Designing optimum water flooding scheme in a heterogeneous depleted reservoir: A simulation case study

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17870

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CERTIFICATION OF APPROVAL

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Approved by

____

(Dr. Mohammed Abdallah Ayoub)

UNIVERSITI TEKNOLOGI PETRONAS
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JAN 2015

CERTIFICATION OF ORIGINALTY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Ahmed Abdalla Salman Ahmed

ACKNOWLEDGEMENT

Alhamdulillah. Thanks to Allah SWT, Who, Alone, brings forgiveness and light and new life to those who call upon Him. It is he who creates from the very beginning, and he can restore life.

I take this opportunity to express my profound gratitude and deep regards to my guide **Dr. MOHAMMED ABDALLA AYOUB MOHAMMED,** for his exemplary guidance, monitoring and constant encouragement throughout the course of this thesis.

The blessing, help and guidance given by them time to time shall carry me a long way in the journey of life on which I am about to embark.

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Lastly, I thank almighty, my parents, sisters and friends for their constant encouragement without them which this assignment would not be possible.

Abstract

Waterflooding is one of the cheapest oil recovery methods and the most popular secondary method to increase oil recovery by injecting water into the reservoir.

This research aims to build a model using Eclipse 100 software in order to increase the oil recovery factor in a heterogeneous depleted reservoir.

This project discusses the main parameters that affecting waterflooding performance in a heterogeneous depleted reservoir and quantify their importance towards an optimum design. So the main objective of this project is addressing the different interrelated parameters and their impact in order to increase the oil recovery factor. Moreover, this project is determining different scaling up schemes and their impact on the final model besides doing a sensitivity study for the parameters that affecting the waterflooding in a heterogeneous reservoir.

Furthermore, at the end of this research a comparative methodology will be proposed to determine the optimum waterflooding scheme to maximize the oil recovery.

This report discusses on both background of the project and the literature review as well as the project work flow. Then followed by results and discussion, and finally concluded by the suggested optimum design for waterflooding which is carried out in this final year project.

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Nomenclature

$Npwf$**:** Waterflood reserves, STB.

Vp **:** Floodable reservoir pore volume (7758AhΦ), barrels.

Boi **:** Original formation volume factor, RB/STB.

Bof **:** Formation volume factor during waterflooding, RB/STB.

Swc **:** Connate water saturation, fraction.

Rp : Primary recovery efficiency, fraction of original oil in place (OOIP).

Evo : Overall volumetric sweep efficiency, fraction of reservoir volume.

ED : Maximum unit displacement efficiency, fraction.

FOE: Field oil recovery efficiency.

FOPR: Field oil production rate.

FWPR: Field Water production rate.

FOPT: Field oil production total.

CHAPTER (1)

INTRODUCTION

1.1 Project Background

Waterflooding is one of the cheapest oil recovery methods and the most popular secondary method to increase oil recovery by injecting water into the reservoir.

The waterflooding method starts on the early 1865, however the waterflooding has been used as a recovery method for the oil came into widespread acceptance and use just before 64 years. Nowadays the demand on waterflooding becomes high to restore the production rates of the oil and to sweep the amount of oil which have been left underground after the reservoir had been utilized by the primary recovery.

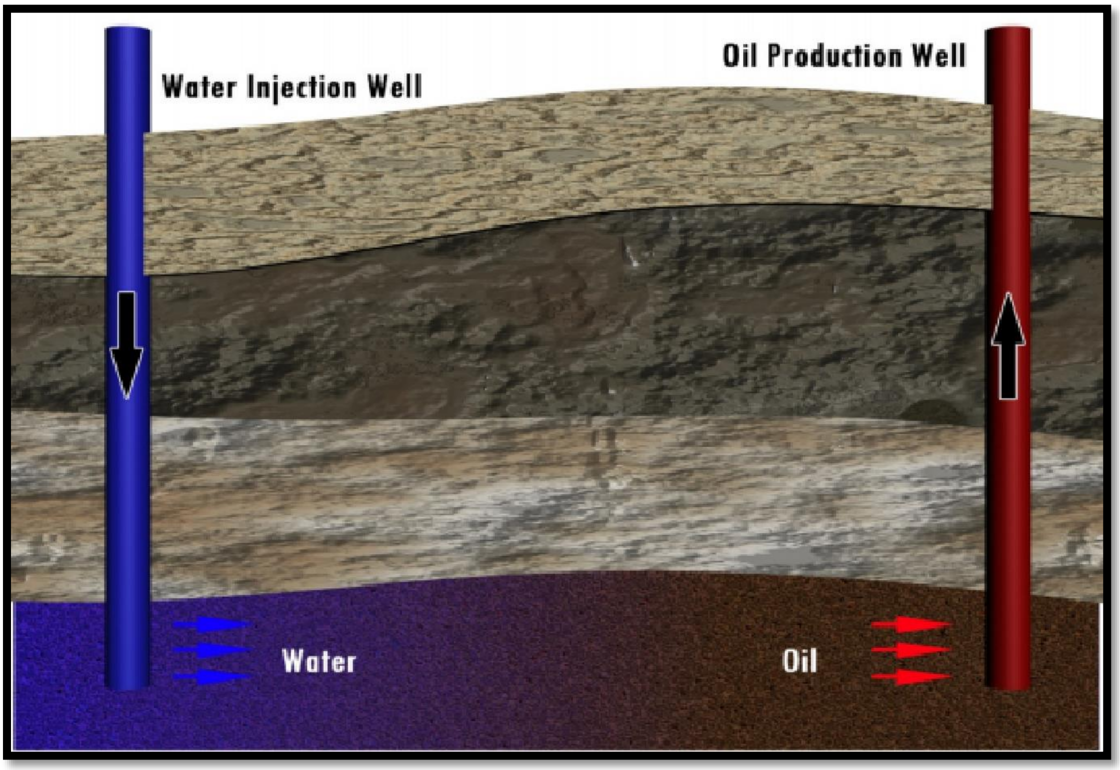


Figure 1.1: The Waterflooding method.

There are many reservoir characteristics that must be considered in determining the appropriateness of an applicant reservoir for waterflooding such as the geometry of the reservoir, the rock and fluid properties, the depth of the reservoir, the primary drive mechanism, lithology, and the uniformity and continuity of the reservoir. All these characteristics have been pointed out by Thomas, Mahoney, and Winter (1989).

The success of the waterflooding design can be evaluated using the equation which has been developed by Callaway (1959) to estimate the total waterflood recoverable reserves:

$$Npwf = Vp * \frac{1 - Swc}{Boi} * \{1 - Rp - \frac{Boi}{Bof} * (1 - Evo - ED)\}$$

To evaluate the success of the water flooding oil recovery, it is essential to define the overall recovery factor, RF. In terms of cumulative oil produced (Np) can be calculated from RF as such:

$$Np = OIIP\ (initial\ oil\ in\ place) * RF$$

According to Sarender (1982), RF is the product of volumetric sweep efficiency (EA x Ev) and fractional oil being displaced (ED):

$$RF = ED * EA * Ev$$

The performance of the waterflooding technique is affected by many inter-related parameters. This project is addressing many of those parameters and their effects towards an optimum and safe recovery at the end of the field life. Scaling up the field’s rock and fluid properties is considered as a major pitfall of producing the expected recovery results.

1.2 Problem Statement

The design of Waterflooding is affected by many factors. The most important factor is the reservoir heterogeneity such as vertical and areal heterogeneity. Scaling the heterogeneity is a tough choice that’s handled by many simulators and would normally produce erroneous results from simulation standpoint of view. The current project will address the main parameters that affecting waterflooding performance in heterogeneous reservoir and tries to quantify their importance towards an optimum design.

The problems which have been identified in this research are:

- The reservoir has been depleted by its natural energy.
- The pressure has been dropped below the bubble point.
- The Large amount of the oil which has been left in the reservoir after the primary recovery.
- The vertical and areal heterogeneity of the reservoir.

1.3 Objectives

The objectives of this simulation case study are:

- To design an optimum waterflooding scheme in a heterogeneous depleted reservoir and quantifying the impact of different interrelated parameters in order to increase the oil recovery factor as much as possible.
- To determine different Scaling up schemes and their impacts on the final model results.
- To do a sensitivity study for the underlined parameters.

1.4 Scope of Study

The scope of study is mainly focusing on increasing the oil recovery from the heterogeneous reservoirs using waterflooding method. This research aimed to build a model using Eclipse software.

Eclipse software will be utilized to simulate the effect of changing diverse reservoir and fluid characteristics on the oil recovery by waterflooding.

1.5 Relevancy of the project

Waterflooding is falling under reservoir engineers disciplinary and the author has to deal with Eclipse software, which is necessary to learn for each petroleum engineer to become a good reservoir engineer. So this research is relevant to the field of study of the author.

1.6 Project Feasibility

This Project is considered as achievable since all required instruments and Eclipse software are accessible at the place of study "Universiti Teknologi Petronas, UTP", and the given time to finish the project is genuinely suitable and sufficient to do the project and convey detailed analysis on the results gained from the simulations.

CHAPTER (2)

LITRATURE REVIEW

This chapter will discuss number of projects which have been introduced to the field of waterflooding especially in heterogeneous reservoirs.

According to Gulick and McCain (1998) stated that for any successful waterflooding plan there are key fundamentals such as understanding the reservoir geology and characteristics; starting the waterfllooding program early; Infill drill to reduce the lateral pay discontinuities; the injection of the water should be below the formation parting pressure; the injected water must be clean; All of the pay must be opened in both producing and injection wells; use the waterflooding pattern that has one injection well per producing to develop the field; the operation of the waterflooding program must be based on injection well tests; and make a surveillance program to monitor what is going on in every well in the field.

The important factor in determining the success of the waterflooding plan is the range of the heterogeneity in the reservoir because it affects the selection of the waterflooding pattern. According to Gulick and McCain (1998) stated that the patterns that have a ratio of one injector to one producer such as direct line drive have been the most popular patterns. The reason behind the success of line drive and five-spot patterns is the equal distance between the producers and the injectors, also the sufficient injection which has been provided by this type of patterns. However the patterns that have a ratio of three producers to one injector (Inverted nine-spot) and 50% of the wells dispersed just 70% as far from the injector as alternate wells, have not proven to work in heterogeneous carbonated reservoir.

Some studies show that the dynamic injection schemes can increase ultimate recovery in highly heterogeneous reservoirs using waterflooding method (Mellado, 1982).

According to Permadi, Yuwono, and Simanjuntak (2004) pointed out that the vertical heterogeneity plays a vital role in predicting the performance of waterflooding in stratified reservoirs. This study shows that increasing in the trend of upward permeability in stratified reservoirs will lead to higher vertical sweep efficiency compare to that case of having a reduction in the trend of upward permeability if all the other parameters remain similar in both cases. Moreover, the waterflooded oil recovery decreases as permeability variation in vertical direction increases, so this decrease will be greater in a reservoir with decreasing in upward permeability trend. With decreasing the upward permeability trends the decrease in oil recovery will be greater. The figures below shows the difference in increasing and decreasing the coefficient of permeability variation, **V_{DP}** with has been designed by Dykstra and Parsons for predicting the performance of waterflooding in stratified reservoirs.

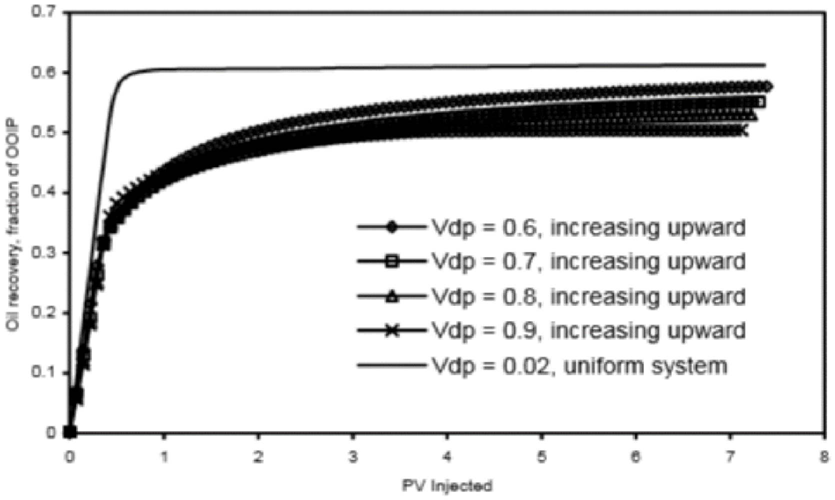


Figure 2.1: Effect of varied V_{DP} with increasing upward permeability trend.

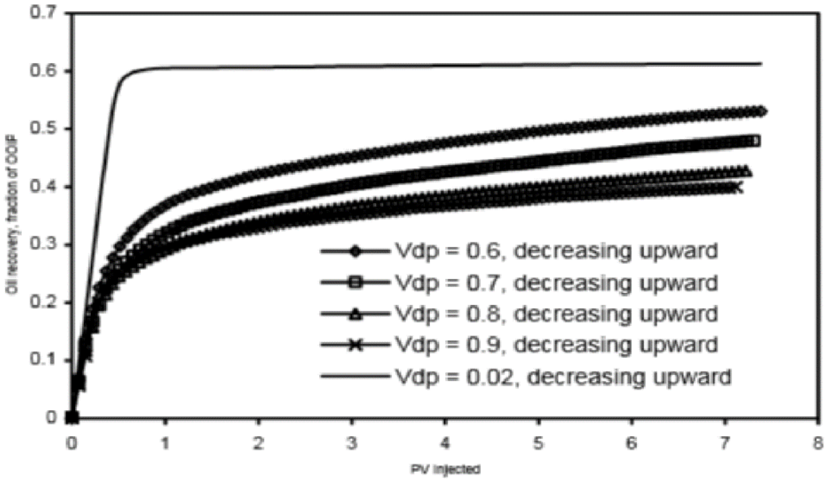


Figure 2.2: Effect of varied V_{DP} with decreasing upward permeability trend.

According to Balaghi *et al* compared between the waterflooding method and the water alternative gas method he came out with this conclusion; the best method to be as secondary recovery for 5-Spot pattern Model is Water Flooding, Water Flooding has the largest Total Field Recovery compared with water alternative gas, waterflooding has the highest reservoir pressure at the end of the project, and also the waterflooding method has the lowest value of producing gas oil ratio. However, the main disadvantage of the waterflooding is its high fractional flow of water.

According to Trisarn. K stated that the oil recovery from primary recovery only ranged from 20 - 23% of the original oil in place. However, when the water flooding is applied into the filed the oil recovery increased to 35 - 48%. The most recovery comes from the bottom water flood due to the higher specific gravity of water yields to higher oil displacement efficiency by displacing up from the bottom. Moreover, the earlier water injection is used (after starting oil production) the more oil recovery, this because of the reservoir pressure is still high allowing more oil displacement efficiency.

CHAPTER (3)

METHODOLOGY

3.1 Research Methodology

This chapter will explain the steps to be followed to design an optimum waterflooding scheme in a heterogeneous depleted reservoir by using Eclipse software.

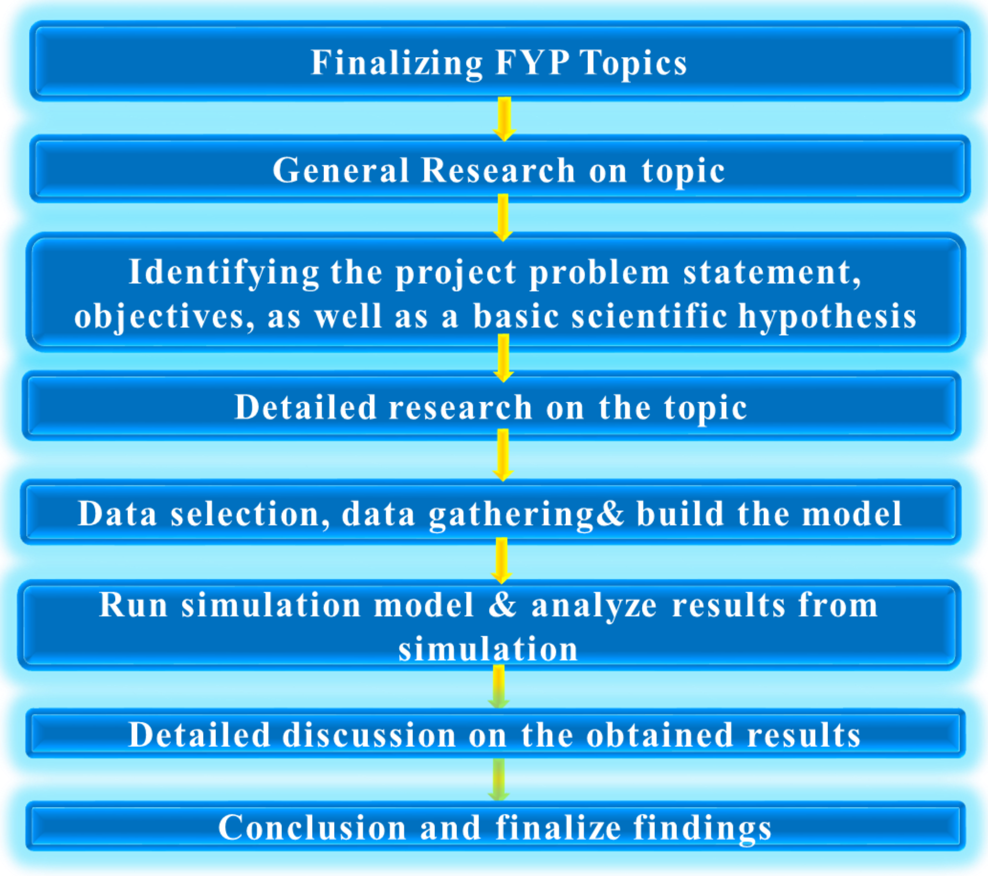


Figure 3.1: Research Methodology

3.2 Project workflow

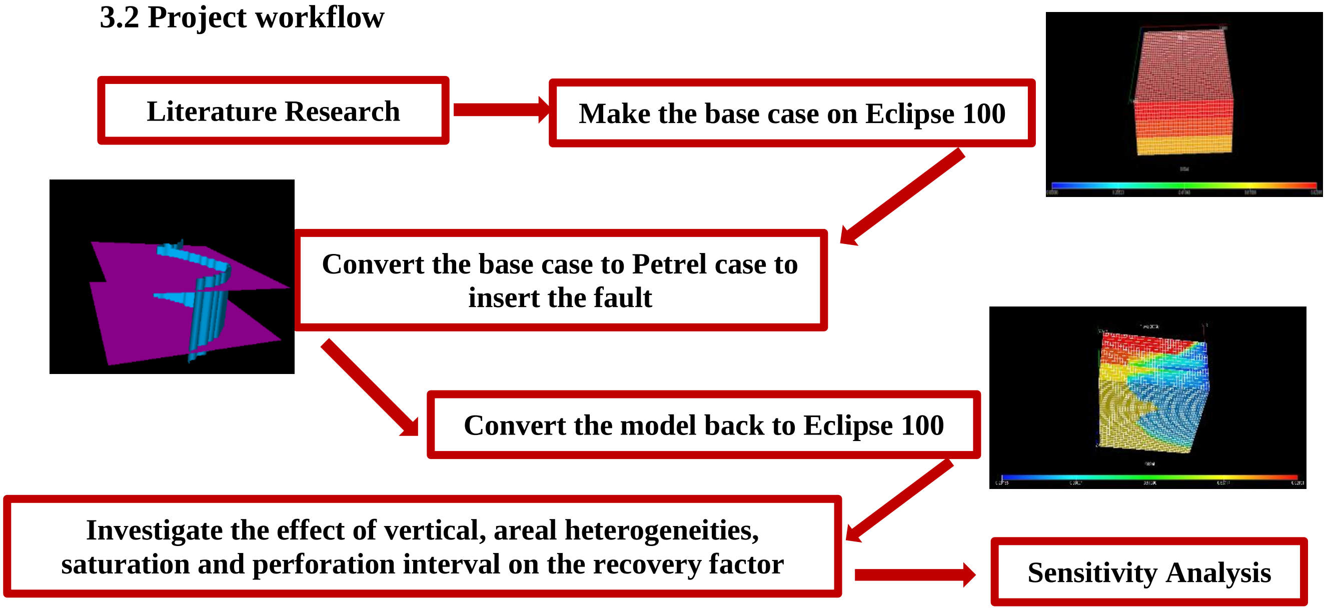


Figure 3.2: Project Workflow

3.3 Tools

- Eclipse 100.
- Petrel software.
- Microsoft office Excel.

3.4 Key Milestone

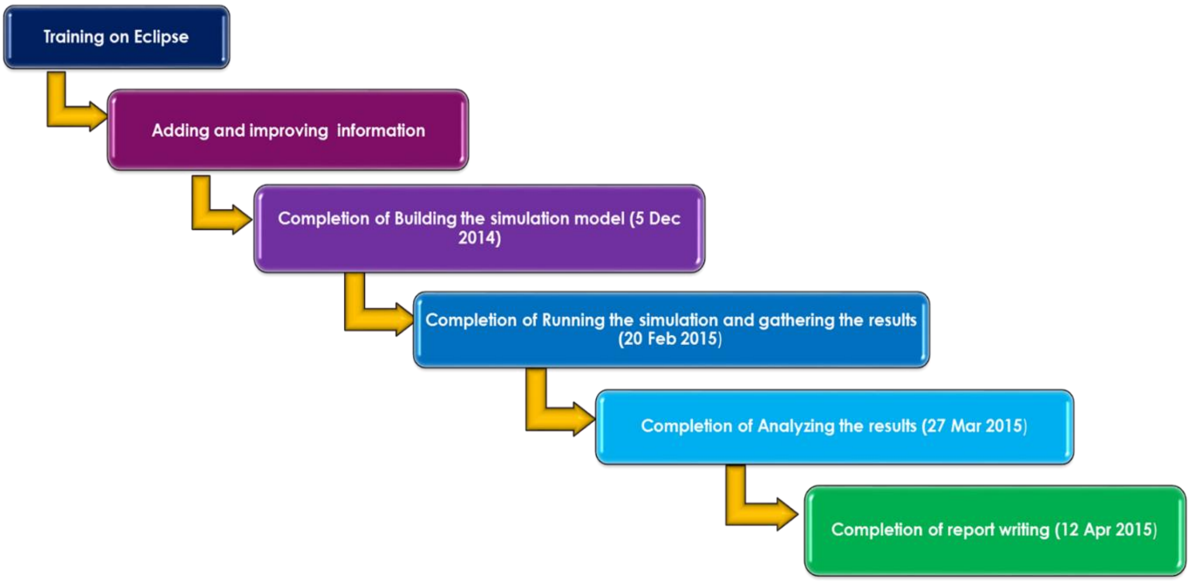
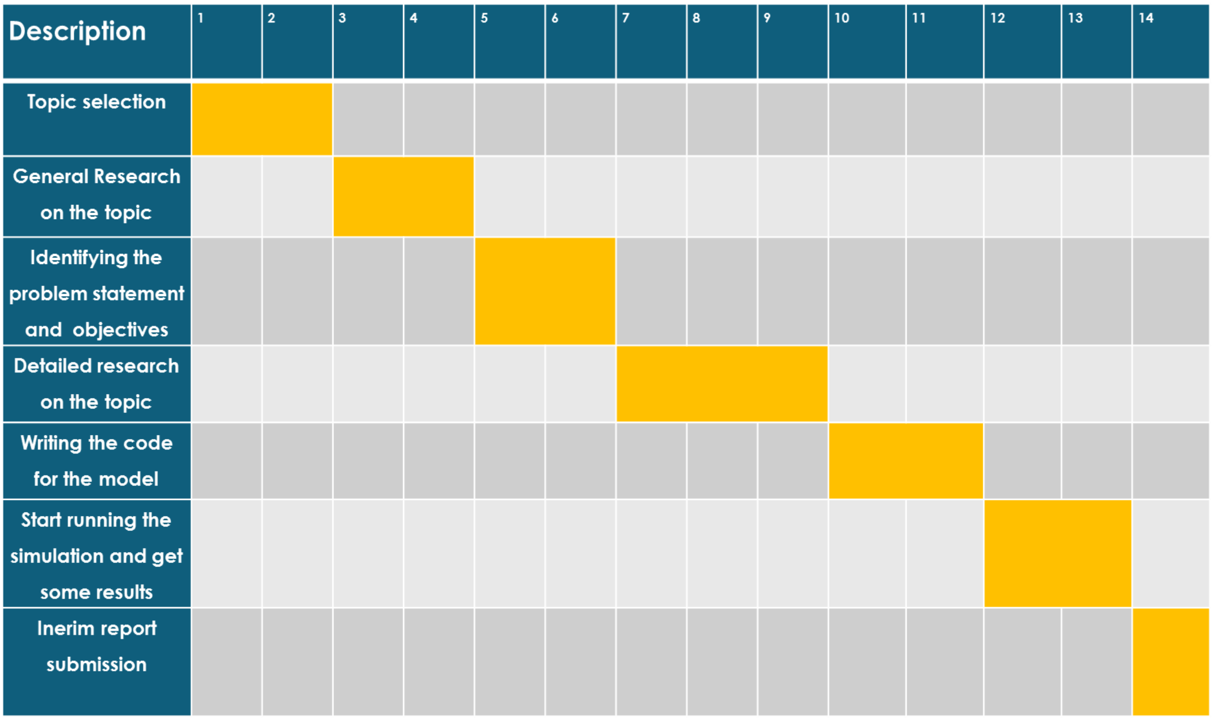


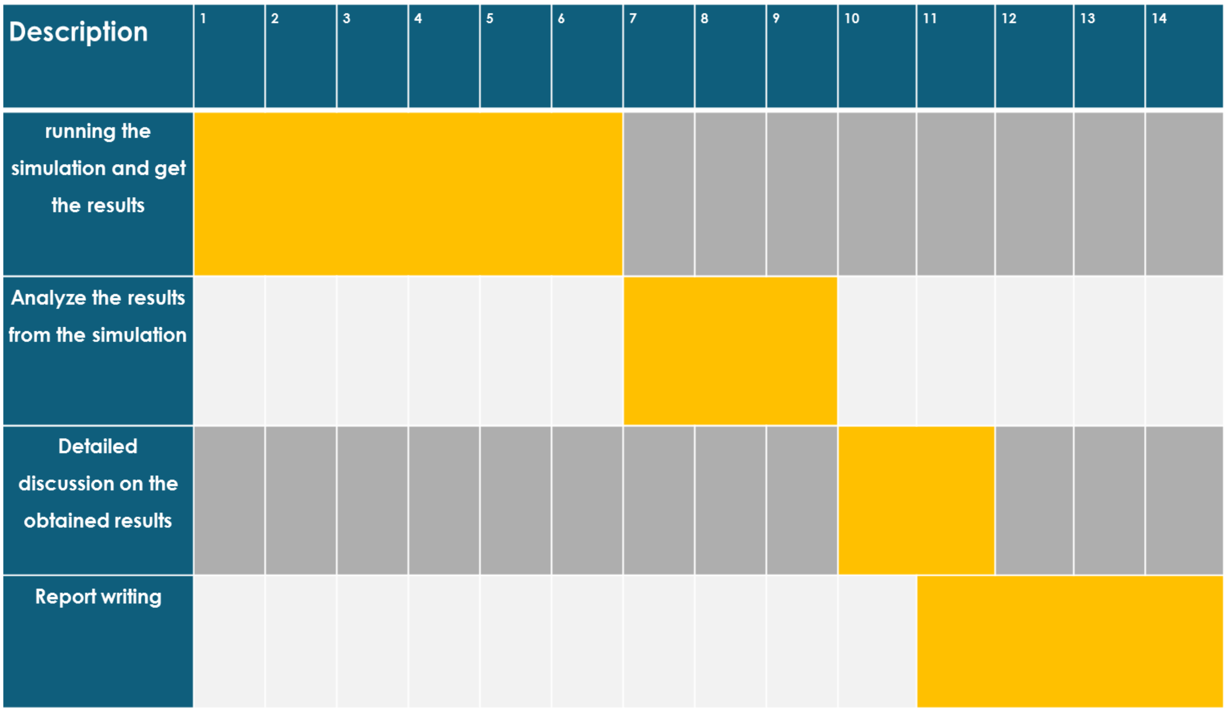
Figure 3.3: Key Milestone

3.5 Gantt Charts



Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Topic selection	🟨	🟨												
General Research on the topic			🟨	🟨										
Identifying the problem statement and objectives					🟨	🟨								
Detailed research on the topic							🟨	🟨	🟨					
Writing the code for the model										🟨	🟨			
Start running the simulation and get some results												🟨	🟨	
Inerim report submission														🟨

Table 3.1: Gantt chart for FYP I



Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14
running the simulation and get the results	🟨	🟨	🟨	🟨	🟨	🟨								
Analyze the results from the simulation							🟨	🟨	🟨					
Detailed discussion on the obtained results										🟨	🟨			
Report writing											🟨	🟨	🟨	🟨

Table 3.2: Gantt chart for FYP 2

Chapter (4)

RESULTS AND DISCUSSION

4.1 simulation data:

- This model contains 40x40x15 grid blocks of which 24000 grids are active.
- This model is two phase flow model (water and oil).
- The total number of wells is 15 wells (9 producers/6 injectors).
- X and Y dimensions of each grid are 100 ft.
- The thickness of each grid (Z dimension) are 20 ft.
- Initial reservoir pressure 4000 psia.
- WOC = 4390 ft, datum depth = 4000.
- The bottom hole pressure lower limit = 500 psia.
- Water phase pressure = 3600.
- Water formation volume factor = 1.00341
- Water compressibility = 3.00E-06.
- Water viscosity = 0.52341.
- Oil density = 55.6 Ib/cu.ft.
- Water density = 64 Ib/cu.ft.
- Injection rate = 2000 STB/day.
- Production rate = 2000 STB/day.
- PVT of the oil:

Oil phase pressure	Oil FVF	Oil viscosity
400	1.2	1.16
1200	1.05	1.164
2000	1.00	1.167
2800	0.988	1.172
3600	0.9802	1.177
4400	0.9724	1.181
5200	0.9646	1.185
5600	0.9607	1.19

Table 4.1: PVT of the oil

- This model contains 12 regions with different permeability in x, y and z direction and also different porosity and net to gross.
- The table below shows the different permeability (x, y & z direction), porosity and net to gross for each region :

	PERMX	PERMY	PERMZ	PORO %	NTG
1	1100	887	91.35	16	0.92
2	1022	850	93.6	22	0.91
3	1300	650	97.4	17	0.99
4	1290	790	104	20	0.95
5	507	680	59.35	22	0.85
6	900	500	70	25	0.90
7	829	420	62.45	21	0.89
8	820	390	60.5	23	0.93
9	250	250	25	17	0.80
10	580	240	41	18	0.83
11	590	200	39	17	0.90
12	700	330	51.5	21	0.96

Table 4.2: regions properties

- This model contains different types of waterflooding patterns such as :
  1. Direct line drive (9 producers / 6 injectors).
  2. Inverted five spot (4 injector / 9 producers).
- Water-oil saturation tables and frictional flow graphs are shown below:

Sw	Krw	Kro	fw
0.18	0	0.9	0
0.22	0	0.7368	0
0.2925	0.0002	0.4936	0.00091
0.365	0.0031	0.3108	0.021937
0.4375	0.0158	0.1799	0.164925
0.51	0.05	0.0921	0.549712
0.5825	0.1221	0.0389	0.875904
0.655	0.2531	0.0115	0.980195
0.7275	0.4689	0.0014	0.998674
0.8	0.8	0	1
1	1	0	1

Table 4.3: Saturation and frictional flow for the top layer

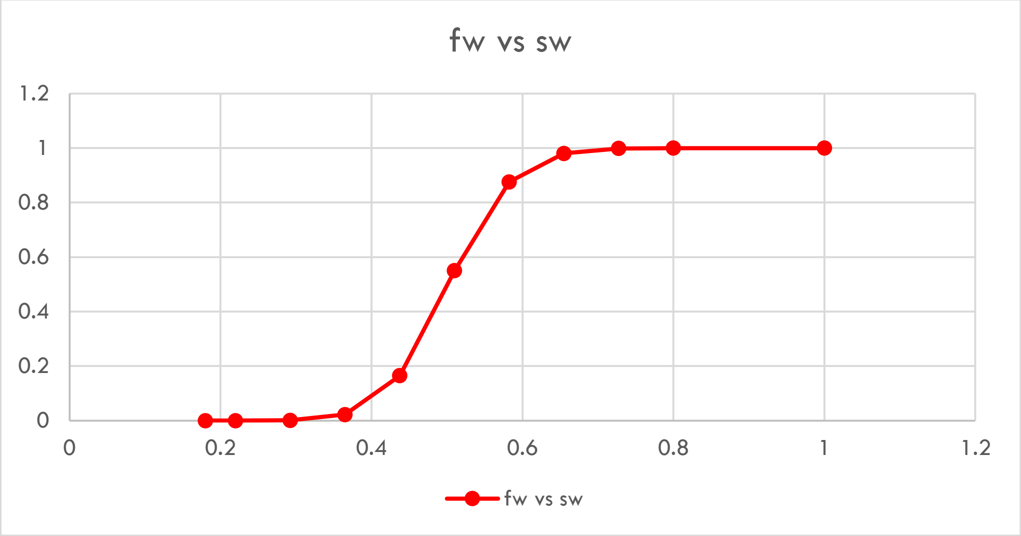


Figure 4.1: Frictional flow curve for the top layer

sw	krw	kro	fw
0.22	0	1	0
0.3	0.07	0.4	0.282395
0.4	0.15	0.125	0.729617
0.5	0.24	0.0649	0.892655
0.6	0.33	0.0048	0.993573
0.8	0.65	0	1
0.9	0.83	0	1
1	1	0	1

Table 4.4: Saturation and frictional flow for the mid layer

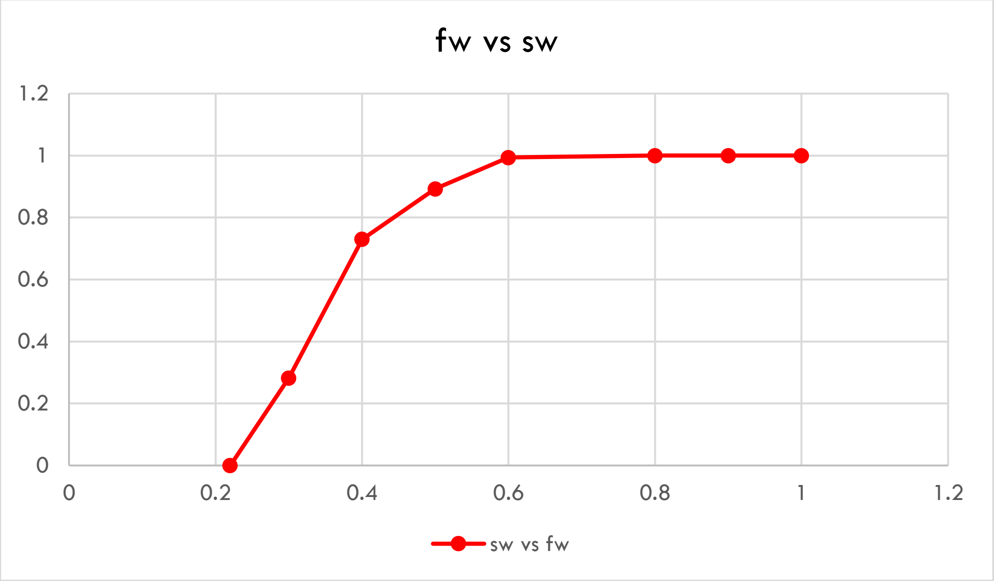


Figure 4.2: Frictional flow curve for the mid layer

Sw	Krw	Kro	fw
0.32	0	0.8	0
0.35	0	0.644	0
0.4	0.0002	0.4314	0.001041
0.45	0.0027	0.2717	0.021858
0.5	0.0138	0.1572	0.164862
0.55	0.0437	0.0805	0.549698
0.6	0.1068	0.034	0.875986
0.65	0.2215	0.0101	0.980126
0.7	0.4103	0.0013	0.998593
0.75	0.7	0	1
1	1	0	1

Table 4.5: Saturation and frictional flow for the bottom layer

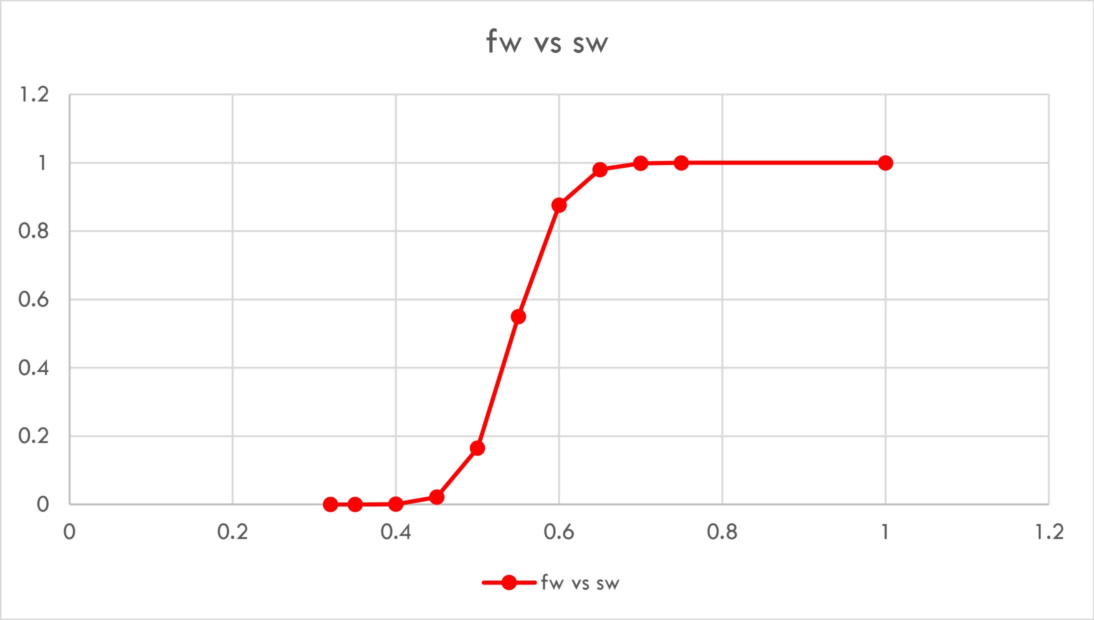


Figure 4.3: Frictional flow curve for the bottom layer

- This model contains a sealing fault which has been designed using Petrel software.

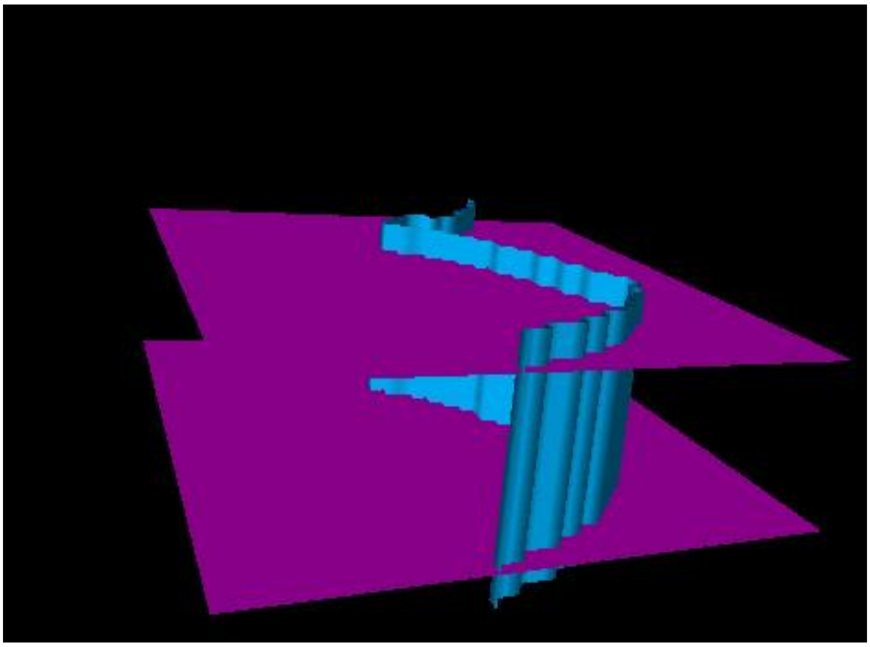


Figure 4.4: The shape of the sealing fault in Petrel software

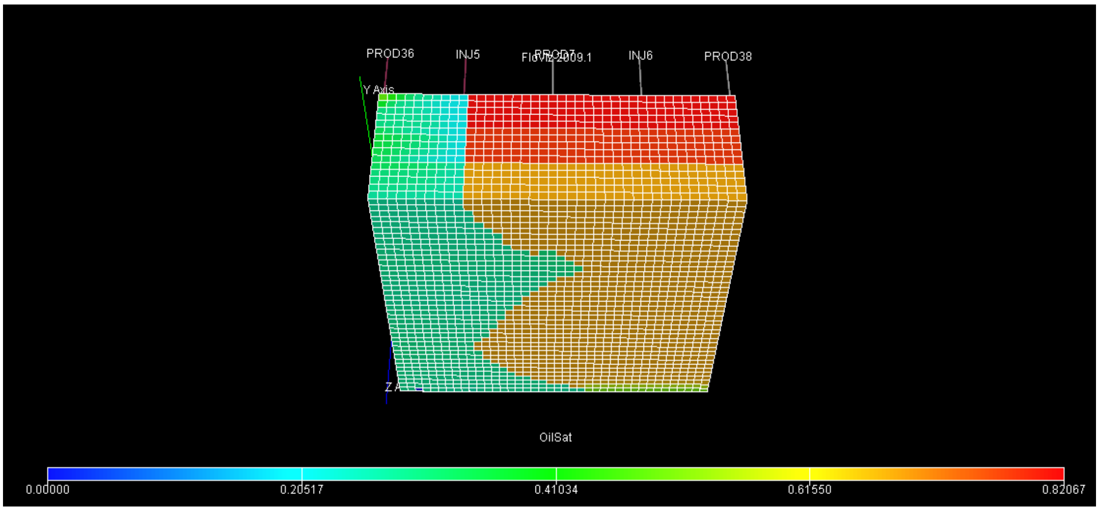


Figure 4.5: The effect of the sealing fault in FloViz

4.2 Results

According to Balaghi *et al* stated that the maximum field oil recovery with waterflooding was 42.53% while using the same parameters which have been used in this project except for the regions (different permeability, saturation, perforation interval, porosity & net to gross), number of wells and the flow patterns.

The next few pages in this part will show the results which have been obtained in this project.

4.2.1 Primary depletion

The graph below shows the FOE (Field oil recovery) using solution gas drive as primary depletion which is equal to 17 % of the STOOIP:

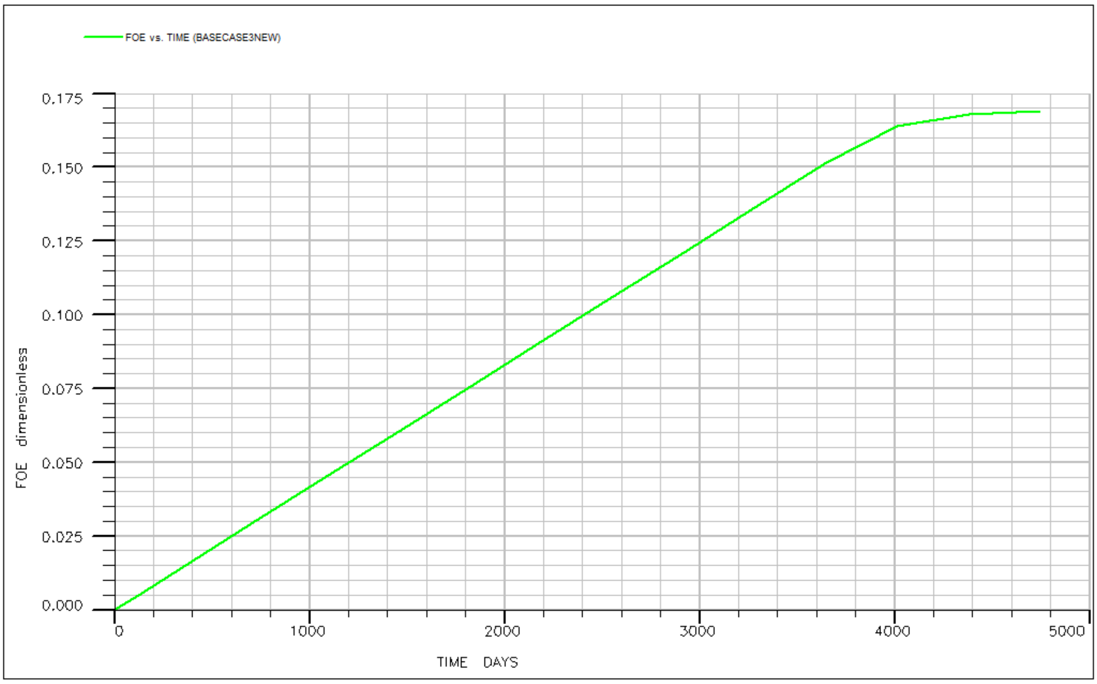


Figure 4.6: Field oil recovery for primary depletion by solution gas drive

The figure below shows the Field water production total for the primary depletion by solution gas drive which is equal to 25.8 MSTB:

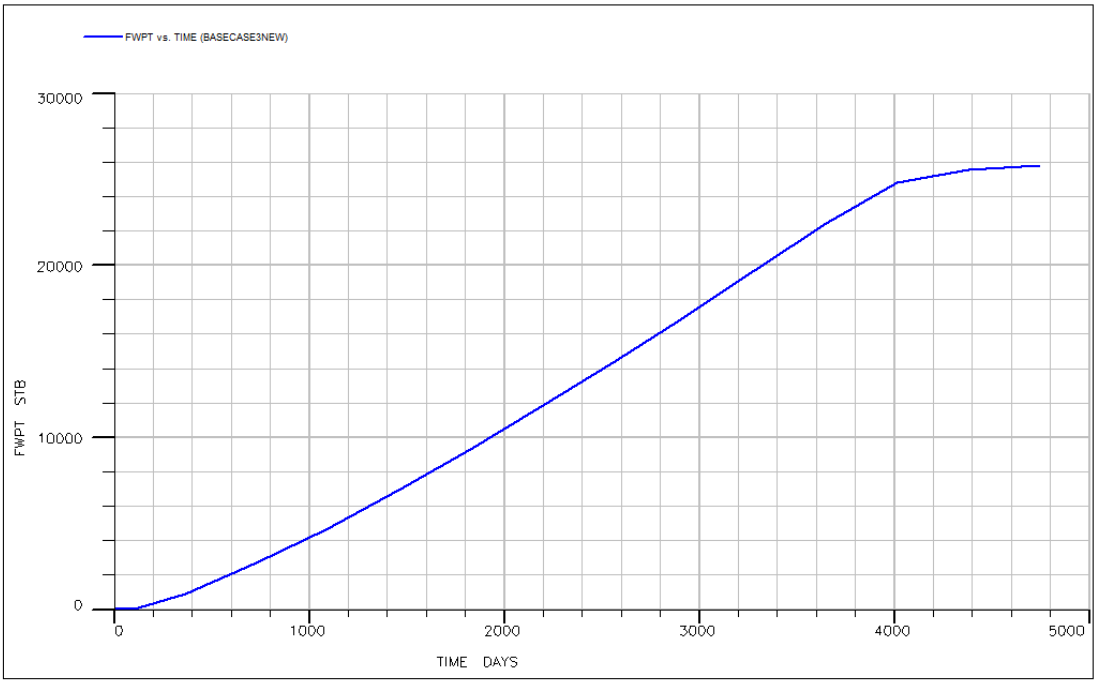


Figure 4.7: Field water production total for the primary depletion by solution gas drive

The graph below shows the FOE (Field oil recovery) using water aquifer drive as primary depletion which is equal to 19 % of the STOOIP:

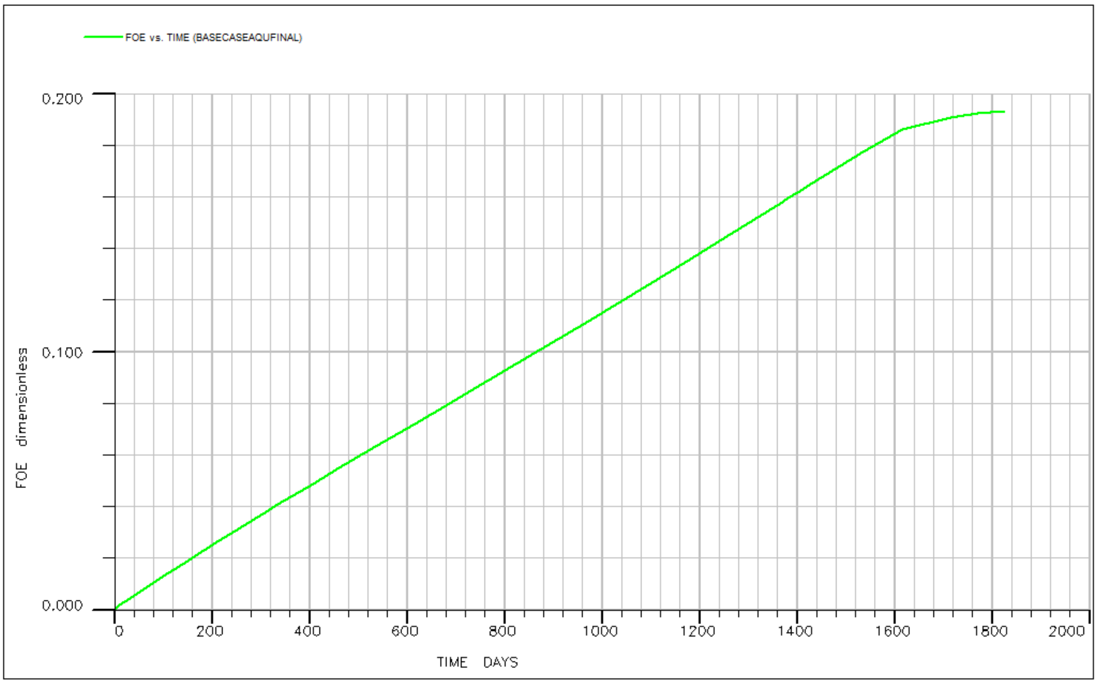


Figure 4.8: Field oil recovery for primary depletion by water aquifer drive

The figure below shows the Field water production total for the primary depletion by water aquifer drive which is equal to 6.4 MMSTB:

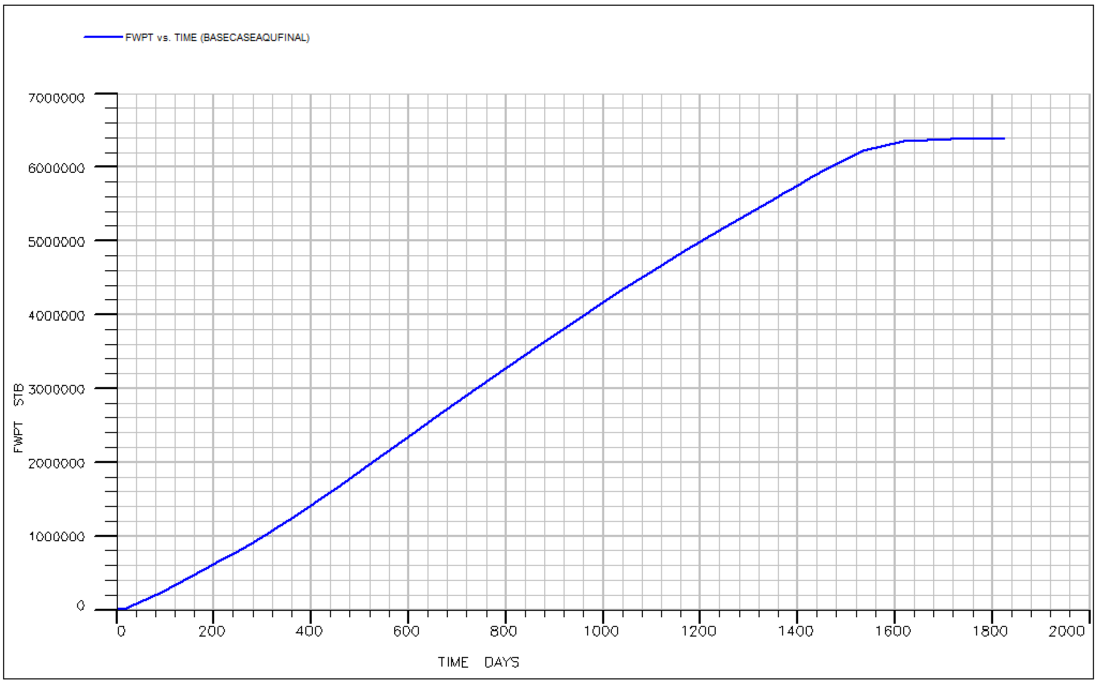


Figure 4.9: Field water production total for the primary depletion by water aquifer drive

4.2.2 Secondary recovery using waterflooding

This part discuss the effect of vertical permeability, saturation and the perforation interval in the recovery factor using waterflooding under different scenarios. The following models have been run for 30 years and the results have been compared

Case (1): Reservoir with solution gas drive:-

- **Line drive**

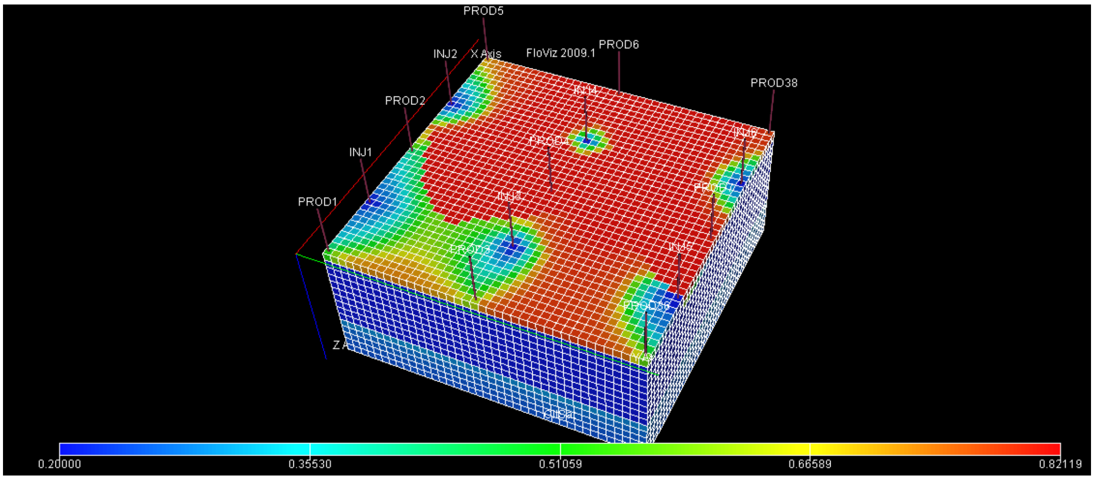


Figure 4.10: Line drive (9 producers/ 6 injectors)

The effect of perforation interval and saturation

Scenario (1): Permeability increases upward

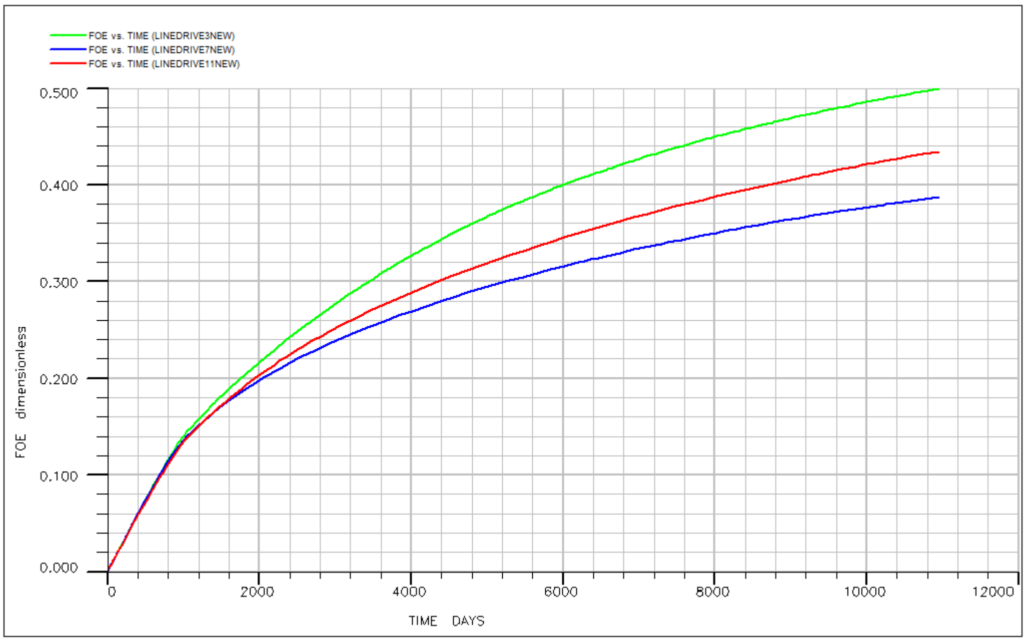


Figure 4.11: The effect of perforation interval and saturation on the field recovery efficiency scenario (1)

Scenario (2): Permeability increases downward

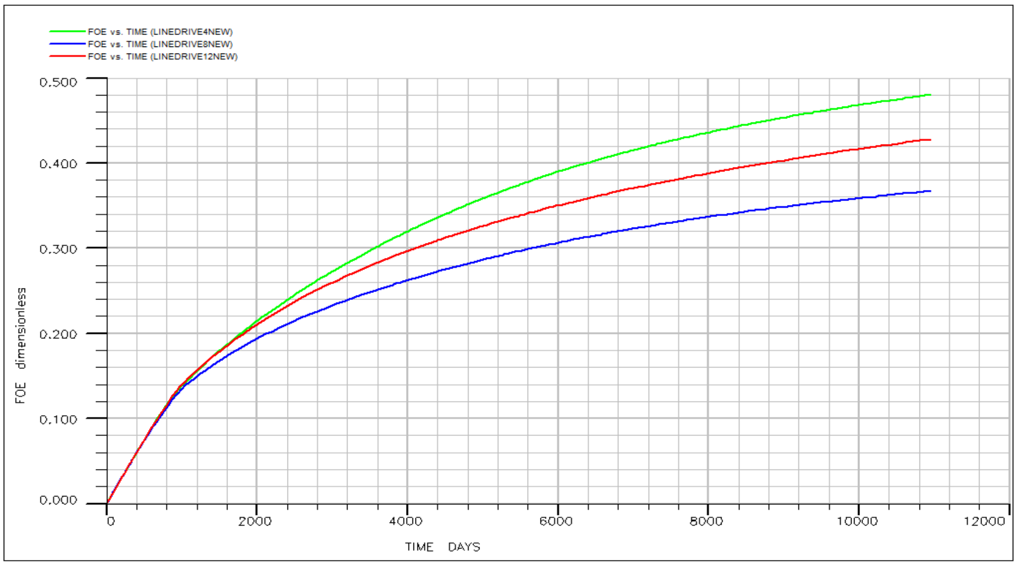


Figure 4.12: The effect of perforation interval and saturation on the field recovery efficiency scenario (2)

🟩: perforation and higher oil saturation on the top layer.

🟥: perforation and higher oil saturation on the mid layer.

🟦: perforation and higher oil saturation on the bottom layer.

The effect of vertical permeability

Scenario (1): perforation and higher oil saturation on the top layer

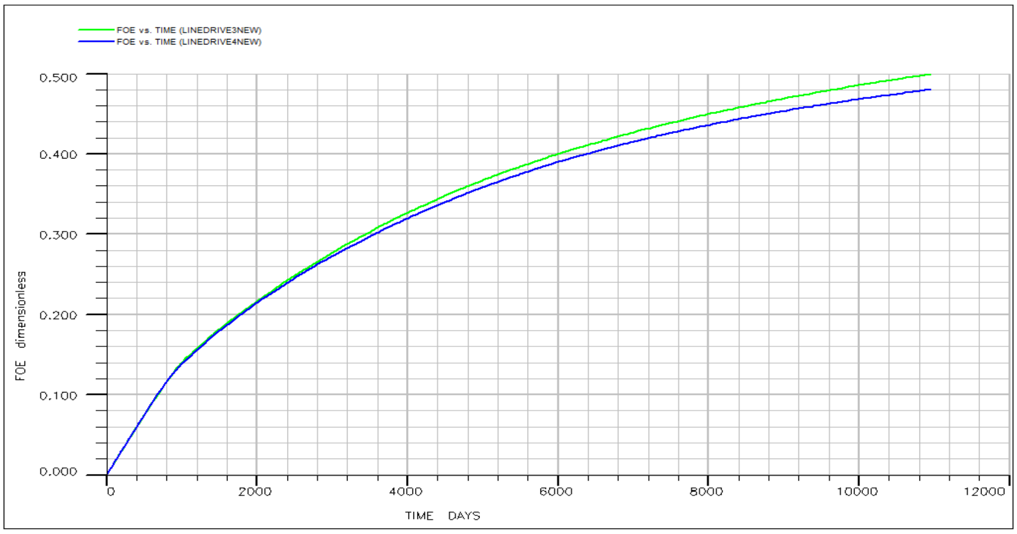


Figure 4.12: The effect of vertical permeability on the field recovery efficiency scenario (1)

Scenario (2): perforation and higher oil saturation on the mid layer

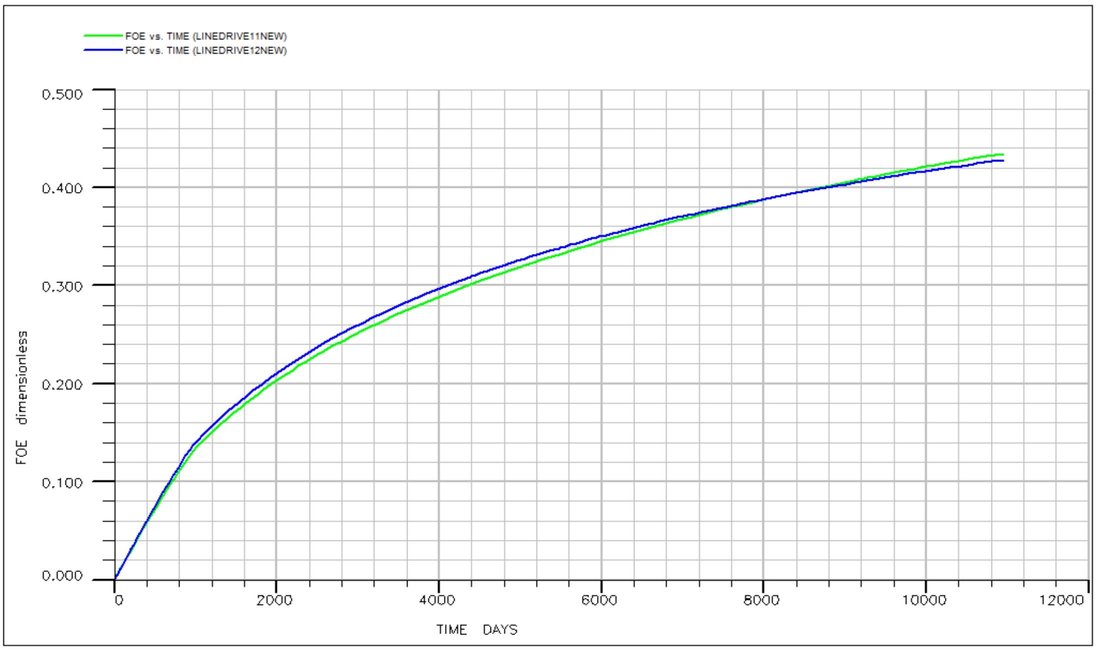


Figure 4.13: The effect of vertical permeability on the field recovery efficiency scenario (2)

Scenario (3): perforation and higher oil saturation on the bottom layer

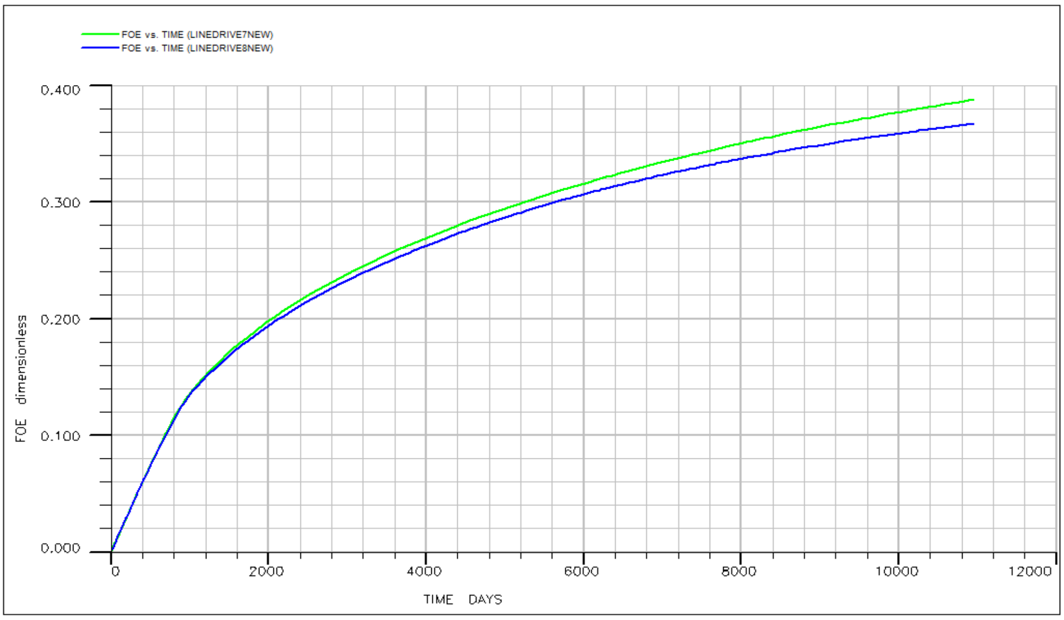


Figure 4.14: The effect of vertical permeability on the field recovery efficiency scenario (3)

🟩 : permeability increases upward

🟦 : permeability increases downward

Comparing the six cases of line drive

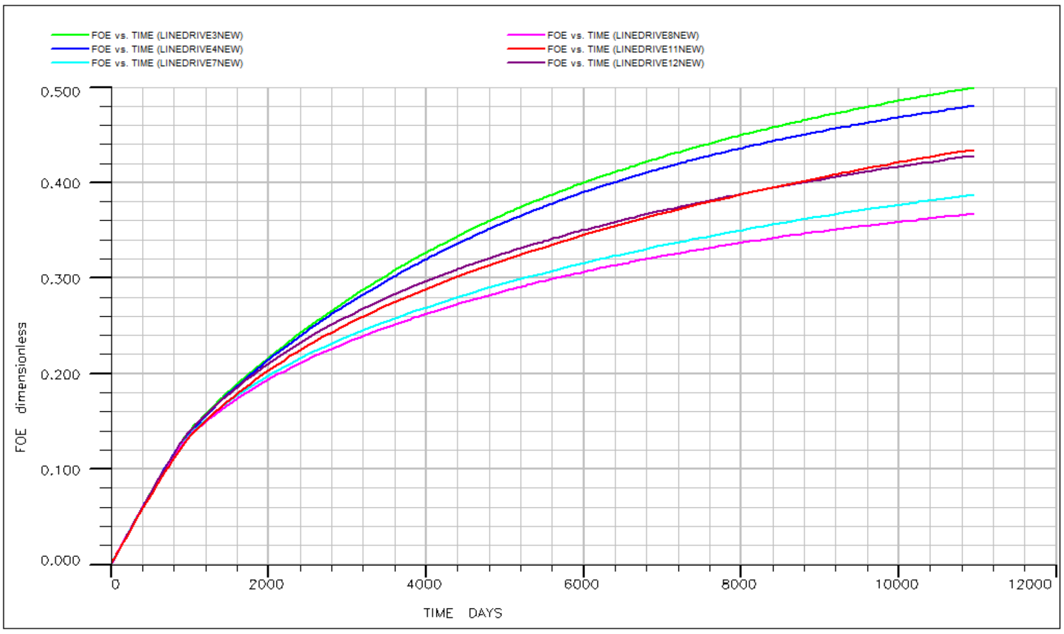


Figure 4.15: The effect of vertical permeability, saturation and perforation interval on the field recovery efficiency under different scenarios

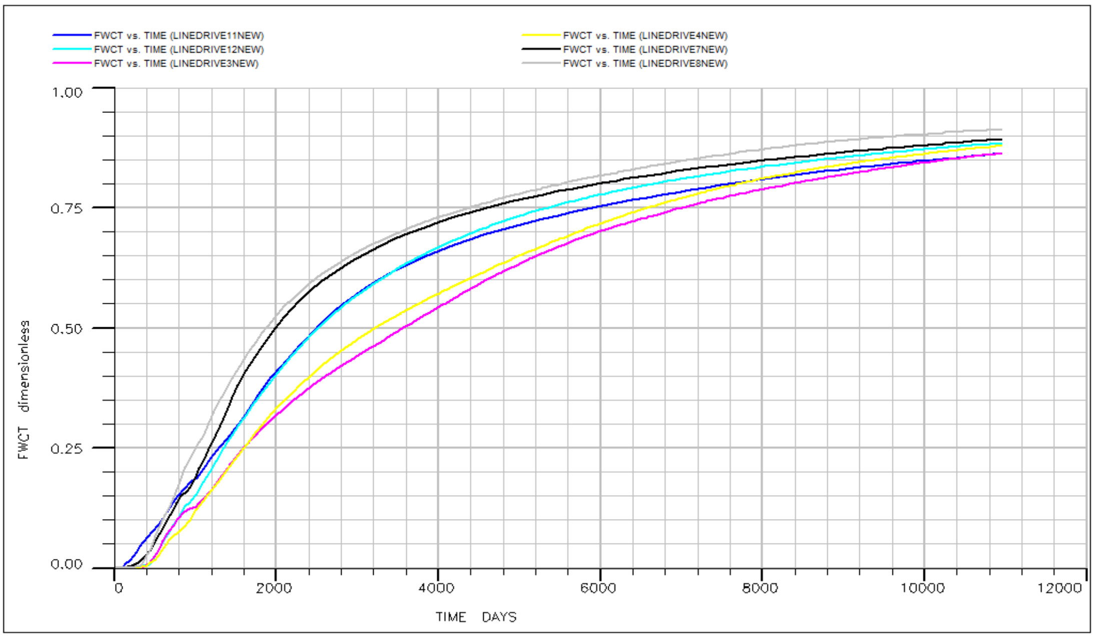


Figure 4.16: The effect of vertical permeability, saturation and perforation interval on the field watercut under different scenarios

❖ Five spot

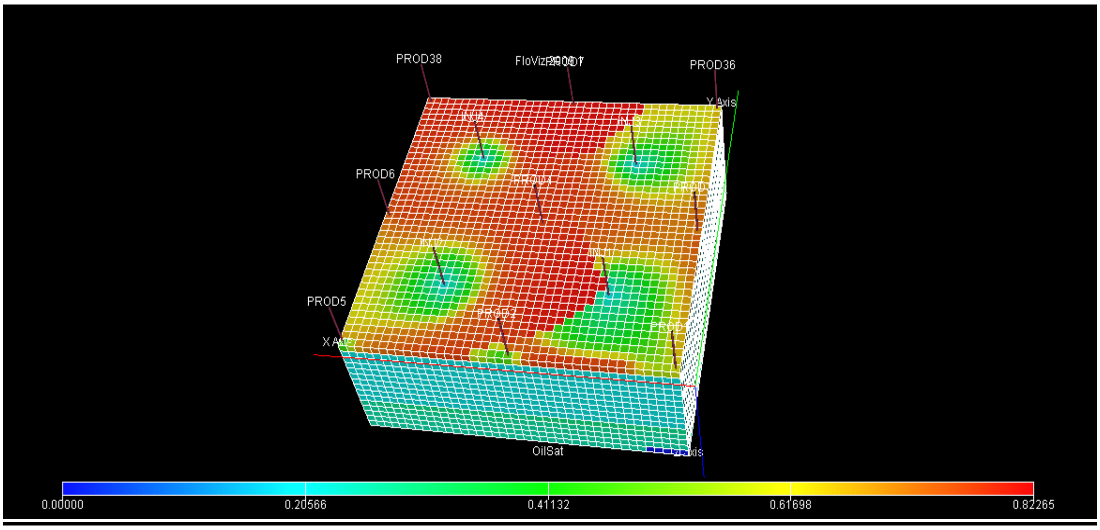


Figure 4.17: Five spot (9 producers/ 4 injectors)

The effect of perforation interval and saturation

Scenario (1): Permeability increases upward

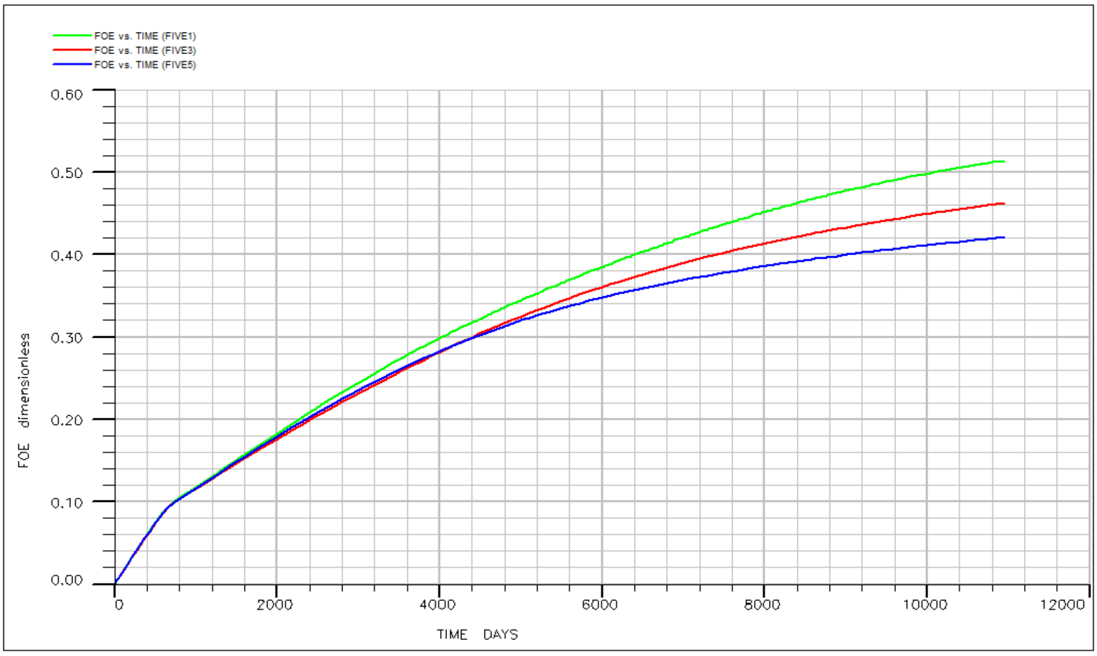


Figure 4.18: The effect of perforation interval and saturation on the field recovery efficiency scenario (1)

Scenario (2): Permeability increases downward

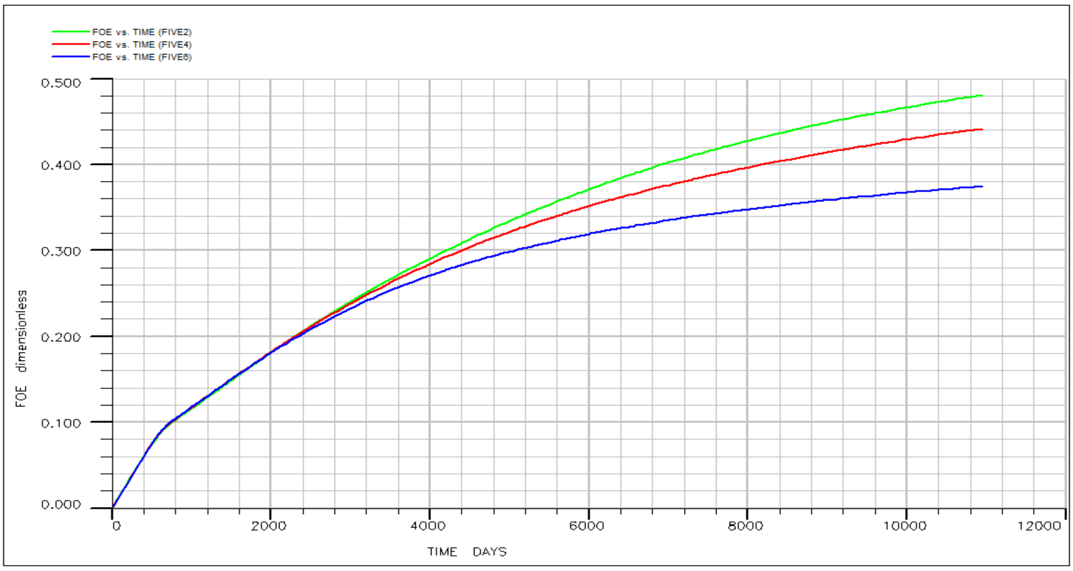


Figure 4.19: The effect of perforation interval and saturation on the field recovery efficiency scenario (2)

▬: perforation and higher oil saturation on the top layer.

▬: perforation and higher oil saturation on the mid layer.

▬: perforation and higher oil saturation on the bottom layer.

The effect of vertical permeability

Scenario (1): perforation and higher oil saturation on the top layer

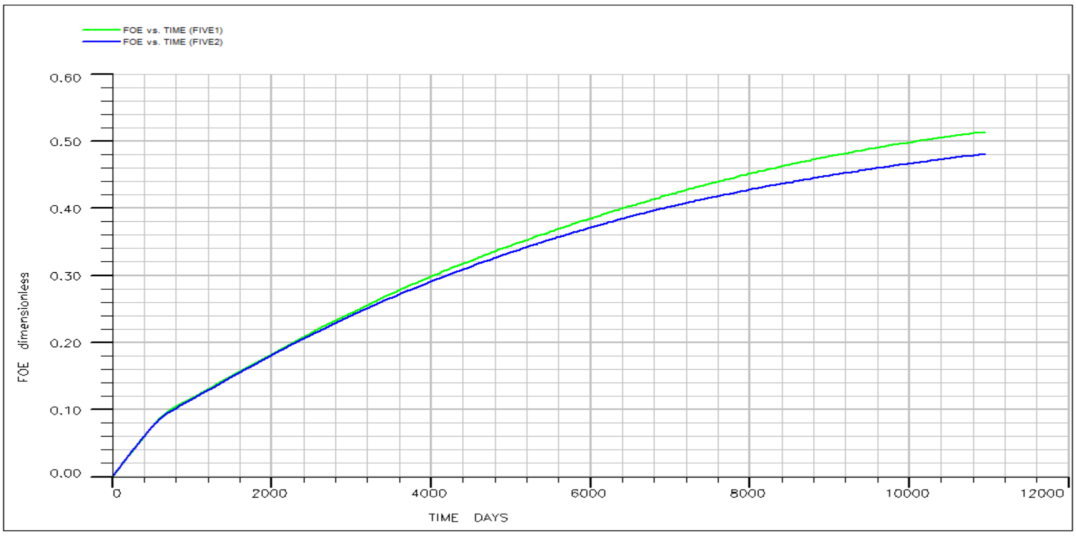


Figure 4.20: The effect of vertical permeability on the field recovery efficiency scenario (1)

Scenario (2): perforation and higher oil saturation on the mid layer

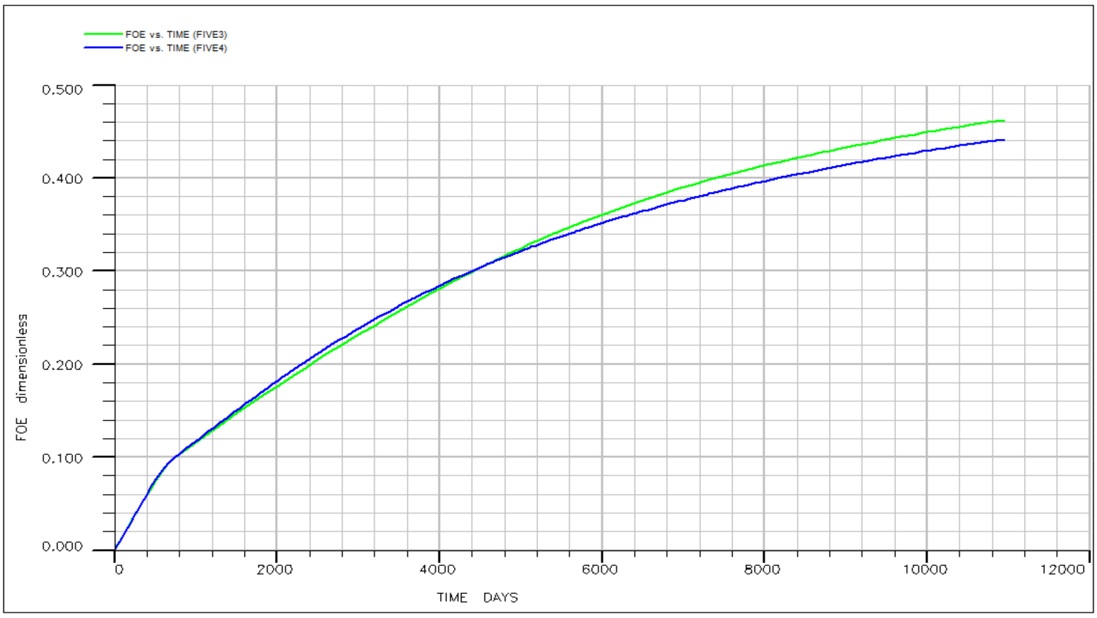


Figure 4.21: The effect of vertical permeability on the field recovery efficiency scenario (2)

Scenario (3): perforation and higher oil saturation on the bottom layer

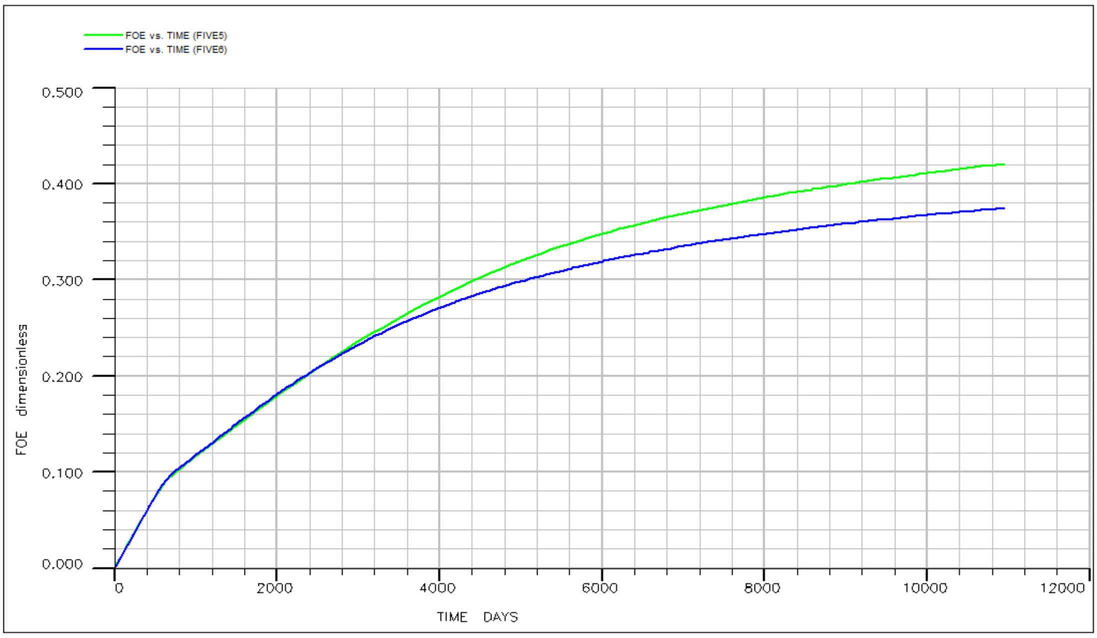


Figure 4.22: The effect of vertical permeability on the field recovery efficiency scenario (3)

🟩 : permeability increases upward

🟦 : permeability increases downward

Comparing the six cases of five spot

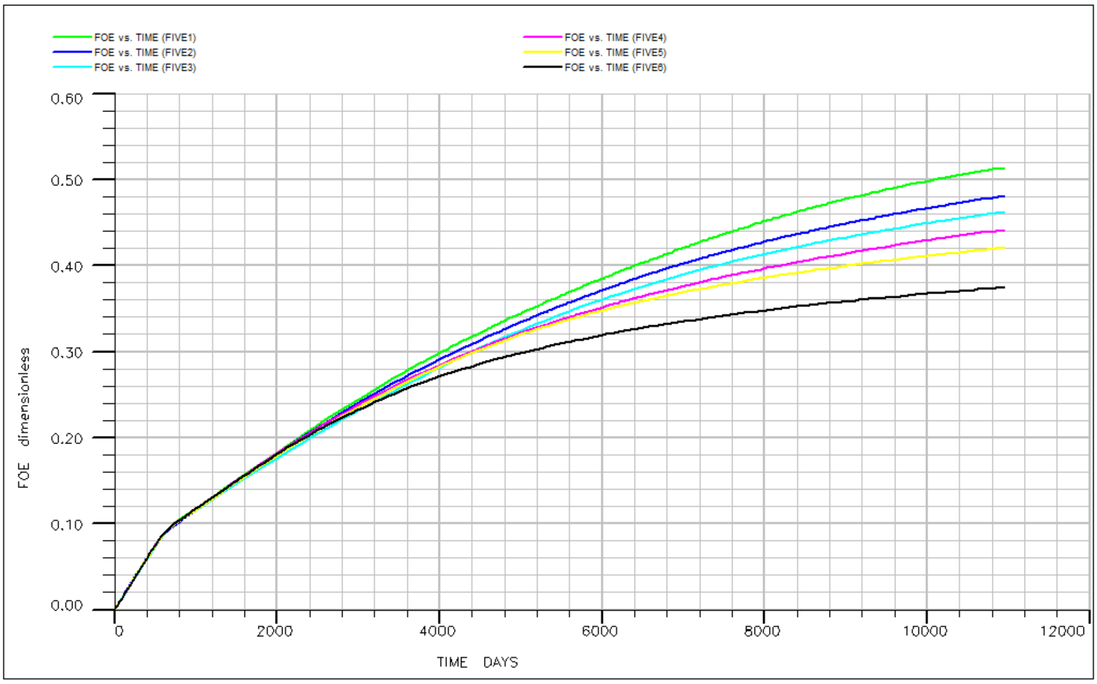


Figure 4.23: The effect of vertical permeability, saturation and perforation interval on the field recovery efficiency under different scenarios

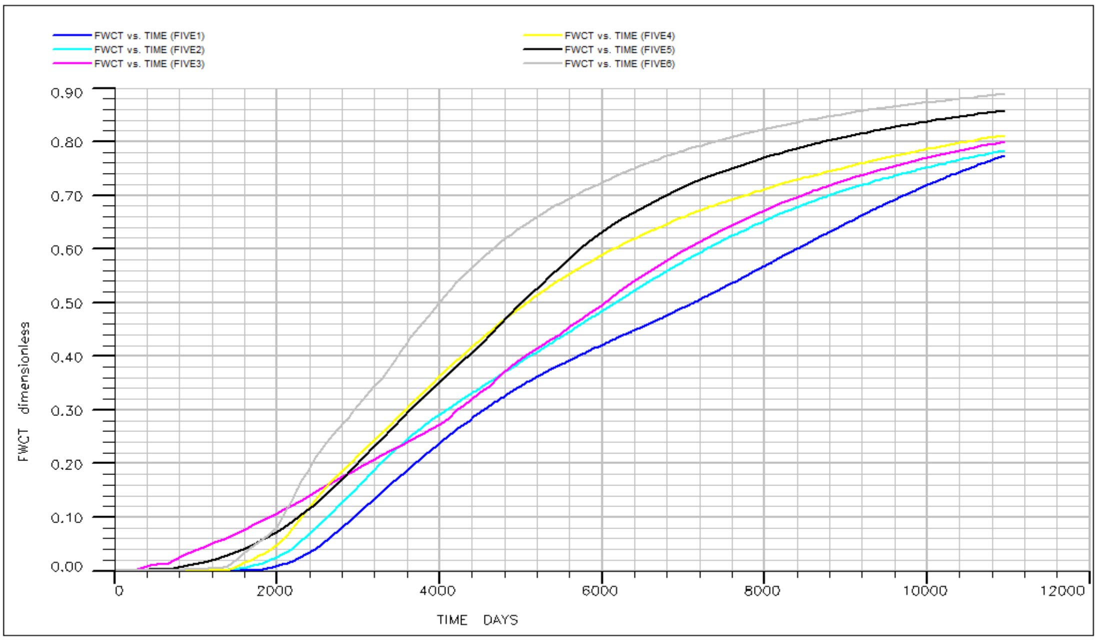


Figure 4.24: The effect of vertical permeability, saturation and perforation interval on the field watercut under different scenarios

- The above results show that as the permeability increases upward in the vertical direction the recovery factor will be higher compared to when the permeability increases downward in the vertical direction.
- The results also show that the highest recovery factor will be when the highest oil saturation and perforation interval is on the top layer while the lowest recovery factor will be when the highest oil saturation and perforation interval is on the bottom layer.
- The best case when the higher oil saturation and perforation on the top layer while the permeability increases upward it gives the highest recovery factor and the lowest watercut.
- The five spot pattern is better than the line drive in term of:
    1. Recovery factor: because it gives a higher recovery factor than line drive.
    2. Watercut: because it gives a lower watercut compared to line drive.
    3. Economics: because there are only 4 injectors in the five spot pattern while there are 6 injectors in the line drive
- Summary of the waterflooding results for case (1) for the reservoir with solution gas drive as primary drive :

Solution gas drive						
Highest Oil saturation & Perforation interval	**Permeability**	**Natural Depletion**	**Five spot**		**Line Drive**	
		Rf	**Rf**	**Wc**	**Rf**	**Wc**
Top layer	**Increases Upward**	**17**	**34.4**	**77.4**	**32.9**	**86.3**
	Increases Downward	**17**	**31.1**	**78.4**	**31**	**87.9**
Mid layer	**Increases Upward**	**17**	**29.2**	**80**	**26.5**	**86.3**
	Increases Downward	**17**	**27.2**	**81.2**	**25.8**	**88.5**
Bottom layer	**Increases Upward**	**17**	**25.1**	**85.8**	**21.8**	**89.2**
	Increases Downward	**17**	**20.5**	**88.9**	**19.7**	**91.5**

Table 4.6: Summary of water flooding results in reservoir with solution gas drive

Case (2): Reservoir with water aquifer drive:-

❖ Five spot

The effect of perforation interval and saturation

Scenario (1): Permeability increases upward

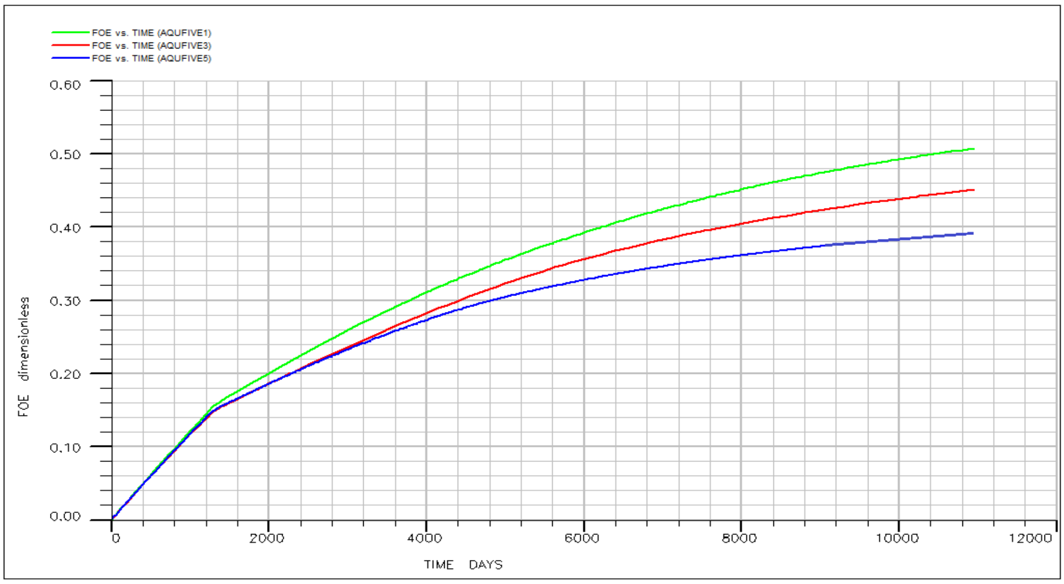


Figure 4.25: The effect of perforation interval and saturation on the field recovery efficiency scenario (1)

Scenario (2): Permeability increases downward

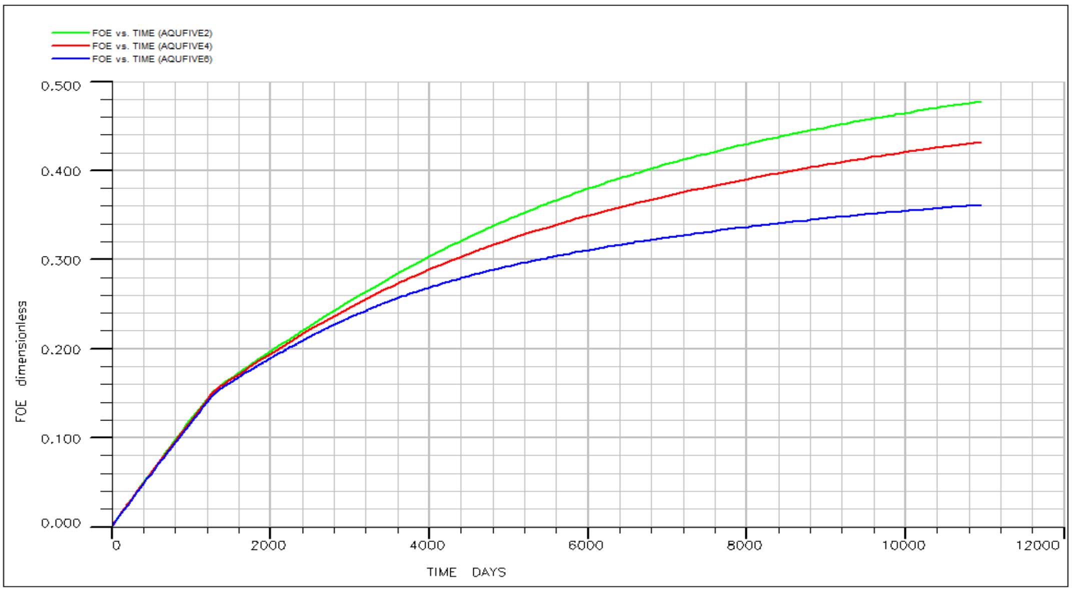


Figure 4.26: The effect of perforation interval and saturation on the field recovery efficiency scenario (2)

🟩: perforation and higher oil saturation on the top layer.

🟥: perforation and higher oil saturation on the mid layer.

🟦: perforation and higher oil saturation on the bottom layer.

The effect of vertical permeability

Scenario (1): perforation and higher oil saturation on the top layer

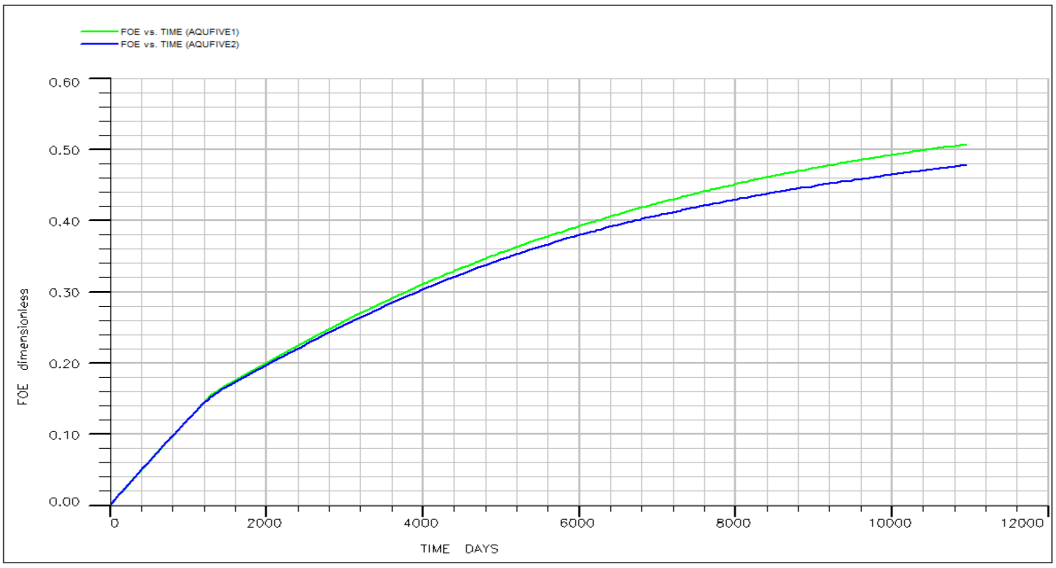


Figure 4.27: The effect of vertical permeability on the field recovery efficiency scenario (1)

Scenario (2): perforation and higher oil saturation on the mid layer

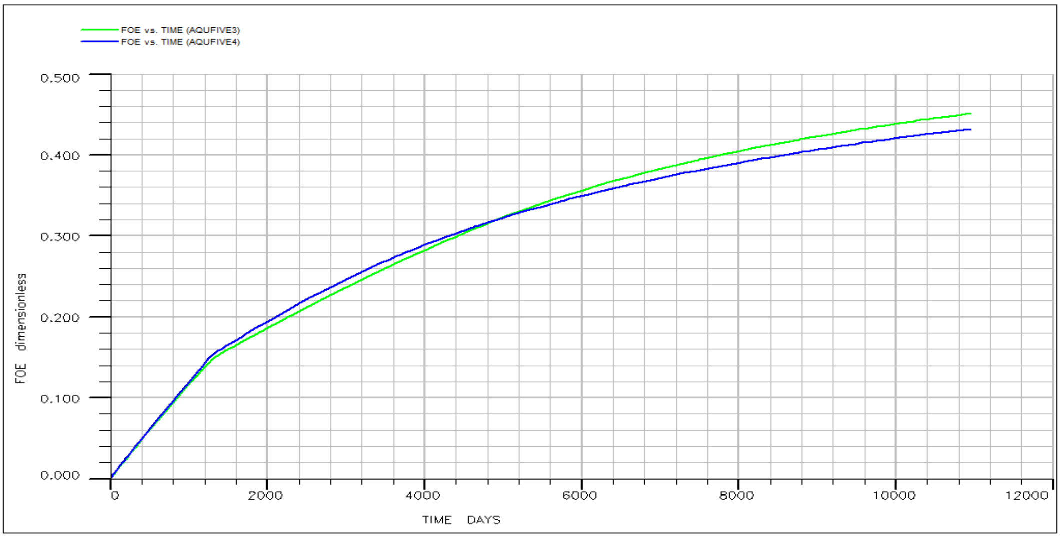


Figure 4.28: The effect of vertical permeability on the field recovery efficiency scenario (2)

Scenario (3): perforation and higher oil saturation on the bottom layer

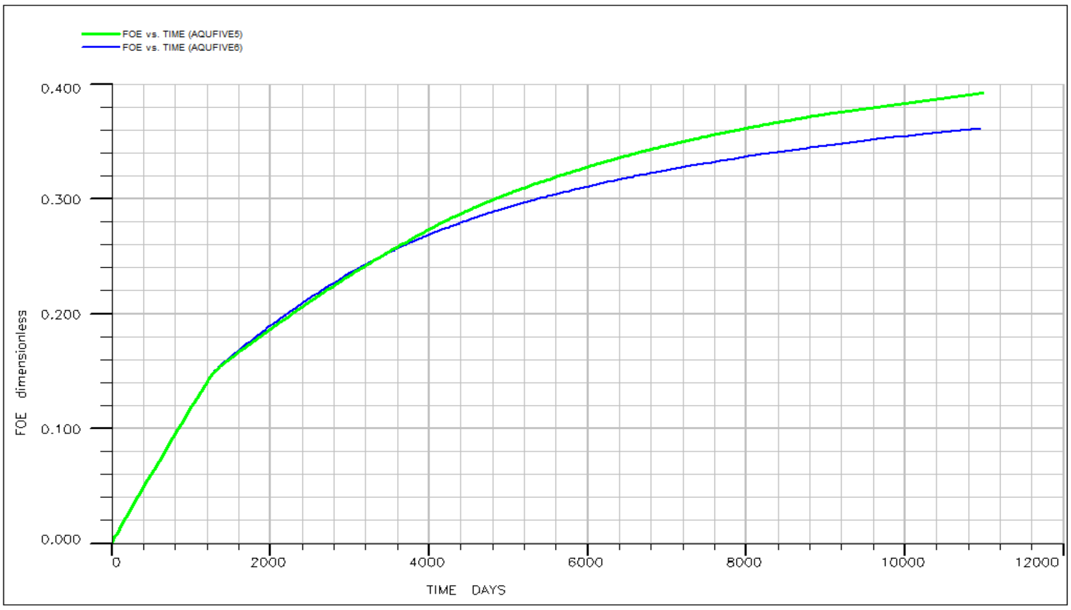


Figure 4.29: The effect of vertical permeability on the field recovery efficiency scenario (3)

🟩 : permeability increases upward

🟦 : permeability increases downward

Comparing the six cases of five spot

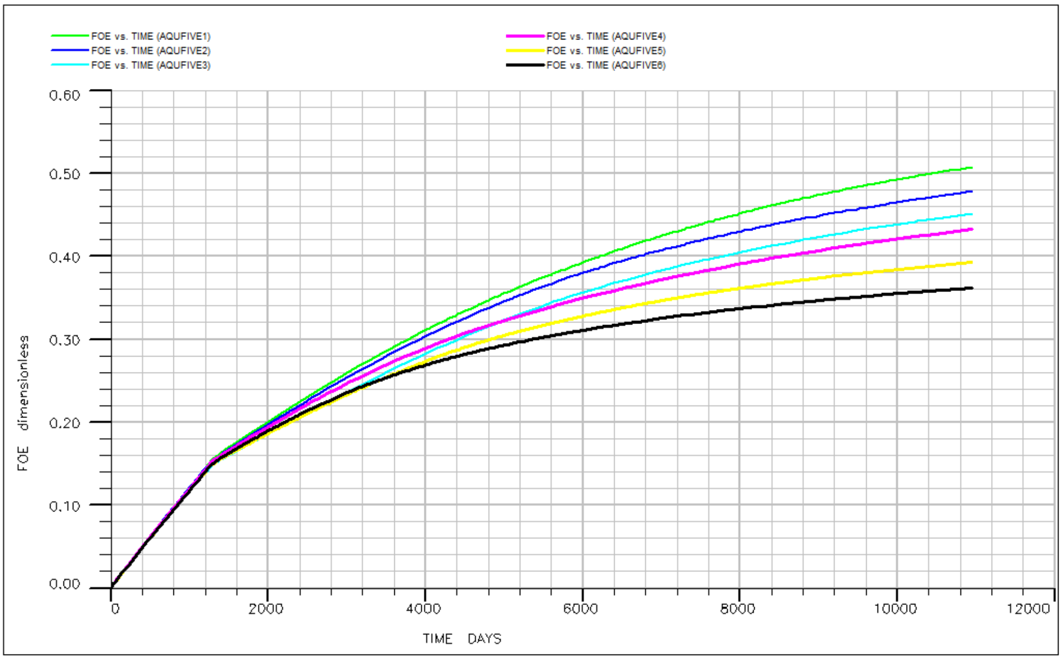


Figure 4.30: The effect of vertical permeability, saturation and perforation interval on the field recovery efficiency under different scenarios

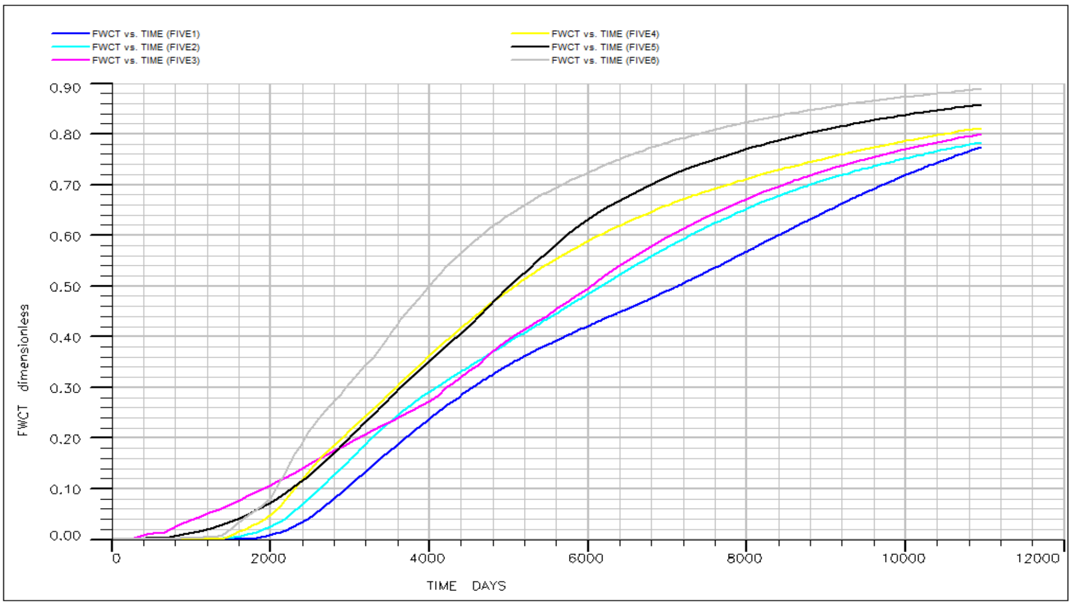


Figure 4.31: The effect of vertical permeability, saturation and perforation interval on the field watercut under different scenarios

- **Line drive**

The effect of perforation interval and saturation

Scenario (1): Permeability increases upward

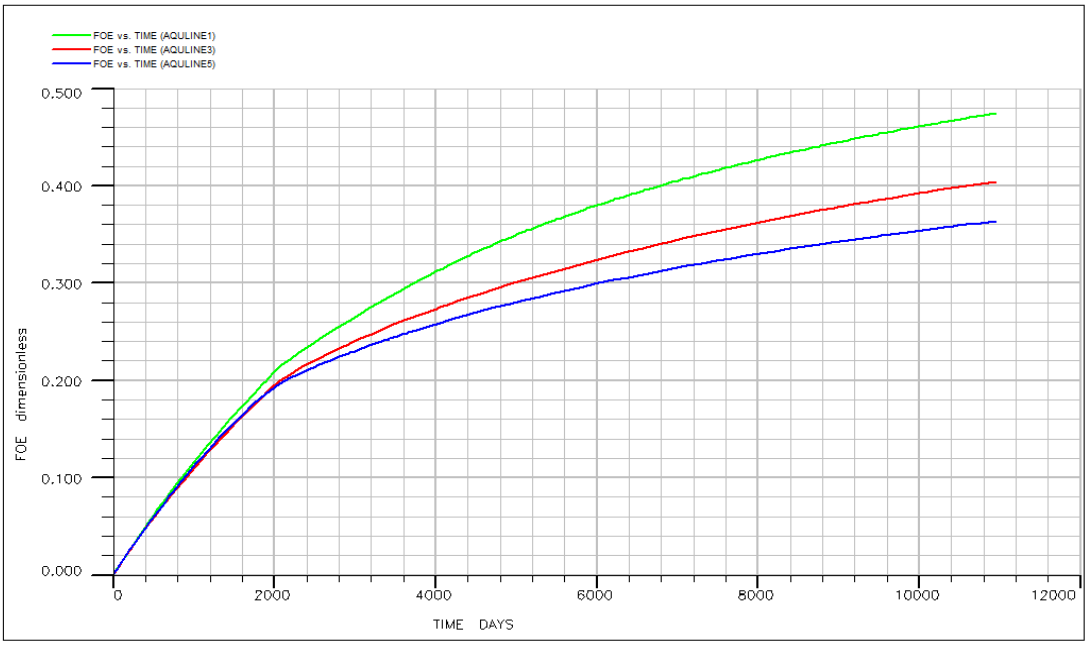


Figure 4.32: The effect of perforation interval and saturation on the field recovery efficiency scenario (1)

Scenario (2): Permeability increases downward

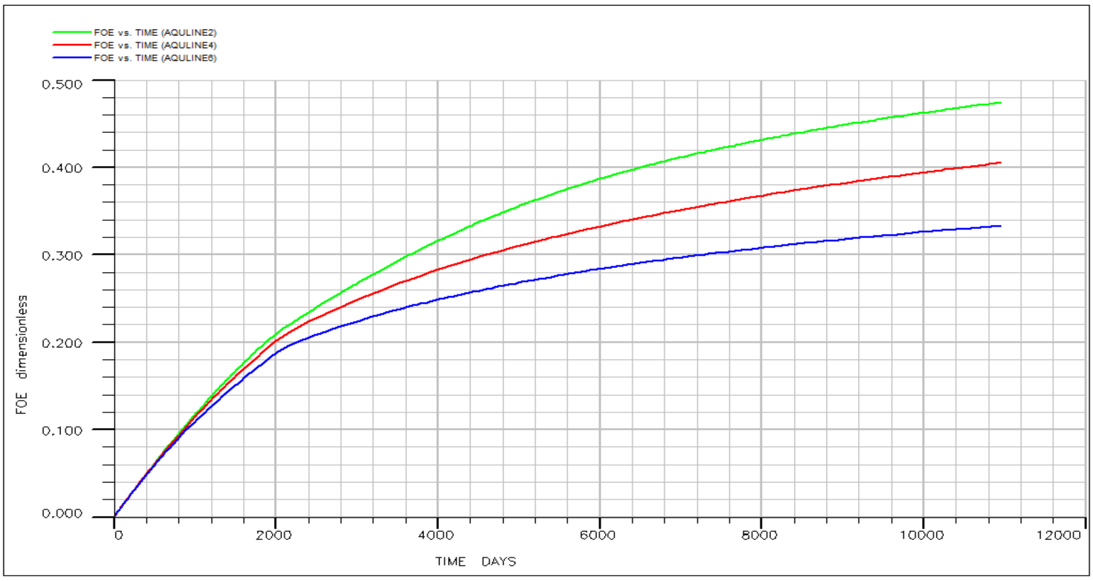


Figure 4.33: The effect of perforation interval and saturation on the field recovery efficiency scenario (2)

🟩: perforation and higher oil saturation on the top layer.

🟥: perforation and higher oil saturation on the mid layer.

🟦: perforation and higher oil saturation on the bottom layer.

The effect of vertical permeability

Scenario (1): perforation and higher oil saturation on the top layer

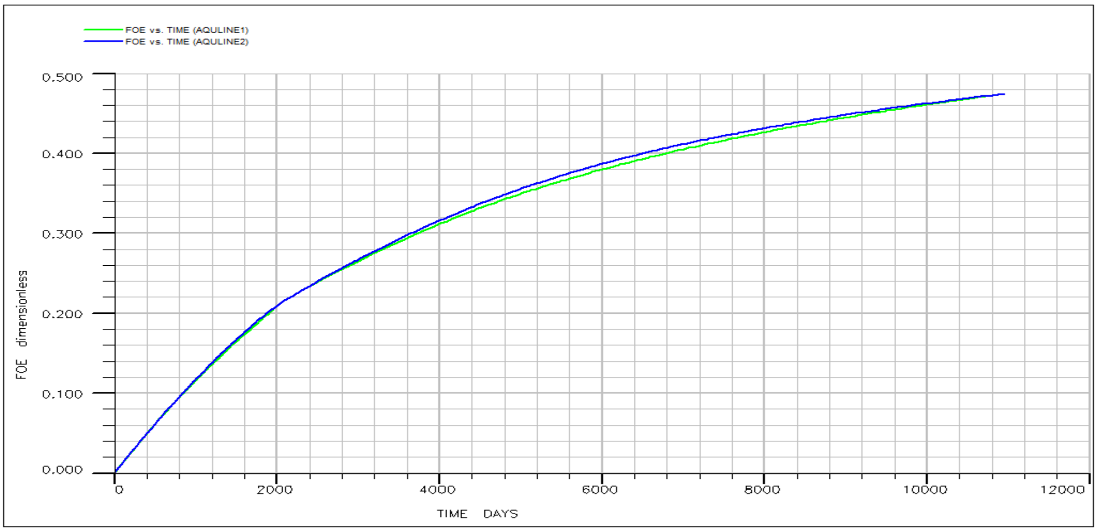


Figure 4.34: The effect of vertical permeability on the field recovery efficiency scenario (1)

Scenario (2): perforation and higher oil saturation on the mid layer

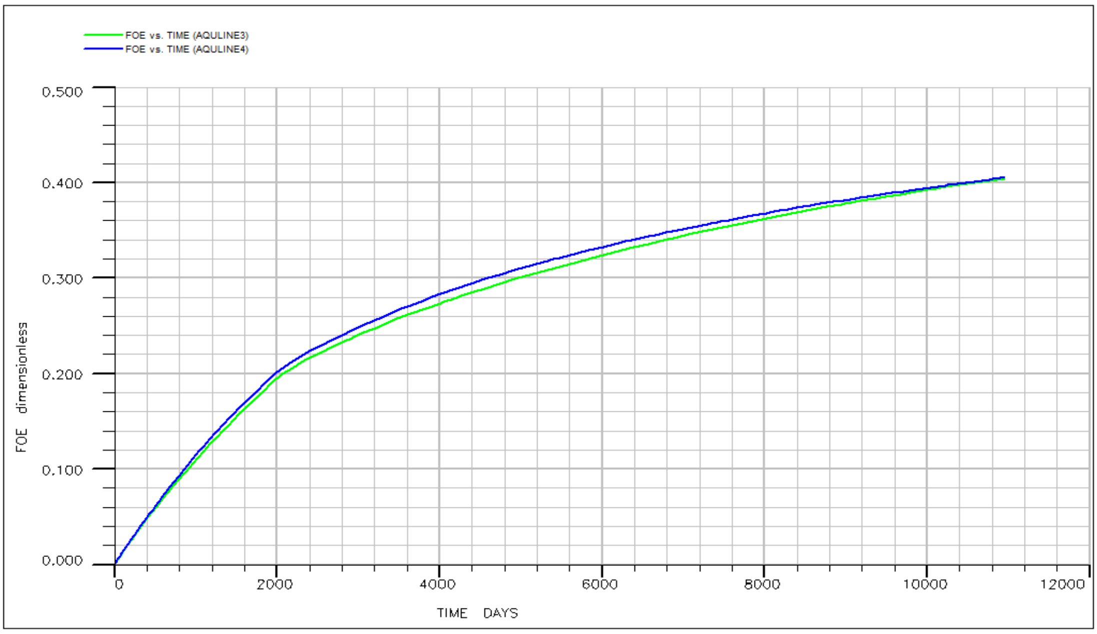


Figure 4.35: The effect of vertical permeability on the field recovery efficiency scenario (2)

Scenario (3): perforation and higher oil saturation on the bottom layer

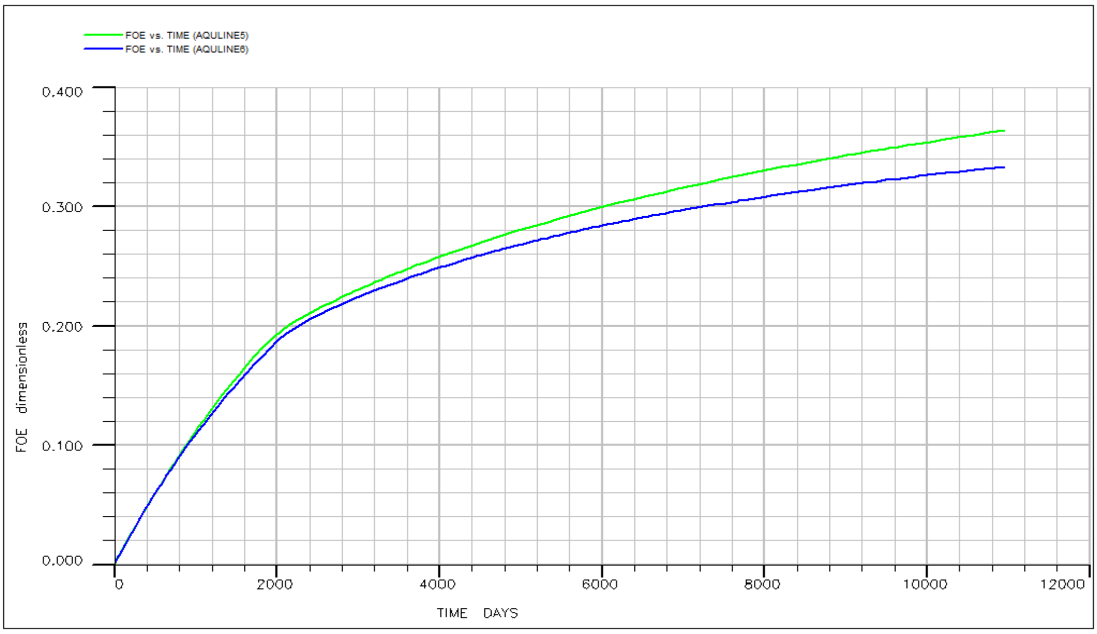


Figure 4.36: The effect of vertical permeability on the field recovery efficiency scenario (3)

🟩 : permeability increases upward

🟦 : permeability increases downward

Comparing the six cases of line drive

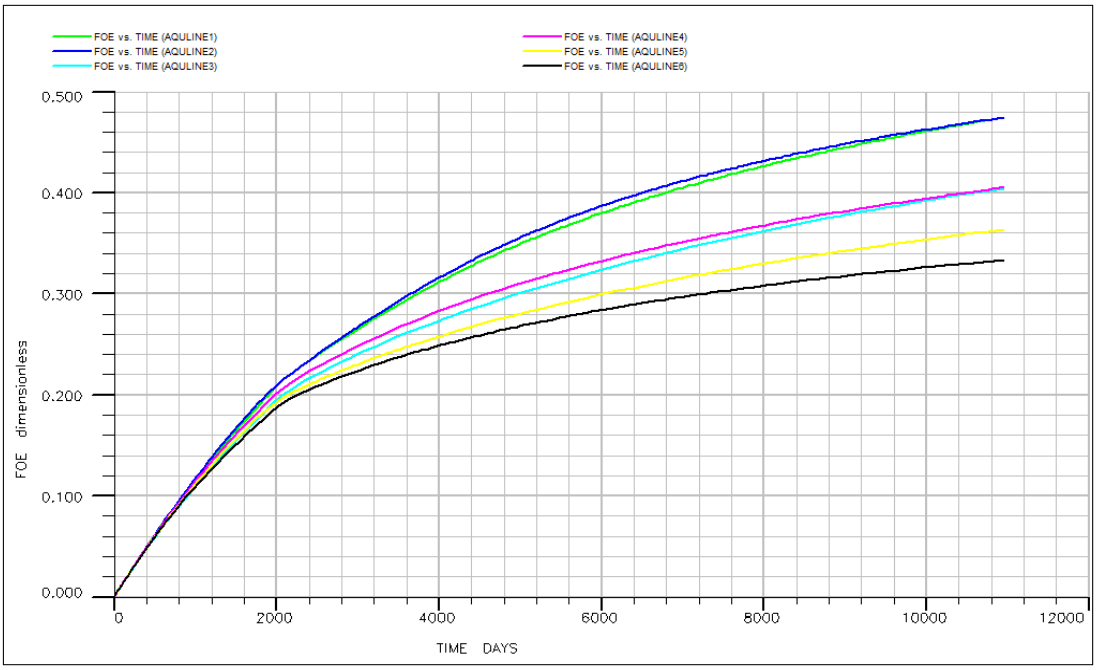


Figure 4.37: The effect of vertical permeability, saturation and perforation interval on the field recovery efficiency under different scenarios

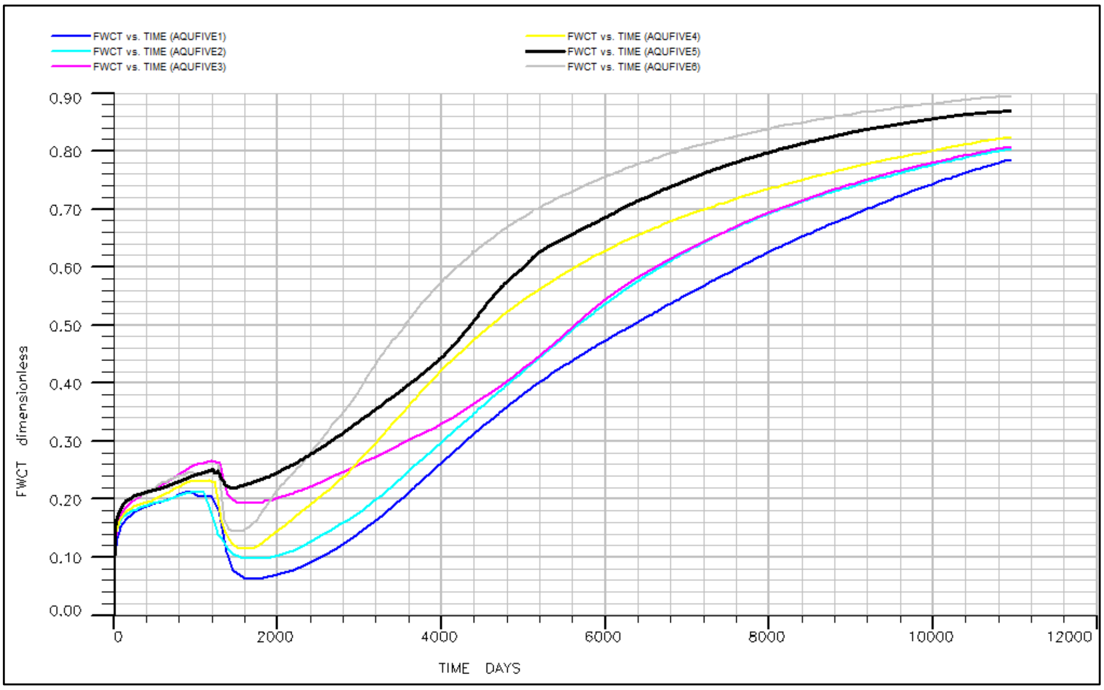


Figure 4.38: The effect of vertical permeability, saturation and perforation interval on the field watercut under different scenarios

- The above results show that as the permeability increases upward in the vertical direction the recovery factor will be higher compared to when the permeability increases downward in the vertical direction.
- The results also show that the highest recovery factor will be when the highest oil saturation and perforation interval is on the top layer while the lowest recovery factor will be when the highest oil saturation and perforation interval is on the bottom layer.
- The best case when the higher oil saturation and perforation on the top layer while the permeability increases upward it gives the highest recovery factor and the lowest watercut.
- The five spot pattern is better than the line drive in term of:
    1. Recovery factor: because it gives a higher recovery factor than line drive.
    2. Watercut: because it gives a lower watercut compared to line drive.
    3. Economics: because there are only 4 injectors in the five spot pattern while there are 6 injectors in the line drive.
- Summary of the waterflooding results for case (1) for the reservoir with water aquifer as primary drive :

Water aquifer drive						
Highest Oil saturation & Perforation interval	**Permeability**	**Natural Depletion**	**Five spot**		**Line Drive**	
		Rf	**Rf**	**Wc**	**Rf**	**Wc**
Top layer	**Increases Upward**	**19**	**31.7**	**78.5**	**28.5**	**86.5**
	Increases Downward	**19**	**28.8**	**80.4**	**28.5**	**88.2**
Mid layer	**Increases Upward**	**19**	**26.1**	**80.8**	**21.4**	**86.9**
	Increases Downward	**19**	**24.2**	**82.5**	**21.5**	**89.2**
Bottom layer	**Increases Upward**	**19**	**20.1**	**87.1**	**17.4**	**90.2**
	Increases Downward	**19**	**17.2**	**89.6**	**14.4**	**92.6**

Table 4.7: Summary of water flooding results in reservoir with water aquifer drive

- The waterflooding is more efficient in the reservoir with solution gas drive than the reservoir with water aquifer drive because it gives a higher recovery factor and lower watercut.
- From the above cases the best case when the higher oil saturation and the perforation interval on the top layer and the permeability increases upward is the one using the five spot pattern for both the reservoir with solution gas drive and the water aquifer drive , so this cases have been run untill the watercut reach 95%.

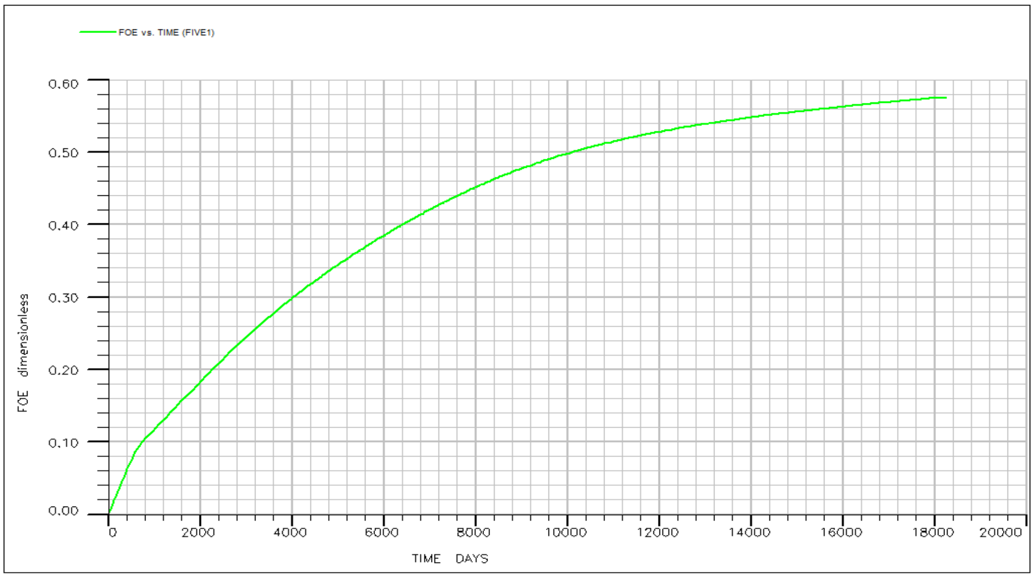


Figure 4.39: The field recovery efficiency for five spot in reservoir with solution gas drive when the watercut reaches 95%

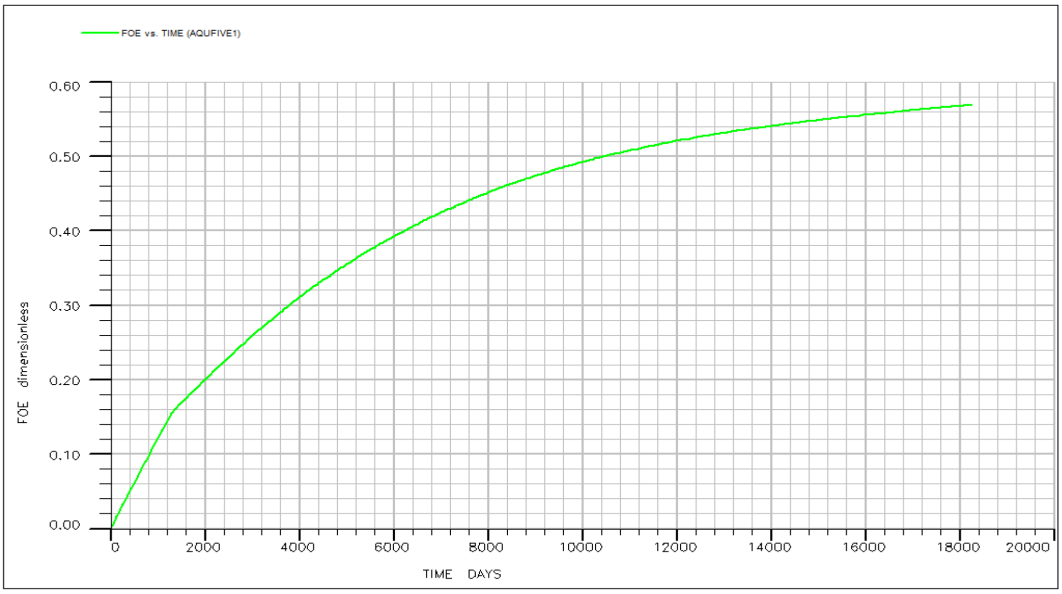


Figure 4.40: The field recovery efficiency for five spot in reservoir with water aquifer drive when the watercut reaches 95%

- The increment in the field recovery factor for five spot in reservoir with solution gas drive by waterflooding when the watercut reaches 95% from figure 4.39 is equal to 40.6 %, and it reaches this value after 37 years of implementing the waterflooding.
- The increment in the field recovery factor for five spot in reservoir with water aquifer drive by waterflooding when the watercut reaches 95% from figure 4.40 is equal to 37.9 %, and it reaches this value after 45 years of implementing the waterflooding.

CHAPTER (5)

CONCLUSION AND RECOMMENDATION

Waterflooding Technique is one of the best oil recovery methods and the reasons behind that because it has a relatively high recovery factor and also because it is cheap.

This project discussed the main parameters that affecting waterflooding performance in a heterogeneous depleted reservoir and quantify their importance towards an optimum design. The author in this project used Eclipse 100 software and Petrel software in order to build the reservoir model.

The main parameters that affecting the waterflooding performance is the range of the reservoir heterogeneity such as areal and vertical permeability, saturation distribution and the perforation interval. The effects of all this parameters have been addressed in the previous chapter of this report.

In addition, the obtained results show that as the permeability increases upward in the vertical direction the recovery factor will be higher compared to when the permeability increases downward in the vertical direction.

Furthermore, the results also show that the highest recovery factor will be when the highest oil saturation and perforation interval is on the top layer while the lowest recovery factor will be when the highest oil saturation and perforation interval is on the bottom layer.

Moreover, waterflooding is more efficient in the reservoir with solution gas drive than the reservoir with water aquifer drive because it gives a higher recovery factor and lower watercut.

The five spot pattern is better than the line drive in term of:

1. Recovery factor: because it gives a higher recovery factor than line drive.
2. Watercut: because it gives a lower watercut compared to line drive.
3. Economics: because there are only 4 injectors in the five spot pattern while there are 6 injectors in the line drive.

As conclusion, the best case when using the stated parameters in the simulation data part when the higher oil saturation and the perforation interval on the top layer and the permeability increases upward is the one using the five spot pattern for both the reservoir with solution gas drive and the water aquifer drive which they lead to increment in the recovery factor by 40.6 %, and 37.9 % respectively when the watercut reaches 95%.

Recommendations:

- Investigate the effect of the interrelated parameters using other software such as CMG.
- Include other factors that affecting the water flooding performance in heterogeneous reservoir such as shale layers and fluid properties.
- Investigate other types of patterns that have 1:1 ratio such as staggered line drive.
- As recommendation for implementing the water flooding is to start it as early as possible to maintain the reservoir pressure, and not to wait until the reservoir pressure declines.

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