LOW SALINITY WATER FLOODING SIMULATION STUDY

by

LOW JUN LEON, 12638

SUPERVISOR: ISKANDAR B DZULKARNAIN

DISSERTATION

Submitted to the Petroleum Engineering Programme

Universiti Teknologi PETRONAS

in partial fulfilment of the requirements

for the Bachelor of Engineering (Hons) Degree in Petroleum Engineering

Universiti Teknologi Petronas
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

May 2013

CERTIFICATION OF APPROVAL

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August 2013

CERTIFICATION OF ORIGINALITY

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.

LOW JUN LEON

ACKNOWLEDGMENTS

First of all, I would like to express my greatest gratitude to my campus, Universiti Teknologi PETRONAS (UTP) for providing a conducive learning environment in completing my Final Year Project. This project has allowed me to have a great exposure on the right methodology to carry out a research. Moreover, I have gained better understanding about prospect of Enhanced Oil Recovery(EOR) mechanism, especially on low salinity water flooding.

Many thanks go to my supervisor, Mr.Iskandar B Dzulkarnain. Without his guidance and supervision throughout these two semesters, this project will not be succeeded. His crucial contribution has kept my research work on the right track.

Lastly, I would like to say thank you to my parents and friends who morally supported and encouraged me during conducting this study.

ABSTRACT

Low salinity water flooding(LSWF) is a recent enhanced oil recovery (EOR) method which is applied by injecting water with a lower salinity than initial connate water. Although a lot of laboratory experiments and tests have shown LSWF's potential in EOR, There have not been done many modelling studies on this field. Moreover, there is lack of economic analysis to justify the application of LSWF for most of the simulation studies. Several hypotheses have proposed as LSWF mechanisms, namely electrical double layer effect, pH effect, fines migration and multicomponent ion exchange (MIE). However, there is still no definite theory that supports LSWF effects. Thus, the main objective of this research is to evaluate the effects of salinity in LSWF on oil recovery.

In this study, effects of salinity in LSWF are investigated through simulations of a 3 dimensional synthetic reservoir model by ECLIPSE 100 software. The model is lateral heterogeneous with only oil and water phase. Moreover, only one type of salt is assumed to be present in the water. There are 2 base cases in the first phase of study. The first base case uses high salinity(HS) water flooding technique by injecting 35000ppm of brine from the starting to the end of production, totally 10 years or 3650 days. The other case uses low salinity water flooding technique by injecting 1000ppm of brine continuously for the same production life, in order to compare the effect of salinity with the HS base case. Large wettability sensitivity was observed, showing that oil/water relative permeability and saturation are the main variables during simulations when BRINE option is activated. Findings obtained after injection of brines with different salinities indicated oil recovery improves with a decrease in salinity of the injected brines. Then, the second phase of the study will be comparing the oil recovery by alternating the LS and HS injection days. HS will be the first phase of injection followed by LS. Different cases will be simulated in this phase and evaluated through economic analysis. The best LSWF case will be selected after considering its economic feasibility.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Maintenance of reservoir pressure is crucial in prolonging production timeline of a reservoir. In primary recovery stage, natural energy such as gas cap drive and water drive mechanisms are sufficient to sustain reservoir pressure. When reservoir pressure can no longer sustained by natural mechanism, an external compatible fluid is injected into the reservoir to provide extra support and assist displacement of oil from subsurface to surface. Normally recovery factor for primary recovery stage is about 10%. While with secondary recovery, it increases by 15% to 40%.

Conventional water flooding technique has been applied widely during secondary recovery stage to maintain reservoir pressure. Recently, a new water flooding method that is low salinity water flooding (LSWF) is extensively studied for the purpose of improving oil recovery (IOR) as well as enhanced oil recovery (EOR), the tertiary recovery stage. Although EOR is able to increase higher recovery factor than secondary recovery stage, application of EOR still remains in conceptual stage in many major oil-producing countries. Research on LSWF will be significant in promoting EOR as it is regarded as one of the most inexpensive methods of EOR. However, LSWF technology is facing a lot of difficulties as there is lack of consensus concerning its recovery mechanisms. Recovery mechanisms are varied in different environment for LSWF. Thus, it will be challenging to determine the exact recovery mechanisms for LSWF. Nevertheless, alteration of wettability towards more water-wet conditions is generally accepted for LWSF effect (Austad, 2010a).

1.2 Problem Statement

1.2.1 Problem Identification

LSWF is still considered as a new oil recovery approach and it requires more research to conclude a definite theory for it. Though there are lots of coreflooding tests to study the mechanisms and effects of LSWF, there have not been done many simulation studies on this field. Besides that, there is no economic analysis to justify the selection of the best case for most of the available simulation studies. Without economic analysis, it will be difficult to evaluate LSWF case in terms of its economic feasibility.

1.2.2 Significance of Project

This simulation will provide a clear view on what is happening in the reservoir by varying salinity in LSWF. ECLIPSE 100 software which is one of commercial reservoir simulators, will be used to conduct studies on LSWF. Moreover, economic analysis will be carried out to show the best salinity in LWSF case in order to optimise LWSF recovery factor.

1.3 Objectives

The objectives of this research are:

a) To investigate the effects of salinity in LSWF on oil recovery and sweep efficiency of the simulated reservoirs.
b) To observe the mechanisms that affect LSWF based on literature review.
c) To learn the ways to simulate reservoir with ECLIPSE 100 for LSWF cases.
d) To justify the application of LSWF by economic analysis.

1.4 Scope of Study

This project begun by researching information about LSWF, such as its mechanisms and its effects on recovery factor. These studies will be useful in results and discussion session. Models of LSWF research will be simulated using ECLIPSE 100 (2009.1). Due to time constraint, this simulation study will assume only one salt in the brine. A base case data file is created to compare the difference before and after LSWF. Furthermore, different cases will also be simulated to investigate low salinity effect and to carry out economic analysis. Oil and water relative permeability, salt concentration and other properties are included in the synthetic model (Jerauld et. al., 2008). Oil recovery factor is the main observed factor from simulation results.

1.5 Relevancy of Project

Formation damage and plugging of pores may occur if too little amount of salinity water is injected into the reservoir. Thus, sensitivity study on LSWF is carried out through simulation to understand the application of LSWF in terms of its efficiency and effectiveness. This project will assist the utilization of LSWF in oil and gas industry.

1.6 Feasibility of the Project within the Scope and Time Frame

This project will be divided into 2 parts which are FYP I and FYP II. Most of the time spent in FYP I will be reading research papers and journals. The author will then learn ways to simulate reservoirs using ECLIPSE 100 based on LSWF functions. The author will familiarize with Eclipse 100 in order to simulate reservoirs with LSWF functions from end phase of FYP I to FYP II phase. Different cases will be simulated and economic analysis will be done to select the best LSWF case.

CHAPTER 2

LITERATURE REVIEW

2.1 Enhanced Oil Recovery (EOR)

Oil recoveries can be classified into three types which are primary, secondary and tertiary oil recovery which is also known as enhanced oil recovery (EOR). Primary oil recovery uses natural drive mechanism to enable oil flows from subsurface to surface. Examples of natural drive mechanisms are gas cap drive, water drive, solution gas drive, etc. Generally, recovery factor for this stage is very low. Therefore, secondary recovery is applied to increase the oil recovery when primary recovery has reached its limit of production. External sources such as water injection or gas injection are used to maintain the pressure or to improve sweep efficiency so that residual oil is displaced toward producing wells (Green and Willhite, 1998). When primary and secondary oil recovery becomes uneconomical, residual oil can be displaced by applying tertiary recovery. Green and Willhite (1998) consider EOR as a process involving the injection of a fluid or fluids of some type into a reservoir. It supplies the additional energy (artificial energy) needed to displace oil to a producing well and interact with the reservoir oil/rock system to create conditions favorable for oil recovery. The targets of EOR are oil remaining in place after primary/secondary oil recovery and oil which is hard to produce (Zolotuchin and Ursin 2000). Based on the definitions, low salinity water flooding (LSWF) should be classified as an EOR process. This is because lots of LSWF experiments and studies have highlighted the increase in oil recovery and displacement of residual oil. Moreover, the chemical composition of the injected water is different from the initial formation brine.

2.2 Low Salinity Water Flooding

Conventional waterflooding is used to improve oil recovery from oil reservoirs. Historically composition of brine injected is ignored to prevent formation damage. Furthermore, laboratory relative permeability tests and displacement tests are done using synthetic formation water as both the connate and injected brine rather than using formation connate brine and the actual field injection water. Importance of injection-brine injection composition started to gain public attention when Yildiz and Morrow (1996) showed that changes in injection-brine composition can improve recovery. This showed that composition of brine could be used to optimise water flood recovery. Subsequently, improve recovery of crude oil by low-salinity water flooding (LSWF), with only modest increase in resistance to flow, was reported by Tang and Morrow (1997).

In addition, laboratory coreflood studies and field tests have also showed that LWSF could increase oil recovery by 2-40% over conventional water flooding, depending on the formation minerals of reservoir as well as brine composition (Mc,Guire, et al., 2005, Lager, et al. 2008). Jerauld et al. (2006) modeled LWSF as secondary and tertiary recovery stages in one dimensional model using salinity dependent oil/water relative permeability functions, resulting from wettability. In Al-Furat Petroleum Company (AFPC), imbibitions experiments, special core analysis (SCAL) experiments and single well field Log-Inject-Log(LIL) experiments have proven that low salinity water alter wettability of clastic oil reservoir. It was a prominent proof of alteration in wettability. However, there is still no exact mechanism that can explain the phenomenon of LSWF. It has been shown that the presence of kaolinite in the reservoir, the presence of divalent cations in the formation brine, and the presence of polar groups in the crude oil lead to improved recovery by low salinity flooding (Austad 2010).

2.3 Conditions for Low Salinity Effects

Most of the following conditions for low salinity effects were referred to Tang and Morrow (1999a). Besides, some explanations were extracted from work by researchers at BP (Lager et al.,2007; Lager et al., 2008a). One of the conditions for low salinity effects is related to the oil property. Low salinity effects will only occur on oil that has polar components that are acids or bases. Low salinity effects do not present in refined oil. Secondly, low salinity effects require a porous medium, such as sandstone and presence of clay. There was no documentation of low salinity effects in pure carbonates but the effects were observed in sandstone containing dolomite crystals (Pu et al.,2008). Furthermore, concentration low salinity injection fluid is also responsible for low salinity effects. The fluid should be around 1000-2000ppm and it seems to be sensitive to ionic composition (Na^{2+} vs Ca^{2+}). However, effects can be observed up to 5000ppm. For low salinity effects to take place, there must have initial formation brine. Moreover, formation brine must contain divalent cations such Mg^{2+}. Nevertheless, not all LSWF tests showed positive results of increasing oil recovery when all the conditions for low salinity effects were fulfilled.

2.4 Proposed Mechanisms for LSWF

As mentioned in previous section, there are still no definite assumptions for LSWF effects. Several mechanisms have been proposed as mechanisms of LSWF over the last decade. This section will discuss some possible mechanisms for LSWF to improve oil recovery.

2.4.1 Electrical Double Layer Effects

Ligthelm et al (2009) reported that certain cations in low salinity brine could help to screen off negative charges of oil and clay. As screening potential of cations is reduced, there will be expansion of electrical double layers that surround negatively charged clay minerals. As salinity decreases, thickness of double layer increases. Therefore, medium is slowly becoming water wet and directly increases oil relative permeability. Knott (2009) had further strengthened the concept of electrical double layer effects (Figure 1). An electrical double layer formed around negatively charged clay minerals in the porous rock structure of an oil-bearing reservoir. Ion concentration in the formation water would influence the thickness of electrical double layers. For example, double layer is more compact in high salinity water because it contains more ions. By injecting low salinity brine, double layer expands and allows monovalent ions such as sodium (Na^+) to penetrate the double layer. Sodium will displace divalent ions, which results in increasing electrostatic repulsion between clay particles and oil. Eventually, oil particles desorbed from clay minerals when repulsive forces overcame the attractive forces through multivalent cation bridges.

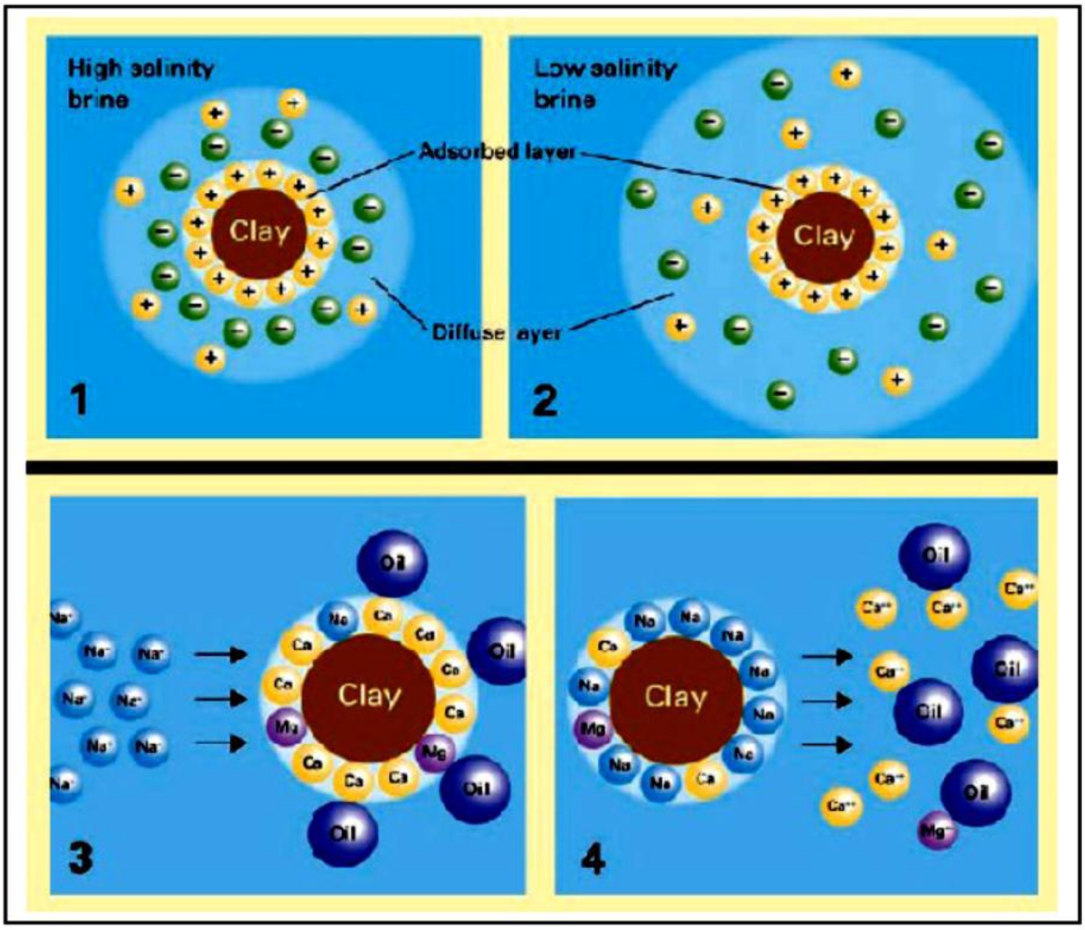


Figure 1: How double layer worked (After Knoott et al.,2009)

In the case of high salinity water containing more ions, the double layer is more compact but when the low salinity water is introduced, the double layer tend to expands as seen in Figure 1(1&2)., respectively. The adsorbed layer of positive ions contains divalent calcium (Ca2+) or magnesium (Mg2+) ions, which acts as tethers between the clay and oil droplets. Injecting reduced salinity water opens up the diffuse layer, enabling monovalent ions such as sodium (Na+), carried in the injection water, to penetrate into the double layer, Figure 1(3). At the same time, monovalent ions displace the divalent ions as results to increase electrostatic repulsion between clay particles and oil. It is believed that once the repulsive forces exceed the binding forces via multivalent cation bridge, the tethers between oil and clay particles is broken and the oil particles may be desorbed from clay surfaces. Thus, this will change the wetting state because of the reduction of the rock surface which is coated by oil and allow the oil to be swept out of the reservoir in Figure.1(4).

2.4.2 pH Effect

McGuire et al. (2005) proposed a low salinity recovery mechanism based on the generation of surfactants from the residual oil at elevated pH levels in accordance with the observations on the changes in reservoir fluids, fluid/rock interactions and changes in wettability. A LSWF experiment was conducted from a North Slope Alaskan field. There was an increased pH from 8 to 10 when low salinity brine was injected and oil recovery increased from 56% to 73%. Lager et al. (2006) proposed two possible reactions increasing the pH during low salinity waterflooding experiments:

- Carbonate dissolution resulting in an excess of OH-

$$CaCO_3 \leftrightarrow Ca^{2+} + CO_3^{2-} \qquad (2.1)$$

$$CO_3^{2-} + H_2O \leftrightarrow HCO_3^{-} + OH^{-} \qquad (2.2)$$

- Cation exchange between clay minerals and the invading water.

However, cation exchange is faster than carbonate dissolution and the mineral surface will exchange H+ present in the liquid phase with cations previously adsorbed, resulting in a pH increase. Austad et al. (2010) gave a clearer view on relationship of pH and salinity. Due to dissolved acidic gases like $CO_{2,}$ the pH of formation water of reservoir is around 5. Within this pH, divalent cations from formation water such as Ca^{2+} will tend to absorb cation exchange material, which are the clay minerals. During LSWF ion concentration of injected brine is significantly lower than initial formation brine. Equilibrium association with the brine-rock is interaction is disrupted, causing desorption of of Ca^{2+} from clay. To replace the loss of Ca^{2+} ion, H+ ion from water close to the clay surface adsorb onto the clay. There will be a local increase in pH close to the brine-clay due to the substitution of Ca^{2+} ion by H+ ion.

2.4.3 Fines Migration

Tang and Morrow (1996) have observed production of kaolinite fines along with the increase in production through LSWF. During LSWF, clay fines are only partially in contact. Mobilisation of these fines resulted in exposure of underlying surfaces, which increase water wetness of system. The theory of fines migration is best illustrated in figure 2. Released of clay minerals could block pore throats and channelled flowing water into non-swept pores to increase its microscopic efficiency (RezaeiDoust, 2009b). Moreover, Berea sandstone used by Morrow et al. (1998) for many of their experiments had predominantly kaolinite clay and quartz. Morrow et al. (1998) have found out that there are effects on oil recovery when varying the ionic composition of both the injected and connate brine. However, there were no sign of fines migration when BP had done various LSWF experiments showing increased in oil recovery (Lager et al. 2006). So fines migration may be an effect of LSWF instead of direct cause of increased oil recovery. In brief, fines migration is still vital in the process of LSWF that increases oil recovery.

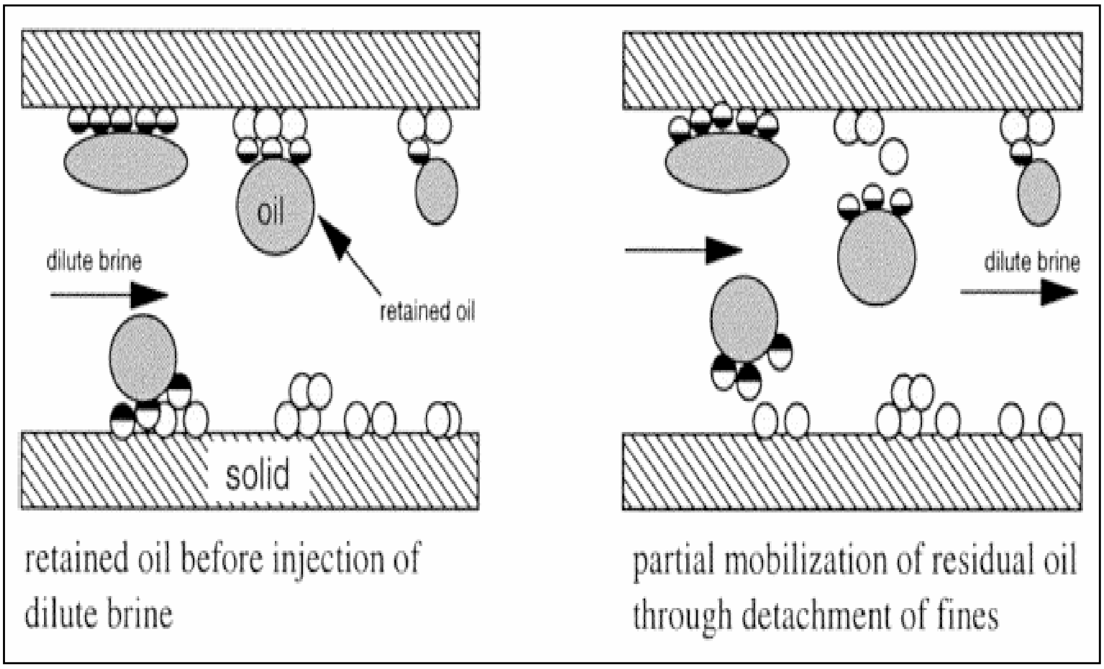


Figure 2: Detachment of clay particles and mobilization of oil (Tang, 1998)

Figure 2 shows the conditions of residual oil before and after injection of dilute brine. Initially oil is retained at clay surface due to oil–wet nature of clay particles. But during LSWF, clay particles are released from the rock surface (solid). Indirect mobilisation of oil occurs due to mobilisation of the clay particles. Consequently, residual oil saturation decreases and it leads to flow through less permeable zones enhancing the sweep efficiency.

2.4.4 Multicomponent Ion Exchange (MIE)

Lager et al. (2006) proposed a mechanism based on Multicomponent Ionic Exchange (MIE) between the invading brine and mineral surface. Positively charged multivalent ion assists polar oil components to connect to a negatively charged clay surface. On the other hand, positively charged multivalent ion will release oil component if it exchanged with a monovalent ion. From the list of mechanisms published by Sposito (1989) for organic matter absorption onto clay material, Lager (2006) had identified four out of eight mechanisms that are affected by possible cation exchange capacity in LSWF. The 4 mechanisms were cation exchange, water bridging, cation bridging and ligand bridging/bonding. Figure below shows attraction between clay surface and crude oil by divalent cations. MIE as one of LSWF mechanisms was proven through coreflooding experiment of the North Slope. Based on the analysis, salinity of injected brine was lower than the salinity of connate water. Decreased of concentration of Ca2+ and Mg2+ were reported, indicating Ca2+ and Mg2+ absorbed by rock matrix.

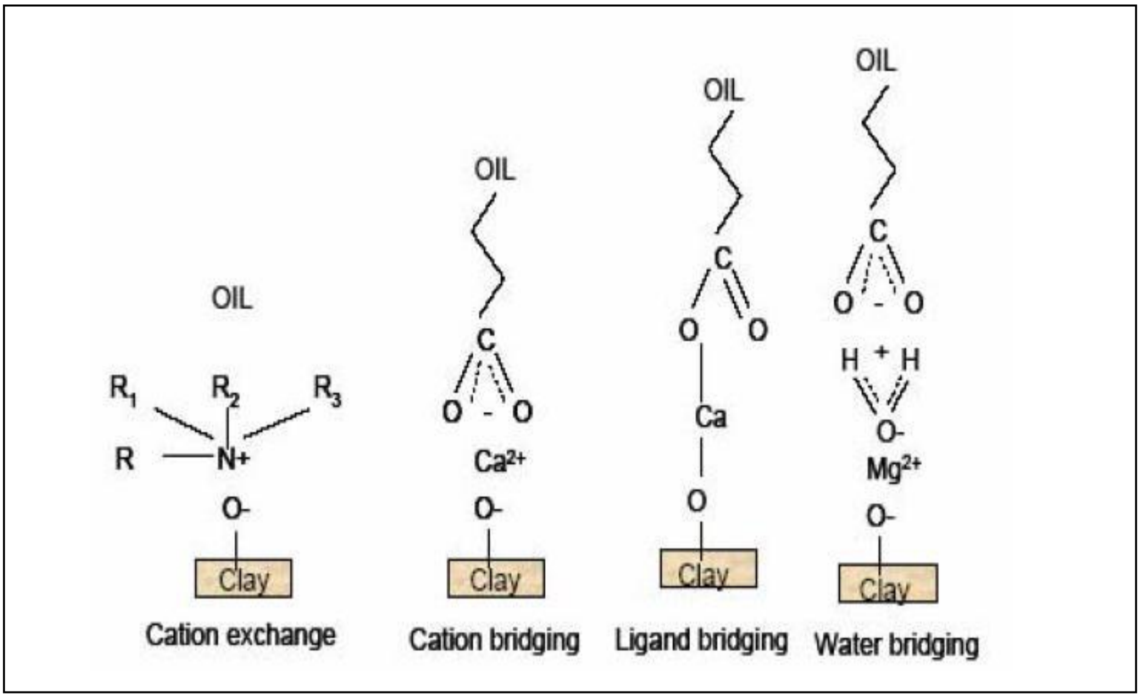


Figure 3: Attraction between clay surface and crude oil by divalent cations (Lager et al. 2008)

Figure 3 shows the four main mechanisms (cation exchange, cation bridging, ligand bridging, water bridging) of organic matter adsorption onto clay mineral that are greatly affected by cation exchange between clay surface and injected water. Different mechanism has different type of organic functional group. For cation exchange, organic functional groups involved are amino, ring NH, heterocyclic N (aromatic ring). Carboxylate, amines, carbonyl and alcoholic OH form the organic functional group of cation bridging. Conversely, Ligand exchange only consists of carboxylate while organic functional group for water bridging is the combination amino, carboxylate, carbonyl and alcoholic OH.

2.5 Low Salinity Water Flooding Model

Jerauld at al. (2008) developed a low salinity model which was based on established modelling approaches for chemical EOR. Modelling of LSWF was derived from conventional water flood modelling. The salt is modelled as an additional single lumped component in the aqueous phase which can be injected and tracked. Salinity will have a significant effect on viscosity and density of aqueous phase. In addition, function of salinity is dependent on relative permeability and capillary pressure as well as residual oil saturation. High and low salinity relative permeability curves are inputs, where shapes are interpolated in between. However, dependence on relative permeability and capillary pressure are not observed at high and low salinities. Part of connate water is made inaccessible to suit the conditions of LSWF effects. In order to model oil bank development, hysteresis between imbibitions and secondary drainage water relative permeability is included.

On the other hand, Wu et al. (2009) presented a mathematical model for modelling low-salinity waterflooding in porous or fractured reservoirs. It can be applied on 1-D, 2-D and 3-D low salinity water flooding simulation. In this conceptual model, salt is treated as additional "component" to the aqueous phase in a gas, oil and water three-phase flow system and is transported only within the aqueous phase by advection and diffusion. Besides, salt is subject to adsorption onto rock solids. Moreover, interaction between mobile and immobile water zones and flow in fractured rock are handled using a general multiple-continuum modelling approach. Same as the model proposed by Jerauld et al. (2008), changes of salinity will affect its relative permeability, capillary pressure and residual oil saturation.

Omekeh et al. (2012) proposed two phase flow oil and water phases to model ion-exchange and solubility in LSWF. The model demonstrated impact on water-oil flow function due to dissolution or precipitation of various carbonate minerals and multiple ion-exchange (MIE). Relative permeabilities depends on desorption of divalent ions with the aid of a weighing function. Results from the model proved that composition of brine is influenced by calcite dissolution and ion exchange.

2.6 Summary

All the proposed LSWF mechanisms are related to wettability alteration, generally towards water-wet conditions. Chemical reactions cause reduction of residual oil which directly improves oil recovery. Thus, relative permeability and saturation will be the main parameters in simulation work. Based on literature review conducted, these parameters are also emphasised in the modelling approach for low salinity flooding model. Wettability affects both end-point saturations and the shape of the capillary pressure curve Pc. For instance, it has been shown that intermediate wettability leads to minimum value for Sor, thus at large scale inducing a higher recovery. Wettability also changes the shape of the Pc curve. controlled mainly by the pore size distribution and is not function of wettability, yet the "level" of Pc depends strongly on wettability: Pc>0 for water-wet systems and Pc<0 for oil-wet systems. Thus we can define a wettability index WI as the logarithm of the ratio A2/A1 of the area under the positive to the negative parts of the Pc curve.

CHAPTER 3

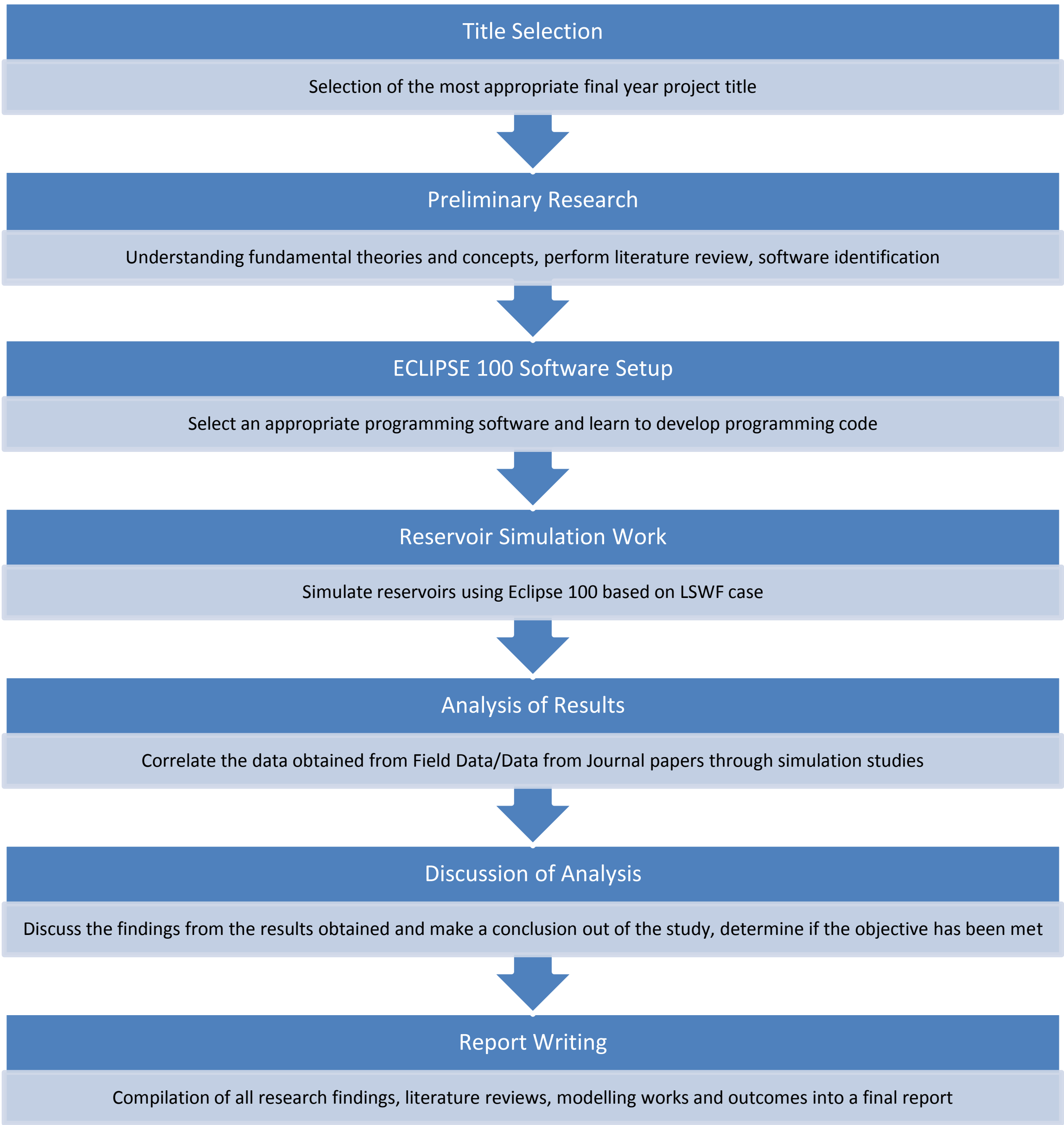
METHODOLOGY

3.1 Research Methodology

This section consists of project analysis which involves data and information gathering, as well as reservoir simulation work. Intensive studies are conducted to gain a better understanding on the subject such as proposed mechanisms for LWSF effects. Main source of this research is technical papers from ONE PETRO website under Society of Petroleum Engineers (SPE). Besides, the author also does plenty of readings on LSWF models. Among the studied LSWF models, one of them will be selected to perform reservoir simulation work.

Main results from the reservoir simulation focus on changes of recovery factor which is attributed to changes of salinity in LSWF. Apart from having research on LSWF technique, studies are also carried out on software which the author is going to use to simulate reservoir models (Eclipse). In the early stage, the author will explore and read the manuals for Eclipse 100 software. The author then starts to familiarize the Eclipse 100 software and the interface. After that the author is going to start working on the simulation. Simulation work will begin at middle stage of FYP I to the whole time frame for FYP II. Results and data obtained from the simulation will be analysed and discussed. Economic analysis will be done to select the best simulation model. Finally, the author will compile research findings, literature review and modelling works into project’s final report.

3.2 Project Activities



3.3 Gantt Chart and Key Milestones

FINAL YEAR 1st SEMESTER (JAN 2013)																
No.	**Detail/ Week**	**1**	**2**	**3**	**4**	**5**	**6**	**7**		**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	**Project title selection**								Mid-semester break							
2.	**Preliminary research work**															
3.	**Extended proposal submission**															
4.	**Study on fundamental concepts related to the project & familiarize the usage of ECLIPSE 100**															
5.	**Topic Defence**															
6.	**Reservoir simulation models using ECLIPSE 100 and economic analysis**															
7.	**Preparation of interim report**															
8.	**Submission of interim report**															

Table 1: Gantt Chart for First Semester Project Implementation

★	Key Milestones
	Project Activities

FINAL YEAR 2nd SEMESTER

(MAY 2013)

No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Reservoir simulation models using ECLIPSE 100 and economic analysis								Mid-semester break								
2.	Results Comparison																
3.	Submission of Progress Report																
4.	Economic Analysis and Selection of Base Case																
5.	Preparation of Final Report																
6.	Pre-SEDEX																
7.	Submission of Draft Report																
8.	Submission of Dissertation (soft bound)																
9.	Submission of Technical Paper																
10.	Oral Presentation																
11.	Submission of Project Dissertation (Hard Bound)																

Table 2: Gantt Chart for Second Semester Project Implementation

	Key Milestones
	Project Activities

3.4 Low Salinity Water Flooding (LSWF): Options in ECLIPSE 100

Eclipse 100 has a brine tracking function, which has a low salinity option. This option can be activated by keyword LOWSALT in the RUNSPEC section. The low salinity option is based on the model described by Jerauld et al. (2008). This model relates the total salinity of the water to relative permeability curves. They defined a curve for low salinity water and one for high salinity water. For values between the curves they interpolate. The interpolation is conducted by a set of equations as shown below

$$\boldsymbol{k_{rw} = F_1 k_{rw}^L + (1 - F_1) k_{rw}^H} \qquad \textbf{\textit{(3.1)}}$$

$$\boldsymbol{k_{ro} = F_1 k_{ro}^L + (1 - F_1) k_{ro}^H} \qquad \textbf{\textit{(3.2)}}$$

$$\boldsymbol{P_{cow} = F_2 P_{cow}^L + (1 - F_2) P_{cow}^H} \qquad \textbf{\textit{(3.3)}}$$

F_1 and F_2 represent functions of the salt concentration. k_{rw} is the water relative permeability while oil relative permeability is refered as $k_{ro.}$ P_{cow} is oil-water capillary pressure. Lastly, subscripts H stands for high salinity curves whereas L stands for low salinity curves. For end point of saturations, it is calculated by following sets of equations:

$$\boldsymbol{S_{wco} = F_1 S_{wco}^L + (1 - F_1) S_{wco}^H} \qquad \textbf{\textit{(3.4)}}$$

$$\boldsymbol{S_{wcr} = F_1 S_{wcr}^L + (1 - F_1) S_{wcr}^H} \qquad \textbf{\textit{(3.5)}}$$

$$\boldsymbol{S_{wmax} = F_1 S_{wmax}^L + (1 - F_1) S_{wmax}^H} \qquad \textbf{\textit{(3.6)}}$$

$$\boldsymbol{S_{owcr} = F_1 S_{owcr}^L + (1 - F_1) S_{owcr}^H} \qquad \textbf{\textit{(3.7)}}$$

F1 is a function of the salt concentration, and corresponds to the third column of the LSALTFNC keyword, k_{rw} is the water relative permeability, k_{ro} is the oil relative permeability and P_{cow} is oil-water capillary pressure.

In addition, this model adds an extra separate salt phase to the existing phase, and a mass conservation equation for the new phase is solved for each grid block in the reservoir. Brine is assumed to exist only in water phase (Schlumberger, 2011).

$$\frac{d}{dt}\left(\frac{VS_wC_s}{B_w}\right) = \sum\left[\frac{Tk_{rw}}{B_w\mu_{seff}}(\delta P_w - \rho_w g D_z)\right]C_s + Q_wC_s \qquad (3.8)$$

In the mass conservation equation above, ρw represents the water density, Σ is the sum over neighboring cells, C_s is the salt concentration in the aqueous phase, μs eff is the effective viscosity of the salt, D_z is the cell center depth, Bw is the formation volume factor for water, T is transmissibility, krw is the water relative permeability, Sw is the water saturation, V is the block pore volume, Q_w is the water production rate, P_W is water pressure and g is gravity acceleration.

Table 3 below shows keywords and functions in ECLIPSE for brine and low salinity simulations:

RUNSPEC	
BRINE	This let the simulator know that it has to deal with injected water with salinity values
LOWSALT	The activation keyword for the low salinity functions of the eclipse simulator. This keyword also activates the BRINE keyword if it has not been written.
TABDIMS	Sets the number of tables used. Need to be specified to allow the sets of relative permeability curves.
GRID	
This part is where the dimension of synthetic model is defined as well as its permeability and porosity	
PROPS	
LOWSALTFNC	Specify the low salinity fraction as function of the salt concentration in the grid block. Here you specify the concentration that is needed to be in either the low salinity, high salinity or in the interpolated area of the flow functions.
PVTWSALT	PVT data of water with salt
SWOF	Input tables of water and oil relative permeability and water-oil capillary pressure as functions of the water saturations.
REGIONS	
SATNUM	Defines which table of saturation function (SWOF) represent high salinity
LWSLTNUM	To associate low salinity number to each grid block
SOLUTION	

SALTVD	Salt concentration versus depth table
SUMMARY	
Don't have any essential keywords to the simulation here. There are some keywords that will show you the salt values in the simulation, but they are not needed to run the simulation. They are however interesting if you want to see how the salinity changes.	
SCHEDULE	
WSALT	Salt concentration for injection well

Table 3: Essential keywords and functions in Eclipse 100 for LWSF simulation

3.5 Synthetic Model and Properties

In this research, synthetic model is of dimension 150 meters, 150 meters and 6 meters in I, J and K directions respectively (Figure 5). Reservoir phase is a two phase model, oil and water for simplifications. The model is simulated in flood test by Eclipse 100 (2009.1) with a dimension of 50, 50 and 3 grids blocks. There are 2 wells: Injector and producer which are placed in grid number 1,1,1-3 and 50,50,1-3 respectively. Both wells are controlled by reservoir volume rate (RESV) at 100 m^3/day. The model is heterogeneous for the different layers. The Norne reservoir and fluid properties are used in the simulation(Table 4). The property details are taken from Emegwalu C.C. (2009), which were used in his enhanced oil recovery flooding study. Synthetic relative permeability of this model (Omekeh et al., 2012) can be found in Appendix A. As mentioned in the low salinity option, there can be 2 inputs for relative permeability and saturation profiles when the low salinity function is activated in ECLIPSE 100. The first input is to be applied during conventional water flooding where in this case it is referred as high salinity flooding. Another input will be used during low salinity water flooding. Keyword SATNUM in the REGIONS section determines which table of saturation function (SWOF) represents the high salinity saturation. To define low salinity table, the keyword LWSLTNUM must be inserted in REGIONS section. Please refer to figure 4 to 6 for the simulated model showing well placements with initial salt concentration, permeability x,y and z respectively. Permeability in y direction is not shown in the following figures as they are the same as the permeability in x direction.

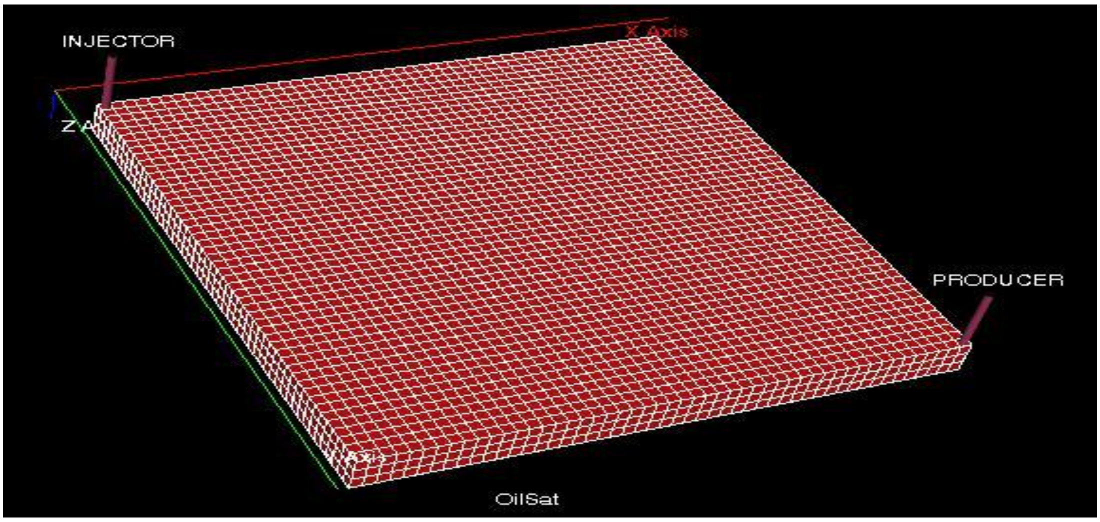


Figure 4: Synthetic model with well placements and initial salt saturation distribution

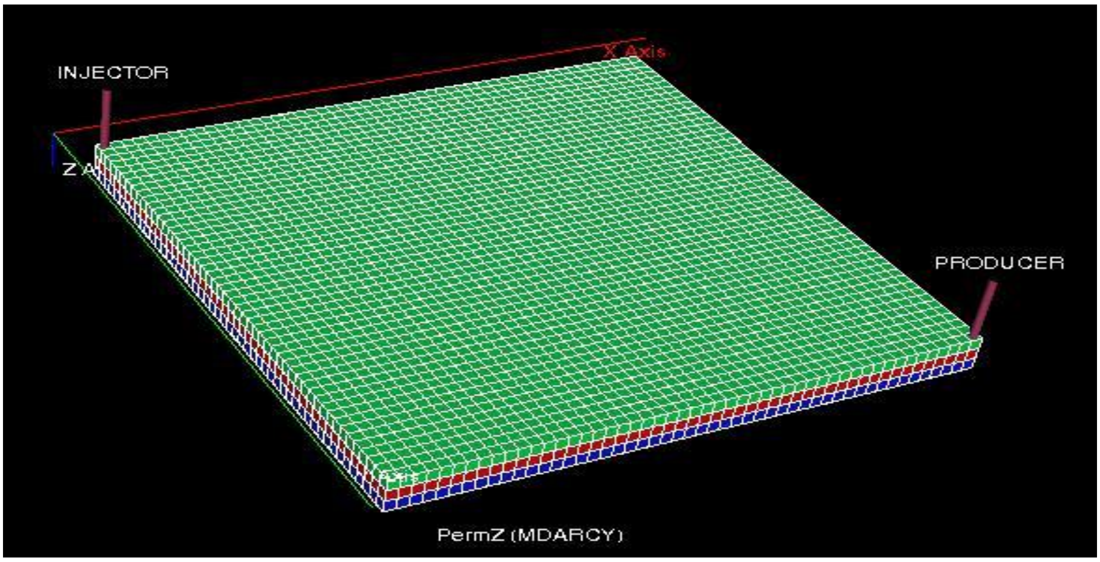


Figure 5: Synthetic model showing permeability Z direction

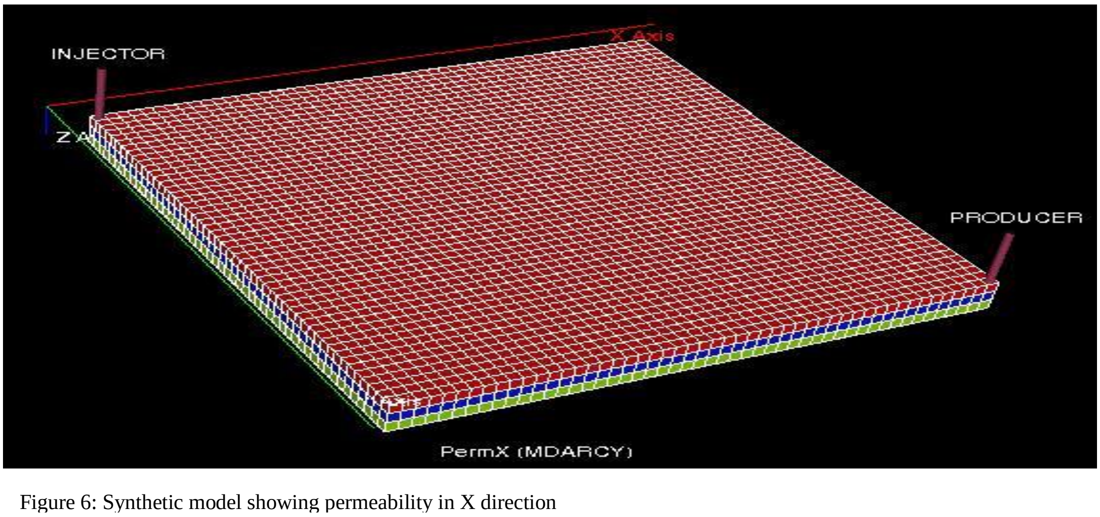


Figure 6: Synthetic model showing permeability in X direction

FLUID PROPERTIES	
Oil Density	860 kg/m3
Water Density	1033 kg/m3
Gas Density	0.853 kg/m3
Water Formation Volume Factor (Bw)	1.038
Water Viscosity	0.318
Compressibility factor	4.67E-5
ROCK PROPERTIES	
Permebility in I and J Directions	1172,1143 and 1162 (md)
Permeability in Z Direction	1050, 1800 and 500 (md)
Porosity	0.3
Reservoir Pressure	277 Bar
Compressibility	4.67 E-5

Table 4: North E-Segment Rock and Fluid Properties used for simulation

In this study, capillary pressures were neglected due to lack of data. The experiment simulated assumes only one salt presents in the brine for simplications. The initial connate water salinity is set to 35 kg/m^3 TDS, approximately the same salinity as seawater. From the literature review, effect of low salinity waterflooding was only observed after salinity is decreased significantly below 5000ppm (McGuire, 2005). Thus, effect of low salinity waterflooding was set at below 5 kg/m^3 TDS or 5000ppm in LSALTFNC table. Moreover, LSALTFNC is also able to decide the amount of high salinity and low salinity saturation and relative permeability profiles that were used during injection of brines with different salinities. LSALTFNC table is found in table 5 below.

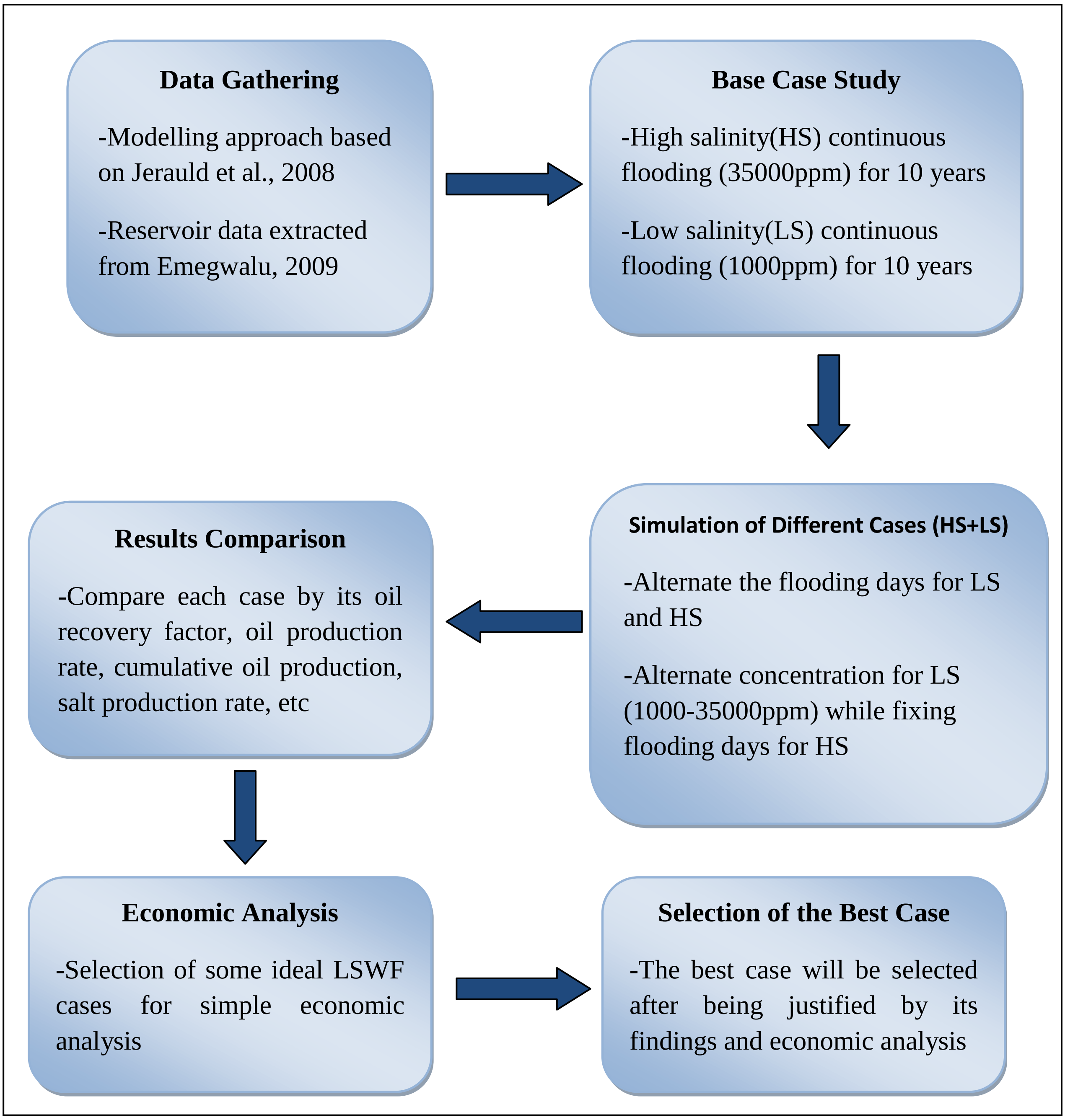
Salt Concentration (kg/m^3)	Salinity (ppm)	F1	F2
0	0	1	1*
1	1000	0.8	1*
4	4000	0.2	1*
5	5000	0	1*
35	35000	0	1*

Table 5: LSALTFNC for the synthetic model

3.5 Studied Cases

The reference case or the base case is the case that uses high salinity (HS) water flooding technique from the starting to the end of production, totally 10 years or 3650 days. Since we injected continuous (HS) water flooding or brine 35000ppm from the first day to the last day of production, the same way with continuous low salinity (LS) or brine 1000 ppm is done in order to compare the effect of salinity in general with the base case. Then, the effect of timing for secondary recovery phase is studied by using HS as the first phase and changing the starting day of continuous LS injection for the second phase. The best result of timing study is continued using for varying the salinity of LS in the tertiary recovery phase. The low salt concentration that could give the reasonable recovery is chosen and is used for all simulation cases in economic analysis. The last scenario is to change the size of LS slug in the second phase, while keeping the same HS flooding in the first phase, the day of starting LS slug and HS flooding for the tertiary phase recovery. The main purpose of doing this is to find out the best time to start and cease low salinity injection, in order to maximize profit while minimizing fresh water injection cost. The most reasonable case will then be chosen after evaluating its economic feasibility.

3.6 Simulation Study Work Flow



Simulation Study Work Flow	Key Milestones
Date Gathering	Week 10 (FYP I)
Base Case Study	Week 13 (FYP I)
Simulation on Different Cases	Week 3 (FYP II)
Results Comparison	Week 4 (FYP II)
Economic Analysis and Selection of base case	Week 7 (FYP II)

Table 6: Key milestones for simulation study work flow

3.7 Tools Required

1) ECLIPSE Software (2009.1)

- Developed by Schlumberger for reservoir simulation purposes
- Focuses on black oil model (ECLIPSE 100)

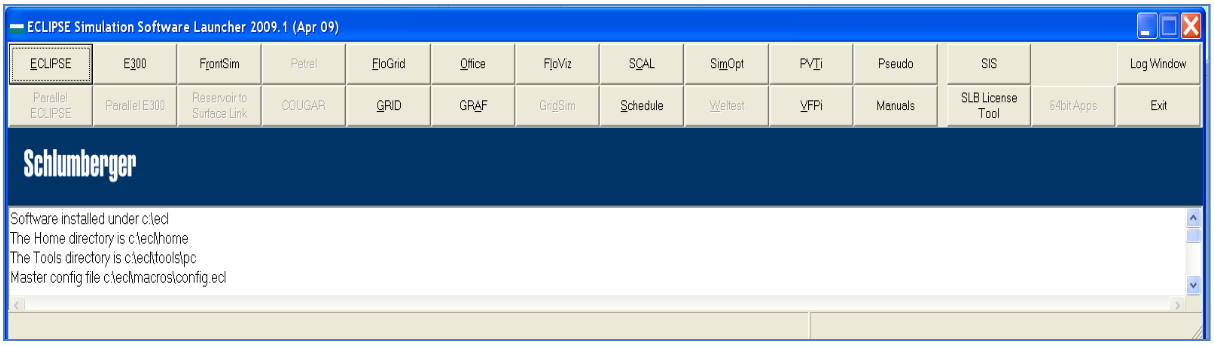


Figure 7: ECLIPSE simulation software launcher 2009.1

2) Hand tools

- Pencil, pen, highlighter, calculator, etc.

3) Microsoft Word 2007

- To prepare report and notes

4) Microsoft Power Point 2007

- To prepare presentation slides

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Effect of LSWF in Secondary Recovery Phase

4.1.1 Effect of the Salinity on Recovery Factor

From Figure 8, it can be seen that the recovery factor gets to 81.7% for the base case with continuous low salinity water flooding while the base case with high salinity water flooding gives only 63.5% recovery factor. This indicates oil recovery improves with a decrease in salinity of the injected brines. The 63.5% for the high salinity base is considered quite high as the simulated model is homogenous for the same layer, leading to a better sweep efficiency of the reservoir.

4.1.2 Effect of salinity on Oil Production Rate and Cumulative Oil Production

Figure 9 shows the effect of salinity in water flooding on oil production rate and cumulative oil production. From the graph, it is seen that a certain period of time is needed before the effect of the low salinity injection takes place. Cumulative Oil Production for LS base case is 56763 sm^3 while 44612 sm^3 is recorded for HS base case. Thus, the oil production rate of LS base case has been higher than HS base case. Cumulative oil production is increasing steadily for both cases until 2000 production days where production starts to be stagnant. Both cases maintain their oil production rates constant until they fall drastically. This means water breakthroughs are reached at 460 days for HS base case and at 430 days for LS base case. This shows that around 430 days are needed for low salinity effect to become visible. The shorter the time for low salinity effect to appear, the better it becomes for the economics.

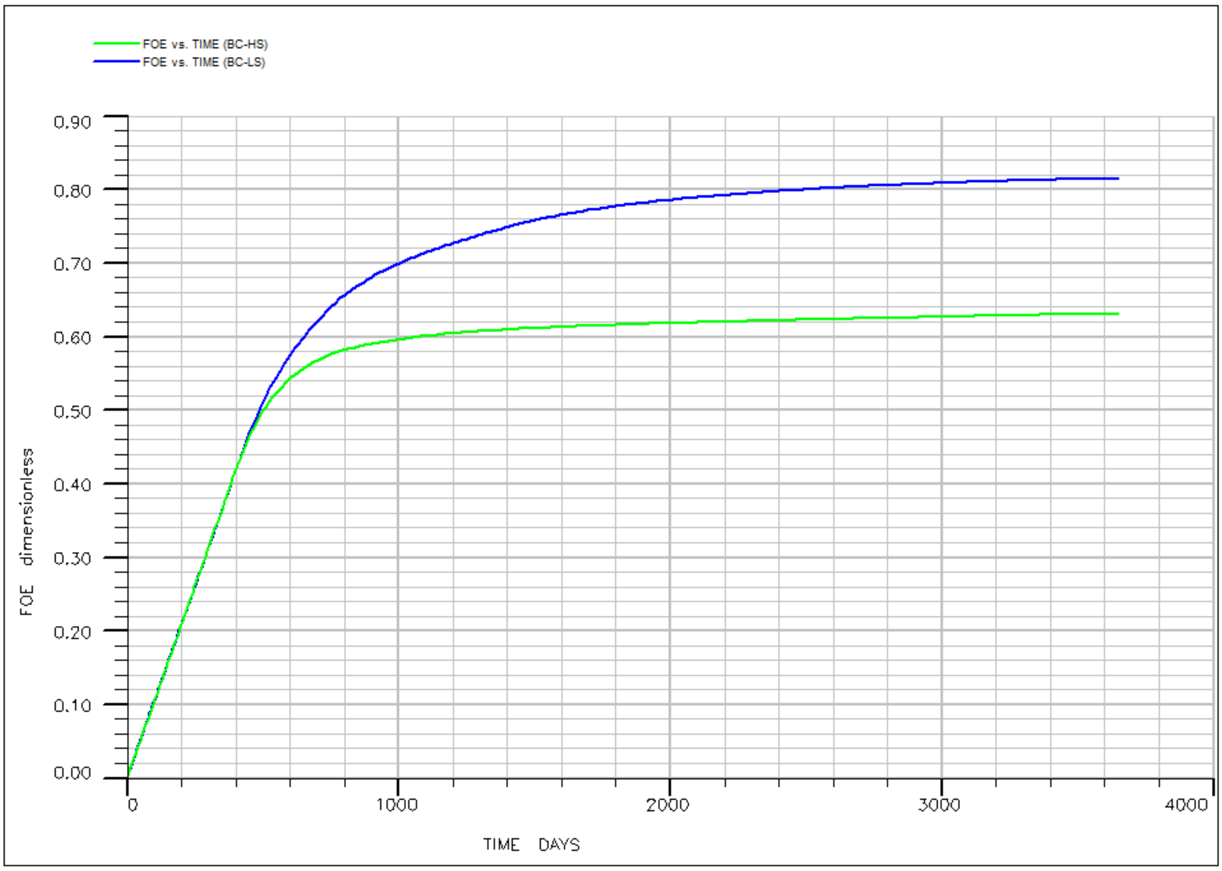


Figure 8: Comparison of oil recovery factor

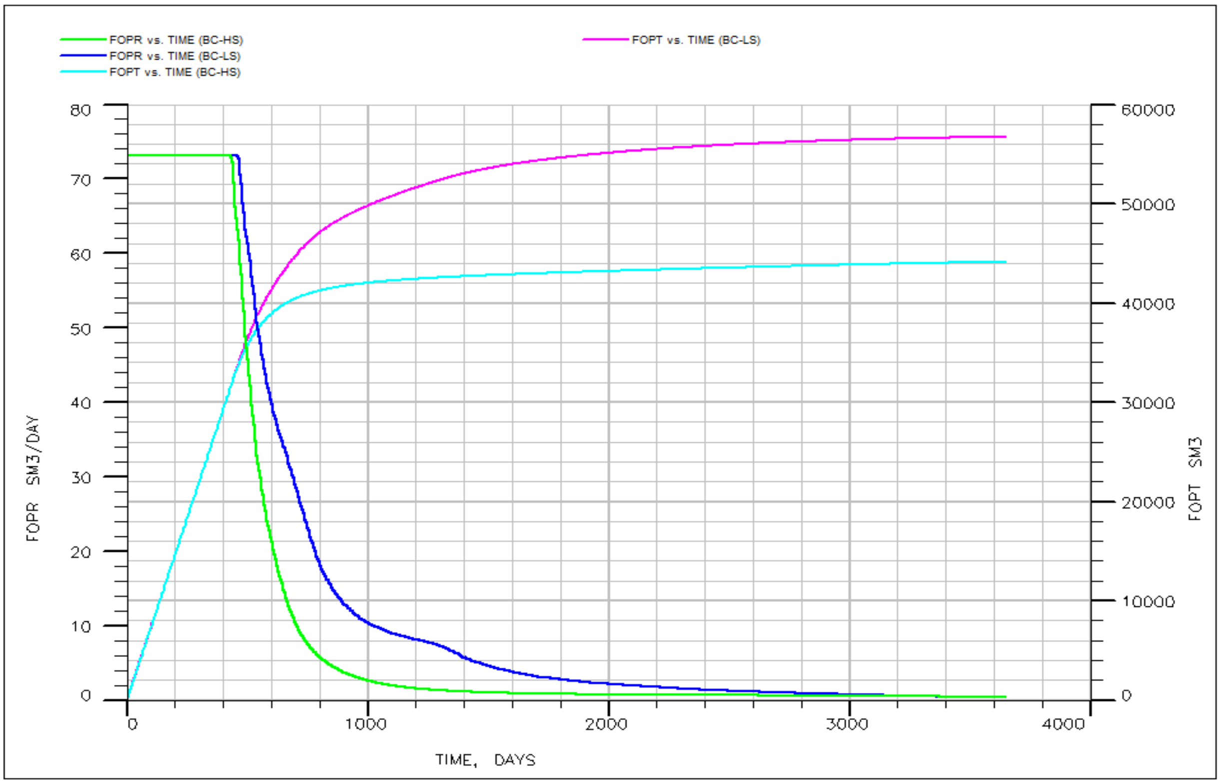


Figure 9: Comparison of cumulative oil production (FOPT) and oil production rate (FOPR)

4.1.3 Comparison of Salt Production Rate and Salt Production Concentration

Salt production rate (figure 10) and salt production concentration (figure 11) clearly follow the injected concentration. Salt production rate and salt production concentration remains constant throughout the production life for HS base case. On the contrary, salt production concentration for LS base case is decreasing gradually until 2000 production days where it stays at about 1 kg/m3 throughout the rest of production days. However as mentioned in section 4.2, low salinity effects only occur after some times from initial injection, around 430 days. This time is also suspected to be the time where water breakthrough. After that, salt production rate still increases slowly and then declines sharply after 560 production days.

4.1.4 Summary of LSWF Simulation Results in Secondary Recovery Phase

The base cases work well, and most of the results are as expected. Due to the initialization of the model, most of the results are also easy to predict. The effect of the low salinity water flooding is very high for the simulated cases. This model is homogenous for the same layer; therefore this made the predictions even easier. The only heterogeneity in this model was seen in the layer depth. No transmissibility or permeability barriers were included such as faults or impermeable zones. This clearly optimizes the effect of low salinity water flooding, because the injected fluids can flow easily through the reservoir and displace the oil.

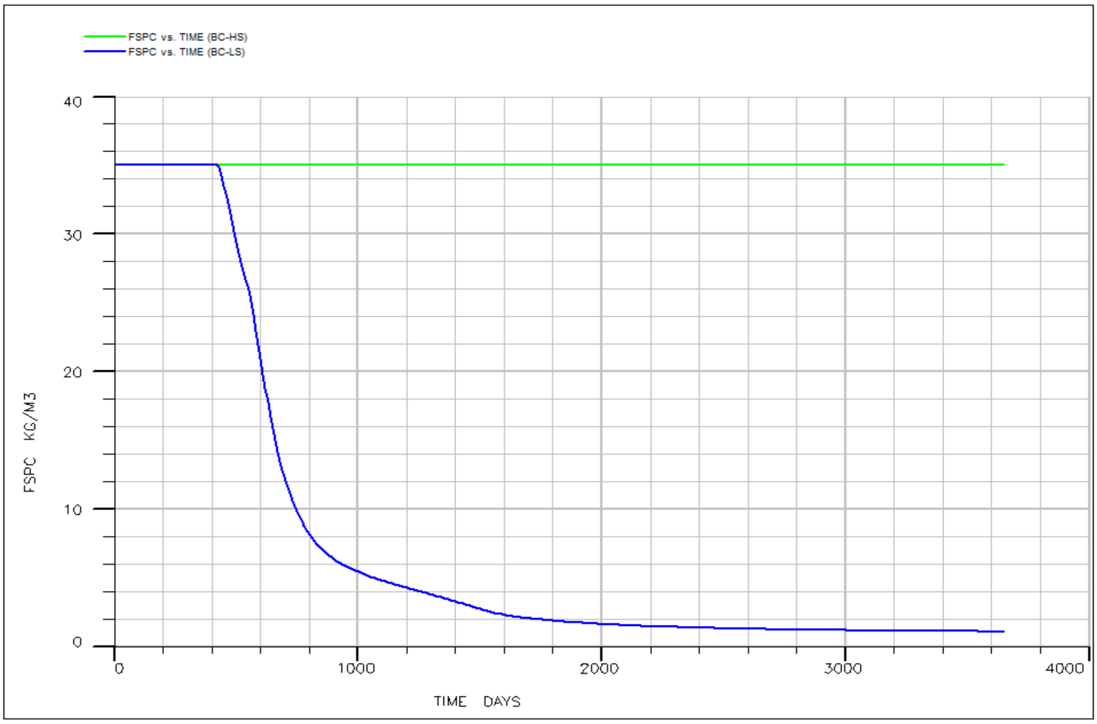


Figure 10: Comparison of salt production concentration

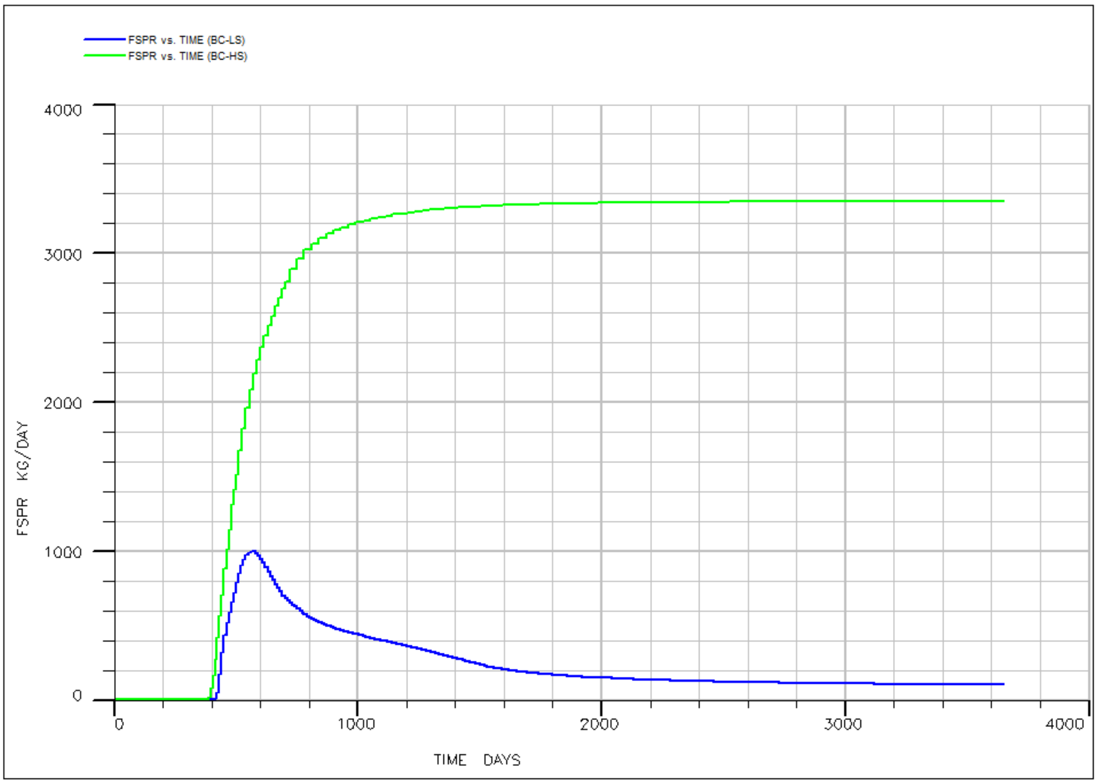


Figure 11: Comparison of salt production rate

4.2 Effect of LSWF in Tertiary Recovery Phase

4.2.1 Effect of Timing of LS injection on Recovery Factor and Oil Production Rate

This part is focused on interval of primary HS injection and time to start secondary injection by LS water. Since we have chosen 1000ppm as LS base case while 35000ppm as HS base case, they would continue to be used in examining the effect of LSWF in secondary recovery phase. The ultimate recoveries will be the study parameter in this phase. Due to time constraint, only 3 different intervals are chosen to investigate the effect of LSWF in secondary phase. The day to start secondary phase are selected at 300 days *(300HS-3350LS)*, 450 days *(450-HS-3200LS)* and 600 days *(600HS-3050LS)* after starting production with HS flooding – with 3350 days, 3200 days and 3050 days of continuous LSWF , respectively.

From figure 12, the graph shows that earlier the LS injection, the higher oil recovery as a result from the longer LS continuing flooding period. Oil recovery results at the end of production life are 80.81%, 80.63% and 80.46% in order of the first LS injection day after HS flooding at 300 days, 450 days and 600 days. The incremental cumulative oil recoveries from HS base case are 17.31%, 17.13% and 16.96%. However, they are less than the total cumulative oil from LS base by 2.19%, 2.37% and 2.54% respectively. The 3 cases are not seen clearly different from each other at the beginning until about 715 production days. However, 3 cases have almost the same oil recovery at the end of production after LSWF take place. Through figure 13, it can be noticed that LS injection at 300 days gives the earliest effect followed by LS injection at 450 days and at 600 days. Hence, oil production rate does not drop as much as the other cases. Oil production rate keeps constant for a while and starts to fall again gradually at 945 days until becoming constant from 2595 production days. Generally, all the 3 cases have the same trend of oil production rate that drop steadily before low salinity brine is injected into the field. After LSWF occurs, oil production rate increases for about 275 days before descend again there upon. At the end of production life, oil production rate and from three cases become almost the same value.

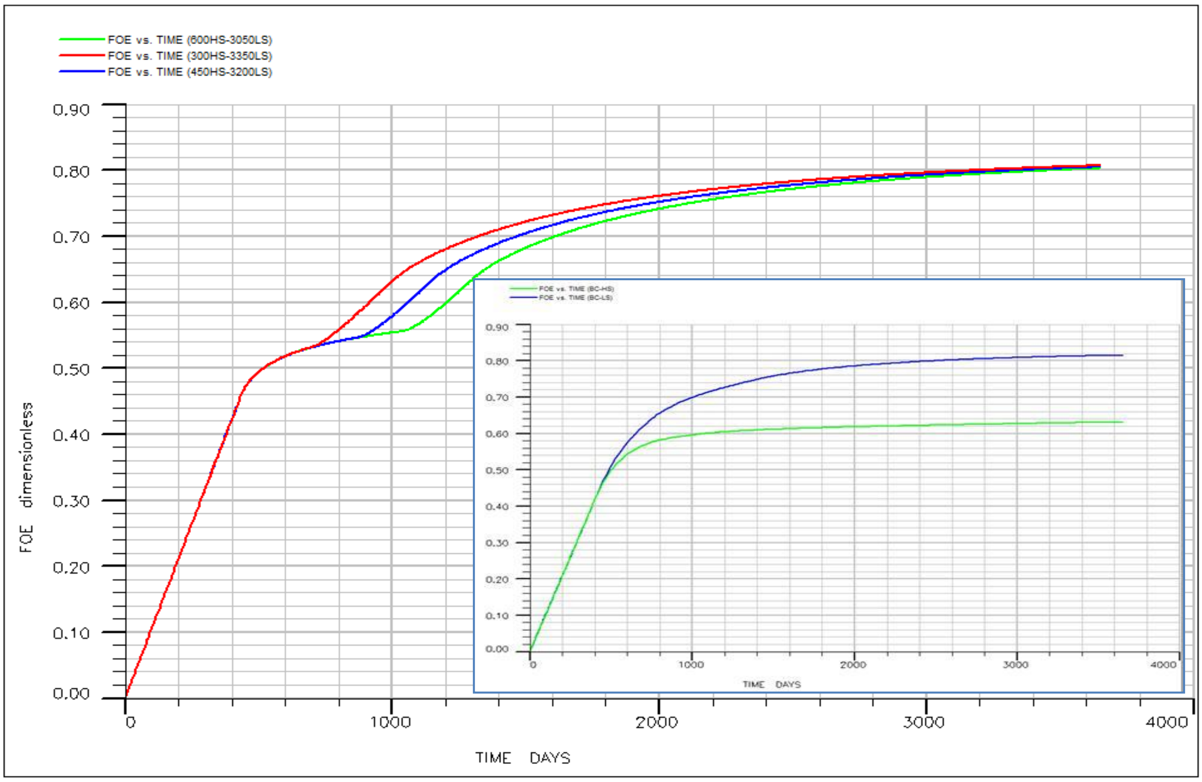


Figure 12 Effect of Timing of LS injection in Secondary Recovery Phase

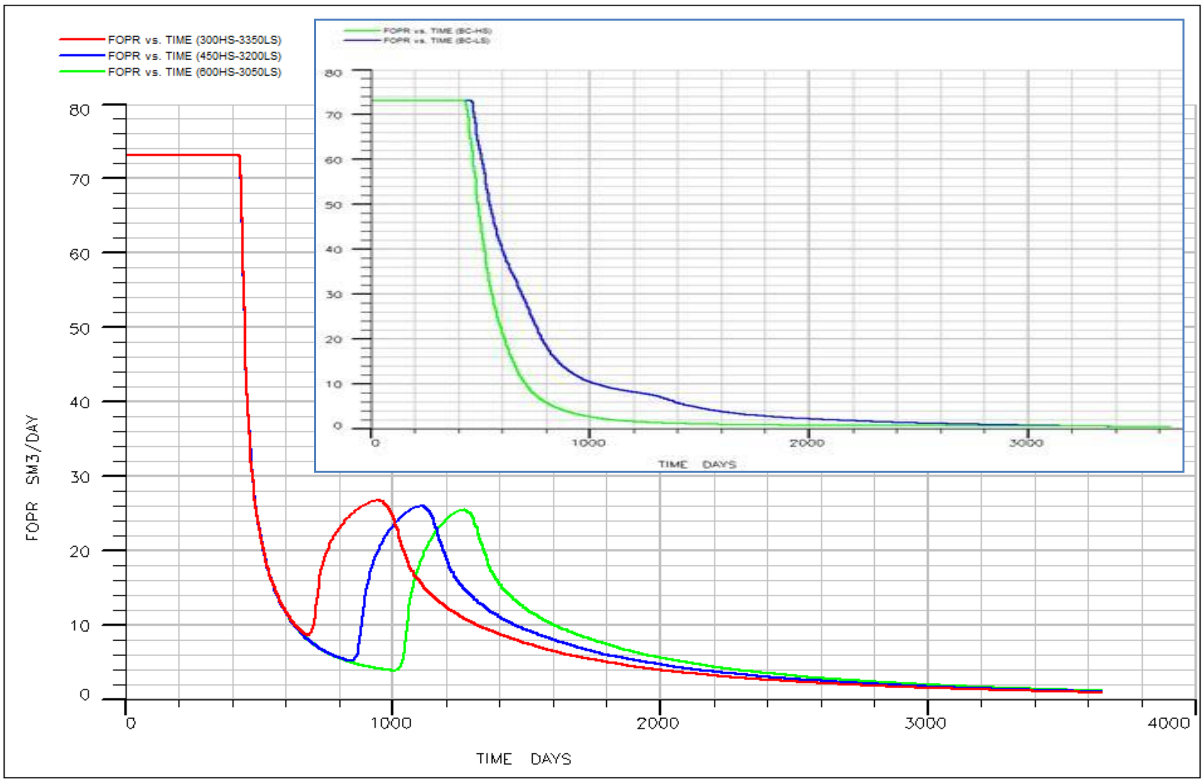


Figure 13 Effect of Timing of LS injection on Field Oil Production Rate (FOPR)

4.2.2 Effect of Salinity Concentration in Tertiary Recovery Phase

This section is to investigate the effect of varying salinity in LSWF on its tertiary recovery phase. Based on the 3 cases studied in section 4.2.1, the case where LS injection at 300 days is chosen as the base case to investigate the effect of salinity in tertiary imbibitions. The tertiary recovery was done by flooding of brines with salinities of 35000, 5000, 4000, 3000, 2000, and 1000 ppm. The results of recovery factor from the injection of different brine salinities are presented in figure 14 and the ultimate recoveries are tabulated in table 6.

Injected Brine Salinity (Ppm)	Recovery Factor (%)
1000	80.46
2000	76.13
3000	71.45
4000	66.76
5000	63.50
35000	63.50

Table 8: Results of recovery factor from different injected brine salinities

As predicted from the model, there is no incremental oil recovery for injection of brines with salinities above 5000ppm. This is because the low salinity effect is set to start at salinities below 5000ppm in LSALTFNC table. Regarding to the oil recovery, an increase in recovery is seen in conjunction with a decrease in salinity. This phenomenon is the same as the literature review discussed in previous section. It is noted that both the rate of recovery and ultimate recovery increased with a decrease in salinity of the injected brines. From figure 15, we can see a range of increasing in oil production rate. Oil production rate showing that oil can be produced at a higher rate is salinity is lower. Moreover, there will be a longer LSWF effect if the salinity is lower. Both figures show a big gap between salinity 1000 ppm and 5000 ppm that are expected to be the lower and the upper thresholds (Jerauld et al, 2008).

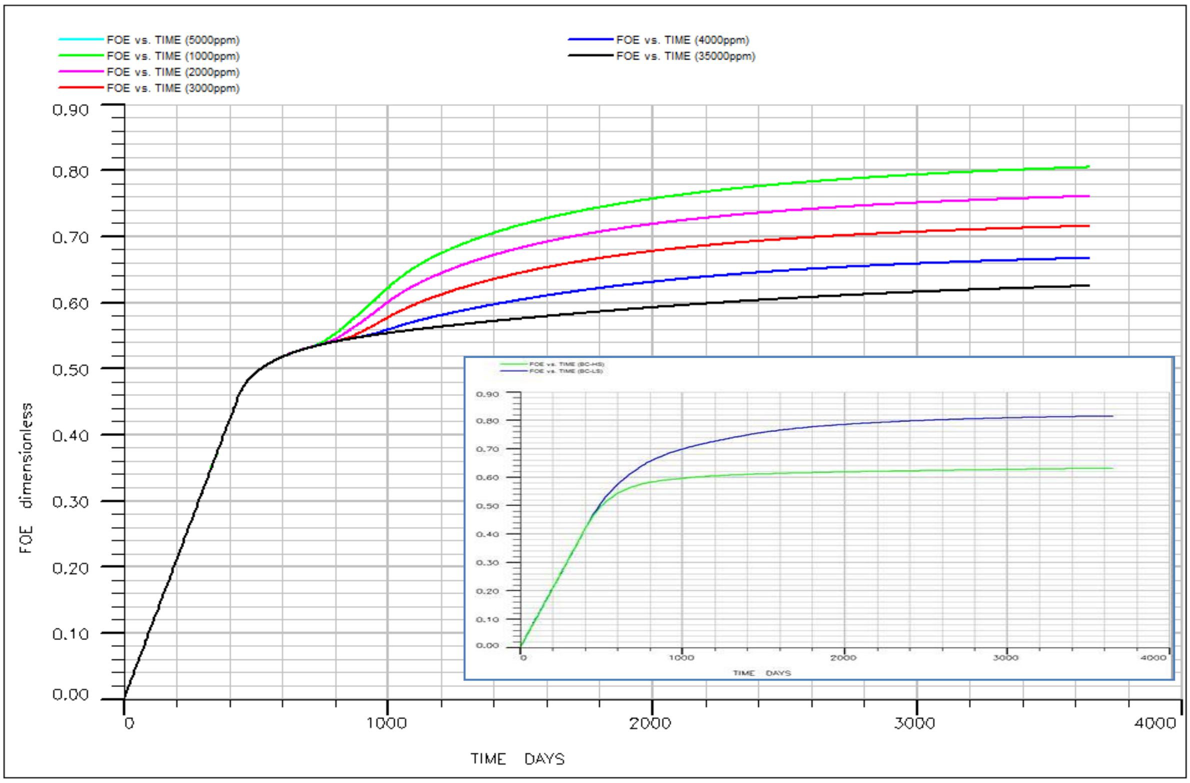


Figure 14 Effect of salinity concentration on recovery factor in tertiary recovery phase

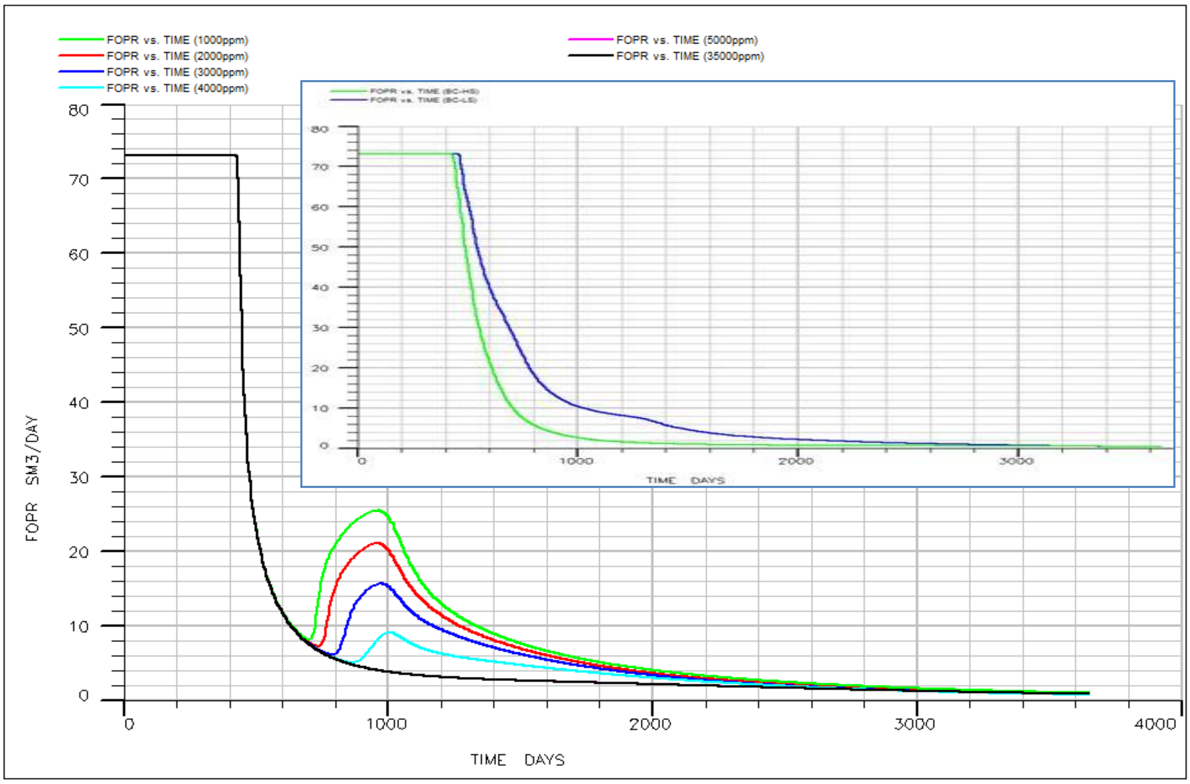


Figure 15 Effect of salinity concentration on oil production rate in tertiary recovery phase

Figures below represent the residual oil sweeping efficiency for base case with continuous low salinity water flooding from 1st year until 10th year production in one of the x and z plane directions:

Oil Saturation

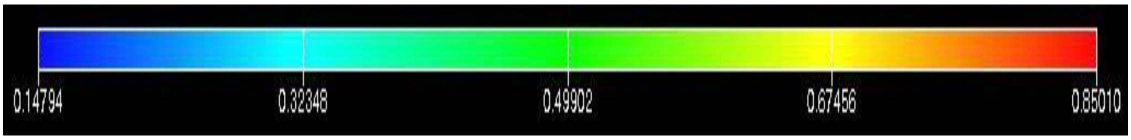


Figure 16 First year oil saturation distribution

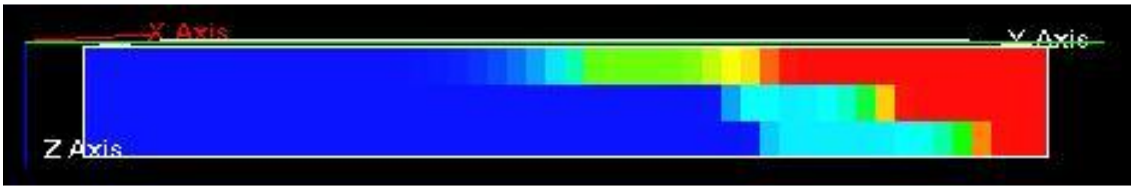


Figure 17 Second year oil saturation distribution

Figure 18 Third year oil saturation distribution

Figure 19 Fourth year oil saturation distribution

Oil Saturation

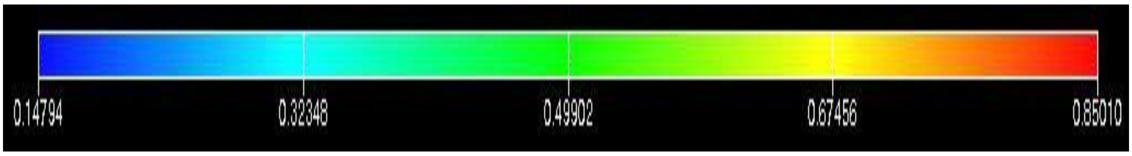


Figure 20 Fifth year oil saturation distribution

Figure 21 Sixth year oil saturation distribution

Figure 22 Seventh year oil saturation distribution

Figure 23 Eighth year oil saturation distribution

Oil Saturation

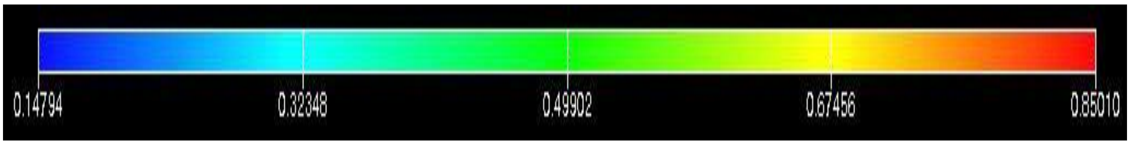


Figure 24 Ninth year oil saturation distribution

Figure 25 Tenth year oil saturation distribution

From figure 16 to figure 25, it is shown that low salinity water flooding affects the oil saturation of the field by reducing the oil saturation from 85% to around 15%. After looking at the displacement of residual oil due to low salinity effect, it shows that different layers of reservoir will have different time for their oil displacement. This is mainly due to the permeability difference across the layers of reservoir. By looking at the graphs, wettability of the reservoir is changing from oil-wet to water-wet. Hence, alteration of wettability plays a vital role in determing the efficiency of LSWF. In addition, effects of salinity concentration on oil distribution are also portrayed through the FLOVIZ models in the following pages.

Figures below represent oil saturation distribution at the end of 10 years production for different salinity concentration:

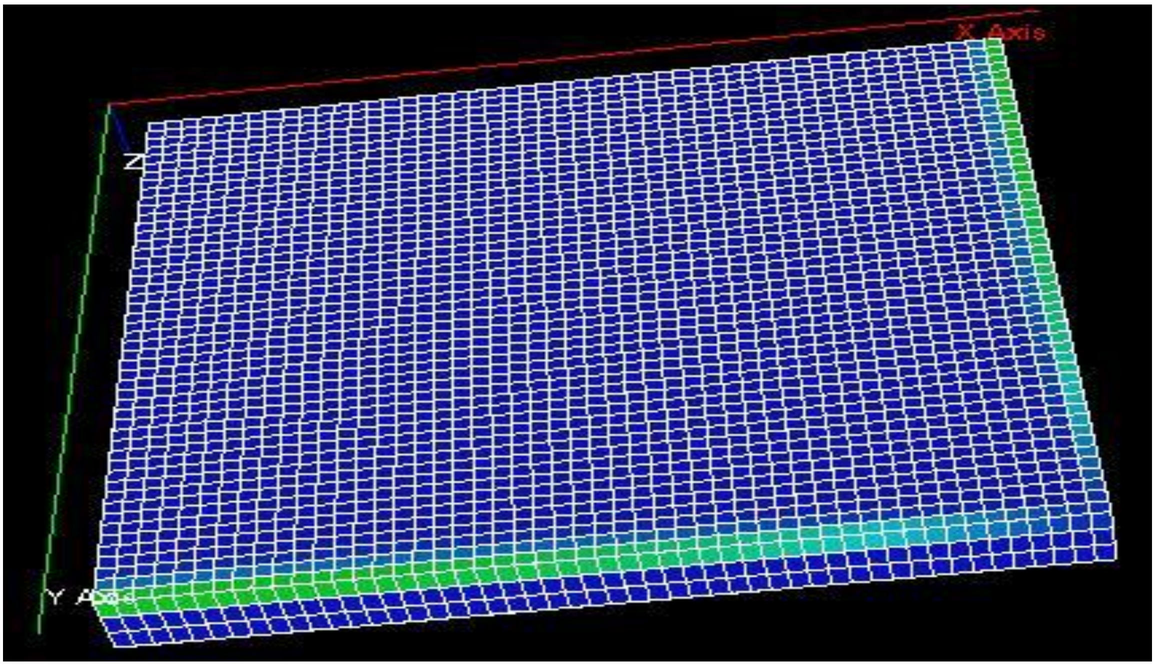


Figure 26 Injection of brine with salinity of 1000ppm

Oil Saturation

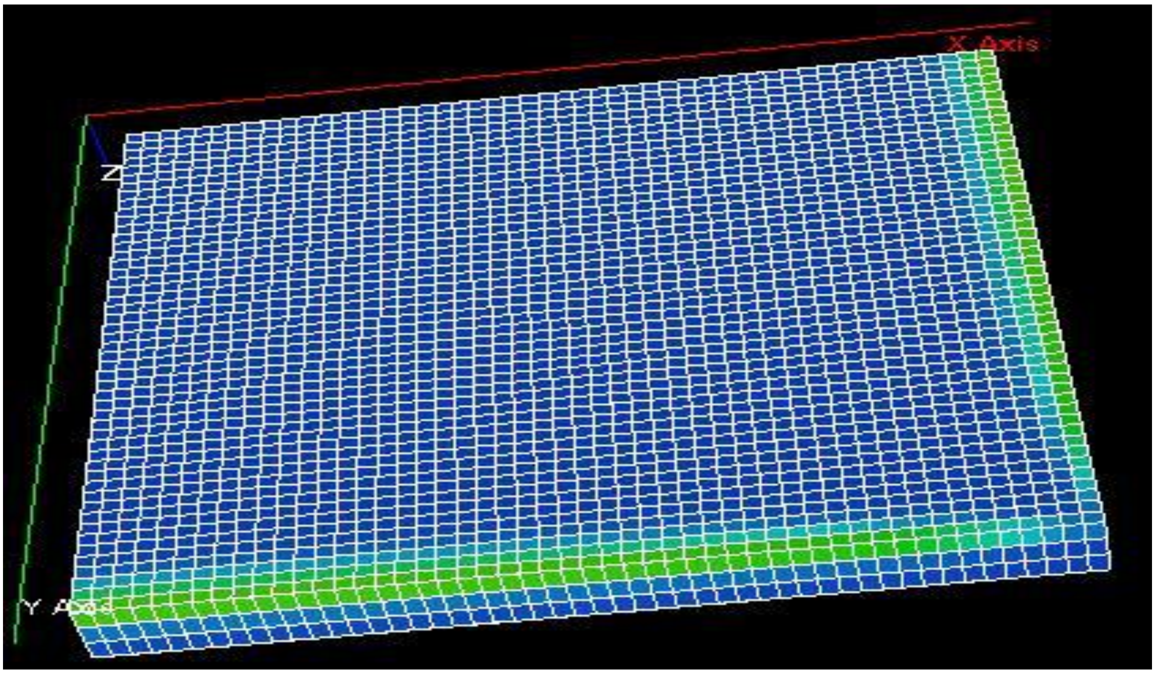


Figure 27 Injection of brine with salinity of 2000ppm

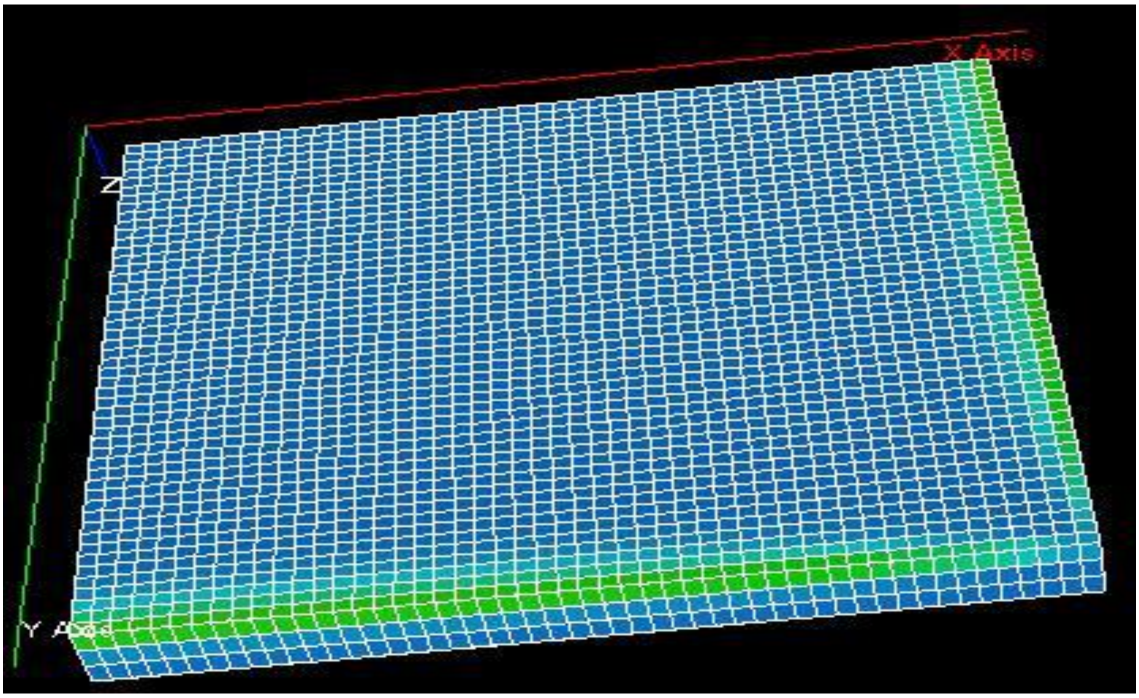
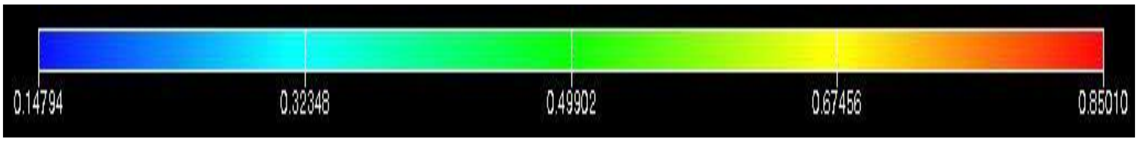


Figure 28 Injection of brine with salinity of 3000ppm

Oil Saturation



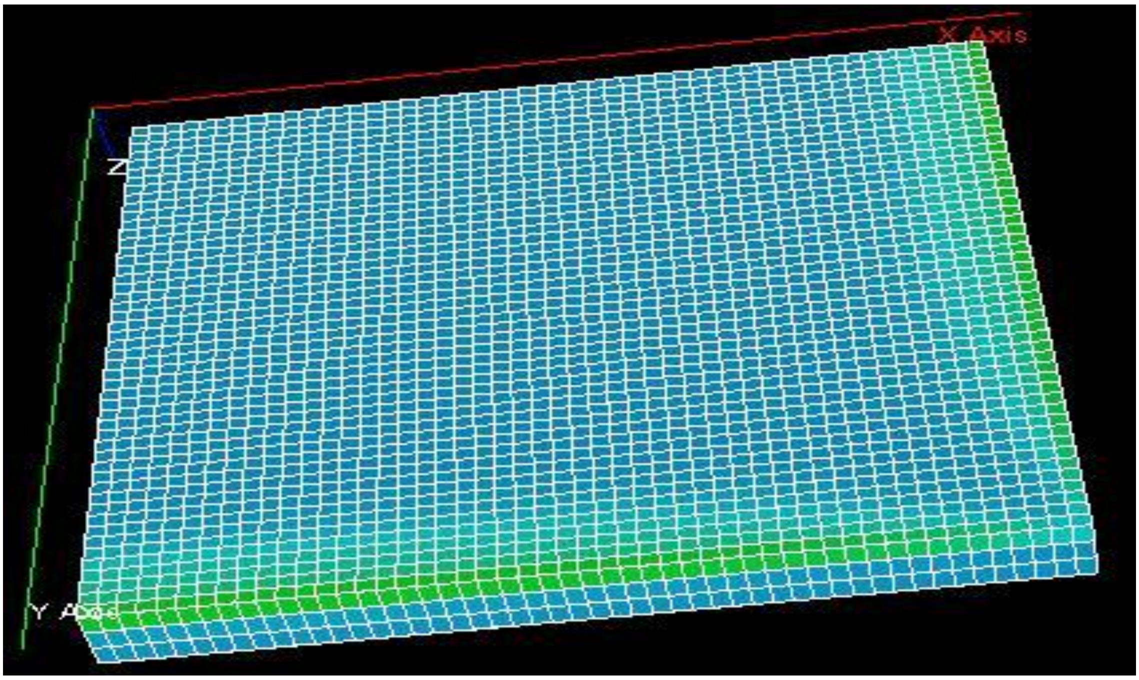


Figure 29 Injection of brine with salinity of 4000ppm

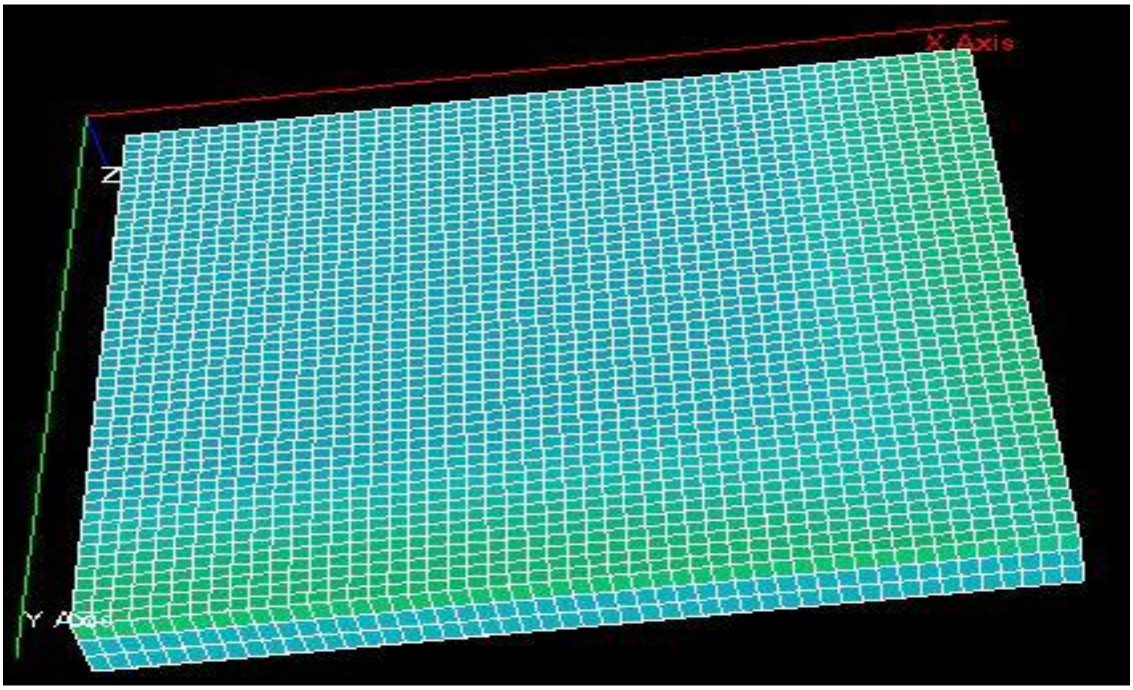


Figure 30 Injection of brine with salinity of 5000ppm

Oil Saturation

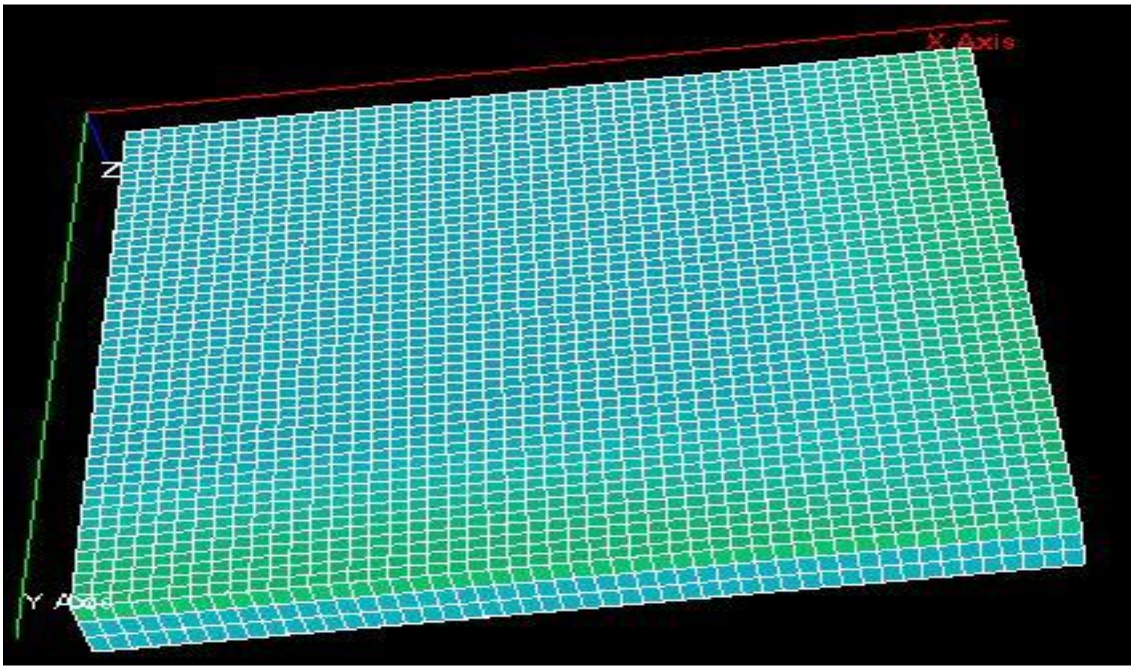


Figure 31 Injection of brine with salinity of 35000ppm

4.2.3 Summary of LSWF Simulation Results in Tertiary Recovery Phase

An increase in oil recovery is seen in conjunction with an earlier injection time. This is as expected because an early injection time means injection of more low salinity brines and this should increase the effectiveness of the LSWF. The difference in ultimate recovery is however not very large compared to the rate of recovery. Oil saturation decreases when salinity of injected brine reduces. Nevertheless, alteration of wettability is still a main factor behind LSWF effects. Through the findings and discussions in section 4.2.1 and 4.2.2, it has shown that LS injection needs transition time to achieve its effect. Furthermore, the effects will only occur for some period on oil production rate where it becomes constant afterwards. In summary, using 35000ppm salinity in HS flooding as primary phase for 300 days and continuing with 1,000ppm salinity in LS flooding as secondary flooding (HS-LS) is the most reasonable case for the tertiary recovery phase study.

4.3 Sensitivity Study of LSWF Economics

4.3.1 Economic Evaluation

In reality, LSWF will not be applied continuously throughout the field's production lifetime. This is due to the economic feasibility in terms of equipment cost and operation cost. Moreover, flooding with low salinity for whole production life may cause economic issues when incremental oil recovery is not high enough. Consequently, the profits generated from increased oil recovery will not cover its cost. In this section, the most reasonable case discussed in section 4.2 will be used for sensitivity study of LSWF economics.

Basically, the success of an EOR process is determined by the amount of incremental oil recovered. For a low salinity water flooding project, the EOR oil will be incremental oil recovery over conventional water flooding which is high salinity flooding in our base case. To determine the best case to perform our low salinity water flooding project, the Net Present Value (NPV) criterion is selected. The NPV calculation is based on incremental oil production from low salinity water flooding compared to conventional water flooding (High salinity).

NPV is a central tool in discounted cash flow (DCF) analysis, and is a standard method for using the time value of money to appraise long-term projects. The NPV must be positive for a project to be accepted. It is defined by the formula

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \quad (4\text{-}1)$$

where r is the discount rate, t is the time, Ct cash flow in year t, and n is time period of the project/investment.

According to the economic sensitivity study done by Chuck Kossak(2012) in his LSWF study, the main interest should be focused in the incremental oil recovery from low salinity water flooding case over the incremental oil recovery from continuous high salinity water flooding. Furthermore, he has come out with a simple cost analysis formula. The following formula will be inserted into Eclipse data file in order to generate a profit versus time graphs for different cases (Figure 32). Besides, some assumptions need to be considered before performing the economic analysis.

Assumptions for Economic Evaluation:

a) The simulated model is assumed to be producing at its residual oil saturation.

b) Provided properties of low salinity brine are compatible with the synthetic model's reservoir and fluid properties.

c) 3 different cases will be selected to examine the economic sensitivity of LSWF:
- Scenario 1: Continuous Low Salinity Flooding throughout production lifetime (Low salinity base case in section 4.1)
- Scenario 2: Initial high salinity flooding with constant high salinity concentration of 35000ppm for 300 days before flooding with constant low salinity concentration of 1000ppm continuously for the rest of production lifetime (Best case chosen in section 4.2)
- Scenario 3: Best time to stop low salinity injection in scenario 2 in order to maximise profit or Net Present Value(NPV)

d) The assumed discount rate, price of oil and price of fresh water through desalination are given in table. Cost of high salinity water is zero as it is easily obtained from sea water.

Oil Price (Income)	$500/sm^3
Fresh Water Through Desalination	$15/sm^3

e) For simplification, only cost of fresh water through desalination is considered as major expense of the LSWF project. No operational and additional facilities costs are considered. Moreover, fluctuation of oil price, discount factor, interest rates and inflation are not included in this economic analysis.

f) All the NPV analysis is done using ECLIPSE software. The plotted graphs will be used to determine the breakeven year, net profit and best case to do LSWF.

```
UDQ
ASSIGN  FUOIL     500  /  oil price ($/Sm3)
ASSIGN  FUFW      15     /  fresh water cost ($/Sm3)
ASSIGN  FUSWOE   44612  /  oil produced by high salt water (Sm3)
DEFINE  FUPROFIT  (FOPT-FUSWOE)*FUOIL-(WWIT
IFRESH)*FUFW / profit ($)
UNITS   FUPROFIT  $      /
UPDATE  FUPROFIT  ON     /
```

Figure 32: ECLIPSE functions for sensitivity study of LSWF economic simulations

Firstly, keyword FUOIL represents oil price which is set at $500 per sm^3. FUFW symbolises fresh water injection cost at $15 per sm^3. FUSWOE is the amount of oil produced by high salinity or conventional water flooding. FUSWOE is considered as the expense of carrying out low salinity water flooding project. In order to calculate the NPV, subtract FUSWOE from the amount of oil recovered through low salinity flooding (FOPT) before multiplying by the oil price (FUOIL). After that, the profit (FUPROFIT) is computed by deducting the amount of fresh water injected into the well (WWIT IFRESH) multiply by the cost of fresh water (FUFW).

For example, FOPT is assumed to recover 54612sm^3 of oil while the amount of injected water is 35000sm^3. Through the function of FUPROFIT, calculated NPV will be $475,000.

(FOPT-FUSWOE)*FUOIL-(WWIT IFRESH)*FUFW

= (54612-44612)*$100 – (35000)*$15

= $ 475,000

In the following sections, NPV graphs will be generated for 3 different cases. These graphs will be useful to find out the breakeven year where the LSWF project starts to gain profit. Moreover, the total net profit will be vital to select the base case for this LWSF study.

4.3.2 Economic Simulation Results and Analysis

4.3.2.1 Scenario 1: Continuous Low Salinity Water Flooding

In this case, the simulated is flooded with low salinity brine throughout its production lifetime for 10 years. Total amount of NPV and injected fresh water is as shown in figure 33. Although first year of NPV recorded -22.6 million USD, the total incremental of NPV is positive and the figure is +9.10 million USD. Payback period or breakeven takes about 2.5 years.

4.3.2.2 Scenario 2: Initial High Salinity Flooding for 300 days followed by Continuous Low Salinity Water Flooding

This scenario is selected from the best case discussed in section 4.2. Total amount of NPV and injected fresh water is as shown in figure 33. Although first year of NPV recorded -22.6 million USD, the total incremental of NPV is positive and the figure is +7.88 million USD. Payback period or breakeven takes about 3.4 years.

Although NPV of scenario 1 is higher than scenario 2, NPV of scenario 1 after 6th year onwards is slightly higher than NPV of scenario 2. Moreover, amount of injected fresh water for scenario is significantly higher than that in scenario 2 by 31000 sm^3. It will be a waste to inject such a big portion of fresh water when NPV is decreasing from year to year. This indicates that both scenarios will be uneconomical in the long run to flood the field continuously with low salinity brine. Therefore, another scenario needs to be simulated to maximise the NPV while reducing the cost of injected fresh water by reducing the amount of injected fresh water.

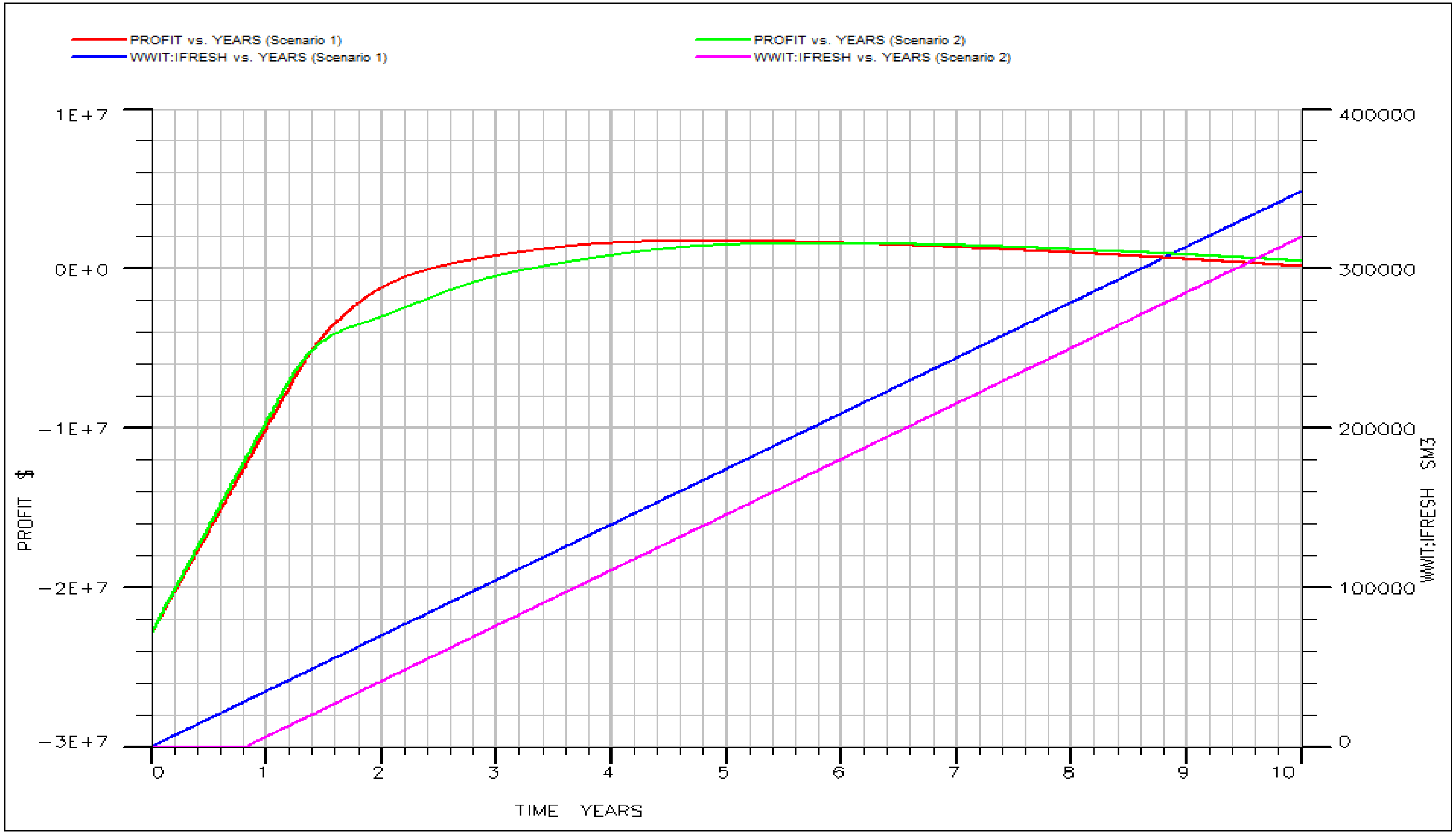


Figure 33: Total amount of NPV and fresh water injection for scenario 1 and 2

4.3.2.3 Scenario 3: Initial High Salinity Flooding for 300 days followed by Continuous Low Salinity Water Flooding for 2000 days before Converting it to High Salinity Flooding for the Rest of Production Lifetime

This scenario is selected from the best time to stop low salinity injection in scenario 2 in order to maximise profit or NPV. Based on figure 34, the optimum NPV is around 5.5 years for scenario 1 and 2. Hence, to optimise NPV, low salinity brine should stop injecting into the well around 2000 days which are close to 5.5 years. After 5.5 years, low salinity flooding should cease but the field should be injected with high salinity brine to recover residual oil. Figure 34 compares the amount of NPV and the injected fresh water among the 3 scenarios. The incremental of Scenario 3 NPV is positive and the figure is +11.01 million USD, which is clearly higher than the NPV of scenario 1 and 2. Even until the end of production, scenario 3 still remains at a steady yet high NPV. In addition, amount of injected fresh water in scenario 3 is comparatively lower than the other 2 scenarios by almost 50%. Breakeven of the year is also fairly early, which is around 3.4 years.

4.3.3 Summary of Economic Simulation Results and Analysis

To optimise LSWF project, economic feasibility must be considered carefully apart from the total oil recovery. The ideal scenario will be having a high NPV while having a short payback period. Furthermore, amount of injected fresh water should be reduced as much as possible without compromising much on the oil recovery. Scenario 3 is the best case to carry out the LSWF project. This is because the NPV is the highest among the 3 scenarios. Besides, it only uses almost half of the amount of injected fresh water compared to other scenarios. Figure 35 shows that cumulative oil production for the 3 scenarios. Scenario 1 recovers more oil in early years but at the end of production, total recovered oil is almost the same for all scenarios. Therefore, it would be a bad decision to select scenario 1 or 2 as there is not much increase in oil recovery despite injecting more than 50% amount of fresh water compared to scenario 3.

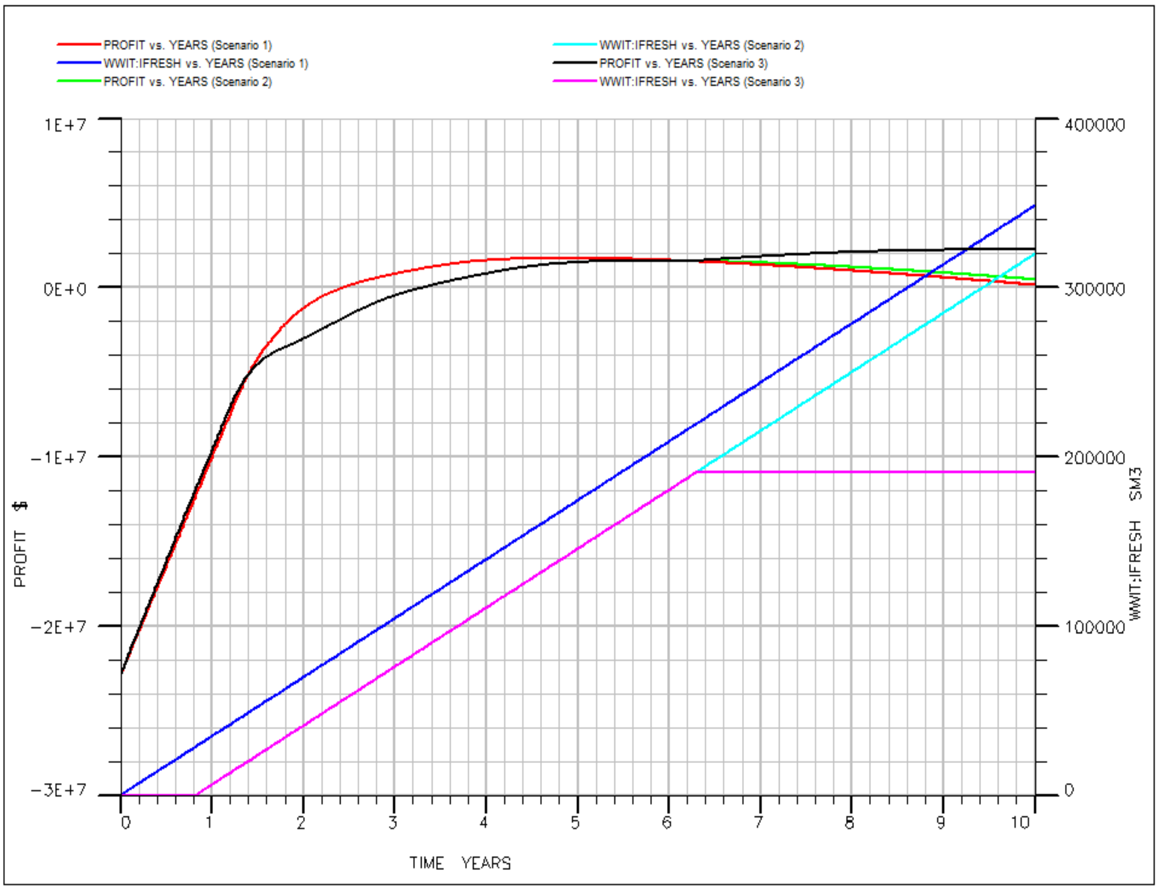


Figure 34: Total amount of NPV and fresh water injection for scenario 1,2 and 3

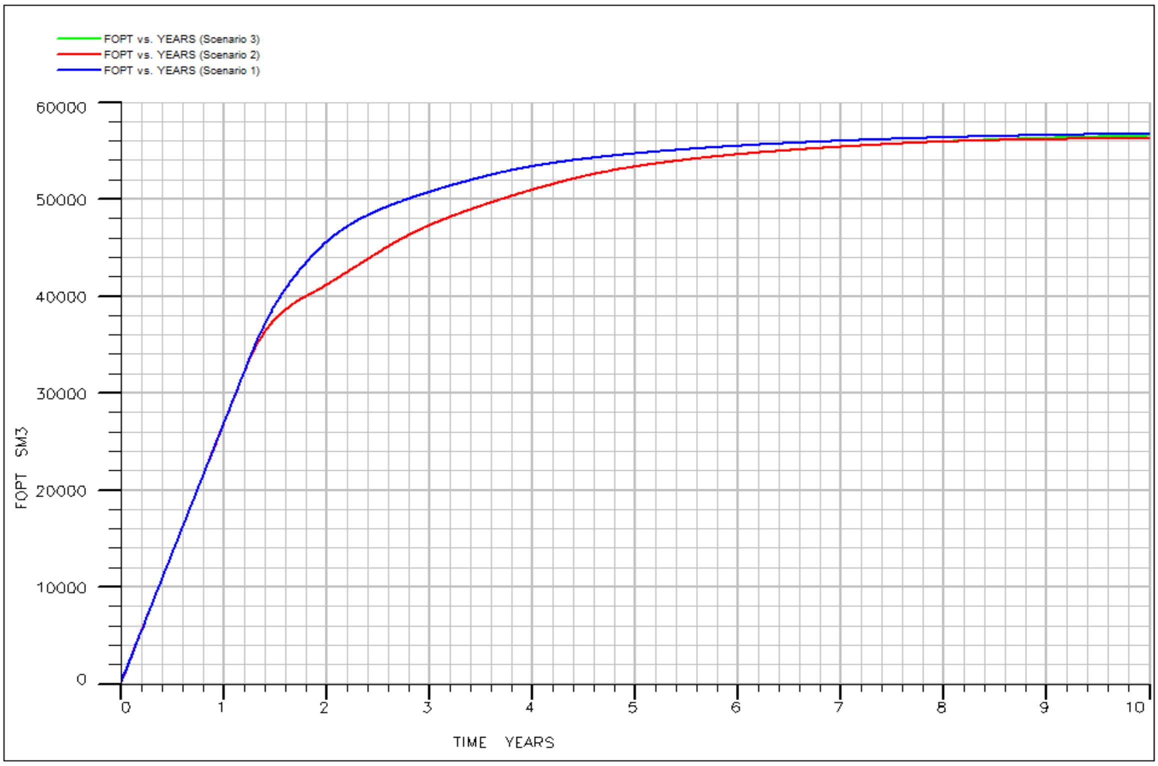


Figure 35: Cumulative oil production for 3 scenarios

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This project is able to be completed within given time frame to meet the relevant objectives. Literature review conducted has enabled the author to have better understanding on low salinity water flooding concepts as well as modelling approaches for low salinity model. In addition, there are also detailed research methodology and simulation work flow to execute this project. This project is able to achieve all the key milestones, which are vital in preparing an efficient yet effective report.

The author has familiarised with ECLIPSE 100 where he is able to simulate LSWF model. The BRINE option in ECLIPSE 100 is dependent on relative permeability, especially residual oil saturation. This is mainly due to ECLIPSE 100's low salinity modelling approach is based on Jerauld et al. (2008). Therefore, ECLIPSE 100 emphasises on wettability alteration, as mentioned in literature review. Base case for LSWF model has been identified and it is useful to simulate different cases in order to examine the effects of salinity on oil recovery and sweep efficiency.

Through initial simulation work until tertiary recovery phase, the author has found out that there is an improvement in oil recovery with a decrease in salinity. Although the simulated model is just a synthetic model, it has clearly shown the potential of LSWF as an EOR mechanism. Last but not least, economic analysis has shown that scenario 3 will be the best case to perform LSWF while not compromising on its cumulative oil production.

5.2 Recommendations for Future Work

This project only focuses on simulation of a synthetic model. Oil recovery increases drastically due to homogeneities of the model. However, in real field situation, most of the reservoirs are heterogeneous with complex permeability barriers such as fault. Therefore in the future research, a full field reservoir data should be applied to investigate the potential of LSWF. The project can also be expanded by adding more salts and ions into the simulation.

On the other hand, Schlumberger (owner of ECLIPSE) should create a new low salinity function based on the modelling work of Omekeh et al. (2012). The current low salinity function is only based on modelling work of Jerauld et al. (2008). If the interpolation of salinity curves is based on ion exchange of certain ion, multicomponent ion exchange mechanisms can be studied more thoroughly. To increase the accuracy of the results, findings from ECLIPSE100 should be compared with findings obtained from other reservoir simulators. Last but not least, this project can be used as a foundation to simulate other EOR flooding project such as alkali, surfactant, polymer as well as ASP flooding.

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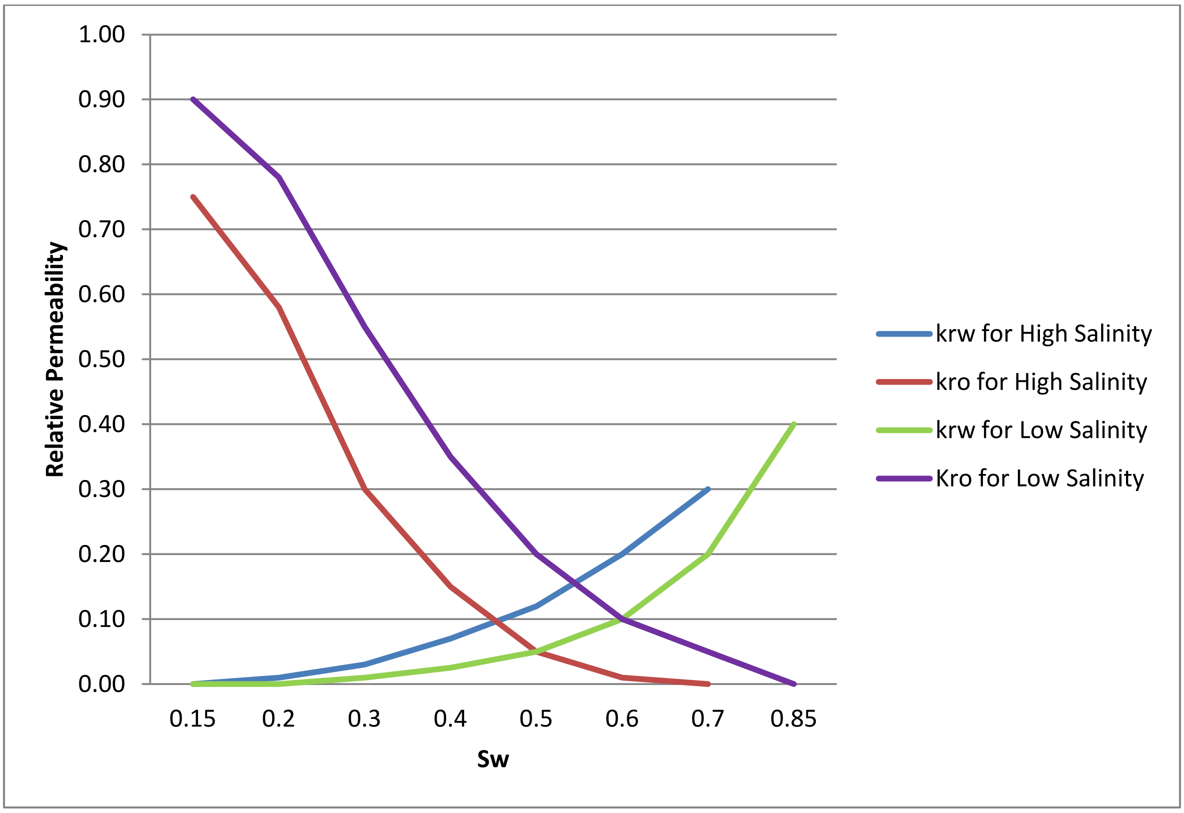
APPENDICES

APPENDIX A

Relative Permeability for High Salinity and Low Salinity Cases

High Salinity		
sw	krw	kro
0.15	0.00	0.75
0.20	0.01	0.58
0.30	0.03	0.30
0.40	0.07	0.15
0.50	0.12	0.05
0.60	0.20	0.01
0.70	0.30	0.00

Low Salinity		
sw	krw	kro
0.15	0	0.9
0.2	0	0.78
0.3	0.01	0.55
0.4	0.025	0.35
0.5	0.05	0.2
0.6	0.1	0.1
0.7	0.2	0.05
0.85	0.4	0



APPENDIX B

Data File for Base Case of Low Salinity Water Flooding (Scenario 1)

```
RUNSPEC
 ===========================
TITLE
 LSWF /

DIMENS
   50   50    3  /

OIL
WATER

LOWSALT
-- automatically turns on Brine option

METRIC

TABDIMS
    2    1   20   20    1   20 /

WELLDIMS
    4    10    1    4 /

START
   1 'JAN' 2012  /

UNIFIN
UNIFOUT

NSTACK
  50 /

UDQDIMS
3* 10 /

GRID
===========================
INIT

DX
  7500*5   /
DY
  7500*5   /
DZ
  7500*2   /
```

```
PERMX
  2500*1172 2500*1143 2500*1162 /

PERMY
  2500*1172 2500*1143 2500*1162 /

PERMZ
 2500*1050 2500*1800 2500*500 /

TOPS
2500*2600 /

PORO
7500*0.3/

PROPS
===========================

-- connate water is 35,000 PPM = 35
Kg/m3

LSALTFNC
-- F1 = 0 for high salinity
-- F1 = 1 for low salinity
--Salt  F1
--conc  factor
--LSALTFNC Table
--conc    F1      F2
--        factor  factor
--kg/sm3
   0.0 1.0 1*
   1.0 0.8 1*
   4.0 0.2 1*
   5.0 0.0 1*
  35.0 0.0 1*/
 /


SWOF
--Sw -Krw - Kro - Pcow
0.15 0     0.75   0
0.2  0.01  0.58   0
0.3  0.03  0.3    0
0.4  0.07  0.15   0
```

```
0.5  0.12  0.05   0
0.6  0.2   0.01   0
0.7  0.3   0      0 / --table 1 high
salinity
0.15 0     0.9    0
0.2  0     0.78   0
0.3  0.01  0.55   0
0.4  0.025 0.35   0
0.5  0.05  0.2    0
0.6  0.1   0.1    0
0.7  0.2   0.05   0
0.85 0.4   0.0    0 / --table 2 low
salinity



PVDO
275 1.314 0.628
300 1.308 0.647
325 1.302 0.665
/

ROCK
 277 4.8E-5 /

DENSITY
-- o   w    g
 860. 1022. 0.853/

PVTWSALT
-- Ref     ref salt conc
-- Press   stock tank water
-- barsa
   277.0       0.0  /
-- salt   FVF   water   water  water
-- conc         compres visc
viscosibility
    0.0  1.038  4.6E-5  0.318     0.0
   35.0  1.038  4.6E-5  0.318     0.0 /




REGIONS
==========================
SATNUM
-- immiscible, high salinity = 1
7500*1 /

LWSLTNUM
-- low salinity curves
7500*2
/

RPTREGS
 24*0 /

RPTREGS
LWSLTNUM LSLTWNUM /

SOLUTION
==========================
PRESSURE
7500*68/

SWAT
7500*0.15/

SALTVD
-- depth  salt
-- meters conc
--         kg/m3
   5000.0  35.0
   5500.0  35.0 /


SALT
--salt concentration initial(FW) kg/m3
7500*35.0/

RPTRST
'BASIC=2'  FIPSALT  SALT  /


SUMMARY
==========================
-- For UDQ
FUPROFIT

FOPT
FSPR
FSPT
FSIR
FSIT
FSIP
FWIR
FOPR
FPR
FWIT
FOE
```

```
FSPR
FSIP
FSIC
FSPC

WBHP
/
WOPR
 /
WWIR
/
WWIT
/


BPR
 1 1 1 /
 1 1 2 /
 4 4 1 /
 5 5 1 /
 7 7 1 /
10 10 1 /
12 12 1 /
14 14 1 /
15 15 1 /
 /

BOSAT
 1 1 1 /
 1 1 2 /
 4 4 1 /
 5 5 1 /
 7 7 1 /
10 10 1 /
12 12 1 /
14 14 1 /
15 15 1 /
/

BOKR
 1 1 1 /
 1 1 2 /
 4 4 1 /
 5 5 1 /
 7 7 1 /
10 10 1 /
12 12 1 /
14 14 1 /
15 15 1 /
/

BWKR
 1 1 1 /
 1 1 2 /
 4 4 1 /
 5 5 1 /
 7 7 1 /
10 10 1 /
12 12 1 /
14 14 1 /
15 15 1 /
/

SCHEDULE
===========================
TUNING
  .001  4 /
 2*50/

-- we will set up 2 injectors to help
keep tract of how much
-- low salinity water we have injected

WELSPECS
   OP     G   50 50  2600  'OIL'  /
  IFRESH  G   1  1   2600  'WAT'  /
  IHSALT  G   1  1   2600  'WAT'  /
/
COMPDAT
--  1       2    3    4   5     6     7   8    9
  OP        1*   1*   1   3  'OPEN'   0  .0
157E-3 /
  IFRESH     1*   1*   1   3  'OPEN'
0  .0   157E-3 /
  IHSALT     1*   1*   1   3  'OPEN'
0  .0   157E-3 /
/

WCONPROD
 OP  OPEN  RESV  4* 100 0.0 4* /
/

-- inject fresh water on RESV control
when open
WCONINJE
 IFRESH    WAT   OPEN  'RESV' 1*
100  /
/

-- inject fresh water slug
```

```
WSALT
 IFRESH 1.0 /
/

-- inject high salinity water on RESV
control when open
WCONINJE
 IHSALT    WAT   OPEN  'RESV' 1*
100  /
/

-- inject produced brine - high salinity
water
WSALT
 IHSALT 35.0 /
/

-- shut high salt injection well while
injecting fresh water
WELOPEN
  IFRESH OPEN /
  IHSALT SHUT /
/

UDQ
ASSIGN  FUOIL     500    /  oil price
($/Sm3)
ASSIGN  FUFW      15     /  fresh
water cost ($/Sm3)
ASSIGN  FUSWOE    44612 /  oil
produced by high salt water (Sm3)
DEFINE  FUPROFIT  (FOPT-
FUSWOE)*FUOIL-(WWIT
IFRESH)*FUFW / profit ($)
UNITS   FUPROFIT  $      /
UPDATE  FUPROFIT  ON     /
/

-- run simulation 1110 total
TSTEP
120*30 50/

END
```

APPENDIX C

Data File for Scenario 2

```
RUNSPEC
 ============================
TITLE
 LSWF /

DIMENS
   50   50    3  /

OIL
WATER

LOWSALT
-- automatically turns on Brine option

METRIC

TABDIMS
    2    1   20   20    1   20 /

WELLDIMS
    4    10    1    4 /

START
   1 'JAN' 2012  /

UNIFIN
UNIFOUT

NSTACK
  50 /

UDQDIMS
3* 10 /

GRID
============================
INIT

DX
  7500*5   /
DY
  7500*5   /
DZ
  7500*2   /

PERMX
  2500*1172 2500*1143 2500*1162 /

PERMY
  2500*1172 2500*1143 2500*1162 /

PERMZ

 2500*1050 2500*1800 2500*500 /

TOPS
2500*2600 /

PORO
7500*0.3/

PROPS
============================
-- connate water is 35,000 PPM = 35
Kg/m3

LSALTFNC
-- F1 = 0 for high salinity
-- F1 = 1 for low salinity
--Salt  F1
--conc  factor
--LSALTFNC Table
--conc    F1      F2
--        factor  factor
--kg/sm3
   0.0 1.0 1*
   1.0 0.8 1*
   4.0 0.2 1*
   5.0 0.0 1*
  35.0 0.0 1*/
 /

SWOF
--Sw -Krw - Kro - Pcow
0.15 0     0.75   0
0.2  0.01  0.58   0
0.3  0.03  0.3    0
0.4  0.07  0.15   0
0.5  0.12  0.05   0
0.6  0.2   0.01   0
0.7  0.3   0      0 / --table 1 high
salinity
0.15 0     0.9    0
0.2  0     0.78   0
0.3  0.01  0.55   0
0.4  0.025 0.35   0
```

```
0.5  0.05  0.2    0
0.6  0.1   0.1    0
0.7  0.2   0.05   0
0.85 0.4   0.0    0 / --table 2 low
salinity

PVDO
275 1.314 0.628
300 1.308 0.647
325 1.302 0.665
/

ROCK
 277 4.8E-5 /

DENSITY
-- o   w    g
 860. 1022. 0.853/
 PVTWSALT
-- Ref     ref salt conc
-- Press   stock tank water
-- barsa
   277.0       0.0  /
-- salt   FVF   water   water  water
-- conc         compres visc
viscosibility
    0.0  1.038  4.6E-5  0.318     0.0
   35.0  1.038  4.6E-5  0.318     0.0 /

REGIONS
===========================
SATNUM
-- immiscible, high salinity = 1
7500*1 /

LWSLTNUM
-- low salinity curves
7500*2
/

RPTREGS
 24*0 /

RPTREGS
LWSLTNUM LSLTWNUM /


SOLUTION
===========================
PRESSURE
```

```
7500*68/

SWAT
7500*0.15/

SALTVD
-- depth  salt
-- meters conc
--         kg/m3
   5000.0  35.0
   5500.0  35.0 /


SALT
--salt concentration initial(FW) kg/m3
7500*35.0/

RPTRST
'BASIC=2'  FIPSALT  SALT  /

SUMMARY
===========================
-- For UDQ
FUPROFIT

FOPT
FSPR
FSPT
FSIR
FSIT
FSIP
FWIR
FOPR
FPR
FWIT
FOE
FSPR
FSIP
FSIC
FSPC

WBHP
/
WOPR
 /
WWIR
/
WWIT
/
```

```
BPR
 1 1 1 /
 1 1 2 /
 4 4 1 /
 5 5 1 /
 7 7 1 /
10 10 1 /
12 12 1 /
14 14 1 /
15 15 1 /
 /

BOSAT
 1 1 1 /
 1 1 2 /
 4 4 1 /
 5 5 1 /
 7 7 1 /
10 10 1 /
12 12 1 /
14 14 1 /
15 15 1 /
/

BOKR
 1 1 1 /
 1 1 2 /
 4 4 1 /
 5 5 1 /
 7 7 1 /
10 10 1 /
12 12 1 /
14 14 1 /
15 15 1 /
/

BWKR
 1 1 1 /
 1 1 2 /
 4 4 1 /
 5 5 1 /
 7 7 1 /
10 10 1 /
12 12 1 /
14 14 1 /
15 15 1 /
/

SCHEDULE
===========================
TUNING
  .001  4 /
 /
  2*  50 /
-- we will set up 2 injectors to help
keep tract of how much
-- low salinity water we have injected
WELSPECS
   OP    G   50 50  2600  'OIL'  /
  IFRESH  G   1  1   2600  'WAT'  /
  IHSALT  G   1  1   2600  'WAT'  /
/
COMPDAT
--  1       2    3    4   5     6     7   8    9
  OP        1*   1*   1   3  'OPEN'   0  .0
157E-3 /
  IFRESH     1*   1*   1   3  'OPEN'
0  .0   157E-3 /
  IHSALT     1*   1*   1   3  'OPEN'
0  .0   157E-3 /
/

WCONPROD
 OP  OPEN  RESV  4* 100 0.0 4* /
/

-- inject fresh water on RESV control
when open
WCONINJE
 IFRESH    WAT   OPEN  'RESV' 1*
100  /
/

-- inject fresh water slug
WSALT
 IFRESH 1.0 /
/

-- inject high salinity water on RESV
control when open
WCONINJE
 IHSALT    WAT   OPEN  'RESV' 1*
100  /
/

-- inject produced brine - high salinity
water
WSALT
```

```
 IHSALT 35.0 /
/
-- shut low salt (fresh water) injection
well while injecting
-- high salinity water
-- open high salinity well

-- shut high salt injection well while
injecting fresh water
WELOPEN
  IFRESH SHUT /
  IHSALT OPEN /
/

-- inject high salinity brine for 300
days
TSTEP
  10*30/

UDQ
ASSIGN  FUOIL     500    /  oil price
($/Sm3)
ASSIGN  FUFW      15     /  fresh
water cost ($/Sm3)
ASSIGN  FUSWOE    44612 /  oil
produced by high salt water (Sm3)
DEFINE  FUPROFIT  (FOPT-
FUSWOE)*FUOIL-(WWIT
IFRESH)*FUFW / profit ($)
UNITS   FUPROFIT  $      /
UPDATE  FUPROFIT  ON     /
/

-- shut high salt injection well while
injecting fresh water
WELOPEN
  IFRESH OPEN /
  IHSALT SHUT /
/

TSTEP
111*30 20/

END
```

APPENDIX D

Data File for Scenario 3

```
RUNSPEC
 ===========================
TITLE
 LSWF /

DIMENS
   50   50    3  /

OIL
WATER

LOWSALT
-- automatically turns on Brine option

METRIC

TABDIMS
    2    1   20   20    1   20 /

WELLDIMS
    4    10    1    4 /

START
   1 'JAN' 2012  /

UNIFIN
UNIFOUT

NSTACK
  50 /

UDQDIMS
3* 10 /

GRID
===========================
INIT

DX
  7500*5   /
DY
  7500*5   /
DZ
  7500*2   /

PERMX
  2500*1172 2500*1143 2500*1162 /

PERMY
  2500*1172 2500*1143 2500*1162 /

PERMZ

 2500*1050 2500*1800 2500*500 /

TOPS
2500*2600 /

PORO
7500*0.3/

PROPS
===========================
-- connate water is 35,000 PPM = 35
Kg/m3

LSALTFNC
-- F1 = 0 for high salinity
-- F1 = 1 for low salinity
--Salt  F1
--conc  factor
--LSALTFNC Table
--conc    F1      F2
--        factor  factor
--kg/sm3
   0.0 1.0 1*
   1.0 0.8 1*
   4.0 0.2 1*
   5.0 0.0 1*
  35.0 0.0 1*/
 /

SWOF
--Sw -Krw - Kro - Pcow
0.15 0     0.75   0
0.2  0.01  0.58   0
0.3  0.03  0.3    0
0.4  0.07  0.15   0
0.5  0.12  0.05   0
0.6  0.2   0.01   0
0.7  0.3   0      0 / --table 1 high
salinity
0.15 0     0.9    0
0.2  0     0.78   0
0.3  0.01  0.55   0
0.4  0.025 0.35   0
```

```
0.5  0.05  0.2    0
0.6  0.1   0.1    0
0.7  0.2   0.05   0
0.85 0.4   0.0    0 / --table 2 low
salinity

PVDO
275 1.314 0.628
300 1.308 0.647
325 1.302 0.665
/

ROCK
 277 4.8E-5 /

DENSITY
-- o   w    g
 860. 1022. 0.853/
 PVTWSALT
-- Ref     ref salt conc
-- Press   stock tank water
-- barsa
   277.0       0.0  /
-- salt   FVF   water   water  water
-- conc          compres visc
viscosibility
    0.0  1.038  4.6E-5  0.318     0.0
   35.0  1.038  4.6E-5  0.318     0.0 /

REGIONS
===========================
SATNUM
-- immiscible, high salinity = 1
7500*1 /

LWSLTNUM
-- low salinity curves
7500*2
/

RPTREGS
 24*0 /

RPTREGS
LWSLTNUM LSLTWNUM /

SOLUTION
===========================
PRESSURE
7500*68/

SWAT
7500*0.15/

SALTVD
-- depth  salt
-- meters conc
--         kg/m3
   5000.0  35.0
   5500.0  35.0 /


SALT
--salt concentration initial(FW) kg/m3
7500*35.0/

RPTRST
'BASIC=2'  FIPSALT  SALT  /

SUMMARY
===========================
-- For UDQ
FUPROFIT

FOPT
FSPR
FSPT
FSIR
FSIT
FSIP
FWIR
FOPR
FPR
FWIT
FOE
FSPR
FSIP
FSIC
FSPC

WBHP
/
WOPR
 /
WWIR
/
WWIT
/

BPR
```

```
 1 1 1 /
 1 1 2 /
 4 4 1 /
 5 5 1 /
 7 7 1 /
10 10 1 /
12 12 1 /
14 14 1 /
15 15 1 /
 /

BOSAT
 1 1 1 /
 1 1 2 /
 4 4 1 /
 5 5 1 /
 7 7 1 /
10 10 1 /
12 12 1 /
14 14 1 /
15 15 1 /
/

BOKR
 1 1 1 /
 1 1 2 /
 4 4 1 /
 5 5 1 /
 7 7 1 /
10 10 1 /
12 12 1 /
14 14 1 /
15 15 1 /
/

BWKR
 1 1 1 /
 1 1 2 /
 4 4 1 /
 5 5 1 /
 7 7 1 /
10 10 1 /
12 12 1 /
14 14 1 /
15 15 1 /
/

SCHEDULE
===========================
TUNING
  .001  4 /
 /
  2*  50 /
-- we will set up 2 injectors to help
keep tract of how much
-- low salinity water we have injected
WELSPECS
   OP     G   50 50  2600  'OIL'  /
  IFRESH  G   1  1   2600  'WAT'  /
  IHSALT  G   1  1   2600  'WAT'  /
/
COMPDAT
--  1       2    3    4   5     6     7   8    9
  OP        1*   1*   1   3  'OPEN'   0  .0
157E-3 /
  IFRESH     1*   1*   1   3  'OPEN'
0  .0   157E-3 /
  IHSALT     1*   1*   1   3  'OPEN'
0  .0   157E-3 /
/

WCONPROD
 OP  OPEN  RESV  4* 100 0.0 4* /
/

-- inject fresh water on RESV control
when open
WCONINJE
 IFRESH    WAT   OPEN  'RESV' 1*
100  /
/

-- inject fresh water slug
WSALT
 IFRESH 1.0 /
/

-- inject high salinity water on RESV
control when open
WCONINJE
 IHSALT    WAT   OPEN  'RESV' 1*
100  /
/

-- inject produced brine - high salinity
water
WSALT
```

IHSALT 35.0 /
/
-- shut low salt (fresh water) injection well while injecting
-- high salinity water
-- open high salinity well

WELOPEN
IFRESH SHUT /
IHSALT OPEN /
/

-- inject high salinity brine for 300 days
TSTEP
10*30/

UDQ
ASSIGN FUOIL 500 / oil price ($/Sm3)
ASSIGN FUFW 15 / fresh water cost ($/Sm3)
ASSIGN FUSWOE 44612 / oil produced by high salt water (Sm3)
DEFINE FUPROFIT (FOPT-FUSWOE)*FUOIL-(WWIT IFRESH)*FUFW / profit ($)
UNITS FUPROFIT $ /
UPDATE FUPROFIT ON /
/

-- shut high salt injection well while injecting fresh water
WELOPEN
IFRESH OPEN /
IHSALT SHUT /
/

TSTEP
66*30 20/

-- shut low salt (fresh water) injection well while injecting high salinity water to maximize NPV

WELOPEN
IFRESH SHUT /
IHSALT OPEN /
/

TSTEP
45*30/

END