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Performance analysis of water flooded reservoir: A case study of field "X", Niger Delta

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Abstract

This study presents the use of classical and conventional analysis technique such as material balance equation (MBE), voidage replacement ratio (VRR), capacitance resistance modelling (CRM) and decline curve analysis (DCA) coupled with performance diagnostics tools (such as GOR and WOR) for production data analysis with slight modification for the characterization, evaluation and performance prediction of water flooded reservoirs.

The conventional Havlena - Odeh straight line plot was used as the basis for this analysis with little modification to accommodate the water injection term ($W_{inj.}$). The single control volume representation of the reservoir was assumed and computations was carried out using Microsoft excel spreadsheet.

The results from analysis shows that VRR and MBE successfully characterized the reservoir as a water flooded reservoir with negligible water influx, CRM indicated close to 70% sweep efficiency and an increase in oil recovery was still possible (up to 18.2% with cumulative production standing at approximately 3MMbbls of oil produced) as indicated from decline curve analysis (DCA). These results obtained showed that the methods and approach followed were coherent and can be extended to other reservoir types.

This technique can be used as a quick and cheap reservoir performance analysis tool where and when time and cost is a constraint. Similarly, results from analysis can be used as a pre-requisite for detailed 3D reservoir simulation studies, as reservoir behavior and performance can be inferred from it.

Keywords: reservoir performance, water flooding, oil recovery, material balance, reservoir characterization

1. Introduction

Efficient development of reservoirs depends on the knowledge of the reservoir behavior. Despite the widespread application of reservoir simulation to study water flooded reservoir performance, petroleum engineers' still need simple predictive tools to forecast production decline, estimate ultimate oil recovery and diagnose the production performance from historical field data.

The principal reason for water flooding is to increase oil production rate and ultimately oil recovery. This is accomplished by "voidage replacement" – injection of water to increase reservoir pressure to its initial level and maintain it near that pressure. However, reservoir engineers have no easy way to identify injection patterns, well-pairs connection or areas of inefficiency beyond standard fixed pattern surveillance technique [3]. The recent approach now is to build a detailed dynamic reservoir model, upscale it, and then perform flow simulations. To estimate the uncertainty in such a system, this has to be repeated for various realizations of the dynamic model. The problem with this approach is that it is computationally very expensive and time consuming [7].

In order to produce hydrocarbons from a reservoir as efficiently as possible, it is important to know the distribution of fluid in the reservoir at any time during the production process [4]. The successful characterization and management of petroleum fields depends largely on the knowledge of the hydrocarbon volumes in place and the flow condition of the fluid phases (water, oil and gas).

To predict recovery as a function of pressure and time, sources of energy for producing the effluent from the reservoir must be identified and their contribution to the reservoir performance evaluated. In achieving this, opportunities abound to modify the original water flood design and operations on the basis of analysis of the actual field production data and the need to characterize and model reservoir performance for future development as water flooding is a dynamic process [1].

In recent years, the work of a number of petroleum engineers, scientist and technologists has resulted in the establishment of certain basic principles, upon which the modern thought of oil reservoir performance is based.

The aim of this work is to develop a methodology that combines the classical techniques for production data analysis (pressure, fluid properties, oil, gas and water production rates etc.) with existing models (in this case WOR, GOR, HCPVI etc.), as this analysis will improve the evaluation of reservoir performance, assist in future development of reservoirs and identification of dominant drive mechanism.

The case study for this research is a reservoir system from a field "X" in Niger- Delta, Nigeria. Oil production started in the year 2001 with two wells and injection followed almost immediately from one injection well into the same reservoir. The production from the reservoir ramped up to its peak in that same year (3600 BOPD) before dropping to a steady decline, after which there was a general field shut down in the year 2003 which lasted till late year 2006 requiring no production from this reservoir during this period. Production resumed again in the year 2007 without a corresponding water injection due to problems with the injection well and sources of water for injection. Production from this reservoir was again shut down due to excessive production of sand for sand clean out operation and recompletion work done on one of the well and the other zone switched to another reservoir. In late year 2012, production was restarted and injection followed after some time. Table 1 is the summary of the reservoir properties while Figure 1, shows the performance history of the reservoir.

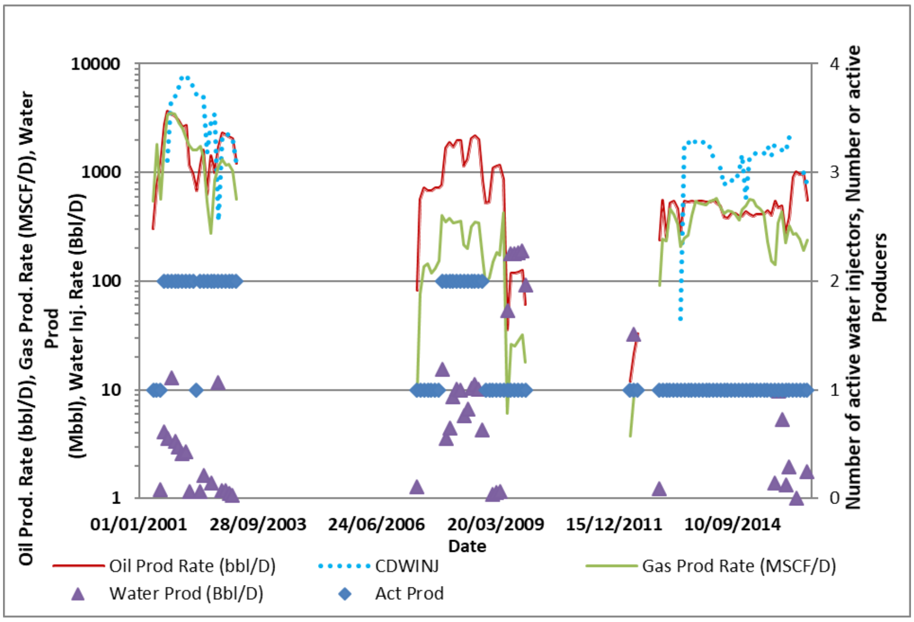

Fig 1: Case Reservoir Performance History

Table 1: Reservoir summary

Reservoir Properties Summary	Value
STOOIP (MMSTB)	22
Porosity (%)	28
Water saturation (%)	34
Number of producers/ injectors	1/1
Depletion strategies	Water flood
Initial reservoir pressure/bubble point pressure	2070/2070
First oil date	2001
Peak oil rate & date	3600BOPD/2001

1.1 Reservoir performance characterization

This is the process of defining, describing, validating, calibrating and detailing the performance of a reservoir system on the basis of actual production data, performance trends and indices, reservoir response and changes in order to capture accurately how to fully and economically exploit the reservoir.

In petroleum engineering, a number of tools have been formulated to characterize the performance of reservoirs and these include voidage replacement analysis (VRR), material balance analysis (MBE) among others.

1.1.1 Voidage Replacement and Voidage Replacement Ratio

Voidage replacement is the process of replacing the volume of oil, gas and water produced from the reservoir by injected fluids and voidage replacement ratio is the ratio of reservoir barrels of injected fluid to reservoir barrels of produced fluid [6]. They are used basically to characterize water injection process in a water flooding scheme.

$$VRR = \frac{Injected\ reservoir\ \ volumes}{\Pr oduced\ \ reservoir\ \ volumes} \tag{1}$$

Mathematically (for water injection), equation (1) can be expressed as;

$$VRR = \frac{i_w B_w}{q_w B_w + B_0 q_0 + q_0 \left(R_p - R_s\right) B_g} \tag{2}$$

In the above equation,

B_o, B_w are the formation volume factors for oil and water respectively

q_w, q_o, i_w Are the production and injection rates for phase α

R_p is the producing gas-oil ratio and R_s is the dissolved gas-oil ratio

The $q_o(R_p - R_s)B_g$ term in the denominator accounts for “free gas” produced that is in excess of the gas in the reservoir that is dissolved in the oil.

The voidage replacement ratio can be calculated on an instantaneous basis using injected and produced fluids over any specific time period (typically daily or monthly) or on a cumulative basis by using the cumulative injected and produced fluids. In the case of the cumulative voidage replacement ratio, it is common to start the cumulative production numbers at the commencement of water flooding. Some authors have used cumulative data starting at fill up (the point at which injected water is estimated to have filled the available gas saturation in the reservoir).

1.1.2 The Havlena and Odeh Material Balance Equation

Material balance is one of the basic and most important tool of the reservoir engineer used in characterizing the performance of the system. The material balance is a volumetric balance of fluids entering, leaving and accumulating in the reservoir.
Havlena and Odeh (1964) examined several cases of varying reservoir types and pointed out that the relationship can be rearranged into the form of a straight line. They derived the linear form of the MBE and this has helped in manipulating the MBE to solve for more than one unknown from one equation. The complete form of the material balance equation together with the injection term is given below.

$$N_p\left(B_o+\left(R_p-R_s\right)B_g\right)+W_pB_w$$

$$=NB_o\left[\frac{\left(B_o-B_{oi}\right)+\left(R_{si}-R_s\right)}{B_{oi}}+m\left(\frac{B_g}{B_{gi}}-1\right)+\left(1+m\right)\left(\frac{c_wS_w+c_f}{1-S_{wc}}\right)\Delta p\right]$$

$$+W_e+G_iB_g+W_{inj}B_w \tag{3}$$

Applying some degree of assumptions to the above equation,

$$N_p\left(B_o+\left(R_p-R_s\right)B_g\right)+W_pB_w=NB_o\left[\frac{\left(B_o-B_{oi}\right)+\left(R_{si}-R_s\right)}{B_{oi}}+m\left(\frac{B_g}{B_{gi}}-1\right)+\left(1+m\right)\left(\frac{c_wS_w+c_f}{1-S_{wc}}\right)\Delta p\right]$$

$$+W_e+G_{inj}B_g+W_{inj}B_{wz}\,. \tag{4}$$

$$N_p\left(B_o+\left(R_p-R_s\right)B_g\right)+W_pB_w=NB_o\left[\frac{\left(B_o-B_{oi}\right)+\left(R_{si}-R_s\right)}{B_{oi}}+m\left(\frac{B_g}{B_{gi}}-1\right)\right]$$

$$+W_{inj}B_w \tag{5}$$

Equation (5) can thus be stated to represents underground withdrawal equal to the sum of total expansion of the hydrocarbon system and the injection terms. Given below in equation (6) as

$$F=NE_t+W_{inj}B_w \tag{6}$$

Where, F= $N_p(B_o+(R_p-R_s)B_g)+W_pB_w$

$$E_t=B_o\left[\frac{\left(B_o-B_{oi}\right)+\left(R_{si}-R_s\right)}{B_{oi}}+m\left(\frac{B_g}{B_{gi}}-1\right)\right] \tag{7}$$

A plot of underground withdrawal (F) against total system expansion (E_t) with water injection term as the intercept will yield a slope which is equal to the stock tank oil initially in place (STOIIP).
Also the material balance equation can be solved to give the reservoir drives indices using the equation below:

$$1=\frac{NB_{oi}\left(B_o-B_{oi}\right)}{A}+\frac{NmB_{oi}\left(B_g-B_{gi}\right)/B_{gi}}{A}+\frac{W_e-W_pB_w}{A}+\frac{NB_{oi}\left(1+m\right)\left[\frac{C_wS_{wi}+C_f}{1-S_{wi}}\right]\left(\rho_i-\rho\right)}{A}$$

With the parameter A as defined by:

$$A = N_p B_t + \left(R_p - R_s\right) B_g$$

$$DDI + SDI + WDI + EDI = 1$$

Where DDI = depletion-drive index $= \frac{N B_{oi}(B_o - B_{oi})}{A}$

SDI = segregation (gas-cap)-drive index $= \frac{N m B_{oi}\left(B_g - B_{gi}\right)/B_{gi}}{A}$

WDI = water-drive index $= \frac{W_e - W_p B_w}{A}$

EDI = expansion (rock and liquid)-drive index $= \frac{N B_{oi}(1+m)\left[\frac{c_w S_{wi} + c_f}{1 - S_{wi}}\right](p_i - p)}{A}$

Since the sum of the driving indexes is equal to one, it follows that if the magnitude of one of the index terms is reduced, then one or both of the remaining terms must be correspondingly increased.

This shows that an effective water drive will usually result in maximum recovery from the reservoir. Therefore, if possible, the reservoir should be operated to yield a maximum water-drive index and minimum values for the depletion-drive index and the gas-cap-drive index. Maximum advantage should be taken of the most efficient drive available. The reservoir production characteristics are controlled by the type of reservoir drive mechanism. The relative importance of each reservoir drive can change with fluid production.

1.2 Reservoir performance evaluation

Reservoir performance evaluation has to deal with the critical review of the performance of the reservoir system and this involves monitoring and analyzing reservoir production performance data on the basis of recognized trends and established key performance indicators (KPIs) which include but not limited to oil production rate, gas oil ratio and water oil ratio.

1.2.1 Gas-oil Ratio and Water-oil Ratio

(Baker, 1998) stated that an indicator of bypassing is a premature drop in gas-oil ratio (GOR); i.e., earlier than expected collapse of gas saturation [3]. Early gas collapse (water fill up) may indicate that channeling has occurred. In layered reservoirs with little or no vertical cross flow, water injection in an initially depressurized layer will cause GOR to drop rapidly. Naturally fractured reservoirs often exhibit fast gas collapse because water fills up the fracture system and does not initially invade the matrix, the desired target for water flooding.

Other key performance indicators are water breakthrough times and subsequent WOR trends, which also can be indicative of channeling and bypassing. However, since wells or patterns showing high WOR rise or quick gas collapse may simply be due to high injection rates, one should plot WOR and GOR versus hydrocarbon pore volume injected (HCPVI) as a quick guide. In general, if water breakthrough occurs before 20% hydrocarbon pore volume injected (HCPVI), channeling or bypassing due to heterogeneity is likely occurring [7].

1.2.2 Capacitance-Resistance Model (CRM)

The Capacitance- Resistance Model (CRM) is a signal processing tool that takes injection rate as an input and production rates as an output. It uses a multivariate nonlinear regression to analyze the relationship between them and determine model parameters. Its fundamental equations are derived from the continuity principle combined with Darcy’s law. It is based on some assumptions such as two-component immiscible displacement, stabilized flow, constant temperature, constant productivity index, no aquifer and slightly compressible fluids [5].

The CRM is an effective tool in obtaining a reservoir description (essentially a basic geologic model), by estimating inter-well connectivity (gains) and time constants. It considers the effect of compressibility, pore volume, and productivity index in nonlinear multivariate regression by introducing a time constant to characterize the time delay of injection signal to producers. Therefore, connectivity indices and time constants can reflect reservoir and fluid properties between injection and producers [8, 9].

In this study, analytical solutions for the fundamental differential equation of the capacitance resistance model based on the superposition in time as developed by (Sayapour, 2008) is used to evaluate the inter-well connectivity. The application is basically a history matching process which is used to obtain model parameters (time constants and inter well connectivity).

1.3 Reservoir performance prediction

1.3.1 Decline curve analysis

Decline curve is used to forecast additional recovery and estimate recoverable reserves. It is based on empirical observation of production rate decline. Production-decline analysis is the analysis of past trends of declining production performance, that is, rate versus time and rate versus cumulative production plots, for wells and reservoirs [2].

The exponential decline equation was used to fit the data and analyzed to get the required results. This is because of the fact that a straight-line relationship result when the flow rate versus time was plotted on a semi-log scale and also when the flow rate versus cumulative production was plotted on a Cartesian scale.

$$q_i = q_o e^{-D_i t} \tag{8}$$

$$Q = \frac{q_o - q_i}{D_i} \tag{9}$$

Where,
q_i = oil production rate
q_o= initial oil production rate
Q = cumulative oil produced
t= time
D_i = nominal decline rate

$$D_i = \frac{n\sum_t (q_t N_P) - \left[(\sum_t q_t)(\sum_t N_p) \right]}{n\sum_t (N_p)^2 - \left(\sum_t N_p \right)^2} \tag{10}$$

The nominal decline rate is given by the above equation using the method of least square by analyzing the production data of interest.

2. Research design and Application

This study is focused on both descriptive and analytical research techniques with the aim to determining reservoir performance characterization, evaluation and prediction. The process flowchart for the methodology adapted for this research work is shown in figure 2.

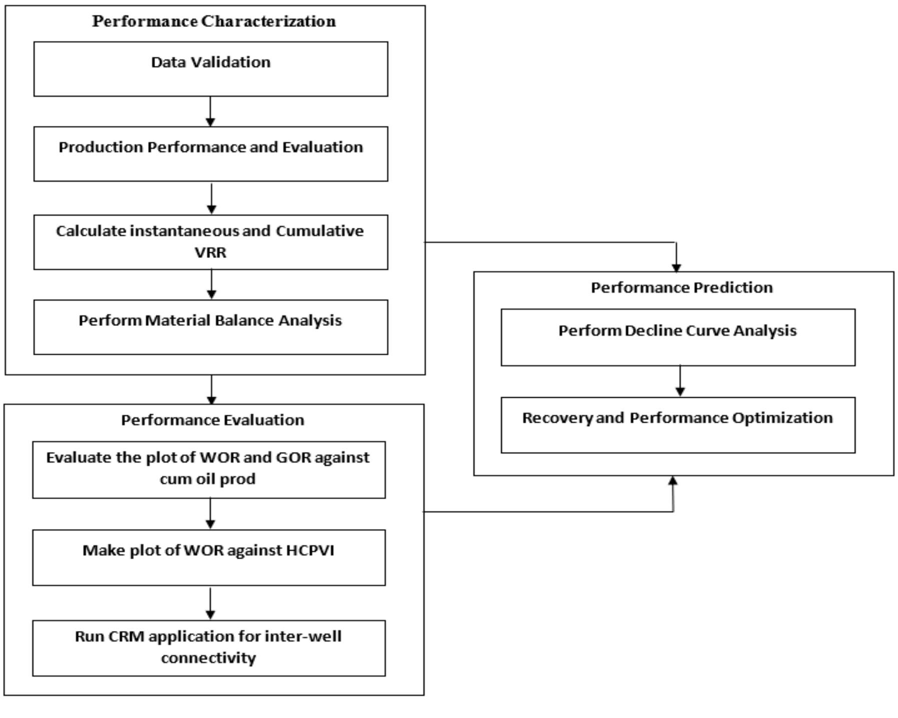

Fig 2: Process Flowchart for the methodology

3. Results and Analysis

3.1 Voidage Replacement Analysis

Voidage replacement ratio versus time plots are used to indicate if reservoir fill up has been achieved and pressure has been maintained by water injection. Therefore, analysis was made to correctly define the system in terms of pressure maintenance and to check for any out of zone injection or fluid influx other than water injection and was done only for estimated pressure points as they are heavily dependent on pressure.

Figure 3 shows the total production and injection history for the reservoir, which is the plot of cumulative withdrawal and cumulative injection against time. It can be seen that the reservoir hasn’t attained fill-up, as the cumulative withdrawal is not equal to the cumulative volume of fluid injected.

The voidage replacement analysis plot shown in figure 4, indicates that the reservoir system benefited solely from water injection and the effect of water influx is negligible. This is drawn from the fact that there were pressure declines in the times there were no water injection. Also the instantaneous VRR follows the same trend with that of pressure against time. This also affirms that the production mechanism for this system is largely by water injection.

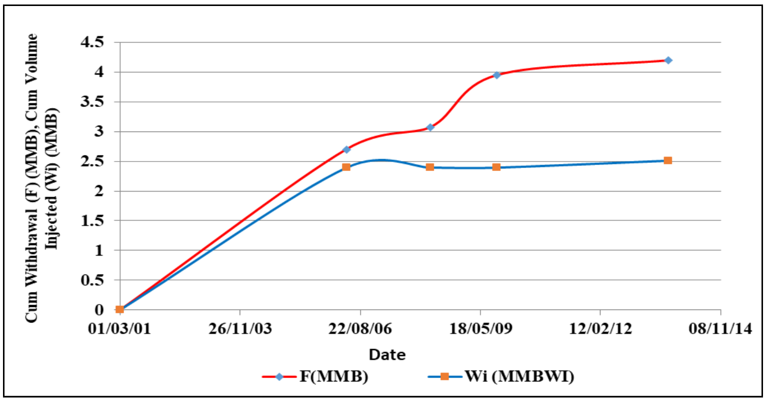

Fig 3: Reservoir Production and Injection History

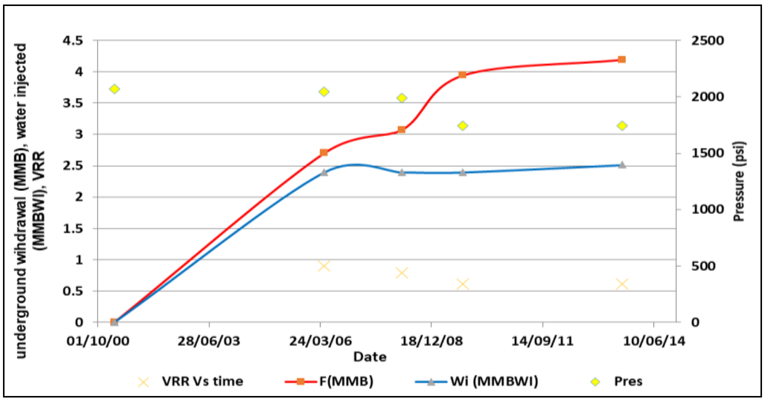

Fig 4: Voidage replacement analysis with pressure

3.2 Material Balance Analysis

Material balance analysis was carried out for the reservoir using the conventional material Balance equation (MBE) and making some assumptions of negligible water influx, rock and connate water expansion. Linearizing the equation and plotting underground withdrawal (F) on the vertical axis and total expansion term (E_t) on the horizontal axis gives a straight line that passes through the water injection term (W_{inj}) on the vertical axis with the slope of this straight line giving stock tank oil initial in place (N) as shown in figure 5 [1]. From the linearized material balance plot, the calculated STOIIP is 19.54MMSTB which correlates with the STOIIP booked at 22MMSTB.

Drive indices defined for oil and gas reservoirs indicate the relative magnitude of various energy sources contributing to the recovery from the reservoir. From the energy plot shown in figure 6, it can be seen that there are three principal drive indices contributing to oil recovery which are gas cap expansion (represented in yellow), depletion drive (represented in blue) and water injection (represented in green) being the dominant drive.

Similarly, it can be seen that initially, water injection contributed the most to reservoir energy. Subsequently when water injection decreased, it gave room for other drive mechanism, mostly the depletion drive due to a reduction in pressure and that can be seen in the performance plot (figure 1).

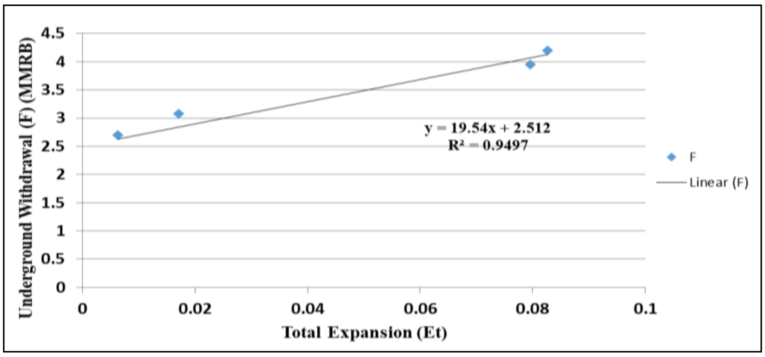

Fig 5: Linearized material balance plot

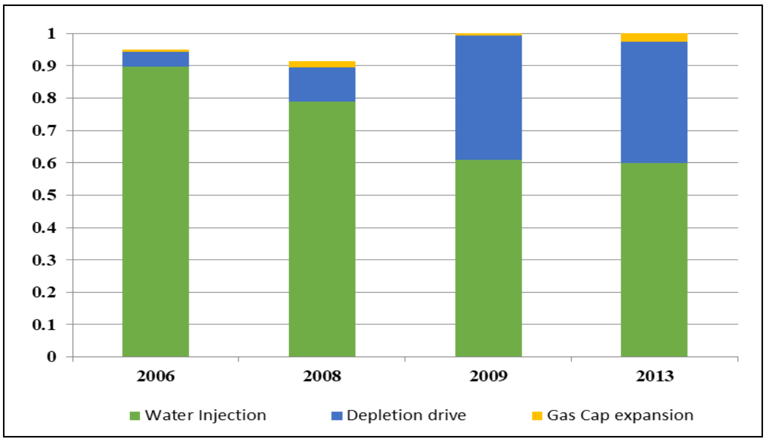

Fig 6: Reservoir energy plot

3.3 Gas-oil ratio and Water-oil ratio

To further evaluate the performance of the reservoir, some key performance indicators (KPIs) like GOR, WOR etc. were also used for this analysis with the results as shown in figure 7, 8 & 9.

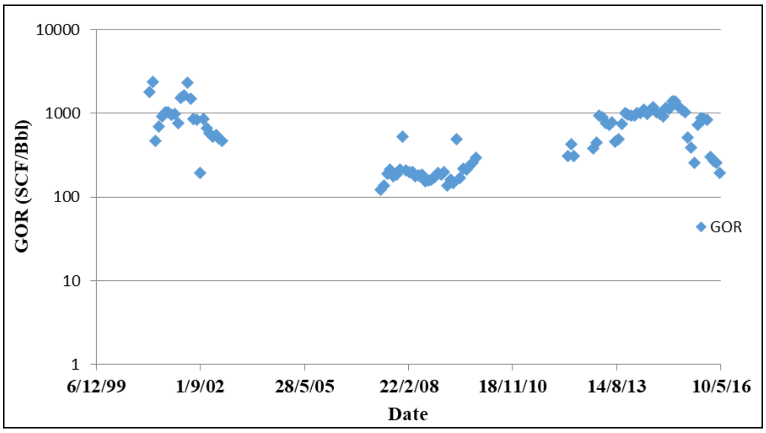

Fig 7: GOR versus time

The plot of producing gas oil ratio against time is useful in evaluating the performance of reservoir in terms of channeling and out of zone injection [10]. This can be indicated by early collapse of gas oil ratio. Also, figure 8 which is a plot of gas oil ratio against cumulative oil produced is a useful tool in evaluating the effectiveness of the water flood project as both channeling and by passing can be inferred from it.

From the plots (Figure 7 & 8) we note that there was no early collapse of gas saturation which is a premature drop in gas oil ratio. It can be concluded that channeling or by passing is not occurring in this reservoir.

The water production rate plot (figure 9), shows that the reservoir performance is not yet affected by water production as the volume of water produced from this reservoir is considerably small with a percentage water cut of less than 5%. This also indicates that there is no form of bypassing despite the large volume of water injected into the reservoir.

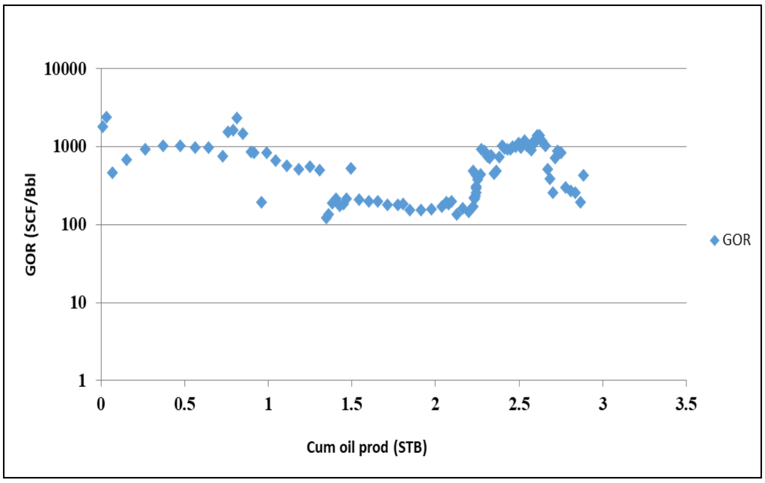

Fig 8: GOR versus Cummulative Oil Produced

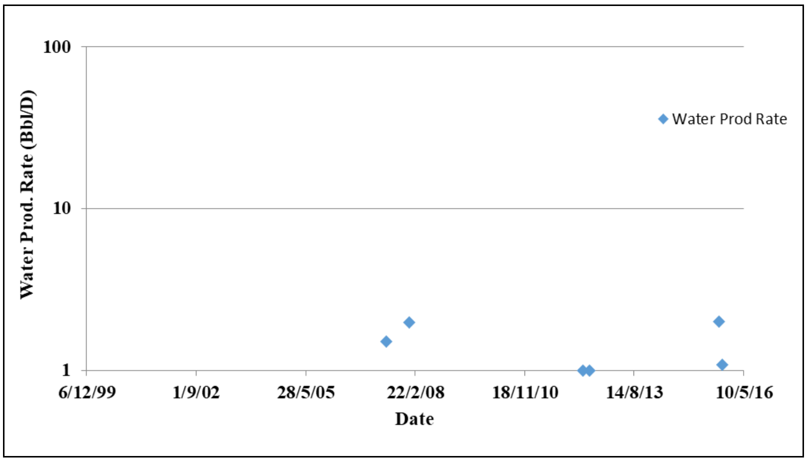

Fig 9: Water production rate versus time

3.4 CRM modelling and analysis

The capacitance resistance modelling was conducted for the reservoir using the tank model otherwise known as CRMT. Two model parameter was determined such as time constants and gain. The values of the gains are powerful quantifiers of connectivity between wells, time constants represent the delay of production response of a producer to the associated injection rate [11, 12].

After the history matching of the Capacitance resistance model which is the nonlinear regression process to fit the calculated output to the observed data (Table 2), the gain (F_f) parameter was approximately 0.7. This means that close to 70% of the injected water volumes is actually injected into the reservoir, giving an indication of sweep efficiency of 70%.

The time constant was also estimated to be 19 which indicates that it takes approximately 19 days for the delay of response from the production well towards the injection well.

Table 2: Output parameters from CRM

Capacitance Resistance Model Output	
F_f	0.7
τ_f	19 days
$q(t_0 = 0)$	3042 BOPD
Rel. error	23.332%

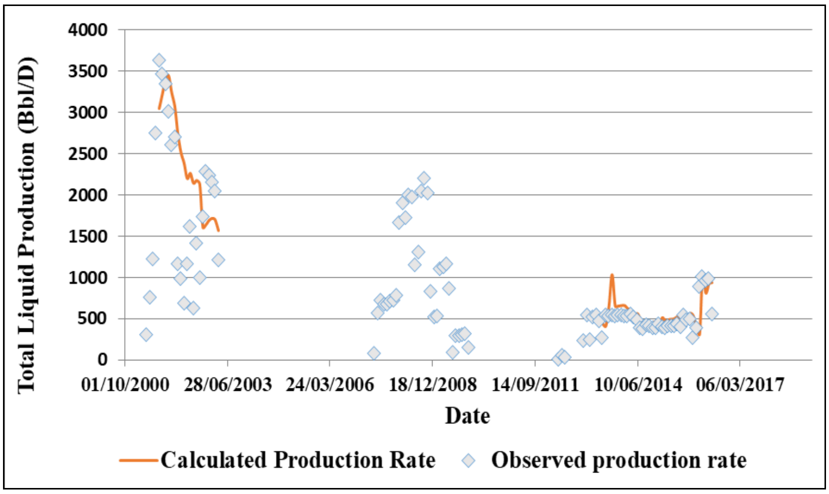

Fig 10: CRM analysis and fitting

3.5 Decline Curve Analysis

The decline curve analysis was carried out using exponential decline as evident from the oil production rate versus time plot (figure 11) and oil production rate versus cumulative oil produced plot (figure 12). The late time was used for fitting decline as it assumes a pseudo- steady state flow. The late time is also an indication of a period of continuous water injection at an almost constant rate [2].

With the exponential decline, and using the method of least square, the nominal decline rate was calculated to be **0.00542** barrel per month

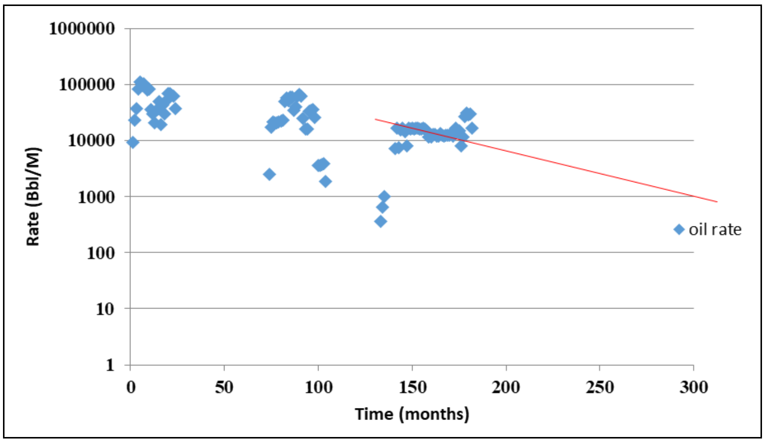

Fig 11: Oil production rate versus time

Prediction was made for the next five years (60 months) assuming the same factors that affects the reservoir performance now will continue for the next five years. Some of the assumed factors include; constant water injection at the same rate it is been injected now, constant choke size, etc.

Figure 13 shows the decline curve prediction plot. A history match was carried out for the late time period of the reservoir to ensure that the DCA model is consistent before prediction was carried out using the exponential nominal decline rate. The increase in recovery for the next five years will be 676,066 barrels of oil produced with oil production rate at the end of 5years standing at 320 barrels of oil per day, totaling the recovery to 18.2% with cumulative production standing at 3,560,743 barrels of oil produced

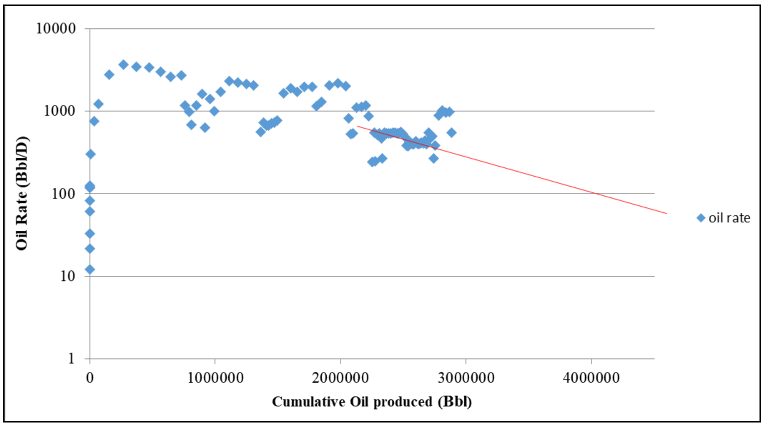

Fig 12: Oil production rate versus Cumulative oil produced

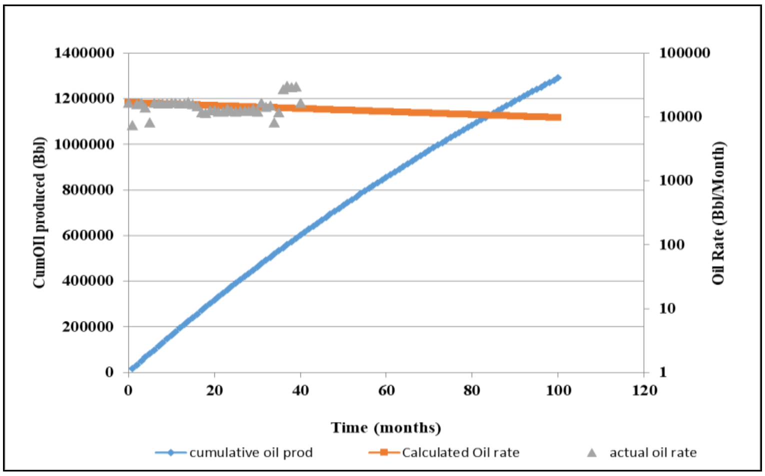

Fig 13: Decline curve prediction plot

4. Conclusion

In this work, analytical and descriptive method of research analysis has been presented and integrated in the analysis of the performance of a water flooded reservoir system. In particular, the development, verification, and application of established reservoir engineering tools were used to analyze the performance of a water flood reservoir. Similarly, the following has being established

- The voidage replacement ratio coupled with the material balance equation can be used to characterize the nature of the flood as well as determine the dominant drive energy in the reservoir which can then be maximized for optimum recovery
- The trends of some key performance indicators (KPIs) such as GOR, WOR etc. can also be used for critical evaluation of the performance of reservoirs
- The Capacitance Resistance Model (CRM) can be used in characterizing the production response to injection which is dependent on the geology of the reservoir system.
- Assuming the same conditions prevails, the decline curve analysis (DCA) can be used as a quick production performance prediction tool

5. Nomenclature

Boi = Formation volume factor of oil at initial reservoir condition, bbl/stb
Bw = Formation volume factor of water, bbl/stb
CRM = capacitance resistance modelling
CRMT = capacitance resistance model
DCA = decline curve analysis
DDI = Depletion drive index
EDI = expansion drive index
G = Initial reservoir gas in place (also denoted OGIP), SCF
GOR = Gas oil ratio, SCF/stb
HCPVI = Hydrocarbon pore volume injected, bbls
MBE = Material balance equation
N = Initial reservoir oil in place (also denoted OOIP), bbls
Np = Cumulative produced oil (also denoted Qo), stb
Pi = Initial reservoir pressure, psi
PVT = pressure volume temperature
qo = Oil rate, bbls/day
qw = Water rate, bbls/day
RF = Recovery Factor
SDI = segregation drive index
Soi = Initial oil saturation
STOIIP = Stock tank oil initially in place,
Sw = Water saturation
Vp = Pore volume, cuft
WDI = water drive index
WI = Cumulative water injected, bbls
WOR = Water oil ratio

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