Sudan University of Science and Technology
College of Petroleum Engineering & Mining
Department of Petroleum Engineering

Project Tittle

Prediction of water flooding performance for stratified reservoir using (CMG) Software in Hegilig main field (case study)

التنبؤ بأدائية الغمر المائي لمكمن متطبق بإستخدام برنامج الـ (CMG) دراسة حالة لحقل هجليج.

Project Submitted to College of Petroleum Engineering & Technology In Partial Fulfillment Of The Requirements For The Degree Of B.Sc. In Petroleum Engineering

Prepared by:

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Supervised by:

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February 2022

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This project is accepted by College of Petroleum Engineering and Technology to Department of Petroleum Engineering.

Project Supervisor………..……………………………………………….

Signature……..……………………...………………………………

Head of Department……………………...…………………………..

Signature……………………………...……………………...........

Dean of College……………………………………….……………………

Signature…………………………………………………......................

Date: \ \ 2022

الاستهلال

بسم الله الرحمن الرحيم

يقول الله تعـــــالى:

(أَلَمْ تَرَوْا أَنَّ اللَّهَ سَخَّرَ لَكُمْ مَا فِي السَّمَاوَاتِ وَمَا فِي الْأَرْضِ وَأَسْبَغَ عَلَيْكُمْ نِعَمَهُ ظَاهِرَةً وَبَاطِنَةً ۗ وَمِنَ النَّاسِ مَنْ يُجَادِلُ فِي اللَّهِ بِغَيْرِ عِلْمٍ وَلَا هُدًى وَلَا كِتَابٍ مُنِيرٍ ﴿٢٠﴾)

صدق الله العظيم

الآية ٢٠ سورة لقمـــان

Dedication

To the one who took care of me with eyelashes and the beads of the heart, who was patient with the bitterness of parting and awaited the moment of successful return. to the fountain that never tires of supplication and giving who woven my happiness with threads.

Our mothers…

Especially to the soul of Beloved friend Ezzeldein's mother, may Allah accept her in hereafter.

To the one who instilled the love of God in my heart and entrenched the doctrine of monotheism in the depths of my heart who was for me a mother in tenderness, a teacher in morals and a brother in advice and guidance

Our fathers…

To whom of their love runs in my veins and meditates reminding them of my heart

Our brothers & sisters and friends …

To the scientific edifice and a beacon of science and knowledge

Sudan University of science and technology

Thank you, Lord, for always being there for us.

To all of you

We ***dedicate this humble project***

Acknowledgements

The extreme gratitude goes to the Allah who enable us to fulfill the project perfectly within the assigned time frame.

We are highly thankful to the entire Collage of Petroleum Engineering and Mining, Department of Petroleum Engineering; especially to our humble supervisor **T.Eng. Satti Merghany Gaily,** Assistant Professor, Department of Petroleum Engineering, for his unconditional support and assistance throughout the research procedure. He contributed with all the corrections, suggestions and makes the review paper come into the light especially for his confidence in us.

Never forgot our honest **teachers** of the collage of petroleum Engineering and mining .for been beside us through this period.

We would also like to deeply thank **Dr: Mohanned Khairy**, **Dr: Husham Elbaloula** and **Eng. Osman Kamal for** serving as in technical issues and informational site.

Our thanks and gratitude to **everyone who helped us** from near or afar to complete this work and in overcoming the difficulties encountered,

Besides heartiest gratitude and thanks go to different unmentioned people in different phases of the work.

Abstract

The research was conducted on stratified reservoir in Heglig main field, the primary objective was to maintain the reservoir pressure hence increasing the recovery of oil in addition to select the optimum flood pattern, favorable mobility ratio and water injection rate as well as to prolong the reservoir production life as much as possible.

Many scenarios have been done by using CMG simulator with changing the injection rate, flood pattern and mobility ratio in each scenario.

The results showed that the highest economic recovery was obtained from the normal five spot and the best injection rate was 5000 m^3/day and also an increase in mobility ratio enhances the recovery of oil.

It could be summarized that this study which is run on four productive zones in Heglig main field included all the objectives that it was conducted according to, and it might be applicable whenever it's realized that the results were economic.

التجريد

أجريت الدراسة على مكمن متطبق في حقل هجليج وكان الهدف الاساسي منها المحافظة على ضغط المكمن ومن ثم زيادة معدل استخلاص النفط بالإضافة إلى اختيار أمثل معدل حقن،شبكة غمر مائى مناسبة و افضل حركية نسبية ثم المحافظة على انتاجية المكمن لأطول فترة ممكنة.

تم اجراء عدة سيناريوهات باستخدام برنامج تقييم ادائية المكمن(CMG) مع تغيير كل من معدل الحقن ، شبكة الغمر المائي ونسبة الحركية لكل سيناريو.

أظهرت النتائج أن أعلى معدل استخلاص اقتصادي كان في شبكة الغمر المائي الخماسية العادية وأن أفضل معدل حقن كان 5000 متر مكعب في اليوم وكذلك تم التوصل إلي أن زيادة نسبة الحركة تحسن من عملية الاستخلاص .

مما سبق يمكن ان نلخص بان هذه الدراسة التي طبقت على أربعة مناطق انتاجية في حقل هجليج قد شملت كل الاهداف التي أجريت من أجلها، ويمكن تطبيقها متى ما تأكد أن النتائج التي تم التوصل إليها اقتصادية.

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Nomenclature.

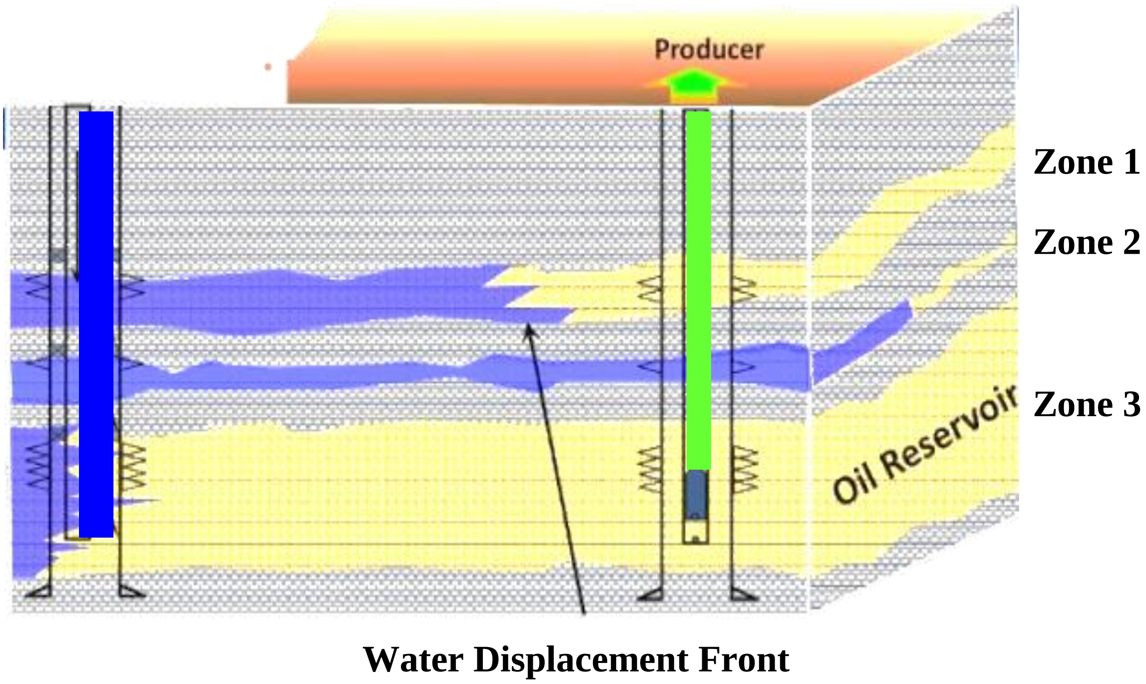
HE	:	Heglig main field
CMG	:	Computer Modeling Group
CIR	:	Constant Injection Rate
CIP	:	Constant Injection Pressure
SPE	:	Society of Petroleum Engineering
LSWF	:	Low Salinity Water Flooding
ANN	:	Artificial Neural Network
E_A	:	Arial Sweep Efficiency
E_v	:	Vertical Sweep Efficiency
E_D	:	Displacement Efficiency
V_{oi}	:	Volume of Oil at Start of Flooding
V_{or}	:	Volume of Remaining after flood
API	:	American Petroleum Institute
IND	:	Injection well
PRO	:	Production well
R&D	:	Research and Development
IOR	:	Improve Oil Recovery
EOR	:	Enhance Oil Recovery
PVT	:	Pressure Volume Temperature
Cp	:	Centipoise
Ca	:	Capillary Number
γ	:	Interfacial tension (mN)
η	:	Dynamic Viscosity (cp)
ρ	:	Fluid Density (lb/ft^3)
M	:	Mobility Ratio (%)
ν	:	Characteristic velocity (ft/s^2)
GEM	:	EOS compositional & geomechenical simulators
IMEX	:	Black oil Simulators

Nomenclature.

STARS	:	K- value compositional , thermal & geomecgenical
Krw	:	relative permeability of water(md)
Kro	:	relative permeability of oil (md)
μ_o	:	oil viscosity (cp)
μ_w	:	water viscosity (cp)
Sw	:	water saturation
WOC	:	water oil contact
P	:	pressure (psi)
S.G	:	specific gravity
Cum-oil	:	cumulative oil
S	:	Scenario
C	:	Case
Equ	:	Equation

Chapter One

Introduction



1.1 General Introduction

Water flooding is a form of oil recovery where in the energy producing well is supplied from the surface by means of water injection and the induced pressure from the presence of additional water.

The design of a water flood involves both technical and economic considerations. Economic analysis is based on estimates of water flood performance. These estimates may be rough or sophisticated depending on the requirements of a particular project and the philosophy of the operator. This chapter presents method of estimating water flood performance for economic analysis. It's organized in order of increasing complexity beginning with first-pass estimates with simple method and ending with an introduction to the capability of reservoir simulators to evaluate water flood designs.

Water flooding is the most widely used fluid injection process in the world today. It has been recognized1 since 1880 that injecting water into an oil-bearing formation has the potential to improve oil recovery. However, water flooding did not experience field wide application until the 1930s when several injection projects were initiated, 2, 3 and it was not until the early 1950s that the current boom in water flooding began. Also is responsible for a significant fraction of the oil currently produced in the world. In fact, in the 21st century, most operators begin to investigate the feasibility of water injection within a short time following the initial field discovery.

Many complex and sophisticated enhanced recovery processes have been developed through the years in an effort to recover the enormous oil reserves left behind by inefficient primary recovery mechanisms. Many of these processes have the potential to recover more oil than water flooding in a particular reservoir. However, no process has been discovered which enjoys the widespread applicability of water flooding. The Primary reasons why water flooding is the most successful and most widely used oil recovery process are: general availability of water low cost relative to other injection fluids ease of injecting water into a formation high efficiency with which water displaces oil The purpose of these notes is to discuss the

Reservoir engineering aspects of water flooding. It is intended that the reader will gain a better understanding of the Processes by which water displaces oil from a reservoir and, in particular, will gain the Ability to calculate the expected recovery performance and to manage the project to maximize oil recovery with a minimum number of wellbores and injection volumes. While written materials will be limited to the displacement of oil by water, the displacement processes and computational techniques presented have application to other oil recovery processes Many of the water flooding design procedures can be prepared as small computer programs. Selected computer subprograms are included to help the student write more complex design programs with a reasonable effort of increasing complexity.

Applying water flooding in multilayer it’s most complex and need deeply known of formation type and reservoir characterization in this project we did the same depending on computer simulator (CMG) software which well be full known in chapter two.

1.2 Problem Statement:

Detailed of individual well performance indicate that water drive is the main mechanism of grater Heglig field and lately still suffering from pressure depletion led to low recovery challenging. Due to cross flow as well as heterogeneous layered in Bentiu-1 with an edge water drive and Bentiu-2, Bentiu-3 are more homogenous have significant bottom water drive component. By occurring cross flow between 1& 2 where pressure differential is not significant to acting as barrier to flow.

1.3 **Objective of the Study:**

1. Pressure maintenance by controlling in injection rate.
2. To increase recoverable oil using alternative energy as Water-flooding.
3. To select optimum flood pattern and rate of injection.
4. To distinguish adaptability of water flooding simulating by CMG program..
5. Predictions of reservoir performance with numerical simulation results. In order to investigate some of the parameters affecting reservoir performance.
6. To extended reservoir life.

1.4 Methodology:

Use of water injection to increase production from oil reservoir. Applying mechanism of oil displacement by water using many types of patterns in partially gas or water saturated porous medium to pressure support filling the void-age left by produced fluid.

- Certain oil wells are converted to water injection wells.
- Other wells are remaining as producers and adding new infill wells.
- The injected well displaces, or "push" oil to the producing well which primarily maintain reservoir pressure and drive the oil toward the well.
- Three scenarios of M, injection rate and flood pattern are applying by maintain two parameters constant & the other changed in each scenario.
- Conducting all above procedure by reservoir simulator CMG

1.5 Thesis Outline:

Chapter two of this thesis comprises literature review, Water flooding background, CMG programing background, Drive Mechanisms, while chapter three consists of Building model procedures, chapter four consists of results and discussion, lastly, chapter five consists of conclusion and recommendation.

1.6 Field background:

Heglig oil field is (Figures 1). Is located in southeast and middle of Block 2B, Muglad Basin, discovered by Chevron. It consists of 10 fields (Heglig main, Toma, El Bakh, El Full, Laloba, Kanga, Barki, Hamra, Simbir East and Rihan).A general structure which follows average distance between fields is about 3 to 5 km. 8 layers are developed i.e., Aradeiba main, Aradeiba B, Aradeiba E, Aradeiba F, Bentiu-1, Bentiu-2 and Bentiu-3 and Abu Gabra. First FDP was carried out in 1998. Last FDP was carried out in 2011. Field development started in June 1999 with development of 29.

In the end of 2012 there are 70 producer and 5 suspended wells divided to Aradeiba main (4 wells), Bentiu-1 (48 wells), Bentiu-2 (4 wells), Bentiu-3 (14 wells plus 8 commingle) which the field performance data summarized as well as following. Water cut (94.24 %) and cumulative oil (126.469 MMBBL).our study is highly fuscous on only Aradeiba (E & D) and Bentiu (1D and 2A).

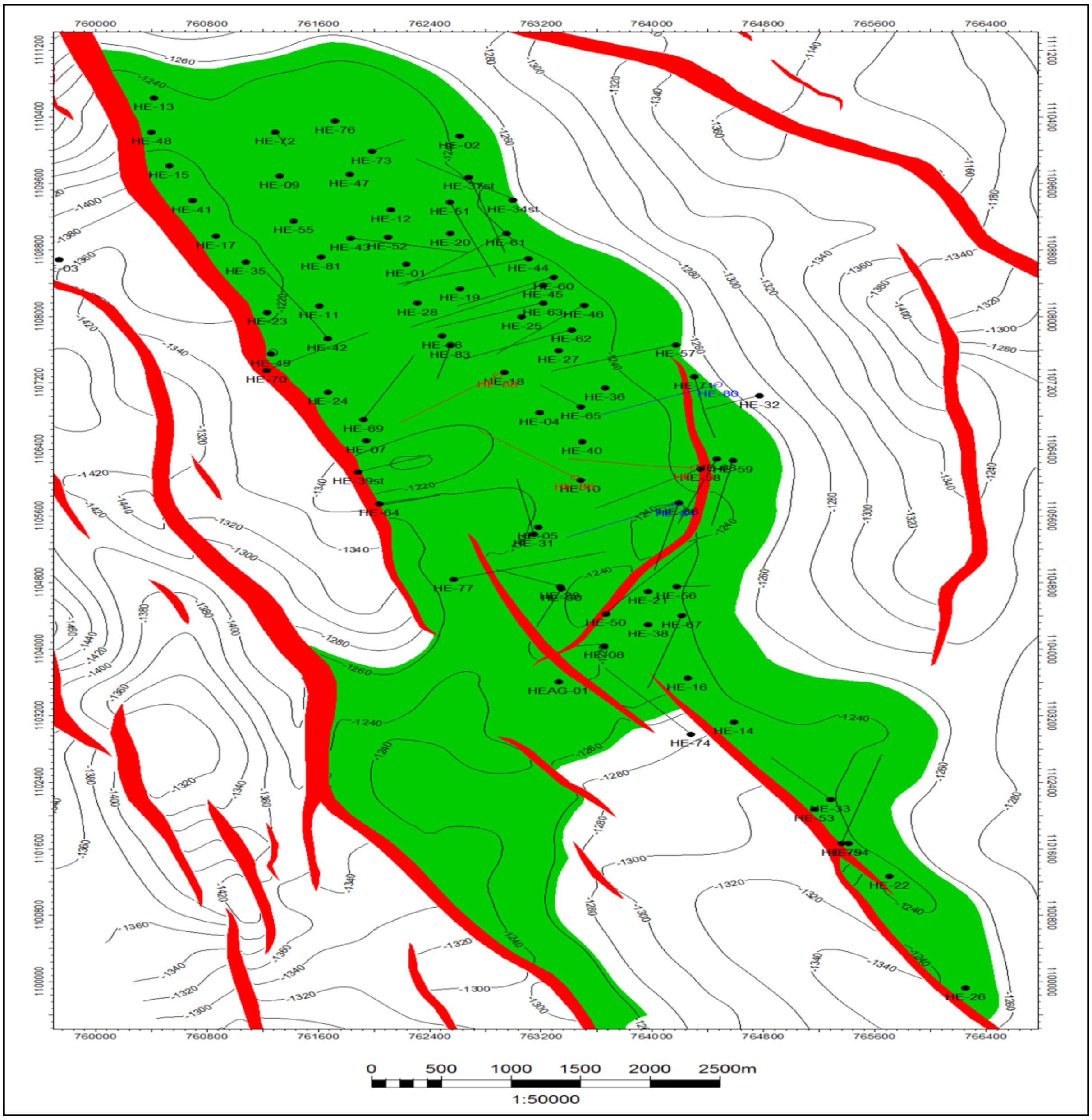


Fig. 1 illustrate Structural map of Heglig main oil Field **(SPE-177984-MS)**

Chapter Two

Literature Review

Literature Review

2.1 Literature Review:

2.1.1 Technical Papers:

Modification to the Dykstra-Parsons method to predict water-flooding performance of multi-layered composite reservoirs. The alteration considers the change in reservoir properties and dimensions both vertically and horizontally. Constant Injection Rate (CIR) and Constant Injection Pressure drop (CIP) were noticed. It was found that water-flooding performance in stratified composite linear reservoirs is controlled by the mobility ratio. Middle East Technical Conference and Exhibition **(Mohammed E Osman, Djebbar Tiab** , **1981).**

Developed a mathematical correlation for water flooding performance in linear stratified systems with and without crossflows. The model forecasts the fractional oil recovery, water cut, total volume injected, and change in injection rate at the water breakthrough in the successive layers. It was found that crossflow between layers improves the oil recovery for systems with mobility ratios less than 1 and retards oil recovery for systems with mobility ratios greater than 1 Society of Petroleum Engineers Journal.(Noaman El-Khatib, **1985).**

Presents an analytical solution for oil recovery from a stratified reservoir by Dykstra-Parsons technique during a polymer flood, which provides concerning the effects of slug sizes, gelling, and permeability reduction. SPE (Jalel E Mahfoudhi, Robert M Enick, **1990**

Developed a correlation for the prediction of water-flooding performance in layered, inclined reservoirs. The gravitational effect is shown in the fractional flow formula by a dimensionless gravity number. This gravity number incorporates the dip angle from the horizontal and the difference in densities of oil and water. Dimensionless time, fractional oil recovery, injectivity ratio and water cut at times of water breakthrough can be estimated by this model in the successive layers. The outcomes were compared with the performance of reservoirs having dip with crossflow. For

Favorable and unit mobility ratios, the effect of cross flow between layers was found to advance fractional oil recovery and vice versa. SPE Journal (Noaman A.F. El-Khatib, **2012).**

Near and radial flow modelling of a waterflooded, stratified, non-communicating reservoir developed with downhole, flow control completions The developed model is constructed from the combination of classical waterflood displacement equations with a recently developed analytical model of a flow control completion. The idea is then extended for light-oil displacement, which replicates piston-like displacement (an extension of Dykstra-Parsons solution to AWC wells) and medium/heavy-oil displacement, which replicate non-piston like displacement (an extension of Buckley-Leverett & Welge solution to AWC wells. Journal of Petroleum Science & Engineering (Bona Prakasa Khafiz Muradov David Davies, **Nov – 2019).**

Presents a novel empirical correlation based on a feed-forward neural network to predict Low-salinity water flooding (LSWF) recovery efficiency in a heterogeneous reservoir at and beyond water breakthrough, To evaluate the performance of the newly developed correlation, Finally They figured that the proposed artificial neural network (ANN) model is limited to a single-stage, low-saline waterfloods for (Ahmed Khan, Shahnawaz Khan, et al **Jan -2021).**

Table A – 1 illustriate related literature revieow

Year	Tittle	Authors	Contribution
1964	"Areal Sweepout Behavior in a 9-Spot Injection Pattern"	KimblerO.K,Caudle.B.H, Cooper H.E,Jr.	This paper presents a number of graphical relationships used to determine the areal sweep efficiency in a nine-spot injection pattern.
1967	"Combination Method for Predicting Waterflood Performance for 5-Spot Patterns in Stratified Reservoirs"	James A.wasson, Leo A, Schrider.	This paper highlights the effect of the viscosity ratio on the waterflood oil recovery.

Table B – 1 Illustrate literature review

Year	Tittle	Authors	Contribution
1970	"Low Areal Sweep Efficiencies in Flooding Hetero geneous Rocks.	Pitts,Gerald N,Crawford, Paul B.	This paper describes how reservoir heterogeneity affects areal sweep efficiency.
1981	Waterflooding Performance And Pressure Analysis Of Heterogeneous Reservoirs	Mohammed E Osman, Djebbar Tiab	With a constant CIR & CIP in stratified linear reservoir is controlled by Mobility (M).
1985	The effect of cross flow on water flooding of Stratified reservoir.	Noaman El-Khatib	By forecasting of IR of water at break through found that cross-flow between layers for M <1 retards oil recovery for systems with M >1.
1988	"Prediction of Waterflood Performance in Stratified Reservoirs"	Tompang.R ,Petronas Kelkar B.G,U of Tulsa	This study analyses the crossflow between layers in a reservoir and how it can affect waterflood performance.
1990	Extension of the Generalized Dykstra-Parsons Technique to Polymer Flooding in Stratified Porous Media	Jalel.E.Mahfoudhi, Robert M Enick	Used Dykstra-Parsons Techniques with a analytical solution to concerning effect of slug size, gelling and K reduction.
2001	"Determination of Volumetric Sweep Efficiency in Barrancas Unit, Barrancas Field"	M.Vicenate,D. Crosta,L.Eliseche et al	This paper describes a number of methods used to determine the volumetric sweep efficiency.

Table C -1: illustrate updated historical review related work done by others which taken as much helpful background to conduct this study.

Year	Tittle	Authors	Contribution
2012	The modification of Dykastra-Parsons Method for inclined stratified reservoirs.	Noaman A.F. El-Khatib	Performance of reservoirs having dip with cross-flow. For favorable and unit mobility ratios, the effect of cross-flow between layers was found to advance fractional oil recovery and vice versa.
2019	Linear and radial flow modeling of a water flooded, stratified,noncommunicating reservoir developed with down hole, flow control completions	Bona Prakasa ,Khafiz Muradov David Davies	Developed model constructed from combination of classical water-flood displacement equations with a recently developed analytical model.
2021	Performing in inclined communicating stratified reservoirs.	Ahmed Khan Shahnawaz Khan,et al	A feed-forward (ANN) model to predict Low-salinity water flooding (LSWF) for a 5-spot pattern

Our Contribution According to the above studies	
In our study mainly we will focus on Linear stratified Reservoir of water flood using Method as same as (Mohammed E Osman, Djebbar Tiab) but we will depend on Computer simulator in our process.	Our prediction of Selecting optimum flow pattern and injection rate going as much as Shams Kalam, Rizwan Ahmed Khan, Shahnawaz Khan, et al study without considering Low-salinity water flooding (LSWF) by CMG modeling.

2.2 Theoretical Background

2.2.1 Introduction:

In general oil recovery process is classified into three main categories, which are Primary recover (process where the recovery of oil occurs by the natural energy of reservoir), Secondary recovery(is the process where the recovery obtains by using external sources of energy i.e water injection and gas injection) and Tertiary recovery is a process for extracting oil that has not already been retrieved through the primary or secondary oil recovery techniques.

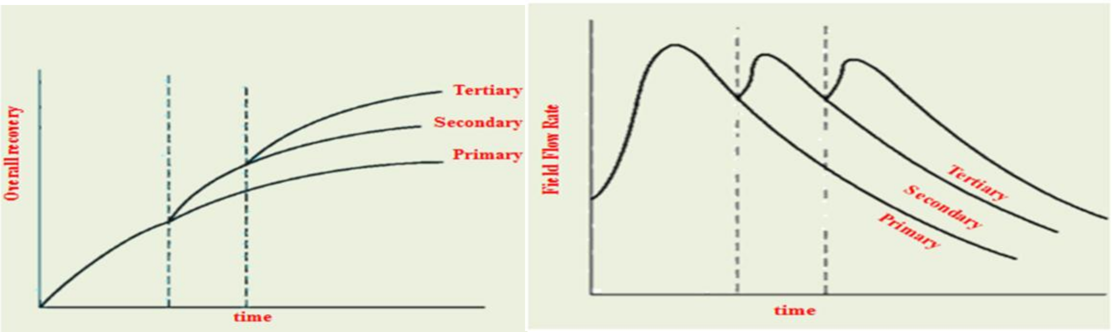


Fig-2 illustrate the main oil recovery stages

2.2.2 Primary Drive Mechanism:

The approximate oil recovery range is tabulated below for various driving mechanisms. Therefore, oil recovery may fall outside these ranges.

Table B – 2: illustrate type of primary drive mechanism

Drive Mechanisms		Oil Recovery Range, %
Rock and Liquid expansion		3 - 7
Solution Gas		5 - 30
Gas cap		20 - 40
Water Drive	(Heglig Mechanism)	35 - 75
Gravity Drainage		<80
Combination Drive		30 - 60

2.2.3 Secondary oil recovery:

The second stage of hydrocarbon production during which an external fluid such as water or gas is injected into the reservoir through injection wells located in rock that has fluid communication with production wells. The purpose of secondary recovery is to maintain reservoir pressure and to displace hydrocarbons toward the wellbore. The most common secondary recovery techniques are gas injection and water-flooding. Normally, gas is injected into the gas cap and water is injected into the production zone to sweep oil from the reservoir. A pressure-maintenance program can begin during the primary recovery stage, but it is a form of enhanced recovery. The secondary recovery stage reaches its limit when the injected fluid (water or gas) is produced in considerable

Amounts from the production wells and the production is no longer economical. The successive use of primary recovery and secondary recovery in an oil reservoir produces about **15%** to **40%** of the original oil in place.

2.2.4 Water flooding:

water flooding can result in significant additional incremental oil recovery in many reservoir situations not all reservoir are prime Water food candidate macroscal features may control the effectiveness of a water flooding, mobility dominate microscal sweep efficiency, additional protocol for evaluation has been presented.

2.2.5 Factors to Consider in Water flooding:

Thomas, Mahoney, and winter (1989) pointed out that in determining the suitability Of a candidate reservoir for water flooding, the following reservoir characteristics must be considered:

1- Reservoir geometry

The areal geometry of the reservoir will influence the location of wells and, if offshore, will influence the location and number of platforms require.The reservoir's geometry will essentially dictate the methods by which a reservoir can be produced through water-injection.

1- Fluid properties

The physical properties of the reservoir fluids have pronounced effects on the

Suitability of a given reservoir for further development by water flooding the viscosity of the crude oil is considered the most important fluid property that affects the degree of success of a water flooding project.

2- Reservoir depth

Reservoir depth has an important influence on both the technical and economic aspects of a secondary or tertiary recovery project.Maximum injection pressure will increase with depth.

3- Lithology and rock properties

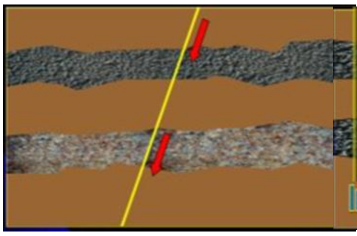
Reservoir lithology and rock properties that affect flood ability and success are: Porosity, Permeability, Clay content, net thickness in some complex reservoir systems, only a small portion of the total porosity, such as fracture porosity, will have sufficient permeability to be effective in water-injection operations.

4- Fluid saturations

In determining the suitability of a reservoir for water flooding, a high oil saturation that provides a sufficient supply of recoverable oil is the primary criterion for successful flooding operations.Note that higher oil saturation at the beginning of flood operations increases the oil mobility that, in turn, gives higher recovery efficiency.

5- Reservoir uniformity and pay continuity

Substantial reservoir uniformity is one of the major physical criterions for successful water flooding.For example, if the formation contains a stratum of limited thickness with a very high permeability (i.e., thief zone), rapid channeling and bypassing will develop. Unless this zone can be located and Shut Off, the producing water oil ratios will soon become too high for the flooding operation to be considered profitable. Main factor controlling the continuity of the reservoir is the depositional system.



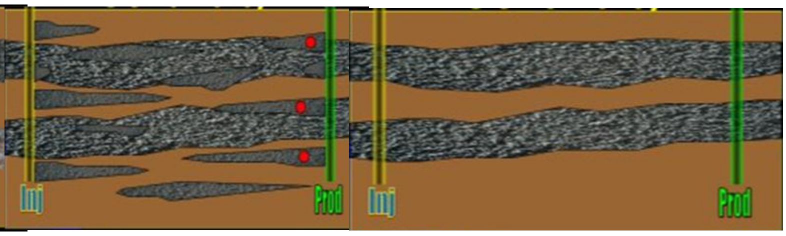


Fig-3 Presence of Sealing Fault Fig-4 Reservoir Continuity

2.2.6. Factors Controlling Water flood Recovery:-

Oil recovery due to water flooding can be determined at any time in the life of a water flood project if the following four factors are known:

2.2.6.1 Oil in place at the start of water flooding:-

The oil-in-place at the time of initial water injection is a function of the floodable pore volume and the oil saturation. Floodable pore volume is highly dependent on the selection and application of net pay discriminators such as permeability (and porosity) cutoffs. A successful flood requires that sufficient oil be present to form an oil bank as water moves through the formation. An accurate prediction of water flood performance or the interpretation of historical water flood behavior can only be made if a reliable estimate of oil-in-place at the start of water flooding is available.

2.2.6.2 Areal Sweep Efficiency (EA):

This is the fraction of reservoir area that the water will contact. It depends primarily upon the relative flow properties of oil and water, the injection production well pattern used to flood the reservoir, pressure distribution between the injection and production wells, and directional permeability. Most parameters which affect **(**EA**)** such as formation dip angle and dip azimuth, presence of fractures, mobility ratio, injection pattern and directional permeability.

2.2.6.3 Vertical Sweep Efficiency:

In a displacement process, the ratio of the cumulative height of the vertical sections of the pay zone that are contacted by injection fluid to the total vertical pay zone height. Vertical displacement efficiency (EI) strongly depends on parameters such as mobility ratio and total volume of fluid injected. Non-uniform permeability may cause an irregular front that affects the vertical displacement efficiency because the injected fluid flows faster in high-permeability zones than in low-permeability zones.

2.2.6.4 Displacement Sweep Efficiency:

Represents the fraction of oil which water will displace in that portion of the reservoir invaded by $E_D = \frac{(Voi - Vor)}{Voi}$ ________________Equ (2.2)

Where:

V_{oi} = volume of oil at start of flood

V_{or} = volume of oil remaining after flood.

2.2.7 Water-flooding Challenges in Stratified Reservoirs:

When Water-flooding in stratified reservoir, one must consider the same issues that affect any type of recovery, which can determine the success of oil recovery. The factors that cannot be changed, the properties of the formation itself, must be worked around and the water used in flooding modified.

Residual oil saturation:-

Accurate determination of residual oil saturation is very important in evaluating the feasibility of water-flooding a reservoir. A reservoir with less than 40% oil saturation following primary depletion may not be the best prospect for water flooding.

- Oil gravity and viscosity:-

Reservoirs with oil gravity more than 25”API, and oil viscosity less than 30 cp, are good water-flooding prospects. A highly viscous fluid, such as heavy oil, is displaced less efficiently by injected water which is relatively less viscous.

- Lithology:-

Both sandstone and carbonate reservoirs are likely candidates for improved oil recovery by water-flooding. However, certain rock heterogeneities, including secondary porosity, fractures, and conductive channels, are frequently observed in the latter, leading to poor recovery.

- Compatibility of injected water:-

Injected water needs to be compatible with the reservoir water to minimize formation damage. Incompatible water may lead to issues related to infectivity.

- Effect of aquifer:-

Reservoirs experiencing strong water influx may not be good candidates for water-Flooding, as the ongoing natural process of water displacing oil may lead to marginal added benefits. However, reservoirs with weak water influx have been water-flooded successfully

- Bottom water zone:

In reservoirs with a bottom water zone, injected water is found to “slump down” from the upper to the lower zone where good vertical communication exists. This can lead to Poor water-flood performance in some instances.

1. **Gas cap:-**

In reservoirs where a gas cap exists, displaced oil may enter pores previously occupied by gas. This is due to the increased reservoir pressure created by water injection. Consequently, a portion of oil migrating to the gas zone cannot be produced as dictated by the residual oil saturation characteristics of the reservoir rock.

2. **Injection pressure:-**

Reservoirs located at a shallow depth or tight reservoirs may have limitations of injectivity. Injection pressure is kept below the fracture pressure of the formation to ensure that rapid pathways are not created for water channeling. In many cases, limited injection pressure and injection rate translate into less-than-optimum recovery. A low injection rate leads to a delayed response at the producer, affecting the net present value of the asset.

2.3 Mobilization of residual oil saturation:-

During the early stages of a water wet reservoir system the brine exists as a film around the sand grains and the oil fills the remaining pore space. At a time intermediate during the flood the oil saturation has been decreased and exists partly as a continuous phase in some pore channels but as discontinuous droplets other channels. At the end of the flood when the oil has been reduced to the residual oil saturation the oil exists primarily as a discontinuous phase of droplets or globules that have been isolated and trapped by the displacing brine. The mobilization of the residual oil saturation in a water wet system requires that the discontinuous globules be connected to form a continuous flow channel that leads to a producing well. The mobilization of oil is governed by the viscous forces (pressure gradients) and the interfacial tension forces that exist in the sand grain oil-water system.

2.4 Effect of trapped gas saturation on oil recovery during the secondary recovery process:-

In petroleum reservoirs with dissolved gas drive the pressure decreases due to depletion and the resulting consequence is liberation of progressively higher quantities of gas from oil, i.e. production is carried out with increasingly higher gas-oil ratios. If the method of reservoir pressure maintenance by flooding is applied to such reservoirs, The gas present in the pore space has a certain influence on the quantity of oil remaining in the reservoir after the completion of that process, as well as on the final oil recovery.

Many professional papers and books in considerable detail describe the physical characteristics of the water flooding processes with the presence of trapped gas. In many cases it has been confirmed that the presence of free gas phase during water flooding leads to lower residual oil saturation than during water flooding with no-gas presence. It also applies to the natural water drive process, but due to the characteristics of such drive to maintain the pressure to a lesser or higher degree, it is simultaneously accompanied by liberation of only small volumes of gas from oil, which may also have a favorable impact. Additionally, if the average reservoir pressure is higher than the saturation pressure, gas is liberated only locally and in even smaller quantities.

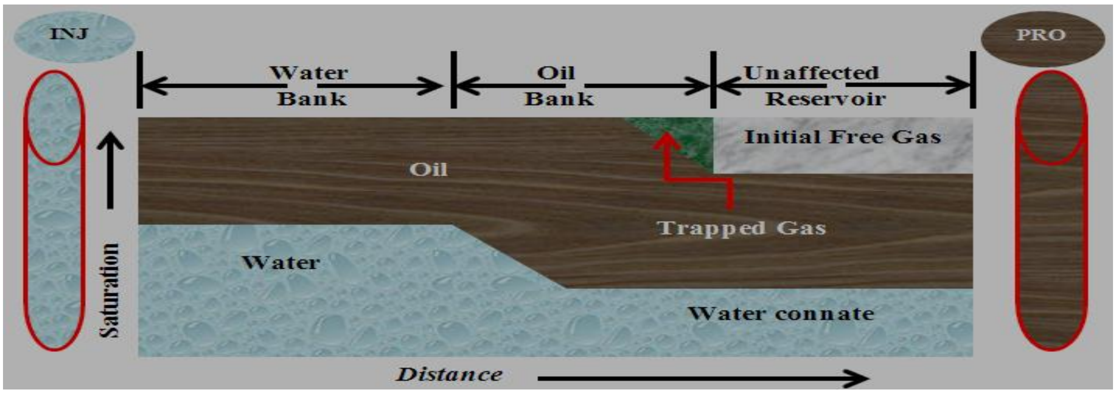


Fig- 5 description of water-flooding processes with the presences of Trapped gas

2.5 Flood Patterns:

Generally, flood patterns are classified into main different categories which are: Regular, irregular and Peripheral.

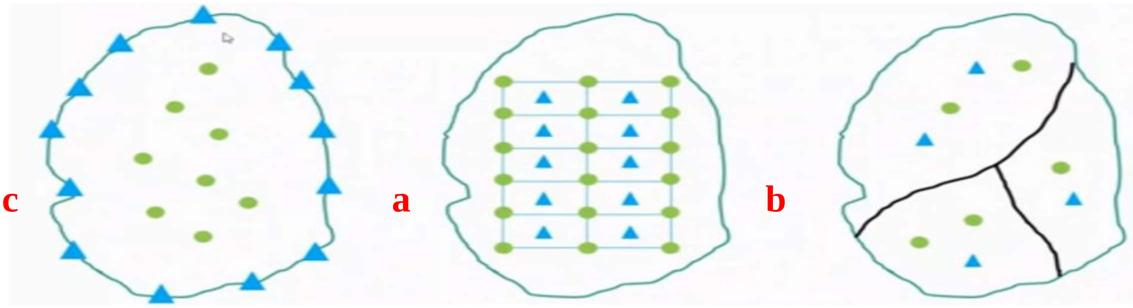


Fig- 6 illustrate general flood patterns (a) Regular, (b) irregular and (c) Peripheral.

- **Regular Injection Patterns**

Fields are developed in a very regular pattern. A wide variety of injection-production well arrangements have been used in injection projects. The most common patterns are The following:

- **Direct line drive**. The lines of injection and production are directly opposed to each other. The pattern is characterized by two parameters: distance between wells of the same type (a) and distance between lines of injectors and producers (d).

Fig -7 Represent direct line drive

- **Staggered line drive**. The wells are in lines as in the direct line, but the injectors, producers are no longer directly opposed but laterally displaced by a distance of a/2.

Fig -8 Represent staggered line drive

- **Five spot**. This is a special case of the staggered line drive in which the distance between all like wells is constant, i.e., a = 2d. Any four injection wells thus form a square with a production well at the center.

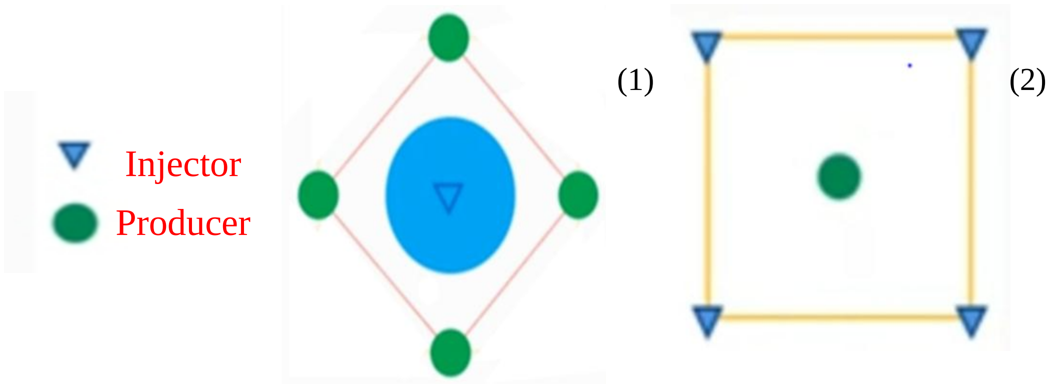


Fig -9 Shows normal 5- spot (2) & inverse 5- spot (1)

- **Seven spot.** The injection wells are located at the corner of a hexagon with a production well at its center.

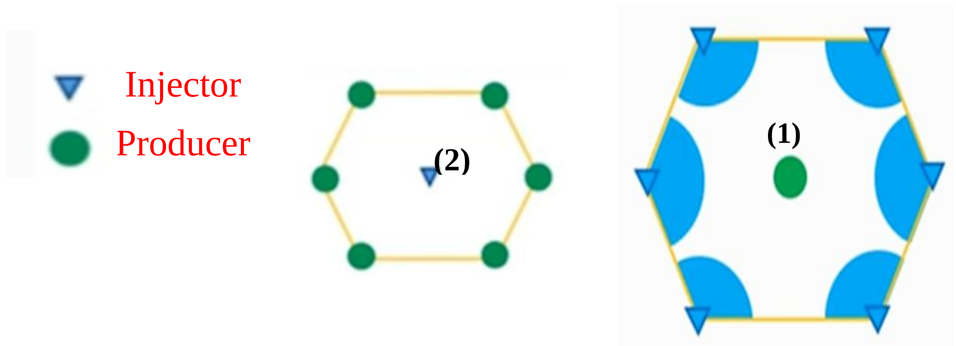


Fig -10 Shows normal 7- spot (2) & inverse 7- spot (1)

- **Nine spot**. This pattern is similar to that of the five spot but with an extra injection well drilled at the middle of each side of the square. The pattern essentially contains eight injectors surrounding one producer. The patterns termed **inverted** have only one injection well per pattern. This is the difference between **normal** and **inverted** well arrangements. Note that the four-spot and inverted seven-spot patterns are identical **Regular Injection Patterns** Due to the fact that oil leases are divided into square miles and quarter square miles.

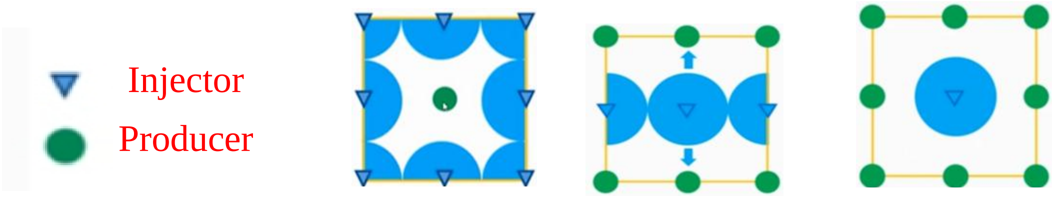


Fig - 11 Shows normal 9- spot (2) , inverse 9- spot (3)& direct line drive (1)

2.6 Reservoir simulation

Reservoir simulation is a developing application technique for reservoir development and management. It can be used to forecast the production behavior of oil and gas fields, optimize reservoir development schemes, and evaluate the distribution of remaining oil through history matching. It is an important tool that facilitates reservoir engineers as they work to optimize the design of well development schemes, improve the efficiency of reservoir development, and enhance oil and gas recovery.

2.7 Definitions: Capillary Number:

The capillary number is a dimensionless quantity that relates the viscous forces in a system to the surface tension forces. It is defined as whenever the forces resulting from fluid motion are to be compared to the forces resulting from surface tension. This is the case if a liquid is moved across a second fluid layer, *e.g.*, a gas or an immiscible second liquid. A good visual example for these effects is **droplets** suspended in an inert liquid in droplet microfluidics. The viscous forces of the surrounding inert liquid may deform the droplets due to, *e.g.*, local increases in pressure due to variations in the flow conditions. However, the interface tension forces between the two liquids are usually significantly higher, in which case the droplet may be locally deformed, but not destroyed.

$$\mathbf{Ca} = \frac{\eta v}{\gamma} = \frac{v\rho v}{\gamma} = \frac{\text{viscousforces}}{\text{surfacetension}} \qquad \text{Equ (2)}$$

Where, **Ca**: Capillary number dimensionless quantity.

v : Characteristic velocity (ft/s^2)

η : Dynamic viscosity (cp)

γ : Interfacial tension (mN)

ρ : Fluid Density (lb/ft^3)

- **Wettability:**

It's the tendency of one fluid to spread on solid surface in the presence of other immiscible fluids.

- **Pressure maintenance:**

Refer to a pumping into the formation from injector wells either water or gas to maintain reservoir pressure such that the well will be flowing again.

- **Reservoir surveillance**

Constant monitoring and surveillance of reservoir performance as a whole is essential to determine whether the performance is conforming to the management plan.

- **Mobility ratio**

The mobility ratio of water to oil is one of the most critical factors to influence water flood efficiency. When mobility is greater than one, it is considered unfavorable as water is more mobile than oil in the porous medium; injected water tends to bypass oil and early breakthrough is experienced at the producers. At a mobility ratio of less than one, water is less mobile than oil leading to better displacement and recovery of oil.

$$M = \frac{Krw}{Kro} x \frac{\mu o}{\mu w} \qquad \text{……………………………………………Equ -2}$$

M : Mobility ratio (dimensionless quantity.)

μo : Oil viscosity (cp)

μw : Water viscosity (cp)

K_{rw} : Relative Permeability of water (md)

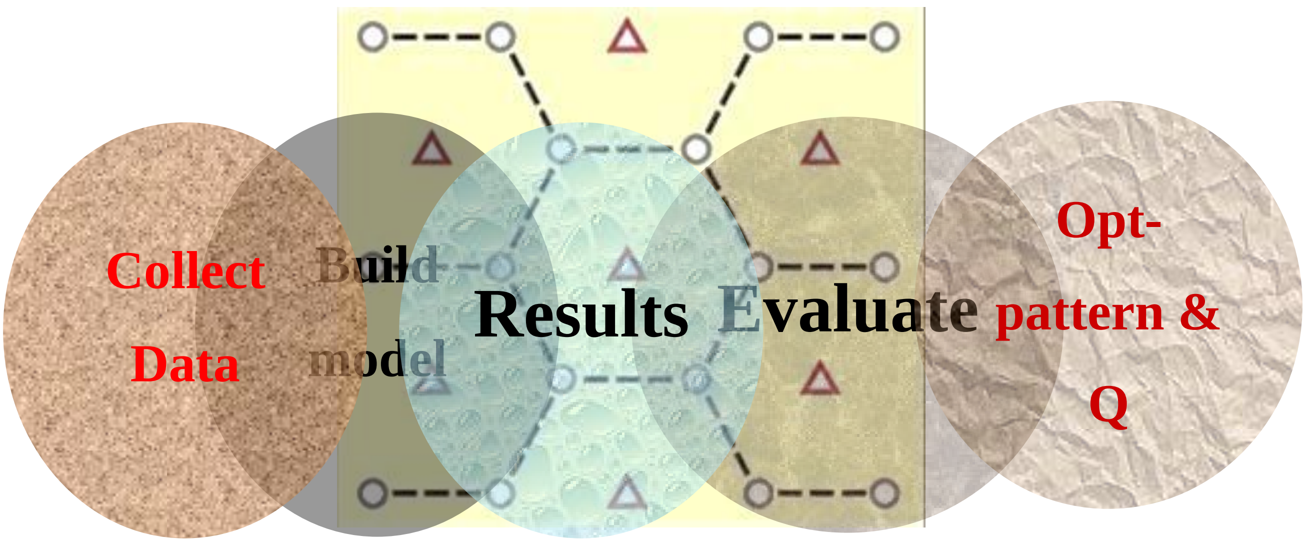
K_{ro} : Relative Permeability of oil (md)

- **Striated reservoir:**

Layered formation having different rock characteristics exhibits a behavior that is very similar to single layer system unless the transmissibility contrast between the two layers is quite significant.

Chapter Three

Methodology & Procedures



3.1 Introduction:

This chapter mentions all procedures of practical issues which followed to build water flooding model for main Heglig field in addition to required data tools CMG software

3.2 CMG Software:

Term CMG is an abbreviation to computer modeling group which has begun in 1978 as a small research company based in Calgary, Canada. Quickly became known for its expertise in heavy oil, and has expanded this knowledge into all aspects of reservoir flow and advanced processes modeling. Since inception, CMG has been providing the ultimate customer experience through R&D investment, superior technology, and unparalleled user support. Today, it is a world-class software technology company with more than 617 oil and gas clients and consulting firms, in 61 countries, using the reservoir simulation tools. The team is at the forefront simulating new recovery methods and developing innovative ways to help in overcome existing technological barriers and reach to strategic goals.

Furthermore, the leader in enhanced oil recovery simulation, delivers software that is easier to use and provides the most accurate results for compositional, conventional, unconventional and advanced IOR/EOR processes. So it consider the industry standard for usability, physics, robustness and performance.

To achieve the objectives of this study, the below methodology had been followed:

1. A deeply Understanding for Heglig main field properties: (reservoir characteristics, reservoir types, reservoir pressure & temperature, PVT properties of the crude oil, fluid properties, rock properties, reservoir parameters).
2. CMG software had been studied.
3. Data collection
4. CMG sector model for Heglig main field data.
5. The model had been built for the Heglig model data

By using Commercial Simulator (CMG) Software to Study Water flooding performance for stratified Reservoir (Heglig main field) by applying different scenarios. CMG software is a group of softwares specialized in reservoir simulation it’s consisting of:

a) Builder

b) GEM - Compositional and Unconventional Oil and Gas Reservoir Simulator

c) IMEX -Three Phase, Black Oil Reservoir Simulator

d) STARS (Thermal simulator)

e) WINPROP (Model generator)

f) CMOST (Optimization Software)

g) RESULTS - Visualization and Analysis.

The CMG model for heglig main field has built for data in range of 212 different layers, the water flooding project of ours has applied to three different zones, each zone compose of multiple layers. These zones are defined as the following:-

1- Zone - 6: The process done in regions defined as Aradeiba 'D' with total layers (64 to 64)

2- Zone - 7 known as Aradeiba 'E' consecutively, and are induced from layer 65 up to layer 74.

3- Zone - 14 :- This zone is so-called Bentiu 1D, and it ranges from layer 133 until layer150.

4- Zone - 17 :- This zone is known as Bentiu 2A, and it ranges from layer no 153 up to layer no 169 . In approach of doing this job, three different scenarios had done for evaluating the overall water flooding performance; as well as the optimum injection rate , pattern and mobility ratio has chosen after applying different flow rates and recording the result of each rate and making comparison based upon

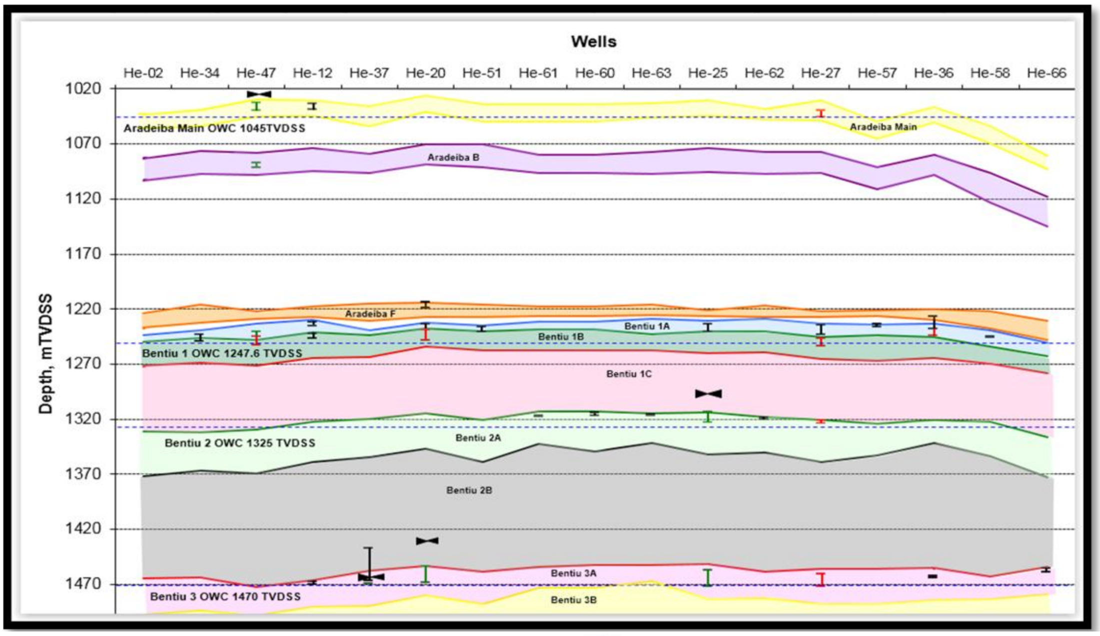


Fig- 12 stick diagram of target zone

3.3 Methodology:

CMG's builder tool allows the user to build a dataset by following logical series of creation steps. These steps defined in builder's tree view (Shown below Fig - 13) help in leading the user to a fully defined data easily and accurately.

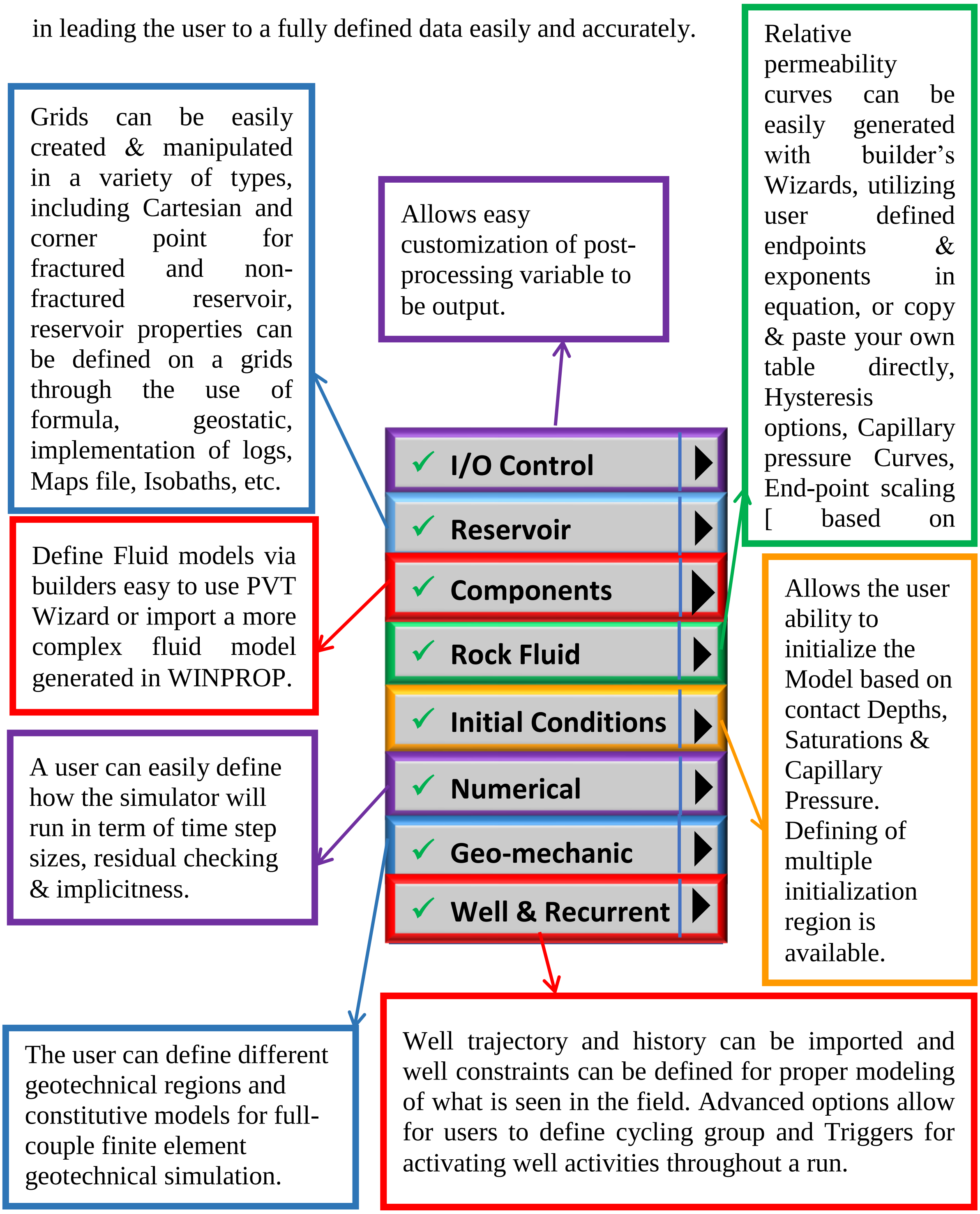


Fig- 13 CMG builder interface

3.4 Steps of bulding a water flooding model using CMG software:

1- I/O Control: This step involves in choose of a proper unit for the model as well as the validation method (IMEX, GEM or STARS). As in figure (14)

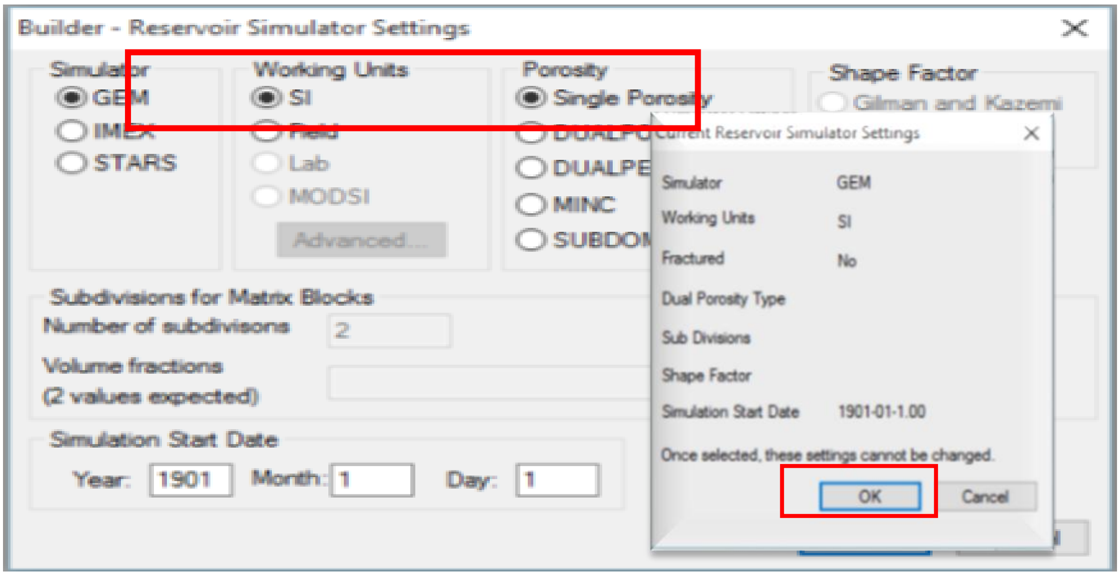


Fig – 14 illustrate I/O Control

2- Reservoir: This involves the definition of pattern type, pattern area, thickness of reservoir and etc. As in figure (15) below:

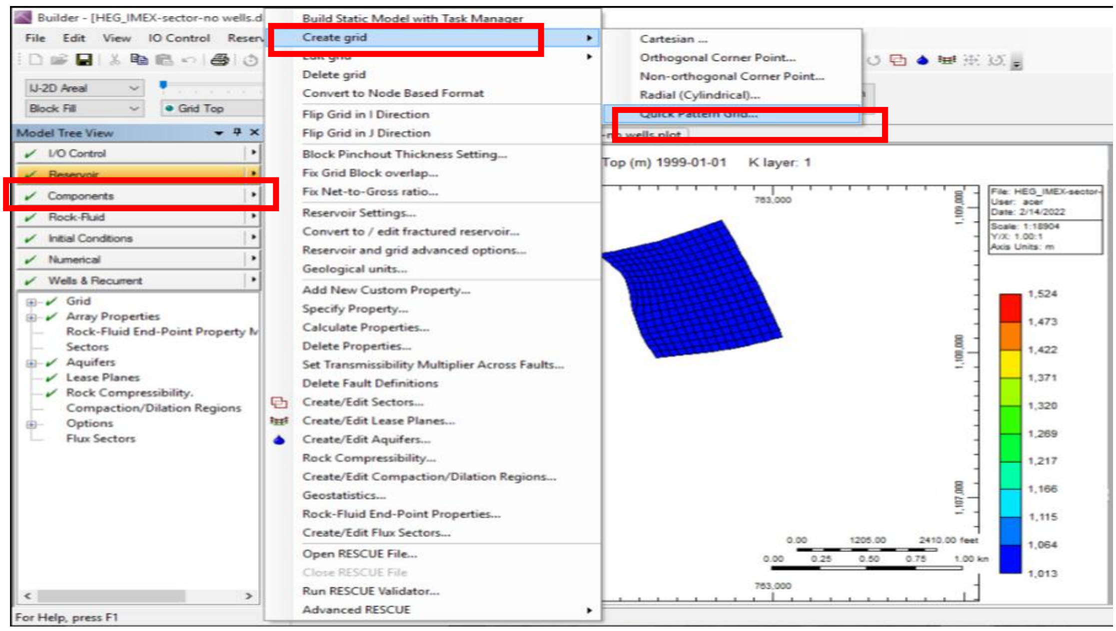


Fig 15 input or edit reservoir data

3- Component: Include the definition of PVT (Black oil PVT model) and definition of units (SI). Figure (16)

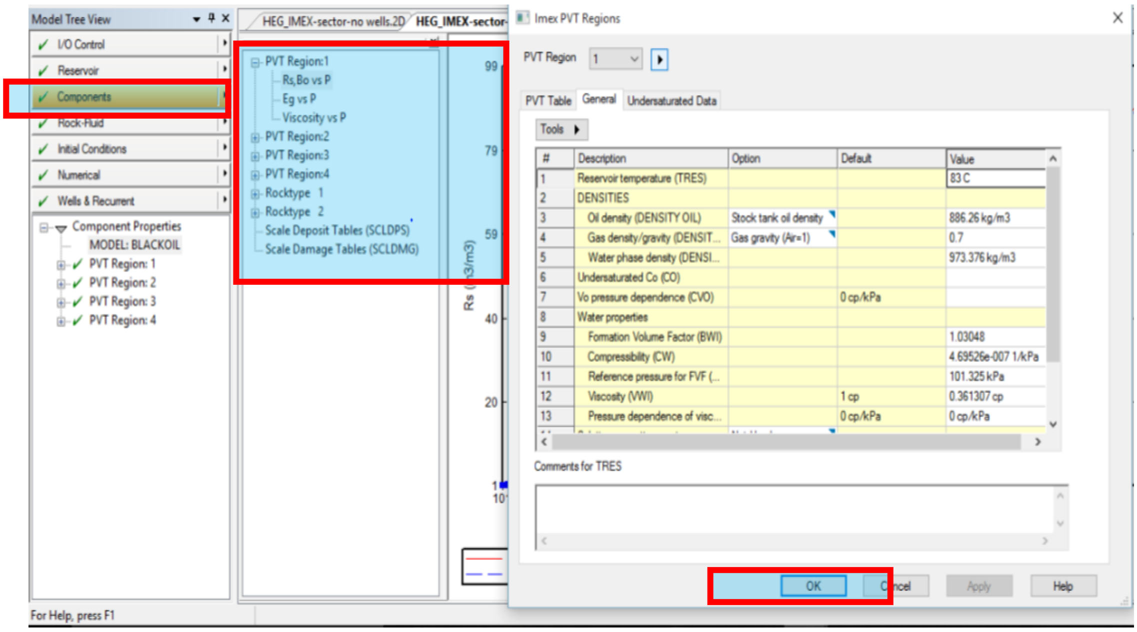


Fig – 16 show Component and other variables.

4- Rock & Fluid properties: Requires the definition of rock type and fluid properties (water saturation, capillary pressure and relative permeability). Show figure (17).

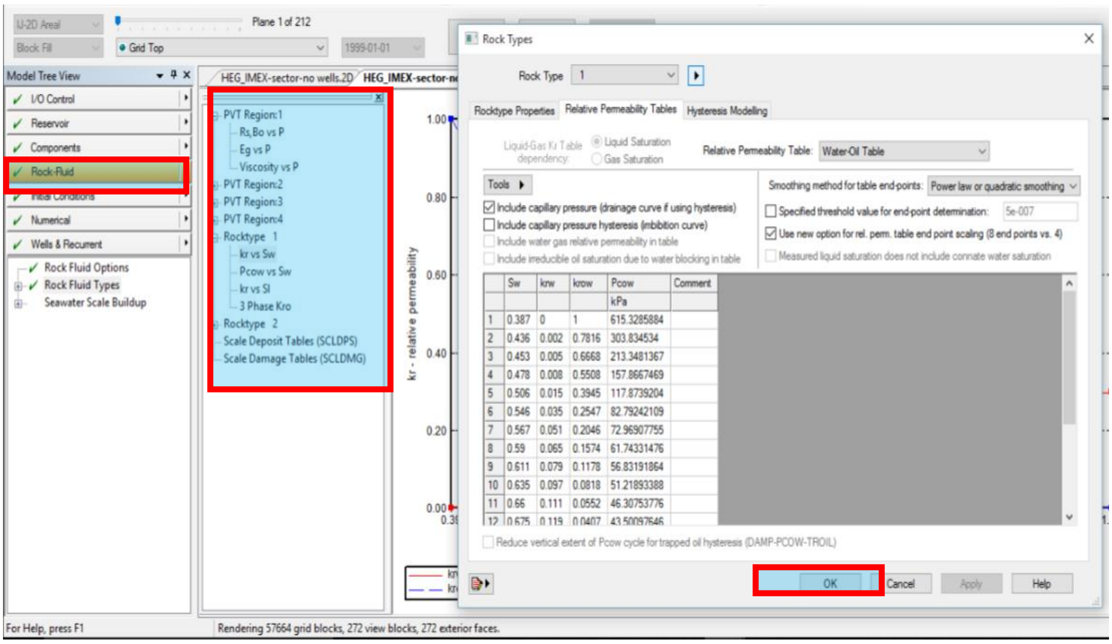


Fig – 17 represent Rock & Fluid properties

5- Initial conditions: Involves determining of reference pressure, reference depth, gas oil and water oil contacts and etc. As figure (18) shows.

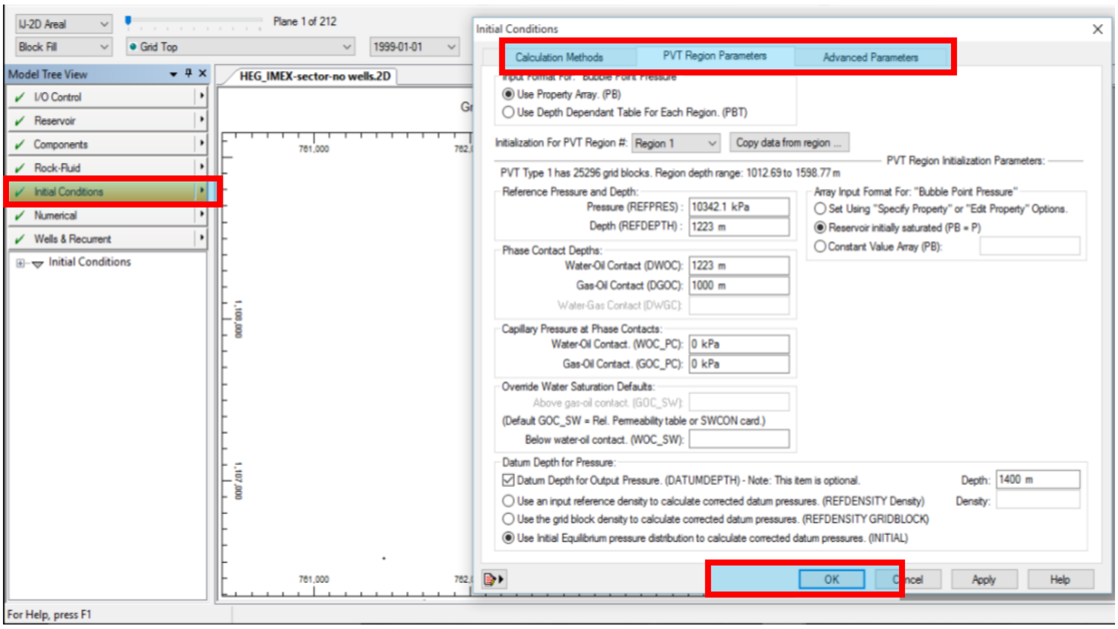


Fig – 18 Initial conditions layout

6- Numerical: Involves time step adjustments plus a lot of numerical equations. As shown in figure (19).

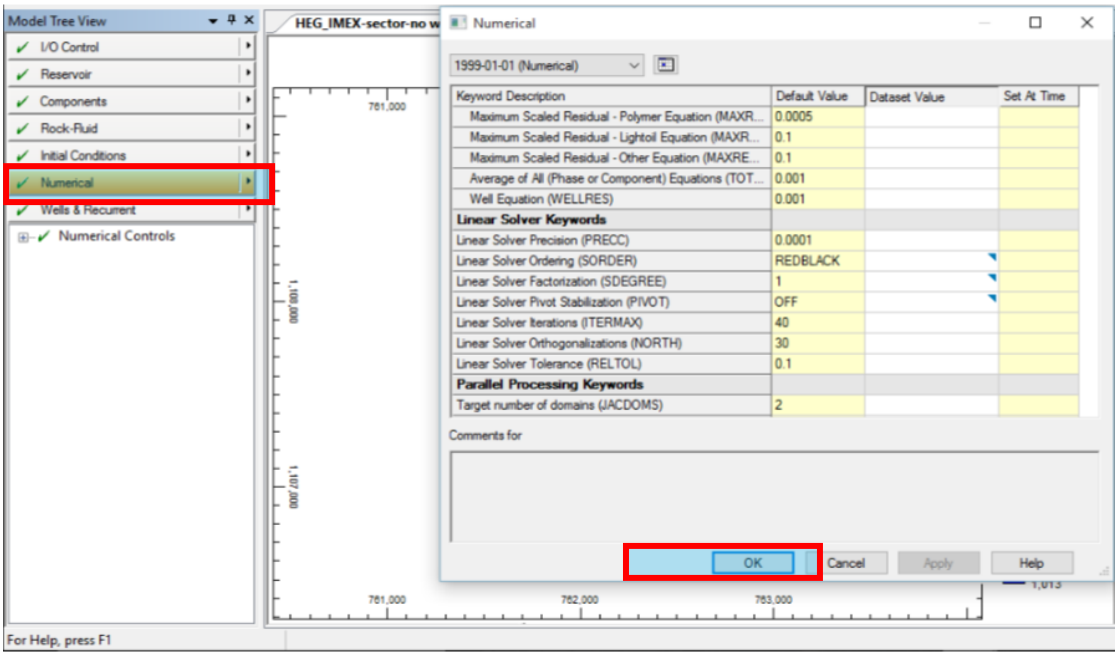


Fig – 19 layout of Numerical icon

7- Well & Recurrent: This involves definition of wells well constraints, dates, perforations and their events. Show figure (20) below.

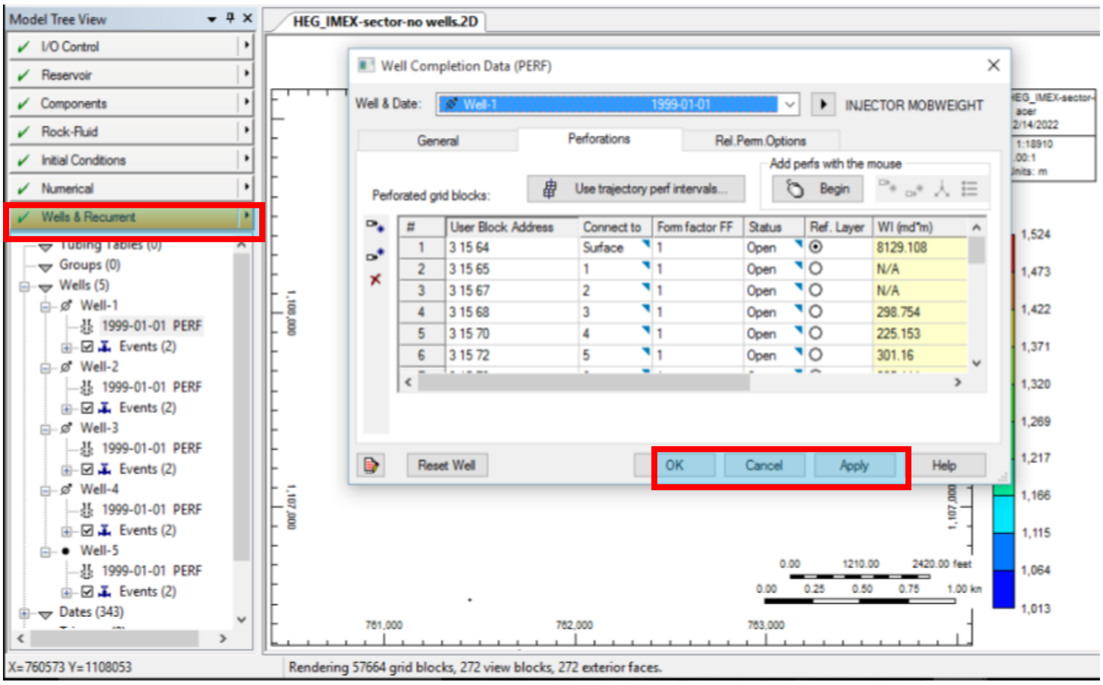


Figure (20) well perforation process or selecting injection interval

8- This step to adapt the prediction period hence to be ready to run as coming in the following figure.

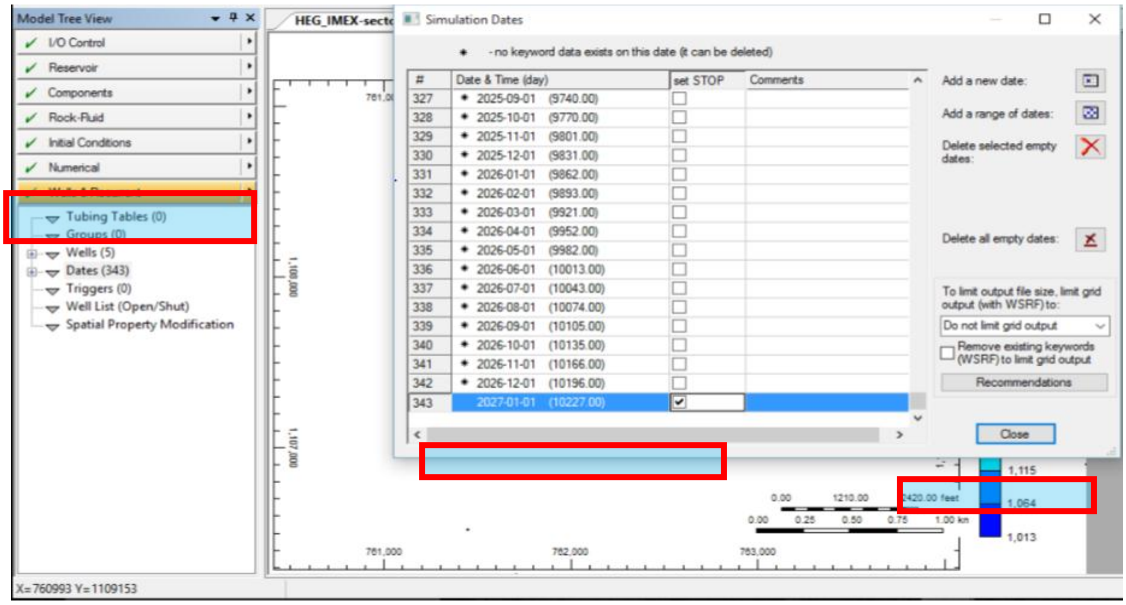


Figure (21) the setting of prediction date

3.5 Raw HE field Data used (only for scope of study)

Table A- 2 illustrate fluid properties data

Pcow (Kpa)	M Assumed	Krw (md)	Kro (md)	µo (cp)	µw (cp)(calculated)	Sw (%)
303.834534	0.1	0.002	0.7816	4.75505	1.858274	0.436
213.3481367	1	0.005	0.6668	4.70699	0.6277242	0.453
157.8667469	10	0.008	0.5508	4.65808	0.3207088	0.478
117.8739204	25	0.015	0.3945	4.60864	0.4848289	0.506

Array Properties

Table A- 3 contain array properties

I direction	J direction	K direction
1	1	1

Table A – 4 all target zones

Properties	Zone - 6.	zone – 7.	zone - 14	zone - 17
Region depth	1012.69 – 1598.77 m	1216.76 – 1598.77 m	1296.6 – 1598.77 m	1439.21 – 1598.77 m
WOC	1223 m	1302 m	1443 m	1500 m
P	10342.1 kpa	12410.6 kpa	13789.5 kpa	17236.9 kpa
Depth	1223 m	1302 m	1443 m	1500 m

General PVT Data :

Table A – 5 Basic HE reservoir properties

Structural	Heglig Main	
Reservoir	Benti-1/2/3	Aredieba
Top depth (m)	1630/1720/1860	1430
Porosity	0.24/0.21/0.22	0.22
Permeability md	50 -6000	2500

Oil density = 886.26 kg/m^3

Reservoir Temperature = 83 C

Water density = 973.376 kg/m3

Rock compressibility = 2.61068 x 10^{-6} 1/kpa

Water viscosity = 0.361307 cp

S.G = 0.7 Cw = 4.9526 E007 1/kpa

3.6 Implemented Scenarios:

Three scenarios are implemented in many in 20 cases for 43 layers as following:

<u>Scenario – 1 (4 cases)</u>

Has taken constant Mobility ratio (0.1) and injection rate (5000 m^3/d) by maintain changing in flood pattern (Normal and inverse 5-spot, 7-spot and peripheral) Where the forecast is done without any other activities added.

Case – 1 Normal 5-spot.

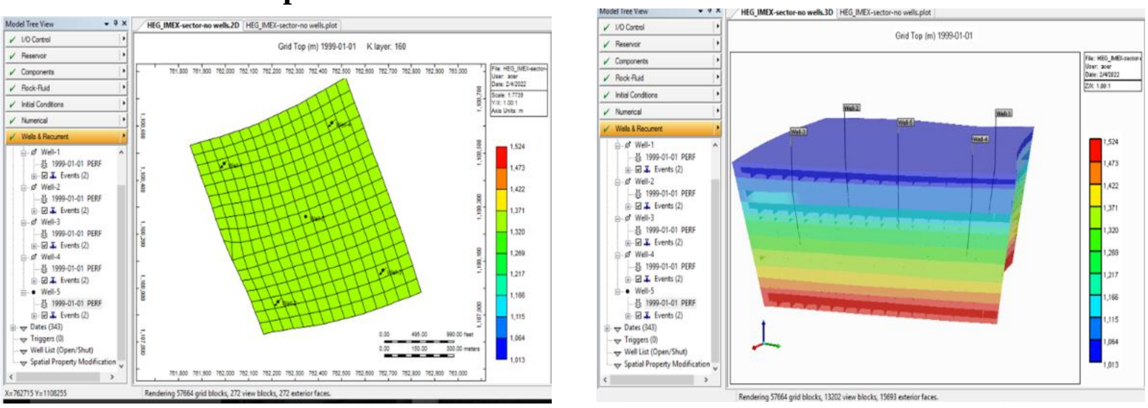


Fig – 22 shows layout of case - 1

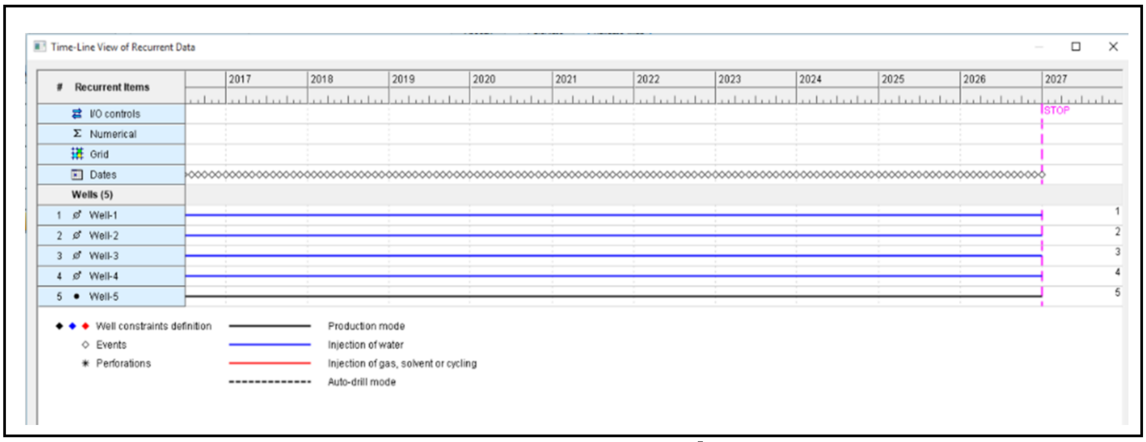


Fig – 23 Case - 1 timeline

Case – 2 Inverse 5-spot (with same timeline of case -1)

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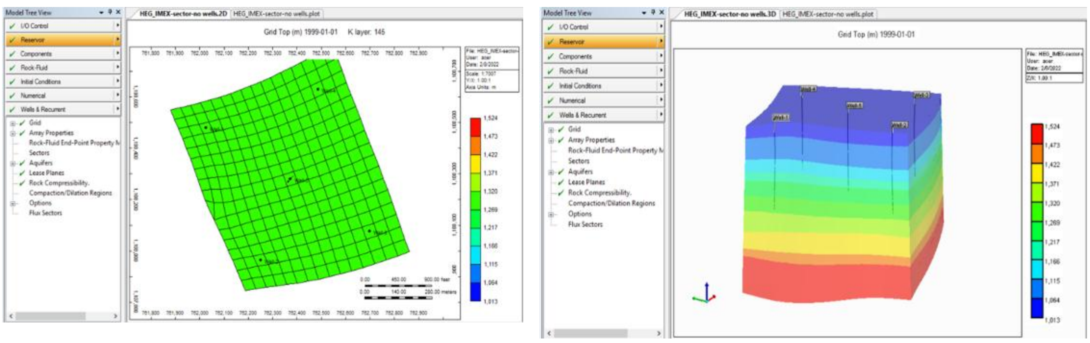


Fig – 24 shows layout of case -2

Case – 3 Inverse 7-spot (2 infill wells added to previous case hence there are 6 producer& 1 injection)

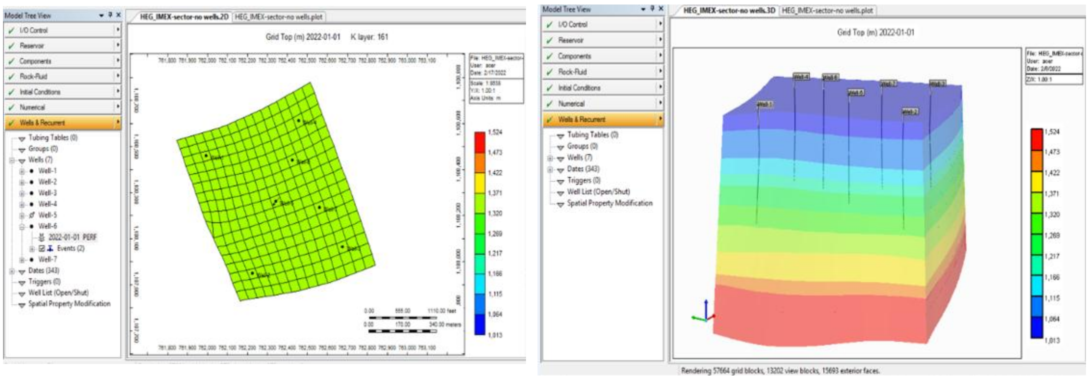


Fig – 25 shows layout of case -3

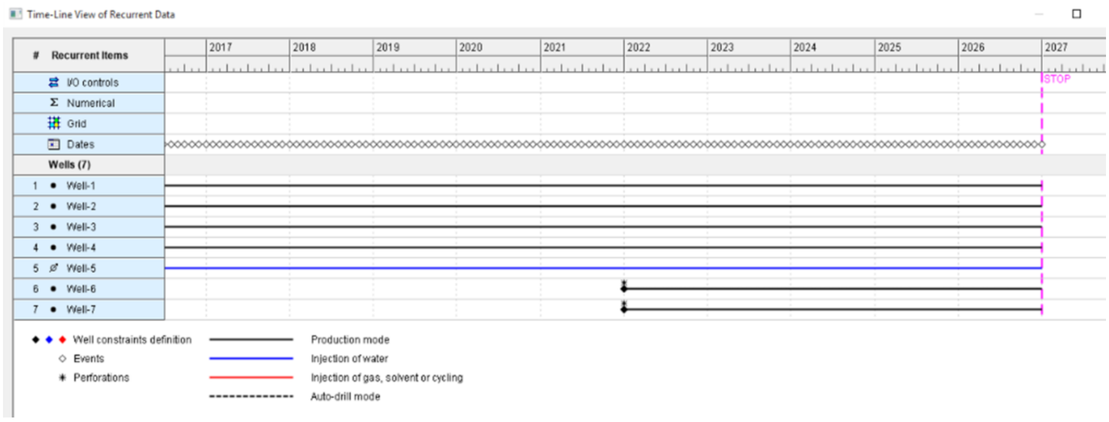


Fig – 26 Case - 3 timeline

Case – 4 Peripheral pattern : with a total of 9 wells **(2wells added in 2022, 2 wells in2023**) which all were operated until the year 2027 maintained 7 wells injectors and two producers to form a peripheral like shape.

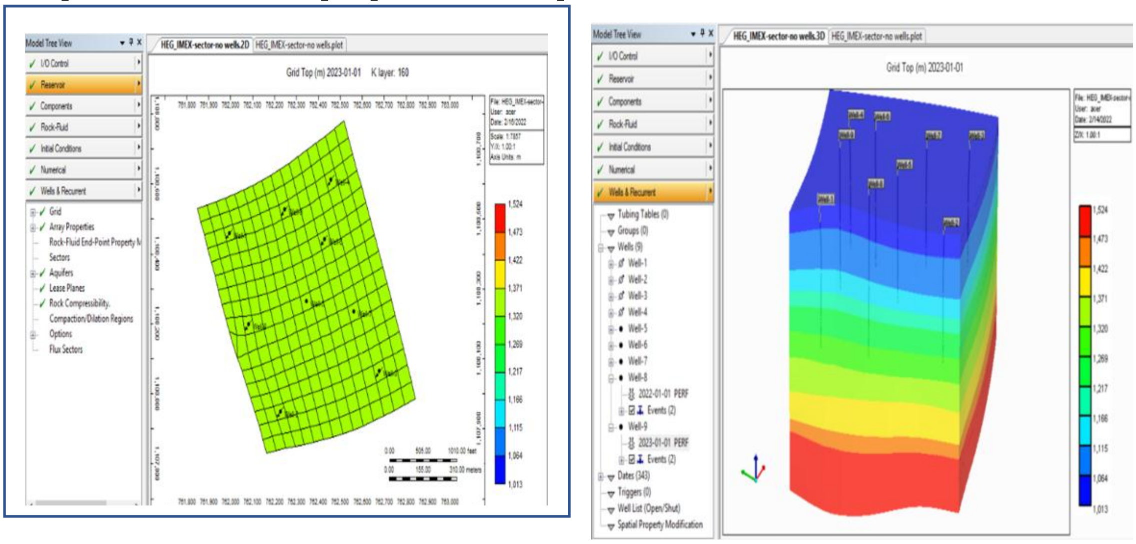


Fig – 27 shows layout of case – 4

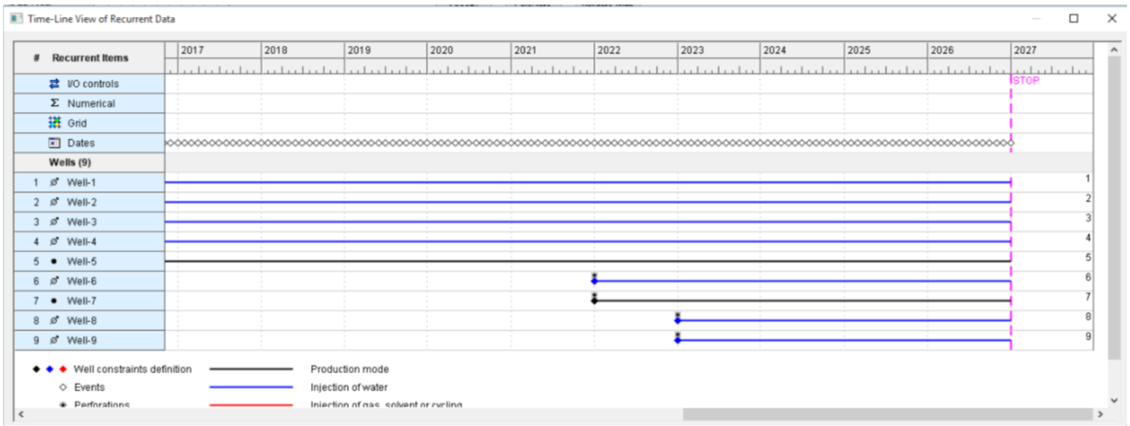


Fig – 28 Case - 4 timeline

Scenario – 2 (8 cases)

In this scenario Has taken constant Mobility ratio (0.1) and flood pattern by maintain changing in injection rate (2000 & 7000 m^3/d) Where the timeline and other figures are same as mentioned in scenario – 1.

Scenario – 3 (8 cases)

Consisting from 8 cases which considered constant flood pattern and injection rate and taken changed in mobility ratio by calculated desired viscosity of injected water

(All above scenarios Results will be discussed carefully in next chapter).

Chapter Four

Results and Discussion

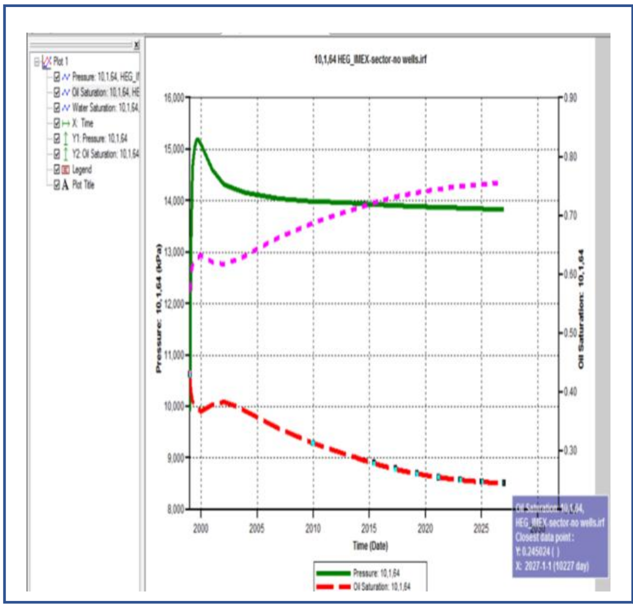
4.1 Introduction:

This chapter consist of whole results and it discussion .

Scenario-1:

This scenario is done at constant injection rate (5000 m^3/day) and it includes four different cases, case-1(normal five spot), case-2 (inverse five spot),case-3 (inverse seven spot) and case-4(peripheral of nine wells).

Case -1 Normal five spot:



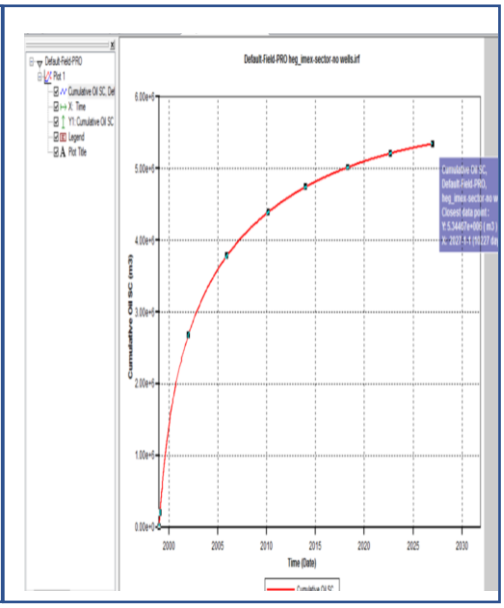
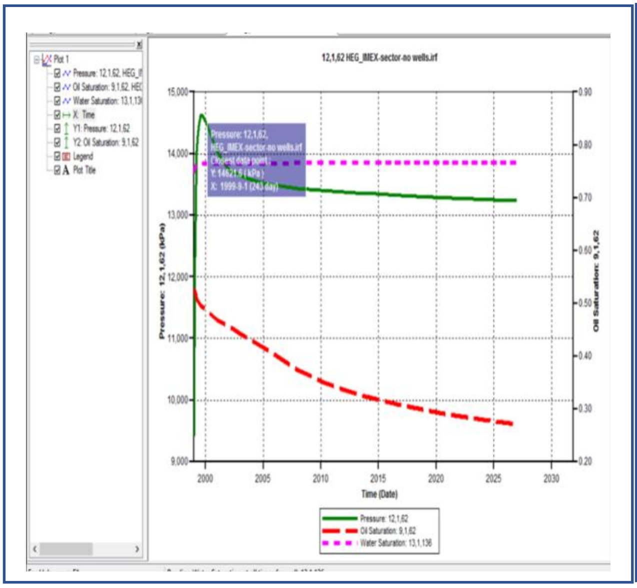


Fig – 29 shows reservoir's liquid S1C1 Fig – 30 shows cum-oil produce S1C1

Case - 2 Inverse 5 - spot



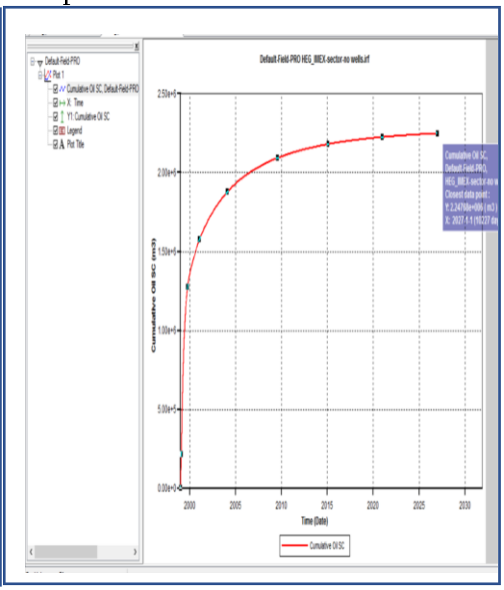
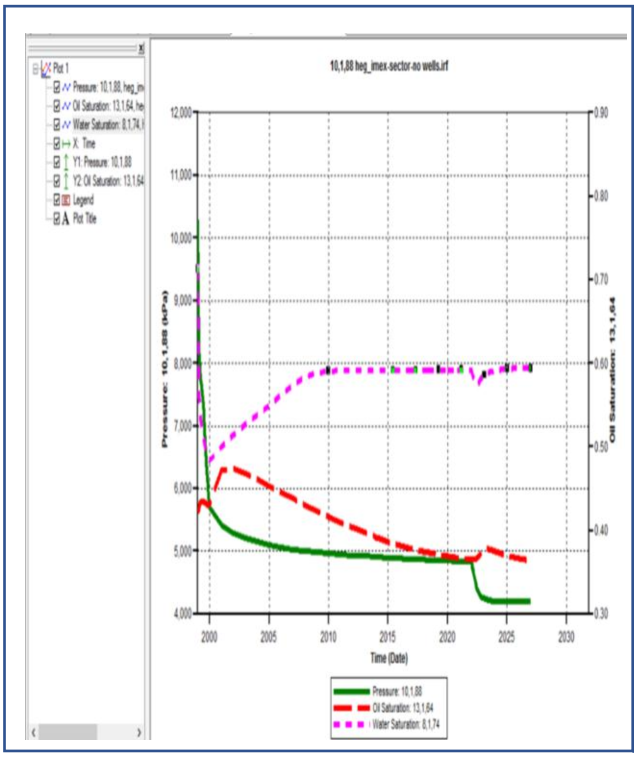


Fig – 31 shows reservoir's liquid S1C2 Fig – 32 shows cum-oil produce S1C2

Case – 3 Inverse seven spot:



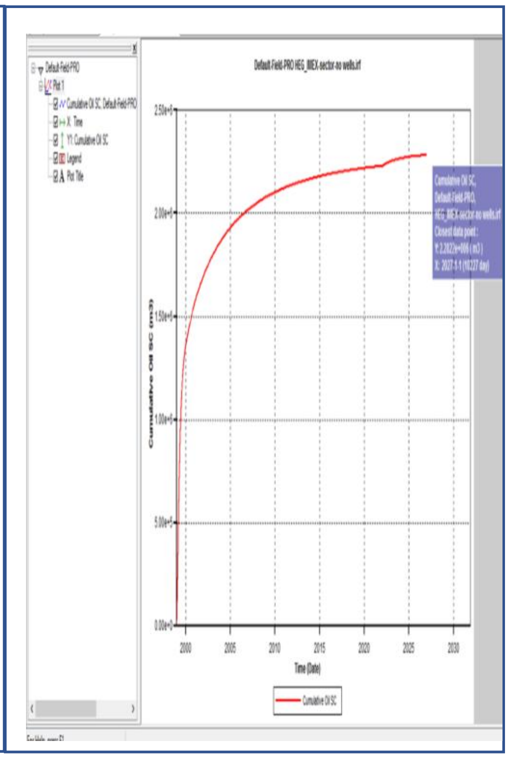
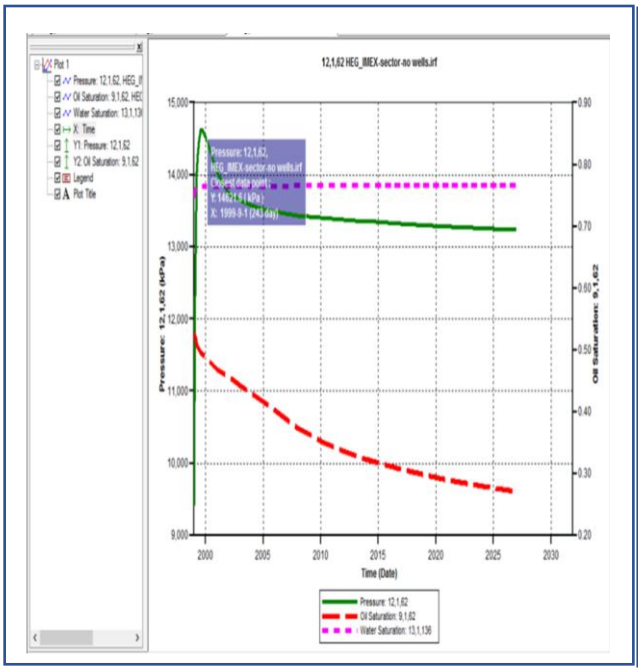


Fig – 33 shows reservoir's liquid S1C3 Fig – 34 shows cum-oil produce S1C3

Case – 4 Peripheral Pattern(nine wells



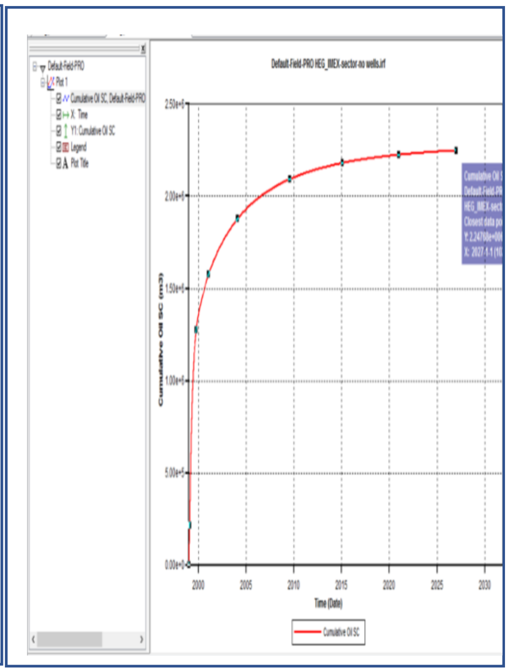
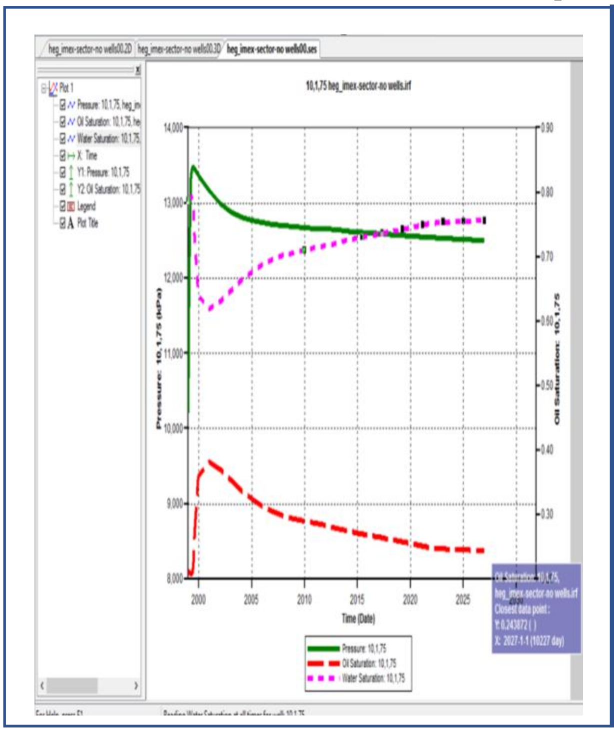


Fig – 35 shows reservoir's liquid S1C4 Fig – 36 shows cum-oil produce S1C4

Scenario -2 :

Case -1 Normal five spot at rate of 2000 m^3/day



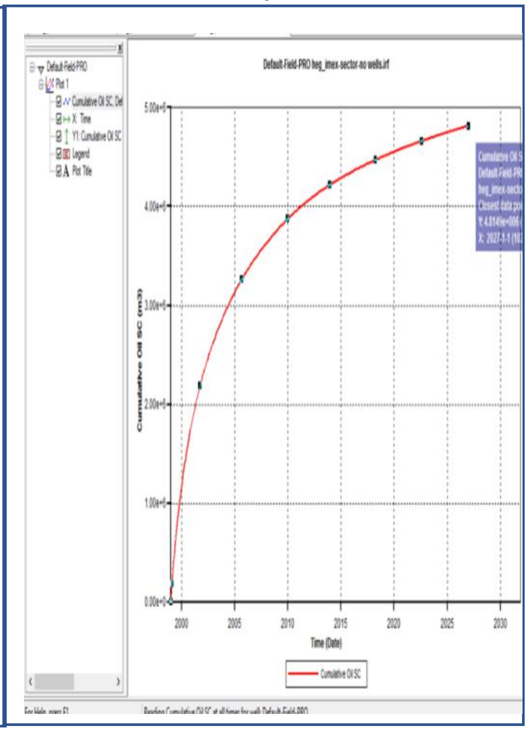
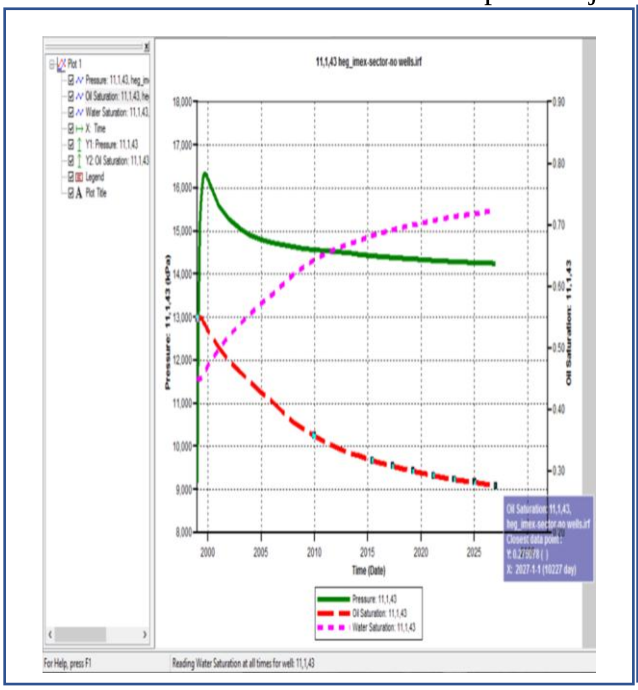


Fig – 37 shows reservoir's liquid S2C1 Fig – 38 shows cum-oil produce S2C1

Case - 2 Normal 5- spot at injection rate of 7000 m^3/day



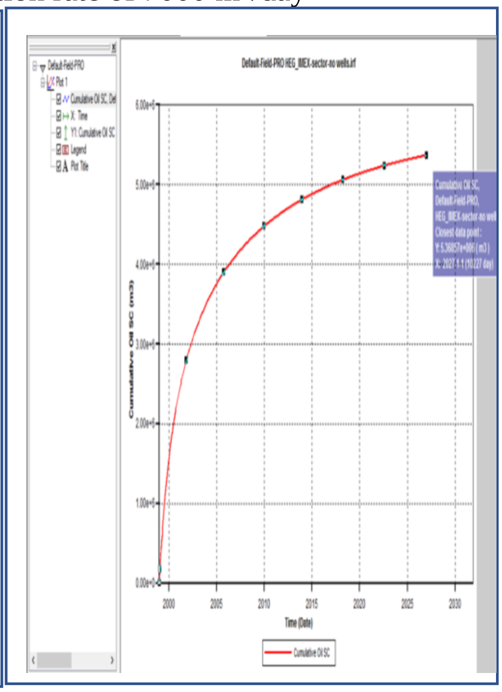
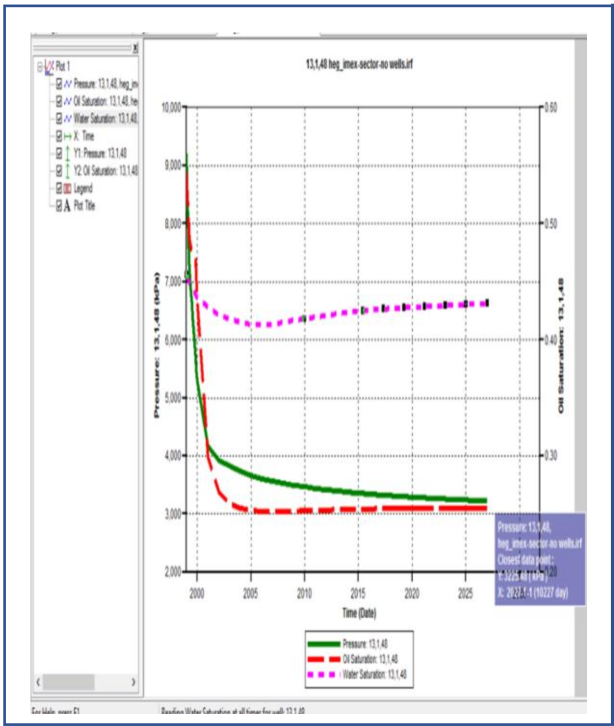


Fig – 39 shows reservoir's liquid S2C2 Fig – 40 shows cum-oil produce S2C2

Scenario -2 :

Case - 3 Inverse five spot at rate of 2000 m^3/day



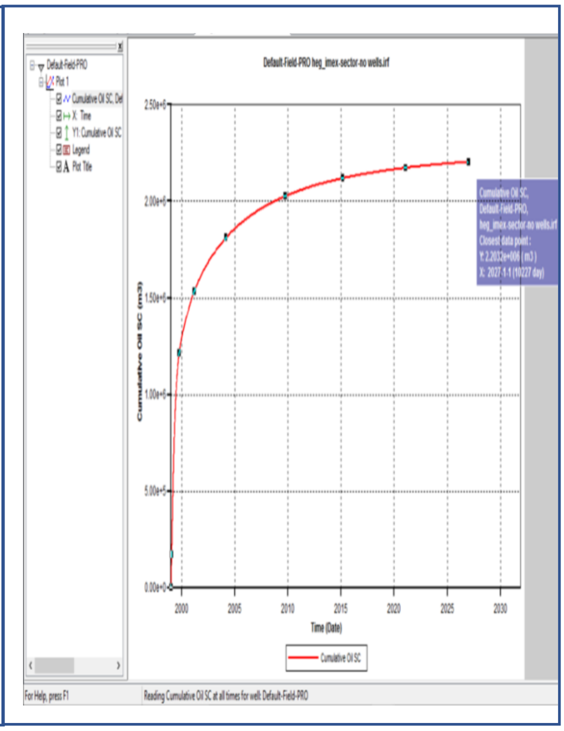
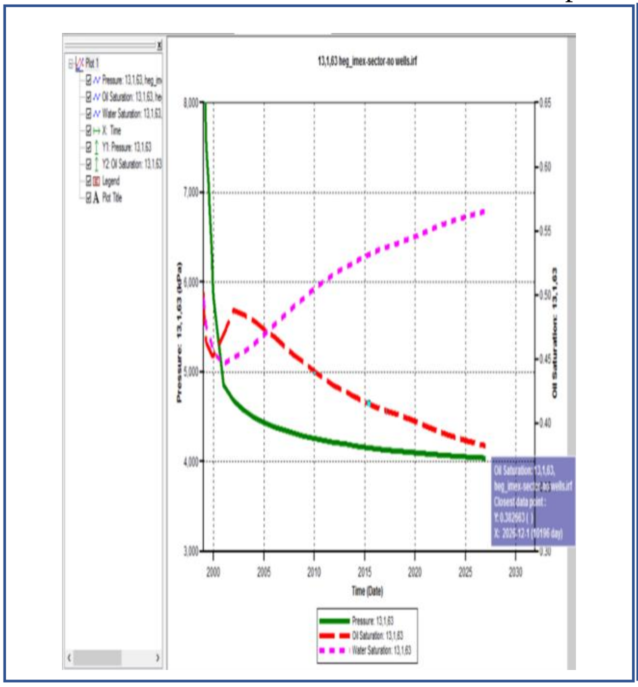


Fig – 41 shows reservoir's liquid S2C3 Fig – 42 shows cum-oil produce S2C3

Case - 4 Inverse seven spot at rate of 7000 m^3/day



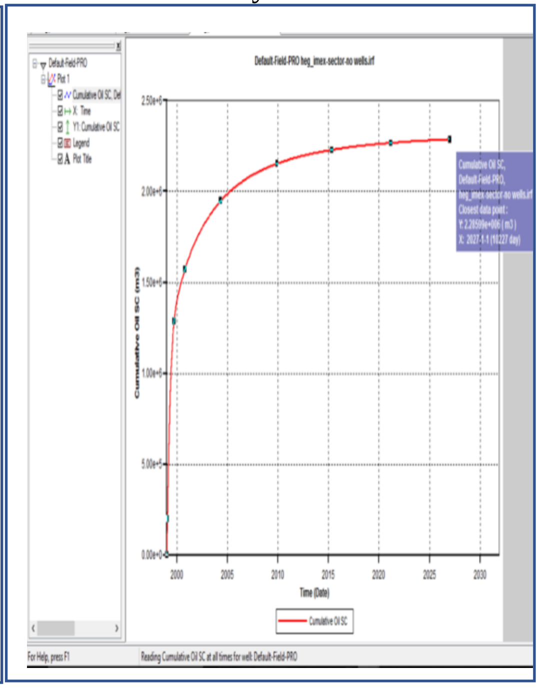
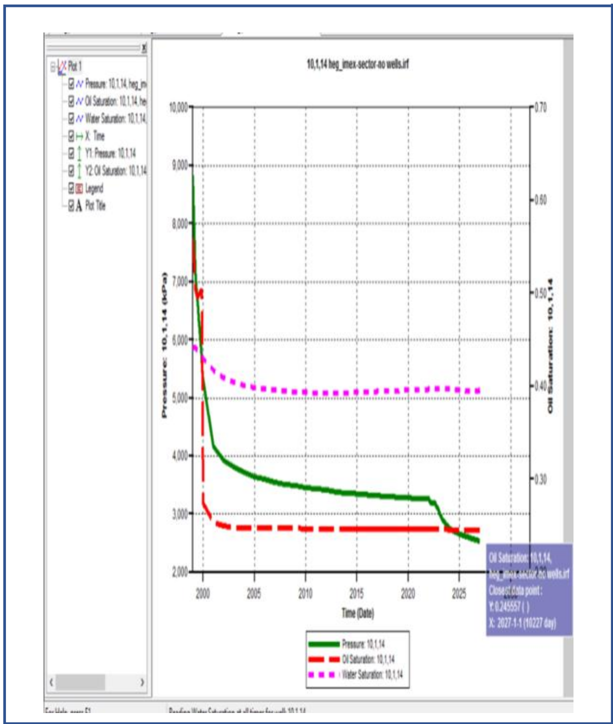


Fig –43 shows reservoir's liquid S2C4 Fig – 44 shows cum-oil produce S2C4

Scenario -2

Case -5 Inverse seven spot at injection rate of 2000 m^3/day



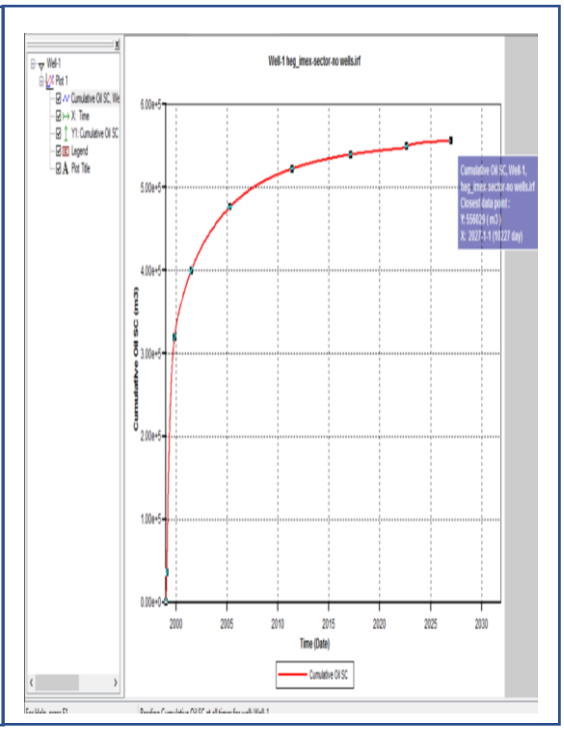
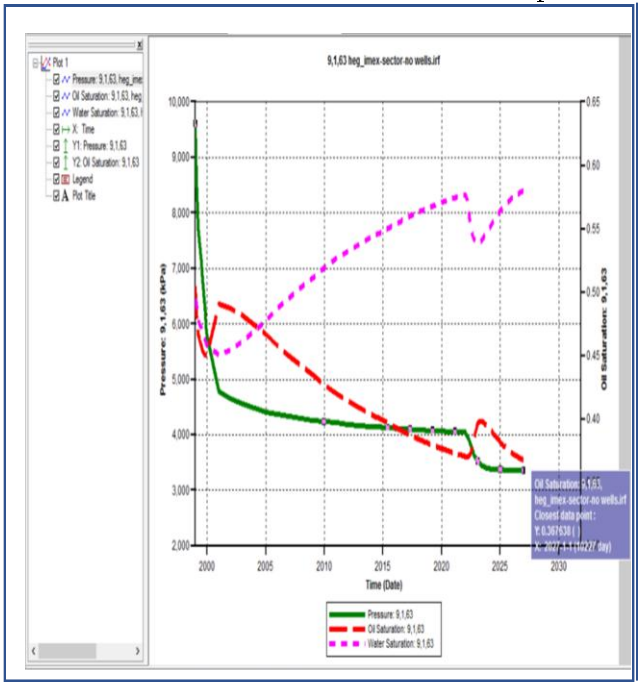


Fig – 45 shows reservoir's liquid S2C5 Fig – 46 shows cum-oil produce S2C5

Case - 6 Inverse five spot with rate of 7000 m^3/day



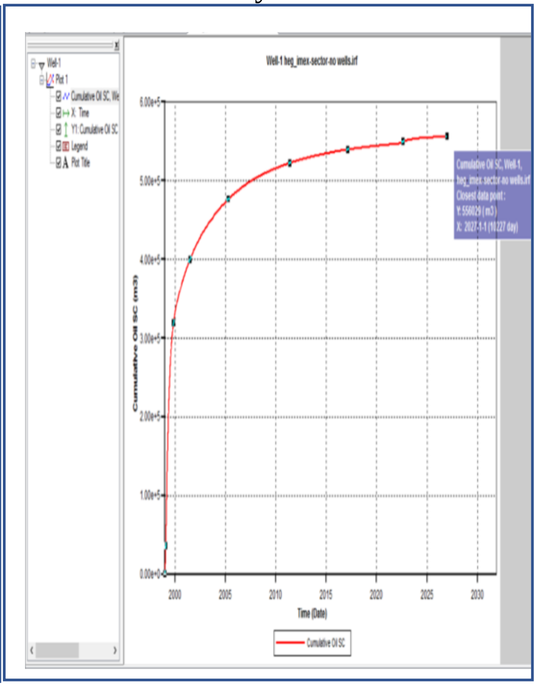
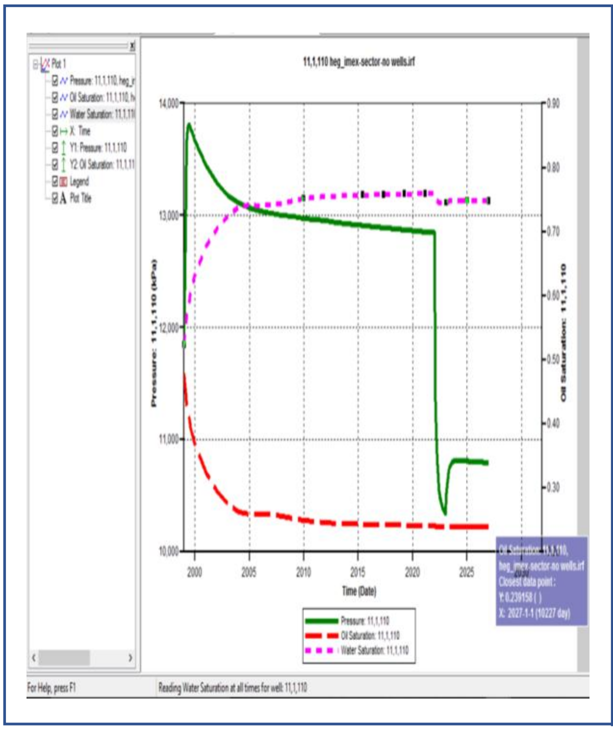


Fig –47 shows reservoir's liquid S2C6 Fig – 48 shows cum-oil produce S2C6

Scenario -2

Case -7 Peripheral pattern at rate of 2000 m^3/day



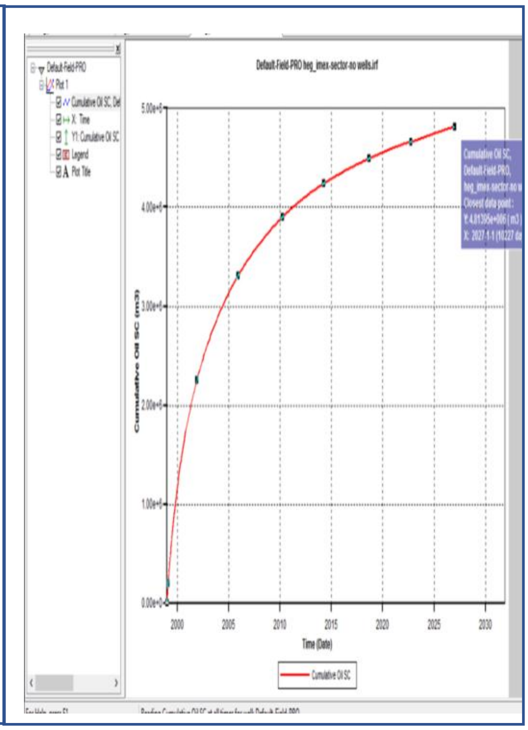
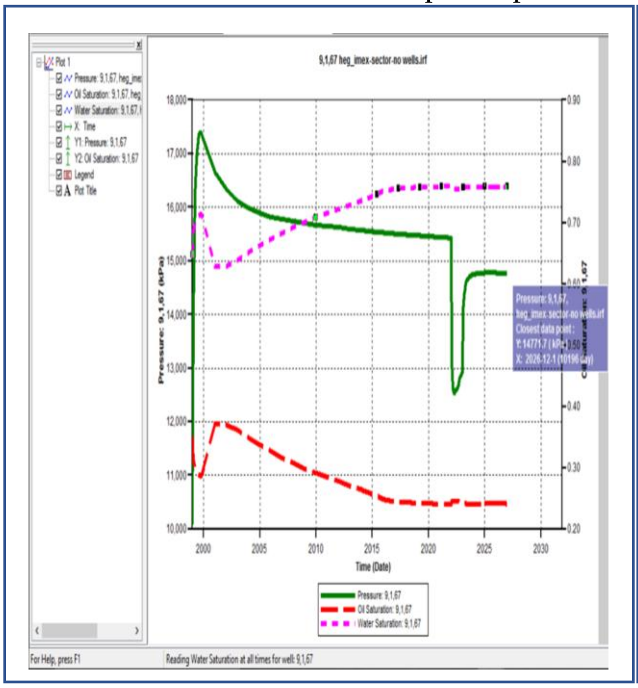


Fig – 49 shows reservoir's liquid S2C7 Fig – 50 shows cum-oil produce S2C7

Case - 8 Peripheral pattern at rate of 7000 m^3/day



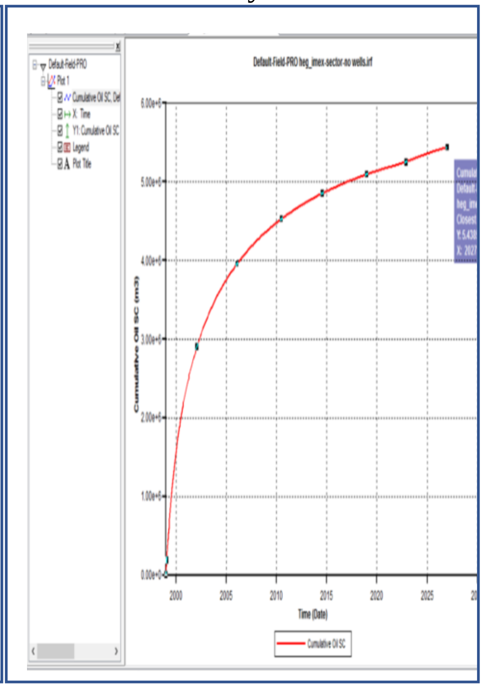
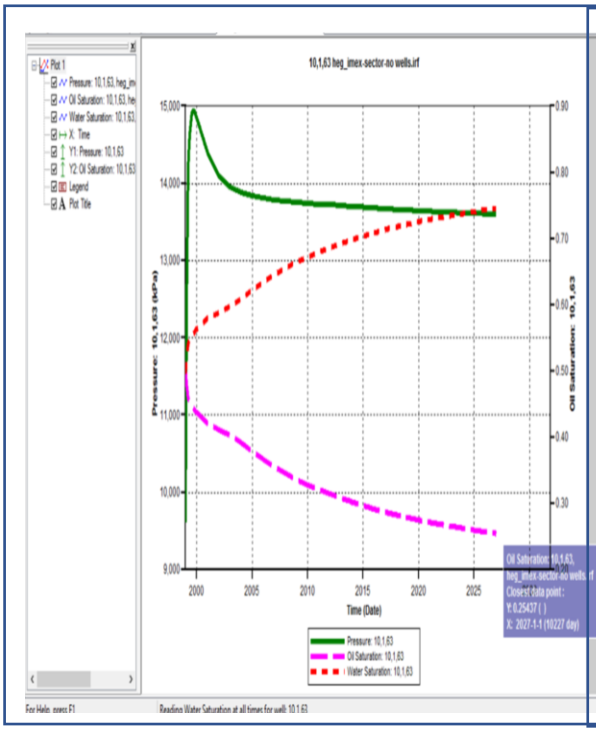


Fig – 51 shows reservoir's liquid S2C8 Fig – 52 shows cum-oil produce S2C8

Scenario - 3

Case - 1 Normal five spot with mobility ratio =1



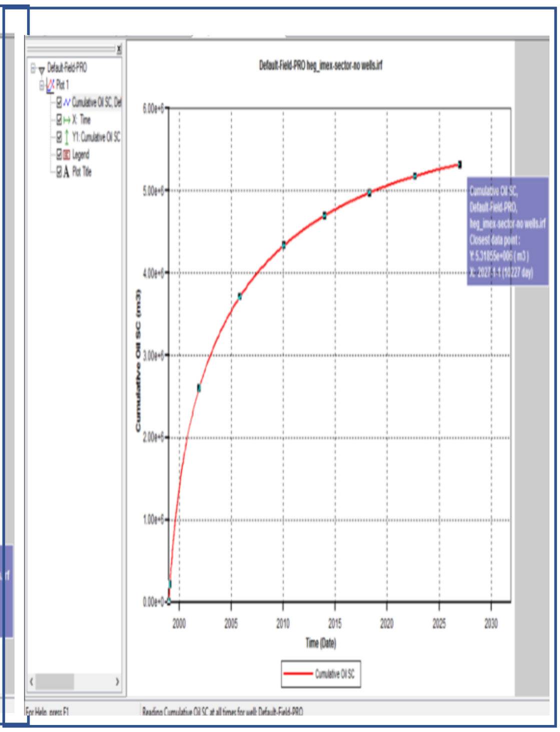
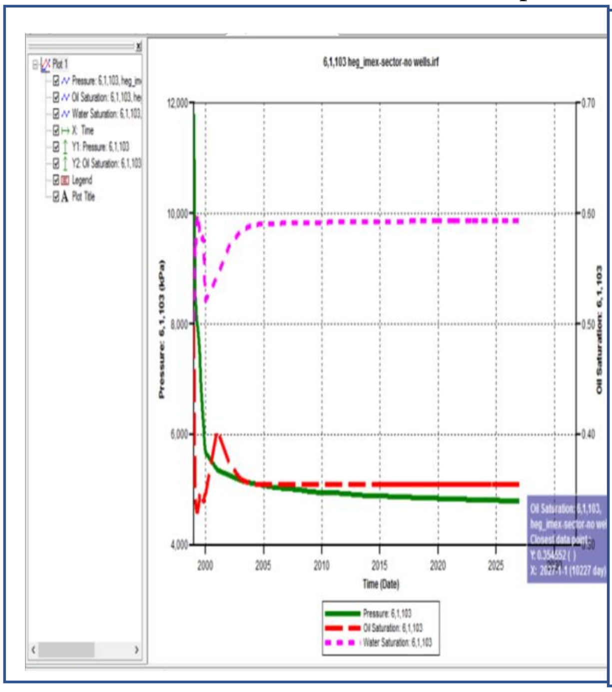


Fig – 53 shows reservoir's liquid S3C1 Fig – 54 shows cum-oil produce S3C1

Case – 2 Normal 5- spot with Mobility ratio (M=1)



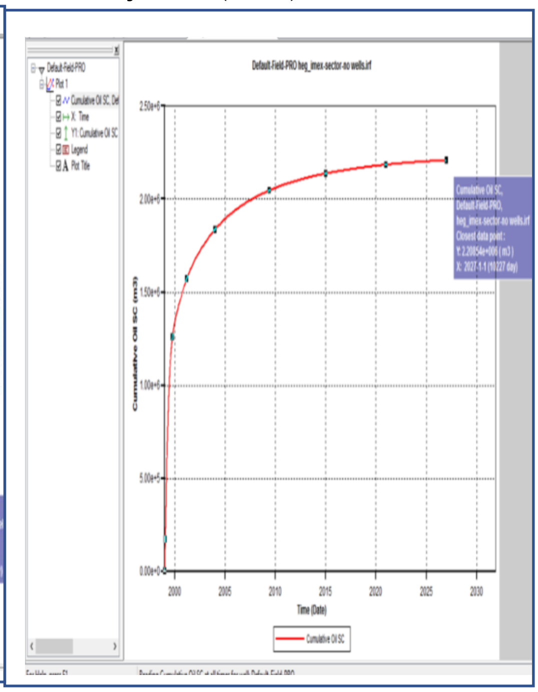
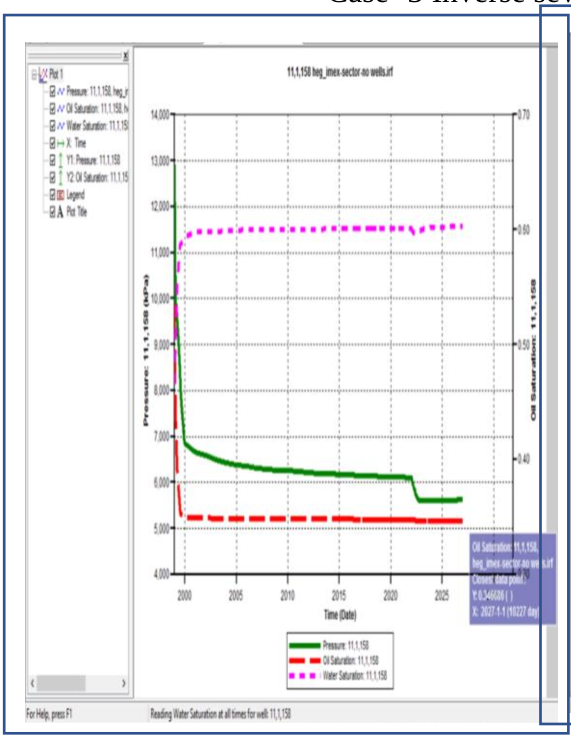


Fig –55 shows reservoir's liquid S3C2 Fig – 56 shows cum-oil produce S3C2

Scenario - 3

Case -3 Inverse seven spot with (M=1):



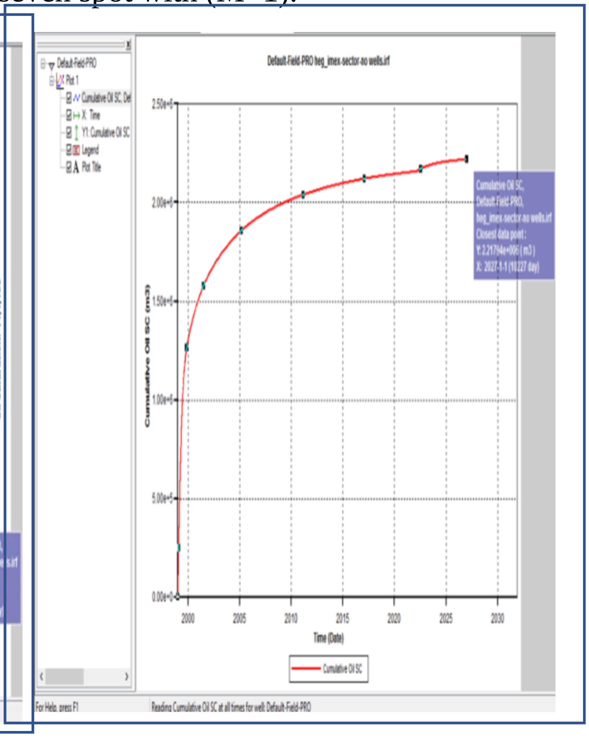
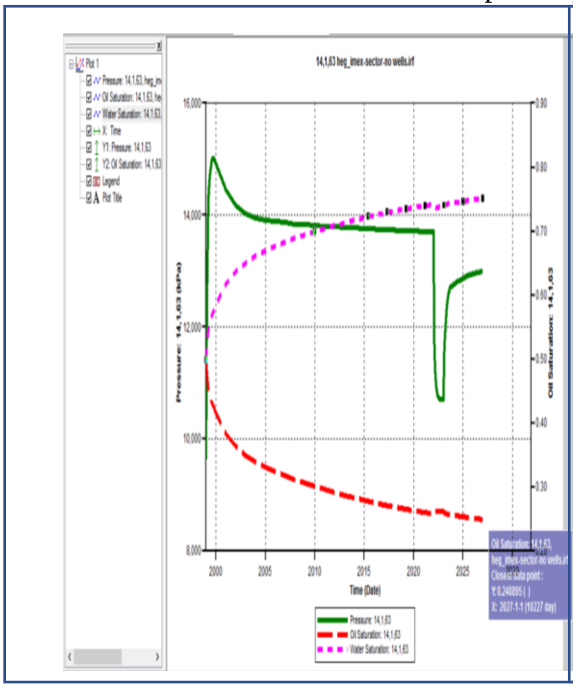


Fig – 57 shows reservoir's liquid S3C3 Fig – 58 shows cum-oil produce S3C3

Case - 4 Peripheral pattern with (M= 1)



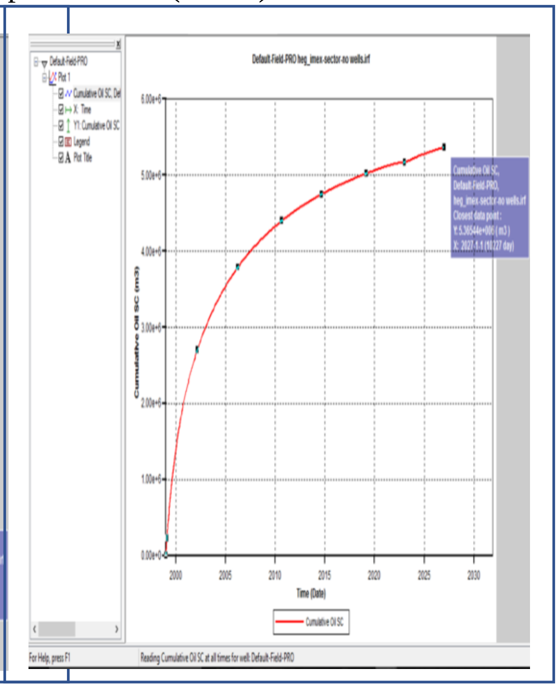
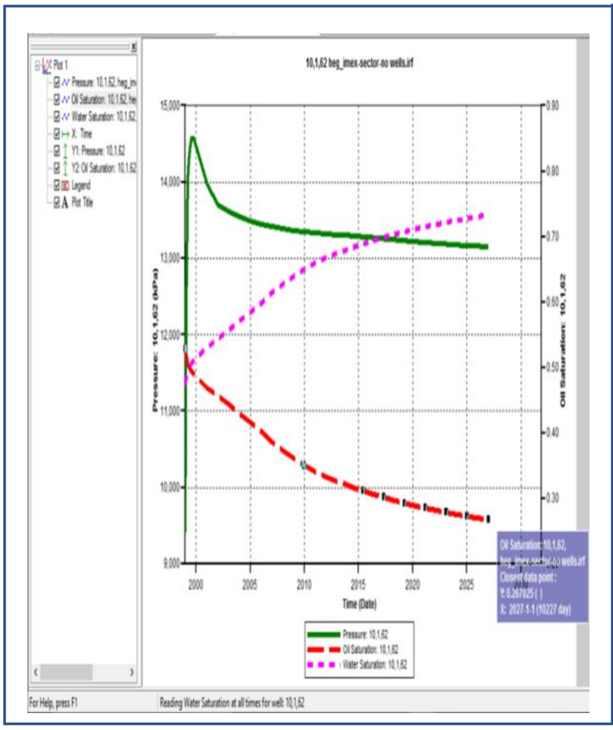


Fig – 59 shows reservoir's liquid S3C4 Fig – 60 shows cum-oil produce S3C4

Scenario - 3

Case -5 Normal five spot with mobility ratio of (M=10).



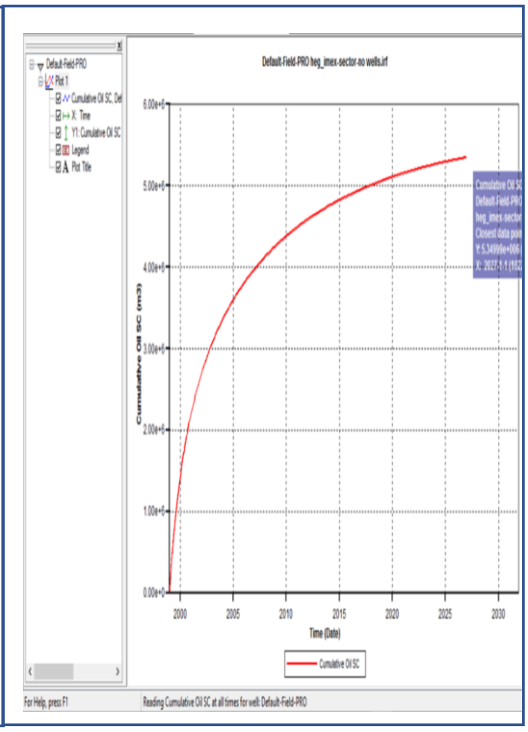
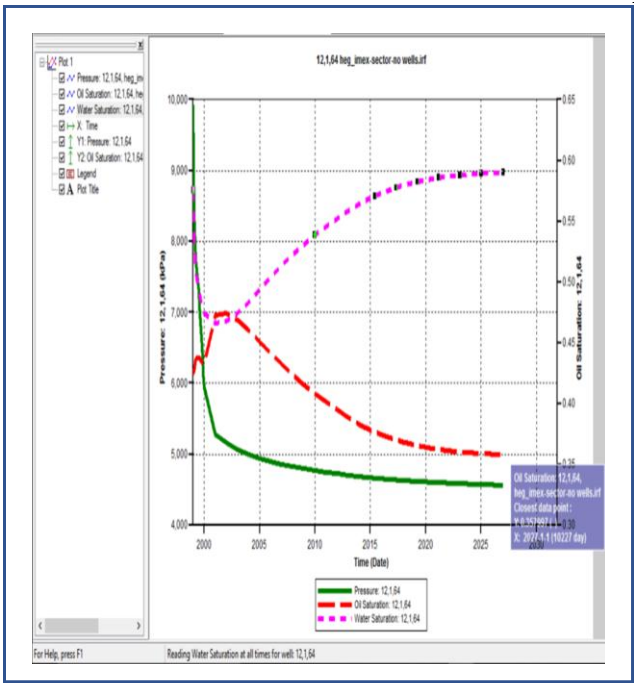


Fig – 61 shows reservoir's liquid S3C5 Fig – 62 shows cum-oil produce S3C5

Case - 6 Inverse 5 – spot (M= 10)



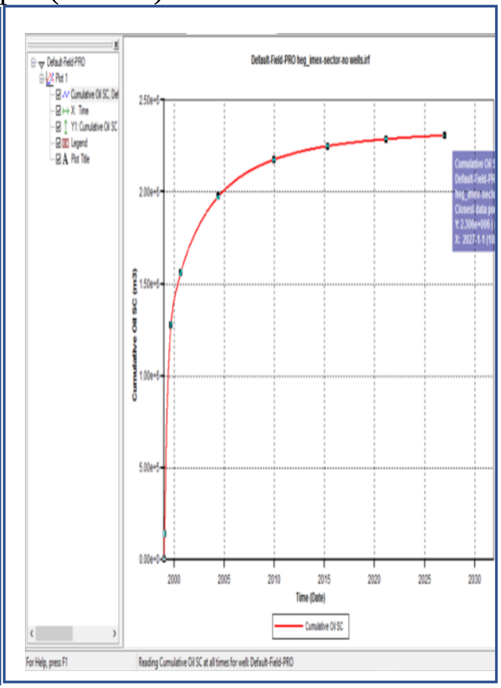
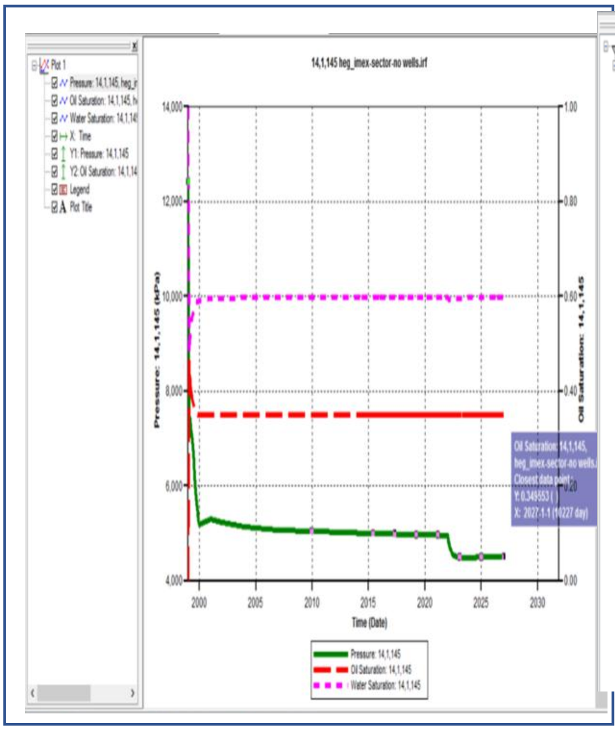


Fig –63 shows reservoir's liquid S3C6 Fig – 64 shows cum-oil produce S3C6

Scenario - 3

Case -7 Inverse seven spot with mobility ratio of (M=10):



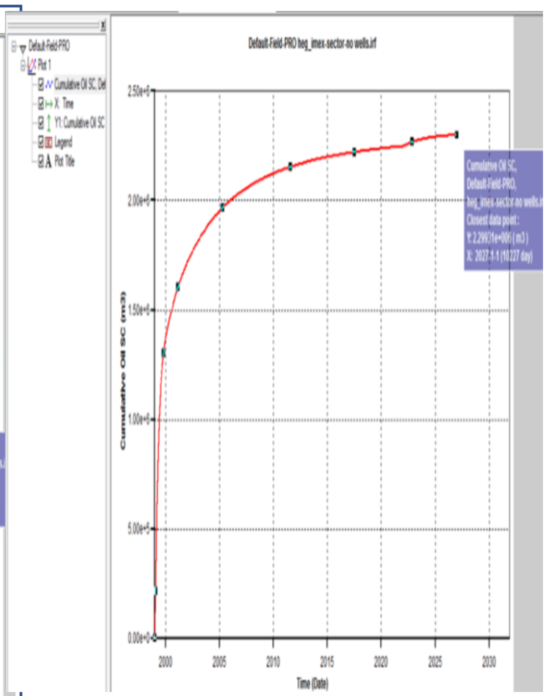
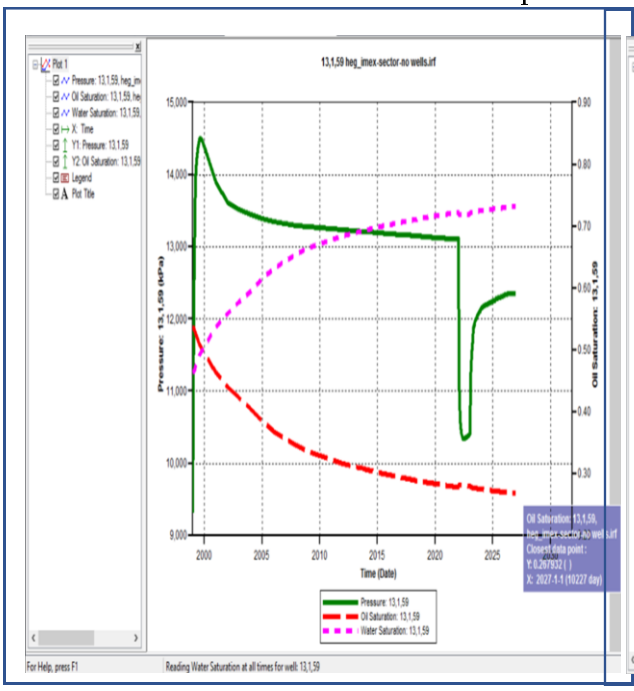


Fig – 65 shows reservoir's liquid S3C7 Fig – 66 shows cum-oil produce S3C7

Case - 8 Peripheral with (M =10)



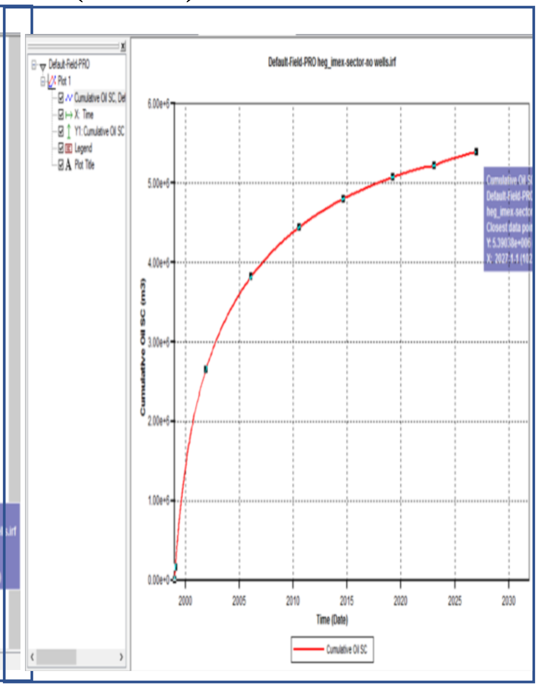


Fig – 67 shows reservoir's liquid S3C8 Fig – 68 shows cum-oil produce S3C8

4.2 Summarized Results in tables

Table A - 6 Results of scenario one:

Scenario no	Case No.	Flood pattern	Injection rate(m^3/day)	Mobility ratio	Cumulative oil produced (m^3)
1	1	Normal five spot	5000	0.1	5.344 x 10^6
	2	Inverse five spot	5000	0.1	2.247 x 10^6
	3	Inverse seven spot	5000	0.1	2.282 x 10^6
	4	Peripheral pattern (9 wells)	5000	0.1	5.352 x 10^6

Table A – 7 Results of scenario Two:

Scenario no	Case No.	Flood pattern	Injection rate (m^3/day)	Mobility ratio	Cumulative oil produced (m^3)
2	1	Normal five spot	2000	0.1	4.815 x 10^6
			7000		5.368 x 10^6
	2	Inverse five spot	2000	0.1	2.203 x 10^6
			7000		2.286 x10^6
	3	Inverse seven spot	2000	0.1	0.556 x 10^6
			7000		1.032 x 10^6
	4	Peripheral (9 wells)	2000	0.1	4.814 x 10^6
			7000		5.438 x 10^6

Table A – 8 Results of scenario Three:

Scenario no	Case No.	Flood pattern	Injection rate (m^3/day)	Mobility Ratio	Cumulative oil produced (m^3)
3	1	Normal five spot	5000	1	5.318 x 10^6
				10	5.349 x 10^6
	2	Inverse Five Spot	5000	1	2.209 x 10^6
				10	2.306 x 10^6
	3	Inverse seven spot	5000	1	2.218 x 10^6
				10	2.299 x 10^6
	4	Peripheral (9 wells)	5000	1	5.365 x 10^6
				10	5.390 x 10^6

4.3 Discussion of Results

Scenario one:

According to table A-6 above for scenario one, we noticed that the highest cumulative oil production is that obtained from case-4 and case-1, but from the economic point of view we selected the case-1 as the proper case in this scenario due to in spite of that it gives a bit less value in cumulative oil production than in case-4, but the less number of injection & production wells are needed to obtain this amount of oil produced.

Scenario two:

From the results shown in table A-7 above for scenario two above we realized that the optimum injection rate which gives a higher cumulative oil production is 7000 m^6/day which hits the maximum value in case-4 of this scenario.

Scenario three:

With the reference to table A-8 of final scenario, we noticed that the favorable mobility ratio that achieves higher cumulative oil production is equal to 10 where definitely found at case-4.

Generally, by discussing the all scenarios we found that normal five spot is a favorable flood pattern, whereas the inverse five spot and inverse seven spot are invalid to application for heglig main field specifically in the four zones(6,7,14,17) where this study take plac

Chapter Five

Conclusion and Recommendations

5.1Conclusion

1. The study of heglig main field for zone-6, zone-7, zone-14 and zone-17 is completely done by using CMG simulator with a real field data.
2. The research is fulfilled the pre-determined objectives by which it has conducted, accordingly we can figure out that the optimum flood pattern is normal five spot and the best injection rate is 5000 m^3/day as well as the favorable mobility ratio is equal to 10 i.e. (M=10).

5.2 Recommendations

1. We recommend doing an economic evaluation analysis of the project to know the economic feasibility of conducting it before implementation.
2. On the other hand, we hopefully recommend that if the other flood patterns that we did not include in this study could be tried.
3. It will be good if new simulation models are generated for stratified reservoirs.
4. Due to high bottom water drive of heglig main field, water flooding project could be implemented until the year 2024for the selected zones of the study, afterwards another recovery method will be required.

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