1'   1    1   1   1   'OPEN'    1*     1*   0.1    1*    0.0 /
/

-- Control data for water injecting well
WCONINJE
--Name  Type   Status  Mode "w_rate" "rf_rate"  BHP
  'I1' 'WATER' 'OPEN' 'RATE'    65        1*     1500 /
/
```

```
-- Total duration of simulation run / frequency of reports of restart files
TSTEP
300*30.5
 /


 /



END
```

Appendix F – Simulator Input Data File for Case 2 – Variable Rate Scenario

```
RUNSPEC   == memory dimensioning of the run ============================

TITLE     -- title of the run
PHASE 4: MODEL a: 3D, HOMOGENEOUS, OIL-WATER SYSTEM

DIMENS    -- dimensions of the model
-- NX    NY   NZ
   48    50     50 / --2D Model XY Section

OIL       -- two phase black oil
WATER     -- water is present, but no gas
METRIC    -- unit specification
START     -- starting date for simulation run
  1 'JAN' 1983 /

EQLDIMS   -- equilibration table size
    1  100   10    1   20 /
TABDIMS   -- size of saturation and pvt tables
    1    1   101   40 /
WELLDIMS  -- max numb of WELLS/CONN per WELL/GROUPS/WELLperGROUP
    2    25    1    2 /

UNIFIN
UNIFOUT
MONITOR
-- UNIFOUT
FMTOUT

NSTACK    -- usually 10
    50 /

GRID      == geometry of our model ====================================
EQUALS    -- set top depth, block sizes and rock properties
          -- valid for a given range of blocks: I1 I2   J1 J2   K1 K2
      'DX'     8   /                       -- default box => all blocks
      'DY'     8   /
--      'PORO'   0.3 /
      'DZ'     1.5  / -- thickness of the layers
--      'PERMX'  50   /
--         'PERMY'  50   /
--         'PERMZ'  50   /

/

INCLUDE
'PORO.DAT'
/
```

```
INCLUDE
'perm.dat'
/
MULTIPLY
PERMX 100 /
/
COPY
 PERMX PERMY/
 PERMX PERMZ/
/

MULTIPLY
PERMZ 0.1 /
/

BOX
1 48 1 50 1 1/

TOPS
2400*70/

ENDBOX


-- request init and grid file, necessary for post processing of the simulation with floviz
INIT
GRIDFILE
 2 /

PROPS     == pvt and relperm tables =============================


-- Specify properties of water phase
PVTW
-- P_reference  FVF  Compressibility Viscosity@Pref
     295      1.00      0.00000000000000000001           1.5 /

-- Specify properties of rock matrix
ROCK
-- P_reference  Compressibility
     295.0         0 /

-- Specify densities for all phases at surface conditions

DENSITY
-- oil    wat    gas
   700   1000  100 /
```

```
-- Specify properties of dead oil (no dissolved gas)
PVDO
--P_oil   FVF  Viscosity

100      1.071   7
200      1.070   7
300      1.069   7
400      1.068   7
500      1.067   7
600      1.066   7
700      1.065   7
800      1.064   7
900      1.063   7
1000     1.062   7
1100     1.061   7
1200     1.060   7
1300     1.059   7
1400     1.058   7
1500     1.057   7
1600     1.056   7
1700     1.055   7




/

--PVCDO
--100 1.071 0.000000001 20 0.0 /


SWOF     -- Wat-oil Relative Permeabilities and Pcow
--sw     krw      krow    Pc
0.00E+00       0.00E+00       1.00E+00       0
1.00E-02       1.00E-04       9.80E-01       0
2.00E-02       4.00E-04       9.60E-01       0
3.00E-02       9.00E-04       9.41E-01       0
4.00E-02       1.60E-03       9.22E-01       0
5.00E-02       2.50E-03       9.03E-01       0
6.00E-02       3.60E-03       8.84E-01       0
7.00E-02       4.90E-03       8.65E-01       0
8.00E-02       6.40E-03       8.46E-01       0
9.00E-02       8.10E-03       8.28E-01       0
1.00E-01       1.00E-02       8.10E-01       0
1.10E-01       1.21E-02       7.92E-01       0
1.20E-01       1.44E-02       7.74E-01       0
1.30E-01       1.69E-02       7.57E-01       0
```

1.40E-01	1.96E-02	7.40E-01	0
1.50E-01	2.25E-02	7.23E-01	0
1.60E-01	2.56E-02	7.06E-01	0
1.70E-01	2.89E-02	6.89E-01	0
1.80E-01	3.24E-02	6.72E-01	0
1.90E-01	3.61E-02	6.56E-01	0
2.00E-01	4.00E-02	6.40E-01	0
2.10E-01	4.41E-02	6.24E-01	0
2.20E-01	4.84E-02	6.08E-01	0
2.30E-01	5.29E-02	5.93E-01	0
2.40E-01	5.76E-02	5.78E-01	0
2.50E-01	6.25E-02	5.63E-01	0
2.60E-01	6.76E-02	5.48E-01	0
2.70E-01	7.29E-02	5.33E-01	0
2.80E-01	7.84E-02	5.18E-01	0
2.90E-01	8.41E-02	5.04E-01	0
3.00E-01	9.00E-02	4.90E-01	0
3.10E-01	9.61E-02	4.76E-01	0
3.20E-01	1.02E-01	4.62E-01	0
3.30E-01	1.09E-01	4.49E-01	0
3.40E-01	1.16E-01	4.36E-01	0
3.50E-01	1.23E-01	4.23E-01	0
3.60E-01	1.30E-01	4.10E-01	0
3.70E-01	1.37E-01	3.97E-01	0
3.80E-01	1.44E-01	3.84E-01	0
3.90E-01	1.52E-01	3.72E-01	0
4.00E-01	1.60E-01	3.60E-01	0
4.10E-01	1.68E-01	3.48E-01	0
4.20E-01	1.76E-01	3.36E-01	0
4.30E-01	1.85E-01	3.25E-01	0
4.40E-01	1.94E-01	3.14E-01	0
4.50E-01	2.03E-01	3.03E-01	0
4.60E-01	2.12E-01	2.92E-01	0
4.70E-01	2.21E-01	2.81E-01	0
4.80E-01	2.30E-01	2.70E-01	0
4.90E-01	2.40E-01	2.60E-01	0
5.00E-01	2.50E-01	2.50E-01	0
5.10E-01	2.60E-01	2.40E-01	0
5.20E-01	2.70E-01	2.30E-01	0
5.30E-01	2.81E-01	2.21E-01	0
5.40E-01	2.92E-01	2.12E-01	0
5.50E-01	3.03E-01	2.03E-01	0
5.60E-01	3.14E-01	1.94E-01	0
5.70E-01	3.25E-01	1.85E-01	0
5.80E-01	3.36E-01	1.76E-01	0
5.90E-01	3.48E-01	1.68E-01	0
6.00E-01	3.60E-01	1.60E-01	0
6.10E-01	3.72E-01	1.52E-01	0
6.20E-01	3.84E-01	1.44E-01	0

```
6.30E-01   3.97E-01   1.37E-01   0
6.40E-01   4.10E-01   1.30E-01   0
6.50E-01   4.23E-01   1.23E-01   0
6.60E-01   4.36E-01   1.16E-01   0
6.70E-01   4.49E-01   1.09E-01   0
6.80E-01   4.62E-01   1.02E-01   0
6.90E-01   4.76E-01   9.61E-02   0
7.00E-01   4.90E-01   9.00E-02   0
7.10E-01   5.04E-01   8.41E-02   0
7.20E-01   5.18E-01   7.84E-02   0
7.30E-01   5.33E-01   7.29E-02   0
7.40E-01   5.48E-01   6.76E-02   0
7.50E-01   5.63E-01   6.25E-02   0
7.60E-01   5.78E-01   5.76E-02   0
7.70E-01   5.93E-01   5.29E-02   0
7.80E-01   6.08E-01   4.84E-02   0
7.90E-01   6.24E-01   4.41E-02   0
8.00E-01   6.40E-01   4.00E-02   0
8.10E-01   6.56E-01   3.61E-02   0
8.20E-01   6.72E-01   3.24E-02   0
8.30E-01   6.89E-01   2.89E-02   0
8.40E-01   7.06E-01   2.56E-02   0
8.50E-01   7.23E-01   2.25E-02   0
8.60E-01   7.40E-01   1.96E-02   0
8.70E-01   7.57E-01   1.69E-02   0
8.80E-01   7.74E-01   1.44E-02   0
8.90E-01   7.92E-01   1.21E-02   0
9.00E-01   8.10E-01   1.00E-02   0
9.10E-01   8.28E-01   8.10E-03   0
9.20E-01   8.46E-01   6.40E-03   0
9.30E-01   8.65E-01   4.90E-03   0
9.40E-01   8.84E-01   3.60E-03   0
9.50E-01   9.03E-01   2.50E-03   0
9.60E-01   9.22E-01   1.60E-03   0
9.70E-01   9.41E-01   9.00E-04   0
9.80E-01   9.60E-01   4.00E-04   0
9.90E-01   9.80E-01   1.00E-04   0
1.00E+00   1.00E+00   0.00E+00   0
/




------------------------------ Solution Section -------------------------------
-- Implies the beginning of Solution section
SOLUTION

-- Specify initial state of the reservoir
```

```
--EQUIL
--   DATUM  DATUM   OWC    OWC    GOC    GOC
--   depth  press  depth   PcOW  depth   PcOG
--      70.0   1400  80.0  0.0    200.0  0.0 /

PRESSURE
120000*1400 /

SWAT
120000*0 /



---------------------------
RPTSOL
'RESTART=2' /

SUMMARY    == output written to summary *.RSM file ====================
RUNSUM     -- additional table in *.PRT file
SEPARATE   -- write a seperate *.RSM file

WOPR       -- 'W'ell 'O'il 'P'roduction 'R'ate
'P1'
/
WWPR       -- 'W'ell 'W'ater 'P'roduction 'R'ate
'P1'
/
WWIR       -- 'W'ell 'W'ater injection 'R'ate
'P1'
/
WBHP       -- and the bottom hole pressure of 'PROD'
 'P1'
 'I1'
/
FPR        -- Average reservoir pressure
FOPR
FWPR
FWIR
FOPT       -- Cumulative oil production of the field, ('F'ield 'O'il 'P'roduction 'T'otal)
FWPT       -- Cumulative water production of the field, ('F'ield 'O'il 'P'roduction 'T'otal)
FWIT       -- Cumulative water injection of the field
FOE        -- request oil recovery
FOPV        -- field oil pore volume
FWPV        -- field water pore volume

SCHEDULE   == operations to be simulated ==============================
RPTSCHED   -- CONTROLS ON OUTPUT AT EACH REPORT TIME
-- 'WELLS=2' 'WELSPECS'/
'SWAT' 'PRES'/
```

```
--RPTRST
-- 3 0 1 0 0 1 /
--/

DRSDT     -- Free gas is not allowed to re-dissolve within oil
  0 /

RPTRST    -- request restart file
'BASIC=2'
/

-- Sets simulator control parameters
TUNING
1* 1 1* 1* 3/
/
/

WELSPECS   == WELL SPECIFICATION DATA ================================
--   WELL   GROUP LOCATION  BHP   PI
--Name  Group   I     J     Datum     Phase
'P1'      'G'     48    50       94.25      'OIL'    /
/


-- Specification for completion of oil producing well
COMPDAT
--Name   I    J   K1   K2   Status  Sattab Trfact  Diam  EffKh  Skin
  'P1'   48   50   48   50   'OPEN'    1*     1*   0.1    1*    0.0 /
/

-- Control data for oil producing well
WCONPROD
--Name Status  Mode "o_rate" "w_ rate" "g_rate" "l_rate" "rf_rate"    BHP
  'P1' 'OPEN' 'RESV'   1*      1*        1*        1*      65      200/
/

-- Specification data for injector well on the left
WELSPECS
--Name  Group   I     J    Datum  Phase
  'I1'   'G'    1    1   70.75  'WATER' /
/

-- Specification for completion of injector well
COMPDAT
--Name   I    J   K1   K2   Status  Sattab Trfact  Diam  EffKh  Skin
  'I1'   1    1   1    1   'OPEN'    1*     1*   0.1    1*    0.0 /
/

-- Control data for water injecting well
```

```
WCONINJE
--Name  Type   Status  Mode "w_rate" "rf_rate"  BHP
  'I1' 'WATER' 'OPEN' 'RATE'    65        1*     1500 /
/

-- Total duration of simulation run / frequency of reports of restart files
TSTEP
50*30.5
 /


WELTARG
'P1' RESV 10 /
'I1' WRATE 10/
/

-- Total duration of simulation run / frequency of reports of restart files
TSTEP
50*30.5
 /

WELTARG
'P1' RESV 35 /
'I1' WRATE 35/
/

-- Total duration of simulation run / frequency of reports of restart files
TSTEP
50*30.5
 /


WELTARG
'P1' RESV 95 /
'I1' WRATE 95/
/

-- Total duration of simulation run / frequency of reports of restart files
TSTEP
50*30.5
 /

WELTARG
'P1' RESV 25 /
'I1' WRATE 25/
/

-- Total duration of simulation run / frequency of reports of restart files
TSTEP
```

```
50*30.5
 /



WELTARG
'P1' RESV 125/
'I1' WRATE 125/
/

-- Total duration of simulation run / frequency of reports of restart files
TSTEP
50*30.5
 /



END
```

Appendix G – Simulator Input Data File for Case 2 – Average Rate Scenario

```
RUNSPEC   == memory dimensioning of the run ============================

TITLE     -- title of the run
PHASE 4: MODEL a: 3D, HOMOGENEOUS, OIL-WATER SYSTEM

DIMENS    -- dimensions of the model
-- NX    NY   NZ
   48    50     50 / --2D Model XY Section

OIL       -- two phase black oil
WATER     -- water is present, but no gas
METRIC    -- unit specification
START     -- starting date for simulation run
  1 'JAN' 1983 /

EQLDIMS   -- equilibration table size
    1  100   10    1   20 /
TABDIMS   -- size of saturation and pvt tables
    1    1   101   40 /
WELLDIMS  -- max numb of WELLS/CONN per WELL/GROUPS/WELLperGROUP
    2    25    1    2 /

UNIFIN
UNIFOUT
MONITOR
-- UNIFOUT
FMTOUT

NSTACK    -- usually 10
    50 /

GRID      == geometry of our model ===================================
EQUALS    -- set top depth, block sizes and rock properties
          -- valid for a given range of blocks: I1 I2   J1 J2   K1 K2
      'DX'     8   /                        -- default box => all blocks
      'DY'     8   /
--      'PORO'   0.3 /
      'DZ'     1.5  / -- thickness of the layers
--      'PERMX'  50   /
--         'PERMY'  50   /
--         'PERMZ'  50   /

/

INCLUDE
'PORO.DAT'
```

```
/


INCLUDE
'perm.dat'
/
MULTIPLY
PERMX 100 /
/
COPY
 PERMX PERMY/
 PERMX PERMZ/
/

MULTIPLY
PERMZ 0.1 /
/

BOX
1 48 1 50 1 1/

TOPS
2400*70/

ENDBOX


-- request init and grid file, necessary for post processing of the simulation with floviz
INIT
GRIDFILE
 2 /

PROPS     == pvt and relperm tables ============================


-- Specify properties of water phase
PVTW
-- P_reference  FVF  Compressibility Viscosity@Pref
    295      1.00      0.0000000000000000001          1.5 /

-- Specify properties of rock matrix
ROCK
-- P_reference  Compressibility
    295.0        0 /

-- Specify densities for all phases at surface conditions

DENSITY
-- oil    wat    gas
```

```
   700   1000  100 /

-- Specify properties of dead oil (no dissolved gas)
PVDO
--P_oil   FVF  Viscosity

100     1.071   7
200     1.070   7
300     1.069   7
400     1.068   7
500     1.067   7
600     1.066   7
700     1.065   7
800     1.064   7
900     1.063   7
1000    1.062   7
1100    1.061   7
1200    1.060   7
1300    1.059   7
1400    1.058   7
1500    1.057   7
1600    1.056   7
1700    1.055   7




/

--PVCDO
--100 1.071 0.000000001 20 0.0 /


SWOF     -- Wat-oil Relative Permeabilities and Pcow
--sw     krw      krow    Pc
0.00E+00        0.00E+00        1.00E+00        0
1.00E-02        1.00E-04        9.80E-01        0
2.00E-02        4.00E-04        9.60E-01        0
3.00E-02        9.00E-04        9.41E-01        0
4.00E-02        1.60E-03        9.22E-01        0
5.00E-02        2.50E-03        9.03E-01        0
6.00E-02        3.60E-03        8.84E-01        0
7.00E-02        4.90E-03        8.65E-01        0
8.00E-02        6.40E-03        8.46E-01        0
9.00E-02        8.10E-03        8.28E-01        0
1.00E-01        1.00E-02        8.10E-01        0
1.10E-01        1.21E-02        7.92E-01        0
1.20E-01        1.44E-02        7.74E-01        0
```

1.30E-01	1.69E-02	7.57E-01	0
1.40E-01	1.96E-02	7.40E-01	0
1.50E-01	2.25E-02	7.23E-01	0
1.60E-01	2.56E-02	7.06E-01	0
1.70E-01	2.89E-02	6.89E-01	0
1.80E-01	3.24E-02	6.72E-01	0
1.90E-01	3.61E-02	6.56E-01	0
2.00E-01	4.00E-02	6.40E-01	0
2.10E-01	4.41E-02	6.24E-01	0
2.20E-01	4.84E-02	6.08E-01	0
2.30E-01	5.29E-02	5.93E-01	0
2.40E-01	5.76E-02	5.78E-01	0
2.50E-01	6.25E-02	5.63E-01	0
2.60E-01	6.76E-02	5.48E-01	0
2.70E-01	7.29E-02	5.33E-01	0
2.80E-01	7.84E-02	5.18E-01	0
2.90E-01	8.41E-02	5.04E-01	0
3.00E-01	9.00E-02	4.90E-01	0
3.10E-01	9.61E-02	4.76E-01	0
3.20E-01	1.02E-01	4.62E-01	0
3.30E-01	1.09E-01	4.49E-01	0
3.40E-01	1.16E-01	4.36E-01	0
3.50E-01	1.23E-01	4.23E-01	0
3.60E-01	1.30E-01	4.10E-01	0
3.70E-01	1.37E-01	3.97E-01	0
3.80E-01	1.44E-01	3.84E-01	0
3.90E-01	1.52E-01	3.72E-01	0
4.00E-01	1.60E-01	3.60E-01	0
4.10E-01	1.68E-01	3.48E-01	0
4.20E-01	1.76E-01	3.36E-01	0
4.30E-01	1.85E-01	3.25E-01	0
4.40E-01	1.94E-01	3.14E-01	0
4.50E-01	2.03E-01	3.03E-01	0
4.60E-01	2.12E-01	2.92E-01	0
4.70E-01	2.21E-01	2.81E-01	0
4.80E-01	2.30E-01	2.70E-01	0
4.90E-01	2.40E-01	2.60E-01	0
5.00E-01	2.50E-01	2.50E-01	0
5.10E-01	2.60E-01	2.40E-01	0
5.20E-01	2.70E-01	2.30E-01	0
5.30E-01	2.81E-01	2.21E-01	0
5.40E-01	2.92E-01	2.12E-01	0
5.50E-01	3.03E-01	2.03E-01	0
5.60E-01	3.14E-01	1.94E-01	0
5.70E-01	3.25E-01	1.85E-01	0
5.80E-01	3.36E-01	1.76E-01	0
5.90E-01	3.48E-01	1.68E-01	0
6.00E-01	3.60E-01	1.60E-01	0
6.10E-01	3.72E-01	1.52E-01	0

```
6.20E-01     3.84E-01     1.44E-01     0
6.30E-01     3.97E-01     1.37E-01     0
6.40E-01     4.10E-01     1.30E-01     0
6.50E-01     4.23E-01     1.23E-01     0
6.60E-01     4.36E-01     1.16E-01     0
6.70E-01     4.49E-01     1.09E-01     0
6.80E-01     4.62E-01     1.02E-01     0
6.90E-01     4.76E-01     9.61E-02     0
7.00E-01     4.90E-01     9.00E-02     0
7.10E-01     5.04E-01     8.41E-02     0
7.20E-01     5.18E-01     7.84E-02     0
7.30E-01     5.33E-01     7.29E-02     0
7.40E-01     5.48E-01     6.76E-02     0
7.50E-01     5.63E-01     6.25E-02     0
7.60E-01     5.78E-01     5.76E-02     0
7.70E-01     5.93E-01     5.29E-02     0
7.80E-01     6.08E-01     4.84E-02     0
7.90E-01     6.24E-01     4.41E-02     0
8.00E-01     6.40E-01     4.00E-02     0
8.10E-01     6.56E-01     3.61E-02     0
8.20E-01     6.72E-01     3.24E-02     0
8.30E-01     6.89E-01     2.89E-02     0
8.40E-01     7.06E-01     2.56E-02     0
8.50E-01     7.23E-01     2.25E-02     0
8.60E-01     7.40E-01     1.96E-02     0
8.70E-01     7.57E-01     1.69E-02     0
8.80E-01     7.74E-01     1.44E-02     0
8.90E-01     7.92E-01     1.21E-02     0
9.00E-01     8.10E-01     1.00E-02     0
9.10E-01     8.28E-01     8.10E-03     0
9.20E-01     8.46E-01     6.40E-03     0
9.30E-01     8.65E-01     4.90E-03     0
9.40E-01     8.84E-01     3.60E-03     0
9.50E-01     9.03E-01     2.50E-03     0
9.60E-01     9.22E-01     1.60E-03     0
9.70E-01     9.41E-01     9.00E-04     0
9.80E-01     9.60E-01     4.00E-04     0
9.90E-01     9.80E-01     1.00E-04     0
1.00E+00     1.00E+00     0.00E+00     0
/
------------------------------ Solution Section -------------------------------
-- Implies the beginning of Solution section
SOLUTION

-- Specify initial state of the reservoir
--EQUIL
--   DATUM  DATUM   OWC    OWC   GOC    GOC
--   depth  press  depth   PcOW  depth  PcOG
--     70.0   1400  80.0  0.0    200.0  0.0 /
```

```
PRESSURE
120000*1400 /

SWAT
120000*0 /



--------------------------
RPTSOL
'RESTART=2' /

SUMMARY    == output written to summary *.RSM file ====================
RUNSUM     -- additional table in *.PRT file
SEPARATE   -- write a seperate *.RSM file

WOPR       -- 'W'ell 'O'il 'P'roduction 'R'ate
'P1'
/
WWPR       -- 'W'ell 'W'ater 'P'roduction 'R'ate
'P1'
/
WWIR       -- 'W'ell 'W'ater injection 'R'ate
'P1'
/
WBHP       -- and the bottom hole pressure of 'PROD'
 'P1'
 'I1'
/
FPR        -- Average reservoir pressure
FOPR
FWPR
FWIR
FOPT       -- Cumulative oil production of the field, ('F'ield 'O'il 'P'roduction 'T'otal)
FWPT       -- Cumulative water production of the field, ('F'ield 'O'il 'P'roduction 'T'otal)
FWIT       -- Cumulative water injection of the field
FOE        -- request oil recovery
FOPV       -- field oil pore volume
FWPV       -- field water pore volume

SCHEDULE   == operations to be simulated ==============================
RPTSCHED   -- CONTROLS ON OUTPUT AT EACH REPORT TIME
-- 'WELLS=2' 'WELSPECS'/
'SWAT' 'PRES'/
--RPTRST
-- 3 0 1 0 0 1 /
--/
```

```
DRSDT     -- Free gas is not allowed to re-dissolve within oil
  0 /

RPTRST    -- request restart file
'BASIC=2'
/

-- Sets simulator control parameters
TUNING
1* 1 1* 1* 3/
/
/

WELSPECS   == WELL SPECIFICATION DATA ================================
--   WELL   GROUP LOCATION  BHP   PI
--Name  Group   I    J     Datum     Phase
'P1'      'G'     48    50      94.25      'OIL'    /
/


-- Specification for completion of oil producing well
COMPDAT
--Name   I    J   K1    K2   Status  Sattab Trfact  Diam  EffKh  Skin
  'P1'   48   50   48   50   'OPEN'    1*     1*   0.1    1*    0.0 /
/

-- Control data for oil producing well
WCONPROD
--Name Status  Mode "o_rate" "w_ rate" "g_rate" "l_rate" "rf_rate"    BHP
  'P1' 'OPEN' 'RESV'   1*      1*       1*       1*      65      200/
/

-- Specification data for injector well on the left
WELSPECS
--Name  Group   I     J    Datum  Phase
  'I1'   'G'    1    1   70.75  'WATER' /
/

-- Specification for completion of injector well
COMPDAT
--Name   I    J   K1   K2   Status  Sattab Trfact  Diam  EffKh  Skin
  'I1'   1    1   1   1   'OPEN'    1*     1*   0.1    1*    0.0 /
/

-- Control data for water injecting well
WCONINJE
--Name  Type   Status  Mode "w_rate" "rf_rate"  BHP
  'I1' 'WATER' 'OPEN' 'RATE'    65       1*     1500 /
/
```

```
-- Total duration of simulation run / frequency of reports of restart files
TSTEP
300*30.5
 /




END
```

Appendix H – Sample calculation algorithm in WATERFLOOD tool

```
public Tuple<List<double>, List<double>, List<double>, List<double>, List<double>, List<double>>
Calculate(ListParam ParamList)
    {


        //Reset();

        double Krocw = ParamList.GetParam("Krocw (fraction)").value;
        double Krwro = ParamList.GetParam("Krwro (fraction)").value;
        double swLookup = ParamList.GetParam("Swi").value;
        double Swc = ParamList.GetParam("Swc (fraction)").value;
        double Sor = ParamList.GetParam("Sor (fraction)").value;
        double Nw = ParamList.GetParam("Nw (Corey Exp)").value;
        double No = ParamList.GetParam("No (Corey Exp)").value;
        double uo = ParamList.GetParam("MiuO (mPa.s)").value;
        double uw = ParamList.GetParam("MiuW (Corey Exp)").value;
        double delta = ParamList.GetParam("Porosity (Fraction)").value;
        double ho = ParamList.GetParam("ho (m)").value;
        double hhor = ParamList.GetParam("Hhor (m)").value;
        double kmain = (ParamList.GetParam("kmain (md)").value);
        double deltap = ParamList.GetParam("Delta P (kg/m3)").value;
        double qangle = ParamList.GetParam("Q Angle (Degrees)").value;
        double wellspacing = ParamList.GetParam("Wellspacing (m)").value;
        double qgross = ParamList.GetParam("QGross (m3/d)").value;
        double waban = ParamList.GetParam("BS & Waban (fraction)").value;




        double step = (1 - Sor - Swc) / 1000.0; // 1 - B23 - B22;

        double sw = Swc;
        double krw = Krwro * Math.Pow(((sw - Swc) / (1 - Swc - Sor)), Nw);
        double Kro = (1 - Sor >= sw + 0.01) ? Krocw * Math.Pow(((1 - sw - Sor) / (1 - Swc - Sor)), No) :
0;
        double fw = 0;
        double swe = sw;
        double initialSwe = swe;

        double fwe = fw;
        double delSwe = 0; // null?
        double delFwe = 0;
        double ddel = 0;
        double slope = 0;
```

```
    double maxSlope = double.MinValue;
    double maxSlopeIndex = 0;

    //double xWidTime = 7.57;
    double onePv = (delta * ho * hhor * wellspacing) / 1000000.0;
    double xWidTime = onePv / (qgross * 365) * 1000000;

    // double swLookup = 0.2;
    bool changed = false;
    int swLookupIndex = 0;



    List<double> slopes = new List<double>();
    int count = 0;

    while (krw <= 1)
    {

        sw = sw + step;

        krw = Krwro * Math.Pow(((sw - Swc) / (1 - Swc - Sor)), Nw);

        Kro = (1 - Sor >= sw + 0.01) ? Krocw * Math.Pow(((1 - sw - Sor) / (1 - Swc - Sor)), No) : 0;

        fw = (1 - (kmain * POW_1015 * Kro * ho * hhor * deltap * 9.8 * Math.Sin(qangle * RAD_C) /
(uo * qgross * TIME_C))) / (1 + (Kro / krw) * (uw / uo));

        delSwe = sw - swe;
        delFwe = fw - fwe;

        swe = sw;
        fwe = fw;

        ddel = delFwe / delSwe;

        slope = fwe / (swe - initialSwe);

        slopes.Add(slope);

        if (slope > maxSlope)
        {
            maxSlope = slope;
            maxSlopeIndex = slopes.Count;
        }

        count++;
```

```
        if (count > 100000)
            throw new Exception("The loop might have fall into infinite loop");
    }




    List<double> OilRateData = new List<double>();
    List<double> WaterRateData = new List<double>();
    List<double> Waterinjcheck = new List<double>();
    List<double> grossratecheck = new List<double>();

    double swex = maxSlopeIndex * step + Swc;
    ParamList.GetParam("BS & Waban (fraction)").value = swex;
    double initialSwex = swex;

    double krwx = Krwro * Math.Pow(((swex - Swc) / (1 - Swc - Sor)), Nw);

    double krox = (1 - Sor) >= swex + 0.01 ? Krocw * Math.Pow(((1 - swex - Sor) / (1 - Swc - Sor)),
No) : 0;

    double mswc = swex - Swc;

    double fwex = (1 - (kmain * POW_1015 * krox * ho * hhor * deltap * 9.8 * Math.Sin(qangle *
RAD_C) / (uo * qgross * TIME_C))) / (1 + krox / krwx * uw / uo);

    double ifwex = 1 - fwex;

    List<double> swexs = new List<double>();
    swexs.Add(swex);

    List<double> mswcs = new List<double>();
    mswcs.Add(mswc);

    List<double> fwexs = new List<double>();
    fwexs.Add(fwex);

    double waterRate = fwex * qgross;
    double oilRate = qgross - waterRate;

    OilRateData.Add(oilRate);
    WaterRateData.Add(waterRate);

    for (int i = 0; i < slopes.Count; i++)
    {

        if (swex >= swLookup && !changed)
        {
            swLookupIndex = i;
```

```
                    changed = true;
                }


                swex = (1 - Sor > swex + step) ? swex + step : swex;
                swexs.Add(swex);

                krwx = Krwro * Math.Pow(((swex - Swc) / (1 - Swc - Sor)), Nw);

                krox = (1 - Sor) >= swex + 0.01 ? Krocw * Math.Pow(((1 - swex - Sor) / (1 - Swc - Sor)), No) :
0;

                mswc = swex - Swc;
                mswcs.Add(mswc);


                fwex = (1 - (kmain * POW_1015 * krox * ho * hhor * deltap * 9.8 * Math.Sin(qangle *
RAD_C) / (uo * qgross * TIME_C))) / (1 + krox / krwx * uw / uo);
                fwexs.Add(fwex);

                ifwex = 1 - fwex;

                waterRate = fwex * qgross;
                oilRate = qgross - waterRate;

                OilRateData.Add(oilRate);
                WaterRateData.Add(waterRate);
            }

            double swexpre = swexs[0] - step;

            double krwxpre = Krwro * Math.Pow(((swexpre - Swc) / (1 - Swc - Sor)), Nw);

            double kroxpre = (1 - Sor) >= swexpre + 0.01 ? Krocw * Math.Pow(((1 - swexpre - Sor) / (1 - Swc
- Sor)), No) : 0;

            double fwexpre = (1 - (kmain * POW_1015 * kroxpre * ho * hhor * deltap * 9.8 *
Math.Sin(qangle * RAD_C) / (uo * qgross * TIME_C))) / (1 + kroxpre / krwxpre * uw / uo);

            // slope modified
            double wid = ((fwexs[1] - fwexpre) >= 0) ? (swexs[1] - swexpre) / (fwexs[1] - fwexpre) : 0;
            //changed slope equation

            double npd = wid;

            double rf = npd / (1 - Swc);

            double time = xWidTime * wid;
```

```
double cumOil = npd * onePv * 1000000;

double cumWater = wid * onePv * 1000000;
double cumWaterP = cumWater - cumOil;

List<double> CumOilData = new List<double>();
List<double> WaterCutData = fwexs;
List<double> CumWaterPData = new List<double>();
List<double> CumWaterData = new List<double>();
List<double> TimeYearsList = new List<double>();

CumOilData.Add(cumOil);
CumWaterData.Add(cumWater);
CumWaterPData.Add(cumWaterP);
TimeYearsList.Add(time);

for (int i = 1; i < slopes.Count; i++)
{
   double f1 = fwexs[i-1];
   double s1 = swexs[i-1];
   double f2, s2;
   if (i+1 == slopes.Count-1)
   {
      f2 = 0;
      s2 = 0;
   }
   else
   {
      f2 = fwexs[i + 1];
      s2 = swexs[i + 1];
   }

   wid = (f2 - f1 > 0) ? (s2 - s1) / (f2 - f1) : wid;

   npd = mswcs[i] + (1 - fwexs[i]) * wid;

   rf = npd / (1 - Swc);

   time = xWidTime * wid;

   cumOil = npd * onePv * 1000000;
   CumOilData.Add(cumOil);

   cumWater = wid * onePv * 1000000;
   cumWaterP = cumWater - cumOil;
   CumWaterData.Add(cumWater);
   CumWaterPData.Add(cumWaterP);
   TimeYearsList.Add(time);
}
```

```
        double cumOilSwc = CumOilData[swLookupIndex];
        double cumWaterPSwc = CumWaterPData[swLookupIndex];
        double cumWaterSwc = CumWaterData[swLookupIndex];
        for (int i = 0; i < CumOilData.Count; i++)
        {
            CumOilData[i] = (CumOilData[i] - cumOilSwc >= 0) ? CumOilData[i] - cumOilSwc : 0;

            CumWaterPData[i] = (CumWaterPData[i] - cumWaterPSwc >= 0) ? CumWaterPData[i] -
cumWaterPSwc : 0;
            CumWaterData[i] = (CumWaterData[i] - cumWaterSwc >= 0) ? CumWaterData[i] -
cumWaterSwc : 0;
        }

        int counter=0;




        List<double> OilRateDatax = new List<double>();
        List<double> WaterRateDatax = new List<double>();
        List<double> swcheck = new List<double>();
        List<double> TimeDiffList = new List<double>();
        List<double> TimeDiffListx = new List<double>();
        List<double> TimeDiffListy = new List<double>();
        int counter2 = 0;
        int counter3 = 0;

       for (int i = 0; i < _modelCumOilcheck.Count; i++)
        {
            Waterinjcheck.Add(_modelCumOilcheck[i] + _modelCumWatercheck[i]);
            grossratecheck.Add(_modelWaterRatecheck[i]+_modelOilRatecheck[i]);

            for (int j = 0; j < CumOilData.Count; j++)
            {
                if (CumWaterData[i] == 0)
                {
                    counter = counter + 1;
                }

                if (counter + 1 >= CumWaterData.Count)
                    break;


                // NEED TO CHECK THE TIME FOR BL
                    if (Waterinjcheck[i] < CumWaterData[counter])
                {
                    WaterRateDatax.Add(fwexs[counter-1] * grossratecheck[i]);
                    OilRateDatax.Add(grossratecheck[i]-  WaterRateDatax[i]);
```

```
                        swcheck.Add(swexs[counter - 1]);
                        TimeDiffList.Add((TimeYearsList[counter-1]));


                         break;
                    }


                    if (counter+1 >= CumWaterData.Count)
                            break;

                     // NEED TO CHECK THE TIME FOR BL
                    if (Waterinjcheck[i] >= CumWaterData[counter] && Waterinjcheck[i] <=
CumWaterData[counter + 1])
                    {

                        counter2=0;
                        WaterRateDatax.Add(fwexs[counter] * grossratecheck[i]);
                        OilRateDatax.Add(grossratecheck[i] - WaterRateDatax[i]);
                        swcheck.Add(swexs[counter]);
                        TimeDiffList.Add((TimeYearsList[counter
                        counter = counter + 1;

                        break;
                    }

                    else
                    {
                        counter = counter + 1;
                    }


                }


                if (counter + 1 >= CumWaterData.Count)
                    break;


                if (OilRateDatax.Count == _modelTimecheck.Count)
                    break;

             }

            double timex = 0;

             //check for the timesteps!!!

            for (int k = counter2; k < OilRateDatax.Count; k++)
```

```
        {




            if (k + 1 >= OilRateDatax.Count)
            {
                counter3 = counter3 + 1;
                break;
            }


            if (TimeDiffList[k] != TimeDiffList[k+1])
            {
                timex = TimeDiffList[k];
            }


        }
        double check = TimeYearsList[0];

        for (int i = 0; i < CumOilData.Count; i++)
        {
            TimeYearsList[i] = TimeYearsList[i] - check;
        }

        for (int i = 0; i < _modelCumOil.Count; i++)
        {
            for (int j = 0; j < CumOilData.Count; j++)
            {


                if (Waterinjcheck[i] < CumWaterData[counter2])
                {
                    TimeDiffListx.Add((TimeYearsList[counter2] - TimeYearsList[counter2 - 1]) /
(CumWaterData[counter2] - CumWaterData[counter2 - 1]) * (Waterinjcheck[i] -
CumWaterData[counter2 - 1]) + TimeYearsList[counter2 - 1]);
                    break;
                }
                else
                    counter2 = counter2 + 1;

                if (counter2 >= CumWaterData.Count)
                    break;

            }

            if (counter2 >= CumWaterData.Count)
                break;
```

```
                if (TimeDiffListx.Count == _modelTimecheck.Count)
                    break;
            }




            return new Tuple<List<double>, List<double>, List<double>, List<double>, List<double>,
List<double>>(CumOilData, CumWaterPData, WaterCutData, _modelTimecheck, OilRateDatax,
WaterRateDatax);
        }
```