WATER CONING MANAGEMENT FOR OIL RESERVOIR WITH BOTTOM AQUIFER BY DOWNHOLE WATER LOOP

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การเกิดกรวยน้ำในหลุมผลิตน้ำมันเป็นปัญหาที่เกิดขึ้นเป็นปกติ โดยเฉพาะในกรณีของการผลิตน้ำมันจากแหล่งกักเก็บที่มีชั้นน้ำด้านล่าง มวลน้ำเคลื่อนที่เข้าสู่หลุมผลิตน้ำมันในรูปทรงกรวยบริเวณรอบหลุมส่งผลให้เกิดการลดทอนประสิทธิภาพการผลิตน้ำมัน เร่งให้เกิดการหยุดการผลิตอันเนื่องมากจากปริมาณน้ำที่มาก ตลอดจนส่งผลให้เกิดค่าใช้จ่ายในการปรับปรุงคุณสมบัติน้ำเพื่อการกำจัดทิ้ง เทคนิคที่ใช้ในการชะลออัตราการเกิดกรวยน้ำในการศึกษานี้ คือการอัดน้ำแบบหมุนวน มีวัตถุประสงค์ที่จะผลิตน้ำมันที่ปราศจากน้ำ โดยทำการผลิตน้ำควบคู่กับน้ำมันจากชั้นน้ำ และอัดกลับน้ำที่ผลิตได้นั้นลงไปในชั้นน้ำด้านล่างอย่างต่อเนื่อง เพื่อต้องการรักษาแนวสัมผัสของน้ำมันและน้ำในแหล่งกักเก็บให้คงที่

จากการศึกษาพบว่าตำแหน่งของการเจาะเพื่อผลิตในชั้นน้ำมันควรอยู่ไกลจากแนวสัมผัสของระดับน้ำมันและน้ำ ในขณะที่ตำแหน่งการเจาะเพื่อผลิตน้ำควรอยู่ใกล้แนวสัมผัสนั้นมากที่สุด โดยน้ำที่ถูกผลิตจากชั้นน้ำควรถูกอัดกลับเข้าไปในชั้นน้ำที่ตำแหน่งไกลที่สุดเท่าที่จะเป็นไปได้จากตำแหน่งที่ผลิตน้ำ จากการศึกษาปัจจัยคุณลักษณะของแหล่งกักเก็บพบว่า เทคนิคการอัดกลับน้ำแบบหมุนวนสามารถช่วยเพิ่มประสิทธิภาพการผลิตได้เป็นอย่างดีในแหล่งกักเก็บที่มีอัตราส่วนความสามารถในการซึมผ่านของชั้นหินในแนวตั้งต่อแนวนอนต่ำ ชั้นน้ำด้านล่างที่มีขนาดใหญ่จะช่วยทำให้การผลิตดำเนินไปได้ยาวนานขึ้นโดยอาศัยการชะลออัตราลดของความดันในแหล่งกักเก็บ ชั้นน้ำมันที่มีความหนามากจะได้รับผลกระทบจากกรวยน้ำต่ำ เนื่องจากสามารถระบุตำแหน่งเจาะผลิตน้ำมันได้ไกลจากแนวสัมผัสของระดับน้ำมันและน้ำ การอัดกลับน้ำแบบหมุนวนในแหล่งกักเก็บน้ำมันที่มีความหนืดต่ำจะช่วยเพิ่มประสิทธิภาพการผลิตน้ำมันได้ดี เนื่องจากปัญหาการแทรกตัวของกรวยน้ำเข้าสู่หลุมผลิตจะถูกชดเชยด้วยอัตราส่วนความสามารถของการไหลระหว่างน้ำมันและน้ำที่มีสภาวะเกื้อหนุน

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KEYWORDS:WATER CONING / DOWNHOLE WATER LOOP

RUNGLUDEE LUIPRASERT. WATER CONING MANAGEMENT FOR OIL RESERVOIR WITH BOTTOM AQUIFER BY DOWNHOLE WATER LOOP. ADVISOR:FALAN SRISURIYACHAI, Ph.D., CO-ADVISOR: ASST. PROF. SUWAT ATHICHANAGORN, Ph.D.,102 pp.

Water coning is a common problem encountered in oil field operation especially for those exploited in reservoir with strong water aquifer beneath hydrocarbon bearing zone. Water moves upward in conical shape into productive oil zone, accelerating termination of well and resulting in cost of water treatment as well as disposal. Delaying of water coning is investigated in this study by the use of Downhole Water Loop (DWL). DWL is a technique producing water-free hydrocarbon in water sink zone and produced is re-injected back into discharge zone.From this method, oil-water contact is stabilized.

The results show that, perforation location of oil bearing zone should be located far from oil-water contact, whereas water sink section should be located just beneath oil-water contact. Water discharge zone has to be located as far as possible from water sink zone in order to avoid inference of oil-water contact stabilization. From a study of reservoir parameters it is found that small ratio of vertical to horizontal permeability shows good results for DWL implementation. Big aquifer size assists DWL function in maintaining oil-water contact level through pressure support and thus oil can be produced for longer period. Thick oil bearing zone results in less effect from water coning problem since perforation interval can be located distance away from oil water contact. Implementing DWL in reservoir containing light oil is favorable since water coning problem that eventually occurs is compensated by favorability of mobility ratio

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List of Abbreviations

BHP	Bottomhole Pressure
cp	Centipoises
DWL	Downhole Water Loop
DWS	Downhole Water Sink
FVF	Formation volume factor
GOC	Gas-Oil Contact
mD	Millidarcy
MSCF	Thousand standard cubic feet
MSCF/D	Thousand standard cubic feet per day
MSCF/STB	Thousand standard cubic feet per stock-tank barrel
OWC	Oil-Water Contact
psia	Pounds per square inch absolute
PVT	Pressure-Volume-Temperature
rb/stb	Reservoir barrel per stock tank barrel
SCAL	Special core analysis
STB/D	Stock tank barrel per day

Nomenclatures

k	Absolute permeability of the porous media
S_{wco}	Connate water saturation
Q_{oc}	Critical oil rate
ρ_g	Density of gas
ρ_o	Density of oil
ρ_w	Density of water
r_e	Drainage radius
S_g	Gas saturation
H	Height of the reservoir
k_h	Horizontal permeability
L	Length of the reservoir
λ_g	Mobility of gas
λ_o	Mobility of oil
M	Mobility ratio
h	Oil column thickness
Q_o	Oil production rate
B_o	Oil formation volume factor
k_{ro}	Oil relative permeability
k_{rog}	Oil relative permeability in presence of gas phase
k_{row}	Oil relative permeability in presence of water phase
S_o	Oil saturation
ϕ	Porosity
t_{BT}	Time water breakthrough
k_v	Vertical permeability
μ_g	Viscosity of gas
μ_o	Viscosity of oil
S_w	Water saturation
h_p	Well perforated interval
r_w	Wellbore radius

CHAPTER I

INTRODUCTION

1.1Background

Water encroachment normally occurs in oil reservoirs driven by aquifer support. It is one of major problems in reservoir management that causes in less total field hydrocarbon recovery. Moreover, it leads to corrosive problem, high cost in handling and disposal management. These problems may result in uneconomical situation at the end. Several methods are implemented to prevent or delay water breakthrough into wellbore, including utilization of horizontal well, multilateral wells, perforating as far as possible from the initial Oil-Water Contact (OWC), producing oil below the critical rate or creating a low permeable zone near the oil contact by injecting polymers or using Inflow Control Devices (ICD).This study proposes another method to improve oil production by using the concept of Downhole Water Loop (DWL).

DWL is a technique with a further development on Downhole Water Sink (DWS) to produce water-free hydrocarbons from the reservoirs supporting by strong bottom water drive and high tendency of water encroachment. DWS uses a hydrodynamic concept of in-situ downhole water drainage to control and reduce excessive volumes of formation brine produced in oil and gas wells.The well configuration of DWS system consists of two completions that are separated from each other by the use of isolation packers. At the top in oil column, the oil production well is horizontally drilled and produced, whereas at OWC or below another horizontal section is drilled for water drainage or so called water sink completion (Wojtanowicz, 1991).This technique is proven by both theoretical and field test that it can delay water influx from produced hydrocarbon with the higher rate than critical flow rate. However, it produces a huge volume of water that needs to be managed in water treatment/disposal system and also accelerates reservoir pressure drop from both producing in oil and water zones.

DWLis developed to eliminate water treatment process and return back the reservoir pressure to the water producing section. Instead of producing water to the surface, one more completed well with a pump is added from downhole water sink system into water zone below sink completion for reinjection of produced water to the reservoir.

The black oil simulator **ECLIPSE®100** commercialized by **GeoQuest Schlumberger** is chosen to perform a reservoir simulation study.The reservoir model is constructed to have a varying value of reservoir and operational parameters, representing controllability and uncontrollability, respectively. The aim of this study is to verify the feasibility of DWL well configuration on water encroachment prevention. Moreover, the optimal conditions obtained from fine-tuning operational parameters will be achieved and will be useful as consideration for DWL implementation. Field oil recovery efficiencyis chosen as major criteria for optimal condition judgment together with the consideration of cumulative water production and total production period.

1.2Objectives

1. To studydownhole water loopin order to delay water encroachment in oil rim well exploiting bottom water driven reservoir.
2. To optimize various operational parameters which are perforation location and intervals of oil zone, water sink zone, and water discharge zone, water production rate from water sink zone and distance from water sink zone to water discharge zone, on effectiveness of downhole water loop implementation.
3. To study the effects of fluid and petrophysicalproperties including ratio ofvertical to horizontal permeability, aquifer thickness, oil zone thickness and oil gravityon the effectiveness of downhole water loop implementation.

1.3Outline of methodology

1. Study variouspublished literatures and gather required data for reservoir simulation model.
2. Construct a reservoir model base case for single vertical well with initial values of controllable and uncontrollable parameters.
3. Investigate the effects of operational parameters over the base case. The only operational parameter in this step is vertical perforation placement (in oil zone)representing by the distance from OWC. The optimized case is taken for the continued steps.
4. Study the effect of DWL implementation, configured by the use of vertical well with perforations in both oil and water zone and water injection in deeper water zone. The following operational parameters are study:
    - DWL perforation interval and placement for water zone.
    - Length of water discharge in water zone.
    - Ratio between oil and water production rate.
5. With an optimal value of operational condition a sensitivity analysis of reservoir parameters is performed. The study parameters are listed below:
    - Ratio of vertical to horizontal permeability.
    - Oil zone thickness.
    - Water aquifer thickness.
    - Oil gravity.

    During sensitivity analysis of one parameter, others study parameters are kept constant throughout the study.

6. Compare and discuss all results from simulationsto summarize the most suitable criteria for well optimization configured with DWL in bottom water drive reservoir.

1.4Thesis outline

The rest of this thesis is divided into five chapters as outline below

Chapter IIreviews previous works on water coning prevention methods which include both field experiments and simulation studies including DWL technique.

Chapter III introduces the important concept of DWLand describes the related theory.

Chapter IVdescribes detail of reservoir model used in this study including reservoir dimension, PVT data, and rockand fluid properties.

Chapter Vpresents the simulation results of traditional vertical well in terms of effect of different design parameters on recovery of oil. These results are also compared with DWLmethods.

Chapter VIprovides conclusion and recommendation.

CHAPTER II

LITERATURE REVIEW

This chapter reviews some previous studies related to water coning and several techniques including Downhole Water Loop (DWL) to delay the water breakthrough.

2.1Water Coning

Peng et al. (1995) emphasized research work on the use of horizontal wells in reservoirs with gas or water encroachment problems. They found that when fluid is produced from a well, a pressure gradient is established near the perforated interval. Water cresting phenomenon occurs when the pressure gradient is generated by production exceeding the gravity head caused by fluid density differences. The critical cresting rate is defined as a maximum oil production rate which can be produced without having cresting breakthrough. It also can be used to estimate the water encroachment time at a specified production rate. Their study indicated that the critical cresting rate and breakthrough time for horizontal wells increase when: 1) distance between horizontal well and contact increases; 2) horizontal well length increases; 3) permeability ratio increases; 4) density difference between fluids increases; and 5) oil viscosity decreases.

Gadelle et al. (1999) reviewed the application of multilateral wells in the actual field cases and summarized that the main advantage of multilateral wells compared to conventional horizontal wells is cost reduction. The cost reduction using a multilateral well instead of several horizontal wells having the same total effective length in the pay zone has been proven. However, it is more important for fields located offshore, on platforms where the number of slots is limited. For the gas and water coning problems, such as oil production from reservoirs with a strong bottom aquifer or an oil pay in the presence of a gas cap, multilateral wells reduce the encroachment of undesired fluids compared to horizontal wells because they permit the same rates for larger reservoir exposure and drainage area, and therefore reduced drawdown of the formation. Many studies were performed to confirm the advantage of using a multilateral well to replace a pattern of parallel horizontal wells to produce an oil reservoir in the presence of an aquifer or of a gas cap.

Fernandes et al. (2009) studied the application of ICD to optimize well production performance in horizontal well with two reservoir driving mechanisms: water drive and gas cap drive. The pressure drop by ICD was included as a local skin factor and the study was proven that ICD can be used to improve well performance and increase recovery. For oil reservoir with water aquifer drive, if the permeability is high and the well is long, friction pressure drop in the well can dominate the flow, resulting in an early water-breakthrough on the toe zone. The ICD can help to balance the flow condition and increase oil production. For gas cap in thin formation, wellbore friction pressure drop is very sensitive to flow condition since drawdown is usually low. For high permeability formations, ICD is likely to yield benefit on the production. However, designing ICD requires avoiding over-restriction to oil production.

Veil et al. (1999) reviewed the using of downhole separator in water management from oil wells. Downhole Oil Water Separator (DOWS) was a technique that is developed to reduce volume of produced water that had to be handled at surface facilities by separating it at downhole itself and simultaneously re-injecting back underground. Its system includes many components, but the two primary functions are an oil/water separation system and a downhole pump. Two basic types of DOWS had been developed, using hydrocyclones to separate oil and water and another by relying on gravity separation. Hydrocyclone-type DOWS could handle at liquid producing rate up to 10,000 bpd while gravity separator-type DOWS could make it up to 1,000 bpd. However, cost of hydrocyclone-type DOWS was quite high. It was approximately double to triple the cost of replacing a conventional submersible pump.

Wojtanowicz et al. (1991) investigated production performance of the well with and without the water sink tailpipe using reservoir simulations. The water sink's location and flow rate were studied as they affected the critical rate of oil. The comparison was made between the amounts of water produced for greater than critical oil production rates in these two systems. The comparison tests were designed as a series of simulated oil production cycles with variation of reservoir properties. Water encroachment control method by DWS yields the advantages of increasing oil production rate, decreasing the water production rate and improving the oil recovery.

Shirman et al. (2000) reported the research and development progress in DWS technology. From field observations, it could be indicated that after DWS implementation, oil production increased and the water cut at the top completion was reduced substantially. However, there was no reduction in the total production water cut. A simple mathematical model for the post-breakthrough water cut calculations in conventional and DWS completions was developed and verified using a reservoir simulator and a physical model. Theoretically, DWS should reduce water cut of both the top completion the total well. Experimental data support the theoretical conclusion that DWS may completely eliminate the water cut at the top completion. Experimental results show that a 38% reduction of the total water cut is possible with DWS for an optimum combination of top production and bottom drainage rates.

2.2Downhole Water Loop (DWL)

Wojtanowicz (1995) proposed the modification on DWS by involved water loop equipment in water zone (under water drainage section). Below the packer, the set of water loop equipment consists of a submersible pump, the upper perforations (water sink), and the lower perforation (water source). Pump would drain the produced water from water sink and then reinject produced water back to the water zone through the water source perforation. Mathematic simulation model was used to evaluate this theoretical feasibility and performance through two reservoir conditions with different in the mobility ratio and the length of downhole water loop. The study gave the result that DWL could increase two-to-four-fold of oil production rate with minimal water cut. Moreover, the result from this study also mentioned about the main issue in the design that was to provide a sufficient lateral departure for the discharge section of the water loop by setting the injection point deeper in the aquifer.

Jin et al (2010) analyzed well performance (nodal) of 3 DWL wells in oil reservoir overlay the known thickness aquifers. Completion depths and the rates of production and drainage/injection were their parameters. The results showed that in each system, there is a combination of oil production rate, bottom drainage-injection rate and drainage-injection distance (D/I spacing) that could produce water-free oil. A two-times increase of water drainage rate could effect to the increasing of critical oil rate by 80%.

Another study, with similar concept to DWL is performed by Buranatavonsom (2011). The investigator proposed the new method called "Downhole Water Dump Flood (DWDF)" to manage water coning in gas reservoir. This method balanced pressure drawdown between hydrocarbon zone and water zone by the same technique as in DWS but produced water was dumped into a different lower zone to perform the waterflood to the connected beside oil well, instead of lifting this produced water up to the surface. From the simulation result, it could be concluded that DWDF can reduce water production rate which would effect to cost of water-treatment and also provided the longer gas production time as well as increased recovery factor. The paper pointed out to the gas perforation interval as the main factor affecting cumulative gas and water production. For beside oil well which was water dumped flooding, DWDF could improve oil recovery factor from twelve to forty-one percent.

CHAPTER III

THEORY AND CONCEPT

This chapter describes the important theoryused to explainmechanism of water coning in vertical well as well as the key conceptof downhole water loop.

3.1Water Coning

Water coning

Water coning is a term used to describe the mechanism underlying the upward movement of water into the perforations of a producing well. Water coning can seriously impact the well productivity and influence the degree of depletion and the overall recovery efficiency of the oil reservoirs.Early water production from water coning will reduce driving pressure. Water production will cause also the corrosion andhighly cost on produced water handling. In brief, water coning will cause the loss of total field overall recovery.The water coning problem in vertical wells is related to the following calculations:

1) **The critical flow rate:**critical rate (Q_{oc}) is defined as the maximum allowable oil flow rate that can be produced to avoid water breakthrough from coning phenomenon. Meyer-Garder(1954) provides a simple and practical estimation for critical flow rate in an isotropic formation in vertical well:

$$Q_{oc} = 0.246 - 10^{-4}\left(\frac{\rho_w - \rho_o}{\ln(\frac{r_e}{r_w})}\right)\left(\frac{k_o}{\mu_o B_o}\right)(h^2 - h_p^2) \qquad (1)$$

where

Q_{oc} =critical oil rate, STB/D

ρ_w = water density, lb/ft^3

ρ_o = oil density, lb/ft^3

r_e = drainage radius, ft

r_w = wellbore radius, ft

k_o = effective oil permeability, mD

μ_o = oil viscosity

B_o = oil formation volume factor

h = oil column thickness, ft

h_p = well perforated interval, ft.

2) **Breakthrough time:** breakthrough time $t_{BT}$is a period that water encroachment will occur after a well produces above its critical rate. Sobocinski and Cornelius (1965) proposed a theoretical correlation for calculating breakthrough time with two dimensionless parameters, cone height and breakthrough time:

Dimensionless cone height Z

$$Z = 0.429 - 10^{-4}\left(\frac{(\rho_w - \rho_o)k_h h(h - h_p)}{\mu_o B_o Q_o}\right) \tag{2}$$

where

Q_o= oil production rate, STB/D

k_h= horizontal permeability, mD

Dimensionless breakthrough time $(t_D)_{BT}$

$$(t_D)_{BT} = \frac{4Z + 1.75Z^2 - 0.75Z^3}{7 - 2Z} \tag{3}$$

And the breakthrough time t_{BT}:

$$t_{BT} = \frac{20{,}325\mu_o h\phi(t_D)_{BT}}{(\rho_w - \rho_o)k_v(1 + M^{\alpha})} \tag{4}$$

where

t_{BT} = time to breakthrough, days

k_v = vertical permeability, mD

M = water-oil mobility

φ = porosity, fraction

α = 0.5 for $M \leq 1$, 0.6 for $1 \leq M \leq 10$

3.2Downhole Water Sink (DWS)

DWS is a technique for producing water-free hydrocarbons from reservoirs supporting by strong bottom aquifer and high tendency of water encroachment. This technology uses a hydrodynamic concept of in-situ downhole water drainage to control excessive amount of produced water in oil and gas wells. In multilateral wells, the whole system is equipped with dual production systems: the lower lateral well is placed in the water zone, and water can be produced concurrently and independently to oil production from the upper lateral well. These two production streams are separated by isolation packers so that water does not mix together with oil. Water encroachment control is performed by adjusting the ratio of water production rate to oil production rate in order to prevent the water breakthrough in the upper lateral well.

The water sink (producing well in the water zone) alters the flow directionaround oil production well, so that the water cresting is suppressed. The upward vertical component of viscous force generated by the flow into the upper oil producing well is reduced by the value of the downward vertical component of the second viscous force generated by the flow into the water sink. At the equilibrium, a stablewater cresting is "held down" around and below the oil-producing perforations.

DWS can provide several advantages which are:

1. Oil production rate can be increasedby delaying of water breakthrough.
2. Well production life is extended longer compared to the well without cresting control.
3. Oil recovery per well is raised due to the following mechanisms:
    a. Production can be continued with high levels of static

        i. Oil-water contact (caused by the bottom water drive invasion)
        ii. even when this level reaches the oil perforations
    b. Well productivity will be high because the near-well zone permeability to oil is not reduced by water encroachment.
4. Produced water will not be contaminated with crude oil, demulsifiers and other agents used in oil production. Therefore, it will more likely meet effluent discharge limitations imposed by the environmental regulations in the area.
5. The water/oil ratio will be reduced with the use of DWS.

3.3Downhole Water Loop (DWL)

The concept of this method is illustrated in Figure 3.1. The well is drilled through both oil and water column. These two zones are separated by isolation packer. For the water zone, the completion consists of:

- Packers
- Submersible water pump
- Water sink perforation (for water drainage)
- The deviated bottom part of wellbore (discharge section)

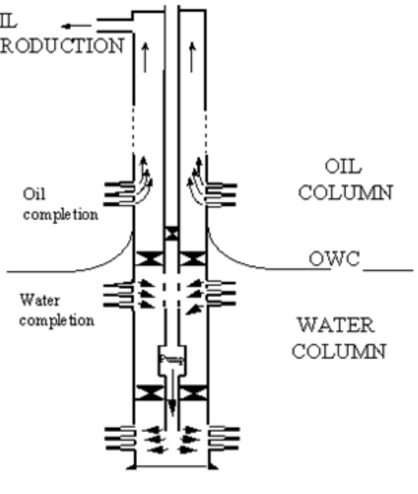

Figure 3.1 Well configuration of downhole water loop

The discharge section is completed in the water column for water loop recirculation. Water from the sink section will be re-injected through this discharge perforation. Advantage of this method does not only include higher oil production, longer well life but also can eliminate disposal water cost and prevent environment pollution (Wojtanowicz, 1995).

CHAPTER IV

RESERVOIR SIMULATION MODEL

Details of reservoir model are described in this section. Reservoir modeling is basically composed of generality of reservoir model, fluid properties, petrophysical properties, well geometry and production schedule. Details of methodology is also extended from introduction section in this chapter.

4.1Reservoir Model and Generalities

The black oil simulator called ECLIPSE®100 is selected as a tool for studying feasibility of DWL. This section describes details of basic properties required for constructing physical reservoir model in ECLIPSE®100 program.

Reservoir models are designed with total number of grid block of 75,000 in which 50, 50, and 30 blocks are in X, Y and Z direction, respectively. Grid sizes in X and Y direction are both 50 ft, resulting in a reservoir area of 51.65 acre. Grid size in Z direction determining thickness of reservoir is varied in certain sections in order to study the effect of formation thickness on DWL and is explained in the following sections. The models are constructed using Cartesian coordinate and physical properties listed in Table 4.1 describe homogeneity of models.

Table 4.1Physical properties of constructed reservoir models

Parameter	**Value**	**Unit**
Porosity	20	%
Datum Depth	7,000	ft
Initial pressure @ datum depth	3,100	psi
Horizontal permeability (k_h)	200	mD
Vertical permeability (k_v)	20	mD
Grid size in X, Y and Z direction	30×30×3	ft

Three reservoir uncontrollable parameters are studied which are 1) ratio of vertical permeability to horizontal permeability, 2) thickness of hydrocarbon bearing zone and 3) thickness of water aquifer. Tables 4.2 to 4.4 summarize values of each studied parameters, respectively.

In the study of effects from vertical connectivity, ratio of vertical permeability to horizontal permeability is chosen. Horizontal permeability is fixed at 200 mD and vertical permeability is varied from 20 up to 60 mD to represent high vertical connectivity and down to 10 mD to represent low vertical connectivity.

Table 4.2Summary of selected values of ratio of vertical permeability to horizontal permeability (k_v/k_h)

Case	**Vertical permeability (mD)**	**k_v/k_h**
High vertical permeability	40	0.2
Moderate vertical permeability (base value)	20	0.1
Low vertical permeability	10	0.05

As explained about varying of grid size value in Z direction previously, changing this value results in different thickness of reservoir. Initial reservoir pressure is kept constant for all three chosen cases and hence, results in different depth of top layer. Another value of oil zone thickness of 60 ft is selected in this study. When oil zone thickness is increased, area of reservoir is reduced to keep volume of oil in place equaled.

Table 4.3Summary of values of oil thickness

Case	**Thickness of grid block (ft)**	**Oil zone thickness (ft)**	**Depth of top layer (ft)**
High oil thickness	6	60	6,985
Low oil thickness (base value)	3	30	7,000

Thickness of water zone represents potential of water influx driving oil into producer. In this study, several sizes of bottom water aquifer are chosen which are 2, 5, and 10 times of oil bearing zone. As explained in previous section, thickness of oil zone at base value is 30 ft, hence total thickness of water zone are varied to 60, 120 and 270 ft, respectively. In reservoir simulation model, thickness of water zone is adjusted by increasing only the bottom most layer which is at grid number 30 in Z direction. Table 4.4 summarizes total thickness and thickness of bottom most grid block of all three cases.

Table 4.4Summary of total thickness and thickness of the bottom most grid (30th)

Case	**Total thickness of aquifer zone (ft)**
2-time aquifer size	60
5-time aquifer size	150
10-time aquifer size	300

Reservoir model with oil bearing zone thickness of 30ft and 2-time bottom water aquifer thickness is chosen as base case mode in this study. Three-dimension model of base case reservoir is illustrated in Figure 4.1. Color scale starts from blue color representing 100 percent water saturation to red color where oil saturation is as high as initial saturation.

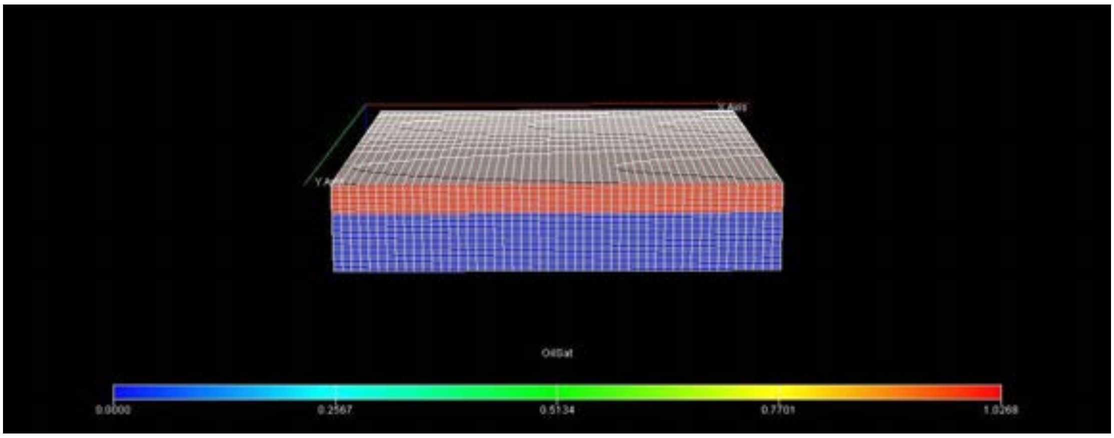

Figure 4.1Three-dimension model at initial reservoir condition representing oil bearing zone on top and two-time thickness of water aquifer zone at bottom

In all cases, production well is located at coordination (26, 26) which is the middle of reservoir from areal view. Figure 4.2 shows production well placement position in base case model.

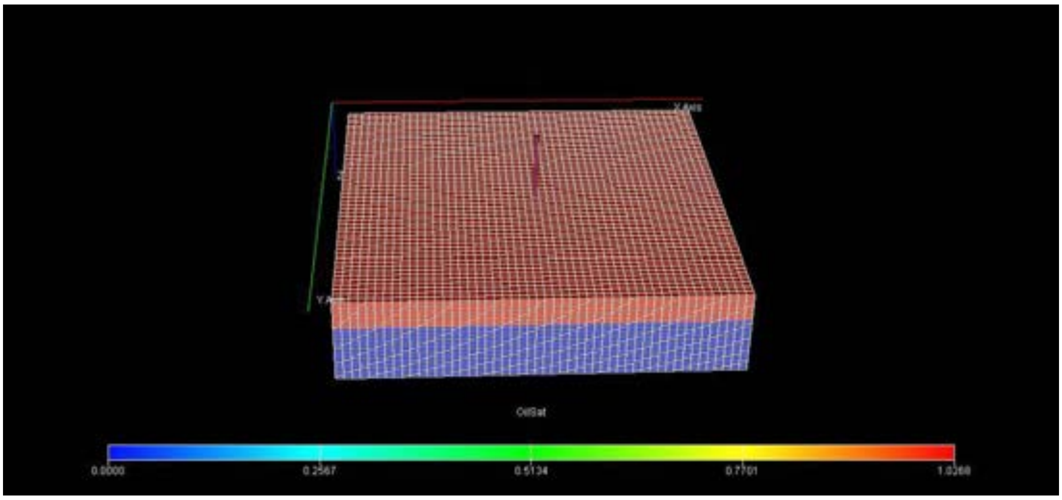

Figure 4.2Production well placement in base case model

4.2Pressure-Volume-Temperature (PVT) Properties

Pressure-volume-temperature properties of reservoir fluid are specified in this section. Oil specific gravity 30 API is selected as the base case. Table 4.4 summarizes PVT properties of water, whereas Table 4.5 addresses fluid densities at surface condition. Live oil properties (with dissolved gas) including formation volume factor (B_o) and viscosity (μ_o) are illustrated in Figure 4.3 as a function of reservoir pressure.

Table 4.5PVT properties of formation water

Property	Value	Unit
Reference pressure (P_{ref})	3,100	psia
Water FVF at P_{ref} (B_w)	1.034592	rb/stb
Water compressibility (C_w)	3.332361×10^{-6}	psi^{-1}
Water viscosity at P_{ref} (μ_w)	0.2472802	cp
Water viscosibility	4.25278×10^{-6}	/psi

Table 4.6Fluid densities at surface condition

Property	Value	Unit
Oil density (ρ_o)	53.00209	lb/ft^3
Water density (ρ_w)	62.42797	lb/ft^3
Gas density (ρ_g)	0.04369958	lb/ft^3

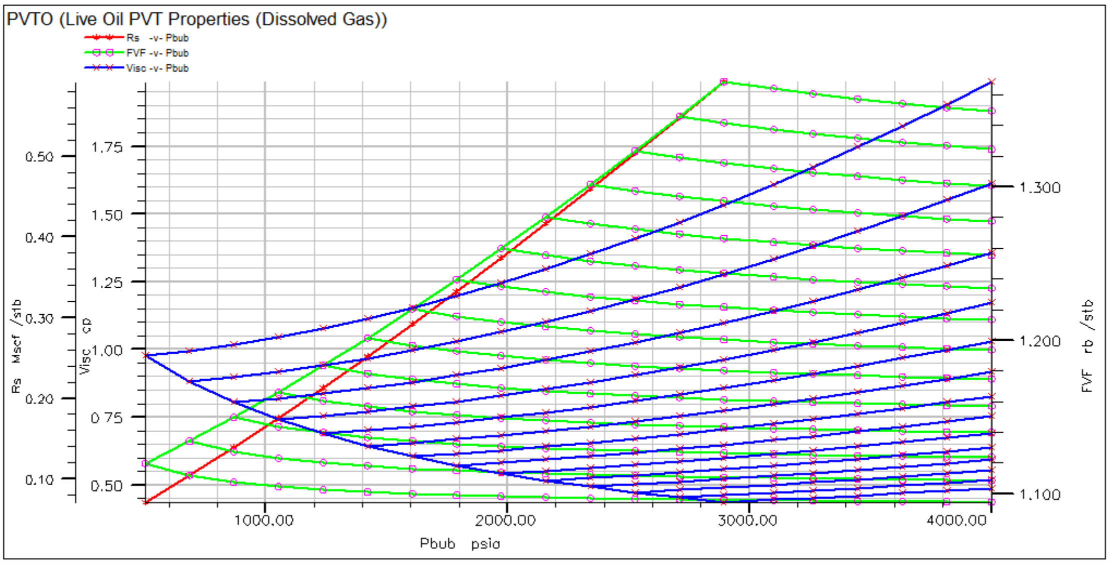

Figure 4.3Live oil PVT properties including oil formation volume factor and oil viscosity as a function of bubble point pressure (with dissolved gas) at oil gravity 35API

PVT data of live oil shown in Figure 4.3 is generated by PVTO function equipped in ECLIPSE®100, requiring two important oil properties which are oil gravity and bubble point pressure at initial reservoir condition. In this study oil gravity of 30 API and bubble point pressure of 3,000 psia are used for generating PVT data. Properties of liberated dry gas are shown in Figure 4.4, including gas formation volume factor and gas viscosity at different reservoir pressures.

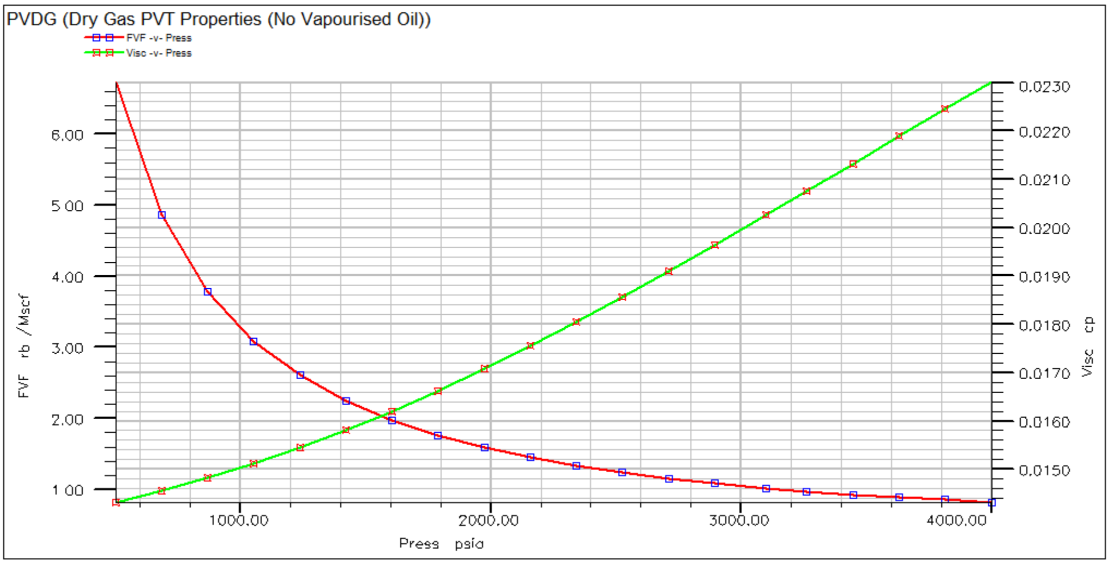

Figure 4.4 Dry gas PVT properties (no vaporized oil) including gas formation volume factor and gas viscosity as a function of reservoir pressure.

In the study of oil quality in sensitivity analysis section, type of oil is varied in terms of gravity. Oil quality is represented by oil gravity and chosen values are 30, 35 and 40 to present increasing trend in degree of lightness of oil. PVT data is then re-generated for different oil lightness, while bubble point pressure is maintained constant at 3,000 psia.

4.3Petrophysical Properties

Relative permeability to both water and oil are shown in Table 4.7. Data shown in Table is obtained from Corey's correlation available in Eclipse®100 reservoir simulation program. All relative permeability values are based on absolute permeability. As a function of water saturation, relative permeability values are tabulated and shown in Table 4.7. Consequently, these values are plotted in curves of relative permeability to water and oil, illustrated in Figure 4.5.

Table 4.7Relative permeability to oil and water

S_w	k_{rw}	k_{ro}
0.3000	0.0000	0.4500
0.3444	0.0019	0.3556
0.3889	0.0074	0.2722
0.4333	0.0167	0.2000
0.4778	0.0296	0.1389
0.5222	0.0463	0.0889
0.5667	0.0667	0.0500
0.6111	0.0907	0.0222
0.6556	0.1185	0.0056
0.7000	0.1500	0.0000
1.0000	1.0000	0.0000

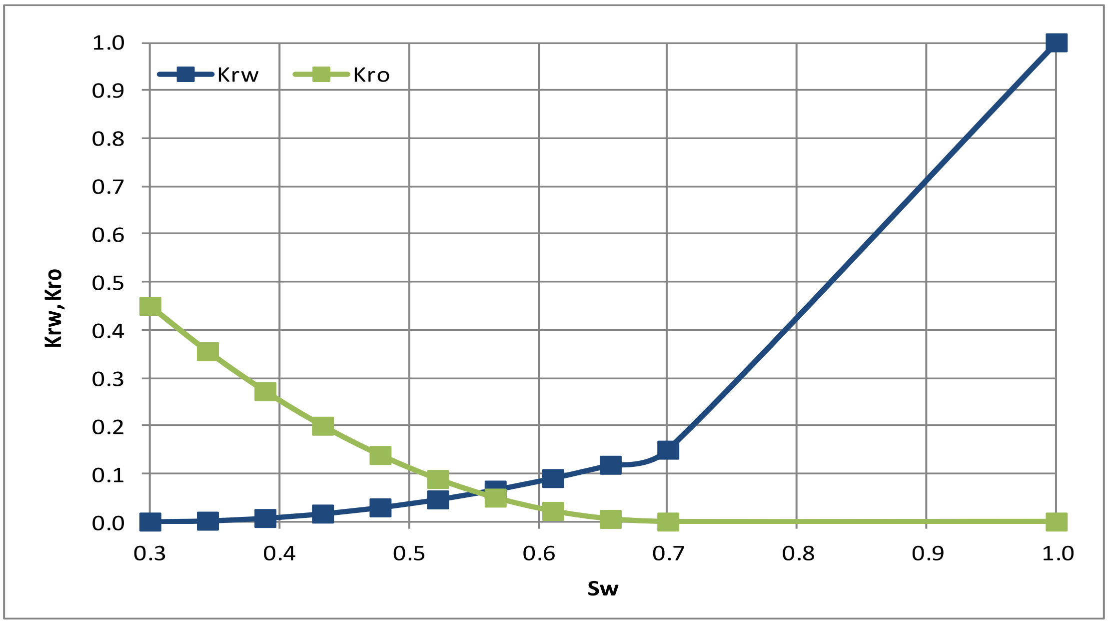

Figure 4.5Relative permeability curves to both oil and water as a function of water saturation

As function of gas saturation, relative permeability values are tabulated and shown in Table 4.8. Consequently, these values are plotted in curves of relative permeability to water and oil, illustrated in Figure 4.6.

Table 4.8Relative permeability to oil and water

S_g	k_{rg}	k_{ro}
0.0000	0.0000	0.4500
0.0500	0.0000	0.3719
0.1125	0.0086	0.2847
0.1750	0.0344	0.2092
0.2375	0.0773	0.1453
0.3000	0.1375	0.0930
0.3625	0.2148	0.0523
0.4250	0.3094	0.0232
0.4875	0.4211	0.0058
0.5500	0.5500	0.0000
0.7000	1.0000	0.0000

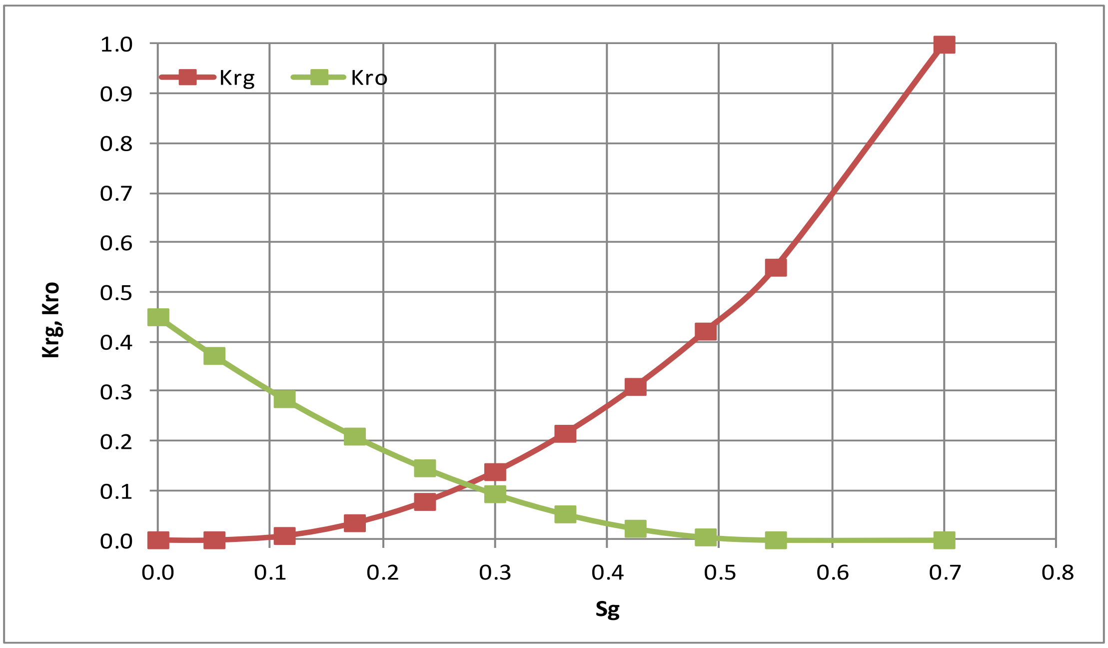

Figure 4.6Relative permeability curves to both gas and oil as a function of gas saturation

4.4Initial Fluid Contact

In the simulation model, Equilibration Data Specification for base case is input as shown in Table 4.9. The location of initial oil water contact is set at the top of 11th grid in Z direction. In case where thickness of oil bearing zone is varied, WOC may slightly change due to different top depth to maintain equal initial reservoir pressure. Gas cap is absent at initial condition since reservoir pressure is higher than bubble point pressure.

Table 4.9 Fluid contact data of base case model

Data	Value	Unit
Datum Depth	7,000	ft
Pressure at datum depth	3,100	psia
WOC depth	7,030	ft

4.5Well Geometry and Completion

In every simulation case, production well has the same wellbore internal diameter. Well geometry including completion system is illustrated in Figure 4.7.

From Figure 4.7 oil is produced from upper oil zone, whereas water is simultaneously produced from bottom layer water zone. All produced water is re-injected into deeper depth of water zone (discharge section) in order to maintain reservoir pressure

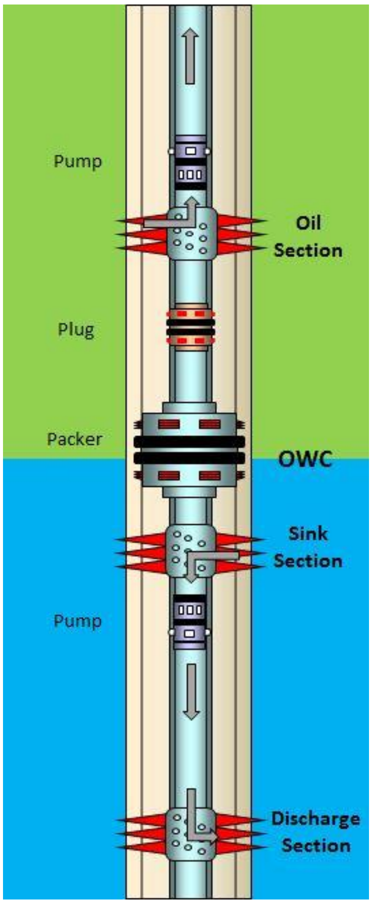

Figure 4.7DWL well geometry and completion system

Location and interval of each section are studied parameters in optimization section. Best location is identified first then perforation interval is extended. Table 4.10 summarizes ranges of both location and perforation interval for hydrocarbon zone, water production (sink) zone and water discharge zone. Location and perforation interval are represented by grid number in Z direction.

Table 4.10Summary of location and perforation interval in each zone

Zone	**Location of Z grid block**	**Perforation interval (ft)**
Oil zone	1, 3 , 5, 7, 9	3, 9, 15
Water production zone	13, 17, 21	3, 9, 15
Water discharge zone	21, 25, 29	3, 15, 27

4.6Well Schedule and Production Constrains

Production conditions are also controllable study parameters. Oil production rate is first fix to observe effect of water coning to values of 500 STB/D. Water production rate from water sink zone is investigated at varied rates for optimizing oil recovery. All produced water is re-injected into discharge section in order to delay declining of reservoir pressure. Re-injection of water is controlled at maximum bottomhole pressure which is set at fracture pressure at 0.75 psi/ft. Therefore, fracture pressure is differently set when location of discharge zone is optimized. Termination of production can be due to minimum oil production rate of 50 STB/D or water cut of 90% or production period reaching 20 years. Table 4.11 summarizes production targets and constraints of this study.

Table 4.11Summary of production constraints

Parameter	**Value**	**Unit**
Target oil production rate	500	STB/D
Target water production rate	500, 1000, 1500, 2000, 2500, 3000, 3500, 4000	STB/D
Maximum bottomhole pressure for production zone	500	psia
Maximum bottomhole pressure for water discharge zone	0.75 psi/ft depends on depth of discharge zone	psia
Minimum oil production rate	50	STB/D
Maximum water cut	90	%
Total production period	20	year

4.7Thesis methodology

This section describes details of study methodology which is mainly aimed for reservoir simulation design. Operational parameters or parameters that can be controlled such as water production rates and completion depth and interval are first studied. Reservoir models with varying of these parameters are run to optimize oil recovery. Optimized values determine the base case which is used for sensitivity analysis in latter section. The best case in this study is judged from the highest oil recovery. In sensitivity analysis section, parameters which are will be used uncontrollable parameters which are previously fixed at constant value are varied in this section. Potential parameters include ratio of vertical permeability to horizontal permeability, thickness of hydrocarbon bearing zone and water zone. At the end, study of oil quality is performed. Major steps of methodology are summarized as followed.

1. Construct an initialized homogeneous oil reservoir. As mentioned in section 4.1, reservoir model is created to represent homogeneity. Physical model is constructed based on based values (for parameters that are studied in sensitivity analysis section.

2. Optimize operational parameters to determine base case for sensitivity study. This section fixes oil production rate at 500 STB/D. Then oil completion depth is varied first to identify location that yields the highest oil recovery. Chosen locations are at vertical grid number 1, 3, 5, 7 and 9.After completion location is identified, completion interval in oil zone is increased from single grid block (3 ft) to chosen values of 9 and 15 ft or equivalent to 3 and 5 vertical grid blocks respectively.

3. Optimize operational parameter in water production zone (sink). Similar to oil production zone, water production zone is optimized in terms of location and interval. Chosen locations are at vertical grid block number 13, 17 and 21.Water production rate is kept constant at 500 STB/D as same as oil

production rate. However, after water production location, water production rate is varied to 500, 1000, 1500, 2000, 2500, 3000, 3500, and 4000 STB/Dto optimize oil recovery. And then perforation interval is increased from 3 ft to 9 and 15 ft which are equivalent to 1, 3 and 5 vertical grid blocks, respectively. All produced water is re-injected back into deeper zone of the reservoir.

4. After optimum water production rate is determined, location and interval of water discharge or water re-injection zone are optimized. Nevertheless, water re-injection rate is not varied in this section as all produced water is totally re-injected back into water aquifer zone. Chosen values for location and interval of water re-injection zones are vertical grid block number 21, 23, 25, 27 and 29, whereas the interval are 3ft, 15ft and 27ft respectively. At this step, base case is finalized and is used throughout sensitivity study.

5. Ratio of vertical permeability to horizontal permeability is the first study parameter. This parameter tends to yield earlier water coning effect when ratio is higher or when vertical connection is better. From base value of 0.1, ratio is adjust to 0.05 and 0.2 by means of decreasing vertical permeability to 10 mDarcy and increasing vertical permeability to 40 mDarcy respectively. Details are shown in Table 4.2 in section 4.1.

6. Thickness of oil zone is varied from 30 ft to 60 ft by increasing thickness of grid size in vertical direction from 3 ft to 6 ft. Depth of top layer is slightly adjusted from 7,000 ft to 6,985 ft in order to keep reservoir pressure constant as well as drainage area is reduced from 51.65 to 25.83 acres in order to keep oil in place constant.

7. Thickness of water zone representing strength of drive mechanism by water is varied by its size compared to base value of thickness of oil zone. Chosen values are 2, 5 and 10 times. In this study, only vertical grid number 30 is adjusted in size to complete desire depth. Summary is shown in Table 4.4 in section 4.1.

8. Later, oil quality is studied and this parameter is represented by oil gravity. Chosen values of oil gravity are 30, 35 and 40 API.

9. From all studying parameters in sensitivity analysis, values that yield adverse oil recovery are included in new model and optimization is performed again. This study is to confirm effectiveness of proper configuration of DWL system when performing in reservoir conditions that are not completely favorable.

All reservoir simulation studies can be summarized and shown in flow chart illustrated in Figure 4.8.

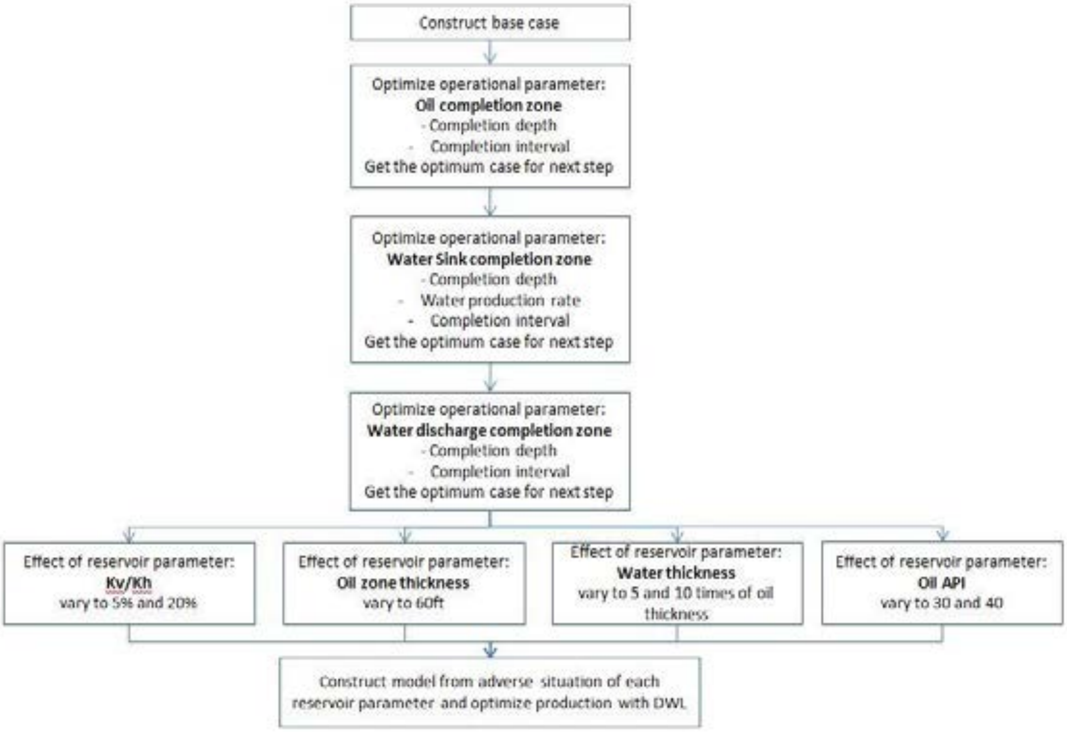

Figure 4.8Flow chart of reservoir simulation study

CHAPTER V

RESULTS AND DISCUSSION

Results obtained from reservoir simulation explained in Chapter 4 are discussed in this chapter. First, discussion is conducted over base cases, performed to study controllable parameters to identify optimized base case. After that, optimized base case is used for sensitivity analysis of uncontrollable reservoir parameters. All simulations are performed within 20 years of total production period which covers entire well life. An economic cut-off of production well is at 90 percent of water cut or oil production rate below 50 STB/D.

5.1Optimization of Controllable Parameters

5.1.1 Optimization in Oil Bearing Zone

Vertical production well is located at the middle of reservoir at coordinate of (26,50) in areal view. The constructed reservoir model contains original oil in place of 1,222,316STB. Thickness of oil bearing zone is 30ft located from top depth of 7,000 ft to 7,030 ft. This oil bearing zone is represented by grid no. 1 to 10 in z direction. Initial oil-water contact is located at 7,030 ft with 60-ft water aquifer inferiorly.

In order to understand production profile of reservoir with bottom drive aquifer, a model of conventional well (only single perforation in oil zone, without DWL completion) is first simulated. Figure 5.1 shows cross section in Y plane of well with perforation at grid Z = 3 at different production periods. When oil is produced, reservoir pressure stored in reservoir fluid starts to decline. At certain period, reservoir pressure reaches bubble point pressure and solution gas is liberated from previously oil phase at the top of reservoir as shown by light blue color. Consecutively, this liberated gas moves downward and invades into perforation area.

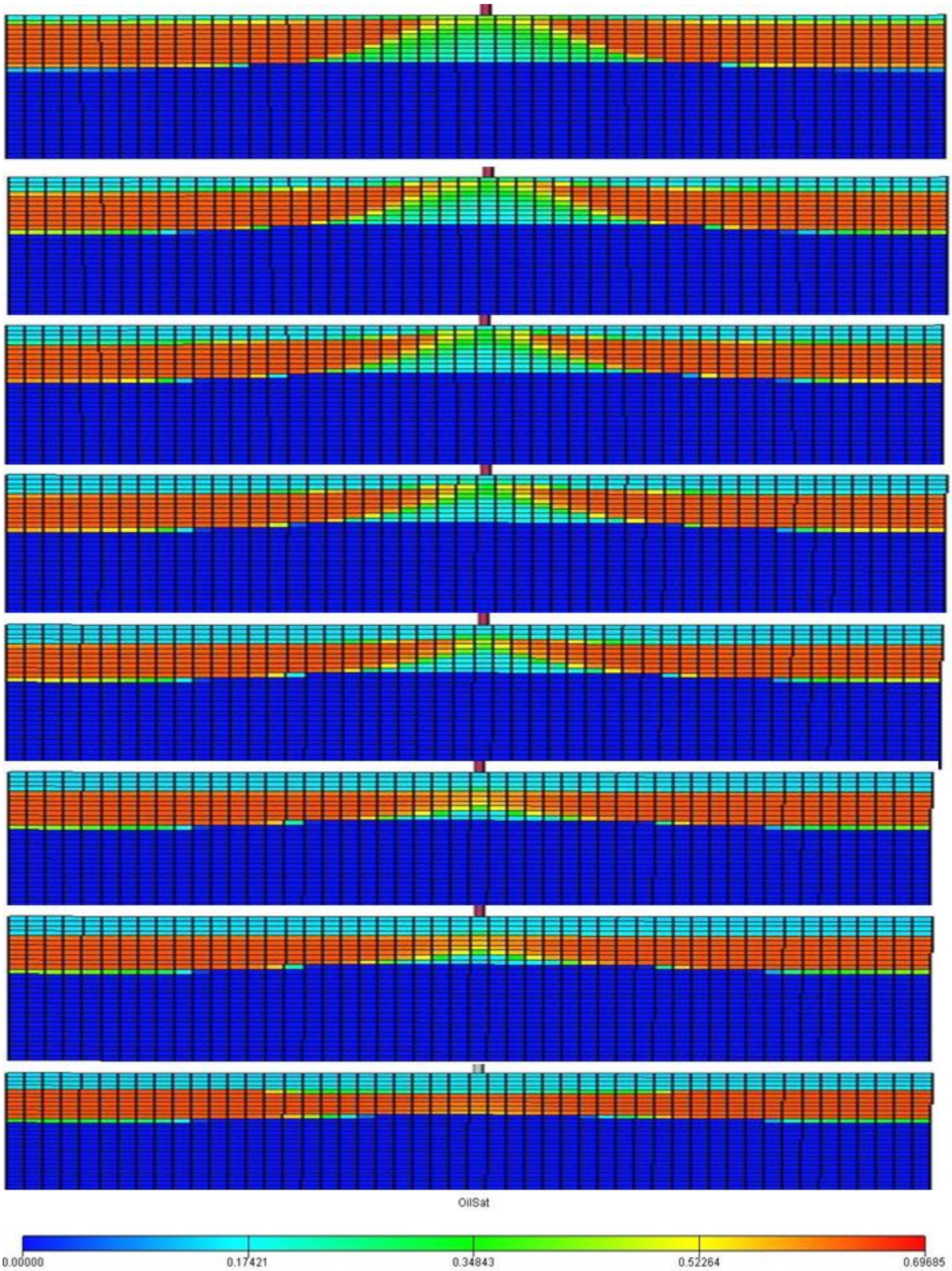

Figure 5.1 Cross-section view in Y plane, showing oil saturation at different production period (production time increases from top to bottom)

For water production, as oil is produced, this creates upward movement of oil-water contact. Therefore water start to cone into perforation section. As production period continues, more oil produces and this results in less reservoir pressure. Higher saturation of liberated gas is found on top of reservoir. Gas-oil contact level expands and shifts downward. At the same time, oil-water contact around wellbore also rises upward. Reservoir pressure declines continuously and depletes oil production rate. At certain time, the well reaches minimum oil production value which is one of production constrains. Production is therefore terminated with balancing of gas, oil and water level at that condition.

To identify the optimum location for perforation location in oil production zone, oil production rate is fixed at 500 STB/D and perforation location is varied, perforating just one grid interval (3ft) at different vertical grid. Chosen grids are grid Z = 1, 3, 5, 7 and 9. Results are shown in Table 5.1 and consecutively Figures 5.2-5.4 compare oil recovery factor in percentage, gas production rates, water-cut ratio, and gas-liquid production ratio, respectively.

Table 5.1Summary of reservoir simulation outcomes from conventional vertical well implementation with different perforation locations

Perforation Interval	**Cumulative production**			**Oil recovery factor (Fraction)**	**Total prod. period (Years)**
	Oil (STB)	**Gas (MSCF)**	**Water (STB)**		
Z = 1-1	69,577	116,522	141,349	0.0571	1.30
Z = 3-3	68,685	123,567	154,078	0.0563	1.33
Z = 5-5	63,082	116,508	165,649	0.0517	1.34
Z = 7-7	54,480	106,584	191,576	0.0447	1.41
Z = 9-9	41,311	74,344	213,103	0.0339	1.41

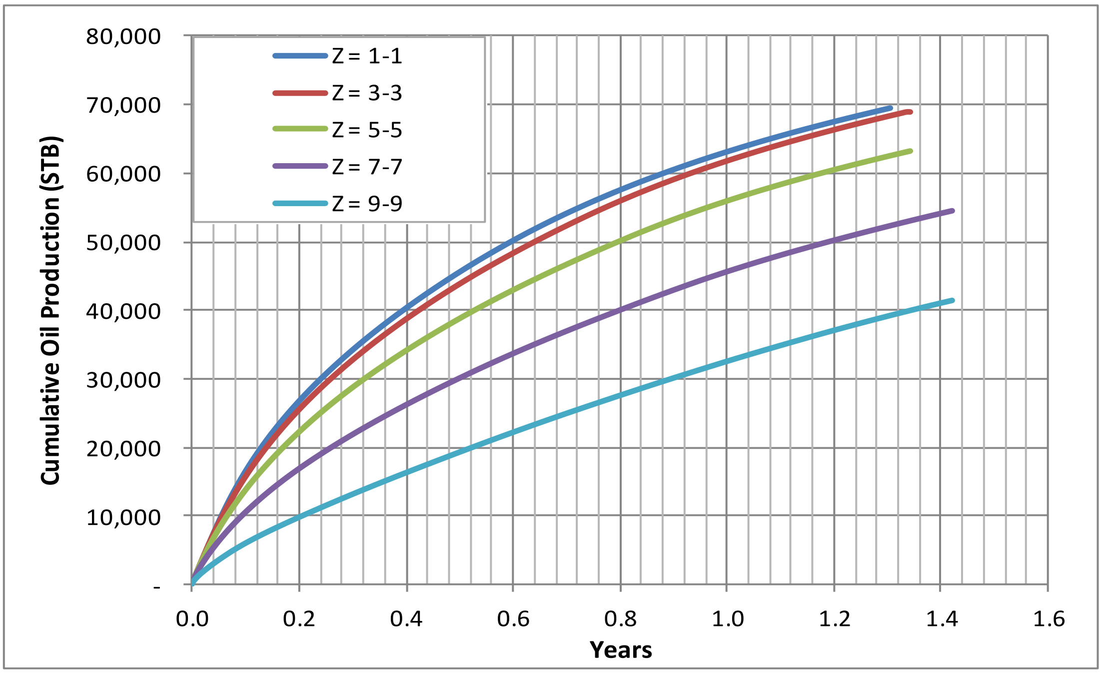

Figure 5.2Oil recovery factors in percentage of conventional wells (without DWL) perforated at various locations as a function of production time

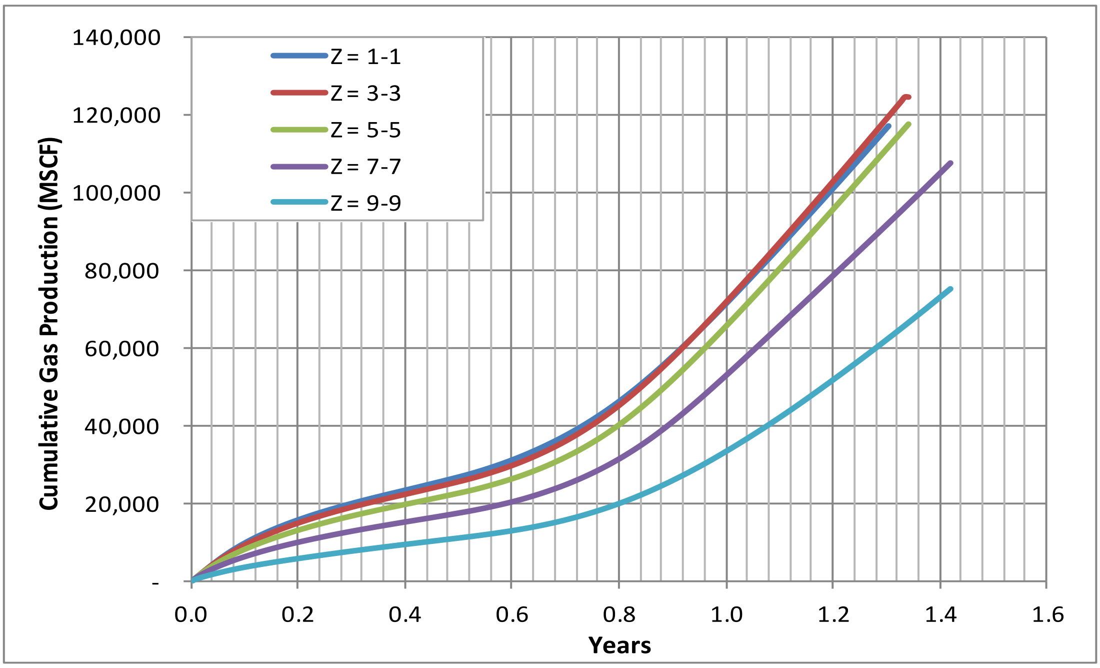

Figure 5.3Cumulative gas productionof conventional wells (without DWL) perforated at various locations as a function of production time

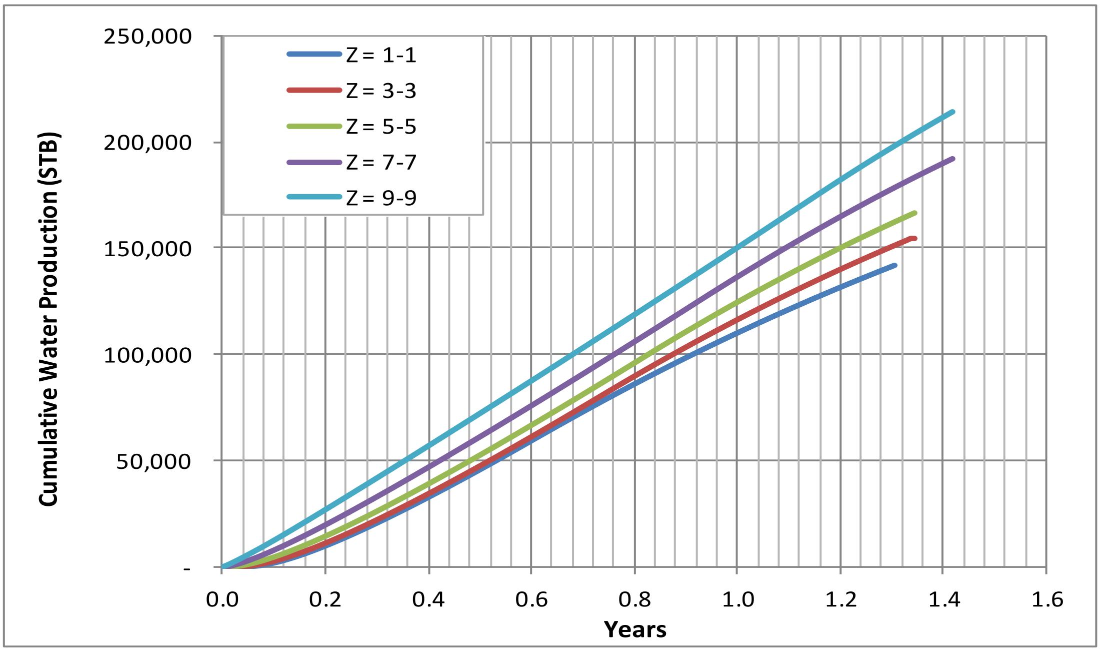

Figure 5.4Cumulative water production of conventional wells (without DWL) perforated at various locations as a function of production time

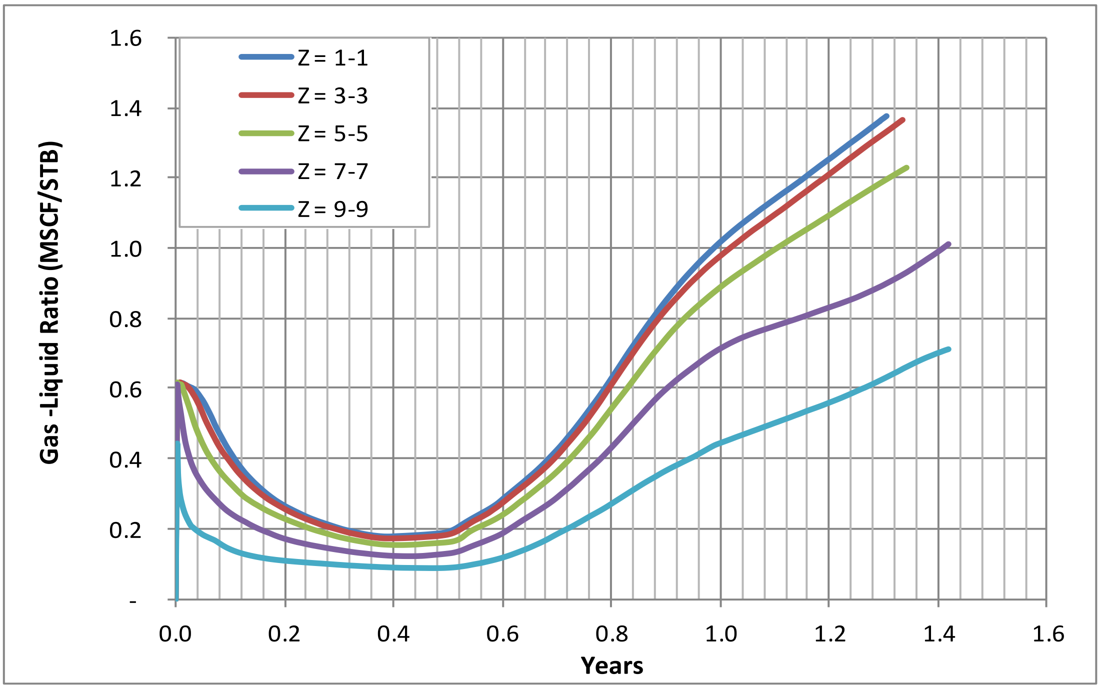

Figure 5.5Gas-liquid ratio of conventional wells (without DWL) perforated at various locations as a function of production

From Table 5.1, perforation location that yields the highest oil recovery factor is found at grid Z =1 (as shown also in Figure 5.2). It is the case where the well is affected the least from water encroachment from bottom drive aquifer that can be seen for the least cumulative water production from Figure 5.4. This is due to its perforation location that is far away from oil-water contact. Even though it is at the upper most layer of reservoir, cumulative gas production is still less than case where perforation location is at grid Z = 3 as illustrated in Figure 5.3. Nevertheless, this does not mean that perforation at Z =1 produced less gas compared to case grid Z =3. Figure 5.5 shows that Gas-Liquid production Ratio (GLR) of all cases and for case grid Z =1, the highest GLR is obtained. But as it produces more gas, oil rate is lower and the well reaches economic constrain which is oil production rate below 50 STB/D before the case of grid Z =3. Case Z =1 totally produces for a production period of 1.3 years, and hence less cumulative gas production compared to case grid Z =3.

On the other hand, case Z= 9 yields the lowest gas production as it is located far most from gas-oil contact, compared to other cases. This case produces the highest water as it is very close to oil-water contact. Therefore, this case produces a lot of water, making case Z = 9 to yield the lowest oil recovery factor. Cases where perforation is performed at grid Z = 1is the best case base on oil production and it ispicked to continue in the study of the perforation interval.

Oil perforation interval is studied. Intervals are varied from 3ft to 9ft,15ft and 21ft as located from grid Z = 1. Summary of results are shown in Table 5.3, whereas Figures 5.6 – 5.10 depict cumulative oil production, cumulative gas production, cumulative oil production, well bottomhole pressure, and oil production rate for the study of optimization of perforation interval in oil bearing zone. In order to pick the optimized interval, oil recovery factor is re-plotted versus perforation interval in Figure 5.11 and at the end of this section, optimized perforation interval is identified.

Table 5.2Summary of reservoir simulation outcomes from conventional vertical well implementation with different perforation intervals

Perforation Interval	**Cumulative production**			**Oil recovery factor (Fraction)**	**Well Life (Years)**
	Oil (STB)	**Gas (MSCF)**	**Water (STB)**		
Z = 1-1 (3ft)	69,577	116,522	141,349	0.0571	1.30
Z = 1-3 (9ft)	82,539	268,193	249,153	0.0677	1.82
Z = 1-5 (15ft)	80,006	259,776	250,943	0.0656	1.81
Z = 1-7 (21ft)	76,104	246,902	253,526	0.0624	1.81

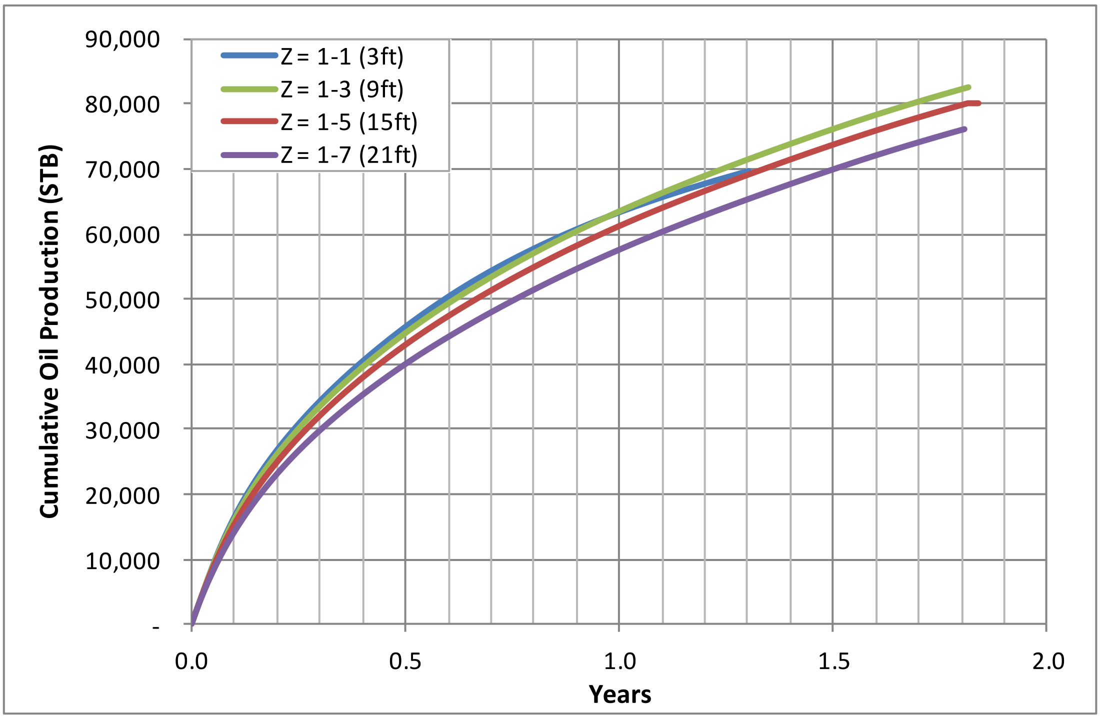

Figure 5.6 Cumulative oil production of conventional wells (without DWL) perforated at various intervals as a function of time

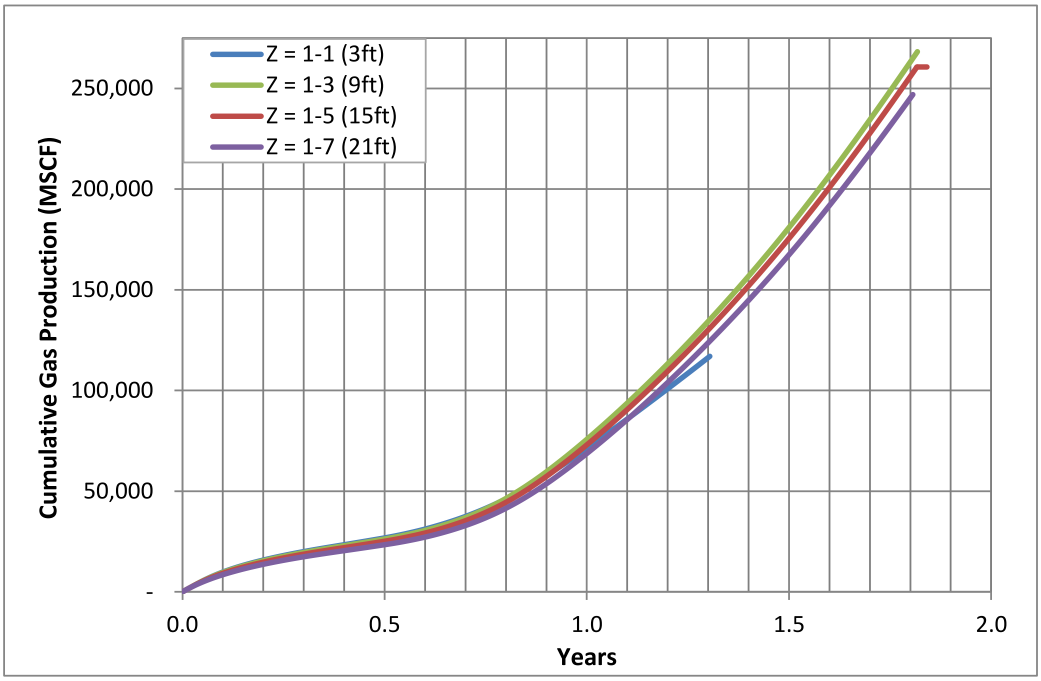

Figure 5.7Cumulative gas production of conventional wells (without DWL) perforated at various intervals as a function of time

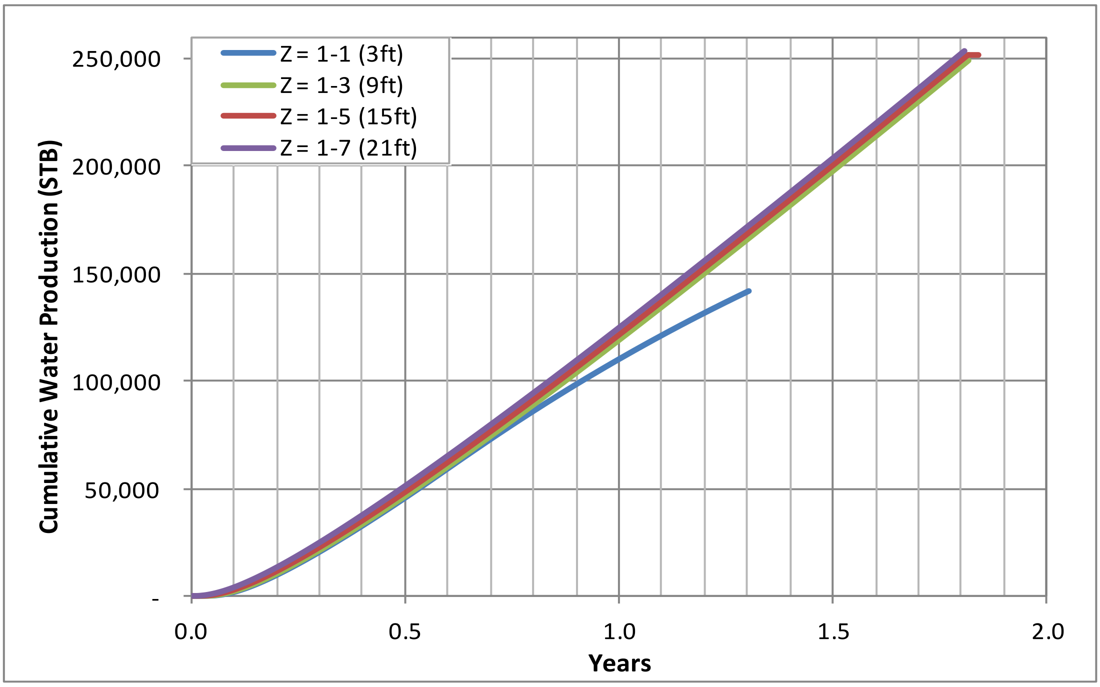

Figure 5.8Cumulative water production of conventional wells (without DWL) perforated at various intervals as a function of time

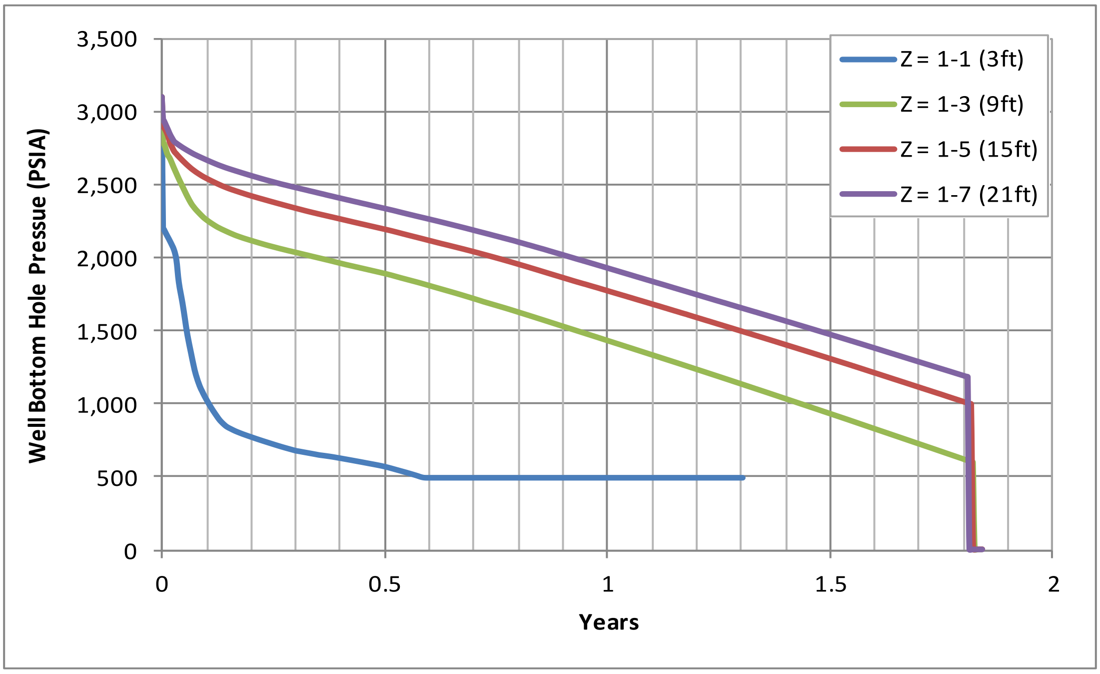

Figure 5.9 Well bottomhole pressure of conventional wells (without DWL) perforated at various intervals as a function of time

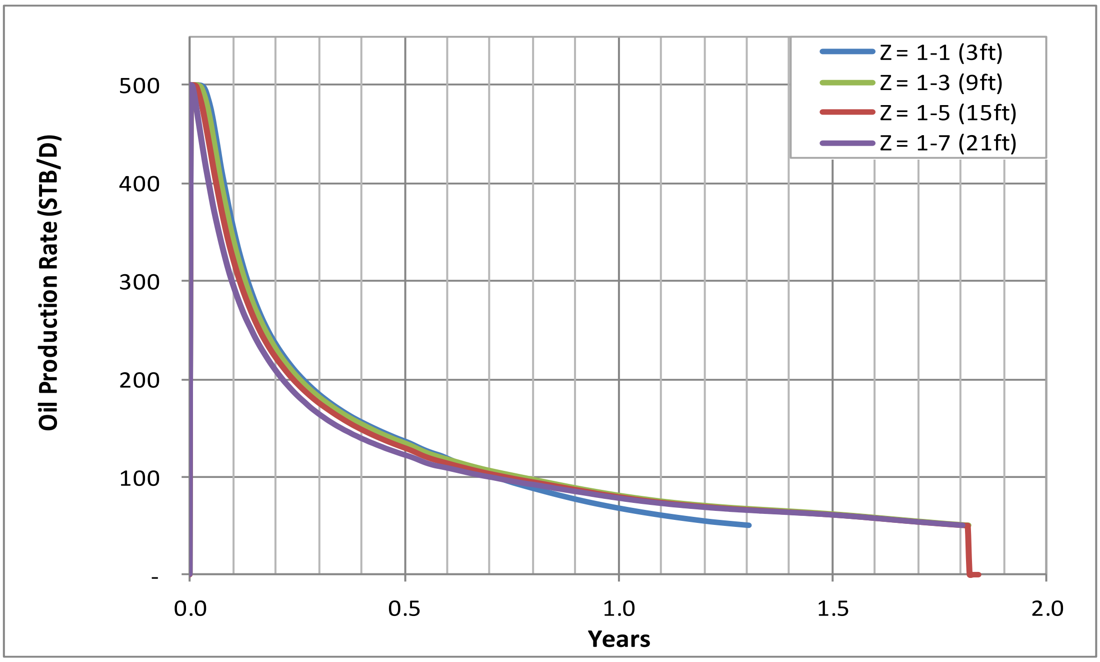

Figure 5.10 Oil production rate of conventional wells (without DWL) perforated at various intervals as a function of time

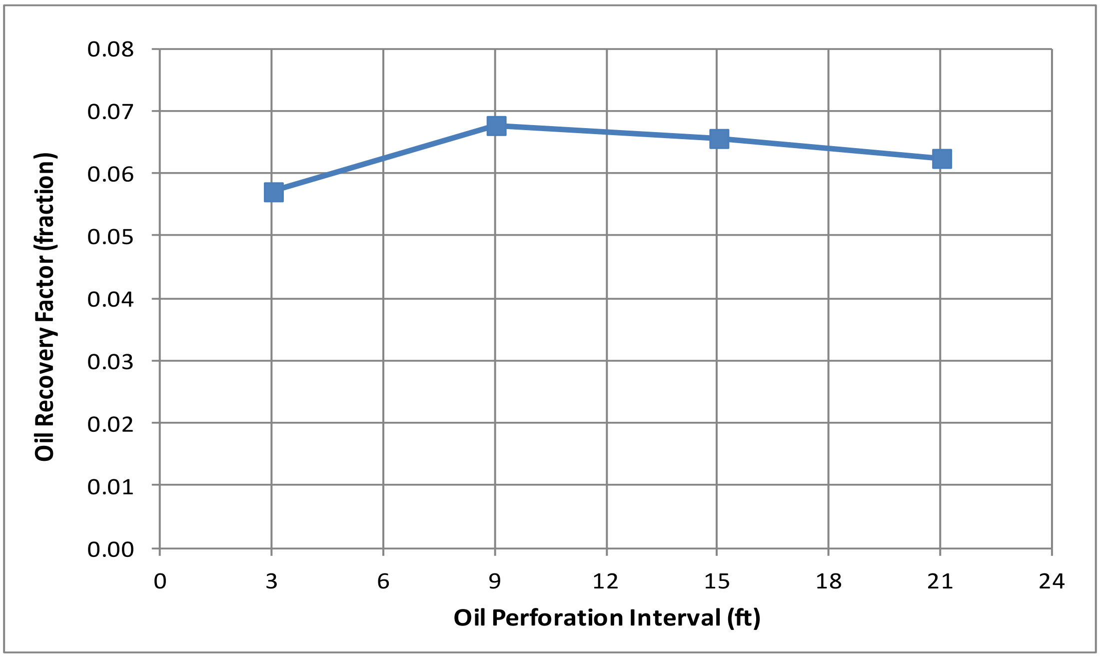

Figure 5.11A plot ofoil recovery factorsversus perforation intervals to identify optimized perforation interval

From Figures 5.6 to 5.10 it can be obviously seen that total production period is extended to 1.8 years for all cases when perforate well over 3ft. From Figure5.6 the highest cumulative oil production is obtained from case of 9-ft perforation interval. From Figure 5.7 high gas production is also obtained in this case since it is located at the top of reservoir. However, since all cases are perforated from the upper most location, they are all affected from high gas production.Nevertheless, slightly lower water production for case of 9-ft perforation interval is shown in Figure 5.8. This can be explained that perforation interval in this case is smaller than cases of 15-ft and 21-ft perforation intervals. Therefore, it is located further from oil-water contact and is affected the least from water encroachment water. As shorter interval it is, oil is more difficult to flow into the well and as the well is controlled by production rate, the shorter interval results in more bottomhole pressure drawndownaround perforation zonein order to reach the desire production rate. The lower bottomhole pressure of 9-ft perforated interval compared to 15-ft and 21-ft cases is illustrated in Figure 9. It can be seen also that 3-ft perforation interval yields the fastest declinationof bottomhole pressure.

According to previous explanations, oil production rate from case of 9-ft perforation interval is therefore the highest one as shown in Figure 5.10. The optimized production interval is therefore clearly depicted by a plot between oil recovery factors as a function of perforation intervals in Figure 5.11. From the figure, perforation at grid z = 1-3 or 9-ft perforation interval yields the highest oil recovery and this cases is chosen as optimized case.

Additional oil production rate is also studied. Previously, oil production is fixed at 500 STB/D. In this section, rate is varied to 250 and 1,000 STB/D.At the same perforation location at grid Z =1-1, 1,000 STB/D creates the highest water production rate. The higher production rate, the higher water rate will cone into the production well. Figure 5.12shows the cumulative water production of each rate as a function of production period.

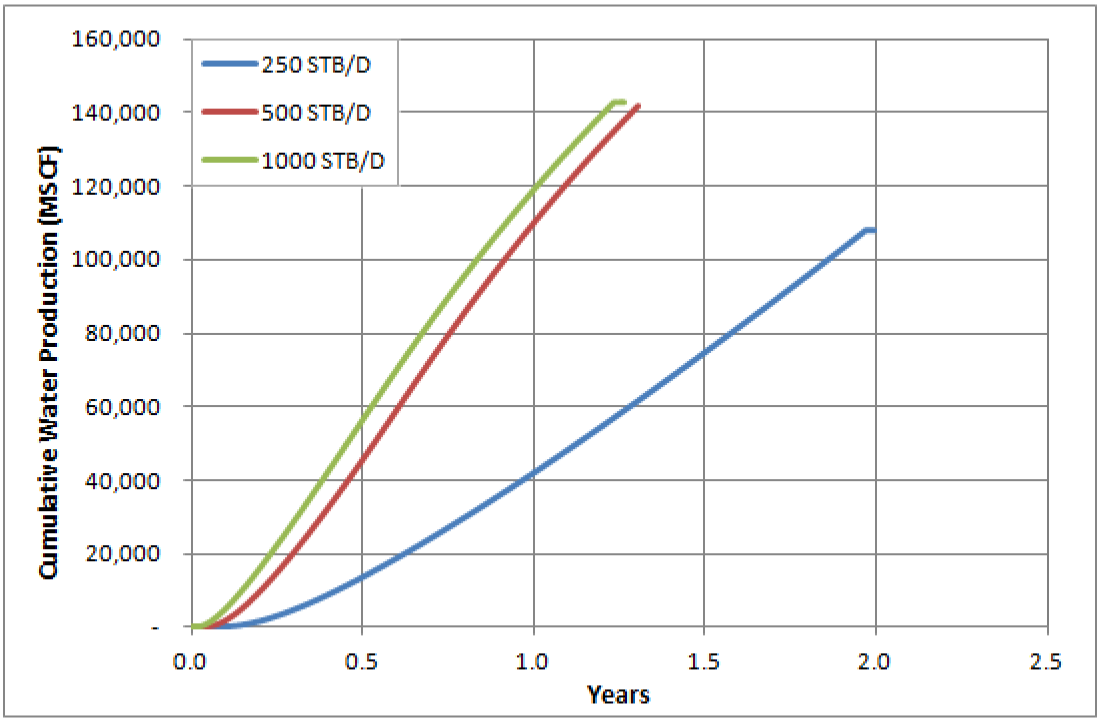

Figure 5.12 A plot of cumulative water production of each rate as a function of production period

These rates are also applied with different perforation location. Figure 5.13showscumulative oil production of each rate as a function of perforation location.

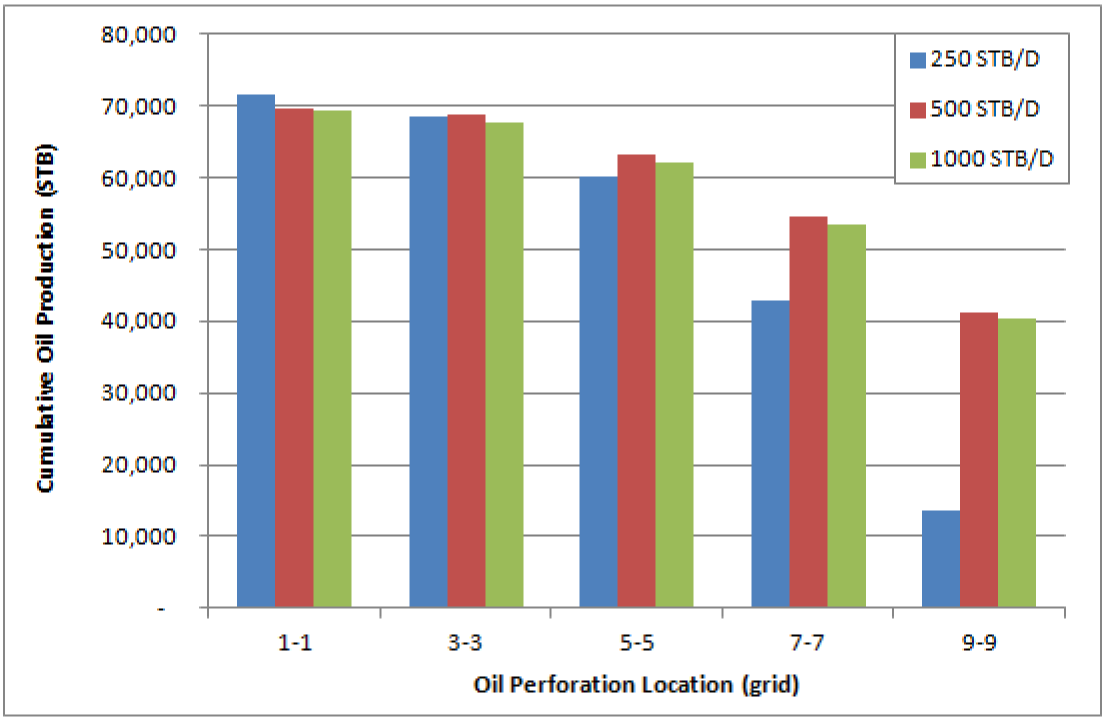

Figure 5.13 A plot of cumulative oil productions versus perforation locationsfor different oil production rates

From Figure 5.13, from all three varied rates it can be confirmed that, the perforation location should be as far as possible from oil-water contact in order to yield the highest oil recovery. And consecutively, Figure 5.13 illustrated the optimum perforation interval for each oil production rate.

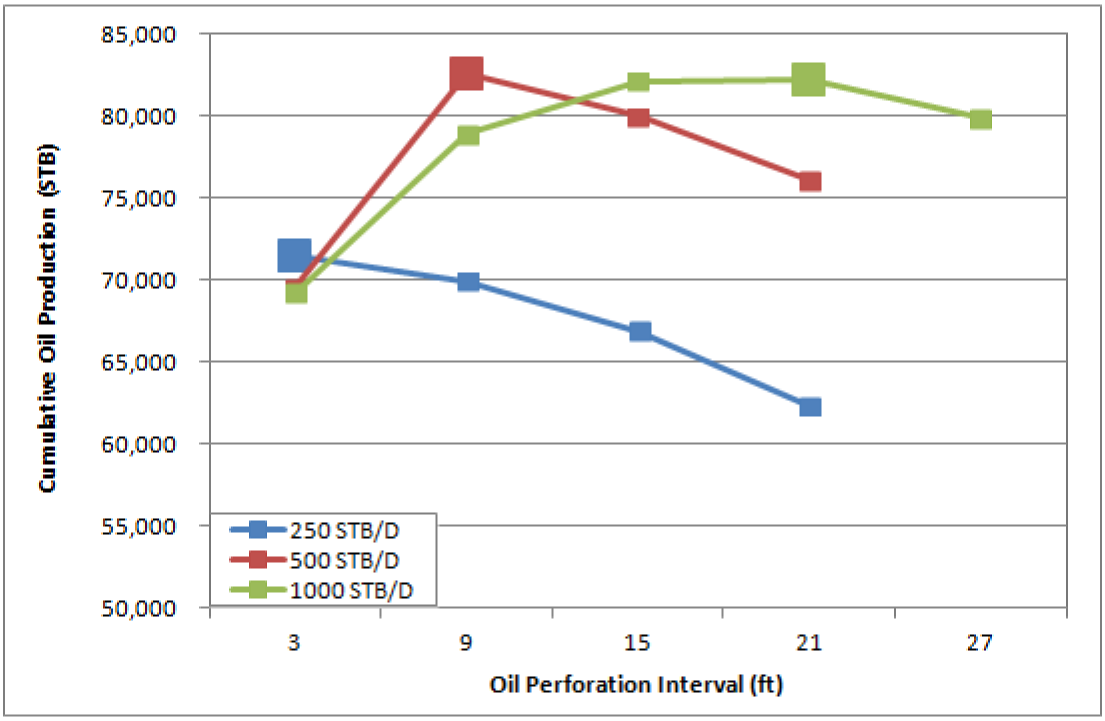

Figure 5.14A plot of cumulative oil productions versus perforation interval for different oil production rates

Figure 5.14shows that higher oil production rate requires longer perforation interval. To yield the highest oil recovery, the longer interval needs to balance between the less of bottomhole pressure drawdown and the closer distance to oil-water contact which results in more adverse effects from water coning.

5.1.2 Optimization of Water Sink Zone

Back to oil production rate of 500 STB/D, perforation location of water sink zone is studied first. Water production rate is firstly fixed at 500 STB/D (equal to oil production rate), location depths of water production perforation are varied from grid z = 13 to 17 and to 21. The location of water discharge zone or re-injector is kept constant in each case of 57 ft away from oil-water contact (grids z = 29. The results including cumulative production of oil, gas and water, oil recovery factor and total production period are summarized as in Table 5.4. And Figures 5.15 to 5.17 illustrate cumulative oil production, cumulative gas production and cumulative water production as a function of production time, respectively.

Table 5.3Summary of reservoir simulation outcomes from DWL implementation with different water sink perforation locations

Water sink grid	**Water discharge grid**	**Cumulative production**			**Oil recovery factor (Fraction)**	**Total prod. period (Years)**
		Oil (STB)	**Gas (Mscf)**	**Water (STB)**		
13-13	29-29	89,757	303,450	250,902	0.0736	1.87
17-17	29-29	87,535	299,025	255,106	0.0718	1.88
21-21	29-29	85,194	287,797	254,835	0.0699	1.86

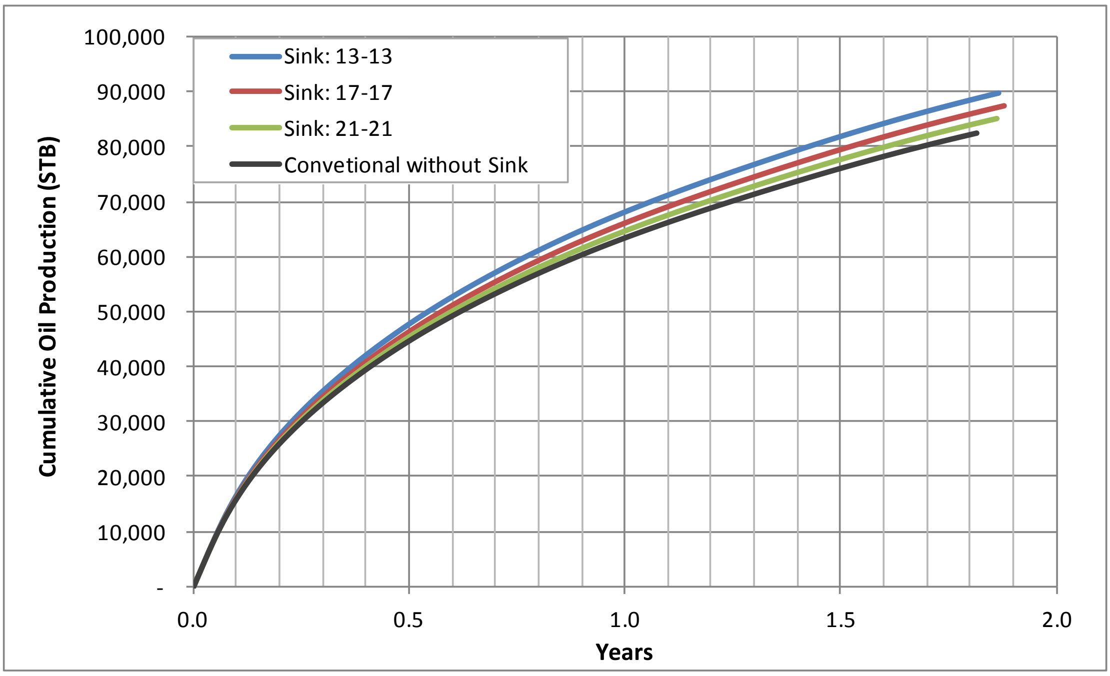

Figure 5.15Cumulative oil production of wells with DWL perforated at various water sink location as a function of time

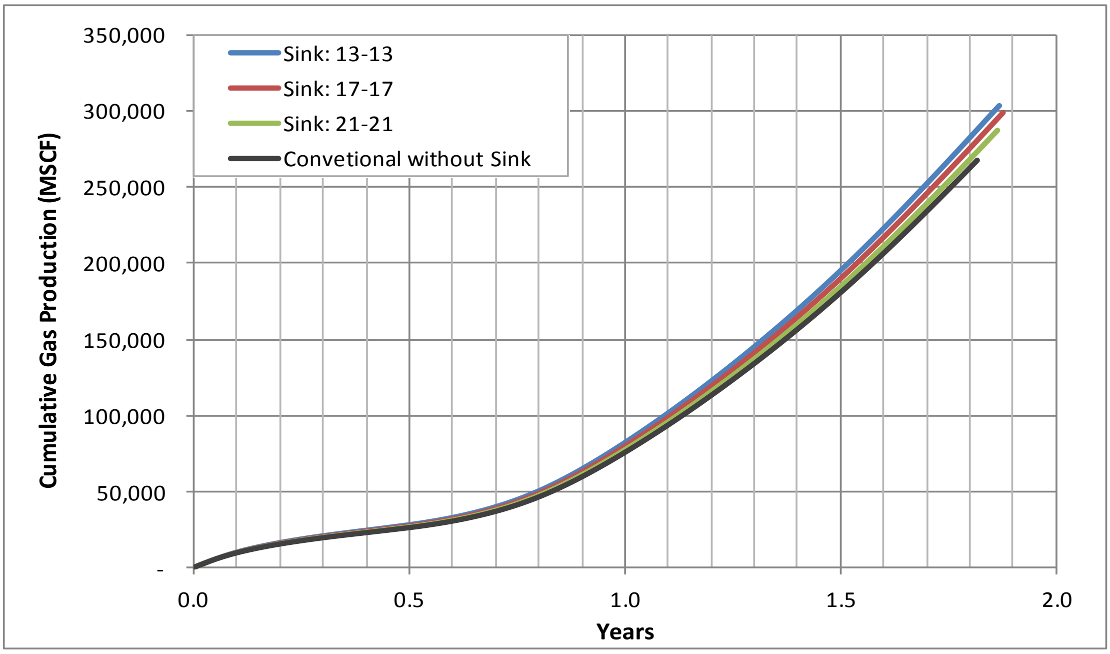

Figure 5.16Cumulative gas production of wells with DWL perforated at various water sink location as a function of time

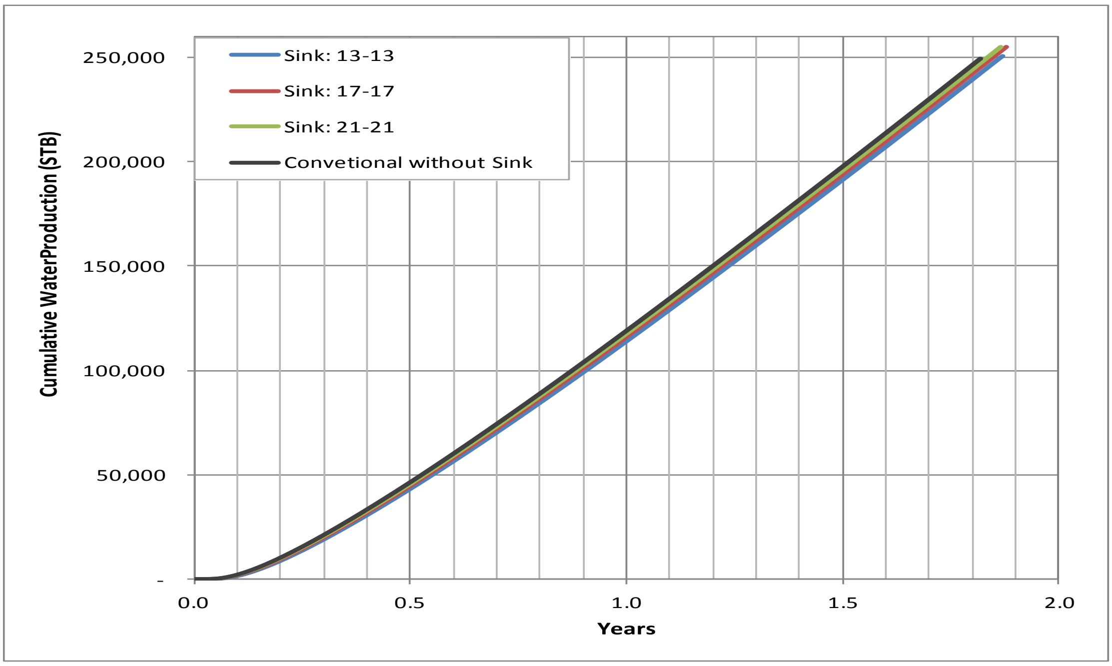

Figure 5.17Cumulative water production of wells with DWL perforated at various water sink location as a function of time

From Table 5.3, it can be seen that these three different water sink location does not change much in total production period which is approximately 1.87 years. However, oil recovery is slightly different. From Figure 5.15, it can be seen that application of water sink concept at the same rate of oil production results in higher oil recovery compared to case without. It can be seen also that, the location of water sink closer to oil-water contact results in the highest cumulative oil production rate. Considering gas and water production in Figures 5.16 and 5.17, all locations do not yield a significant different in production. Water sink location of grid Z=13 causes the highest gas production. This could be interpreted that since water is prevented to cone into the well, oil can be produced effectively, reservoir pressure therefore decreases faster than other two cases. And this results in liberation of higher amount of gas. To confirm this, total water production is found to be the lowest for case grid Z=13 as shown in Figure 5.17.

A plot between oil recovery factor and distance of water sink zone away from oil-water contact is shown in Figure 5.18 and this figure is used to identify optimize location of water sink zone.

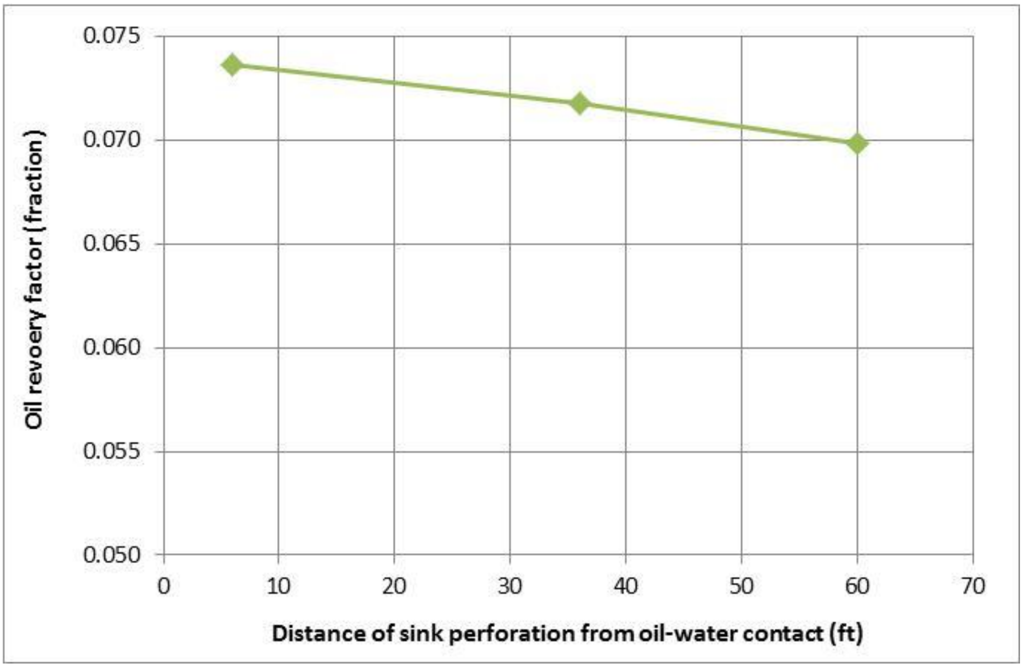

Figure 5.18A plot of cumulative oil productions versus distance of water sink zone from oil-water contact

Atwater production rate from water sink zone of 500 STB/D, perforation location in sink zone which is close to oil-water contact yields the higher oil recovery. This location is therefore chosen as optimized location of water sink zone.

Next, optimization is also performed on water production rate. Water production rate is varied from 500 to other values which are 1,000, 1,500, 2,000, 2,500, 3,000, 3,500 and 4,000 STB/D. For all cases, location of water zone is fixed at grid Z=13 as discussed previously. The results of water production rate is summarized in Table 5.14, including cumulative oil, gas and water productions, oil recovery factor and total production period.

Table 5.4Summary of reservoir simulation outcomes from DWL implementation at different water production rate

Water Production Rate in sink (STB/D)	**Cumulative production**			**Oil recovery factor (Fraction)**	**Total prod. period (Years)**
	Oil (STB)	**Gas (MSCF)**	**Water (STB)**		
500	89,757	303,450	250,902	0.0736	1.87
1,000	94,680	317,625	244,143	0.0776	1.86
1,500	98,753	324,454	235,654	0.0810	1.84
2,000	101,664	321,199	226,678	0.0834	1.80
2,500	103,723	319,079	221,114	0.0851	1.78
3,000	105,198	316,547	216,659	0.0863	1.76
3,500	106,458	317,099	216,343	0.0873	1.77
4,000	106,029	316,653	215,109	0.0870	1.76

From Table 5.4, it can be seen that oil recovery factor increases with water production period. In the same time, total production period decreases with this trend. Nevertheless, it can be noticed that, the optimum point exists, considering oil recovery factor. In order to assist this discussion, cumulative water production and oil production rate are plotted with time and shown in Figures 5.19 and 5.20, respectively.

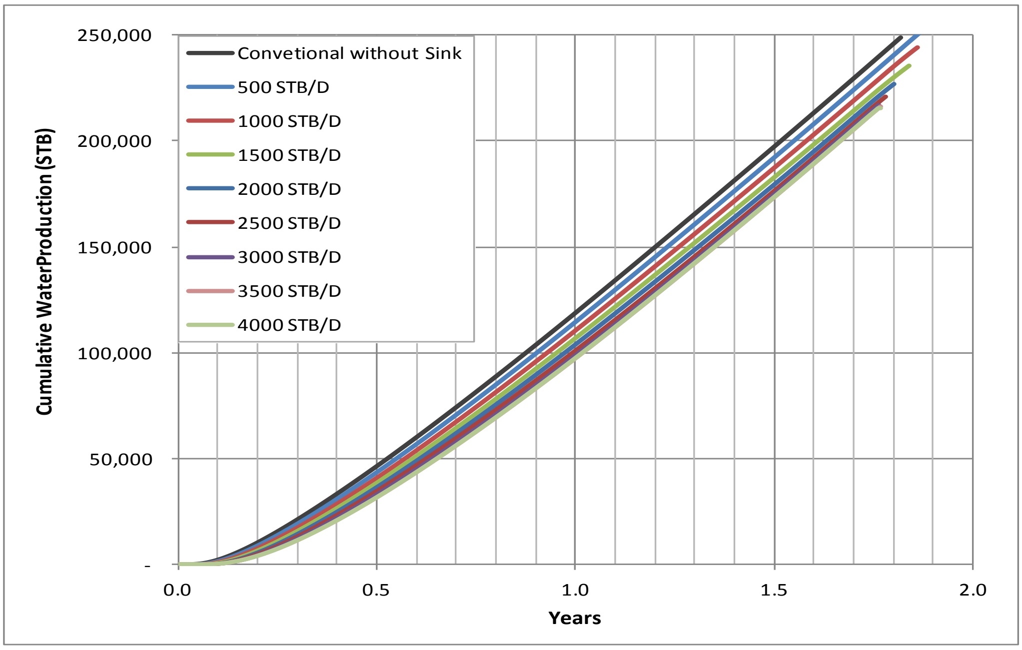

Figure 5.19Cumulative water production of wells with DWL with at different water production rates from sink zone as a function of time

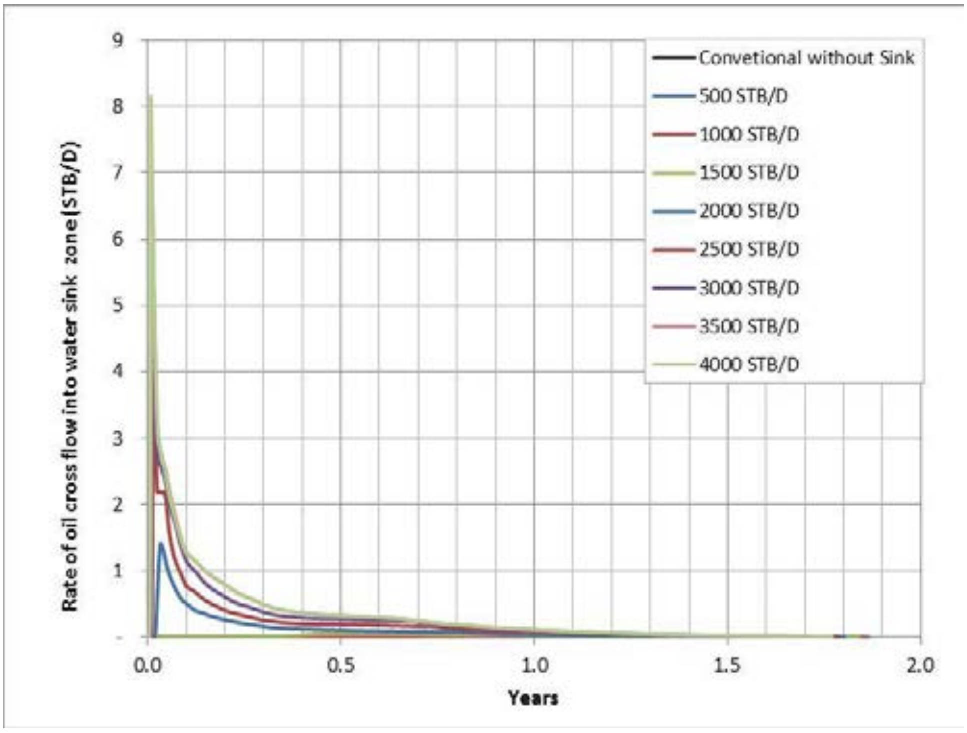

Figure 5.20Rate of oil cross flow into water sink zone of wells with DWL with at different water production rates from sink zone as a function of time

Figure 5.19 clearly shows that higher water production rate in sink zone results in better oil recovery. This prevention of water coning results in higher oil production rate which can be seen in Figure 5.20 that high oil production rate can be obtained from when water production rate in water sink zone is raised. Nevertheless, at the rate of 3,500 STB/D percentage of oil recovery starts to decline. This could be explained that higher water production rate in water sink zone does not reduce only water coning phenomenon but this also create oil cone into this water sink zone which later is re-injected into discharge zone and does not contribute oil recovery for oil production zone. A plot between oil recovery factor and water production rate from water sink zone is illustrated in Figure 5.21. Balancing between water cone into oil zone and oil cone into sink zone, results in the optimum rate.

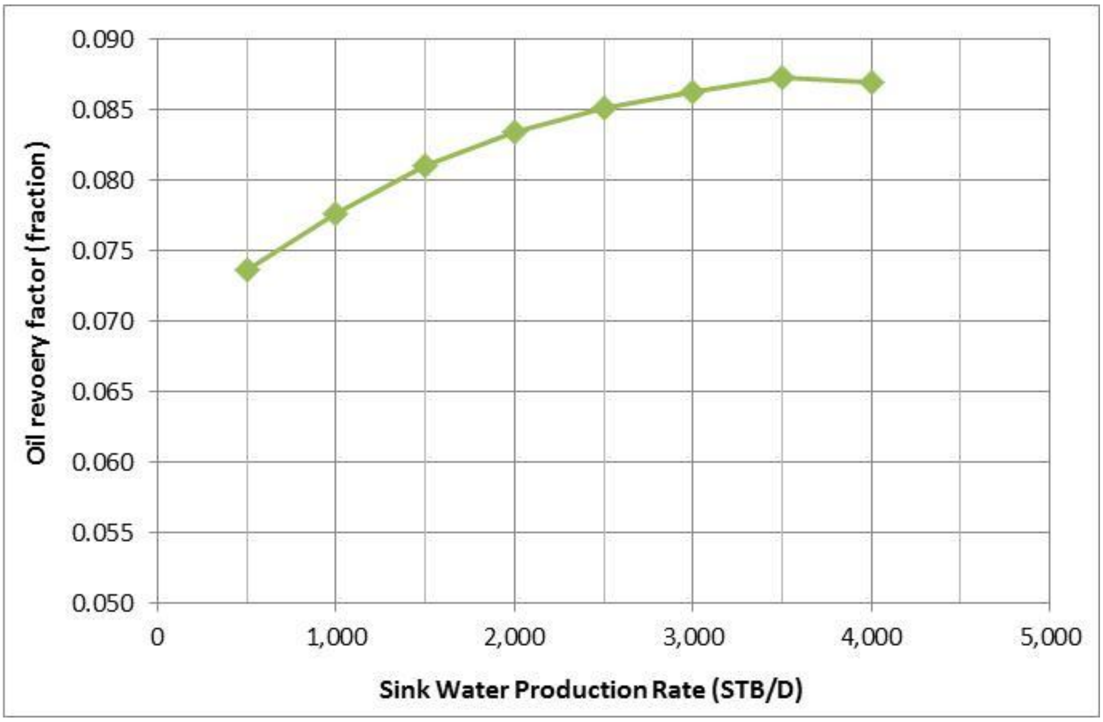

Figure 5.21A plot of oil recovery factors versus water production rate in water sink zone distance of water sink zone

From Figure 5.21, optimum water production rate in sink zone is observed at 3,500 STB/D and this rate is applied for the following steps. Previously, perforation of water sink zone is fixed at 3 ft. The next step is to identify optimized perforation interval of water sink zone. In this section, perforation interval is varied from 3ft to values of 9, 15 and 21 ft. All cases are performed with fixed location of grid Z = 13 and water production rate of 3,500 STB/D. Table 5.5 summarizes cumulative oil, gas and water production, oil recovery factor and total production period.

Table 5.5Summary of reservoir simulation outcomes from DWL implementation with different water sink perforation intervals

Water sink grid	**Water discharge grid**	**Cumulative production**			**Oil recovery factor (Fraction)**	**Total prod. period (Years)**
		Oil (STB)	**Gas (MSCF)**	**Water (STB)**		
13-13	29-29	106,458	317,099	216,343	0.0873	1.77
13-15	29-29	111,525	373,974	221,462	0.0915	1.88
13-17	29-29	108,996	363,817	224,643	0.0894	1.87
13-19	29-29	107,153	356,865	227,052	0.0879	1.86
13-21	29-29	105,322	350,215	229,398	0.0864	1.86

From Table 5.5, it can be observed that increasing in perforation interval results in higher cumulative oil production in relatively short interval. Perforation interval of 9 ft shows the highest oil recovery of about 9.15 percent. This value also comes together with longer production period. It can be explained that as perforated interval increases, well bottomhole pressure is kept at higher value in order to maintain water production rate. Therefore, oil cone problem that previously happened in cases of 3-ft perforation interval is mitigated. Nevertheless, as perforation interval is increased beyond 9 ft, cumulative oil production as well as total production period starts to decline. This can be explained that, since discharge zone is fixed at grid Z=29, longer perforation interval implies to more overlapping between water sink zone and water discharge zone. Water sink is mainly performed to reduce coning problem of water into oil production zone. When water sink and water discharge zones are located close to each other, this situation will create a loop of water, reducing ability of maintaining oil-water contact. Therefore, it can be seen that the closer distance between water sink zone and water discharge zone, the less ability to maintain oil-water contact and hence the less cumulative oil production. From data in Table 5.4, a plot between oil recovery factor and perforation interval in water sink zone is depicted in Figure 5.22. From the figure, it is clearly shown that the optimum perforation interval is 9 ft, that is perforating from grid Z = 13 to 15.

Figure 5.22A plot of oil recovery factors versus perforation intervals of water sink zone

Base on results obtained from previous section, it can be seen that distant between water sink zone and discharge zone plays important role in maximizing oil recovery. In order to ensure the optimum perforation interval in water sink zone obtained from previous case, distance between water sink zone and water discharge zone is then kept constant. An interval of 12 ft (4 grid blocks in Z direction) is added into the bottom level of water sink zone and this determines location of water discharge zone. Table 5.6 summarizes cases and results obtained from simulation, including cumulative oil, gas and water production, oil recovery factor, and total production period. Location of discharge zone is also shown in this table.

Table 5.6Summary of reservoir simulation outcomes from DWL implementation with different water sink perforation interval (with constant distance between sink and water discharge zone of 12ft)

Water sink grid	**Water discharge grid**	**Cumulative production**			**Oil recovery factor (Fraction)**	**Total prod. period (Years)**
		Oil (STB)	**Gas (MSCF)**	**Water (STB)**		
13-13	18-18	94,392	300,426	231,163	0.0774	1.78
13-15	20-20	100,770	335,656	235,528	0.0826	1.86
13-17	22-22	102,125	339,525	233,653	0.0838	1.86
13-19	24-24	103,043	342,208	232,357	0.0845	1.86

From Table 5.6, it can be seen that when distance of discharge zone is kept constant, the longer perforation interval results in better oil recovery as well as total production period. In order to explain these results, Figures 5.22 to 5.26 are plotted to represent cumulative oil production, cumulative gas production, cumulative water production, well bottomehole pressure and water production rate, respectively.

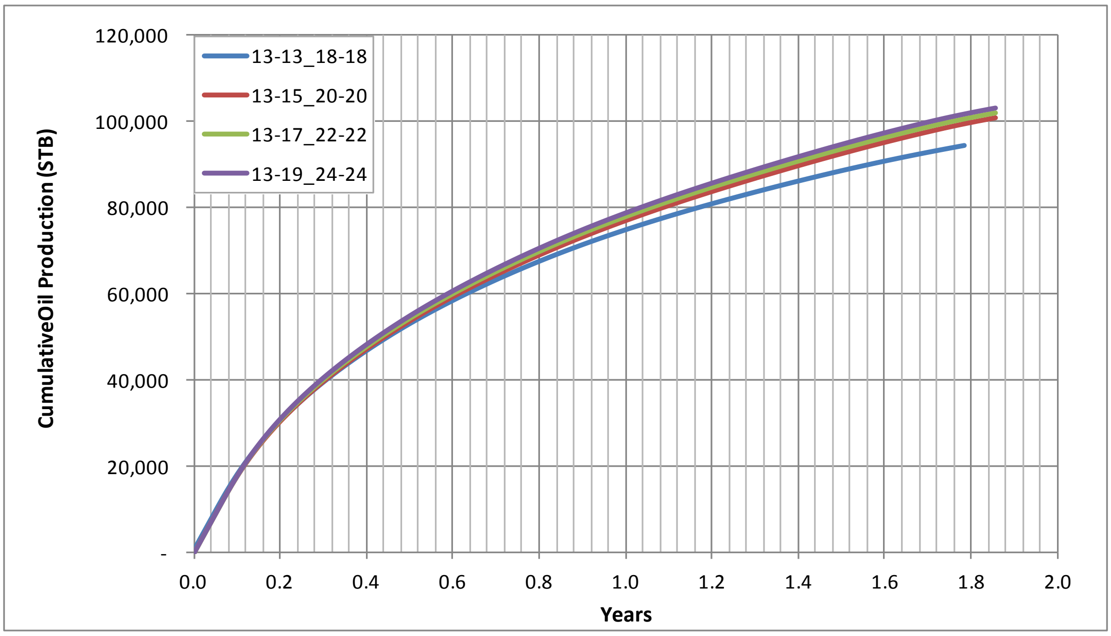

Figure 5.23 Cumulative oil production of wells with DWL perforated at various water sink locations with fixed interval from discharge zone as a function of time

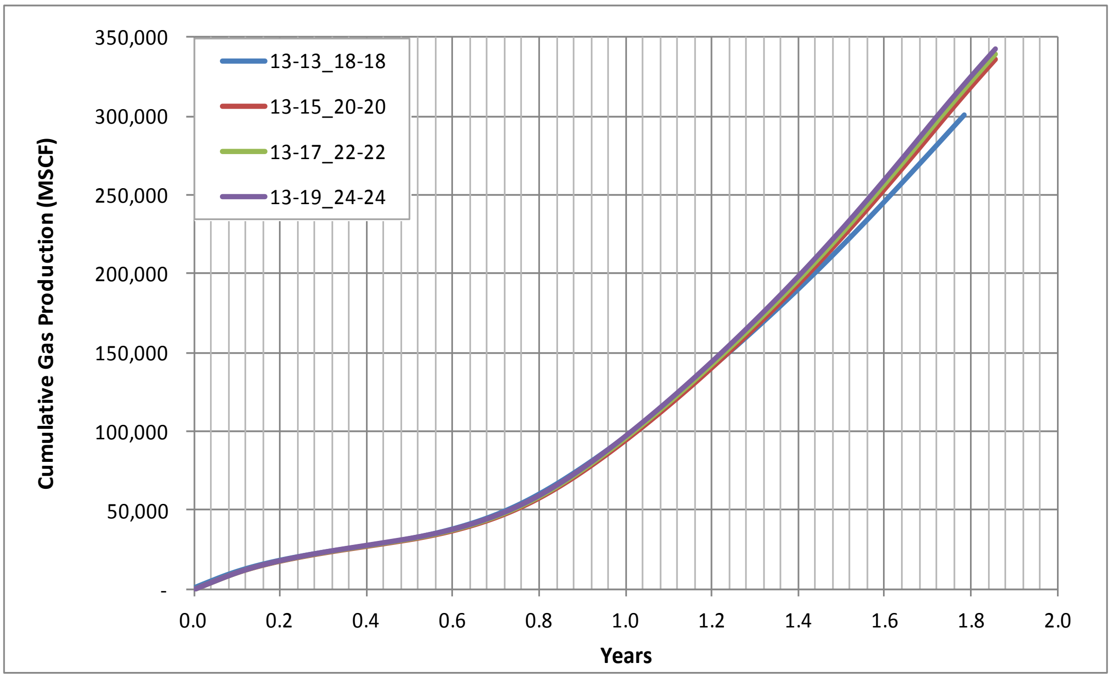

Figure 5.24Cumulative gas production of wells with DWL perforated at various water sink locations with fixed interval from discharge zone as a function of time

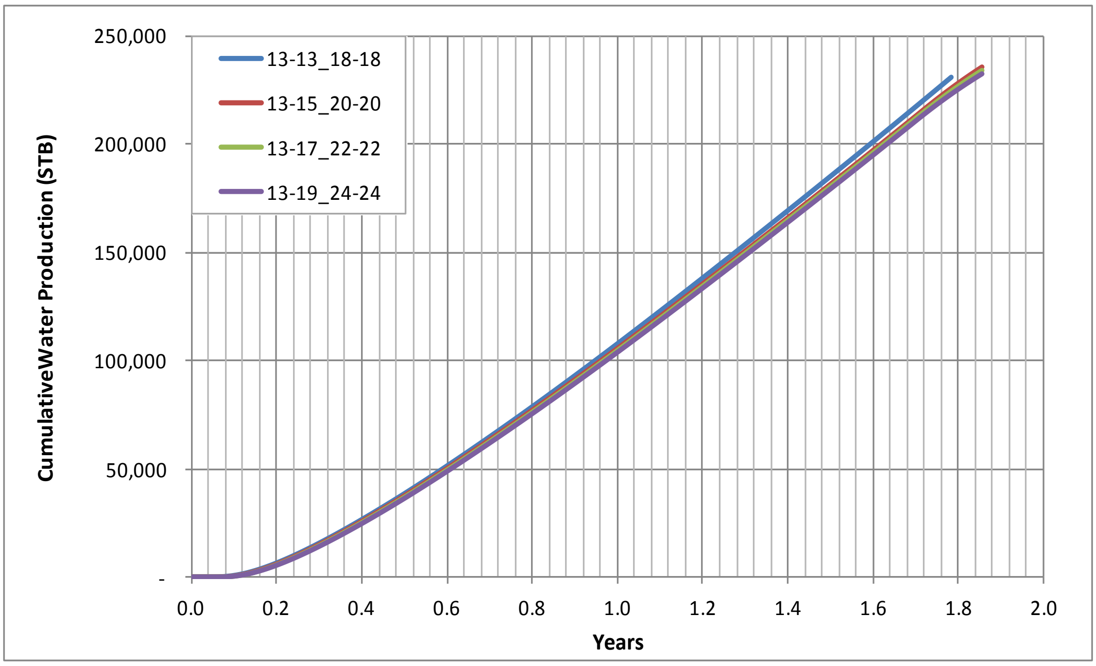

Figure 5.25Cumulative water production of wells with DWL perforated at various water sink locations with fixed interval from discharge zone as a function of time

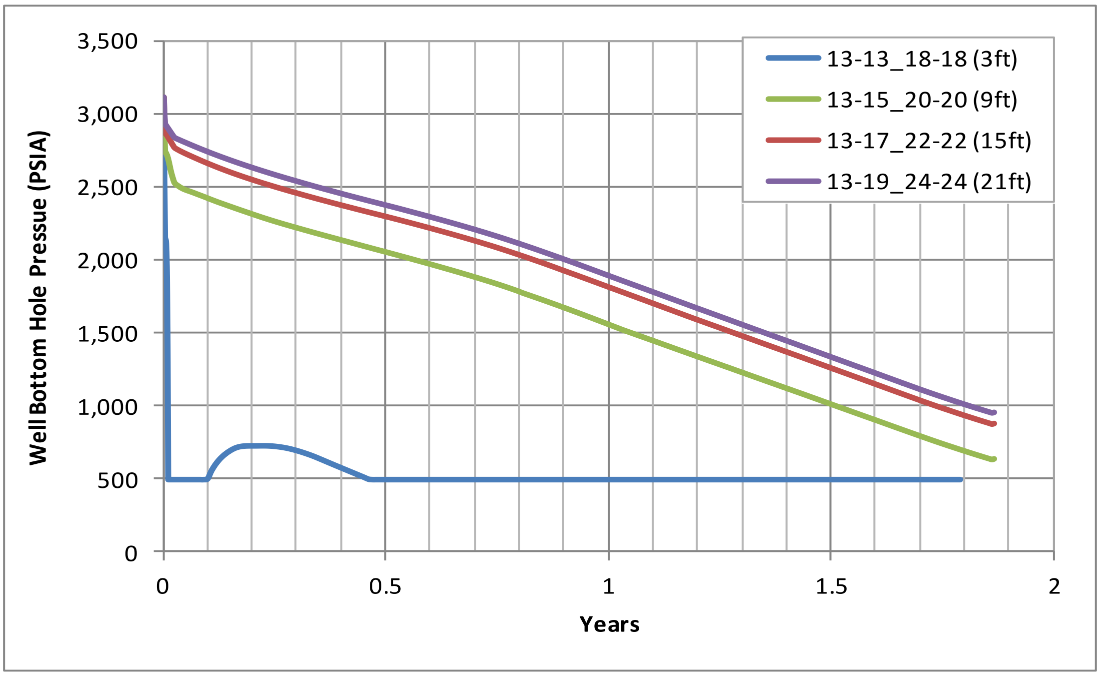

Figure 5.26Bottomhole pressure of wells with DWL perforated at various water sink locations with fixed interval from discharge zone as a function of time

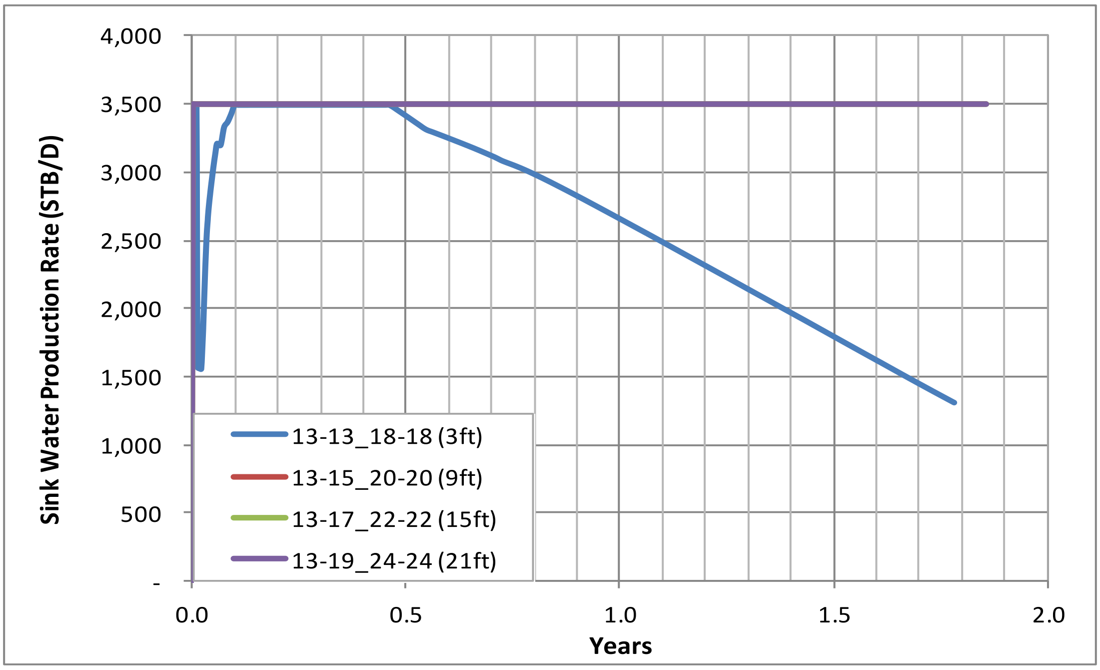

Figure 5.27Water production rates of wells with DWL perforated at various water sink locations with fixed interval from discharge zone as a function of time

From Figure 5.23, cumulative oil production is the highest when perforated interval is extended. The case where total perforated interval equals to 21 ft results in the highest gas production but the smallest water production as shown in Figures 5.24 and 5.25, respectively. With the same reason as explained in the study of oil zone perforation interval, the shorter perforation interval creates more BHP drawdown around sink. Producing water at 3,500 STB/D from water sink well from just 3ftinterval is difficult, resulting in a declination of BHP immediately as can be seen in Figure 5.26. Its ability to produce water is lower corresponding to its pressure. It can be seen that at early production time of 3ftwater sink perforation interval, the top oil zone is supported by water sink rate just around 1,500 STB/D as shown in Figure 5.27. With the lower water production rate at 1,500 STB/D, its BHP starts to increase with the fill in of reservoir pressure again. Then water production rate increase and then decline againas in Figure 5.27.A plot of oil recovery factors and perforation interval in water sink zone is illustrated in Figure 5.28.

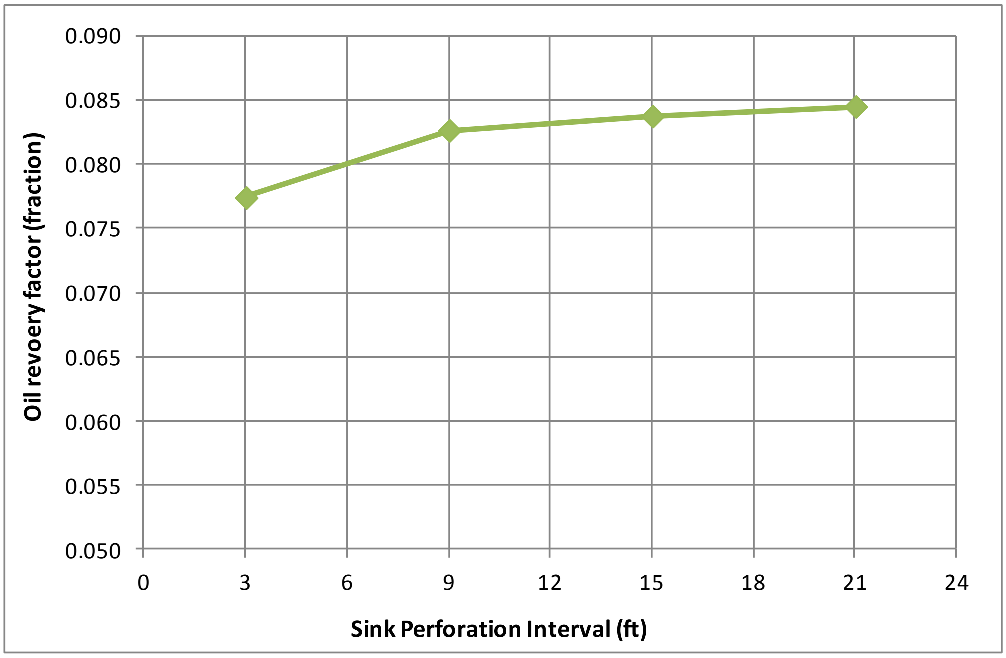

Figure 5.28A plot of oil recovery factors versus perforation intervals of water sink zone when distance between water sink and discharges zone is constant

From Figure 5.28it shows and confirms that the longer perforation interval gives the better oil recovery. Because the longer interval allows fluid to flow easier even the production is control to have the same initial production rate.

Nevertheless, perforated interval cannot be increased definitely since the increment in interval can result in adverse effect due to overlapping of water from the discharge zone. From all the study performed in water sink zone section, the optimum case is to produce water at grid Z = 13-15 which is equivalent to 9 ft andre-injector in discharge zone should be kept as far as possible which is at grid Z = 29 at water production rate 3,500 STB/D. This water production interval is proved to have best in terms of controlling water production rate and in the same time is affected the least from water discharge zone. As discharge location affects to total length of wellbore, optimization of discharge zone is next section.

5.1.3 Optimization of Discharge Zone

The study on optimization of water discharge zone is discussed in the section. Depth of re-injection is varied to the location of grid Z = 21, 25 and 29. The results are summarized in Table 5.7 including cumulative oil, gas and water production, oil recovery factor, and total production period.

Table 5.7Summary of reservoir simulation outcomes from DWL implementation with different water discharge locations

Water sink grid	**Water discharge grid**	**Cumulative production**			**Oil recovery factor (Fraction)**	**Total prod. period (Years)**
		Oil (STB)	**Gas (MSCF)**	**Water (STB)**		
13-15	21-21	102,743	342,186	232,960	0.0843	1.86
13-15	25-25	108,744	363,845	225,282	0.0892	1.87
13-15	29-29	111,525	373,974	221,462	0.0915	1.88

From Table 5.7, it can be observed that oil recovery factor increases as water discharge zone is placed far away. This supports explanation in previous sections about interfering of water produced and water discharged. Oil recovery factors obtained from each case is then plotted with distance of discharge zone and is illustrated in Figure 5.29.

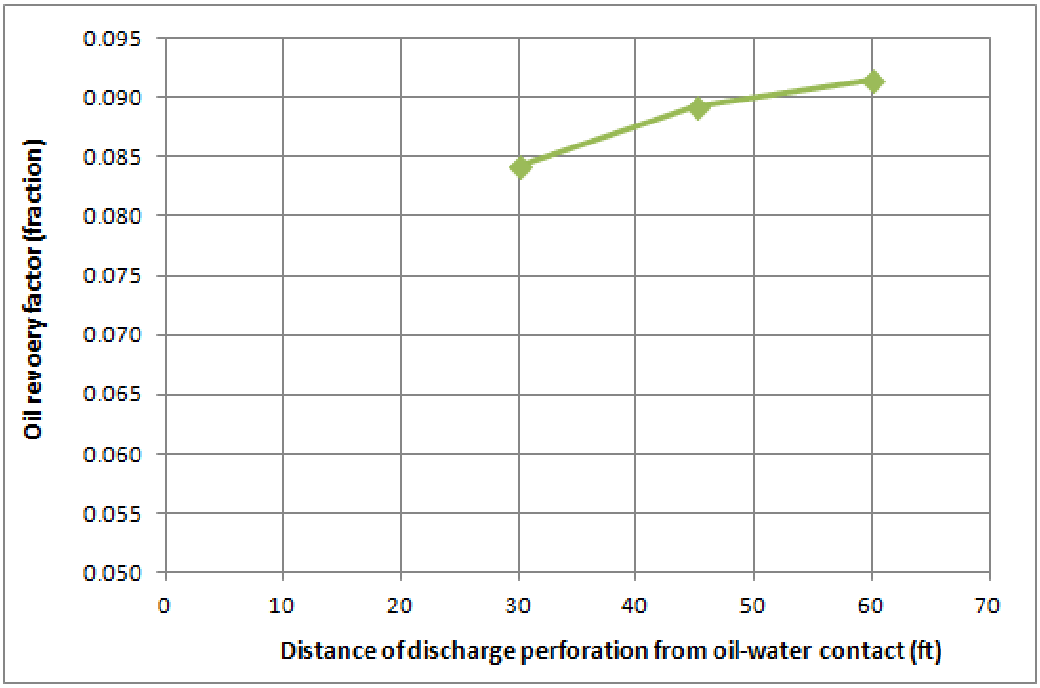

Figure 5.29A plot of oil recovery factors versus distance of discharge zone from oil-water contact

It can be clearly seen that as far as the discharge zone from water sink perforation, the better oil recovery in oil zone is obtained.

Interval of discharge zone is also studied. Distance from bottom perforation of water sink zone to the injector is kept constant at 21 ft (7 grid blocks in Z direction). Water discharge is then started from grid Z = 21 and interest discharge intervals are 3, 15 and 27 ft. The results are summarized in Table 5.8including cumulative of oil, gas and water production, oil recovery factor and total production period. After that oil recovery factors are plotted with water discharge interval in Figure 5.30 in order to identify the optimum value.

Table 5.8Summary of reservoir simulation outcomes from DWL implementation with different water discharge intervals

Water sink Grid	Water discharge grid	Cumulative production			Oil recovery factor (Fraction)	Total prod. period (Years)
		Oil (STB)	Gas (MSCF)	Water (STB)		
13-15	21-21	102,743	342,186	232,960	0.0843	1.86
13-15	21-25	105,879	352,881	228,709	0.0868	1.86
13-15	21-29	107,922	360,376	226,119	0.0885	1.87

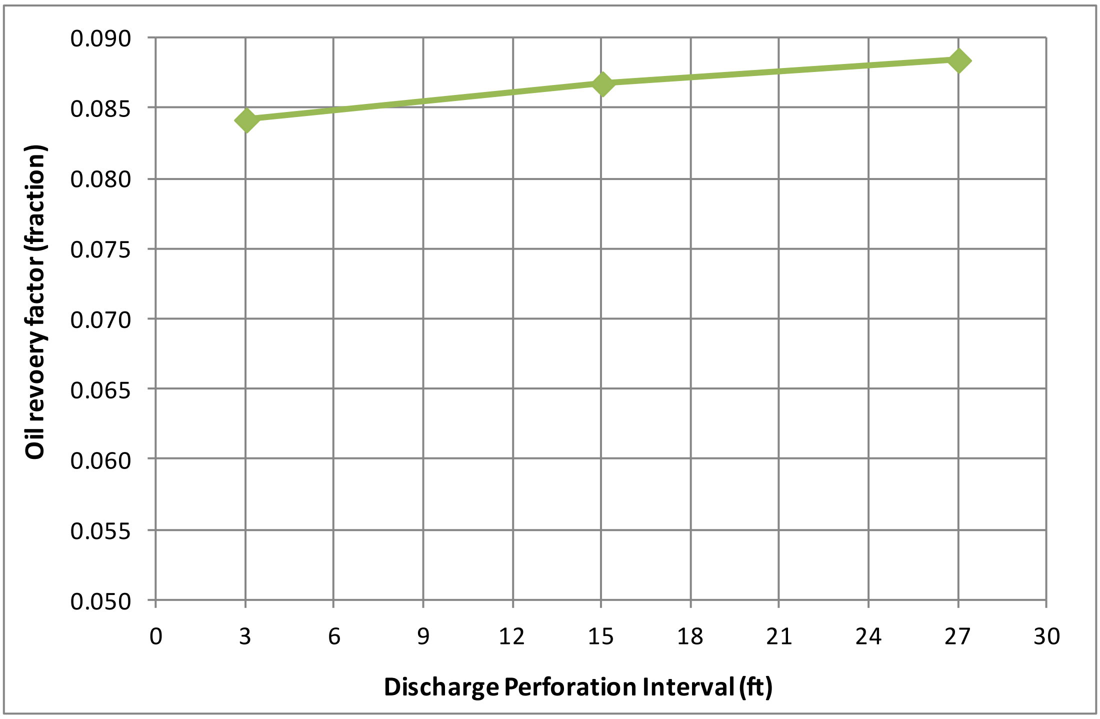

Figure 5.30A plot of oil recovery factors versus water discharge interval

From summary in Table 5.8 and a plot shown in Figure 5.30 it can be seen that the longer interval of perforation zone results in better ability for fluid to flow into the well. However, the maximum oil recovery is just 8.85 percent which is still less than oil recovery obtained the case where water discharge location is placed at grid Z=29 and perforation is just 3 ft (oil recovery is 9.15 percent). Therefore, it can be concluded that distance of water discharge zone is much more important and contribute greater effect on total oil recovery compared to perforation interval of water discharge zone.

5.2Study of Reservoir Parameters

In this section base case from previous section is carried over to study several interest reservoir parameters which are ratio of vertical to horizontal permeability, thickness of water aquifer and thickness of oil zone.Previously, the case where the highest oil recovery is obtained is from oil production rate of 500 STB/D which is perforated at location grid Z= 1-3 (9 ft). Water sink zone is produced at grid Z = 13-15 (9ft) at the rate of 3,500 STB/D. And water discharge zone is located at Z = 29 (3ft).

5.2.1 Effect of Ratio of Vertical to Horizontal Permeability

As mentioned in methodology section, ratio of vertical to horizontal permeability is varied from initial value of 10% to be the lower of 5% and higher of 20%. The results are displayed in Table 5.9 including cumulative production of oil, gas and water, oil recovery factor and total production period.

Table 5.9Summary of reservoir simulation outcomes from DWL implementation in reservoir with different ratio of vertical to horizontal permeability

k_v/k_h	Cumulative production			Oil recovery factor (Fraction)	Total production period (Years)
	Oil (STB)	Gas (MSCF)	Water (STB)		
0.05	140,127	413,735	157,552	0.1149	1.76
0.10	111,525	373,974	221,462	0.0915	1.88
0.20	88,607	321,853	265,683	0.0727	1.94

From Table 5.9, ratio of vertical to horizontal permeability seems to have big effect on DWL system. It can be obviously seen that, oil recovery factor reaches the highest value of about 11.5 percent when ratio is 0.05. This can be explained that as vertical permeability is low, oil production zone is affected coning phenomenon at later period. However, total production period in this low ratio case is the shortest one. In order to better describe reservoir mechanism, oil production rate, water production rate, cumulative oil production and cumulative water production are plotted as a function of production time, illustrated in Figures 5.31 to 5.34, respectively.

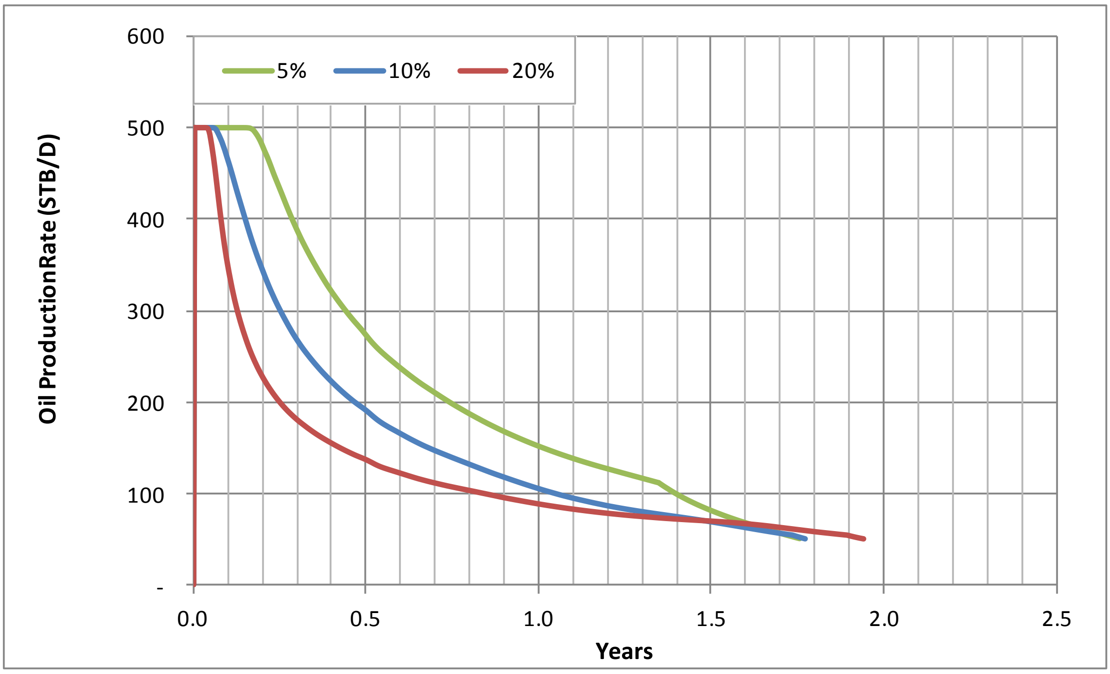

Figure 5.31 Oil production rate of wells with DWL as a function of time at different ratio of vertical to horizontal permeability

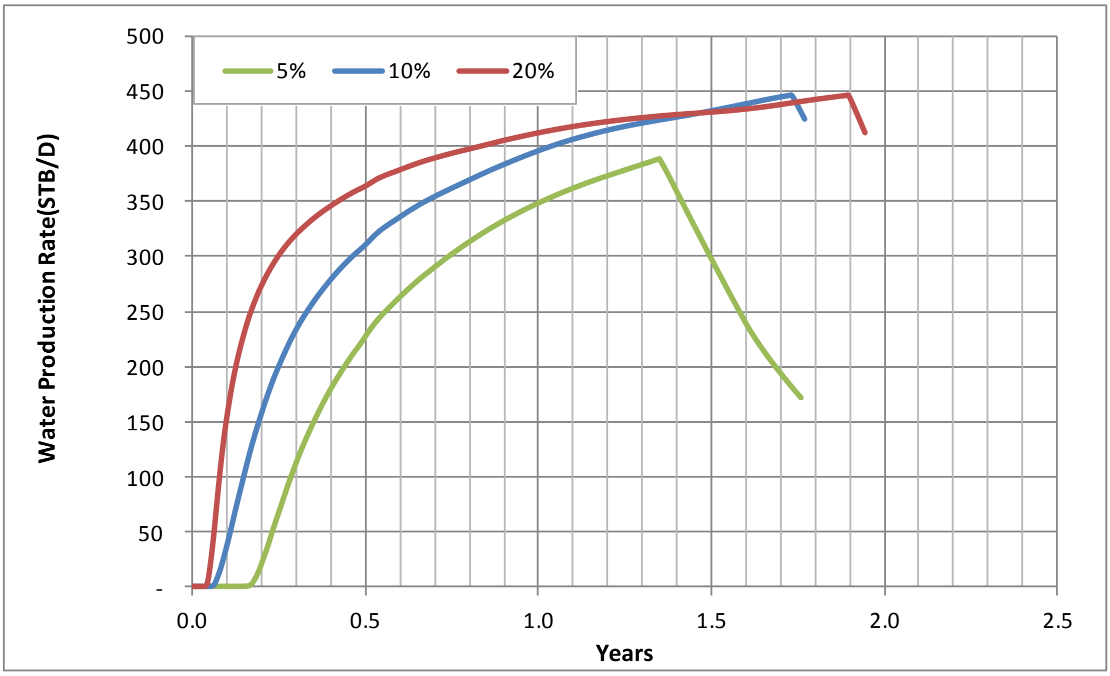

Figure 5.32Water production rate of wells with DWL as a function of time at different ratio of vertical to horizontal permeability

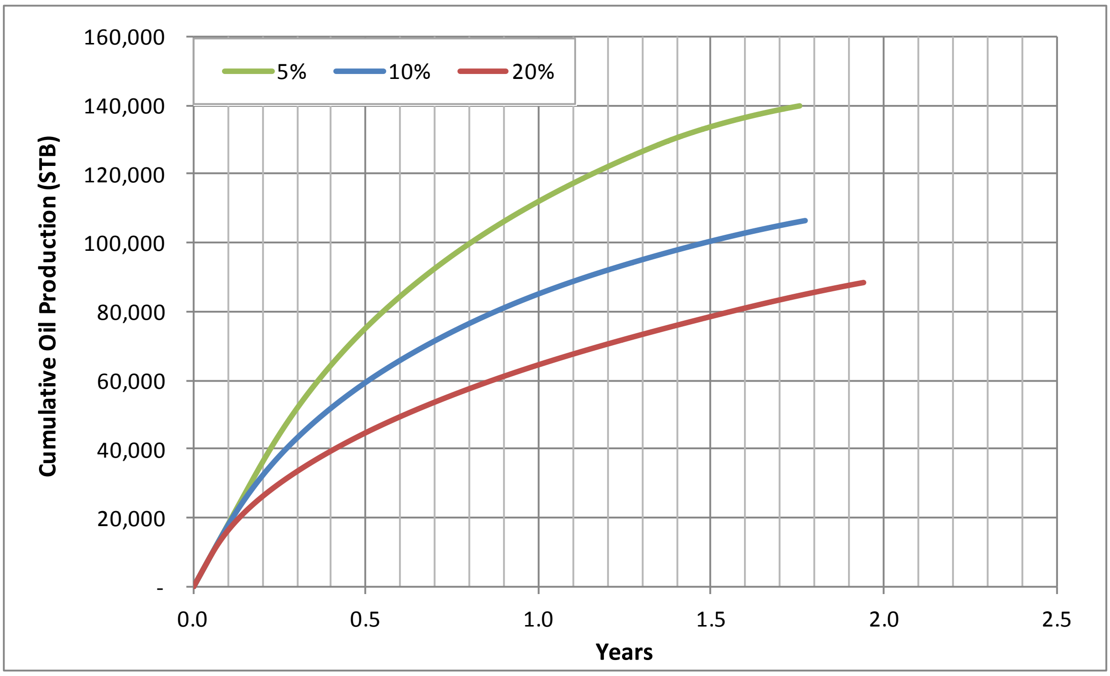

Figure 5.33Cumulative oil production of wells with DWL as a function of time at different ratio of vertical to horizontal permeability

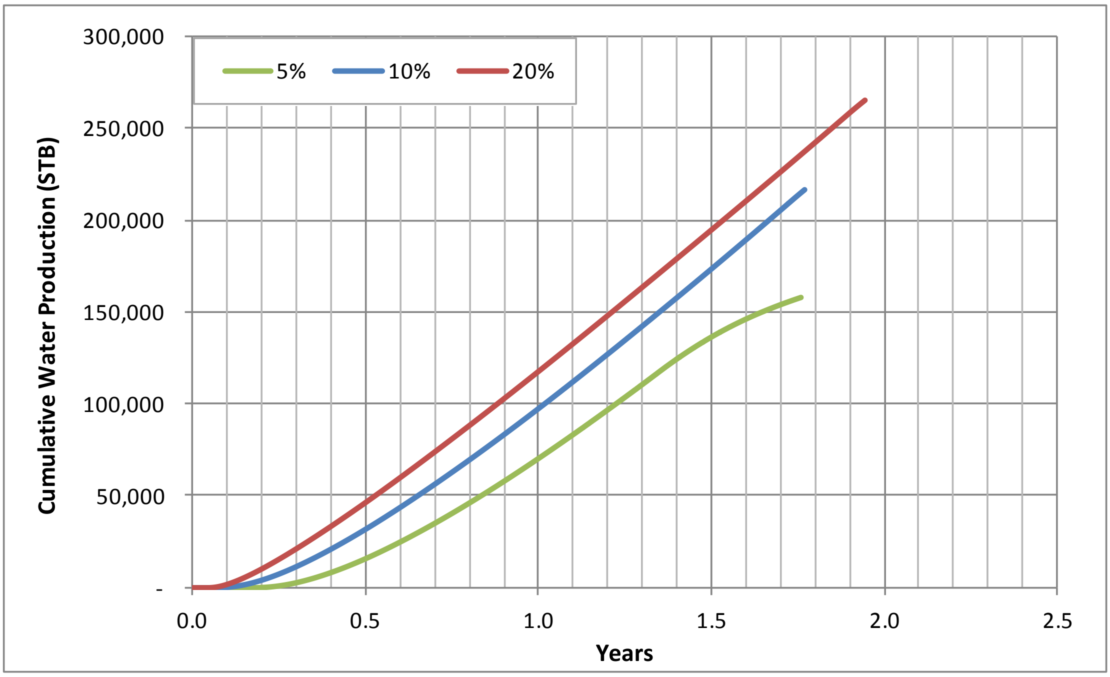

Figure 5.34Cumulative water production of wells with DWL as a function of time at different ratio of vertical to horizontal permeability

From Figure 5.31, it can be seen that oil production rate is maintained at a plateau rate of 500 STB/D for the longest period in case of smallest ratio. Moreover, declination of oil production is also less compared to cases of ratio 0.1 and 0.2. Therefore, less vertical permeability retards an arrival of water coning, helping to maintain desired oil production rate. Considering water production rate, it can be obviously seen that water production rate keeps increasing for all cases as water starts to cone into productive oil zone. At certain time, water production rate suddenly drops. This could be explained that, as reservoir pressure decreases with production period, gas is liberated out from oil phase, forming gas chamber on top of reservoir. As gas-oil contact and oil-water contact encounter each other, three-phase flow occurs in inferior zone, reducing suddenly flow ability of water. This flow reduction can be slightly seen for oil production rate as well but since oil saturation is much less compared to water, flow ability is therefore minimally affected. Reduction of water production rates occurs first for the case where ratio of 0.05 is applied due to quick reduction of reservoir pressure as well as faster downward movement of gas-oil contact.

Cumulative oil productions of varied cases are shown in Figure 5.33 and consecutively cumulative water productions are plotted in Figure 5.34. This confirms sensitivity of ratio of vertical to horizontal permeability on DWL system. It can be seen that lower k_v/k_h ratio tends to yield better result compared to higherk_v/k_h. Nevertheless, implementation of DWL might show a benefit in case of higher ratio since in case of low vertical permeability, conventional well might work well without an assist of DWL system.

5.2.2 Effect of Aquifer Thickness

Thickness of aquifer is another concern reservoir parameter to study. Aquifer provides drive energy for oil production. When oil production continues, oil is pulled out from the reservoir. Water then expands helping reservoir to displace oil. At certain oil production rate, if aquifer size is big enough, reservoir pressure will be maintained because produced oil is effectively replaced by expanded water. In the other hand, if aquifer is small, reservoir pressure will quickly fall. Displacement of water from aquifer into oil bearing zone also affects to coning rate. If aquifer is strong with the high rate of water encroaching into oil zone, water coning rate will appear to be high and affect to lessen oil production rate.

Previously, aquifer size in base case was fixed at 60 ft. Aquifer size is increased to 150 and 300 ft in order to increase strength of water influx ability.Table 5.10 shows results including cumulative production of oil, gas, and water, oil recovery factor, and total production period.

Table 5.10Summary of reservoir simulation outcomes from DWL implementation in reservoir supported by different aquifer thickness

Aquifer thickness (ft)	**Cumulative production**			**Oil recovery factor (Fraction)**	**Total production period (Years)**
	Oil (STB)	**Gas (MSCF)**	**Water (STB)**		
60	111,525	373,974	221,462	0.0915	1.88
150	126,450	400,181	240,338	0.1037	2.08
300	137,482	406,229	298,719	0.1128	2.44

As described at the start of this section, bigger size of aquifer results in higher energy. From Figure 5.10, it can be seen that aquifer thickness of 300 can maintain production period up to 2.44 year and reaches oil recovery factor of 11.28 percent. More explanations are illustrated by Figures 5.35 to 5.38 showing oil production rate, water production rate, average reservoir pressure, and gas production rate respectively.

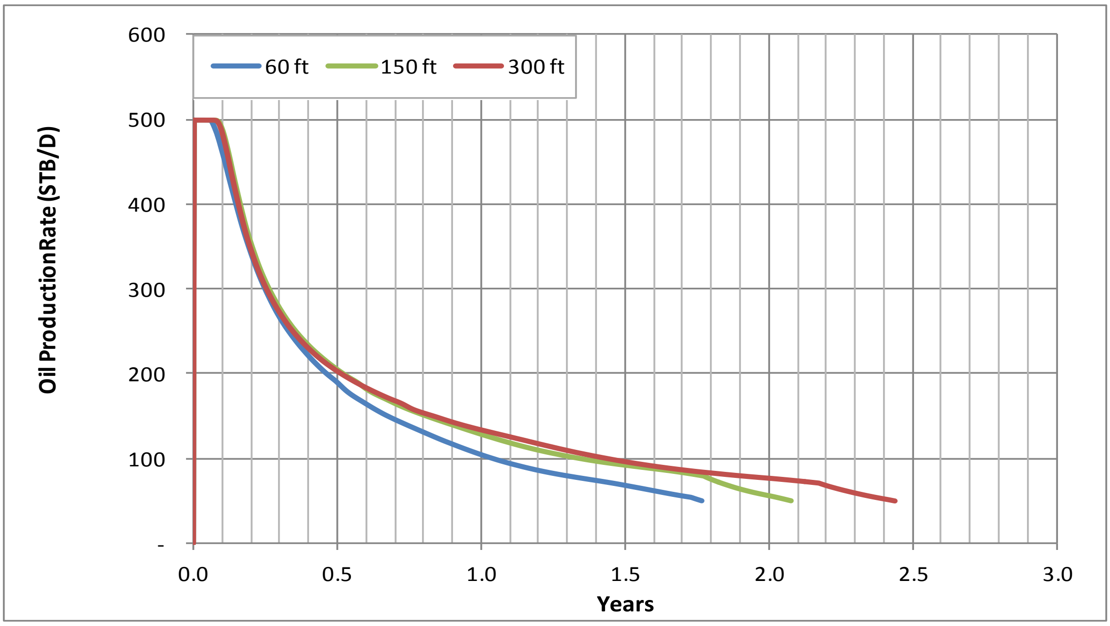

Figure 5.35Oil production rate of wells with DWL as a function of time at different aquifer size

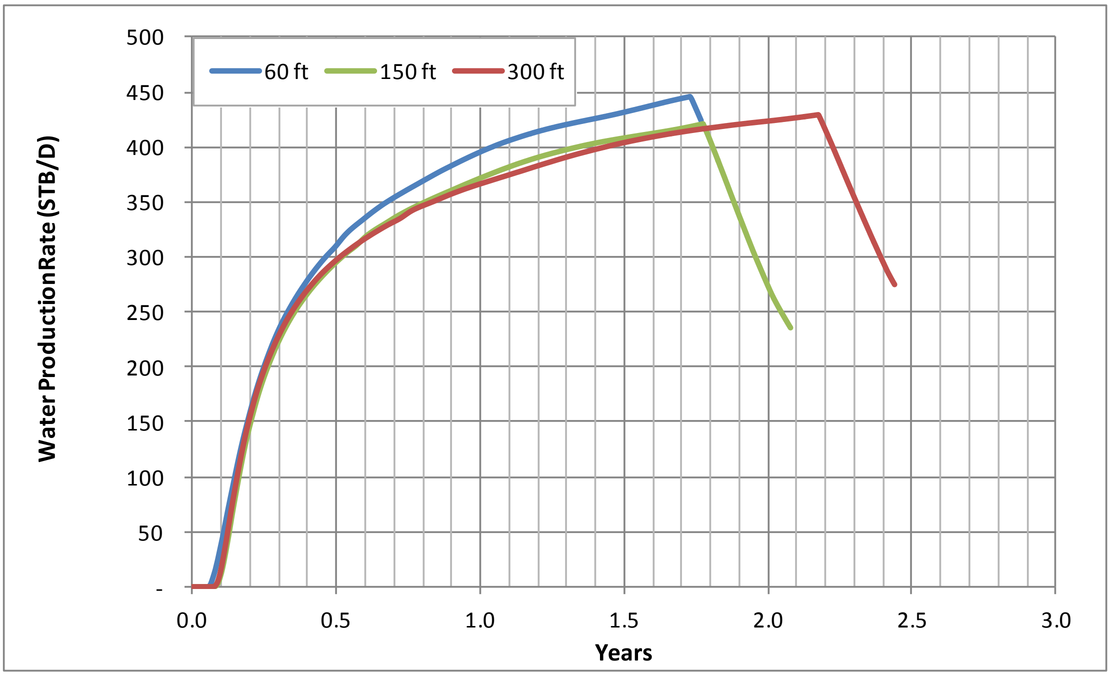

Figure 5.36Water production rate of wells with DWL as a function of time at different aquifer size

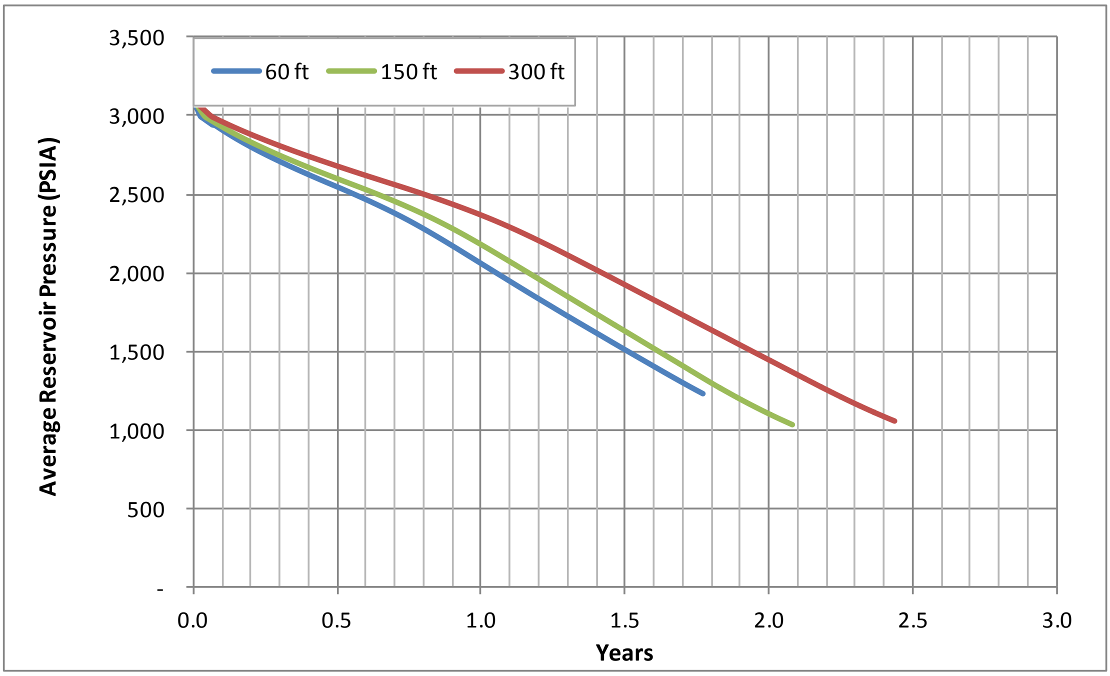

Figure 5.37Average reservoir pressureof wells with DWL as a function of time at different aquifer size

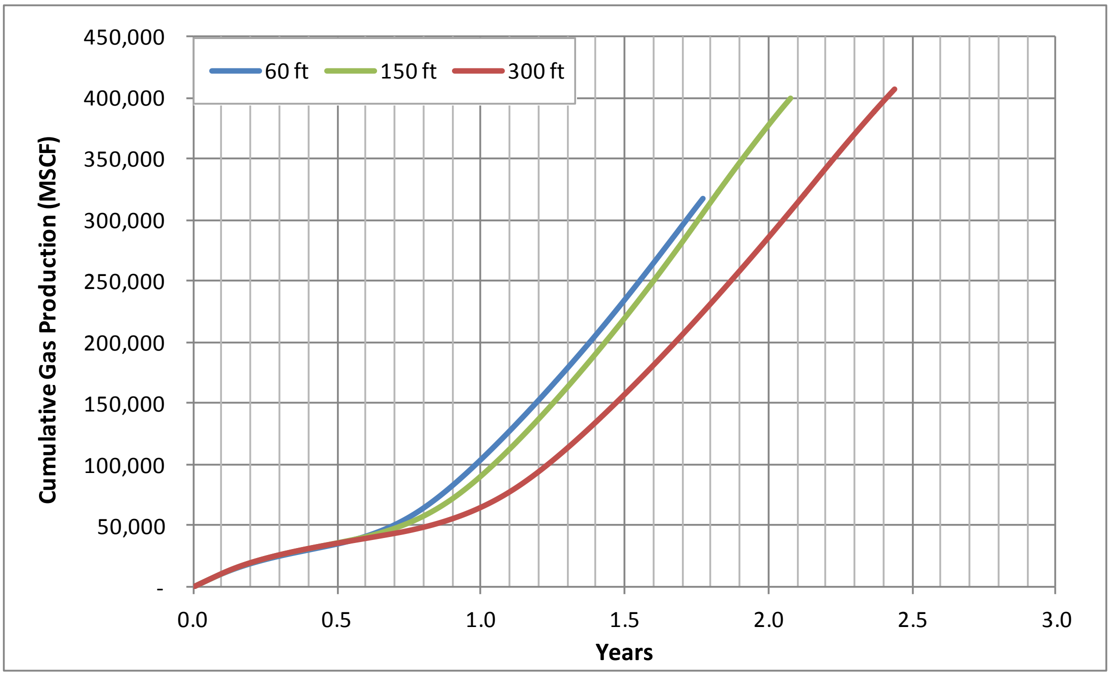

Figure 5.38Gas production rateof wells with DWL as a function of time at different aquifer size

From Figure 5.35, oil production rate from the case of 60-ft aquifer thickness starts to decline first. As explained before, this smallest size of water aquifer possesses the least energy support.Reservoir pressure also drops first as shown in Figure 5.37. As reservoir pressure quickly drops solution gas is appeared and produced into the well as in Figure 5.38. Gas is produced in oil zone of 60ft aquifer at the higher rate. As explained in previous section (effect of ratio of vertical to horizontal permeability) when more gas is liberated in the reservoir, gas-oil contact is getting lower due higher amount. This eventually encounters with oil-water contact from the inferior section, resulting in competitive flow and consecutively reducing of water flow ability. As gas is produced more, the well that is controlled by liquid production rate therefore has to accelerate its production. Higher water production rate is then observed for the case of 60-ft aquifer thickness as can be seen from Figure 5.36. For the case of 300-ft aquifer thickness, pressure support from aquifer takes effect for longer period. Hence, liberation of gas occurs after other cases, resulting long period to produce oil effectively. Nevertheless, reduction of water production rate also occurs at late stage as gas-oil contacts moves downward and encounters oil-water contact. Considering function of DWL in application of big aquifer size, it can be seen from Figure 5.36 that water production rate is slightly lower than the case of small aquifer size. As explained previously this is combination effect between pressure support from big aquifer together with ability to reduce water coning effect.

It can be concluded that, DWL may work well in an assist of high pressure support which helps to prevent high reduction of reservoir pressure. Moreover, without DWL system, oil production from this well performed in big aquifer should yield much smaller oil recovery due to higher rate of water coning.

5.2.3 Effect of Thickness of Oil Bearing Zone

Another reservoir parameter to be studied is thickness of oil zone. In order to observe the effect of the distance of production zone from oil-water contact on water coning phenomena, reservoir model is varied in shape to have the thicker oil thickness from base case of 30ft to 60ft with constant oil in place as well as average initial reservoir pressure. Area of reservoir is therefore reduced in case of thick oil zone to balance its in place volume.

Results of DWL implementationin reservoirs with different thickness of oil zone are summarized in Table 5.11. The table includes cumulative production of oil, gas and water, oil recovery factor, and total production period.

Table 5.11Summary of reservoir simulation outcomes from DWL implementation in reservoir with different oil zone thickness

Thickness of oil zone (ft)	**Cumulative production**			**Oil recovery factor (Fraction)**	**Total production period (Years)**
	Oil (STB)	**Gas (MSCF)**	**Water (STB)**		
30	111,525	373,974	221,462	0.0915	1.88
60	194,973	558,959	17,556	0.1599	1.33

It can be clearly seen that 60ft oil zone thickness produces much less water compared to the case of 30ft oil thickness. Not only cumulative water production that is much less compared to the base case, cumulative oil production and total production period are also increased. Figures 5.39 to 5.43 illustrate oil production rate, water production rate, cumulative oil production, and cumulative water production as a function of time, respectively.

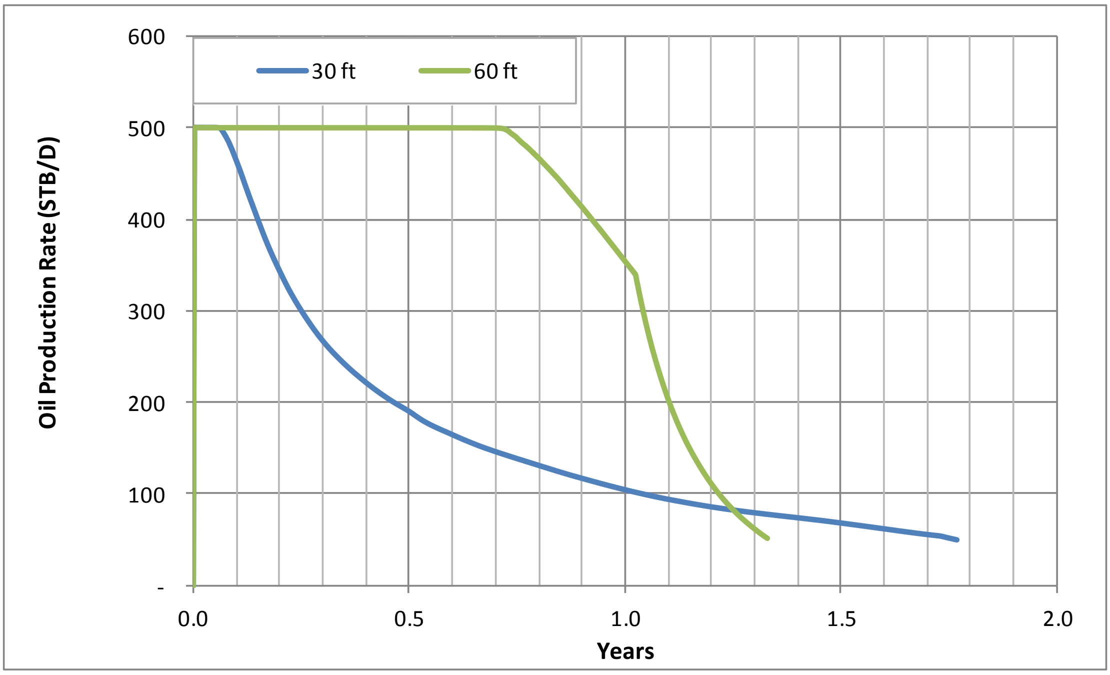

Figure 5.39Oil production rateof wells with DWL as a function of time with different oil zone thickness

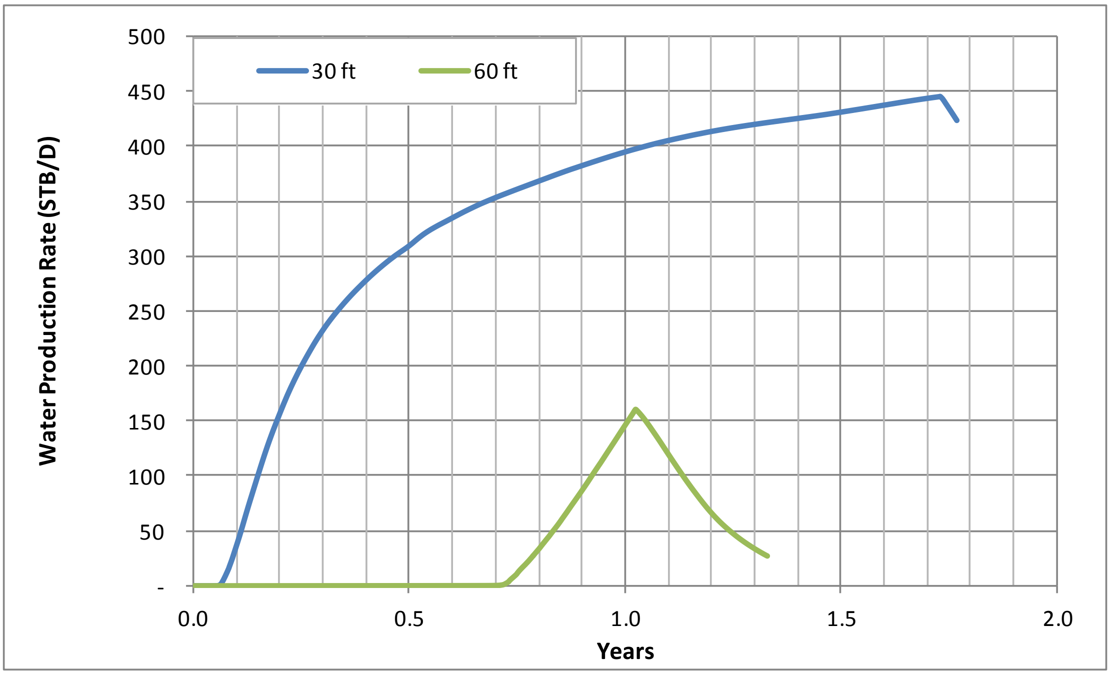

Figure 5.40Water production rateof wells with DWL as a function of time with different oil zone thickness

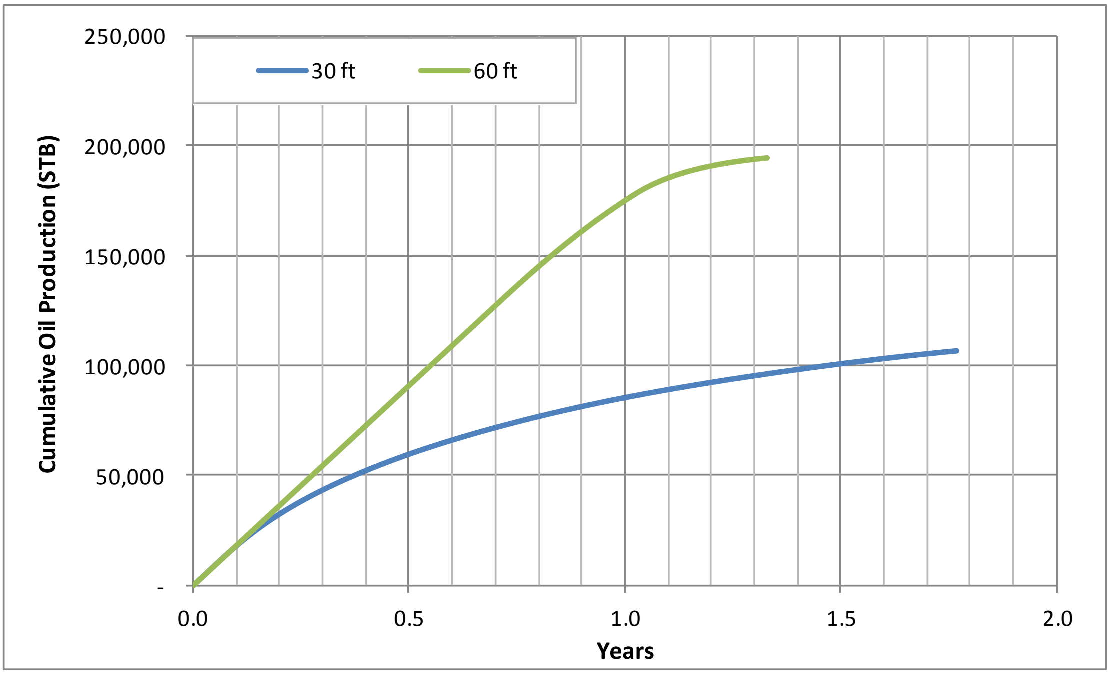

Figure 5.41Cumulative oil productionof wells with DWL as a function of time with different oil zone thickness

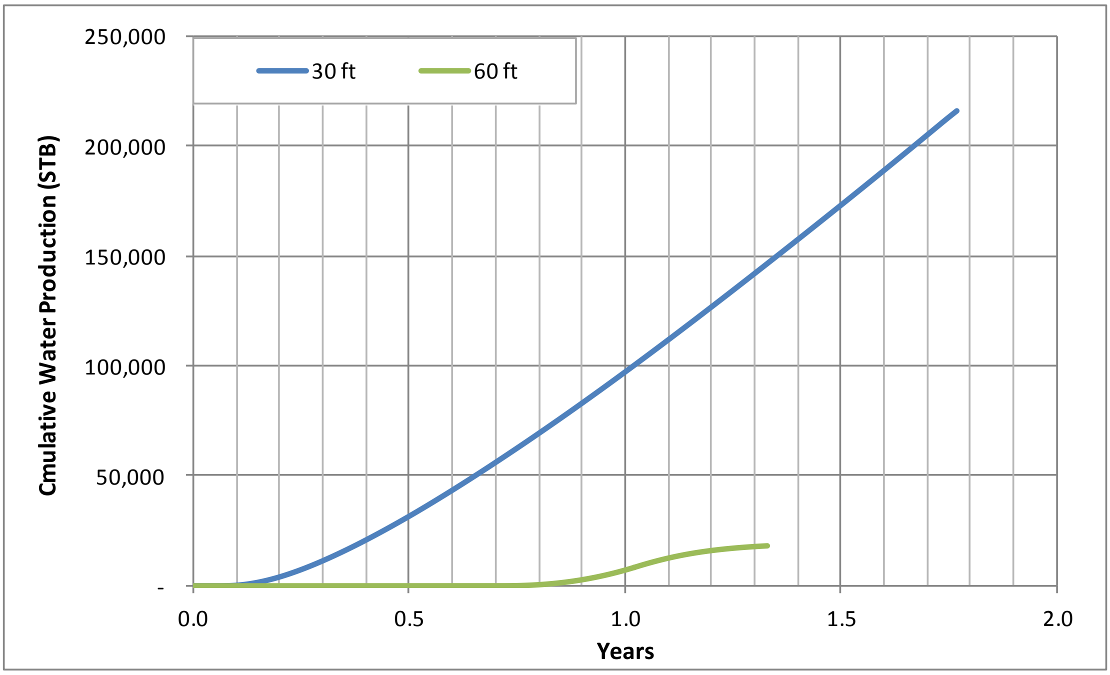

Figure 5.42Cumulative water production of wells with DWL as a function of time with different oil zone thickness

From Figure 5.39, oil production rate can be maintained at plateau rate of 500 STB/D for the case of 60-ft oil zone thickness. After 0.7 years oil production rate starts to decline as more volume of oil is removed from reservoir pore volume, resulting in reservoir pressure drop. In case of 30-ft oil zone thickness, water coning starts invading just one month after production as can be seen from Figure 5.40. An effect of gas coning also present in both cases, for thicker oil zone model, since reservoir pressure drops faster due to higher oil production at the same time, solution gas is more liberated. Movement of gas-oil contact downward encountering oil-water contact results in reduction of water flow ability even water production is still small. According to Figures 5.41 and 5.42 it can be obviously seen that thick oil reservoir is more shows better results compared to thin sand when DWL is implemented.

As oil production zone is located far away from oil-water contact, the effect of water coning is much less. However, this does not mean that implementation of DWL will yield always the outstanding benefit. Conventional well might yield just fair results since the oil productive zone is minimally affected from water coning problem.

5.2.4 Effect of Oil Quality

Oil gravity is chosen to represent oil quality in this study. Value of oil specific gravity is varied from base case of 35 API to lower value of 30 and higher value of 40 API. Initial bubble point pressure is set at 3,000 psia. Reservoir simulation outcomes are summarized in Table 5.12, including cumulative production of oil, gas and water, oil recovery factor and total production period.

Table 5.12Summary of reservoir simulation outcomes from DWL implementation in reservoir with different oil gravities

Oil gravity (API)	**Cumulative production**			**Oil recovery factor (Fraction)**	**Total production period (Years)**
	Oil (STB)	**Gas (MSCF)**	**Water (STB)**		
30	101,396	302,873	227,213	0.0832	1.83
35	111,525	373,974	221,462	0.0915	1.88
40	157,912	555,036	207,152	0.1295	2.15

When oil gravity is heavier, oil is more viscous. When oil is more viscous, it results in good ability of water to flow compared to oil. From Table 5.12 it is obvious that lighter oil can be produced for longer period as well as much higher oil recovery factors. Figures 5.43 to 5.46 illustrate oil production rate, water production rate, cumulative oil production and cumulative water production as a function of production time, respectively.

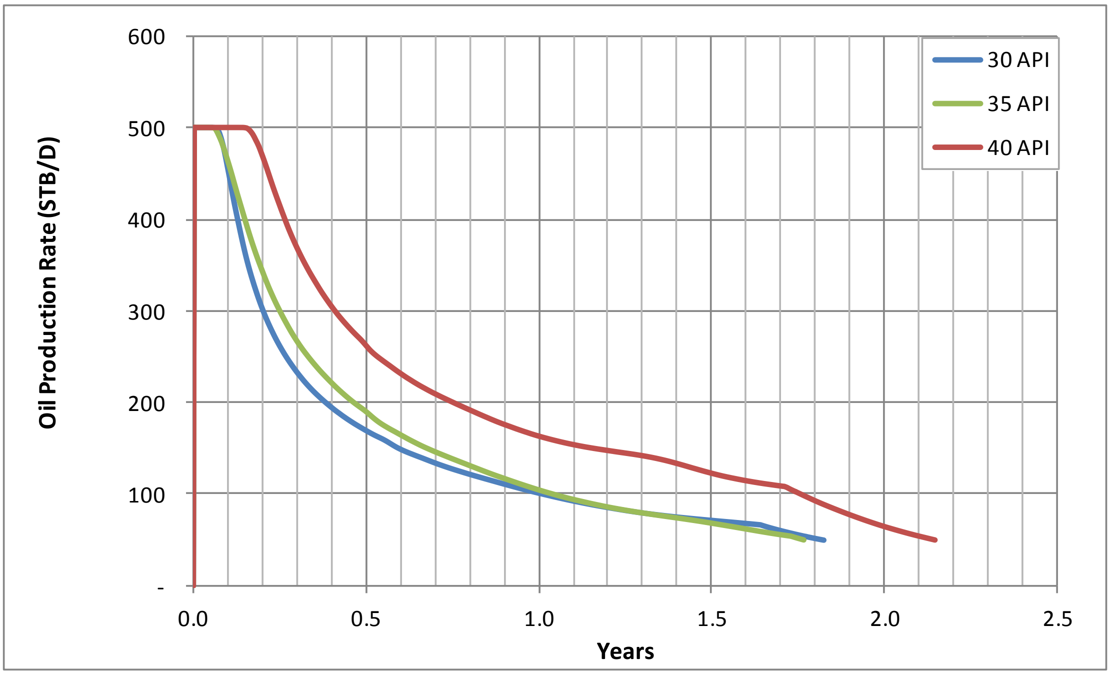

Figure 5.43Oil production rate of wells with DWL as a function of time with different oil gravity

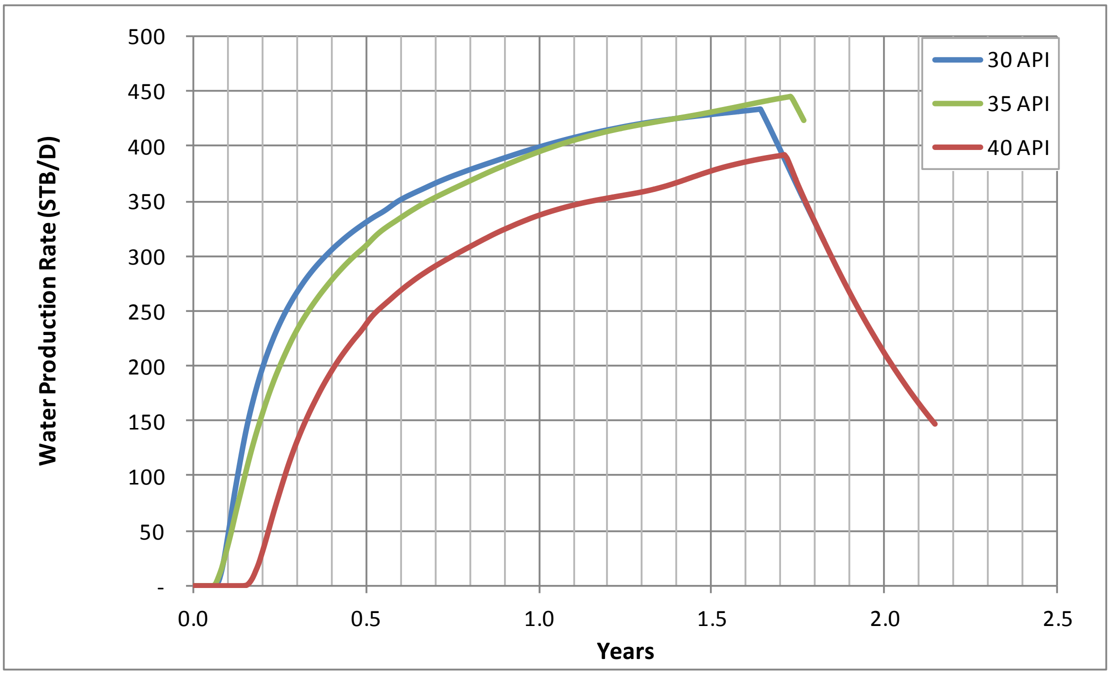

Figure 5.44Water production rate of wells with DWL as a function of time with different oil gravity

Figure 5.43 shows oil production rate from reservoir model with different oil specific gravity. Reservoir containing lighter oil with a gravity of 40 API can produce oil at plateau rate for longer period compared to cases with 35 and 30 API. As mobility ratio is favorable oil is easily move, resulting in lower water production rate as can be seen in Figure 5.44. All three cases however are affected from gas coning as well since gas can be produced when reservoir pressure is lower than bubble point pressure. According to this explanation, cumulative oil production is therefore the highest for the case of 40-API oil gravity as shown in Figure 5.45. And since mobility ratio is more favorable in lighter oil case, cumulative water production is hence lower as illustrated in Figure 5.46.

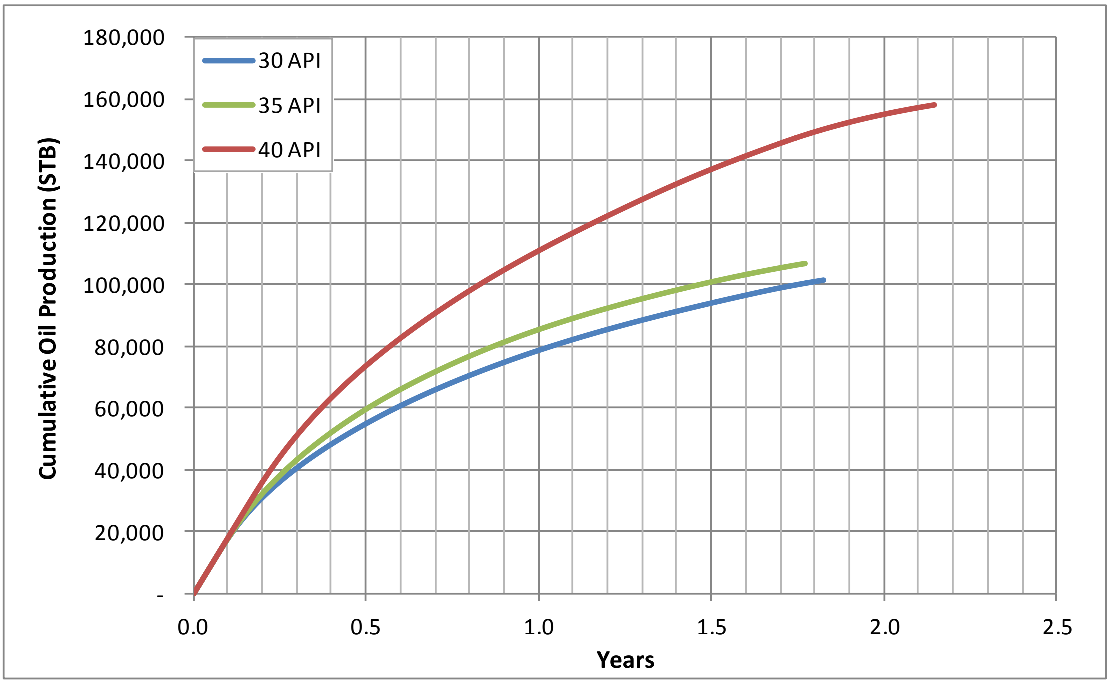

Figure 5.45Cumulative oil production of wells with DWL as a function of time with different oil gravity

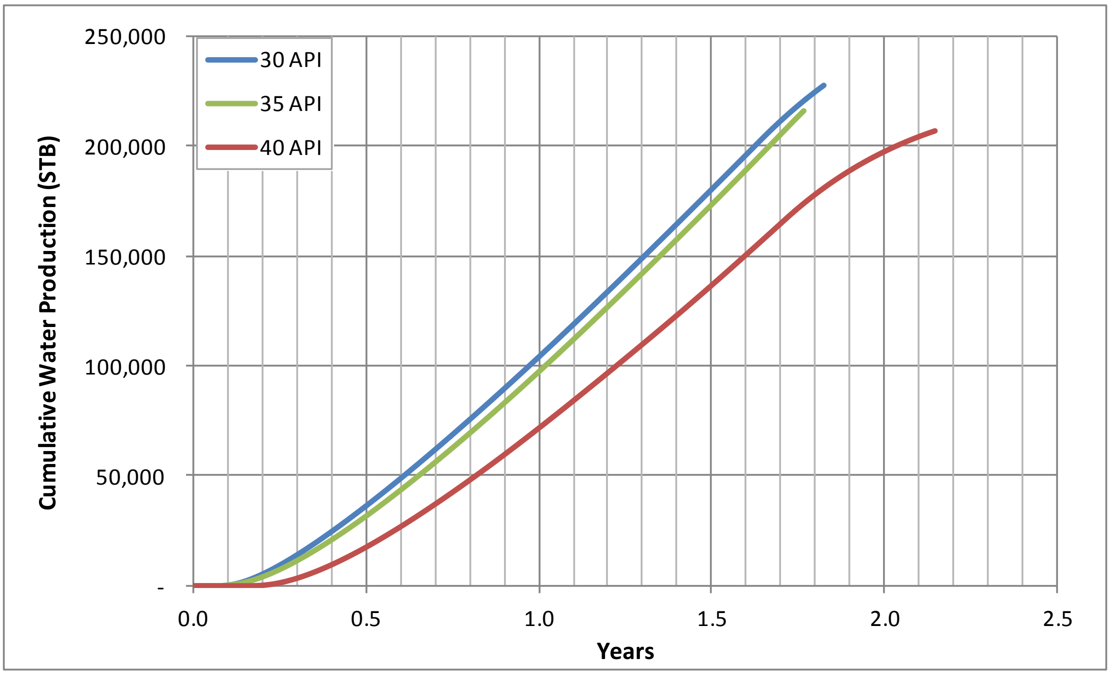

Figure 5.46Cumulative water production of wells with DWL as a function of time with different oil gravity

According to results in this section, reservoir containing lighter oil is then favorable case for DWL implementation since mobility control assists effectively retarding water coning in oil zone.

5.3Favorable Conditionsof Water Coning Case

From all study parameters in sensitivity analysis section, values that yield adverse effects from water production into oil zone are included in a new model. Chart displays the comparison of water production to total production of well variedby each parameter, are used to select the value of each parameter. Then theoperational parameter of DWL optimization on this new reservoir condition is performed again. Table 5.13 summarized propertied applied to new adverse model compared to the previous values of base case model.

Table 5.13 Selected reservoir parameters for new adverse model optimization compared to the base case

Case	k_v/k_h	**Oil gravity (API)**	**Aquifer thickness (ft)**	**Oil zone thickness (ft)**
Base case	0.10	35	60	30
Case of adverse parameters	0.20	30	60	30

This new reservoir condition consists of reservoir property values of the most effect from water coning in each studied parameter. Optimization of DWL is re-performed, starting from oil perforation location. The results are in Table 5.14 and similar to the base case, the perforation location in oil zone on the top of reservoir yields the highest oil recovery. This location takes most effect of gas but anyway effect from water coning is much less. Compare to Table 5.1, with the favorable condition for water coning, cumulative oil production at the same location is much lower at the same perforation location as can be seen in Figure 5.47.

Table 5.14Summary of reservoir simulation outcomes from conventional vertical well implemented in reservoir model with favorable conditions for water coning with different perforation locations

Oil zone grid	**Cumulative production**			**Oil recovery factor (Fraction)**	**Total production period (Years)**
	Oil (STB)	**Gas (MSCF)**	**Water (STB)**		
1-1	44,630	45,724	140,015	0.0348	1.04
3-3	43,891	48,373	147,320	0.0342	1.06
5-5	40,508	46,401	153,250	0.0316	1.07
7-7	34,184	39,119	159,081	0.0266	1.06
9-9	24,572	22,473	155,428	0.0191	0.99

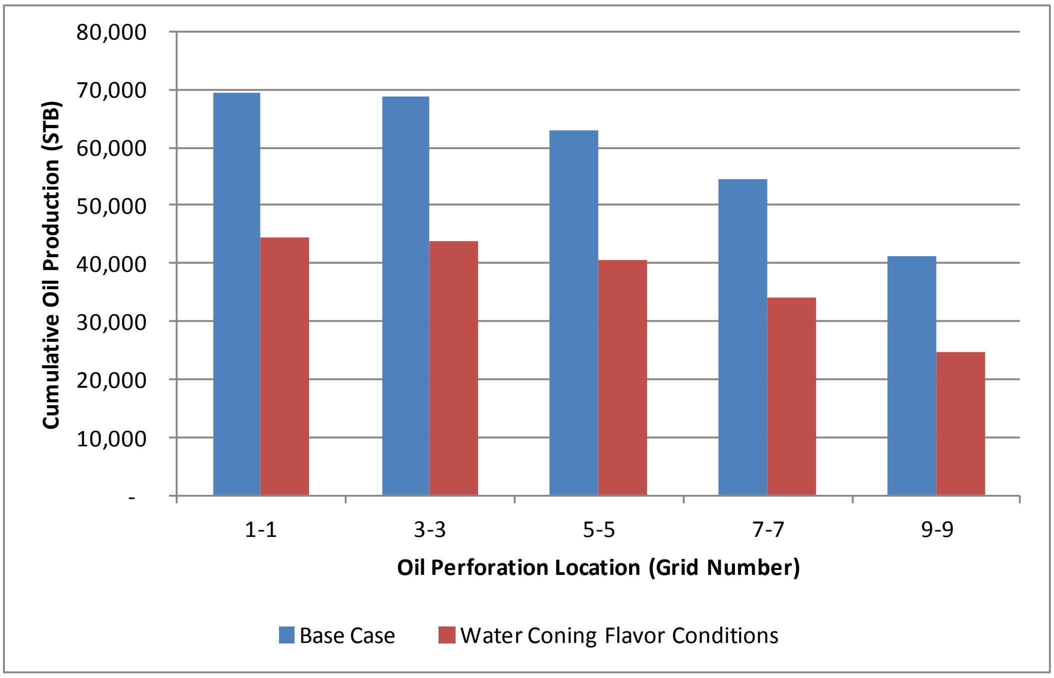

Figure 5.47 Comparison of cumulative oil production at the same perforation location between base case and case with favorable condition for water coning

Then, grid Z = 1 is varied for perforation interval. The results are summarized in Table 5.15. From this Table, optimum perforation interval in oil zone is at grid Z = 1-3 which is equivalent to 9 ft.

Table 5.15Summary of reservoir simulation outcomes from conventional vertical well implemented in reservoir model with favorable conditions for water coning with different perforation intervals

Perforation Interval (ft)	**Cumulative production**			**Oil recovery factor (Fraction)**	**Total production period (Years)**
	Oil (STB)	**Gas (MSCF)**	**Water (STB)**		
Z = 1-1 (3ft)	44,630	45,724	140,015	0.0348	1.04
Z = 1-3 (9ft)	47,740	70,772	172,760	0.0372	1.21
Z = 1-5 (15ft)	45,942	66,616	171,558	0.0358	1.19
Z = 1-7 (21ft)	43,535	63,033	172,465	0.0339	1.18

Oil zone perforation at grid Z = 1-3 is picked for water sink optimization. Water sink locations are simulated again. Then, optimized water production rate in water sink zone is identified as same as perforation interval. About the water discharge zone, the base case shows that distance of discharge zone should be kept as far as possible from water sink zone. Therefore, water discharge zone is fixed at grid Z=29-29 as same as the base case. The new optimum operation conditions compared to the base case are shown in Table 5.16.

Table 5.16 Selected operational parameters for new optimized model compared to the base case

Case	**Oil Zone**		**Water sink Zone**		**Discharge Zone**
	Oil Rate (STB/D)	**Perforation Location**	**Water rate (STB/D)**	**Perforation location**	**Perforation location**
Base case	500	Z = 1-3	3,500	Z = 13-15	Z = 29-29
Case of adverse parameter	500	Z = 1-3	4,000	Z = 13-15	Z = 29-29

Comparing to the base case, in order to optimize oil from reservoir with high tendency of water coning problem, DWL completion is required to produce water at higher rate in water sink zone with a wider perforation interval.Table 5.17 summarizes the simulation outcomes obtained from new optimum case.

Table 5.17Summary of reservoir simulation outcomes from well DWL with optimized conditions implemented in reservoir model with favorable conditions for water coning

Optimum Case	**Cumulative production**			**Oil recovery factor (Fraction)**	**Total production period (Years)**
	Oil (STB)	**Gas (MSCF)**	**Water (STB)**		
1-3_4000-13-15_29-29	80,560	262,154	265,858	0.0628	1.90

From Table 5.17 oil recovery obtained from the adverse is approximately 6.28 percent. When the conventional well is performed (without DWL system), oil recovery is about 3.72 percent. It can be seen that even though oil recovery factor from the optimized case is such low when water coning problem is severe, implementation of DWL can improve oil recovery approximately 70 percent.

5.4Comparison of DWL to the other production strategies

In order to compare efficiency of DWL to increase oil recovery, two additional cases are simulated. The first production strategy is to produce oil in reservoir with favorable conditions for water coning as explained in section 5.3 by the use of two conventional wells instead. Both wells are produced at 250 STB/D in order to achieve 500 STB/D as equal as DWL case. Wells are located at coordinates (15, 26) and (35, 26). Perforation interval in Z direction are at grid Z = 1-1 as it is the optimum interval for rate 250 STB/D from the study in section 5.1. Figure 5.48 illustrates location of two vertical wells in three dimension model.

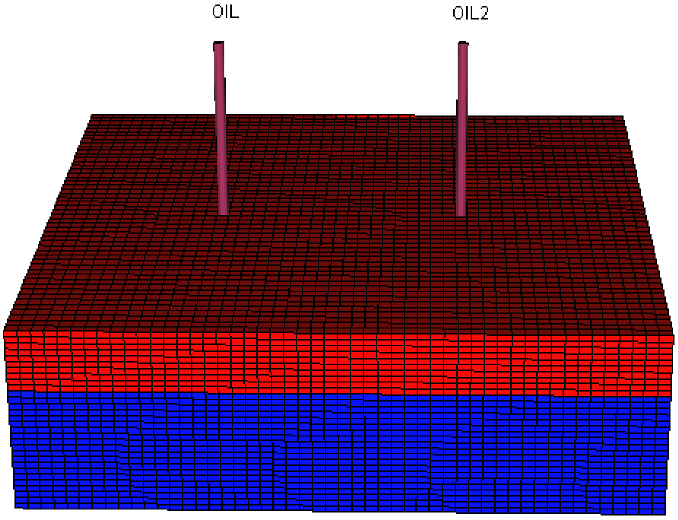

Figure 5.48 Locations of two conventional wells simulated to compare oil recovery with DWL system

The second comparative case is performed through other two conventional wells at the different oil production rate. They are set to produce at 500 STB/D in each well. Their perforation interval in Z direction are at grid Z = 1-3 as same as in DWL case. And theyare located at the same location as in Figure 5.48

Cumulative oil production of all three cases are plotted as a function of time and compared in Figure 5.49.

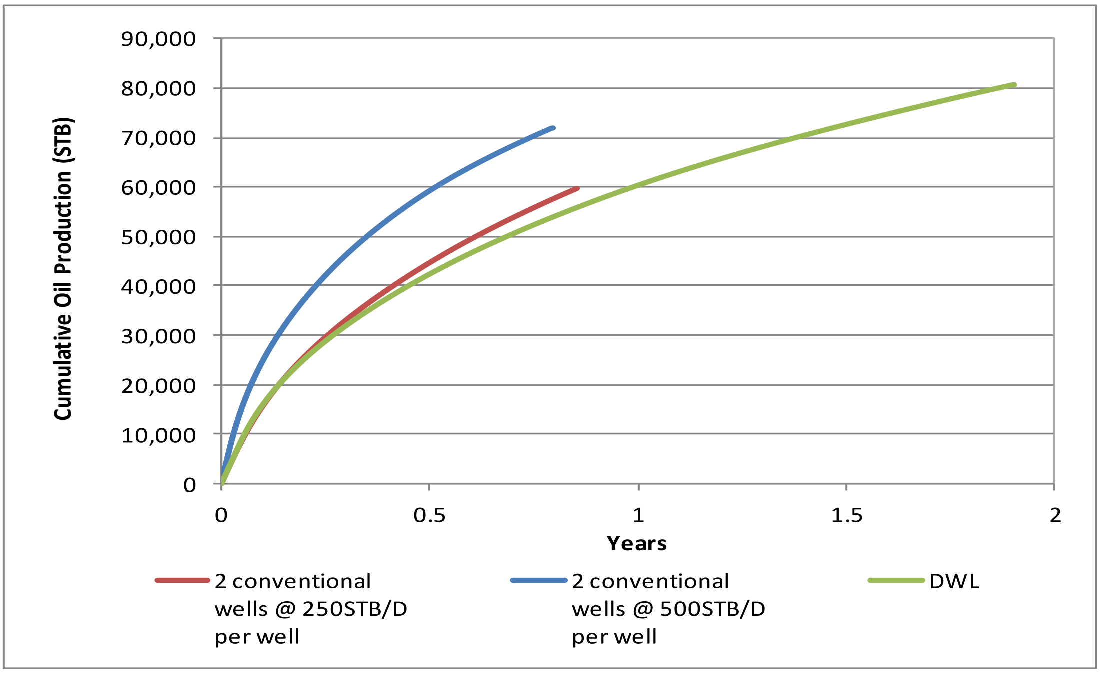

Figure 5.49Comparison of cumulative oil production from three production strategies simulated in reservoir model with favorable condition

From Figure 5.49it can be seen that DWL system still yield more oil recovery factor compared to implementation of two conventional wells. With the efficiencyof DWL, it becomes a competitive selection to exploit reservoir with favorability to water coning problem.

CHAPTER VI

CONCLUSION AND RECOMMENDATION

6.1Conclusion

In this section, conclusion is made for both effects of operational parameter and reservoir parameters on Downhole Water Loop (DWL) system.

6.1.1 Effect of operational parameters on DWL

Chosen parameters include optimization of production in oil bearing zone, water sink zone, and water discharge zone. Effect of these parameters on effectiveness of DWL can be summarized as below:

1) For optimization of oil bearing zone, it is found that location perforation for oil zone should be located as far as possible oil-water contact in order to avoid effects of water coning. This location is also affected from gas coning since gas is liberated after certain period of production that results in pressure decline below bubble pressure. Nevertheless, it is shown in this study that effect of water coning is much greater on reducing effectiveness of oil production zone compared to gas coning effect. Longer perforation interval in oil zone shows better production. However, the optimum interval exists since this longer interval could result in closer distance to oil-water contact.

2) For optimization of water sink zone, location of water sink perforation should be located close to oil-water contact in order to effectively stabilize fluid contact and hence, to prolong production period. The longer perforation interval in water sink zone shows better oil recovery in oil bearing zone. However, this also results in closer distance to discharge zone. Another concerned property to optimize or water sink zone is water production rate. Optimum rate should be identified for each case. This rate

should keep stabilizing oil-water contact and should not exceed the rate that could results in coning down of oil into water sink zone.

3) For optimization of water discharge zone, water reinjection unit should be located as far as possible from water sink zone to yield the highest oil recovery in oil bearing zone. This is due to reduce interference in maintaining fluid contact. The longer interval of water reinjection also results in better oil recovery. Nevertheless, this increment of perforation interval should be independent from distance from water-sink zone.

6.1.2 Effect of reservoir parameters on DWL

After optimized DWL is identified, interest reservoir parameters are study. From this study it is observed that:

1) Ratio of vertical to horizontal permeability shows visible effect on effectiveness of DWL. It can be seen that higher ratio allows fluid to flow in vertical direction. More water is produced from this case. Small ratio of vertical to horizontal permeability ratio shows better performance of DWL, prohibiting water coning effect that moves in vertical direction. However, the improvement of DWL compared to conventional vertical well could be small since oil bearing zone can be produced effectively without early water coning effect by the use of conventional vertical well.

2) Big aquifer size favors effectiveness of DWL. High pressure support from water aquifer results in smaller pressure drawdown. Effect from liberated solution gas is therefore retarded and oil can be produced effectively at longer plateau maximum rate.

3) Effect of water coning into oil production zone is much less in thicker oil zone when reservoir is produced at the same rate (in thin reservoir). However, implementation of DWL may not show much benefit compared

to conventional well since water coning is prohibited from larger distance between perforate oil zone and oil-water contact.

4) Oil gravity is one parameter that shows sensitivity on effectiveness of DWL system. Better oil recovery can be achieved in case of lighter oil due to favorable mobility ratio. Unavoidable water coning problem is mitigated by more effective displacement mechanism at favorable mobility ratio between water and oil.

6.1.3 Favorable Conditions for Water Coning Case

Reservoir conditions that result in favorability of water coning are summed up in one model. In this case, water production rate in water sink zone requires adjustment to be higher compared to the base case. The rest operational parameters are found mostly the same. Nevertheless, oil recovery is obviously improved from 3.7 percent in case where conventional well is implemented to 6.28 percent when DWL system is applied. This increment which is quite small in terms of absolute value but relatively, this increment is approximately 70 percent. Compared DWL system with two conventional wells, it still can be seen that implementation of DWL still provide better oil recovery factor.

6.2Recommendations

Recommendations for the further studies are stated here as follow:

1) As aquifer support in this study is varied its size by the thickness adjustment, it could be more interesting for a trial by varying pore volume of water zone. It could affect to the thickness and the distance of water sink perforation as well as water discharge zone.

2) Only vertical DWL well is performed in this study. Further study can be appliedto adjust well configuration having its completion into other directions, such as to the side. This could reduce the need of big water aquifer for the water discharge location and hence, DWL can be fit in thinner aquifer.

3) Horizontal or multi-lateral wells could be applied integrating with DWL system. This could be helpful to improve oil production.

4) To apply DWL of this study into the field operation, an appropriate well bore radius should be considered such that the completion equipment can be fitted in the applied well.

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APPENDIX

APPENDIX

ECLIPSE 100 INPUT DATA FOR RESERVOIR MODEL

Reservoir simulation models are constructed by completing the required data in Eclipse office simulator with details as listed below

Case Definition:

Simulator: Black Oil
Model dimensions
Number of grid in x direction: 50
Number of grid in y direction: 50
Number of grid in z direction: 30
Simulation start date: 1 Jan 2001
Grid type: Cartesian
Geometry type: Block Center
Oil-gas-water properties: Water, oil and dissolved gas

Grid:

Active Grid Block X (1-50)= 1
Active Grid Block Y (1-50)= 1
Active Grid Block Z (1-30)= 1
X Permeability: 200 md
Y Permeability: 200 md
Z Permeability: varied by k_v/k_h ratio (10, 20 and 40 md)
Porosity: 0.2
Grid block sizes: 30 ft for x and y directions and 3 ft for z direction (base case)

PVT:

Live Oil PVT Properties (Dissolved gas): 35 API (base case)

PVT properties of formation water

Property	Value	Unit
Reference pressure (Pref)	3,100	Psia
Water FVF at Pref	1.034592	rb/stb
Water compressibility	3.268907E-6	/psi
Water viscosity at Pref	0.253419	Cp
Water viscosibility	6.91314E-6	/psi

Fluid densities at surface condition

Property	Value	Unit
Oil density	53.00209	lb/cuft
Water density	62.42797	lb/cuft
Gas density	0.04369958	lb/cuft

Dry Gas PVT Properties (No Vaporized Oil)

Press (psia)	FVF (rb /Mscf)	Visc (cp)
2,000	1.5926	0.0173
2,143	1.4845	0.0176
2,286	1.3911	0.0180
2,429	1.3098	0.0185
2,571	1.2386	0.0189
2,714	1.1758	0.0193
2,857	1.1202	0.0198
3,000	1.0706	0.0202
3,100	1.0391	0.0205
3,286	0.9865	0.0211
3,429	0.9507	0.0216
3,571	0.9182	0.0220
3,714	0.8888	0.0225
3,857	0.8619	0.0230
4,000	0.8374	0.0234

Live Oil PVT Properties (Dissolved Gas)

Rs (Mscf /stb)	Pbub (psia)	FVF (rb /stb)	Visc (cp)
0.3823	2,000.0000	1.2734	0.4398
	2,142.8571	1.2644	0.4398
	2,285.7143	1.2578	0.4447
	2,428.5714	1.2539	0.4509
	2,571.4286	1.2514	0.4575
	2,714.2857	1.2491	0.4645
	2,857.1429	1.2470	0.4719
	3,000.0000	1.2452	0.4797
	3,100.0000	1.2440	0.4853
	3,285.7143	1.2420	0.4962
	3,428.5714	1.2405	0.5049
	3,571.4286	1.2393	0.5140
	3,714.2857	1.2381	0.5233
	3,857.1429	1.2370	0.5329
	4,000.0000	1.2359	0.5429
0.4154	2,142.8571	1.2891	0.4251
	2,285.7143	1.2791	0.4251
	2,428.5714	1.2720	0.4296
	2,571.4286	1.2689	0.4355
	2,714.2857	1.2664	0.4418
	2,857.1429	1.2640	0.4485
	3,000.0000	1.2620	0.4555
	3,100.0000	1.2606	0.4606
	3,285.7143	1.2583	0.4705
	3,428.5714	1.2567	0.4784
	3,571.4286	1.2553	0.4866
	3,714.2857	1.2539	0.4951
	3,857.1429	1.2527	0.5039
	4,000.0000	1.2515	0.5129
0.4490	2,285.7143	1.3049	0.4116
	2,428.5714	1.2949	0.4116
	2,571.4286	1.2893	0.4158
	2,714.2857	1.2845	0.4215
	2,857.1429	1.2816	0.4275
	3,000.0000	1.2792	0.4339
	3,100.0000	1.2777	0.4385
	3,285.7143	1.2751	0.4475
	3,428.5714	1.2734	0.4547
	3,571.4286	1.2717	0.4622

	3,714.2857	1.2702	0.4700
	3,857.1429	1.2688	0.4780
	4,000.0000	1.2676	0.4863
0.4830	2,428.5714	1.3210	0.3992
	2,571.4286	1.3110	0.3992
	2,714.2857	1.3044	0.4031
	2,857.1429	1.2996	0.4086
	3,000.0000	1.2969	0.4144
	3,100.0000	1.2953	0.4186
	3,285.7143	1.2924	0.4269
	3,428.5714	1.2904	0.4335
	3,571.4286	1.2886	0.4404
	3,714.2857	1.2869	0.4475
	3,857.1429	1.2854	0.4548
	4,000.0000	1.2840	0.4624
0.5174	2,571.4286	1.3373	0.3876
	2,714.2857	1.3273	0.3876
	2,857.1429	1.3190	0.3915
	3,000.0000	1.3151	0.3968
	3,100.0000	1.3133	0.4006
	3,285.7143	1.3101	0.4082
	3,428.5714	1.3079	0.4143
	3,571.4286	1.3059	0.4206
	3,714.2857	1.3041	0.4272
	3,857.1429	1.3023	0.4339
	4,000.0000	1.3008	0.4409
0.5522	2,714.2857	1.3538	0.3769
	2,857.1429	1.3438	0.3769
	3,000.0000	1.3350	0.3807
	3,100.0000	1.3318	0.3843
	3,285.7143	1.3283	0.3912
	3,428.5714	1.3259	0.3968
	3,571.4286	1.3236	0.4027
	3,714.2857	1.3216	0.4087
	3,857.1429	1.3197	0.4150
	4,000.0000	1.3179	0.4215
0.5874	2,857.1429	1.3704	0.3669
	3,000.0000	1.3604	0.3669
	3,100.0000	1.3537	0.3693
	3,285.7143	1.3469	0.3757
	3,428.5714	1.3442	0.3809
	3,571.4286	1.3418	0.3864
	3,714.2857	1.3395	0.3920

	3,857.1429	1.3374	0.3978
	4,000.0000	1.3355	0.4038
0.6229	3,000.0000	1.3872	0.3576
	3,100.0000	1.3772	0.3576
	3,285.7143	1.3679	0.3616
	3,428.5714	1.3630	0.3664
	3,571.4286	1.3603	0.3714
	3,714.2857	1.3579	0.3766
	3,857.1429	1.3556	0.3821
	4,000.0000	1.3535	0.3876

Live Oil PVT Properties (Dissolved gas): 30 API

<u>PVT properties of formation water</u>

Property	Value	Unit
Reference pressure (Pref)	3,100	Psia
Water FVF at Pref	1.034592	rb/stb
Water compressibility	3.268907E-6	/psi
Water viscosity at Pref	0.253419	Cp
Water viscosibility	6.91314E-6	/psi

<u>Fluid densities at surface condition</u>

Property	Value	Unit
Oil density	54.64302	lb/cuft
Water density	62.42797	lb/cuft
Gas density	0.04369958	lb/cuft

Dry Gas PVT Properties (No Vaporized Oil)

Press (psia)	FVF (rb /Mscf)	Visc (cp)
2,000.00	1.59	0.02
2,142.86	1.48	0.02
2,285.71	1.39	0.02
2,428.57	1.31	0.02
2,571.43	1.24	0.02
2,714.29	1.18	0.02
2,857.14	1.12	0.02
3,000.00	1.07	0.02
3,100.00	1.04	0.02
3,285.71	0.99	0.02
3,428.57	0.95	0.02
3,571.43	0.92	0.02
3,714.29	0.89	0.02
3,857.14	0.86	0.02
4,000.00	0.84	0.02

Live Oil PVT Properties (Dissolved Gas)

Rs (Mscf /stb)	Pbub (psia)	FVF (rb /stb)	Visc (cp)
0.321377	2,000.00	1.217585	0.701022
	2,142.86	1.217032	0.703149
	2,285.71	1.216209	0.712699
	2,428.57	1.215323	0.722932
	2,571.43	1.214417	0.733816
	2,714.29	1.212747	0.745321
	2,857.14	1.211177	0.757425
	3,000.00	1.209577	0.770102
	3,100.00	1.208547	0.779307
	3,285.71	1.206801	0.7971
	3,428.57	1.205588	0.811383
	3,571.43	1.204473	0.826166
	3,714.29	1.203445	0.841433
	3,857.14	1.202494	0.857169
	4,000.00	1.201612	0.873359

0.349213	2,142.86	1.230892	0.6733
	2,285.71	1.229538	0.674999
	2,428.57	1.228985	0.684105
	2,571.43	1.227968	0.69382
	2,714.29	1.226755	0.704115
	2,857.14	1.225068	0.714965
	3,000.00	1.223372	0.72635
	3,100.00	1.222215	0.734626
	3,285.71	1.220255	0.750641
	3,428.57	1.218894	0.763511
	3,571.43	1.217643	0.776843
	3,714.29	1.21649	0.790621
	3,857.14	1.215423	0.804831
	4,000.00	1.214433	0.819459
0.377431	2,285.71	1.244258	0.647976
	2,428.57	1.243455	0.649375
	2,571.43	1.242598	0.658083
	2,714.29	1.241277	0.667335
	2,857.14	1.239257	0.677107
	3,000.00	1.237553	0.687378
	3,100.00	1.236261	0.694854
	3,285.71	1.234074	0.709339
	3,428.57	1.232555	0.720994
	3,571.43	1.231159	0.733077
	3,714.29	1.229872	0.745575
	3,857.14	1.228681	0.758472
	4,000.00	1.227577	0.771756
0.40601	2,428.57	1.257685	0.624749
	2,571.43	1.257056	0.625968
	2,714.29	1.255811	0.634315
	2,857.14	1.253944	0.643151
	3,000.00	1.252117	0.652456
	3,100.00	1.250683	0.659238
	3,285.71	1.248254	0.672395
	3,428.57	1.246567	0.682996
	3,571.43	1.245017	0.693998
	3,714.29	1.243588	0.705385
	3,857.14	1.242267	0.717145
	4,000.00	1.241041	0.729265
0.434935	2,571.43	1.271174	0.603367

	2,714.29	1.270255	0.604513
	2,857.14	1.268758	0.612532
	3,000.00	1.267065	0.620993
	3,100.00	1.265478	0.627169
	3,285.71	1.262793	0.639168
	3,428.57	1.260928	0.648848
	3,571.43	1.259216	0.658905
	3,714.29	1.257637	0.669323
	3,857.14	1.256176	0.68009
	4,000.00	1.254822	0.691194
0.46419	2,714.29	1.284726	0.583614
	2,857.14	1.283206	0.584788
	3,000.00	1.281994	0.592507
	3,100.00	1.280577	0.59815
	3,285.71	1.27769	0.609131
	3,428.57	1.275637	0.618003
	3,571.43	1.273752	0.627229
	3,714.29	1.272014	0.636797
	3,857.14	1.270406	0.646692
	4,000.00	1.268916	0.656904
0.493761	2,857.14	1.298342	0.565308
	3,000.00	1.296994	0.566601
	3,100.00	1.295707	0.571774
	3,285.71	1.292943	0.581855
	3,428.57	1.290691	0.590012
	3,571.43	1.288624	0.598505
	3,714.29	1.286718	0.607321
	3,857.14	1.284956	0.616446
	4,000.00	1.283322	0.62587
0.523635	3,000.00	1.312021	0.548294
	3,100.00	1.311066	0.548294
	3,285.71	1.308552	0.556981
	3,428.57	1.30609	0.564504
	3,571.43	1.30383	0.572346
	3,714.29	1.301748	0.580493
	3,857.14	1.299822	0.588935
	4,000.00	1.298037	0.597659

Live Oil PVT Properties (Dissolved gas): 40 API

PVT properties of formation water

Property	**Value**	**Unit**
Reference pressure (Pref)	3,100	Psia
Water FVF at Pref	1.034592	rb/stb
Water compressibility	3.33236E-6	/psi
Water viscosity at Pref	0.253419	Cp
Water viscosibility	6.91314E-6	/psi

Fluid densities at surface condition

Property	**Value**	**Unit**
Oil density	51.45684	lb/cuft
Water density	62.42797	lb/cuft
Gas density	0.04369958	lb/cuft

Dry Gas PVT Properties (No Vaporized Oil)

Press (psia)	FVF (rb /Mscf)	Visc (cp)
2,000.00	1.592607	0.017257
2,142.86	1.484523	0.017644
2,285.71	1.391128	0.018045
2,428.57	1.309825	0.018458
2,571.43	1.238583	0.018881
2,714.29	1.175792	0.019313
2,857.14	1.120157	0.019753
3,000.00	1.070625	0.0202
3,100.00	1.039112	0.020516
3,285.71	0.986549	0.021108
3,428.57	0.950686	0.021568
3,571.43	0.918235	0.022029
3,714.29	0.888768	0.022492
3,857.14	0.86192	0.022955
4,000.00	0.83738	0.023418

Live Oil PVT Properties (Dissolved Gas)

Rs (Mscf /stb)	Pbub (psia)	FVF (rb /stb)	Visc (cp)
0.454791	2,000.00	1.318613	0.302093
	2,142.86	1.310613	0.302093
	2,285.71	1.303278	0.304087
	2,428.57	1.297908	0.308266
	2,571.43	1.294919	0.31272
	2,714.29	1.292251	0.317436
	2,857.14	1.289854	0.322404
	3,000.00	1.28769	0.327614
	3,100.00	1.286295	0.3314
	3,285.71	1.283934	0.338723
	3,428.57	1.282294	0.344607
	3,571.43	1.280788	0.3507
	3,714.29	1.279398	0.356996
	3,857.14	1.278113	0.363487
	4,000.00	1.276921	0.370169
0.494183	2,142.86	1.338195	0.293549
	2,285.71	1.330195	0.293549
	2,428.57	1.321668	0.295363
	2,571.43	1.316288	0.299392
	2,714.29	1.313271	0.303669
	2,857.14	1.310561	0.308183
	3,000.00	1.308114	0.312926
	3,100.00	1.306538	0.316376
	3,285.71	1.30387	0.323059
	3,428.57	1.302017	0.328434
	3,571.43	1.300315	0.334006
	3,714.29	1.298746	0.339767
	3,857.14	1.297295	0.345711
	4,000.00	1.295948	0.351832
0.534115	2,285.71	1.358046	0.285644
	2,428.57	1.350046	0.285644
	2,571.43	1.34032	0.28736
	2,714.29	1.334927	0.291254
	2,857.14	1.331882	0.295373
	3,000.00	1.329132	0.299708
	3,100.00	1.327362	0.302866
	3,285.71	1.324364	0.308992
	3,428.57	1.322283	0.313924
	3,571.43	1.320372	0.319042
	3,714.29	1.31861	0.324338
	3,857.14	1.316981	0.329806

	4,000.00	1.31547	0.33544
0.574559	2,428.57	1.378152	0.278302
	2,571.43	1.368152	0.278302
	2,714.29	1.35922	0.279995
	2,857.14	1.353815	0.283767
	3,000.00	1.350741	0.287745
	3,100.00	1.348762	0.290647
	3,285.71	1.345413	0.296283
	3,428.57	1.343089	0.300828
	3,571.43	1.340954	0.305548
	3,714.29	1.338986	0.310437
	3,857.14	1.337167	0.315487
	4,000.00	1.335479	0.320695
0.615491	2,571.43	1.398501	0.27146
	2,714.29	1.388501	0.27146
	2,857.14	1.379358	0.273199
	3,000.00	1.372939	0.276862
	3,100.00	1.370738	0.279538
	3,285.71	1.367013	0.284742
	3,428.57	1.364429	0.288945
	3,571.43	1.362055	0.293314
	3,714.29	1.359868	0.297842
	3,857.14	1.357846	0.302525
	4,000.00	1.355971	0.307357
0.656891	2,714.29	1.419082	0.265064
	2,857.14	1.409082	0.265064
	3,000.00	1.399523	0.266914
	3,100.00	1.394585	0.269389
	3,285.71	1.389162	0.27421
	3,428.57	1.3863	0.278109
	3,571.43	1.383673	0.282166
	3,714.29	1.381253	0.286376
	3,857.14	1.379016	0.290733
	4,000.00	1.376941	0.29523
0.698737	2,857.14	1.439885	0.259069
	3,000.00	1.429885	0.259069
	3,100.00	1.423505	0.260079
	3,285.71	1.413556	0.264558
	3,428.57	1.408701	0.268186
	3,571.43	1.405805	0.271965
	3,714.29	1.403137	0.27589
	3,857.14	1.400671	0.279956
	4,000.00	1.398385	0.284156

0.741013	3,000.00	1.460901	0.253434
	3,100.00	1.45009	0.253434
	3,285.71	1.43751	0.255677
	3,428.57	1.43163	0.259062
	3,571.43	1.428448	0.262592
	3,714.29	1.425517	0.266262
	3,857.14	1.422809	0.270066
	4,000.00	1.420299	0.274

SCAL:

Water/Oil Saturation Functions

Sw	Krw	Kro
0.3000	-	0.4500
0.3444	0.0019	0.3556
0.3889	0.0074	0.2722
0.4333	0.0167	0.2000
0.4778	0.0296	0.1389
0.5222	0.0463	0.0889
0.5667	0.0667	0.0500
0.6111	0.0907	0.0222
0.6556	0.1185	0.0056
0.7000	0.1500	-
1.0000	1.0000	-

Gas/Oil Saturation Functions (additional to live oil simulation model)

Sg	Krg	Kro
-	-	0.4500
0.0500	-	0.3719
0.1125	0.0070	0.2847
0.1750	0.0281	0.2092
0.2375	0.0633	0.1453
0.3000	0.1125	0.0930
0.3625	0.1758	0.0523
0.4250	0.2531	0.0232
0.4875	0.3745	0.0058
0.5500	0.5500	-
0.7000	1.0000	-

Initialization:

Equilibration data specification

Datum depth: 7,000 ft

Pressure at datum depth: 3,100 psia

WOC depth: 7,030 ft

Regions: N/A

Schedule:

Oil zone's schedule

Well specification [WELSPECS]

Well name: OIL

Group: 1

I Location: 26

J Location: 26

Preferred phase: OIL

Inflow equation: STD

Automatic shut-in instruction: SHUT

Cross flow: Yes

Density calculation: SEG

Well connection data [COMDAT]

Well name: OIL

K upper: 1 (for dead oil) and 9 (for live oil)

K lower: 1 (for dead oil) and 9 (for live oil)

Wellbore ID: 0.729ft

Direction: Z

Skin: 1.072

Production well control [WCONPROD]

Well name: OIL
Open/Shut Flag: OPEN
Control: LRAT
Liquid rate: 500 STB/D
BHP target: 500 psia

Sink zone's schedule

Well specification [WELSPECS]

Well name: SINK
Group: 2
I Location: 26
J Location: 26
Preferred phase: WATER
Inflow equation: STD
Automatic shut-in instruction: SHUT
Cross flow: Yes
Density calculation: SEG

Well connection data [COMDAT]

Well name: SINK
K upper: 11(for dead oil) and 11 (for live oil)
K lower: 15 (for dead oil) and 25 (for live oil)
Wellbore ID: 0.729ft
Direction: Z
Skin: 1.072

Production well control [WCONPROD]

Well name: SINK
Open/Shut Flag: OPEN
Control: LRAT
Liquid rate: 3,000 STB/D (optimization rate)
BHP target: 500 psia

Injection zone's schedule

Well specification [WELSPECS]

Well name: INJ
Group: 2
I Location: 26
J Location: 26
Preferred phase: WATER
Inflow equation: STD
Automatic shut-in instruction: SHUT
Cross flow: Yes
Density calculation: SEG

Well connection data [COMDAT]

Well name: INJ
K upper: 29
K lower: 29
Wellbore ID: 0.729ft
Direction: Z
Skin: 1.072

Injection well control [WCONINJE]

Well name: INJ

Injector type: WATER

Open/Shut Flag: OPEN

Control mode: GRUP

BHP target: 5,315.25psia

Group Injection/control limit [GCONINJE]

Group: 2

Phase: WATER

Control mode: VREP

Total voidage replacement fraction upper limit: 1

VITAE

Rungludee Luiprasert was born on November 20th, 1977 in Bangkok, Thailand. She obtained her bachelor degree in Applied Physics from the Faculty of Science, King Mongkut Institute of Technology Latkrabang in 1997. She started her study in Master degree of Petroleum Engineering, Faculty of Engineering, Chulalongkorn University since the academic year of 2010.