# Aquifer Characterization and Modelling, a Case Study of Bahi Oil Field

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## Abstract:

*Natural influx of water in oil reservoir surrounded by water aquifers play a very important role in increasing oil recovery. The calculation of water influx is very difficult as it involves many uncertainty such as aquifer size, shape, and structure and aquifer rock properties. The main objective of this work is to detect the presence of aquifer as well as characterize the relative strengths of aquifers associated with Bahi oil field. In this study, Campbell and energy plots are used as diagnostic tools to identify the aquifer type based on the signature of production and*

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*pressure behavior. In model ranking, three models are investigated; Van Everdingen-Hurst unsteady-state model, Schilthuis steady-state model and Fetkovich pseudo steady-state model. The findings of this work showed that, the Van Everdingen and Hurst model is the best model to describe the Bahi aquifer with correlation coefficient of 98.64%. Further, results showed the water drive strength in the Bahi oil field is strong with edge aquifer size approximately twelve times the size of the reservoir and water encroachment angle is 278 degree.*

***Keywords:*** *Aquifer, Campbell plot, energy plot, Van-Everdingen-Hurst model, correlation coefficient, encroachment angle.*

## 1. Introduction.

Aquifer is one of the sources of water influx into the reservoir. Other sources of water influx into the reservoir include recharge of the reservoir by surface water from outcrops and water injection from the surface to supplement a weak aquifer. Water drive is usually the most efficient reservoir driving force in oil reservoirs. Recovery efficiencies may vary from 30% to 80%, depending upon the size and strength of the aquifer. Other driving energy for production of hydrocarbon includes fluid expansion due to change in condition such as pressure and temperature, gravity-drainage drive due to fluid density differences, gas cap drive due to expansion of gas in the gas cap or expansion of liberated solution gas, and formation, and connate water compressibility [1],[2]. Suppose that an aquifer underlies the reservoir and they are hydraulically connected to each other, once the reservoir pressure starts to decline due to production, the aquifer will react by encroaches water into the reservoir to offset the reservoir pressure from declining thus increasing hydrocarbon recovery. This tendency of water to encroach into the reservoir is what referred in this study as water influx. The conceptual influx of water into the petroleum reservoir is illustrated in Figure 1.

Aquifer characterization is the challenging task in aquifer modelling. This is because most of aquifer properties such as aquifer size, aquifer permeability, aquifer porosity and water encroachment angle are uncertain. One of the main reason which is the cost of drilling wells into the aquifer to gain necessary information is often not justified [3]. This is reasonable; however, the uncertainties associated with aquifer properties should be reduced to have an efficient aquifer model [4].

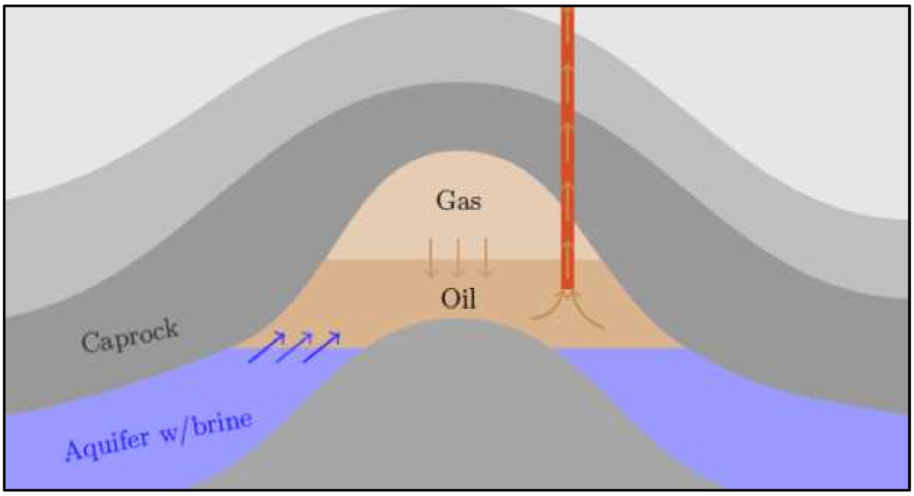


**Figure 1.Conceptual influx of water into the petroleum reservoir [5].**

Successful reservoir management relies on the ability togenerate reliable reservoir performance behavior. Theprimary questions that reservoir engineers are expected toanswer are given in the following, in order of priority [6]**:**

1. What are the expected quantities of original oil and gas in place (OOIP and OGIP)
2. How much oil and gas can be economically recovered given the associated probabilities and risks؟

3. How can a newly discovered field be developed، followed by implementation of the reservoir management plan and monitoring and evaluation of reservoir performance?

It is well known that, the accuracy of MBE results highly depends on the reservoir and aquifer definitions, such as structure geometry, size and rock properties continuity, it also depends on the accuracy of engineering information such as PVT data, pressure and production history. The inclusion of aquifer into reservoir simulation model cannot be isolated from aquifer characterization. It should begin with aquifer characterization to increase the understanding of its properties and strength. In addition, the inclusion of aquifer into the reservoir simulation model may help to capture uncertainties in reservoir simulation model and thus increasing its predictive capability in terms of hydrocarbon recovery factor for better management of the reservoir [7].

## 2. Case Study - Bahi Oil Field

The Bahi oil Field is located in the concession 32 (see Figure A.1 in appendix A). The Bahi structure, located on the northern edge of abroad, the paleo- Platform, first came into existence in late Maestrichtian time and remained in existence until the end of Danian time which trends east-west. The upper part of the Gheriat (Satal) formation is considered to be Lower Paleocene (Danian) in age defined as the PL-7 member. The PL-7 member averages about 450 to 500 feet in thickness and rest with apparent conformity on carbonate rocks of Maestrichtian age. The upper 150 to 200 ft of the PL-7 member forms the reservoir rock. The Lower Paleocene is the carbonate, also defined as the Upper Satal member. Beneath this lies the Lower Satal member which is Upper Cretaceous in age. The Upper and Lower Satal members contain an aquifer which is the driving force for oil recovery in this field. The PL-7 reservoir production commenced in January 1970 with 25 wells.From (1970-1982), a peak oil production of 135,000 bopd (barrel of oil per day) was achieved for a few months. Table A.1 in Appendix A summarizes main reservoir data of the field.

The production performance history of Bahi field includes the daily oil rate, daily water cut percentage and cumulative oil production as seen in Figure A.3 in Appendix A. As of January 1st, 1970 a total of 83 wells have been drilled in Bahi field, 50 wells were on line, 17 shut-in wells, 16 plugged and abandoned wells as depicted in Table 1. As of March, 2013, the oil rate is 9,935 bopd, at 90.05 percent water cut, the cumulative oil production to the end of December, 2013 is 497.25 MMSTB which represents a recovery factor of 75 % of the current booked reserves [8].

**Table 1. The status of Bahi wells [8].**

| Total wells | On line | Shut-in | Plugged & Abandoned |
|---|---|---|---|
| 83 | 50 | 17 | 16 |

Average fluid properties and average Rock Properties of Bahi oil field are shown in Table 2 and Table 3 respectively. Figure A.3 to Figure A.5 in Appendix A show the oil formation volume factor ($B_o$), solution gas oil ratio ($R_s$) both corrected to separator conditions and oil viscosity ($\mu_o$). Table 4 shows the average rock and fluid properties of Bahi aquifer.

**Table 2.Average Fluid Properties of Bahi Oil Field [8].**

| Fluid Properties | Symbol | Value |
|---|---|---|
| Saturation Pressure | $P_b$ | 267 Psig |
| Gas Oil Ratio | GOR | 165 scf/stb |
| Oil Formation Factor | $B_{oi}$ | 1.1413 bbl/stb |
| Oil Viscosity | $\mu_o$ | 0.7 cp |
| Oil Gravity @ 60ºF | ºAPI | 43 |

**Table 3.Average Rock Properties of Bahi Oil Field [8].**

| Rock properties | Symbol | Value |
|---|---|---|
| Porosity | | 25% |
| Horizontal Permeability | k | 110md |
| Water Saturation | $S_{wi}$ | 49% |

**Table 4.Average rock and fluid properties of Bahi aquifer [8].**

| Rock Properties | Symbol | Value |
|---|---|---|
| Average Thickness | h | 900 – 1280 ft |
| Aquifer Drainage Radius | $r_a$ | 292,568.91 ft |
| Water Compressibility | $C_w$ | 2.802E-6 1/psi |
| Rock Compressibility | $C_f$ | 4.14E-6 1/psi |
| Average Horizontal Permeability | $k_h$ | 110 md |
| Vertical Permeability | $k_v$ | 20 – 100 md |
| Average Average Porosity | $\phi$ | 25 % |
| Water Formation Factor | $B_w$ | 1.020 bbl/stb |
| Water Viscosity | $\mu_w$ | 0.515 cp |

## Pressure Data:

The Bahi original reservoir pressure is 1,188 psi at Datum depth of 2,590 ft, the saturation pressure is 267 psi and by production started, the pressure start drop slightly, and every year Waha oil company is measuring the pressure for each well in Bahi field as shown in Figure 2. The average pressure of all wells is then known as the average reservoir pressure in that year [8]. Table A.2 in Appendix A shows pressure at Oil Water Contact from 1971 to 2011.

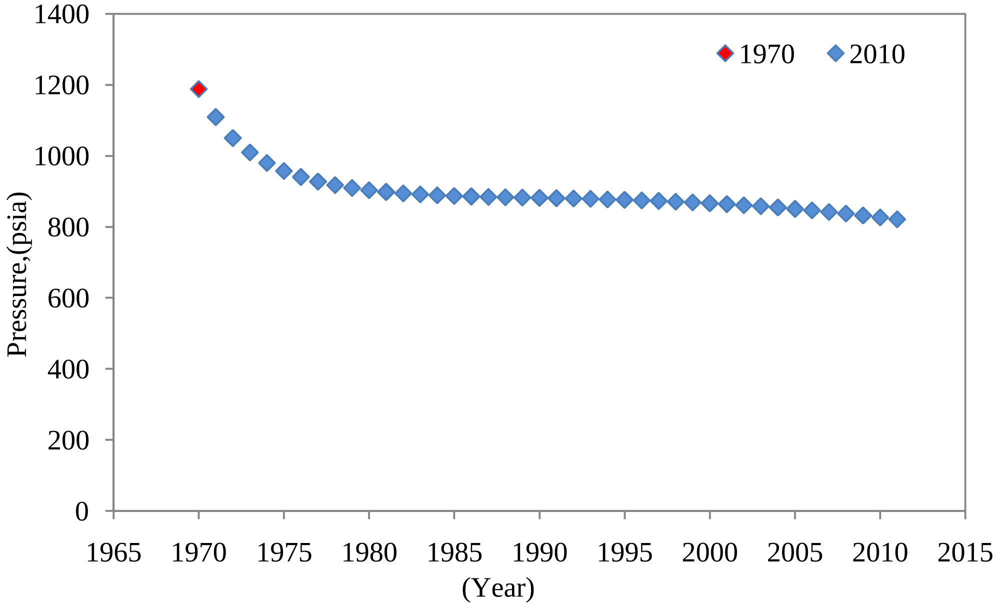


**Figure 2.The average reservoir performance.**

## 3. Material Balance Method

Material balance Analysis is one of the techniques we use to evaluate reservoir production performance. We use the traditional approach which gives detailed analysis of fluid behavior in the reservoir with time. Schilthuis in 1941 was the first to present the general form of the material balance equation. The equation is derived as a volume balance which equates the cumulative observed production, expressed as an underground withdrawal to the expansion of the fluids in the reservoir resulting from a finite pressure drop. Evaluating the volume balance in reservoir barrels, he obtained; Underground withdrawal (rb) = Expansion of oil + originally dissolved gas (rb) + Expansion of gas cap gas (rb) + Reduction in hydrocarbon pore volume HCPV due to connate water expansion and decrease in the pore volume (rb) Mathematically,

$$N_p\left[B_o+(R_s-R_{si})B_g\right] = NB_{oi}\left[\frac{(B_o-B_{oi})+(R_{si}-R_s)B_g}{B_{oi}}+m\left(\frac{B_g}{B_{gi}}-1\right)+(1+m)\left(\frac{C_wS_{wi}+C_f}{1-S_{wi}}\right)\Delta\bar{P}\right]$$

$$+\left(W_e - W_p\right)B_w \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Approximately two decades after the work of Schilthuis, Havlena and Odeh (1963) presented two papers describing MBE as a technique of interpreting the MBE as an equation of a straight line, the first paper describes the technique [9], and the second illustrates the application to reservoir case histories of various fields [10]. One measure of the relative importance of the various drive mechanisms is the intrinsic energy of the different substances, more specifically the compressibility-volume product, which compensates for reservoir voidage (production) in maintaining reservoir pressure. Aquifer strength has to be sufficient (size and connectivity) to sweep the oil at elevated pressure. It is the relative aquifer size, by comparison to the oil leg (and gas cap) that is of importance. Unfortunately, aquifer strength is usually not proven before development takes place but the chance for a strong or sufficient aquifer is accessed based on regional geology. This aspect is particularly important in offshore situations where pre-investment into a water injection plant has to be considered if the chance of a sufficient aquifer is relatively low. In this study, the Campbell and energy plot will be used to detect aquifers as well as to characterize them [11].

## 4. Water Influx Models

Several models have been developed for estimating water influx that are based on assumptions that describe the characteristics of the aquifer. Due to the inherent uncertainties in the aquifer characteristics, all of the proposed models require historical reservoir performance data to evaluate constants representing aquifer property parameters since these are rarely known from exploration-development drilling with sufficient accuracy for direct application. The material balance equation can be used to determine historical water influx provided original oil-in-place is known from pore volume estimates. This permits evaluation of the constants in the influx equations so that future water influx rate can be forecasted The mathematical water influx models that are commonly used in the petroleum industry include[1, 3]:

1. Pot aquifer model
2. Schilthuis' steady-state model
3. Hurst's modified steady-state model
4. The Van Everdingen-Hurst unsteady-state model
    a. Edge-water drive.
    b. Bottom-water drive.
5. The Carter-Tracy unsteady-state.
6. Fetkovich's method pseudo steady - state
    a. Radial aquifer.
    b. Linear aquifer.

In this study, three models were investigated; Van-Everdingen-Hurst unsteady-state model, Schilthuis steady-state model and Fetkovich pseudo steady-state model and they ranked based on statistical analysis and agreement between OIIP value estimated by Volumetric and MBE method.

## 5. Diagnostic Plots

Diagnostic plots such as Dake, energy and Campbell are used as diagnostic tools to identify the reservoir type [2].

### Campbell Plot

For oil reservoirs, the Campbell plot is used as diagnostic tool to identify the reservoir type based on the signature of production and pressure behavior. The plots are established based on the assumption of a volumetric reservoir, and deviation from this behavior is used to indicate the reservoir type [2]. If there is water influx into the reservoir, the withdrawal over total expansion term will increase proportionally to the water influx over total expansion. The Campbell plot can be more sensitive to the strength of the aquifer. In this version of the material balance, using only $E_T$ neglects the water and formation compressibility (compaction) term. During diagnoses of water drives, we should be assumed to be neglected in order to ascertain its presence [11]. Plotting F/Et on the Y axis versus F on the X-axis will yield a plot with one of the characteristic curve shapes as shown in Figure 3. If there is no water influx, the data will plot as a horizontal line.

$$F = N(E_o + mE_g + E_{f,w}) + W_e \quad \text{.............................} \quad (2)$$

$$E_t = E_o + mE_g + E_{f,w} \quad \text{.............................} \quad (3)$$

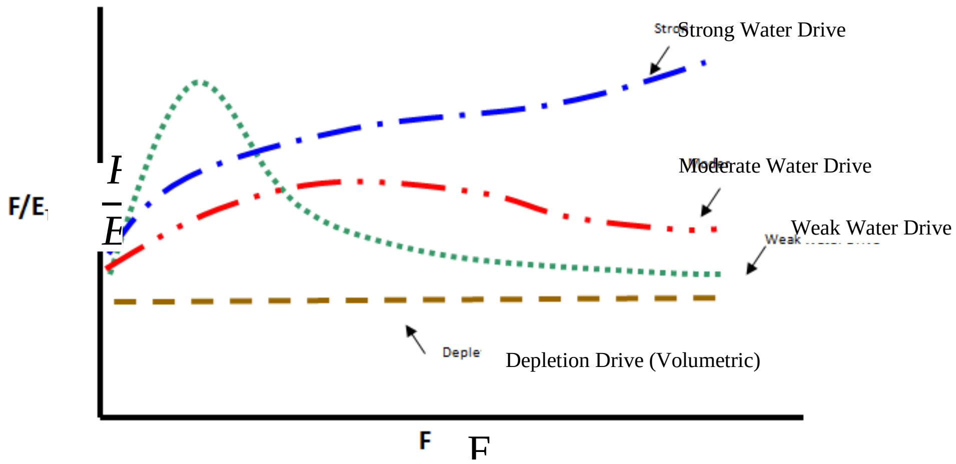


**Figure 3. Campbell plot [2].**

## Energy Plot

Many other graphical methods have been proposed for solving the MBE that are useful in detecting the presence of water influx. One such graphical technique is called the energy plot. This plot shows the relative contributions of the main source of energy in the reservoir and aquifer system. It does not in itself provide you with detailed information, but indicates very clearly which parameters and properties you should concentrate on [8] and [12].

## 6. Results and Discussion

Field production history, PVT data and reservoir pressure history were prepared to apply the material balance equation. In this work, MBAL and Microsoft Excel were used to carry out Material Balance calculations and aquifer modeling. MBAL is a part from The IPM suite Integrated Production Modelling which is developed by Petroleum Experts.

Identification of reservoir drive mechanism was first performed by the Campbell Plot to see strength of the aquifer and the drive index value. Campbell plot of (F/Et) vs. (time) gave a clear deviation which means there is a strong water influx in the field as illustrated in Figure 3 and Figure 4. The data will plot as a horizontal line, if there is no water influx.

In the case of drive indices plot (Energy plot), various sources of energy available in the Bahi reservoir are drawn in a single plot as a function of time by using MBAL software. The result showed that drive mechanism is dominated by Water Drive and it could be seen clearly that effect of the water influx from the initial production. Drive indices plot, DDI (Depletion-Drive Index), SDI (Segregation (gas-cap)-Drive Index), WDI (Water-Drive Index) and EDI (Expansion (rock and liquid)-Drive Index), are drawn in a single plot as a function of time as seen in Figure5.

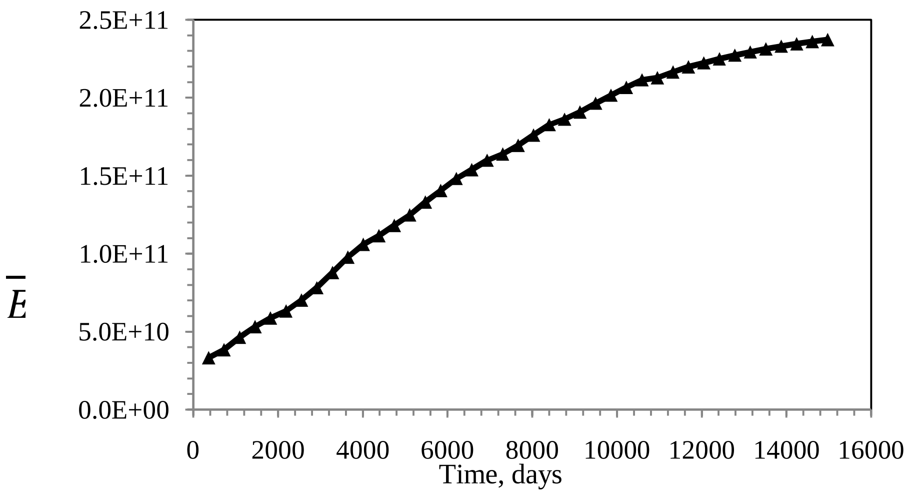


**Figure 4.Campbell Plot of Bahi oil field.**

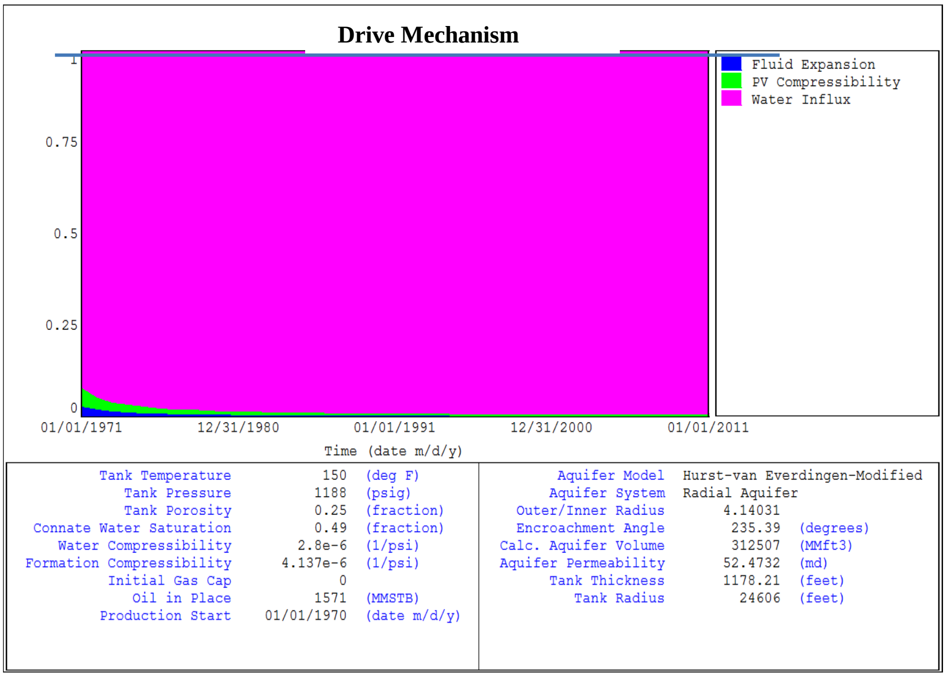


**Figure 5.Energy plot by MBAL software.**

Since it was proved, that the reservoir is produced under strong water drive mechanism, the next stage is to evaluate and find out the most representing water influx model for the reservoir. Most of aquifer properties such as aquifer size, aquifer permeability, aquifer porosity and water encroachment angle are uncertain. In this study, three models were investigated; Van-Everdingen-Hurst unsteady-state model, Schilthuis steady-state model and Fetkovich pseudo steady-state model. The correlation coefficient ($R^2$) and the agreement between OIIP value estimated by volumetric and MBE method were used in this study to select the suitable water influx model for the studied reservoir. We have concluded that the aquifer properties such as aquifer size, water encroachment angle, aquifer porosity and permeability are very well described by using Van Everdingen-Hurst unsteady model, edge-water drive. Figure 6 shows a good matching with high R-Squared of 98.65%. The OIIP result obtained in Material Balance method using Van Everdingen-Hurst unsteady model, edge-water drive showed excellent agreement with volumetric and simulation methods result. Table 5 summarizes main optimum aquifer parameters based on the fitted aquifer model.

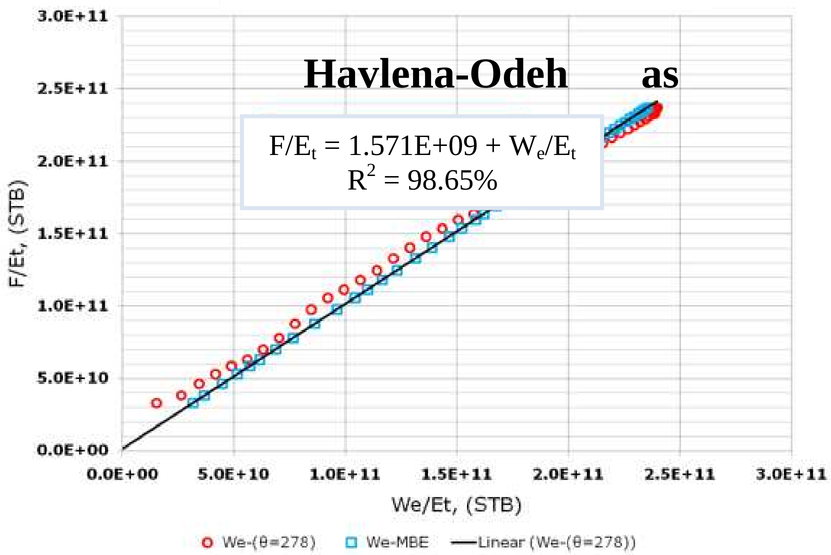


**Figure 6. OIIP Calculation Using Van Everdingen-Hurst Unsteady-State Model, Edge water drive.**

**Table 5.Optimum rock and fluid properties of Bahi aquifer.**

| Rock Properties | Symbol | Value |
|---|---|---|
| Aquifer Radius | $r_a$ | 292,569 ft |
| Reservoir Radius | $r_e$ | 24,606 ft |
| Avg. Permeability | $k_{avg}$ | 81.24 md |
| Porosity | $\phi$ | 25% |
| Aquifer Thickness | $h$ | 900 ft |
| Encroachment Angle | $\theta$ | 278 deg |
| Water Influx Constant | B | 817,207 bbl/day/psi |

## 7. Conclusions

From this study, the following summarizes the major conclusions:

1. The Campbell plot and energy plot are very useful as diagnostic tools for detecting and characterizing aquifer and water drive strength. The plots showed a strong water drive for the reservoir.
2. Bahi aquifer properties such as aquifer size, water encroachment angle, aquifer porosity and permeability are very well described by using Van Everdingen-Hurst unsteady model, edge-water drive with correlation coefficient of 98.64%.
3. The material balance method has proven to be a very useful tool to the reservoir engineer with regards to aquifer detection and characterization. It has not been replaced by reservoir simulation; rather, it is complementary to simulation and can provide valuable insights to reservoir performance that cannot be obtained by simulation.

## Acknowledgment

The authors would like to thank Waha Oil Company for providing the necessary data to complete this research.

## Nomenclature

| | |
|---|---|
| $B_g$ | Gas formation volume factor, bbl/scf |
| $B_{gi}$ | Gas formation volume factor at initial reservoir pressure, bbl/scf |
| $B_o$ | Oil Formation Volume Factor, bbl/STB |
| $B_{oi}$ | Oil Formation Volume Factor at initial reservoir pressure, bbl/STB |
| $B_w$ | Water Formation Volume Factor, bbl/STB |
| $c_f$ | Formation compressibility, $psi^{-1}$ |
| $c_w$ | Water compressibility, $psi^{-1}$ |
| $E_g$ | Cumulative gas expansion, bbl/STB |
| $E_{f,w}$ | Cumulative formation and water expansion, bbl/STB |
| $E_o$ | Cumulative oil expansion, bbl/STB |
| $E_t$ | Cumulative total expansion, bbl/STB |
| F | Cumulative reservoir voidage, bbl |
| m | ratio of initial gas cap volume to initial oil zone volume at reservoir conditions, dimensionless |
| N | Stock tank oil initially in place, STB |
| $N_p$ | Cumulative Oil Production, STB |
| $R_s$ | Gas Solubility, scf/ STB |
| $R_{si}$ | Gas solubility at initial reservoir pressure, scf/STB |
| $S_{wi}$ | Initial water saturation, fraction |
| $W_e$ | Cumulative water influx ,bbl or STB |
| $W_p$ | cumulative water production, STB |
| $\mu_o$ | Oil viscosity, cp |
| $\Delta\bar{P}$ | Average change in reservoir pressure, (pi − p), psia |
| $p_i$ | Initial reservoir pressure, psia |
| p | Volumetric average reservoir pressure, psia |

## References :

[1] *Tarek, A. (2006). Reservoir Engineering Handbook. 2nd Edition, Houston, Texas, USA.: Gulf Professional Publishing.*

[2] *Fekete. (2014). Material Balance Analysis Theory. Retrieved January 15, 2017, from [http://www.fekete.com/san/webhelp/feketeharmony/harmony_webhelp/content/html_f iles/reference_material/analysis_method_theory/Material_Balance_Theory.htm](http://www.fekete.com/san/webhelp/feketeharmony/harmony_webhelp/content/html_files/reference_material/analysis_method_theory/Material_Balance_Theory.htm)*

[3] *Craft, B. C., Hawkins, M., & Terry, R. E. (1991). Aplied Petroleum Resrvoir Engineering (2nd ed.). Englewood cliffs, New Jersy: Printice Hall, PTR.*

[4] *Petrowiki. (2015). Water influx models. Retrieved January 13, 2017, from [http://petrowiki.org/Water_influx_models](http://petrowiki.org/Water_influx_models).*

[5] *Knut, A. L. (2015). User Guide for the Matlab Reservoir Simulation Toolbox (MRST). Oslo: SINTEF ICT.*

[6] *Omotayo, O. Adewale, Sunday, I. (2015). Aquifer Detection and Characterisation Using Material Balance: A Case Study of Reservoirs A, B, C and D. International Journal of Science, Technology and Society, Vol. 3(2): pp 55-64, Science Publishing Group.*

[7] *Maganga, S. P. (2017). Aquifer Characterization and Modelling, a case study of Norne field. Department of Geoscience and Petroleum, Norwegian University of Science and Technology.*

[8] *Annual Technical Report, (2014). Waha Oil Company, Tripoli, Libya.*

[9] *Havlena, D., and Odeh, A. S. (August 1963). The Material Balance as an Equation of a Straight Line," Part I-Field Cases, JPT, pp. 896–900.*

[10] *Havlena, D., and Odeh, A. S. (July 1964). The Material Balance as an Equation of a Straight Line. Part II-Field Cases," JPT, pp. 815–822.*

*[11] Campbell, R.A. and Campbell, J.M. (1978). Mineral Property Economics, Vol. 3: Petroleum Property Evaluation. Norman, Oklahoma: Campbell Petroleum Series.*

*[12] Pirson, S. J. (1958). Elements of Oil Reservoir Engineering, 2nd ed. New York: McGraw-Hill, 1958, pp 635-693.*

*[13] Pletcher, J. L. (February 2002). "Improvements to Reservoir Material Balance Methods" SPE Reservoir Evaluation and Engineering, pp 49-59.*

## Appendix A. Field data.

**Table A.1. Reservoir data.**

| Reservoir Data | | |
|---|---|---|
| Formation Producing | Paleocene PL-7 | |
| Top of Pay Formation (D) | 3,700 | ft KB |
| Datum Depth (D) | 2,600 | ft SS |
| Total Producible Wells | 65 | Well |
| Wells Currently Producing | 52 | Well |
| Average Net Pay (h) | 103.2 | ft |
| Reservoir Temperature at Datum ($T_{Res.}$) | 150 | deg F |
| Average Drainage Radius ($r_e$) | 24,606.30 | ft |
| Initial Water Saturation ($S_{wi}$) | 0.49 | fraction |
| Formation Compressibility ($c_f$) | $4.137 \times 10^{-6}$ | $psi^{-1}$ |
| Reservoir Permeability (k) | 150 | md |
| Oil Initial In Place (OIIP or N) | * | MMSTB |

***confidtional***

**Table A.2. Pressure at Oil Water Contact.**

| Pressure @ Oil Water Contact | |
|---|---|
| Time (Year) | Pressure @ OWC (psi) |
| 1970 | 1,202.00 |
| 1971 | 1,137.90 |
| 1972 | 1,103.15 |
| 1973 | 1,079.04 |
| 1974 | 1,060.43 |
| 1975 | 1,045.34 |
| 1976 | 1,032.75 |
| 1977 | 1,022.05 |
| 1978 | 1,012.85 |
| 1979 | 1,004.87 |
| 1980 | 997.92 |
| 1981 | 991.84 |
| 1982 | 986.52 |

| Pressure @ Oil Water Contact | |
|---|---|
| Time (Year) | Pressure @ OWC (psi) |
| 1983 | 981.87 |
| 1984 | 977.81 |
| 1985 | 974.27 |
| 1986 | 971.21 |
| 1987 | 968.58 |
| 1988 | 966.34 |
| 1989 | 964.47 |
| 1990 | 962.93 |
| 1991 | 961.69 |
| 1992 | 960.75 |
| 1993 | 960.07 |
| 1994 | 959.64 |
| 1995 | 959.45 |
| 1996 | 959.48 |
| 1997 | 959.71 |
| 1998 | 960.14 |
| 1999 | 960.76 |
| 2000 | 961.56 |
| 2001 | 962.52 |
| 2002 | 963.64 |
| 2003 | 964.92 |
| 2004 | 966.34 |
| 2005 | 967.90 |
| 2006 | 969.59 |
| 2007 | 971.41 |
| 2008 | 973.36 |
| 2009 | 975.42 |
| 2010 | 977.59 |
| 2011 | 979.88 |

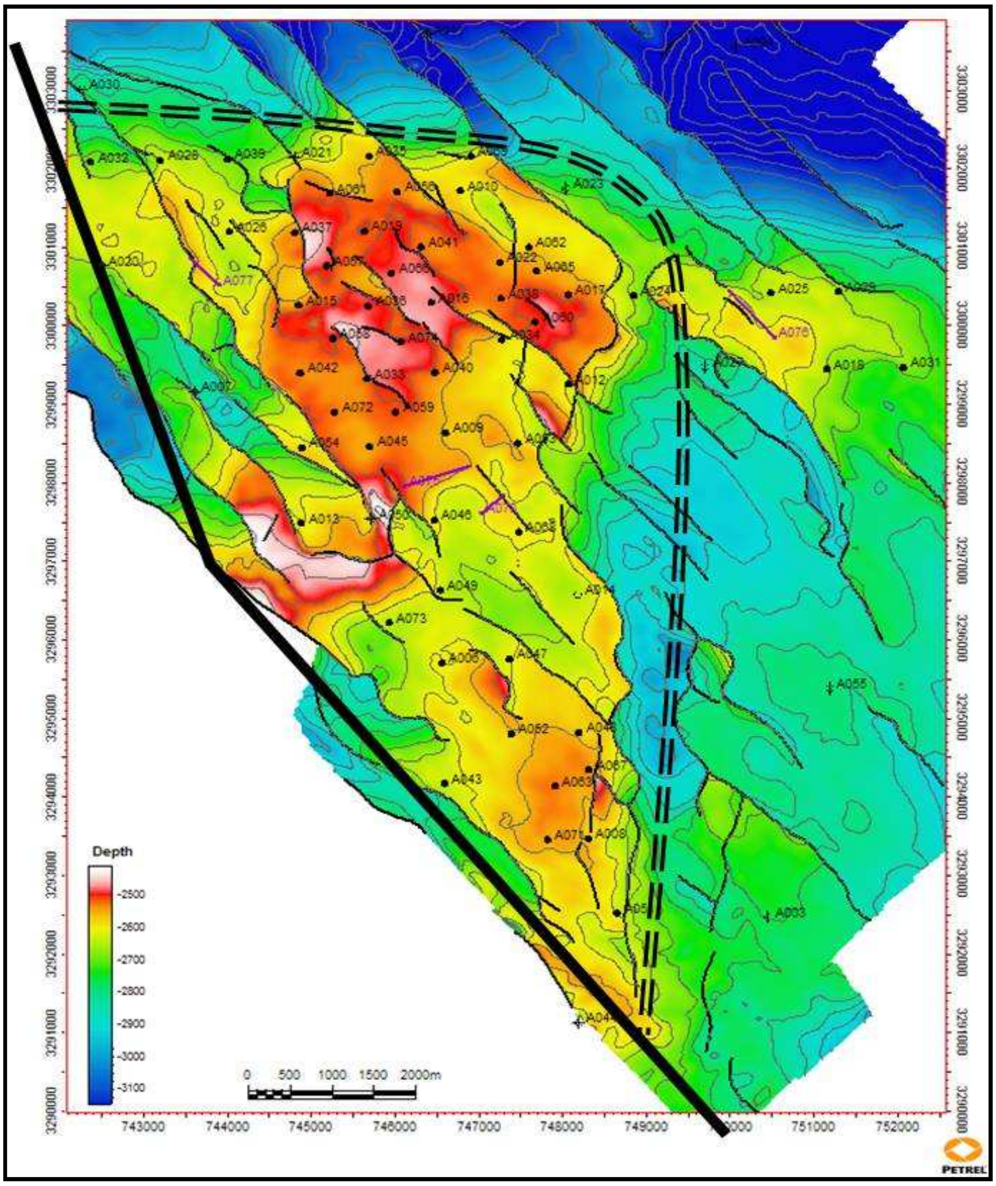

**Figure A.1. Location Map of Bahi Oil Field.**

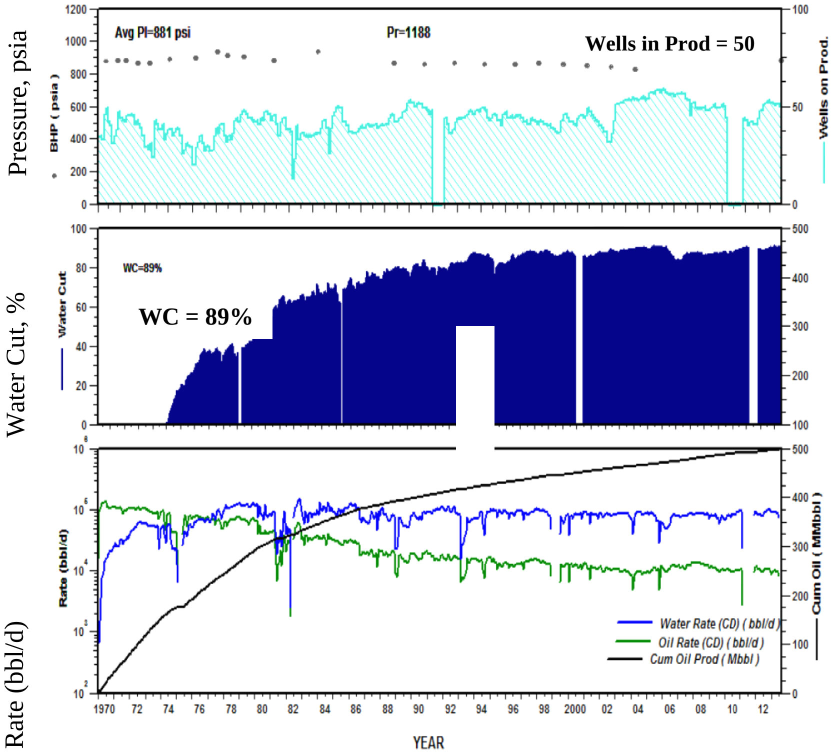


**Figure A.2. Production History.**

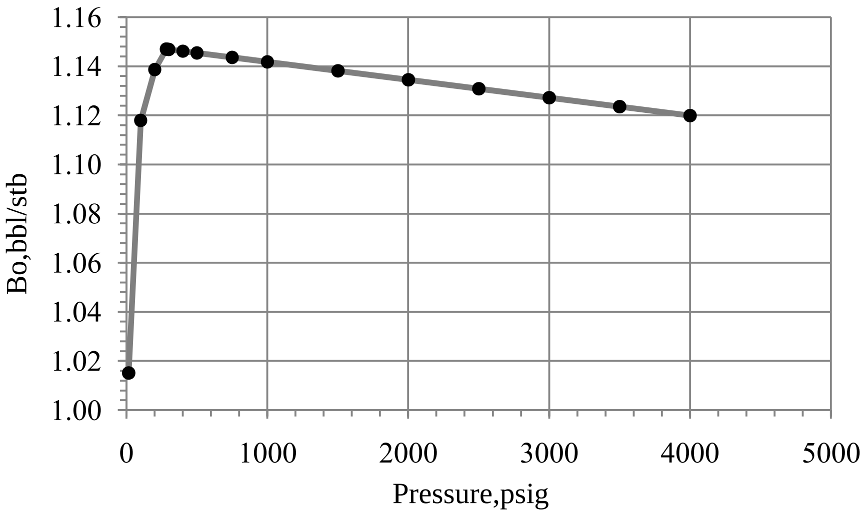


**Figure A.3. Adjusted Oil Formation Volume Factor for Well A-17.**

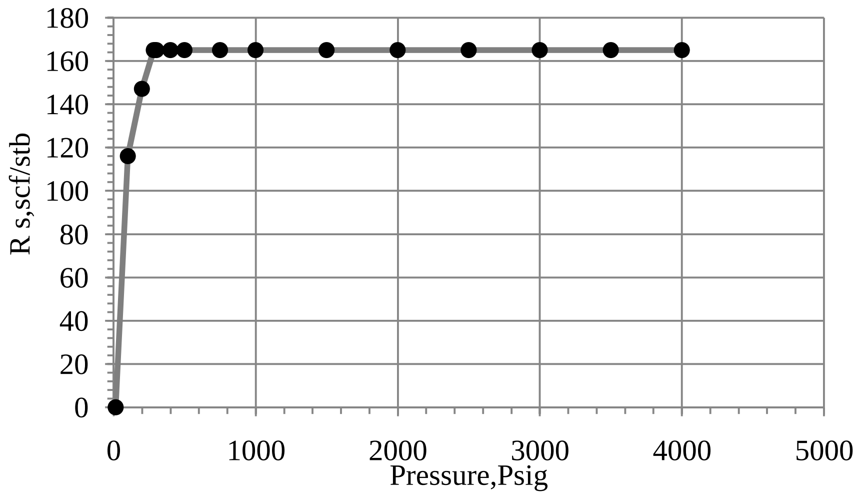


**Figure A.4. Adjusted Solution Gas-Oil Ratio for Well A-17.**

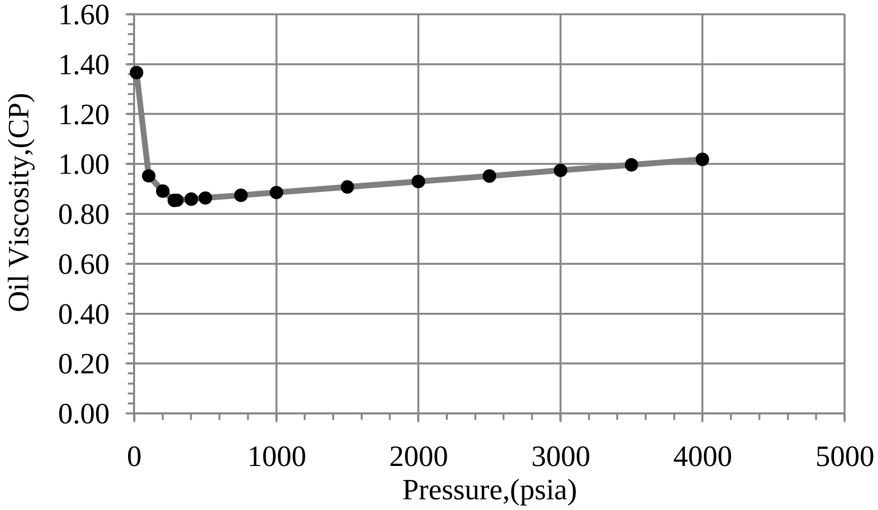


**Figure A.5. Oil Viscosity for Well A-17.**