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Application of Combined Analytical and Numerical Models for Water Production Diagnosis in Oil Wells

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ABSTRACT

Water production is inevitable in oil and gas fields, regardless of the field's viability. Since water production is a big concern associated with oil and gas production, properly identifying its source is paramount, as this will aid in applying remedial techniques suitable to address it. Without proper diagnosis, a cost increase in treatment, handling and management of this water results. Furthermore, production will be shut down at its early stage, which is not a wise decision. This problem can be curtailed if identified early by applying the necessary remedial techniques. Due to these issues, the comparative investigation into the complex dynamics of water production in oil reservoirs leads to the application of combined Analytical and Numerical models to diagnose the water production problems. The applied models were validated against real reservoir data from 3 wells. The robustness and accuracy of these models were confirmed as a result of positive outcomes from the diagnosed wells. Water production problems were experienced in all case studies. Water production problems arising from the flow through the channel were diagnosed by applying the Piecewise linear model, early coning with late channeling was diagnosed using the hybrid model, and coning was diagnosed using the exponential growth model. These analytical models were used to determine the water breakthrough time for each well experiencing water production problem, while Meyer, Gardner & Pison Method was used for Critical Coning rate determination for well experiencing coning. Eclipse Simulation software, the Numerical Model, simulates the water production process, giving more detailed information about the mechanism. These findings were validated against observed data and goodness-of-fit metrics, from which excellent results indicated that the models explain 80% to 100% of the wells' behaviours. From the findings, the petroleum industry has been equipped with predictive tools to optimise reservoir performance, making this work stand at the forefront of reservoir and production engineering, offering innovative solutions to longstanding challenges.

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1. INTRODUCTION

Water production has become a household word for decades, meaning water is produced along with hydrocarbons (Al-Hasani *et al*, 2008). This water can either be from a nearby aquifer, injected water or water from the formation, as water is sometimes injected into oil reservoirs to improve extraction or for pressure maintenance (Aminian,2009).

Produced water is considered as one of the major challenges experienced during crude oil production. It affects economics, the environment, and the production process (Elphick and Seright, 1997). Due to the large volume of water produced along with the oil, some argue that the oil industry is effectively a water industry producing oil as a secondary product, which makes it a major factor contributing to low oil well productivity (Gasbarri *et al*, 2008).

According to Bondar and Blasingame (2002) Produced water is the biggest concern associated with oil production and finding a layer of water under the oil layer is one of the general phenomena. It is expected that the total water production for a field is more than ten times the oil inflow (Bedaiwi *et al*, 2009). Many wells have been completely closed due to this problem. Also Azari *et al* (1997) explained that the extraction of petroleum is organically linked to the extraction of water with each barrel. Furthermore, Al-Ghanim and Al-Nufaili (2010) stated that it is worth knowing that the amount of associated water starts with relatively small quantities but increases with time until the production volume increases to more than 90% of the total production. Notwithstanding, Abass and Merghany (2011) identified that the water extracted from the oil is either high brine, medium salt, or fresh water. This water has a negative impact on the rocks of the earth's crust if it is disposed on the earth surface of the earth (Reyes *et al*, 2010). In most oil reservoirs, surrounding layers contain water that may be produced with the oil through fingering or coning (Chan, 1995).

Moreover Rabiei, M. *et al*. (2010) reveals that produced water has posed a threat to efficient oil and gas production for decades. Nevertheless Tabatabaei *et al* (2011) added that during oil and gas production, water is always produced because, from the origin, water was in place before oil and gas migrated to traps or can originate from a nearby aquifer. When this water is produced beyond the economic limit set by the company, a challenge is encountered as water cannot be sold as oil (Yortsos *et al* , 1999). Still, it will increase costs for treating, handling and managing this produced water. Therefore, proper diagnosis is required to pinpoint the source of this produced water and formulate a suitable remedial approach to mitigate it (Egbe and Appah ,2005).

i. *MATERIALS AND METHOD*

This study is focused on water production diagnosis within Niger Delta fields. Proposed models used in this work will be validated using data from Niger Delta Field Operator, following a standard workflow that will be established in this work to enable its application on other oil fields in other regions globally. This study was carried out on three wells, L1, LU1 and U1, in X onshore oil and gas field located in the Niger Delta region of Nigeria. The field has initial oil and free gas in place of about 1.5 billion STB and 5620 Bscf, respectively. Cumulative oil produced is about 180 MMstb from 50 wells completed on 22 reservoirs. Reservoir depths ranged between 7450 and 12700ft in stacked series of anticlinal or dip and fault-bounded structures. The gravity of the oils varies between 20° and 35° API. Porosity ranges between 16% and 34%, and the average permeability is about 2 Darcies. Currently, the field production rate is about 17,000

STB/D to the FPF (Field Production Facility), with 60% or more of the water cut due to the high production rate of the wells. Many wells were screened out of the 50 in the field. Almost 11 of the wells are active, 11 are shut down, 5 of them due to high water cuts and nine wells converted to water injectors. A total of 3 wells was finally used for the study.

Analytical models (Exponential growth model, Piecewise linear model, Hybrid and Meyer, Gardner & Pison Method for water coning rate determination) and Numerical models (Eclipse simulation software) were successfully applied. The Python programming language was used for Analytical model calibration and validation using the R-squared method and graph plots, which Python programming libraries also support.

ii. *Materials*

The following materials are typically required for combined analytical and numerical modeling of water production: production data (water cut, oil rate, gas rate, water rate, and bottom hole pressure); well-logging data (porosity, permeability, saturation, and resistivity); and Geological data (reservoir structure, stratigraphy, and fluid properties).

2.2 Method

A step-by-step workflow is established here to diagnose water production problems properly. Data Collection and Preparation: This step is considered as the first step, as it entails the collection and preparation of all necessary data. This includes cleaning and formatting water cut percentage, oil and water flow rate, bottom hole pressure for each well, and cumulative days collected over time. It also ensures that the analysis of channeling, coning, and the water production mechanism is consistent and complete. Model Selection: The appropriate model(s) must be selected once the data is prepared and cleaned. There are various analytical and numerical models, each with strengths and weaknesses. The various models can be used to diagnose water production problems depending on the specific reservoir and wellbore conditions. The analytical models and Numerical model used in this study are expressed below:

2.2.2 2.2.1 Analytical Models for Water Breakthrough time and Coning rate determination

I. *Introduction to the Exponential Growth Model for Coning*

The exponential growth model is a widely used analytical model to describe the increase in water cut over time due to coning in an oil reservoir. This model is based on the concept that water coning phenomena lead to the gradual influx of water into the producing well, resulting in an exponential growth pattern for the water cut.

Mathematical Formulation of the Exponential Growth Model

The mathematical formulation of the exponential growth model is expressed as follows:

$$Wc = A * (1 - \exp(-k * T))$$

(1)

Where;

Wc is the water cut at time t (expressed as a percentage)

A is the ultimate water cut due to coning

k is the rate constant of controlling the rate of water cut increase over (expressed in units of 1/time)

T is the time in months often represented by 1/months

II. *Introduction to the Piecewise Model for Channeling*

If a sudden breakthrough in the water cut (Wc) data indicates an abrupt increase followed by stabilisation. It might suggest the presence of channeling behaviour in the reservoir. channeling involves the preferential flow of water or gas through high permeability pathways, leading to a rapid breakthrough of the fluids into the production well.

In such a case, the water cut time plot might show a pattern where the water cut remains relatively stable after the sudden increase. This could indicate establishing these preferential flow paths, causing the water cut to stabilise constantly as long as the Channeling persists.

Mathematical formulation of the Piecewise model for Channeling

A step function-like function-like behaviour represents the sudden breakthrough followed by stabilisation in the water cut plot. The model could be a piecewise function where the water cut remains constant before the breakthrough and stabilises at a different constant level.

Piecewise Model

$$\mathbf{Wc = B * (T \geq Tchannel) * (C * (T - Tchannel) + D)} \quad (2)$$

Model components;

Recall in the equation of a straight line y = mx + b, y is the dependent variable (e.g., water cut Wc), x is the independent variable (e.g., time T), m is the slope of the line (how y changes with x), and b is the y-intercept (the value of y when x is 0).

$\mathbf{B * (T \geq Tchannel)}$: This term acts as a switch that controls whether the linear behaviour applies. It equals B when T ≥ Tchannel (when the switch is "on") and 0 when T < Tchannel (when the switch is off ").

$\mathbf{(C * (T - Tchannel) + D)}$: In the context of the channeling model, (C ∗ (T − Tchannel) + D) is a way to represent a linear relationship between Wc and T after Channeling begins (T ≥ Tchannel), C is analogous to the slope m in y = mx + b, representing the rate at which Wc changes with respect to time (T) after Channeling starts. T − Tchannel plays the role of x in y = mx + b, representing the initial value of Wc at the time Tchannel. In essence, the expression (C ∗ (T − Tchannel) + D) is a way to mathematically represent the linear increase in Wc over time after channeling initiation (T ≥ Tchannel), similar to how y = mx + b represents a linear relationship between two variables.

This term represents the linear segment after the switch is "on". It is similar to the linear equation y = mx + b, where C represents the slope of the line, T − Tchannel is the equivalent of x, and D is the y-intercept.

So, by combining these components, the equation can be understood as follows:

i. When T < Tchannel, the equation evaluates to 0 (switch is "off").

ii. When T ≥ Tchannel, the equation evaluates B ∗ (T ≥ Tchannel) ∗ (C ∗ (T − Tchannel) + D), which is a linear function with slope C and y-intercept D.

iii. Wc = Water cut (%) at time T.

iv. B = Magnitude of channeling effect on water cut. This parameter controls the amplitude of the channeling event. A higher value indicates a larger jump in water cut at T = Tchannel. When T ≥ Tchannel, B = 1; otherwise, B = 0.

v. Tchannel = time at which Channeling occurs. This parameter represents the time when the channeling event causes a sudden increase or decrease in water cut.

vi. C = Slope of the Wc against T plot after the channeling event. This parameter represents the rate of change in water cut after T = Tchannel; the decline rate is controlled by the coefficient C, which represents the exponential decay rate.

vii. D =. The coefficient D represents the water cut value at Tchannel (The baseline water- -cut).

In summary, the equation $\boldsymbol{Wc} = \mathbf{B} * (\mathbf{T} \geq \mathbf{Tchannel}) * (\mathbf{C} * (\mathbf{T} - \mathbf{Tchannel}) + \mathbf{D})$ encapsulates the behaviour of a piecewise linear function that starts at Tchannel with slope C and y-intercept D, but only when T is greater than or equal to Tchannel. This is a simplified way to model the behaviour of water cut after Channeling starts.

III. Hybrid Model for Coning and Channeling

The need for a hybrid model that captures both exponential growths for coning behaviour and linear increase behaviour for Channeling arises from the complex and the devised nature of reservoir behaviour observed in the field. Coning and Channeling are distinct phenomena with unique characteristics, and a single model that combines both behaviours can offer a more comprehensive and accurate representation of reservoir dynamics.

Derivation of the Mathematical Formulation of the Hybrid model for coning and channeling

This model combines exponential growth for coning and linear increase behaviour for Channeling. The information will be based on water cut (Wc) against time T plot

Step 1: Exponential growth for coning

The exponential growth behaviour for coning can be represented as follows;

$$\boldsymbol{Wc} = \mathbf{A} * (\mathbf{1} - \mathbf{exp}\,(-\mathbf{k} * \mathbf{T}))$$

(3)

Where;

A is the initial water cut when production starts. K is the exponential growth rate constant.

Step 2: Linear increase for Channeling

The linear increase for Channeling can be represented as

$$\text{Wc channeling} = B * (T \geq Tchannel) * (C * (T - Tchannel) + D)$$
(4)

Where;

B is the linear growth rate constant for Channeling

Tchannel is the time when Channeling begins (Transition point) C is the initial water cut at the time when Channeling starts.

Step 3: Hybrid model formulation

A piecewise function was used to create a hybrid model that captures both behaviours. This function will use the exponential growth formula for coning until Tchannel and then switch to the linear increase formula for channeling after Tchannel. The Hybrid model for coning and Channeling can be defined as follows;

$\mathbf{Wc} = \mathbf{A} * (\mathbf{1} - \mathbf{exp}(-\mathbf{k} * \mathbf{T})) + \mathbf{B} * (\mathbf{T} \geq \mathbf{Tchannel}) * (\mathbf{C} * (\mathbf{T} - \mathbf{Tchannel}) + \mathbf{D})$ (5)

Step 4: Combining both behaviors

The hybrid model provides a seamless transition from exponential coning behaviour to linear channeling behaviour at the specified Tchannel. This allows the model to capture reservoir behaviour in various production stages accurately.

Step 5: Model parameters and interpretation

Understanding the model's key parameters is paramount to determining its efficiency and robustness. Below are its key parameters and their interpretation.

i. A: Initial water cut at the beginning of production
ii. k: Exponential growth rate constant, affecting the speed of coning
iii. B: Linear growth rate constant for channeling, representing the rate of linear water cut increase.
iv. C: Initial water cut when Channeling starts
v. Tchannel: Transition time from coning to Channeling, indicating the point where behavior changes.

The Hybrid model for water coning and channeling behaviour parameters allows for the control of onset and rate of coning and channeling behaviours, making it a versatile tool for predicting and understanding reservoir dynamics. This model offers a comprehensive approach to modelling coning and channeling behaviours by seamlessly combining exponential and linear growth behaviours.

This formulation accurately represents the complex reservoir dynamics observed in the field, allowing for more informed decision making and enhanced reservoir management.

IV. Meyer, Gardner & Pison Method For Coning Rate Determination

The model which will be applied in this work is the MEYER, GARDNER AND PERSON MODEL due to its simplicity and accuracy. It also has the advantage of capturing both water and gas coning.

For Water Coning;

$$q_o = 0.246 * 10\text{-}4 * \frac{\rho_w - \rho_o}{\left(\frac{r_e}{r_w}\right)}\left(\frac{k_o}{\mu_o B_o}\right)) \quad (6)$$

For Gas Coning;

$$q_o = 0.246 * 10\text{-}4 * \frac{\rho_o - \rho_g}{\left(\frac{r_e}{r_w}\right)}\left(\frac{k_o}{\mu_o B_o}\right))] \quad (7)$$

For Simultaneous Gas and Water Coning,

$$q_o = 0.246 * 10\text{-}4 \; *7 \left(\frac{k_o}{\mu_o B_o}\right)\frac{(h^2 - h_p^2)}{\left(\frac{r_e}{r_w}\right)} \times \left[(\rho_w - \rho_o)\left(\frac{\rho_o - \rho_g}{\rho_w - \rho_g}\right)^2 + (\rho_o - \rho_g)\left(1 - \frac{\rho_o - \rho_g}{\rho_w - \rho_g}\right)^2\right] \quad (8)$$

Where; $h_p = h - Dt$ (9)

and $Dt = (h - h_p)\left[1 - \left(\frac{\rho_o - \rho_g}{\rho_w - \rho_g}\right)\right]$ (10)

q_o = critical rate (maximium oil rate without gas coning), STB/day

ρ_o = oil density, gm/cc

ρ_w = water density, gm/cc

ρ_g = gas density, gm/cc

r_e = drainage radius, ft

r_w = wellbore radius, ft

k_o = effective oil permeability, md

μ_o = oil viscosity, cp

B_o = oil formation volume factor, RB/STB

h = perforated interval, ft

h_p = oil column thickness, ft

Dt = optimum distance from the Gas-Oil-Contact to the top of the perforations

2.2.2 Numerical Model for Simulating the water breakthrough process and Drive Mechanism Determination.

I. Eclipse Reservoir Simulator

A Reservoir Simulator is a computer generate d model that aims to represent a reservoir's full geological extent and structure. Using the computer model to solve a Reservoir Engineering problem is generally known as "reservoir simulation". The reservoir simulator allows the reservoir engineer to study and analyse the performance of the reservoir under various operating conditions. The pre-and post-processor of the Eclipse reservoir simulation interface is used in this work because it is well-known in the oil and gas industry. With ECLIPSE, a user can develop reservoir simulation cases that aid in studying and analysing the performance of reservoirs to facilitate final decision making for reservoir management. Modelling requires a computer and large amounts of data compared to most other reservoir calculations. The model requires a grid system to describe the field under study, usually called cells or grid blocks.

The Eclipse office main window is divided into the following areas:

i. Menu Bar
ii. Application launch buttons.
iii. Information area.
iv. Status bar.
v. Data tree area.
vi. Module launch buttons.

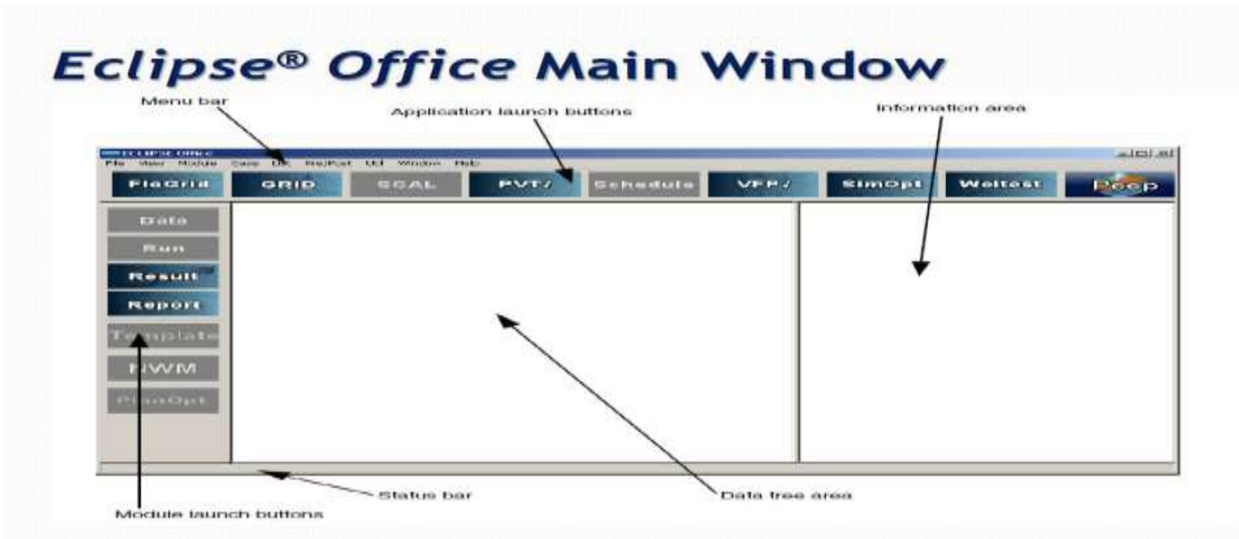

Plate 1: Eclipse Office Main Window

Eclipse Office is a tool that helps manage reservoir simulations. It provides a convenient user interface for;

i. Launching and managing any of the Eclipse applications.
ii. Running a rapid quick-look simulation from start to finish.
iii. Allowing you to check your results during simulation runs.
iv. Editing and reviewing simulation results and generating reports.

Eclipse Office offers an integrated desktop for launching all the applications in the Eclipse product line. This includes the pre and post processing applications and the Eclipse simulator. Eclipse Office also features modules that greatly improve your control of the simulation workflow:

i. Case Manager

The case manager allows you to build up a tree of runs or cases. These cases can derive from the parent case or can be independent. A case consists of a series of 'include' files for each section of the simulator data input: GRID, PVT, SCAL, INITIALIZATION, REGIONS, SCHEDULE and SUMMARY. When a case is selected, an existing data set can be imported to create these INCLUDE files. The tree information and case definitions are stored in an Eclipse office project file (.OFF).

ii. Data Manager

The data manager allows you to create, edit, insert, delete and review all the data corresponding to the selected case. The data manager sections include case definitions, Grid, PVT, SCAL, Initialization, Schedule, and Summary. The data manager handles all simulator keywords and options.

a) Case Definition

The case definition section allows you to select the important options. It is similar to the RUNSPEC section of the simulators, except that it does not require input of table dimensions as Eclipse Office calculates these.

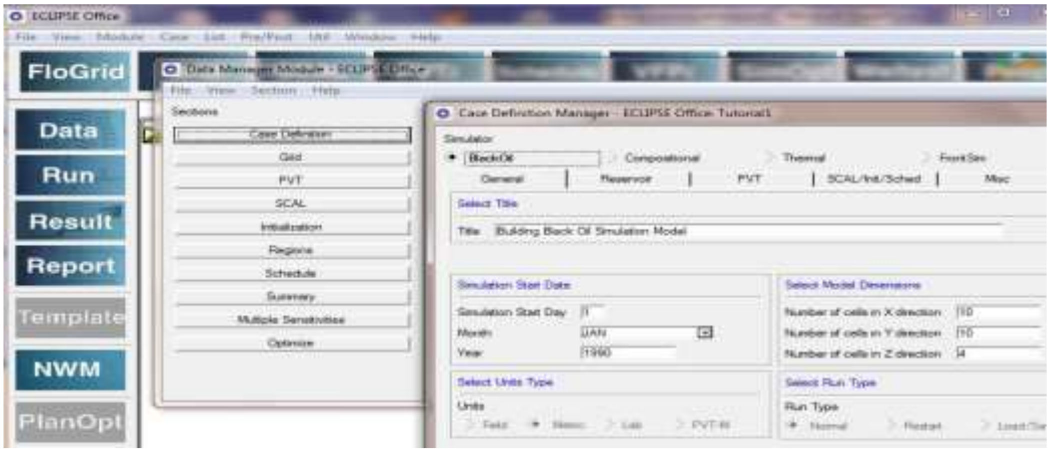

Plate 2: Case Definition

b) Grid Section

The Grid section gives you access to the GRID and EDIT keywords, where you can edit the data. Data can be imported from include files generated by FloGrid and GRID. Region keywords relating to the Grid Section are also accessed here: Fluid-in-Place (FIPNUM) and others. The grid section also allows you to look at grid block properties on the simulation grid in either 2D or 3D. The simulation grid can be generated by reading an existing GRID file, running the simulator, or creating it using the keywords.

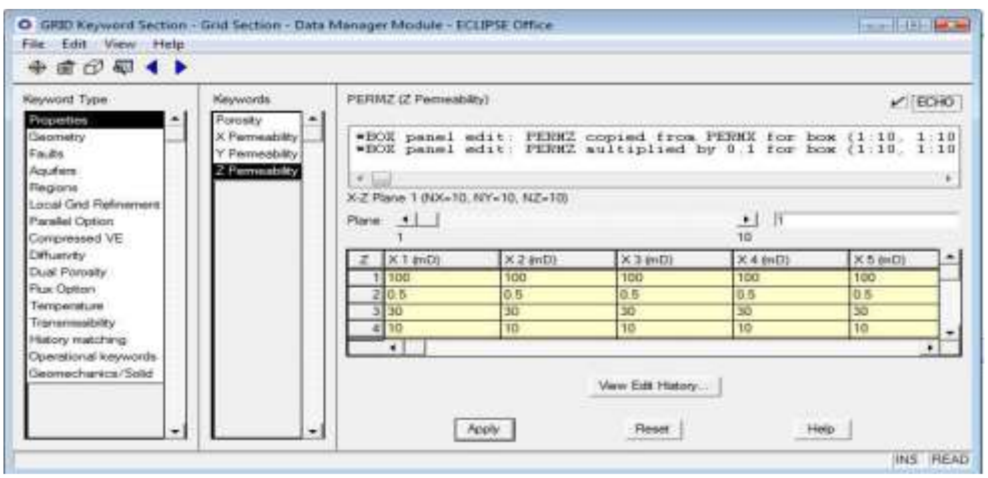

Plate 3: Grid Section

c) PVT Section

The PVT Section gives you access to the PVT keywords of the simulator PROPS Section. Allow you to add all OIL, GAS, and WATER PVT properties.

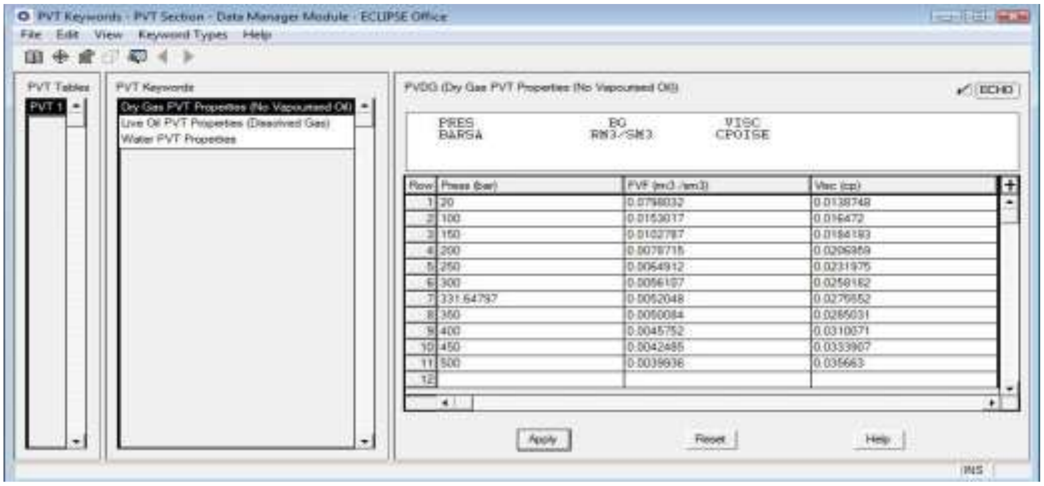

Plate 4: PVT Section

d) SCAL Section

SCAL stands for **S**pecial **C**ore **A**nalysis. Like a typical laboratory core analysis, the purpose of SCAL is to model the Capillary Pressure and relative permeability of the fluid phases in the reservoir as a function of their saturation.

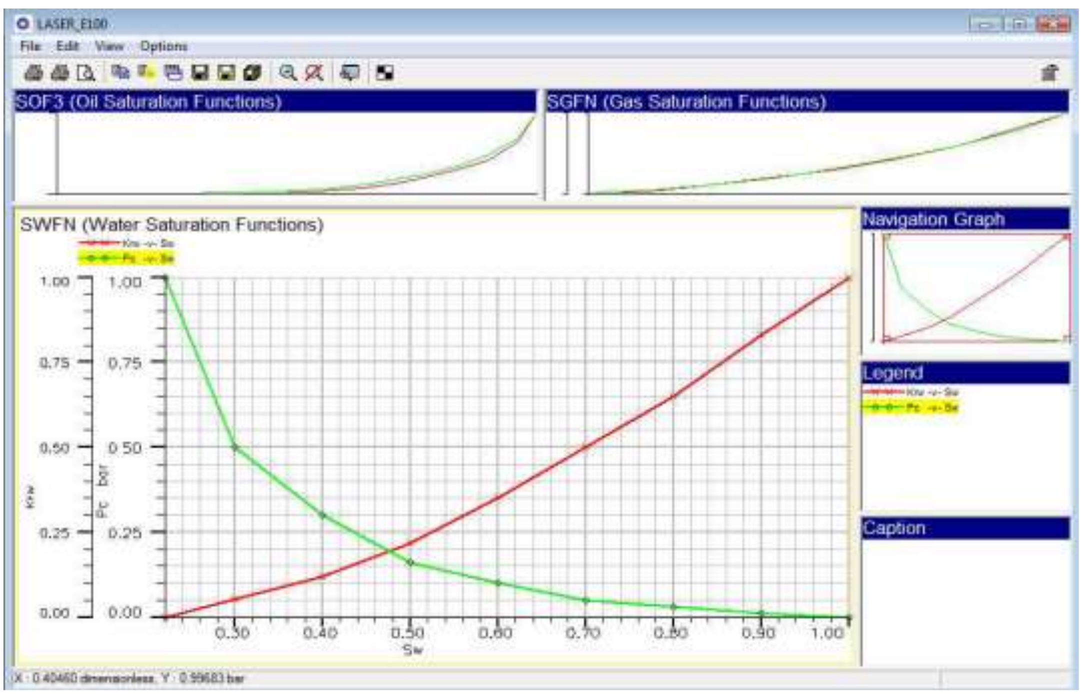

Plate 5: SCAL Section

e) INITIALIZATION Section

This section allows you to add Datum depth, Pressure at datum depth, WOC depth, GOC depth, aquifer data, and other necessary data, usually left blank.

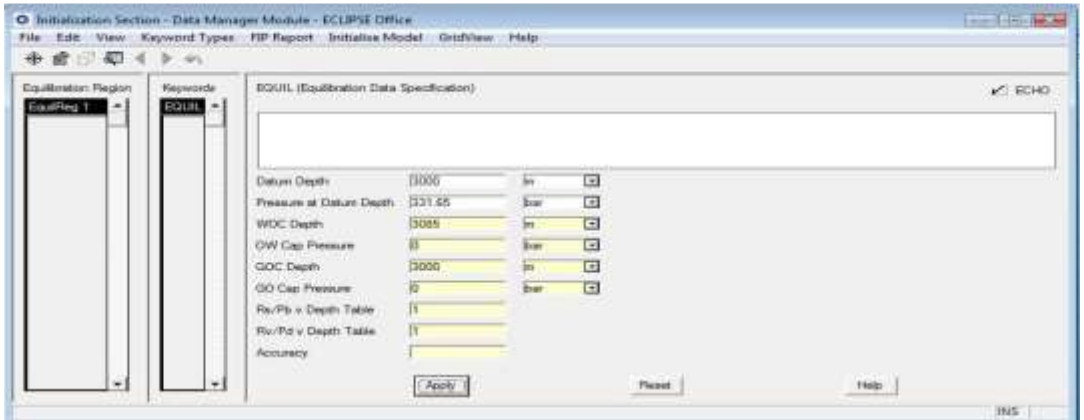

Plate 6: INITIALIZATION Section

f) SCHEDULE Section

This section gives you access to the SCHEDULE keyword and enable you to add wells and well completion specification data.

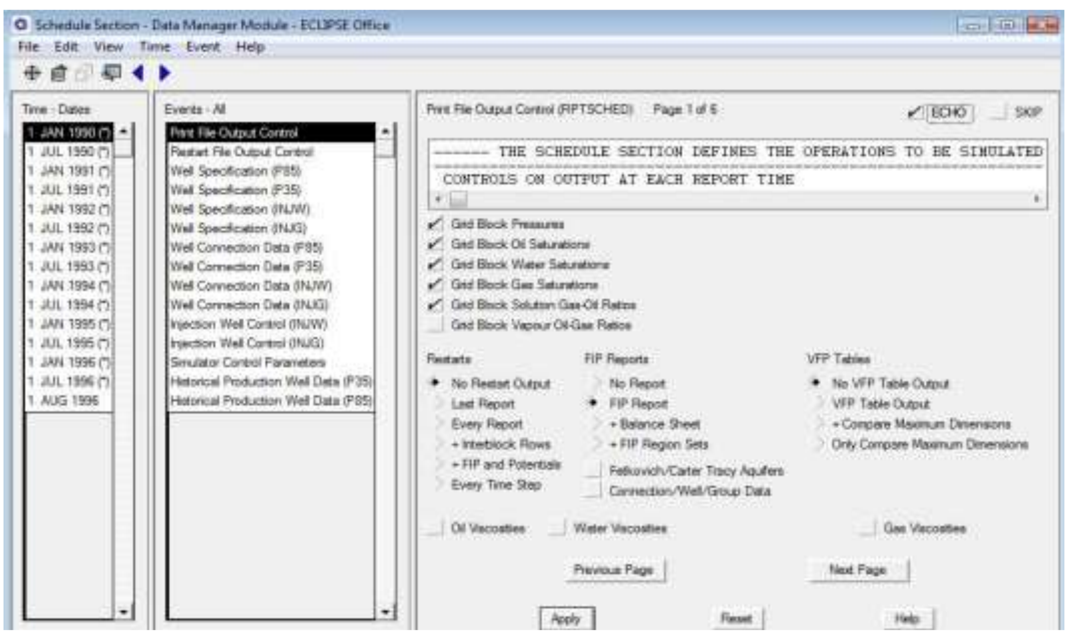

Plate 7: SCHEDULE Section

g) SUMMARY Section

Summary variables contain vector data, such as production rates, gas production rates, water production rates, and more, for each report step and are saved in the—Sn files during the simulation run.

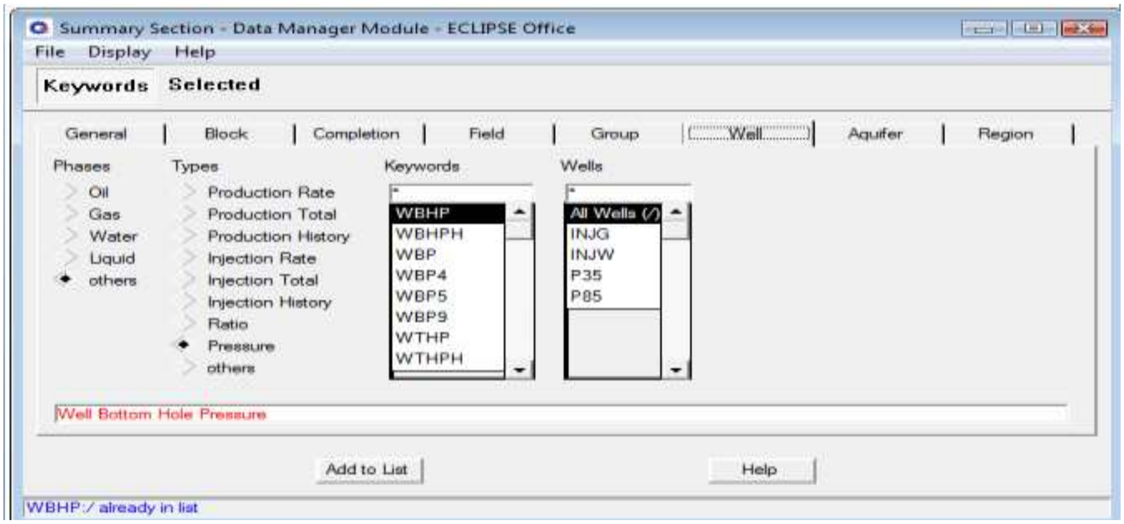

Plate 8: SUMMARY Section

iii. Run Manager

The Run Manager offers an environment for launching, monitoring and controlling

simulation runs. With the Run Manager, it is possible to monitor the progress of runs

on line plots and solution displays.

iv. Result Viewer

The result viewer can display simulation results in both two and three dimensions. It

can also be used to create and view solution displays and line plots of production data.

v. Report Generator

The Report Generator creates reports by extracting relevant information from the SUMMARY files.PRT file and put them in a form

required for the creation of written reports.

The standard workflow to follow when using ECLIPSE simulation software includes;

i. Construction of the Simulation Grid and Cell Properties.

ii. Fluid Modeling.

iii. SCAL Modeling.

iv. Initialisation.

v. Scheduling.

vi. History Matching (Optimisation).

vii. Performance Prediction.

2.2.3 Calibration and Parameter Estimation

In this section, Analytical and Numerical models will be fit to production data using curve fitting or statistical techniques and Eclipse Reservoir Simulator. However, this work will use non-linear regression techniques to calibrate the analytical models. Model calibration involves determining the model parameters that best represent the observed behaviour in the data. Once calibrated, the model can be used to make predictions and analyse the occurrence of coning, Channeling and a combination of both phenomena in the Hybrid model in the reservoir.

Let's break down the calibration and validation process for applying Analytical and Numerical models.

I. Data Collection
II. Selected Model
III. Choose Calibration Techniques
IV. Non-linear regression techniques will estimate the model parameters that best fit the water cut vs time data.
V. Performing Calibration
VI. The flowchart in Appendix B shows the steps followed to perform calibration using non-linear regression and estimate the values of model parameters that best fit the water cut data.
VII. Calibrated Model parameters
VIII. Critical Coning rate determination (optional - if the model applied is an Exponential growth model or if the well produces water via coning.
IX. Refine calibration (if needed): If the model prediction closely matches the actual water cut values in the validation dataset, no refinement is necessary.
X. Finalise Model Parameters: If the calibration is satisfactory, we can confidently use the model for water cut behaviour and assess the impact of water coning over time.
XI. Assessing Model performance through goodness-of-fit metrics (R-squared, MSE, etc.): A higher R-squared value and lower MSE and RMSE indicate a better fit of the model to the data.
XII. Interpretation.
XIII. Numerical Model Calibration and Result: History matching the collected data to fit the Numerical Model using Eclipse Simulation software by adjusting the production data and pressure performance. This consists of adjusting the reservoir parameters and production data until the simulated performance matches the observed or historical behaviour. The following are usually matched;
   i. Pressure matching
   ii. Saturations matching
   iii. Productivity matching

I. Pressure matching: The average reservoir is matched using the following steps:

- **i.** Adjust rates to correct for total voidage
- **ii.** Adjust total compressibility, porosity, permeability thickness, and water influx from the aquifer to correct for the pressure level.
- **iii.** Adjust permeability for pressure shape.
- **iv.** Adjust total compressibility, porosity thickness, and water influx from the aquifer to correct for individual well performances.

II. **Reservoir saturation matching** involves the following.

- i. Adjust relative permeabilities and capillary pressures for field water/oil ratio and gas/oil ratio.
- ii. Adjust local relative permeabilities and capillary pressures for well water/oil and gas/oil ratios.
- iii. Repeat pressure match

III. **The productivity match** procedure involves the following.

i. Adjust the well productivity index and injectivity index for well productivity.

ii. Make the final history match run followed by prediction.

Parameters that are matched;

i. Pressures

ii. Flow rates

iii. GOR

iv. WOR

Parameters modified to get a match;

i. Rock data: k, h, φ, saturation

ii. Fluid data: PVT, Ct, μ

iii. Well data: Skin, bottom-hole flowing Pressure

i. RESULTS AND DISCUSSION

3.1 Results

Below are the data used for the analysis when the combined model is applied to real-life wells experiencing coning, Channeling, or a combination of both. These production data are from 3 wells with a history of water production. The combined application of an analytical and numerical model was used to identify the dominant behaviour experienced by the wells.

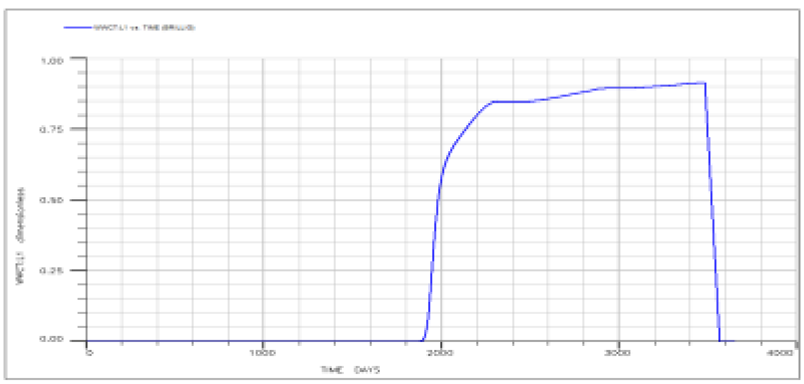

Figure 1: Water cut against Time for **Well L1**

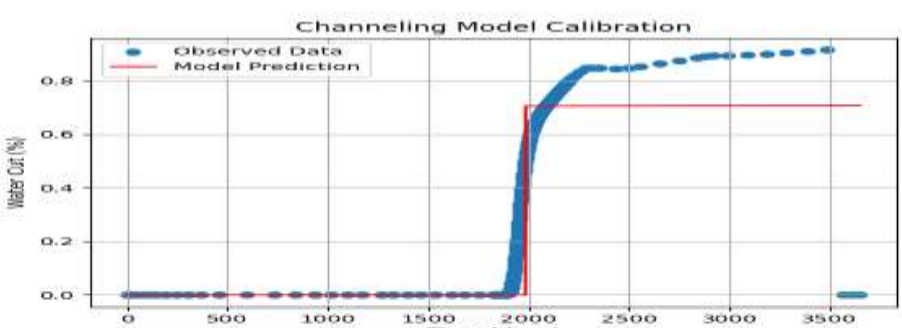

Figure 2: Water cut against time - validated results for Well L1

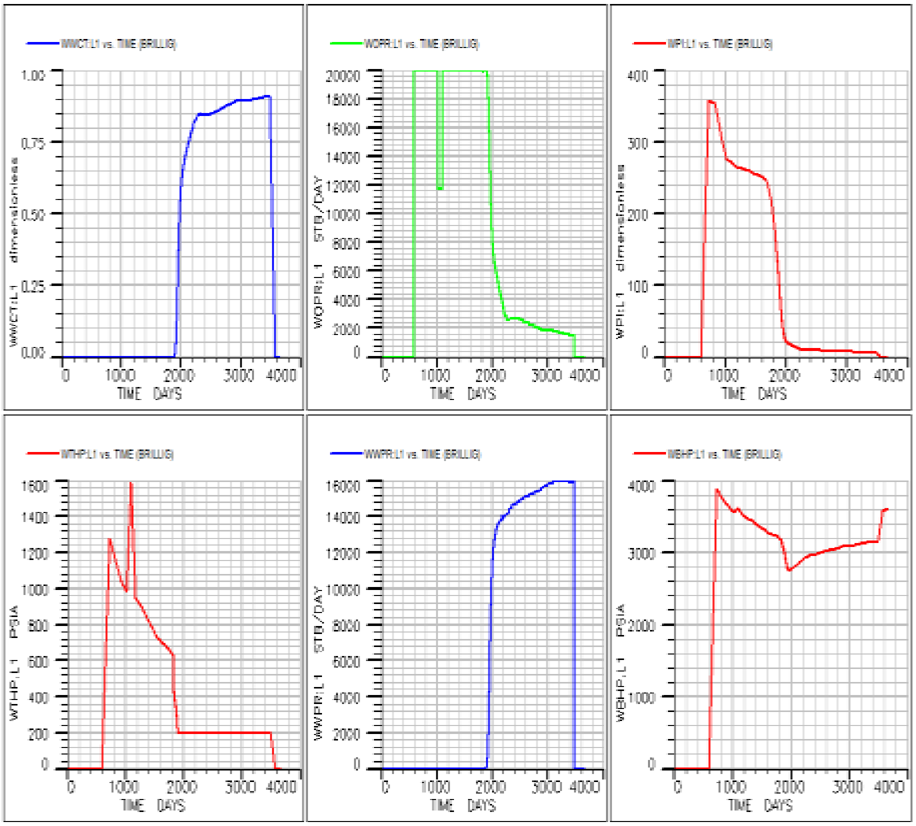

Figure 3: Separated Simulated Results for Well L1

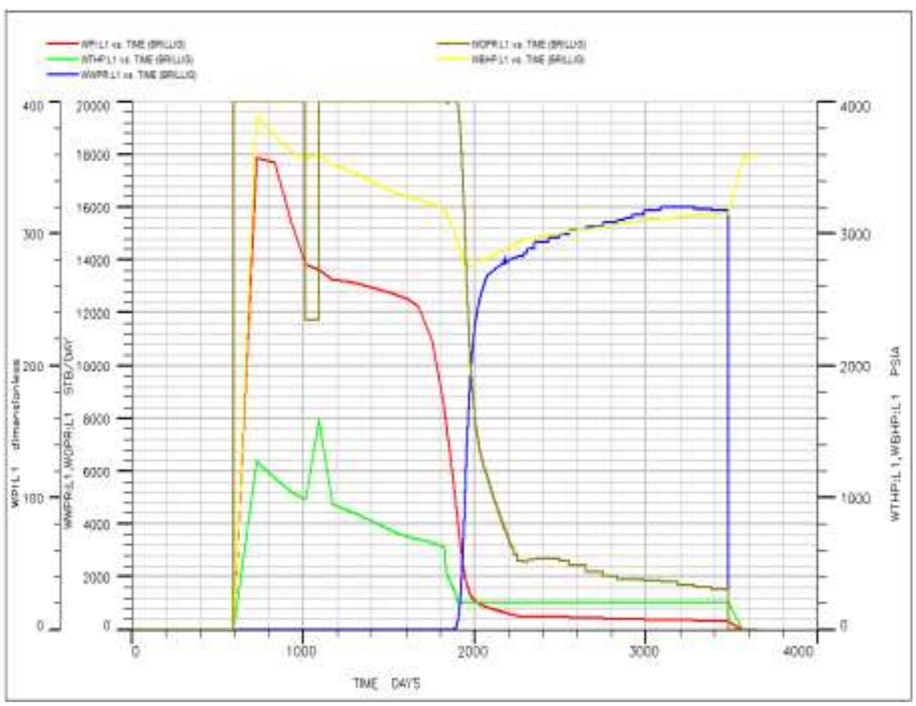

Figure 4: Combined Simulated Results for **Well L1**

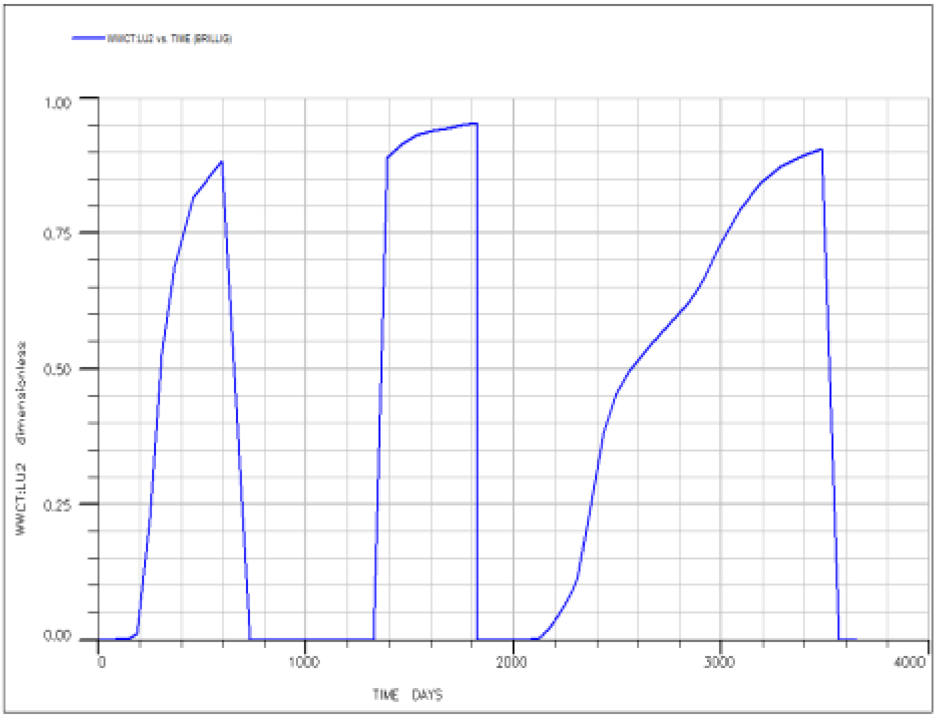

Figure 5: Water cut against Time for Well LU2

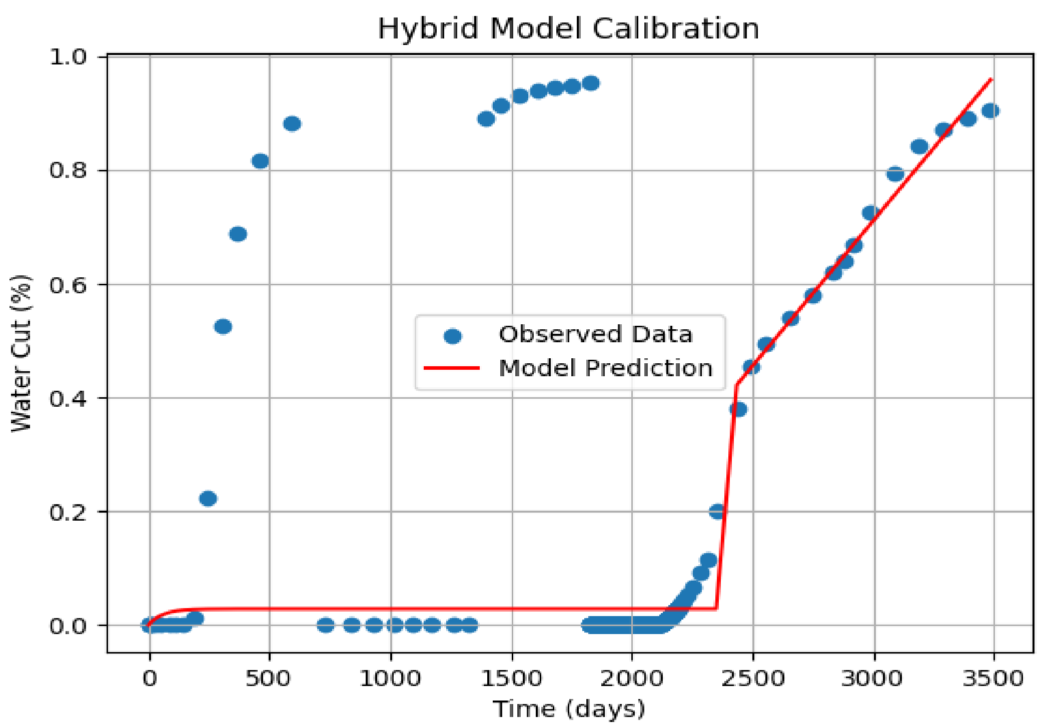

Figure 6: Water cut against time - validated results for **Well LU2**

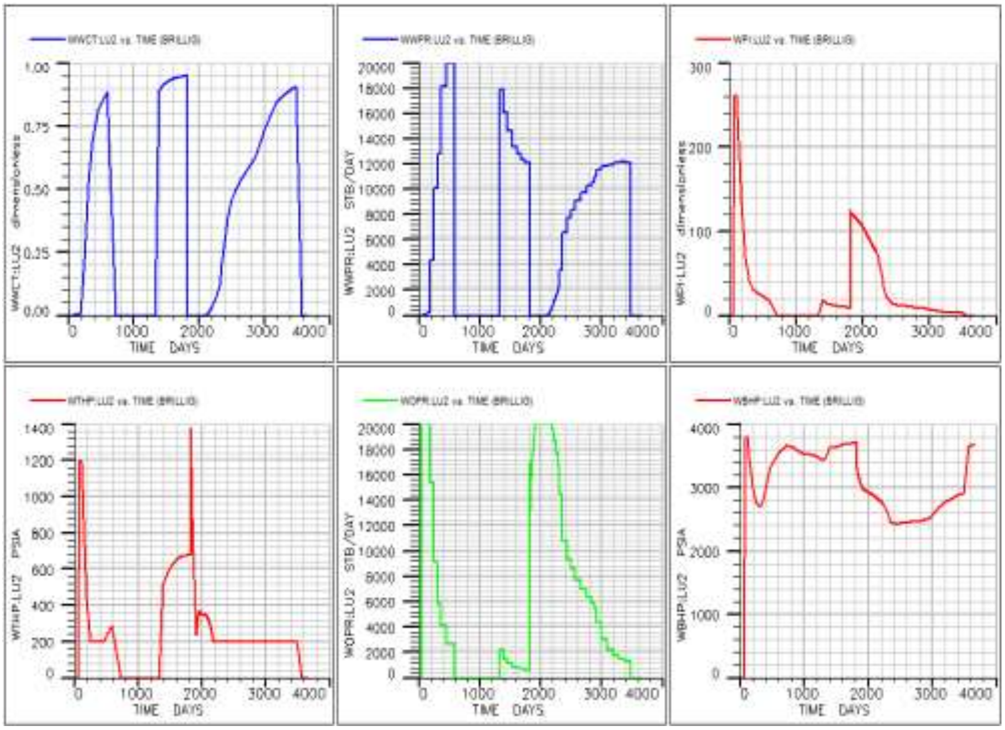

Figure 7: Separated Simulated Results for **Well LU2**

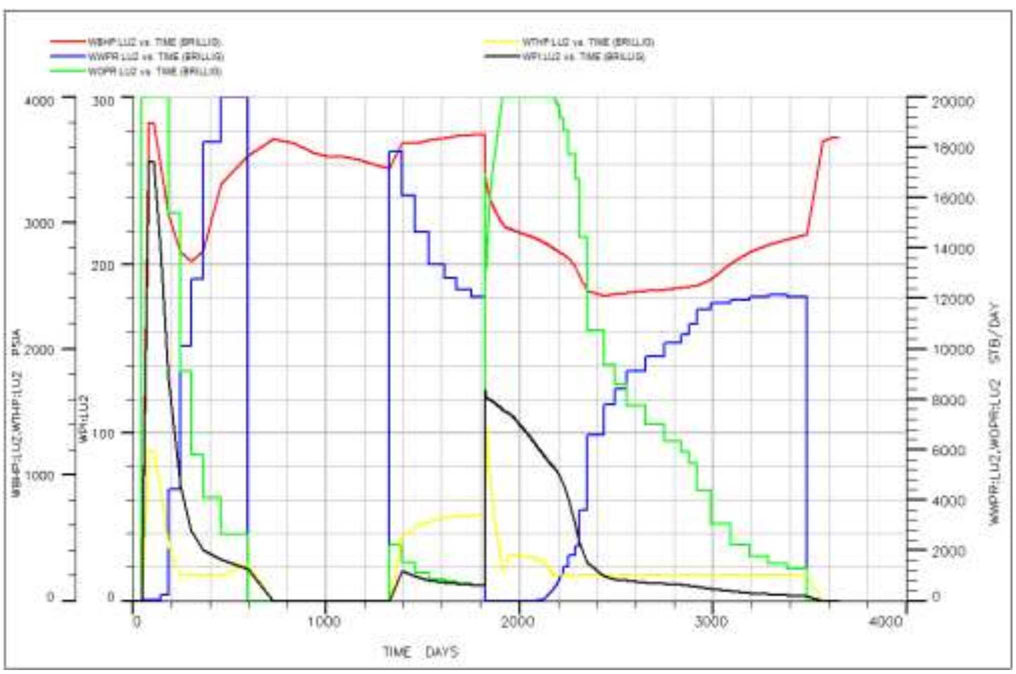

Figure 8: Combined Simulated Results for **Well LU2**

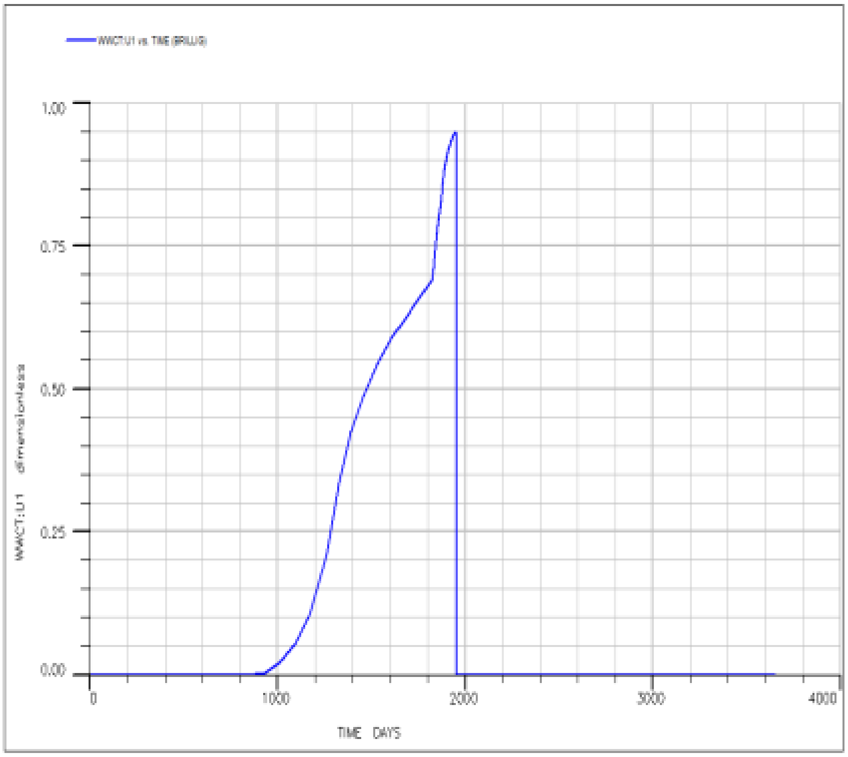

Figure 9: Water cut against Time for **Well U1**

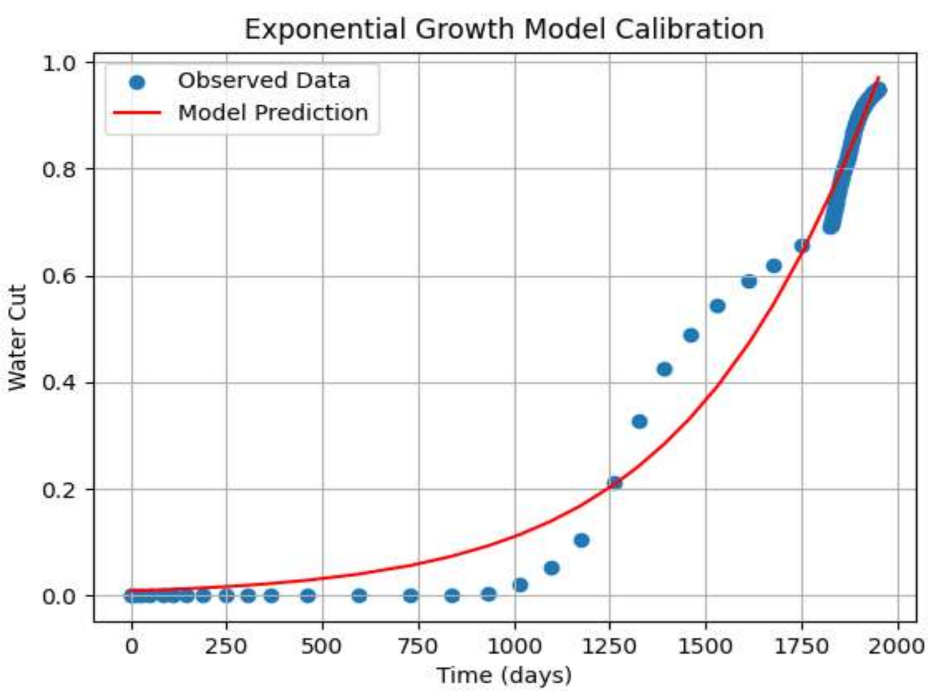

Figure 10: Water cut against time - validated results for **Well U1**

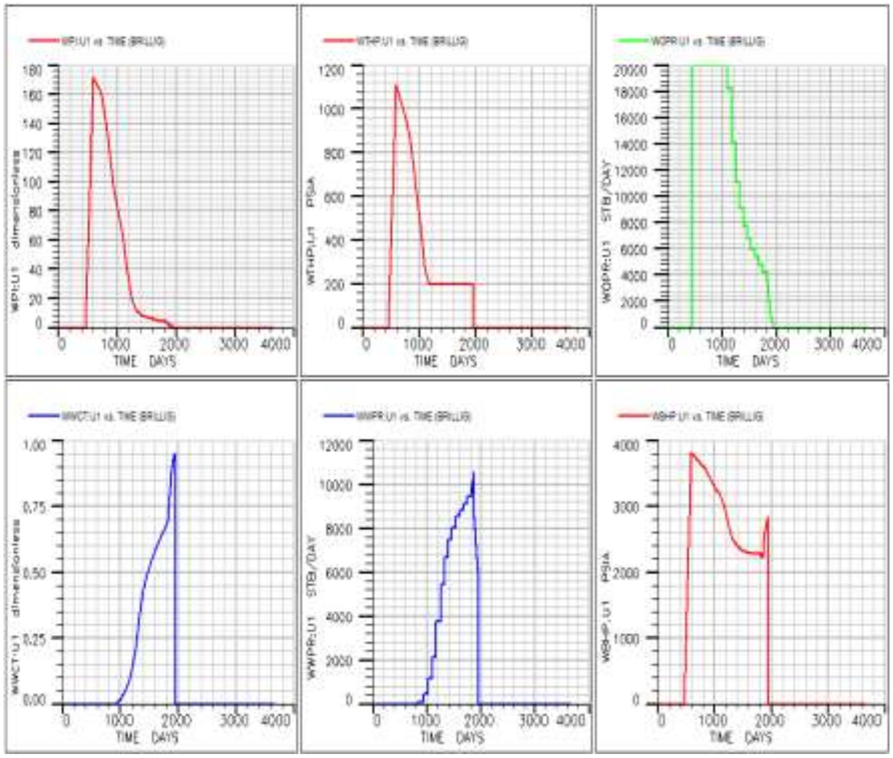

Figure 11: Separated Simulated Results for **Well U1**

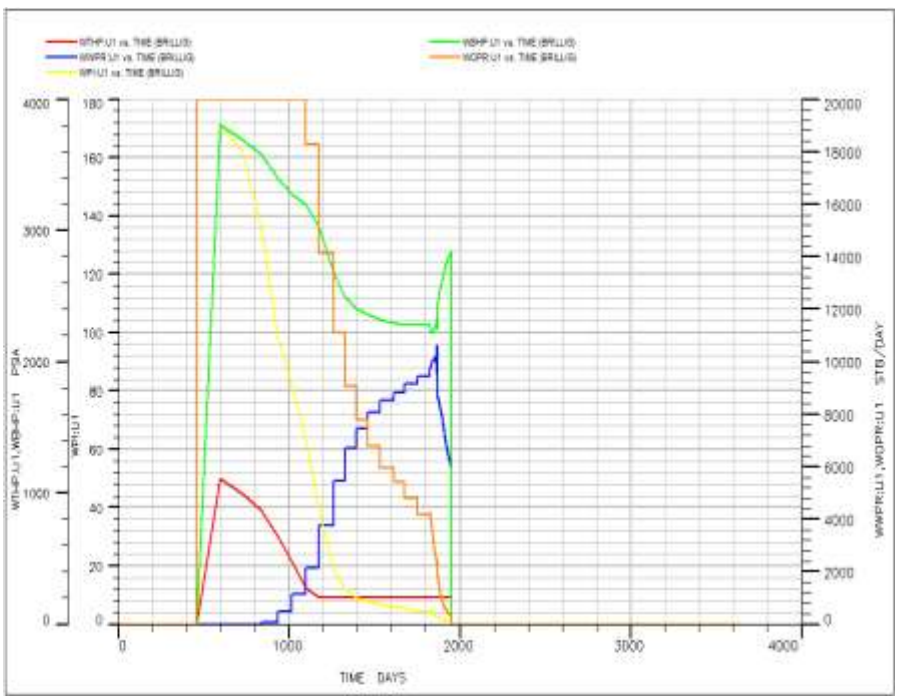

Figure 12: Combined Simulated Results for **Well U1**

ii. *3.2 Discussion*

After successfully applying the combined analytical and numerical model to real-life cases, the following observations from each well which the combined model diagnosed are;

Well L1*:* This well from the plot and verification plot made with Python shows that Channeling is a major cause of the water production problem. The well is producing water from the edge water drive mechanism due to the fact that the production rate, as observed from the simulation carried out, reduces gradually before a sudden spike. The well was water-free at the start of production, indicating 0% water cut until the water breakthrough began in 1984. Days the water cut increased sharply after that, leading to the stop of production. The well has an R- R-squared value of 0.790, indicating that the model represents the well's behaviour with 80% certainty.

Well LU1: Early coning with late channeling is diagnosed as the source of produced water from the validation plot and the simulated water production process. This well produced water from a bottom water drive mechanism. This is because the oil production rate declined rapidly almost immediately when production commenced. The well was shut down, and a workover operation was carried out for a long period of time, but this still didn't handle the situation. A major water breakthrough occurred at 2279 days. The well water production rate is higher than WELL L1, so close monitoring is essential to initiate water treatment intervention early to mitigate the water production. The model fits 50% of the well's behaviour.

Well U1: The water production rate from this well is slow and gradual, suggesting from the simulated water production rate process that an edge water drive mechanism supports the well and that coning is the cause of the water problem observed. This coning can be reduced or delayed if the production rate is 500STB/day. At this rate, only 100% oil will be produced without water or gas coning. The combined model explains the well behavior with some degree of accuracy since it has an R-squared value of 0.98.

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

iii. *Models have been applied in this study and used to diagnose the source of produced water in the wells successfully. The results from the use of the combined analytical and numerical models in the diagnosis are as follows;*

iv. *The results of the case studies validate the combined usage of both models, proving that they are efficient and robust in water production problem diagnosis.*

v. *Also, the results successfully addressed the challenge faced by other numerical and analytical models, which cannot account for the occurrence of coning and channeling using a single model, taking into account reservoir complexibilities.*

4.2 Recommendations

The following issues must be considered when conducting further research on this or a closely related topic.

i. Choosing the optimum solution for the specified problem to reduce or prevent excess water production.
ii. Close monitoring using logs and well tests improves understanding of reservoir flow behaviour and identifies water production mechanisms during the well's life.
iii. The Water cut vs. Time plots can easily be misunderstood. It should be considered to help achieve highly accurate results in pinpointing the specific mechanism causing the water production problem.

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Appendices

Appendix A: Definition of Terms

Water cut: In the context of oil production and reservoir engineering, refers to the proportion or percentage of water present in the fluids produced from an oil well. It is typically expressed as a percentage and represents the water fraction in the total fluid mixture produced from the well.

Coning: "water coning" or "gas coning," occurs when water or gas migrates into the wellbore and rises toward the production zone in a conical shape. In the case of water coning, water creeps into the production zone, displacing oil or gas.

channeling: channeling refers to the preferential flow of one fluid (usually water) through a specific path in the reservoir formation, bypassing the rest of the formation. This can create channels or channels through which water flows more easily than oil or gas.

A (Amplitude): The amplitude parameter in the exponential growth model represents the initial water cut, the water cut that the production starts with, or the baseline water cut at the onset of production.

k (Growth Rate): The growth rate parameter in the exponential growth model determines how fast the water cut increases over time.

B: A coefficient in the piecewise linear model indicates the change in water cut after T exceeds Tchannel.

Tchannel (Transition Time): The time the piecewise linear model transits from one linear segment to another.

D (Intercept): The intercept of the linear segment after T exceeds Tchannel. It represents the baseline or initial water cut level at the time Tchannel. It's the water cut value at the onset of Channeling.

C (Slope): The slope of the linear segment after T exceeds Tchannel; it quantifies how steeply the water cut increases with time beyond the channeling threshold.

Appendix A: Calibration Process Flow Chart