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Improved Oil Recovery Through Low Salinity Water Flooding

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background Information

The need to produce more oil and gas fields efficiently as well as more economically is generally on the rise due to the ever-increasing demand for petroleum worldwide (Meshioye *et al*., 2010). With the decline in discovery of new oil and gas fields, and more mature fields still holding significant volumes in reserves. The need to use secondary recovery process as a means of recovery for these fields that are yet to recover optimally is becoming more and more imperative. Waterflooding is one of the most widely used secondary recovery means of production after primary depletion energy has been exhausted (Ogbeiwi *et al*., 2017).

Over the years, waterflooding has been the most widely used secondary oil recovery method after the exhaustion of the primary depletion energy of the reservoir (Aladeitan *et al*., 2017). Waterflooding is a process that entails the injection of water through a well directly into the reservoir. The water pumped through the injection well into the reservoir is either gotten from the reservoir itself in form of produced water or any source of bulk water e.g. sea water, aquifer water, river water etc. Nevertheless the disadvantage of injecting any source of bulk water that is not directly from the reservoir, can lead to formation damage due to injection of incompatible fluids. The injected water must be of the same chemical composition with the reservoir to avoid severe damage of the whole process. The produced water gotten from the reservoir is never sufficient to be re-injected, so additional make-up must be provided and properly treated before use. During waterflooding, the pumped water is sent to the water injection plant and then it forcefully passes through the pore spaces and sweeps the oil in the direction of the producer wells. This process results to an increment in the total oil produced from the reservoir as well increase in the percentage of water along with the recovered oil (Udebhulu *et al*., 2017). It has been proven that on the average, waterflooding process can lead to the recovery of about one-third of the original oil in place (OOIP), leaving behind about two-third (Meshioye *et al*., 2010).

1.1.1 Factors Controlling Waterflooding Recovery

Waterflooding despite being proved successful on various attempts, has some factors that are taken into considerations to ensure optimal delivery of the process (Tarek, 2006). The four very essential factors that control waterflooding process include;

1. Oil-in-place at the start of waterflooding
2. Areal sweep efficiency
3. Vertical sweep efficiency
4. Displacement sweep efficiency.

1.1.2 Factors to Consider in Waterflooding

Thomas (1989) pointed out that in determining the suitability of a candidate reservoir for waterflooding, the following reservoir characteristics must be considered:

i. Reservoir geometry
ii. Fluid properties
iii. Reservoir depth
iv. Lithology and rock properties
v. Fluid saturations
vi. Reservoir uniformity and pay continuity
vii. Primary reservoir driving mechanisms

1.1.3 Factors That Affects Waterflooding Recovery

Some properties that affect waterflooding recovery include (Smith *et al*., 1990):

i. Wettability
ii. Oil viscosity
iii. Angle of inclination
iv. API gravity
v. Mobility ratio
vi. Rock characteristics
vii. Density
viii. Injection rate

The major reason for waterflooding in an oil reservoir is to increase the oil production rate and most importantly, oil recovery. Basically waterflooding is achieved by "voidage replacement"; the injection of water to increase the reservoir pressure. The injected water (which is injected through the injector well) displaces oil from the pore spaces, but such displacement is efficient depending on many factors (e.g. oil viscosity and rock characteristics).

Moreover, during the waterflooding process, the objective is to displace oil successfully. However, achieving this seems difficult without proper analysis. Frontal advance theory provides the answer to this in 1-D (Abbas, 2015). It's been observed over time that the oil recovered in an immiscible displacement system is largely a function of the viscosity ratio. This is due to the fact that the waterflood displacement efficiency is affected by the viscosity ratio of the displaced fluid to the displacing fluid (Green *et al*., 1998). Therefore, an analytical study of viscosity ratio alteration to avoid unfavorable viscosity ratios and to predict recoveries correspondingly becomes of paramount importance.

1.2 Aim/Objectives of Project

The aim of this project is to model a reservoir system that can optimize oil recovery through low salinity waterflooding by using Schlumberger Eclipse 100.

The objectives of the project include;

1. Develop a base case reservoir model that requires supplementary energy drive (via waterflooding) to improve its production rate and oil recovery.
2. Estimate the amount of injected water needed to stabilize the reservoir pressure decline.
3. To make an estimate of the additional recovery the water injection would give.

1.3 Statement of Problem

Waterflooding as a secondary recovery process has been used successfully for production optimization across the world. However, it is not a commonly practiced optimization process in Nigeria's oil rich Niger delta because most reservoirs in this region have a fairly strong energy drive. However several factors i.e. oil viscosity, wettability, mobility ratio etc. have limited the performance of this process.

1.4 Justification of the Project

Every reservoir is initially recovered using its primary natural source of energy (reservoir pressure maintenance) but over time, this natural energy depletes even when there is still large accumulation of crude to be produced. The need to supplement the natural energy drive is what leads to the use of waterflooding (injection of water into the producing well) to optimize the rate of production.

Waterflooding process has been practiced over the world with great success but there are certain properties of the reservoir that can limit optimal use of the process.

This project is limited to the development of a reservoir which will make use of the waterflooding process to increase the current production rate of the reservoir and the model will take into consideration the effect of oil viscosity on the waterflooding process. Eclipse, an industry proprietary tool is used for this project, this tool aids in performing simulations for waterflood studies or operations, the scope of this project also includes development of the reservoir as well as analysis which highlights the effect of oil viscosity at various viscosity values.

The key deliverable of this project using Eclipse software is to develop a reservoir model showcasing the value of waterflooding operations as an enabler to reservoir optimization while detailing the importance of the reservoir fluid property (oil viscosity) as a consideration for a successful and optimal waterflood design.

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CHAPTER THREE

3.0 METHODOLOGY

3.1 Study Approach

The tool used for this study is listed below:

a. ECLIPSE® 100

3.2 Reservoir Simulation

Basically, reservoir simulation is known as the use of computer software's (applications) to predict or estimate the flow of hydrocarbons (oil and gas) through a porous media i.e. the reservoir. The term "reservoir simulation" is basically used to describe the activities involved in the building and execution of a model that represents the reservoir, such that the behavior of the model mirrors or "simulates" as much as possible the observed behavior of the reservoir (Ezekwe, 2011).

The model built in this case consists of sets of mathematical equations that represent material balance, fluid flow and other physical processes occurring in the reservoir, subject to some defined constraints and conditions. The core equations involved in reservoir simulation tools include: Material Balance equations, they are the fundamental equations in black oil simulators. There are no analytical solutions to these non-linear partial differential equations. Solutions to these equations are generally based on numerical methods to solve these partial differential equations.

3.3 Eclipse 100 Simulator

This section of the study is mainly focused on the implementation of a dynamic reservoir simulation tool ECLIPSE 100 specialised in black oil modelling for further reservoir development options. For this purpose, the software used with basic features of the reservoir are delineated to characterize fluid properties such as viscosity, density, API gravity, and rock properties (porosity, relative permeability, compressibility) oil and gas production rate, pressure of reservoir, depth of the reservoir, area of the field of operation. Following this simulation, development options were performed on the oil rim reservoir under pressure depletion for the hypothetical reservoir with three producing horizontal wells with sensitivity in the horizontal well lateral length and a single deviated well.

The Eclipse reservoir simulator is a software owned by the Schlumberger firm and consists of two separate simulators, which include;

i. Eclipse 100: specialised in black oil modelling
ii. Eclipse 300: specialised in compositional modelling

For the purpose of this study Eclipse 100 was used. The limitation of Eclipse 300 over Eclipse 100 is that Eclipse 100 consists of a fully–implicit, three- phase, three dimensional, general purpose black oil simulator with gas condensate options inclusive.

ECLIPSE Office offers an integrated desktop for launching all the applications in the ECLIPSE product line, which includes the pre- and post-processing applications and the ECLIPSE simulators. The ECLIPSE Office is essentially embedded with five modules that greatly improve the control of the Reservoir simulation. There are; Case Manager, Data Manager, Run Manager, Result Viewer, Report Generator and Templates.

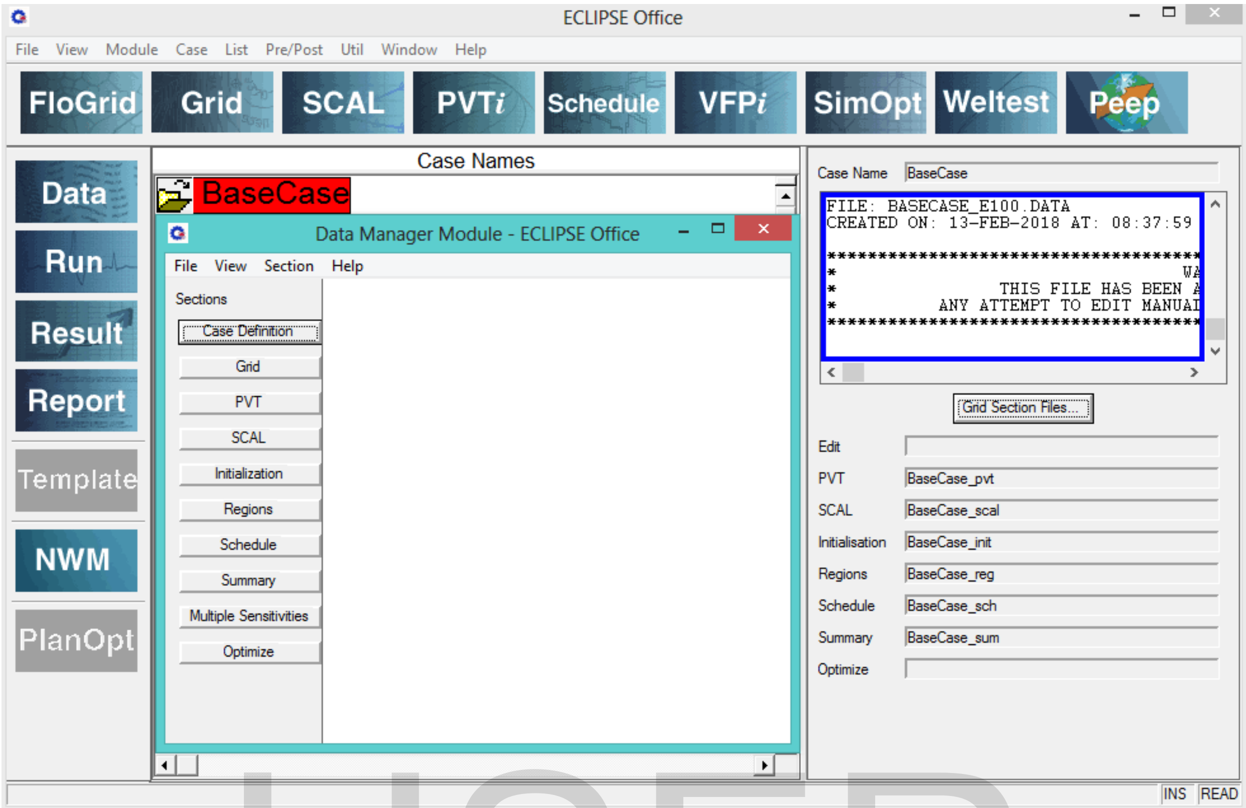

Figure 3.1: ECLIPSE office workflow

3.3.1 Case manager

The Case Manager helps to capture the relationship between runs and graphically display them. Runs are shown as children to Cases from which they were derived by simply modifying some available data. The Case Manager permits the buildup of a tree of runs, or cases. These cases may be independent or derived from the parent case. A case consists of a series of 'include' files for each section of the simulator data input, that is 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).

3.3.2 Data manager

Dynamic reservoir simulation using eclipse software requires set of data files to illustrate the reservoir properties and characteristics at a given period of time. An Eclipse data input file is split into sections, each introduced by a keyword. A list of all section- header keywords is given below.

Some keywords are recognized by both Eclipse 100 and 300, while others are valid in only one of the simulators. Eclipse simulator offers a platform for the user accommodating platform and enables data sets to be uploaded. Some of which are optional and others indispensable. When these data are inputted the eclipse template permits construction for the required properties by applying substantial information in respective sections of the data manager module.

A. ***RUNSPEC:***

i. Title, problem dimensions, switches, phases, present, components, etc.

ii. This keyword is always required

B. **GRID:**

i. Specification of the geometry of the computational grid (location of the grid block corners), and of rock properties (porosity, absolute permeability, etc.) in each grid block.

ii. The keyword is always required

C. **EDIT:**

i. This keyword is optional and modifications with the computed pore volumes, grid block centre depths and transmissibility.

D. **PROPS:**

i. Contains the equation of States, tables of properties and this keyword is required

E. **REGIONS:**

i. Computational grid is split into regions to calculated; PVT properties, Saturation properties, initial conditions, fluids in place, EOS Regions.

ii. This keyword is optional and if this section is omitted, all grid blocks are put in Region 1.

F. **SOLUTIONS:**

i. This involves initialization conditions of the given reservoir and this keyword is always required.

G. **SUMMARY:**

i. This involves specification of data to be written to the summary file after each time.

ii. If this section omitted, no summary files generated and such it is optional

H. **SCHEDULE:**

i. It specifies the operations to be simulated at the time at which output reports are necessary.

ii. This section is always required.

I. **OPTIMIZE:**

i. Specifies the reservoir optimization problem

ii. This section is optional (not used for this work)

The files must be specified in the data Manager in the order given above. When these data are inputted the eclipse template permits construction for the required properties by applying substantial information in respective sections of the data manager module.

The Data Manager ensures a user-friendly access to the keywords for all the simulators, and to some basic features of FloGrid, Schedule, Special Core Analysis (SCAL) and PVT. In the ECLIPSE workflow using Office, the data manager can be further segmented into seven (7) they are; Case definition, Grid, PVT, SCAL, Initialization, Schedule, and Summary.

1. **Case Definition:** The Case Definition Section allows you to select the important options for the case, such as; case title, date production commenced, etc. It is similar to the RUNSPEC section of the simulators, except that it does not require input of table dimensions as these are calculated by ECLIPSE Office.

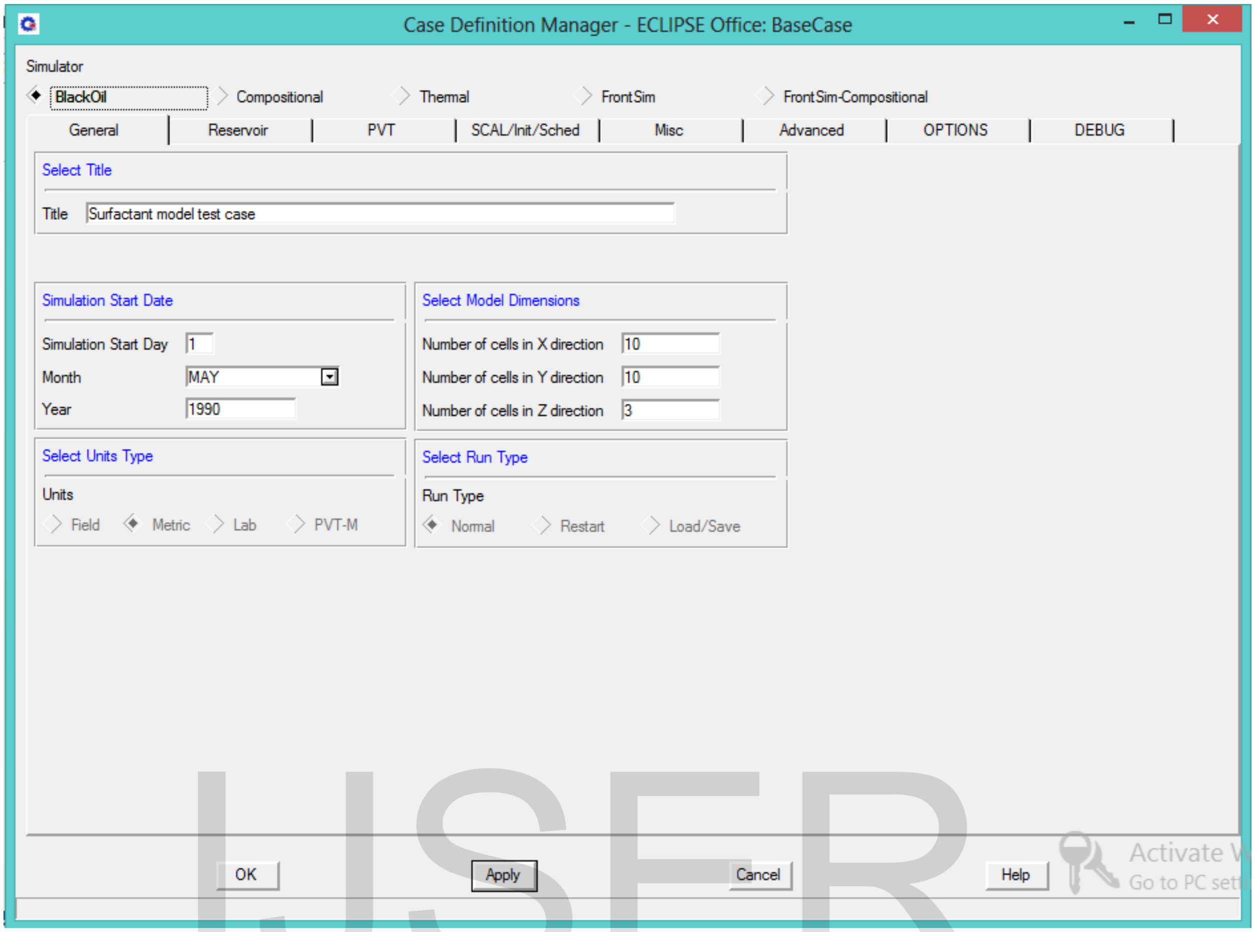

Figure 3.2: Case definition manager

2. **Grid section:** The Grid section allows the importation of the grid and its properties generated by FloGrid and GRID (usually developed in a static model). This section permits access to the GRID and EDIT keywords where data can be edited. Region keywords relating to the Grid Section are also accessed here, that is Fluid-in-Place (FIPNUM), and others such as FLUXNUM, FIPXXX, etc. The Grid Section also offers the capability of looking at grid block properties on the simulation grid in either 2D or 3D. The simulation grid can be generated either by reading an existing GRID file, running the simulator, or creating it from the keywords. In addition, properties, such as porosity (PORO), can be viewed in either a 2D Viewer or a 3D Viewer.

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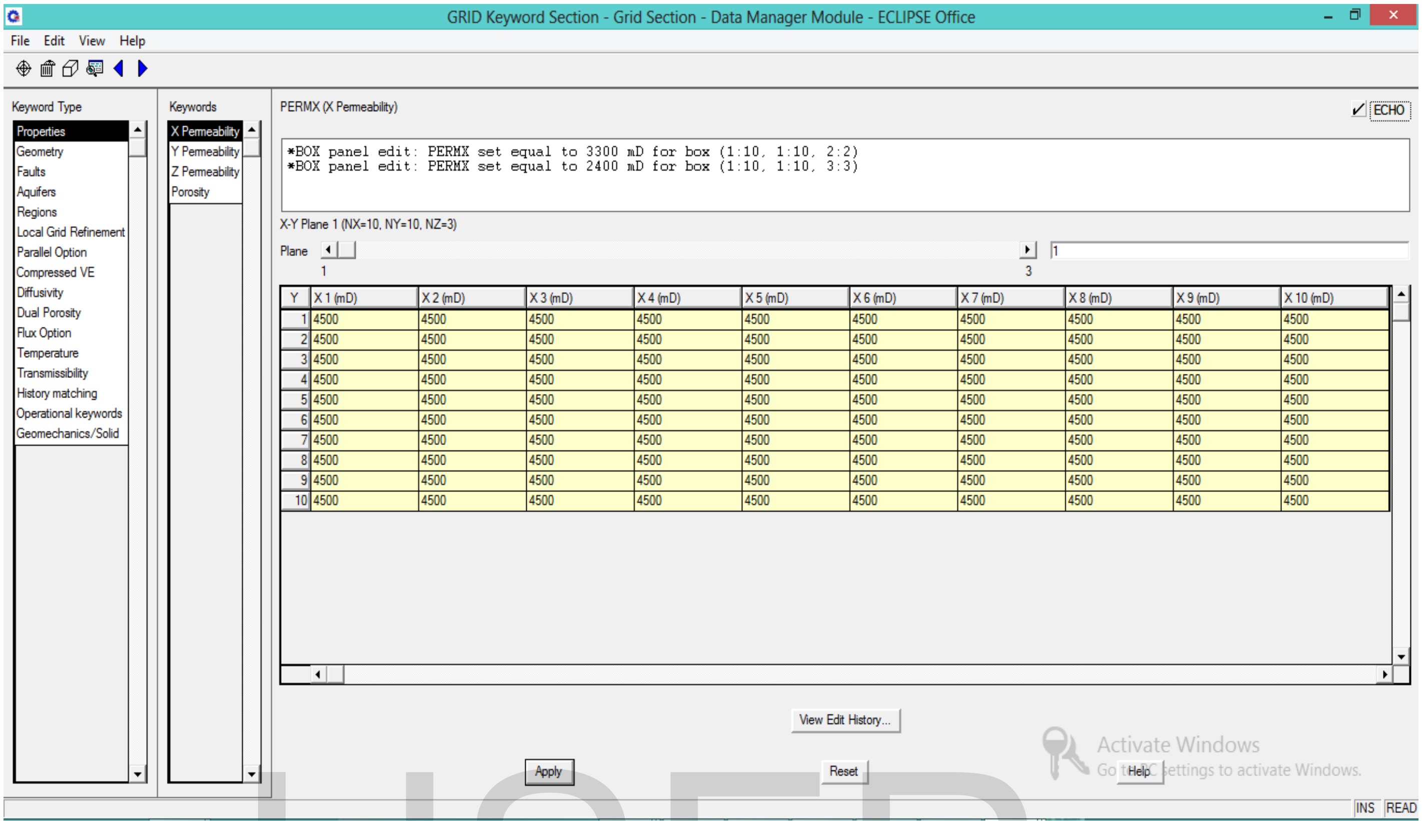

Figure 3.3: Grid section manager

3. **Pressure-Volume-Temperature (PVT) Section:** Basically, this is the section where the fluid properties are inputted in order to define the fluid. In other words, it provides access to the PVT keywords of the simulator PROPS section. Data can be imported from INCLUDE files generated by PVTi. Region keywords relating to the PVT Section can be accessed here, such as PVT Regions (PVTNUM) and others. Also, Region data can be displayed on a simulation grid in either 2D or 3D. In the 2D Viewer the data can be edited. Note; no graphical editing of the data is allowed.

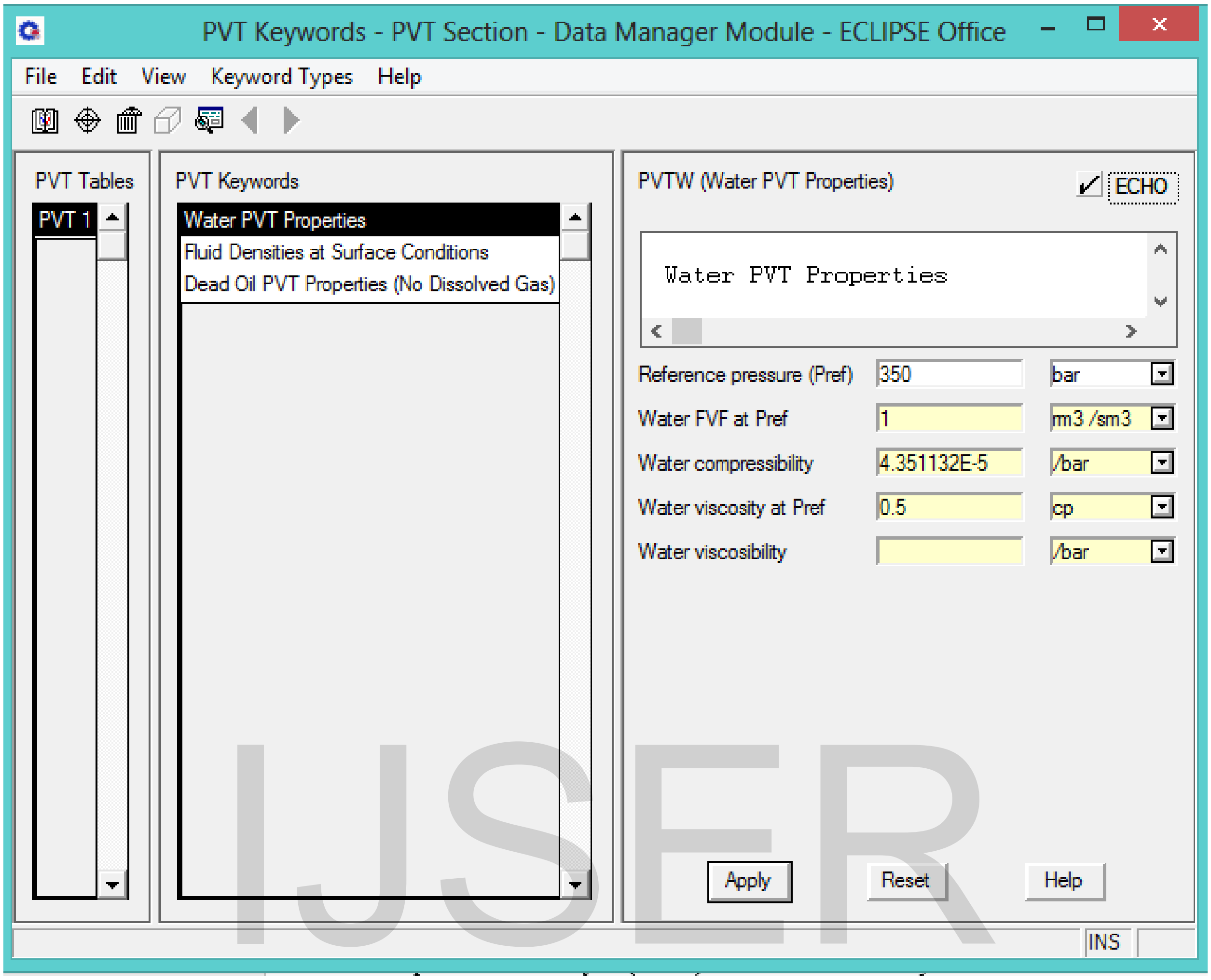

Figure 3.4: PVT section manager

4. **Special Core Analysis (SCAL) Section:** SCAL is very much different from the routine core analysis. In SCAL, a wireline tool is lowered to obtain a relatively bulk portion of the formation, then air, water, etc. is allowed to flow through the formation depending on what property is to be obtained. The SCAL Section gives access to the SCAL keywords of the simulator PROPS section. Data can be imported from INCLUDE files generated by the SCAL program. Keywords can be generated through the Corey correlation. Region keywords relating to the SCAL Section are also accessed here, for example Saturation Regions (SATNUM). Also, Region data and grid block properties can be displayed on a simulation grid in either 2D or 3D. In the 2D Viewer the data can be edited. Note; no graphical editing of the data is allowed.

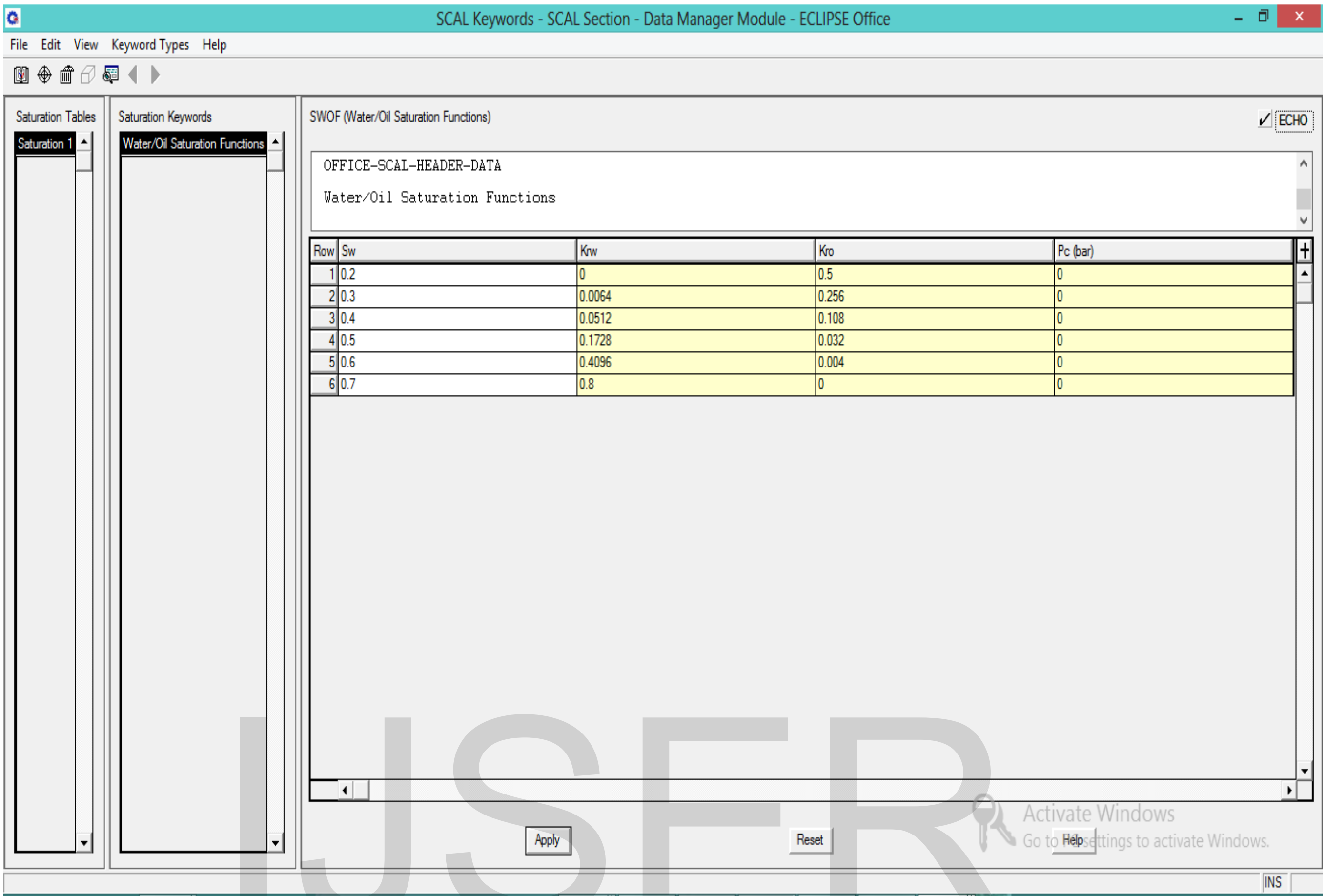

Figure 3.5: SCAL section manager

5. **Initialization Section:** The "Initialization section" is an imperative section in the ECLIPSE workflow that helps to compute the reservoir dynamic volume of hydrocarbons originally present in the reservoir. This section gives access to the SOLUTION keywords of the simulator. Region keywords relating to the Initialization Section, or equilibration regions, for example EQLNUM, are also accessed here. The model can also be initialized by running the simulator, when the simulation run is finished the initial solutions are available in the 2D and 3D Viewers. A tabular display of the Fluid-in-place reports is also available at the end of the simulation run, this reports are usually compared to the estimated static reservoir volume to check for significant disparities.

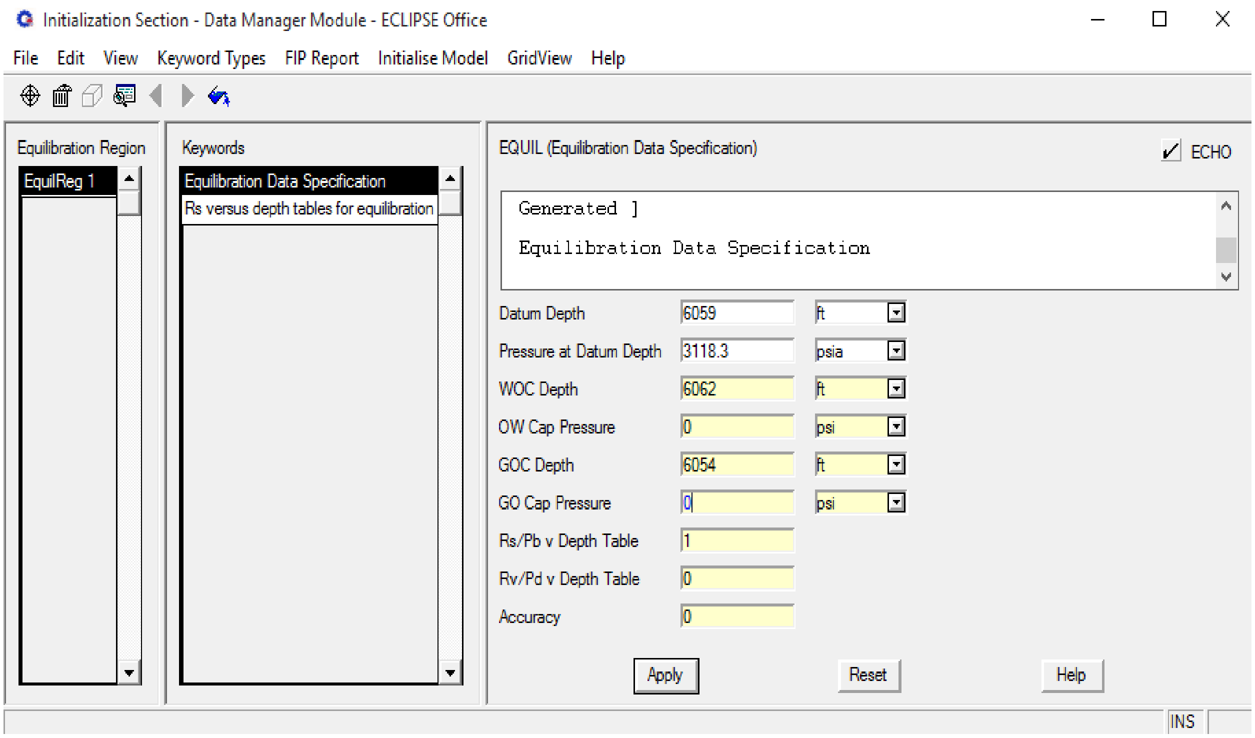

Figure 3.6: Initialization section manger

6. **Regions section:** The Regions Section gives you access to the REGIONS keywords of the simulator. Region data and grid block properties can be displayed on a simulation grid in either 2D or 3D. The simulation grid can be generated by either reading an existing GRID file, or by running the simulator.

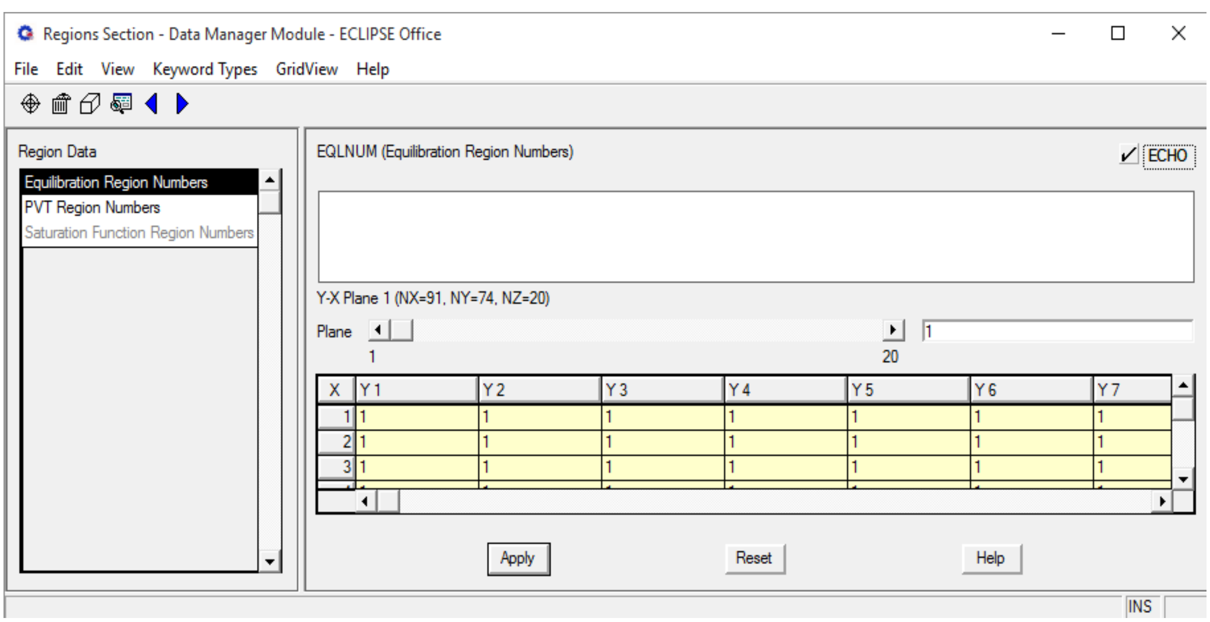

Figure 3.7: Regions section manager

7. **Schedule Section:** This section avails access to the SCHEDULE keywords of the simulator. Data can be imported from INCLUDE files generated by the Schedule program. Time steps and keywords can be viewed, edited, inserted and deleted. The schedule facility enables multiple sensitivities to be run from a single case. These keywords are the well and group production/injection rates, economic limits and well completions, well completion specification data, etc. basically, this section helps to combine the production history and events that previously occurred in the reservoir. It also aids in carrying out production forecast.

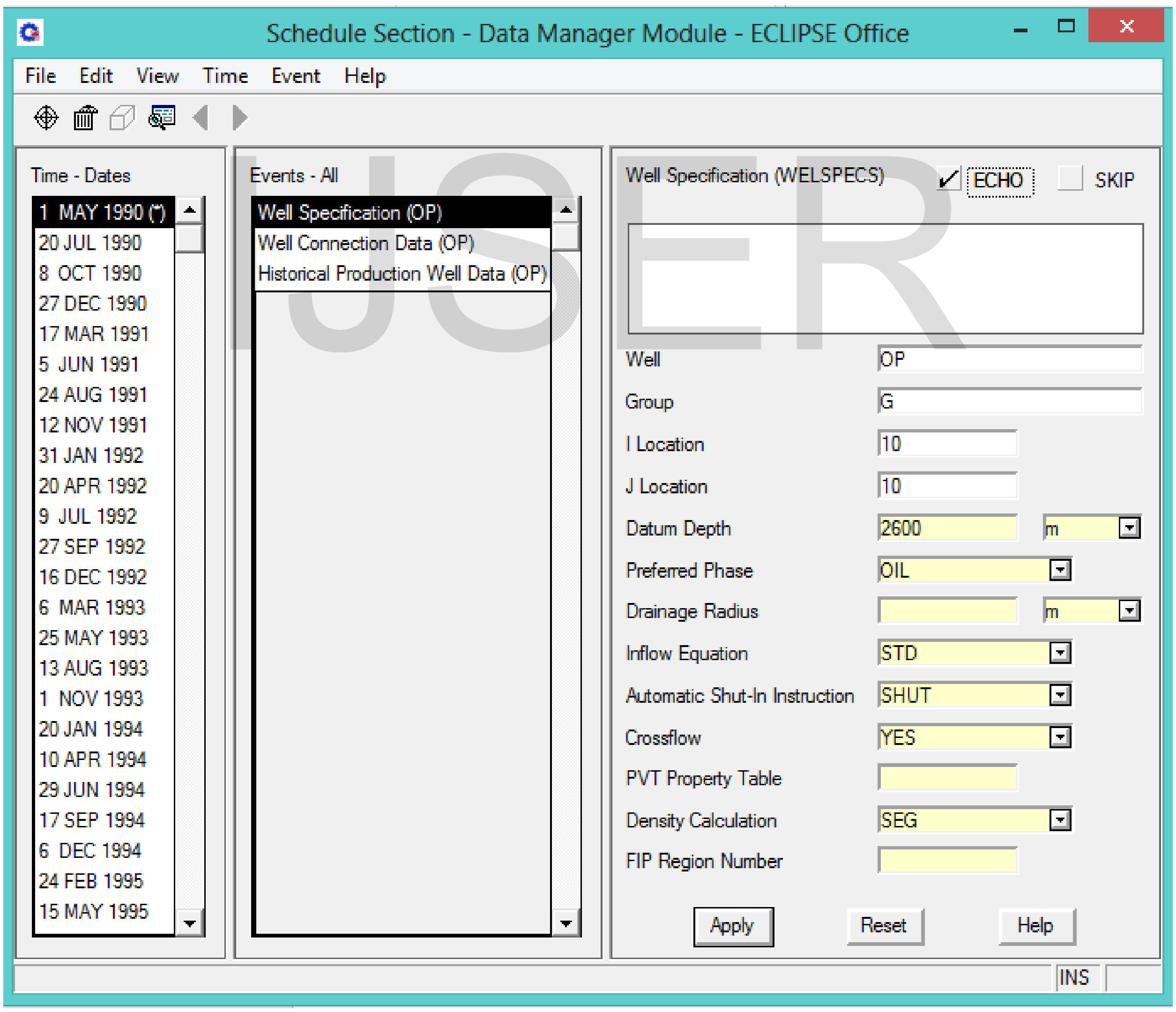

Figure 3.8: Schedule section manager

8. **Summary Section:** The "Summary Section" gives access to the SUMMARY keywords of the simulator. All possible output vectors are organized and displayed, thereby permitting the selection of the required vectors by use of the mouse.

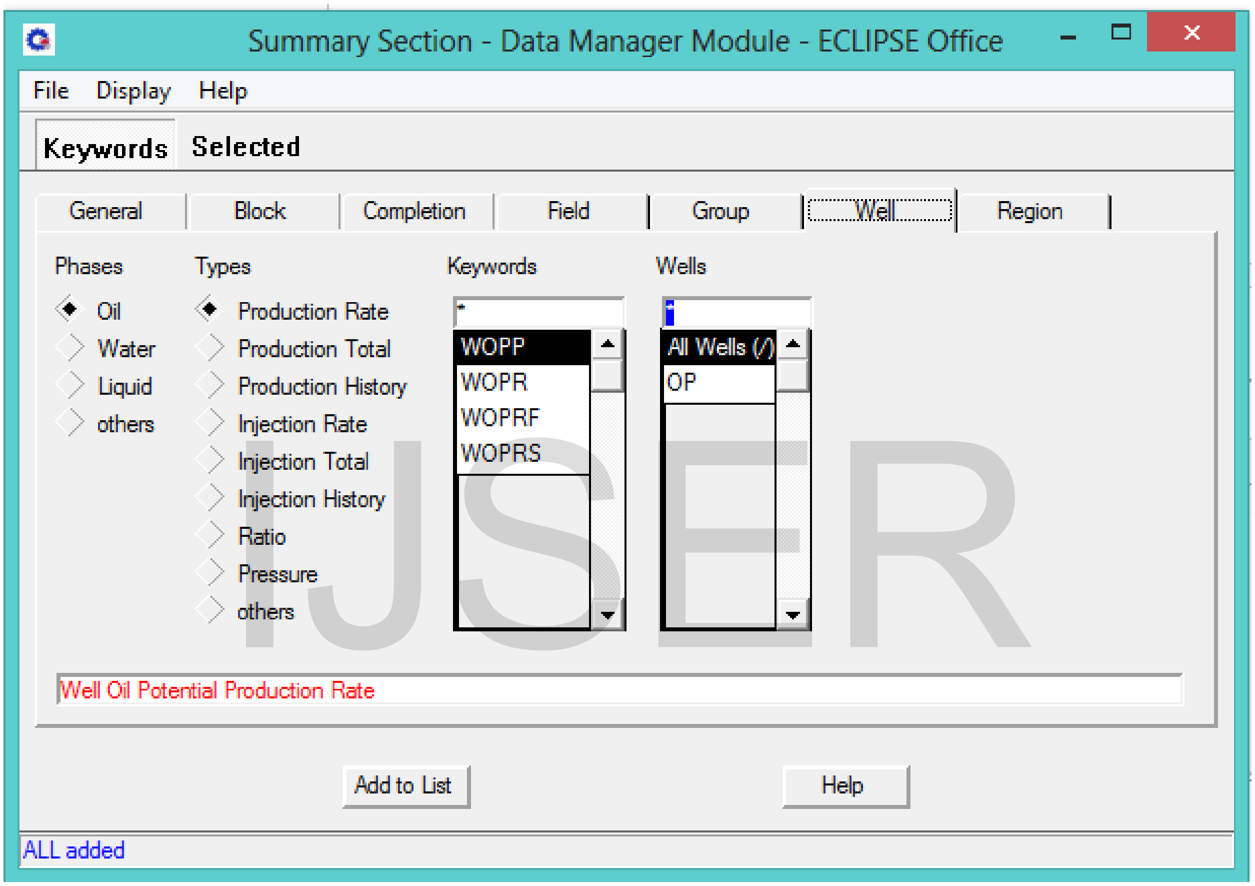

Figure 3.9: Summary section manager

3.3.3 Run manager

The "Run Manager" provides a suitable environment for launching, monitoring and controlling simulation runs. Runs may be started locally or over the network on a server. Multiple realizations generated for well control options and multiple cases may be run simultaneously. Using the Run Manager, it is possible to monitor the progress of runs on line plots and solution displays, and if they are not delivering the required results, the runs can be stopped. Then, proper checks can be made to determine the cause of obtaining undesirable results.

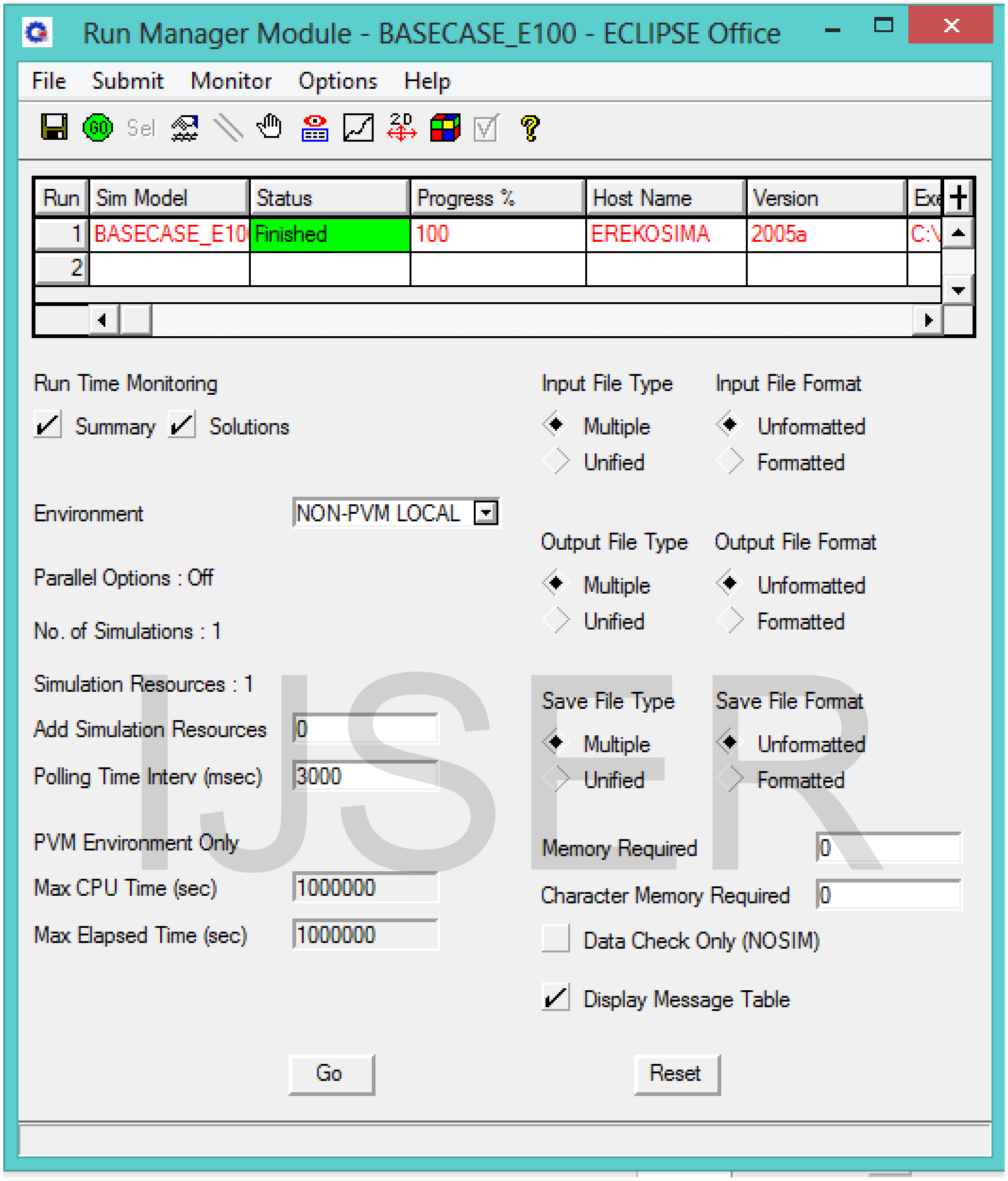

Figure 3.10: Run manager module

3.3.4 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 as a replacement for graphical illustrations. Results from multiple runs can also be displayed simultaneously for comparative purposes and as an aid to make quick and precise decisions.

3.3.5 Report generator

The "Report Generator" is used to create reports from the extraction of relevant information from the SUMMARY files or from the print (PRT) file generated by the simulator, and put them in a form required for the creation of written reports. A list of all reports available is presented for each report step, from which selections may be extracted. The extracted reports are displayed in the output window and saved to file. ERRORS, BUGS, WARNINGS, COMMENTS, MESSAGES, STEPS and PROBLEMS output by the simulator can also be viewed. The Report Generator also has the ability to interpolate summary vectors output from the simulator. The output is in the form of a table that can be exported to a file or the clipboard (on PC) for input into a spreadsheet.

3.4 IMPES method

We can trace the origin of the *Implicit Pressure, Explicit Saturation (IMPES)* method back to the works of Sheldon *et al.*, (1959), and Stone and Gardner (1961). For the IMPES formulation, the flow equations are combined to eliminate unknown saturations, thereby generating a single pressure equation. The pressure equation is solved implicitly for pressures at each gridblock at the current timestep designated as n+1, using parameters at the previous timestep designated as n. This is then followed by the explicit substitution of the pressures into the corresponding flow equations, to calculate saturations at the current timestep, (n+1), for each gridblock. The advantages of the IMPES method are that it requires less computing time per time step and less computer memory for storage (Okereke, 2017). The main disadvantage of the IMPES method is that it is relatively unstable at large time steps. There are techniques for improving the stability of the IMPES method as reported by (Coats, 2003). To improve the stability of IMPES formulations, (Macdonald, 1970) introduced a modification to the IMPES formulation which was later named the Sequential method by Spillete *et al.,* 2003 The basic strategy of this method is to obtain a single equation in which the sole unknown is the pressure of one of the phases. We achieve this by combining the partial differential equations for each phase in such a way as to eliminate the saturation derivatives. Furthermore, we assume capillary pressure to be constant during any time step. By so doing, we obtain just one partial differential equation, with a phase pressure as the only unknown (this is usually the water-phase pressure).

After writing the finite-difference approximation to this partial differential equation, we obtain the appropriate characteristic equation. When we apply this characteristic equation at the grid nodes, we generate a system of linear algebraic equations. The coefficients appearing in this system of equations are functions of the pressures and saturations; therefore, they are estimated using the information available at the previous iteration level. At any iteration level, when solution for the phase pressure (e.g., Pw) distribution is obtained, the next step is to solve explicitly for that phase saturation distribution, Sw from the partial differential equation describing the flow of that phase. At this stage, we know the Pw and Sw distributions. This enables us to determine the oil phase pressure distribution using the capillary pressure relationship between the oil and water phases. Similar to the determination of Sw, after obtaining the Pw distribution, we explicitly solve the oil-phase partial differential equation for the oil phase saturation, S_o. With the values of S_o and S_w calculated, we can easily determine Sg (Sg = 1 - So - Sw). Finally, using the capillary pressure relationship between the oil and gas phases, we obtain the gas phase pressure (Pg) distribution. This completes one iteration; we then repeat the whole procedure until we achieve convergence. At the beginning of each iteration, all the pressure and saturation dependent terms are updated using the most recent information available. Figure 3.2 is a flow chart highlighting the major steps involved in the IMPES method.

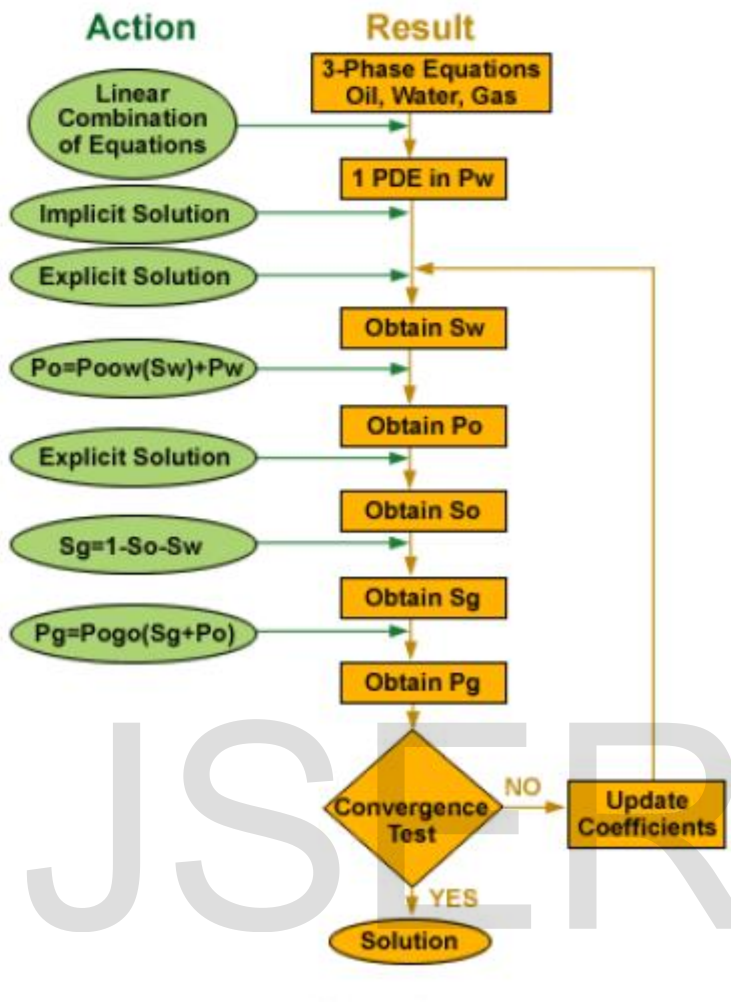

Figure 3.11: Steps involved in IMPES method.

3.4.1 Fully Implicit Solution with Newtonian iteration

In the *Fully Implicit Solution with Newtonian iteration* method, we reduce the six principal unknowns of the three-phase flow equations to three linearly independent principal unknowns (most often one phase pressure and two saturations) by using the capillary pressure and saturation relationships. We then use finite-differences to approximate the three partial differential equations that result.

By treating the coefficients implicitly (at the same level as the principal unknowns) we generate a system of non-linear algebraic equations. We can linearize these equations using the generalized Newton-Raphson procedure, such that we can implement a Newtonian iteration. In the solution process, a residual function is formed and its derivative calculated with respect to each principal unknown to construct the Jacobian. We then use a numerical differentiation scheme to obtain the elements of the Jacobian matrix.

3.5 Mechanism of Low Salinity Water Flooding

Low salinity water flooding is an incremental oil recovery technique used to inject low salinity water floods to alter the wettability or migrate the fines from the reservoir in order to reduce the residual oil saturation and hence increase the amount of oil produced from the reservoir. Low salinity water floods damages the permeability in the water swept zones to control the mobility of the injected flood (fines assisted). Whereas they also alter the wettability of the rock by desorption/absorption of ions and make it more water wet from oil wet, in order to release the trapped oil and thus increase recovery.

When a reservoir is subjected to water flood of very low salinity water, the reservoir fines become mobilized and migrates. These migrated fines or solid particles can clog pore throats, and as a result would cause hindrance for fluid to flow through those pore throats, therefore decreasing the permeability in the clogged throats. The reduction in phenomenon is intentionally avoided in oil and gas recovery practice as it damage the permeability and hence reduction in permeability translates into reduction in productivity from reservoir wells.

3.5.1 Rock Migration and Permeability Damage Mathematical Model

The fine particle is subjected to many forces which causes it to detach from the rock, become mobile and therefore migrate with the flood. These forces are lift (Fl), drag (Fd), electrostatic (Fe) and gravitational (Fg). The force and torque balances were applied on these particles by (Freitas *et al.*, 2001; Bradford *et al.*, 2011). The resulting equation is as follows.

$$6_a = 6_{cr}(\varepsilon), \qquad \varepsilon = \frac{\left(\frac{Id}{In}\right) Fd(U) + Fl(U)}{Fe + Fg}$$

Here ε, σ_a, σ_{cr}, Id, In and U corresponds to erosion number (torque ratio), volumetric concentration of attached particles, maximum volumetric concentration of captured particles, drag force lever, normal force lever and overall flow velocity respectively.

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The decreased permeability or permeability damage is given by;

$$K(6_S) = \frac{K_O}{1 + \beta 6_S}$$

Where k,6_S, K_o and β, corresponds to absolute permeability, volumetric concentration of strained particles, initial absolute permeability and formation damage coefficient respectively (Pang *et al.*, 1997).

3.5.2. Oil and Low Salinity Water Diffusivity Model

The mathematical model consists of equations for volumetric balance of two phase flux. It assumes the phases to be incompressible, and modifies the traditional flow equations of two phase including the capillary effects.

$$\boldsymbol{\nabla(U) = 0}$$

The water volumetric balance is given as follows:

$$\frac{\partial[(\emptyset - 6_a - 6_S)S]}{\partial t} + \mathrm{U}\nabla f(S, 6_S) = -\frac{K6_{wo}\, cos\theta}{\sqrt{\frac{K}{\emptyset}}}\nabla\left(\frac{fK_{ro}(S)}{\mu_O}\nabla J(S)\right)$$

$$f\,(\mathrm{S}, 6_S) = [1 + \frac{K_{ro}(S)\mu_w(1+\beta 6_S)}{K_{rw}(S)\mu_o}]^{-1}, P_c(S) = \frac{6_{wo}\, cos\theta}{\sqrt{\frac{K}{\emptyset}}}\,\mathrm{J(S)}$$

Where Ø, kro, krw, μ*o*, c*os*θ, S, Pc, Ϭ and f are porosity, relative permeability of oil, relative permeability of water, oil viscosity, wettability index, water saturation, capillary pressure, water oil surface tension and fractional flow of water respectively. The mass balance for the particles is given by the following governing equation;

$$\frac{\partial[(\emptyset - 6_a - 6_S)Sc + 6_a + 6_S]}{\partial t} + \mathrm{U}\nabla(cf) = -\frac{K6_{wo}\, cos\theta}{\sqrt{\frac{K}{\emptyset}}}\nabla\left(c\frac{fK_{ro}(S)}{\mu_O}\nabla J(S)\right) - \nabla(Ds\nabla c)$$

Where c and D corresponds to concentration of suspended particles and diffusion coefficient respectively.

The maximum retention function is given by the following equation.

$$6_a(U_W, \Upsilon, S) = \frac{A_W(S,\Upsilon) + 6_{a0}[A - A_W(S,\Upsilon)]}{A}$$

$U_w = (U\, f(S, 6_S))/(S(\emptyset - 6_a - 6_S))$

Where γ, A and Aw corresponds to brine ionic strength, area and fraction of rock surface exposed to water.

The kinetics of fines straining is modelled as follows:

$$\frac{\partial 6_S}{\partial t} = \lambda_S C \frac{f}{S}$$

Where λs is the filtration coefficient for straining.

The mass balance of salt is given by:

$$\frac{\partial[(\emptyset - 6_a - 6_S)S\Upsilon]}{\partial t} + \nabla[\Upsilon f(S, 6_S)U] = -\frac{K6_{wo}\, cos\theta}{\sqrt{\frac{K}{\emptyset}}} \nabla \left(\Upsilon \frac{f K_{ro}(S)}{\mu_O} \nabla J(S)\right) - \nabla(Ds\nabla\Upsilon)$$

The Darcy's Law is modified for the model as follows:

$$U = -K \left[\frac{K_{rw}(S)}{\mu_w(1+\beta 6_S} + \frac{K_{r0}(S)}{\mu_o}\right] \nabla_P$$

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Model Description

Fines assisted waterflooding is a relatively new technique and although some laboratory experimentation validates the concept, it lacks the conclusive evidences. As a result, no commercially available simulation package support this model till date. Moreover, the laboratory experimentation is based on 1-D core flood and, therefore, it is necessary to confirm the results by running a 3-D numerical reservoir simulation model.

In order to model this concept on commercially available simulators, fines assisted water flooding model can be related to polymer flooding model (Zeinijahromi *et al.*, 2014), as both the models work on the principle of permeability reduction in the water swept zone. However, it is necessary to modify certain equations as both the models differs in certain aspects.

Eclipse is a commercially available reservoir simulator which has an in built feature for wettability altered low salinity water (LSW) flooding, but due to the reasons discussed above, it lacks fines assisted features. The available polymer flooding model for Eclipse can be used for this purpose. Table 4.1 summarizes the keywords used in Eclipse for polymer flooding.

Table 4.1: Polymer Flooding Keywords Used in Eclipse

SECTION	KEYWORDS
RUNSPEC	POLYMER
PROPS	PLYADS PLYSHEAR PLYVISC PLYROCK PLMIXPAR PLYMAX

SCHEDULE	WPOLYMER

The polymer flooding keywords mentioned in the table above must be assigned appropriate values in order to adapt and behave as a waterflood model.

Polymer adsorbs onto the rocks and gets lost, this is not the case in fines assisted water flooding, and hence the adsorption is considered to be negligible in the model. Therefore PLYADS keyword was modified to make adsorption equal to zero.

Shear-thinning occurs in polymers and there viscosity reduces, but in fines assisted water flooding, the velocity change is almost negligible therefore the PLYSHEAR keyword is assigned a constant value which serves the purpose for this case.

Hussain *et al.*, 2013 conducted some experiments on sandstone core plugs and tabulated the data, which showed that by the injection of water floods of varying salinities, viscosity changes slightly. PLYVISC keyword is, therefore, assigned values for this purpose. It must be noted, however, that the PLYVISC keyword has a condition that the concentrations and viscosities must increase monotonically down the column which is obvious in the case of polymer flooding, where the sole purpose is to increase the viscosity of the flood by increasing the polymer concentration in order to induce damage to the formation. This limitation has been dealt with by making an assumption that by injecting the water floods of increased salinity, the viscosity of the waterflood will increase thereby increasing the oil recovery. This would mean that a low salinity water flood should decrease the viscosity and consequently increase oil recovery. This assumption is made just to deal with the limitation of Eclipse keyword PLYVISC.

Inaccessible Pore Volume (IPV), resistance factor and residual resistance factors are important features of polymer flooding, and are catered for in the keyword PLYROCK. For our case, we have assigned this keyword assumed constant values. Similar approach has been used for the keyword PLMIXPAR. The actual values can be assigned by history matching, but the sole purpose here is just to use polymer flooding model for fines assisted water flooding. A maximum salinity value has been assigned to PLYMAX keyword at maximum concentration.

It must be noted here that salinity is used in terms of equivalent sodium chloride (NaCl) concentrations, as there is limitation in Eclipse for multi-ion models to be used with POLYMER keyword. Similarly BRINE keyword is avoided and WATER keyword is used due to the limitations of Eclipse in handling salinity with polymer flooding. If BRINE keyword had been used, the keyword PLYVISC should have been replaced with PLYVISCS.

4.2 Eclipse Simulation Model

In order to run a 3D field scale reservoir simulation, a synthetic reservoir was assumed. The reservoir was assumed to have three layers with varying permeabilities. 10x10x3 grid was used in black-oil simulator with negligible capillary pressure. The flow rates of both the injection and production wells are set at 2600 m^3/d. Time for the simulation was set to a value of 80 steps of time, where each step was assumed to be 30 days each. The simulation was started in 1990. All the characteristics of the model has been summarised in the table 4.2 below:

Table 4.2: Eclipse Model Characteristics

	LAYER 1	**LAYER 2**	**LAYER 3**
Blocks	100	100	100
Reservoir Top Depth	2600m	2600m	2600m
Layer Depth	0.58m	0.84m	0.47m
Porosity	25%	25%	25%
Permeability X	4500md	3300md	2400md
Permeability Y	4500md	3300md	2400md
Permeability Z	1050md	1800md	500md

Table 4.3: PVT Properties (SI units)

PROPERTIES	**VALUES**
Initial water saturation	0.2
Residual Oil saturation	0.3
Krw_max	0.8
Kro_max	0.5

Water viscosity	0.88
Water density	998
Oil density	850
Water compressibility	3.6×10^{-5}
Reference Pressure	270

4.3 Results and Discussion

After conducting the numerical reservoir simulation using the data and the assumptions presented above, following results have been plotted, and their explanation has been provided with each outcome.

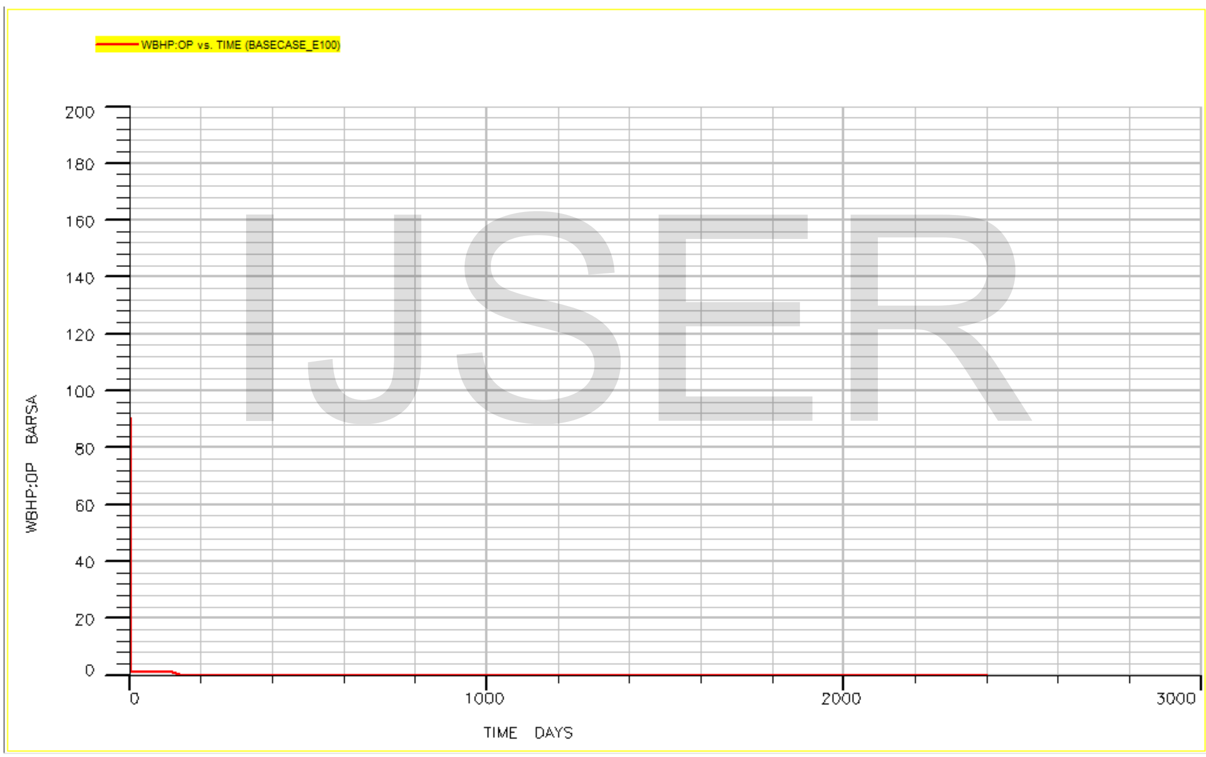

Figure 4.1a: Well Bottom Hole Pressure (bars) Production well vs time (days) without IOR

This plot (Figure 4.1a) above shows the depleting well bottom hole pressure before IOR flooding. At the initial base case when the well began to produce, there existed a flowing bottom hole pressure that depleted from about 90 psi down to 0 psi (where the reservoir lost its natural driving energy). At 0 psi, the bottom hole pressure began static thereby making the pressure equal to the hydrostatic pressure of the reservoir on the annular side. This plots indicates the incapability of the reservoir to produce effective and the need for improved oil recovery in order to boost production.

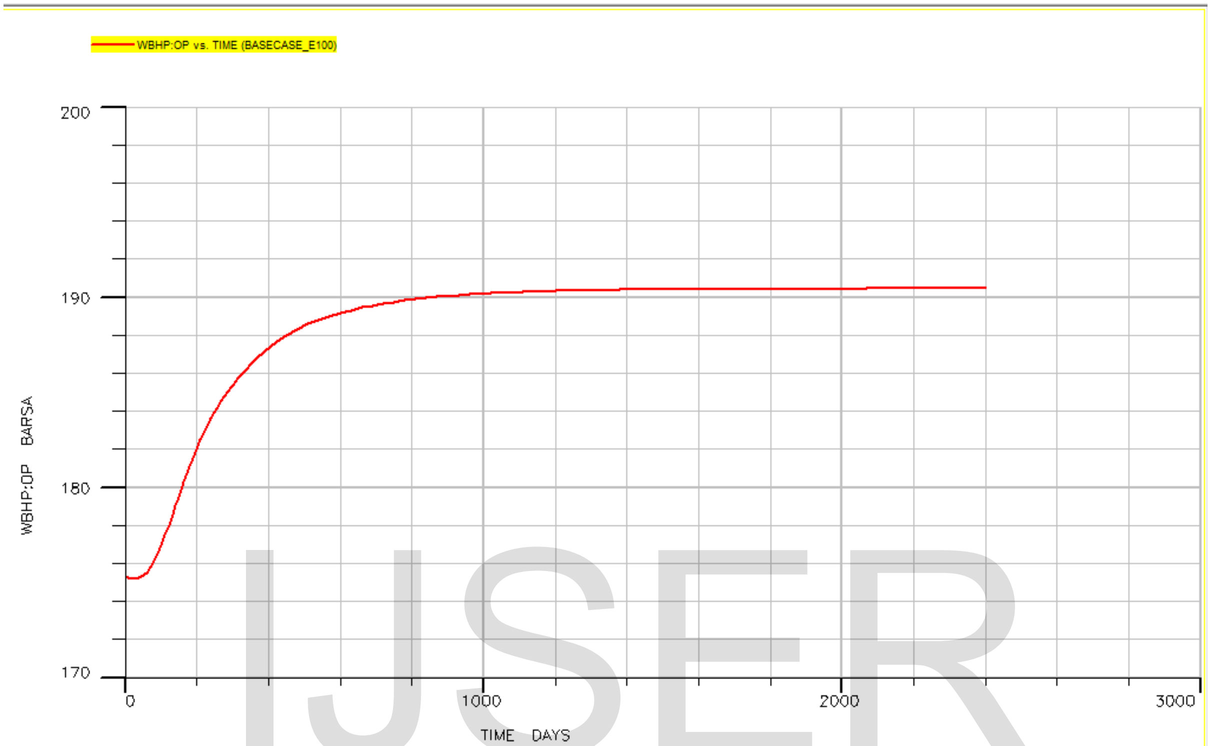

Figure 4.1b: Well Bottom Hole Pressure (bars) Production well vs time (days) with IOR

This plot (Figure 4.1b) above shows the very swift increase in the well bottom hole flowing pressure immediately the producing well is supported with an enhanced recovery technique. From Figure 4.1a, it was deduced that at a particular time in the reservoir the bottom hole pressure depleted to a dead pressure flow. This plot above indicates the increase in the flowing bottom hole pressure due to enhancement of the reservoir properties (like the reduction the viscosity of the crude etc.). Figure 4.1b shows that the reservoir increased from a dead pressure and gradually increased until it began to produce at a steady state where the bottom hole pressure produced linearly at 191 psi.

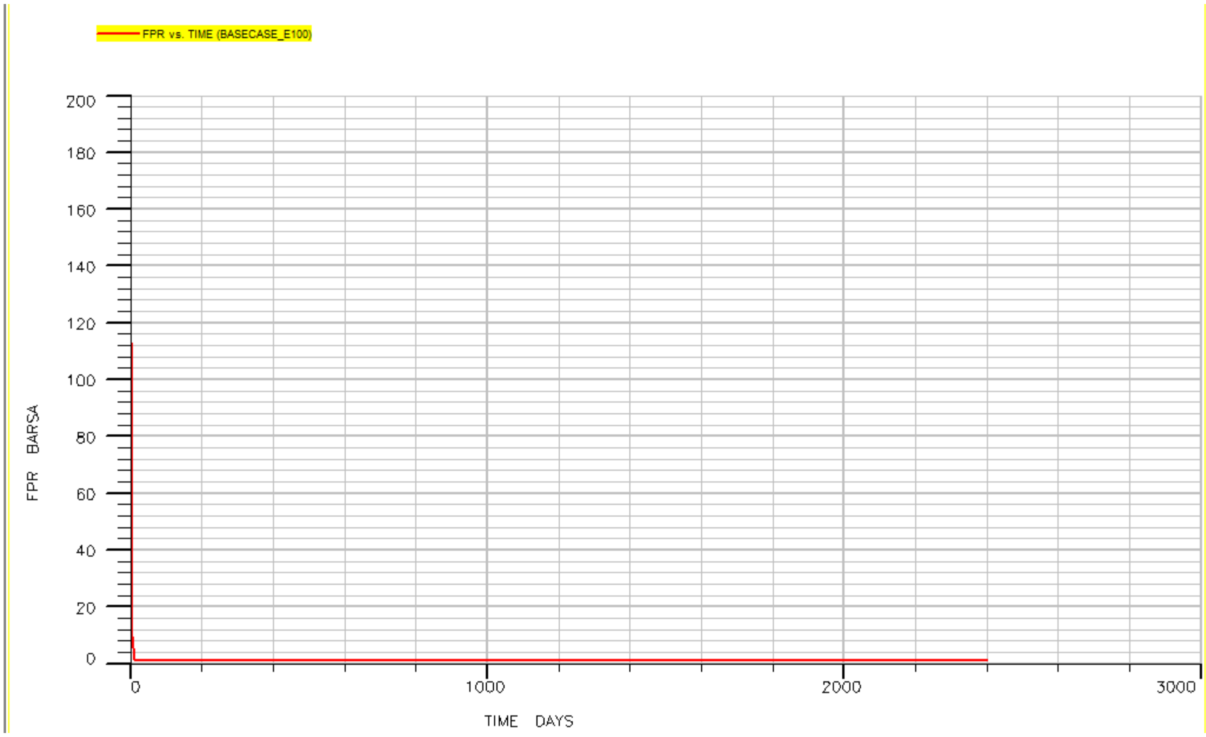

Figure 4.2a: Average Reservoir Pressure (bars) vs time (days) without IOR

Average reservoir pressure is a function of field production rate and time. It indicates how much fluid is remaining in the reservoir. At the initial production stage of the base case reservoir when no enhancement have been done to the reservoir, the average reservoir pressure indicates a drastic drawdown in the field from 120 psi down to zero (0) psi which indicates dead oil stage, where the amount of fluid remaining is not known due to lack of energy. Figure 4.2a indicates a drawdown period in the reservoir with no flow or fluid production over a period of time.

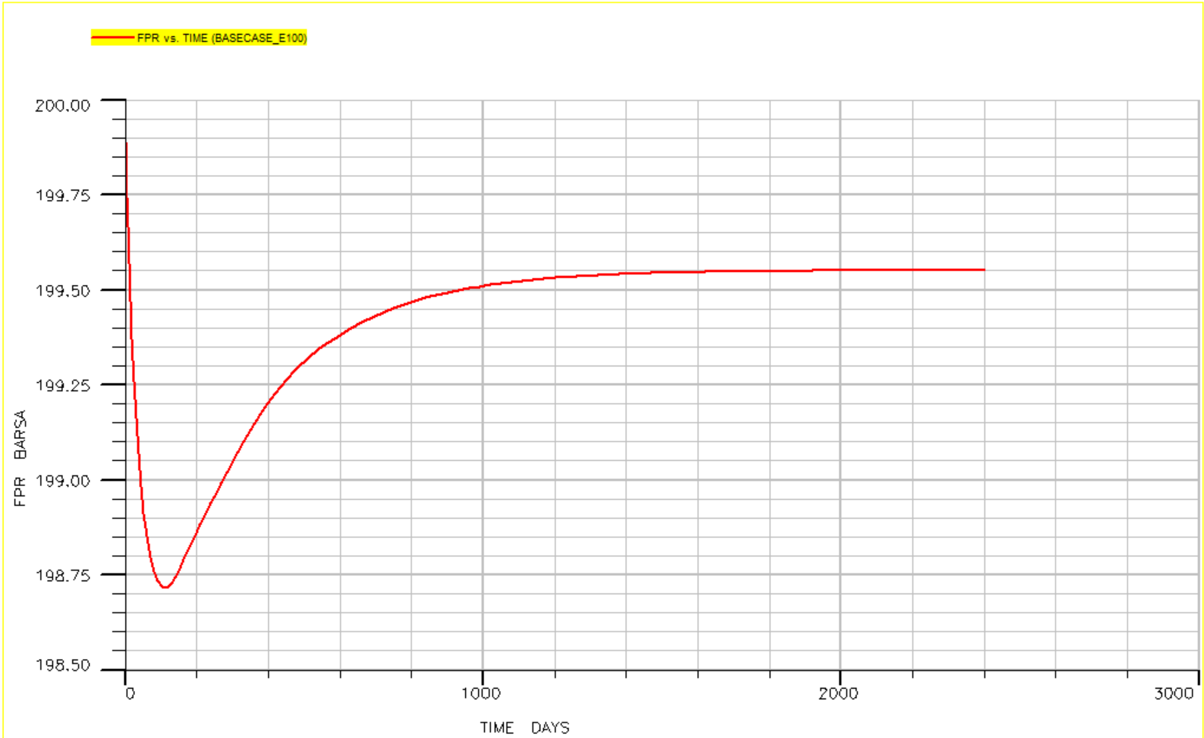

Figure 4.2b: Average Reservoir Pressure (bars) vs time (days) with IOR

After enhancement of the reservoir properties, there existed a sharp buildup in the average pressure of the reservoir. The average pressure increased until fluid production became linearly at 199.55 psi. This plot above signifies increase the total fluid production from the reservoir.

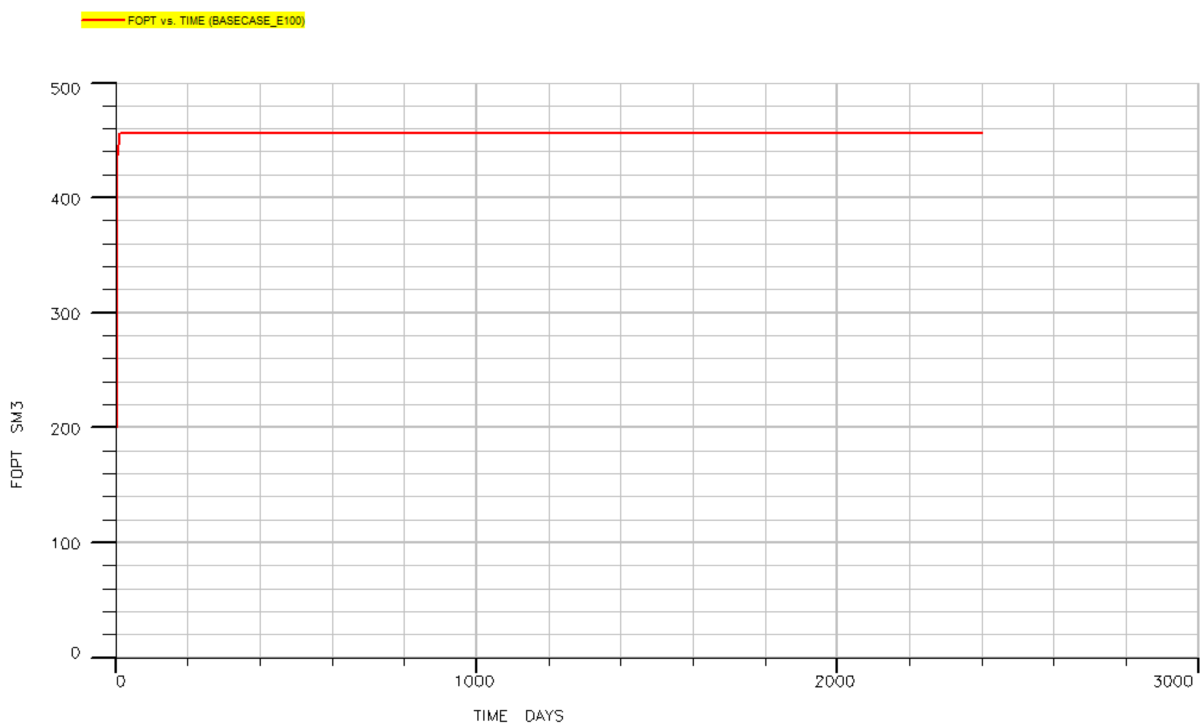

Figure 4.3a: Cumulative Oil Production (cubic meters) vs time (days) without IOR

Figure 4.3a indicates the rate of reservoir fluid produced over a period, and from the plot, it can be deduced that fluid production began initially at 200 sm^3/day, production increased until fluid were recovered linearly at 450 sm^3/day. The cumulative linearly production of fluid over a period of time is as a result of depletion in the bottom hole flowing pressure. Cumulative oil production rate is a function of bottom hole pressure, and since there exist a depletion in the bottom hole pressure, there would also be a gradual drop in the cumulative oil production as seen in figure 4.3a.

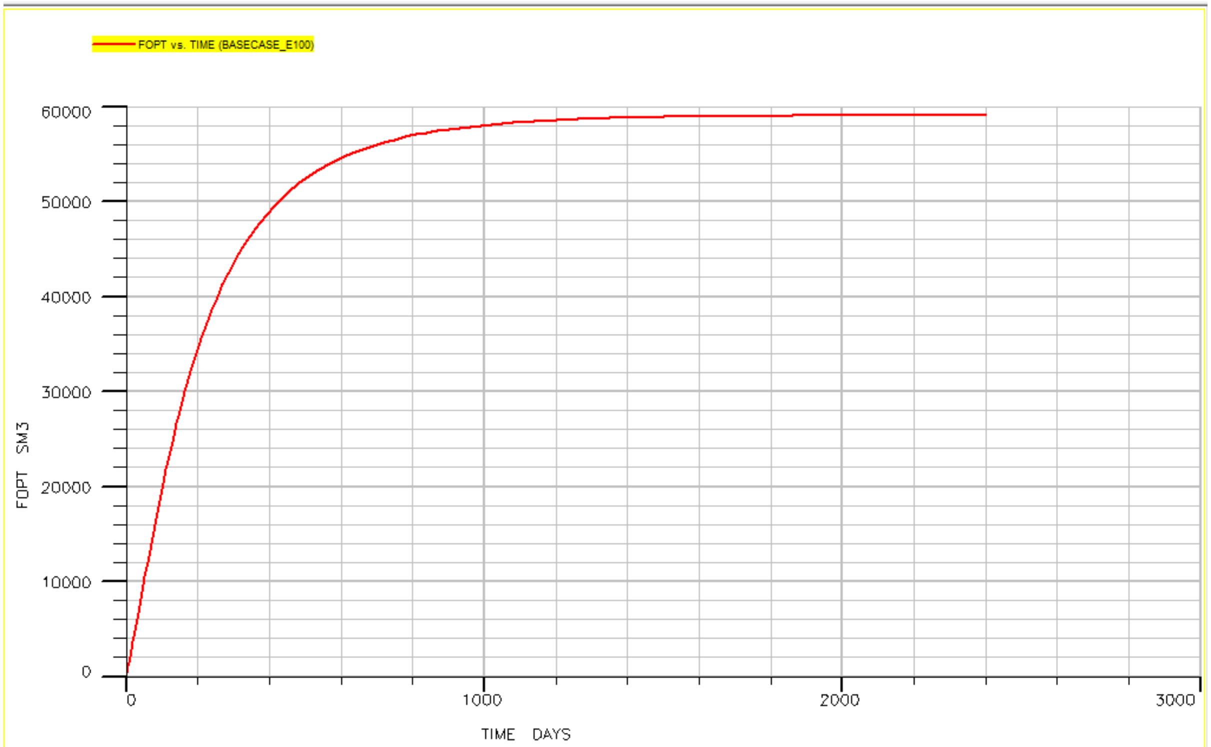

Figure 4.3b: Cumulative Oil Production (cubic meters) vs time (days) with IOR

In Figure 4.1b there was a drastic build-up the bottom hole flowing pressure due to enhancement of the reservoir properties and since cumulative oil production is a function of time, Figure 4.3b shows an equal increase in the volume of oil produced over time. From the plot, total oil produced from the reservoir increased from 0m^3 to 60,000 m^3.

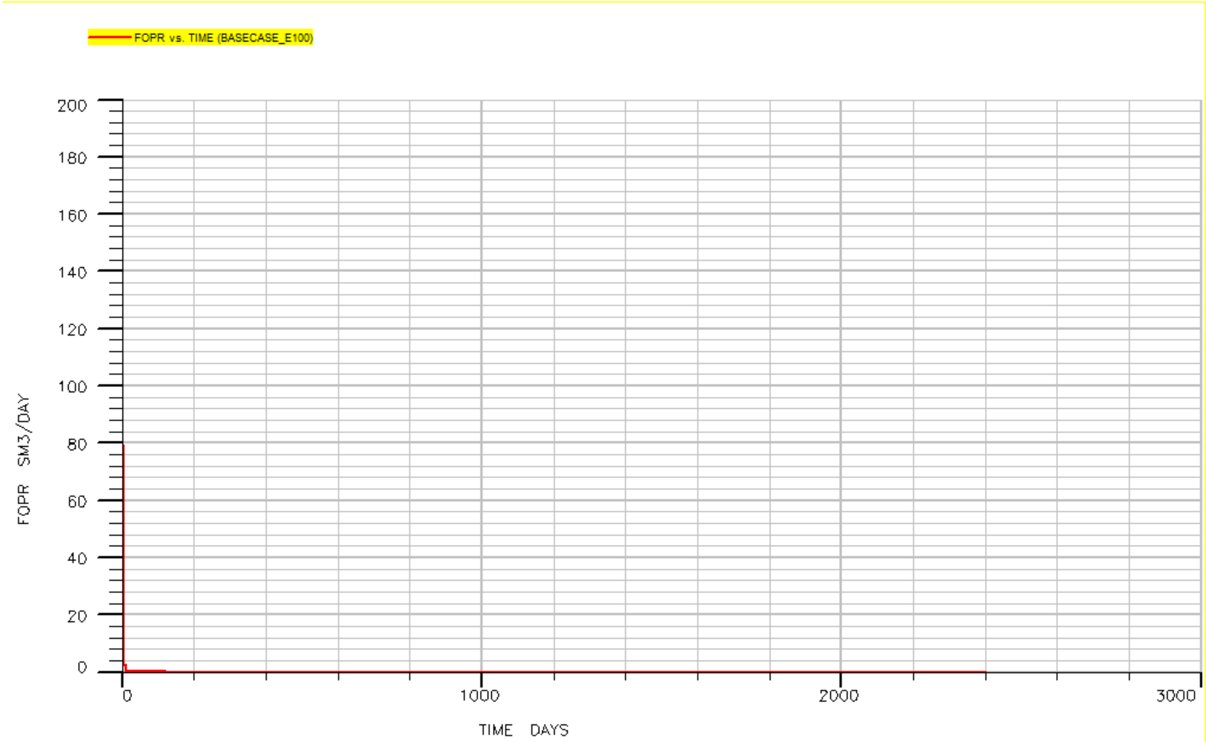

Figure 4.4a: Oil Production Rate (cubic meters per day) vs time (days) without IOR

Oil production rate is a function of time and bottom hole flowing pressure at a specified period of time. In Figure 4.1a, the plot indicates a drastic pressure drop over time in the reservoir which in turn leads to a drastic fall in oil production rate from 80 m^3/day to 0 m^3/day over time as seen in Figure 4.4a above.

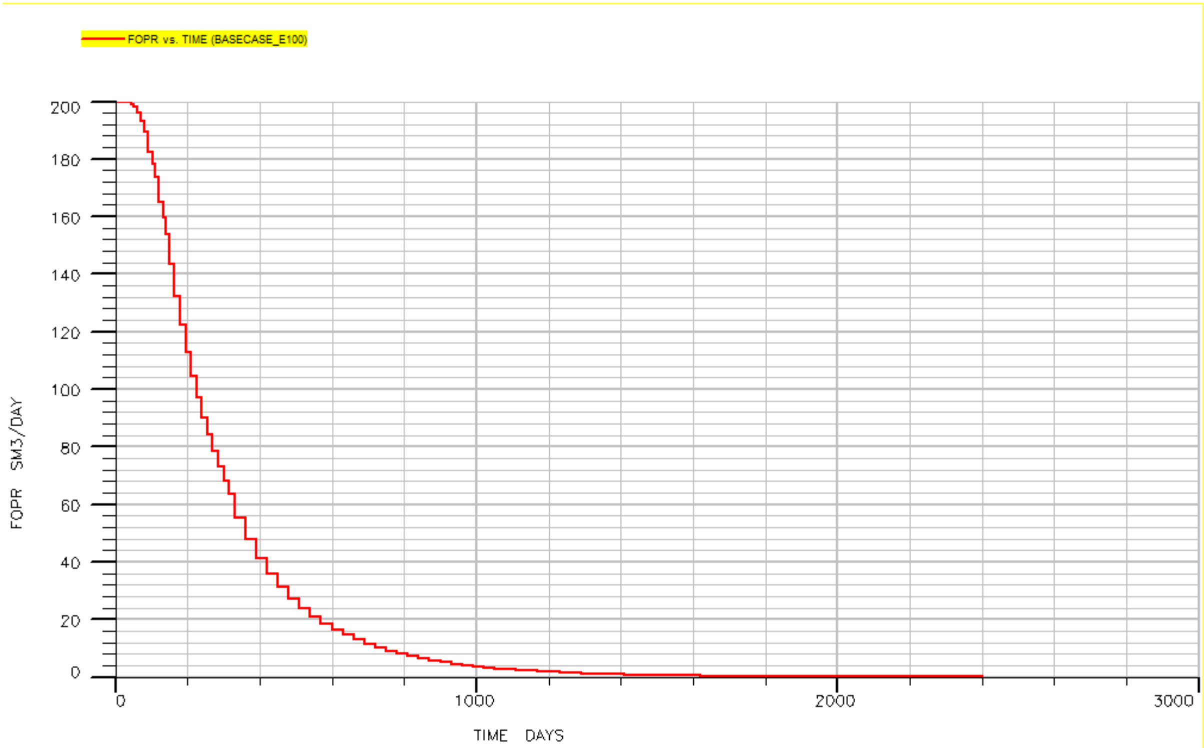

Figure 4.4b: Oil Production Rate (cubic meters per day) vs time (days) without IOR

Due to the increase in the bottom hole flowing pressure as seen in Figure 4.1b, that lead to a depletion in the volume of oil produced per day as seen in Figure 4.4a, the increase in bottom hole flowing pressure resulted to a sharp increase in the volume of oil produced over time.

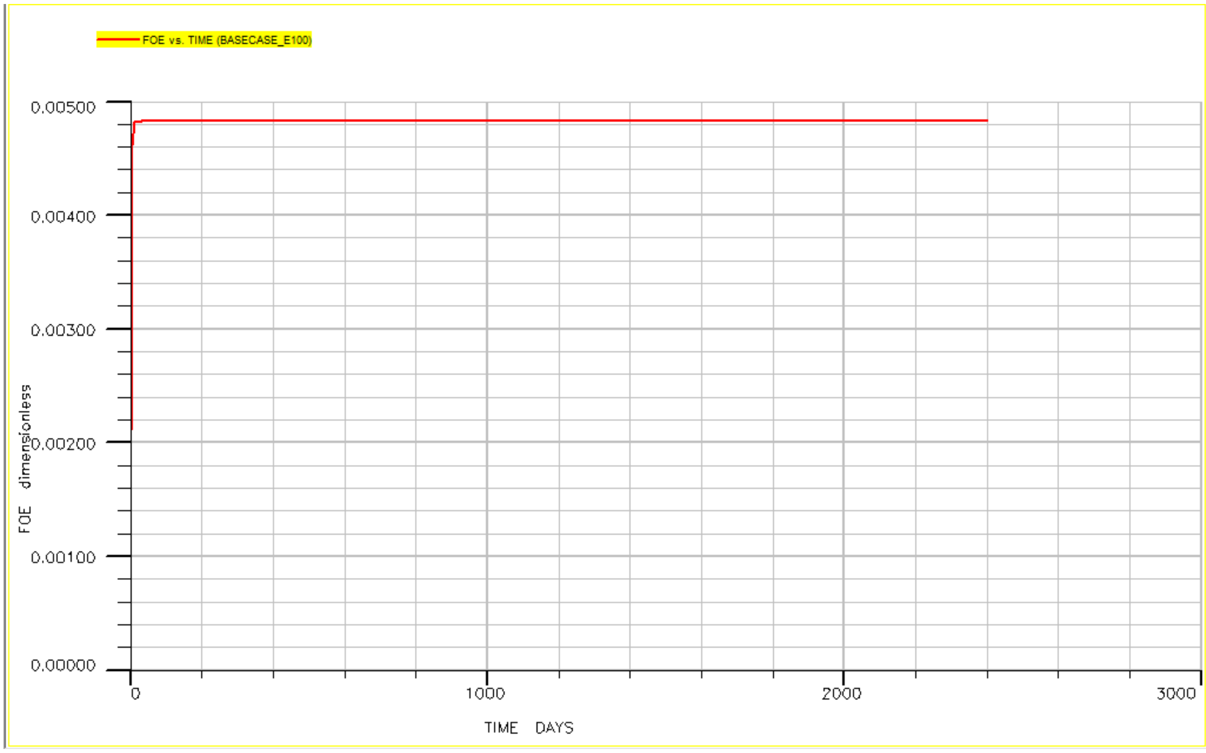

Figure 4.5a: Production to initial reserves (dimensionless) vs time (days) without IOR

This plot above explains the recovery factor of the reservoir. Recovery factor is the recoverable amount of hydrocarbon initially in place, normally expressed as a percentage. The recovery factor is a function of the displacement mechanism.

Due the drastic depletion in the reservoir and a sharp reduction in the oil produced, the recovery factor for this reservoir before it was enhanced shows a linear recovery factor. From the plot above it can be seen that the recovery factor rose from about 0.00200 to 0.004900 where it became constant over that period of time.

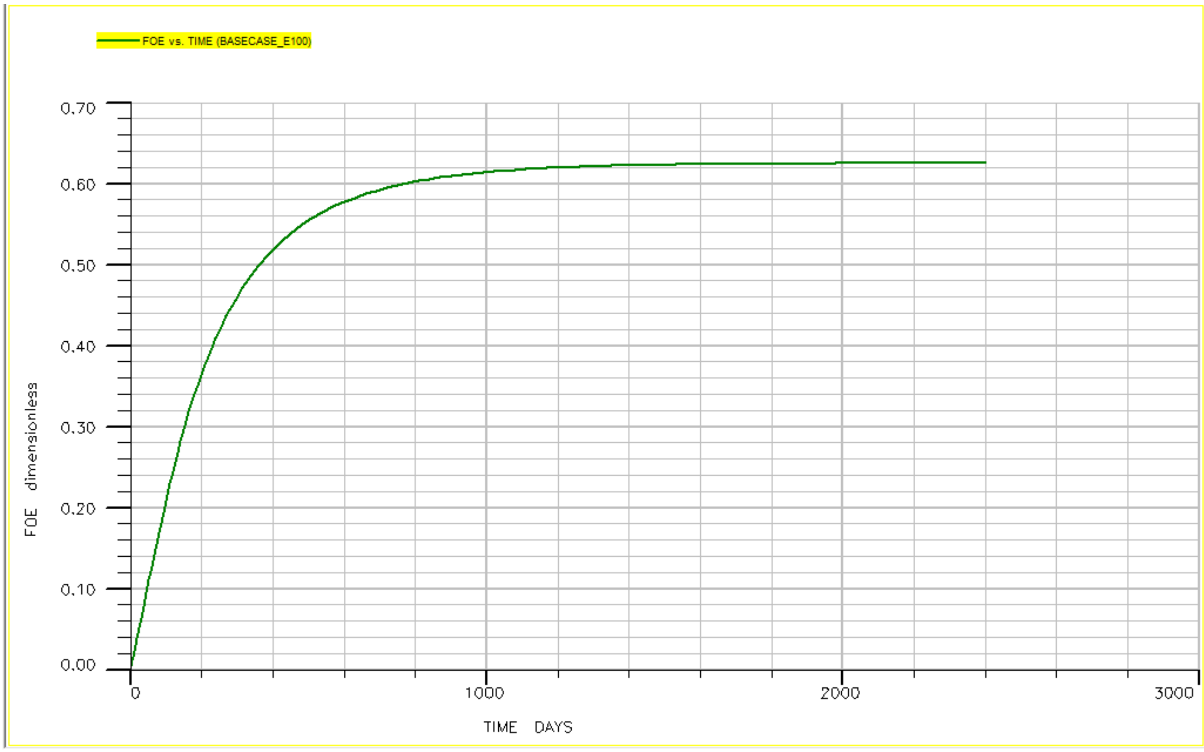

Figure 4.5b: Production to initial reserves (dimensionless) vs time (days) with IOR

The aim of considering recovery factor it is because it indicates the recoverable amount hydrocarbon initially in place and this helps one to understand what drives the reservoir. From Figure 4.5b above, it shows that after the reservoir was enhanced using the polymer flooding, the recovery factor increased greatly over the life of the reservoir and normalized at 0.62

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

This chapter presents finding of the research work carried out. This section is divided into two: the research summary and the conclusions for the main research topic.

The outcome of the research presented in this work is focused on the simulation of the developed base case for the waterflooding project and the model developed to improve oil recovery.

5.1.1 Research Summary

The following research was carried out;

1. Development of the base case reservoir before initialization of the waterflooding project proper.
2. A set of simulated data was generated from the multiphase flow mathematical model to model a base case reservoir.
3. Development of an Eclipse model to simulate the base case reservoir.
4. Generation of real-time data from Eclipse simulator to characterize the base case reservoir properly.
5. Generation of plots for the base case simulation to determine the current functional conditions of the reservoir and to determine the optimizing technique to use.
6. Generation of plots after applying the optimizing technique to improve the condition of the base case reservoir.
7. Comparison of the results gotten from the base case simulation and the improved base case simulation.

5.1.2 Objectives and Findings

The research aimed at improving the production rate for a particular reservoir X by means of low salinity waterflooding and to understand the effect of viscosity in achieving this aim. Three objectives were outlined to achieve the aim of this study. This section explained how each of the objectives was achieved and their significance.

Objective 1 and Findings

Develop a base case reservoir model that requires supplementary energy drive (via waterflooding) to improve its production rate and oil recovery:

Compared to other forms of natural energy drive, solution gas drive is one that shows a favorable characteristics for waterflooding. The ratio of pressure decline in solution gas drive is relatively low, there little or no water production and the gas-oil ratio is relatively high. Eclipse simulator was used to develop a model describing a solution gas drive and its characteristics.

As seen in Appendix C figure 4.6a, the figure below shows that the reservoir pressure begin at 68.8psia and declines sharply to zero. Also as seen in Appendix C Figure 4.6b, the figure above indicated that the amount of water produced per day from the model generated is 0.0688bbl/day which has little significance to the reservoir.

In summary, the objective to develop a base case reservoir that requires supplementary energy was achieved successfully using the Eclipse simulator.

Objective 2 and Findings

Estimate the amount of injected water needed to stabilize the reservoir pressure decline:

After developing the model to improve the base case reservoir, the amount of water needed to be injected into the reservoir in order to continue production at a stabilized pressure was expected with time (in days). The plot in Appendix C figure 4.7a showed that the rate at water is produced to stabilize the reservoir pressure decline. And the plot in Appendix C figure 4.7b indicated that the reservoir pressure is maintained at 1200bbl/day and the total amount of water injected is shown to be 247706stb.

Objective 3 and Findings

To make an estimate of the additional recovery the water injection would give:

From figure 4.3a above, it showed that the cumulative oil produced stabilized at 450sm^3/day but immediately the reservoir was enhanced, figure 4.3b above indicated that there was a rise in production up to 60,000m^3/day. So we can conclude that a water injection of 247,706stb increased the production volume rate from 450sm^3/day to 60,000m^3/day.

In conclusion, based on the numerical reservoir simulation technique used and the assumed analogy, it can be concluded that as compared to the production without IOR, in low salinity water floods:

a) Average reservoir pressure stays high
b) Production Bottom Hole pressure (BHP) stays high
c) Oil production rate stays high

It can also be said that the alteration of salinity affects the well performance due to the migration of fines. Therefore, the numerical reservoir simulation confirms the evidences presented in the literature based on the assumptions and analogy discussed in the previous sections. The following are the limitations to improve the results gotten from this study.

1. Low salinity waterflooding is a relatively new technique and although some laboratory experimentation validates the concept, it lacks the conclusive evidences. As a result, no commercially available simulation package support this model till date. Moreover, the laboratory experimentation is based on 1-D core flood and, therefore, it is necessary to confirm the results by running a 3D numerical reservoir simulation model.
2. An economic analysis should be done with respect to the results obtained in this research project to evaluate the cost implication.