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# Aquifer Characterization and Modelling, a case study of Norne field.

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## **DISCLAIMER**

The views expressed in this thesis are the views of the author and do not necessarily reflect the views of Statoil and the Norne license partners.

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## ACRONYMS

ANTHEI	Angolan, Norwegian and Tanzanian Higher Education Initiative
AQUNUM	Keyword that specifies blocks representing one-dimensional numerical aquifers
AQUCON	Keyword that specifies connection data for numerical aquifers
AQUDIMS	Keyword that specifies dimensions for aquifers
AQUCT	Keyword that specifies the property data for Carter-Tracy aquifers
AQUFET	Keyword that specifies specification data for Fetkovich aquifers
AQUANCON	Keyword that specifies connection data for analytical aquifers
AQUFLUX	Keyword that specifies constant flux aquifers
AQUCHWAT	Keyword that specifies the property data for constant head water aquifers
AQUCHGAS	Keyword that specifies the property data for constant head gas aquifers
FPR	Field average pressure
FAQT	Field cumulative aquifer influx
FOE	Field oil recovery factor
IO Center	Center for Integrated Operation in the petroleum industry
MBAL	Material balance software
NNCs	Non-neighbour Connections
NTNU	Norwegian University of Science and Technology
PVT	Pressure, Volume, and Temperature
UDSM	University of Dar es Salaam
UDOM	University of Dodoma
VEH	van Everdingen and Hurst
WTI	West Texas Intermediate

## **ABSTRACT**

The purpose of this research is to characterize the Norne aquifer and testing its performance in the reservoir in terms of additional oil recovery factor with aquifer model included in reservoir simulation model by considering the use of Carter-Tracy model, Fetkovich model and van-Everdingen-Hurst (VEH) model.

The methodology applied involves four stages: Aquifer characterization, model ranking aquifer modelling and economic analysis.

The characteristics of the Norne aquifer considered are aquifer strength and aquifer properties such as aquifer size, aquifer permeability, aquifer porosity and water encroachment angle. The aquifer strength is determined by using diagnostic plots such as a production decline curve of oil rate versus time in semi-logarithm scale and drive indices plot. Estimation of aquifer properties is achieved by using a non-linear regression method in material balance software (MBAL). This approach involves history matching of the average reservoir pressure with computed pressure data by using production data, fluid injection rates and PVT properties. The computed pressure data from the tank model are history matched by regressing the most uncertain parameters in aquifer such as aquifer size, permeability, porosity, and water encroachment angle until the computed pressure matches with historical average reservoir pressure.

In model ranking, three models are investigated. These are van-Everdingen-Hurst (VEH) model, Carter-Tracy model and Fetkovich model based on the standard deviation after regression analysis.

In aquifer modelling, the Carter-Tracy model in Eclipse software is applied by using the estimated Norne aquifer properties. To introduce the Carter-Tracy aquifer in reservoir simulation model, three keywords are added in Eclipse data file. These are AQUUDIMS for specifying dimensions for aquifer, AQUUCT which specifies property data for Carter-Tracy aquifer and AQUANCON which specifies connection data for analytical aquifer.

In economic analysis, total additional revenue is computed by using two main parameters, additional volume of oil produced with aquifer model included in reservoir simulation model and an average WTI crude oil price for historical period from 1997 to 2006.

The findings of this research show that, the van Everdingen and Hurst (VEH) model is the best model to describe the Norne aquifer with standard deviation of 8.38919, followed by Carter-Tracy model with standard deviation of 19.57410 and Fetkovich is the least model with standard deviation of 43.67590.

Further, results show the water drive strength in the Norne field is strong with aquifer size approximately three times the size of the reservoir (as the reservoir radius is 9618 feet), the aquifer permeability is 2495 millidarcy, aquifer porosity is 20.04 percent, aquifer thickness is 561.12 feet and water influx angle is 51.9133 degree.

Furthermore, the behaviour of the cumulative water influx into the Norne reservoir is observed to correlate with the average reservoir pressure trend.

In addition, by adding an aquifer model in full field Norne reservoir simulation model of 2004, the oil recovery factor is observed to increase by 1.0-1.6 percent at the end of historical and prediction periods respectively. This means the corresponding total additional revenues between 435.0-696.1 million USD are generated when the aquifer model is included during the historical and prediction simulation periods respectively.

Therefore, including the aquifer in Norne reservoir simulation model improves the Norne field reservoir description for better management of the reservoir.

# CHAPTER 1

## INTRODUCTION

Aquifer is one of the source of water influx into the reservoir. Other sources of water influx into the reservoir includes recharge of the reservoir by surface water from outcrops and water injection from the surface to supplement a weak aquifer. Water influx contributes to the total driving energy used for production of oil and gas from the reservoir to the surface. Other driving energy for production of hydrocarbon includes fluid expansion due to change in condition such as pressure and temperature, gravity-drainage drive due to fluid density differences, gas cap drive due to expansion of gas in the gas cap or expansion of liberated solution gas, and formation, and connate water compressibility (Ahmed, 2006; Fekete, 2014). Suppose that an aquifer underlies the reservoir B and they are hydraulically connected to each other, once the reservoir pressure starts to decline due to production, the aquifer will react by encroaches water into the reservoir to offset the reservoir pressure from declining thus increasing hydrocarbon recovery. This tendency of water to encroach into the reservoir is what referred in this research as water influx. The conceptual influx of water into the petroleum reservoir is illustrated in Figure 1.

Estimation of water influx volumes into the reservoir is significant in number of applications such as material balance for estimation of reserves, reservoir simulation studies for model calibration, production scheduling and setting up development strategies to optimize hydrocarbon recovery (Al-ghanim, Nashawi, & Malallah, 2012). An accurate estimation of water influx into the reservoir is required with the aid of an efficiency aquifer model that can capture the real dynamics of petroleum subsurface system. Further, it is important to characterize the aquifer behaviour before start aquifer modelling or inclusion of aquifer into the reservoir simulation model. This is because during aquifer characterization, the understanding of aquifer properties and strength is increased.

Aquifer characterization is the challenging task in aquifer modelling. This is because most of aquifer properties such as aquifer size, aquifer permeability, aquifer porosity and water encroachment angle are uncertain. One of the main reason is the cost of drilling wells into the aquifer to gain necessary information is often not justified. (Craft, Hawkins, & Terry, 1991). This is reasonable; however, the uncertainties associated with aquifer properties should be reduced to have an efficient aquifer model. For example, uncertainties of aquifer model

parameters can be reduced by using history matching method or material balance method (Petrowiki, 2015).

The inclusion of aquifer into reservoir simulation model cannot be isolated from aquifer characterization. It should begin with aquifer characterization to increase the understanding of its properties and strength. In addition, the inclusion of aquifer into the reservoir simulation model may help to capture uncertainties in reservoir simulation model and thus increasing its predictive capability in terms of hydrocarbon recovery factor for better management of the reservoir.

Previous studies on the influence of water influx into the Norne reservoir has not been detailed on aquifer characterization (Odinukwe & Correia, 2010). This becomes difficult to estimate in accurate the cumulative water encroaches into the reservoir as a function of time and its impact in terms of additional oil recovery factor with aquifer model inclusion in reservoir simulation model.

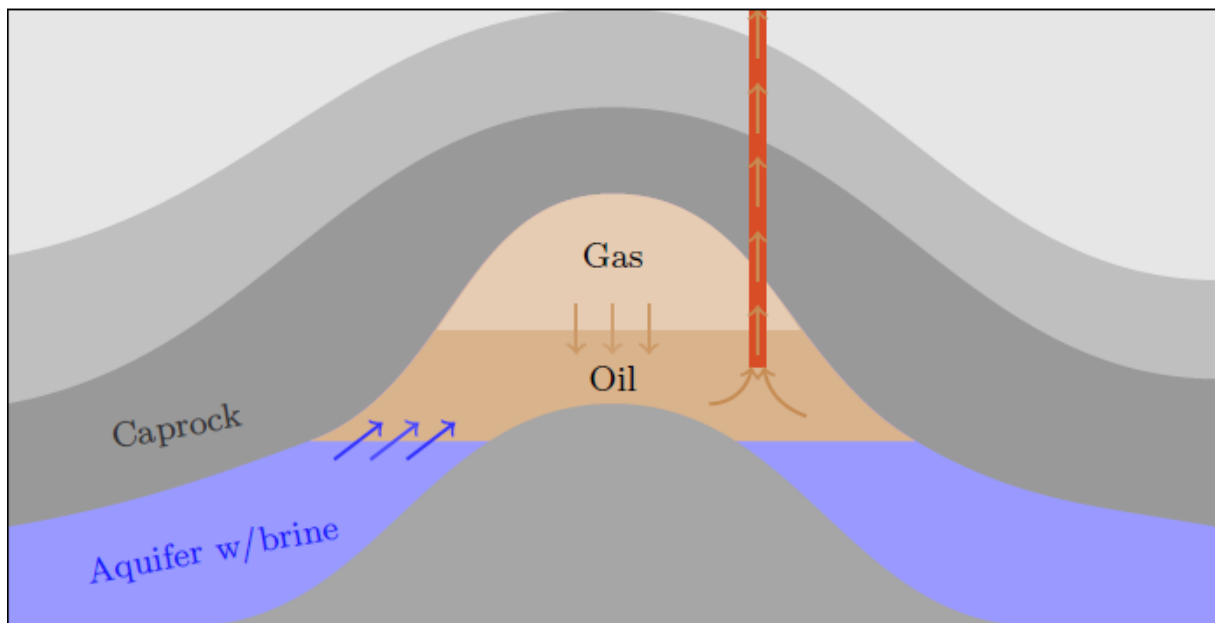


Figure 1 Conceptual influx of water into the petroleum reservoir (Knut, 2015)

## **1.1 Problem Statement**

The Norne reservoir is underlain with an aquifer whose characteristics such as aquifer size, strength, permeability, porosity, and water encroachment angle has not been fully explored. Despite the fact water drive is the dominant driving energy for production of oil in the Norne reservoir, the full field reservoir simulation model of 2004 which is available in the Norne database for student research does not include any aquifer model, hence provide limitation for estimating water influx into the reservoir as a pressure support to optimize the reservoir performance. This requires an investigation of this kind of study. The understanding of Norne aquifer properties will help to calibrate the Norne reservoir simulation model for better management of the reservoir.

## **1.2 Objectives**

The main objective of this research is to characterize the Norne aquifer and testing its performance in the reservoir in terms of oil recovery factor with and without aquifer model inclusion in reservoir simulation model by considering the use of Carter-Tracy model, Fetkovich model and van Everdingen-Hurst model.

The main objective can be broken down into the following specific objectives:

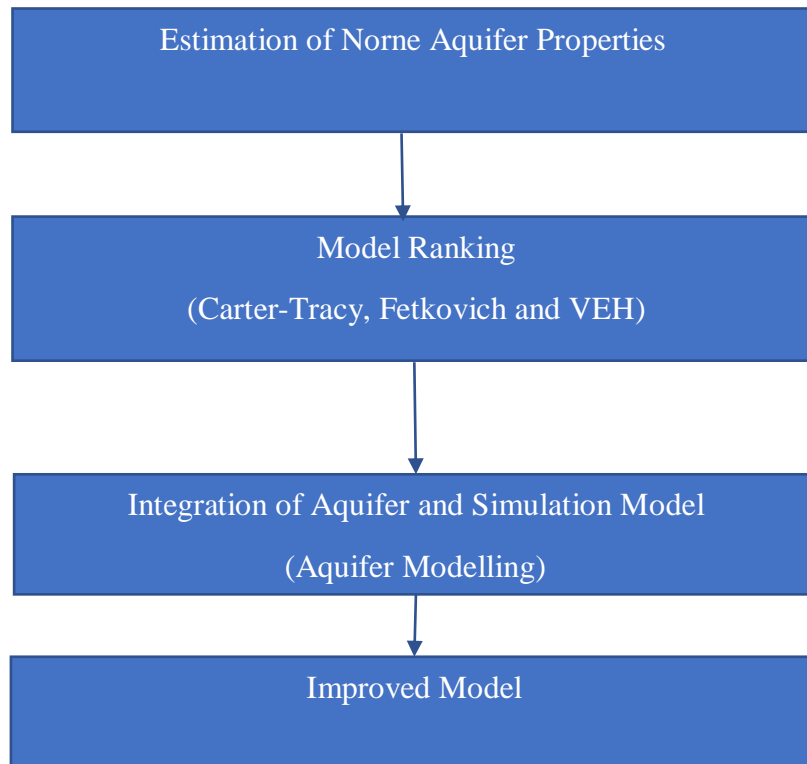
- To estimate aquifer size, strength, permeability, porosity, water encroachment angle and drive indices in the Norne field.
- To rank the frequently used aquifer models based on standard deviation
- To determine the performance of aquifer model based on cumulative water influx.
- To compare oil production in terms of oil recovery factor and economics with and without aquifer model included in reservoir simulation model.

## **1.3 Scope of the Thesis**

This thesis will characterize the Norne aquifer and testing its performance in the reservoir by considering the use of Carter-Tracy model, Fetkovich model and van Everdingen-Hurst model. The characteristics of the Norne aquifer to be investigated will include aquifer size, aquifer strength, aquifer permeability, water encroachment angle and drive indices. The reservoir performance that will be analysed is oil recovery factor. Further, economic analysis will be performed on total additional revenues generated when the reservoir is produced under the influence of aquifer.

## 1.4 Research Design

This research is quantitative in nature. It will contain three parts. The first will be estimation of aquifer properties as an input in aquifer modelling. The second part will involve ranking of the most frequently used aquifer models. The third part is the integration of aquifer with reservoir simulation model to obtain an improved model that captures the real dynamics of petroleum subsurface system. The conceptual framework of the research design is shown in Figure 2.



*Figure 2 Conceptual research design (Author's construction)*

## 1.5 Research Methodology

The methodology of this research will involve four stages: Aquifer characterization, model ranking, aquifer modelling and economic analysis.

- The characterization of aquifer properties in the Norne field will be achieved by using a non-linear regression technique in material balance software (MBAL) from Petroleum Experts. This approach will involve history matching of average reservoir pressure data or sometimes called tank pressure data with computed pressures by using production data, fluid injection rates and PVT properties. The computed pressure data from the tank model is history matched by regressing the most uncertain parameters in the aquifer



model such as aquifer size, porosity, permeability, and water encroachment angle until the computed pressure data matches with historical average reservoir pressure data.

- Model ranking. Three models will be investigated based on the standard deviation after regression analysis. These include the van Everdingen-Hurst model, Carter-Tracy model and Fetkovich model. The model that will have small standard deviation will be chosen as the best model to describe the Norne aquifer.
- In aquifer modelling, the simulation of the reservoir performance will be done in terms of oil recovery factor with and without aquifer model included in reservoir simulation model by using Eclipse software from Schlumberger.
- In economic analysis, total revenues will be computed based on the additional volumes of oil produced when the aquifer is included in reservoir simulation model.

## **1.6 Chapter Outlines**

The chapter outlines of this research are as follows. Chapter 1 has explained an introduction of research topic, problem statement, objectives, scope of research, research design and methodology. Chapter 2 will contain review of water influx models covering an introduction of the reservoir-aquifer system, their classification, factors causing water influx into the reservoir, the significance of estimating water influx into the reservoir, description of models applied in estimating water influx into the reservoir, their limitation, aquifer modelling facilities available in Eclipse and conclusion. Chapter 3 will explain the Norne field as a case study covering the description of the Norne field, geological and petrophysical information of the Norne field, the drainage strategy of the Norne field, fluid in place volumes, recoverable and remaining reserves, Norne field hydrocarbon composition and conclusion. Chapter 4 will contain the methodology of this research covering data collection, data cleaning process, aquifer characterization, model ranking, aquifer modelling and economic analysis. Chapter 5 will contain results and discussion of results and Chapter 6 will conclude the research and give some recommendations based on the findings.

## CHAPTER 2

### REVIEW OF WATER INFLUX MODELS

The literature review of this research covers an introduction of reservoir-aquifer system, their classification, factors causing water influx into the reservoir, the significance of estimating water influx into the reservoir, the description of the models applied in estimating water influx into the reservoir, their limitation in terms of application and aquifer modelling facilities available in Eclipse software.

#### 2.1 Classification of Reservoir-Aquifer System

A reservoir-aquifer system refers to the reservoir which is bounded with an aquifer. A reservoir is a subsurface body of rock having sufficient porosity and permeability to store and transmit fluids. While, a water bearing rock is called an aquifer. (Schlumberger, 2017). The fluids referred in this contest are oil, gas, and water. Reservoir-aquifer systems are commonly classified based on the following four categories (Ahmed, 2006).

- Flow regimes
- Flow geometry
- Outer boundary conditions and
- Degree of pressure maintenance

##### 2.1.1 Flow regimes

Three flow regimes are basically considered in describing fluid flow in the reservoir. These are steady state, semi-steady state, and unsteady state. Steady state flow regime occurs when the rate of change of pressure at every location in the reservoir is zero. This is when the reservoir is supported by pressure maintenance operations or when there is a recharge from strong aquifer. Semi-steady state occurs when the rate of change of pressure is constant and unsteady state flow regime occurs when the rate of change of pressure is not zero or constant (Ahmed, 2006).

##### 2.1.2 Flow geometry

The reservoir-aquifer system can be classified based on flow geometry as edge water drive, bottom water drive and linear water drive based on the direction of water encroachment into the reservoir. In edge water drive, water encroaches through the flanks of the reservoir when the reservoir pressure declines due to production. In bottom water drive, water encroach the reservoir in vertical direction from the bottom especially when the aquifer completely underlies

the reservoir. In linear water drive, water encroach from one side of the reservoir in linear direction. Figure 5 illustrate in detail (Ahmed, 2006).

**2.1.3 Outer boundary conditions**

The reservoir-aquifer classification based on outer boundary condition can be infinite or finite. Infinite system is when the pressure changes at the reservoir-aquifer boundary is not felt at the aquifer boundary. While the finite system is when the change of pressure at the reservoir-aquifer boundary is felt at the aquifer boundary (Ahmed, 2006).

**2.1.4 Degree of pressure maintenance**

The reservoir-aquifer classification based on the degree of pressure maintenance can be grouped into three categories. Active water drive, partial water drive and limited water drive. In active water drive system, there is 100 percent voidage replacement, meaning that the rate of water influx is equals to the total production rate. The plot of oil rate versus time on the semi-logarithm scale tends to be flat as shown on Figure 3 (AAPG WIKI, 2016)

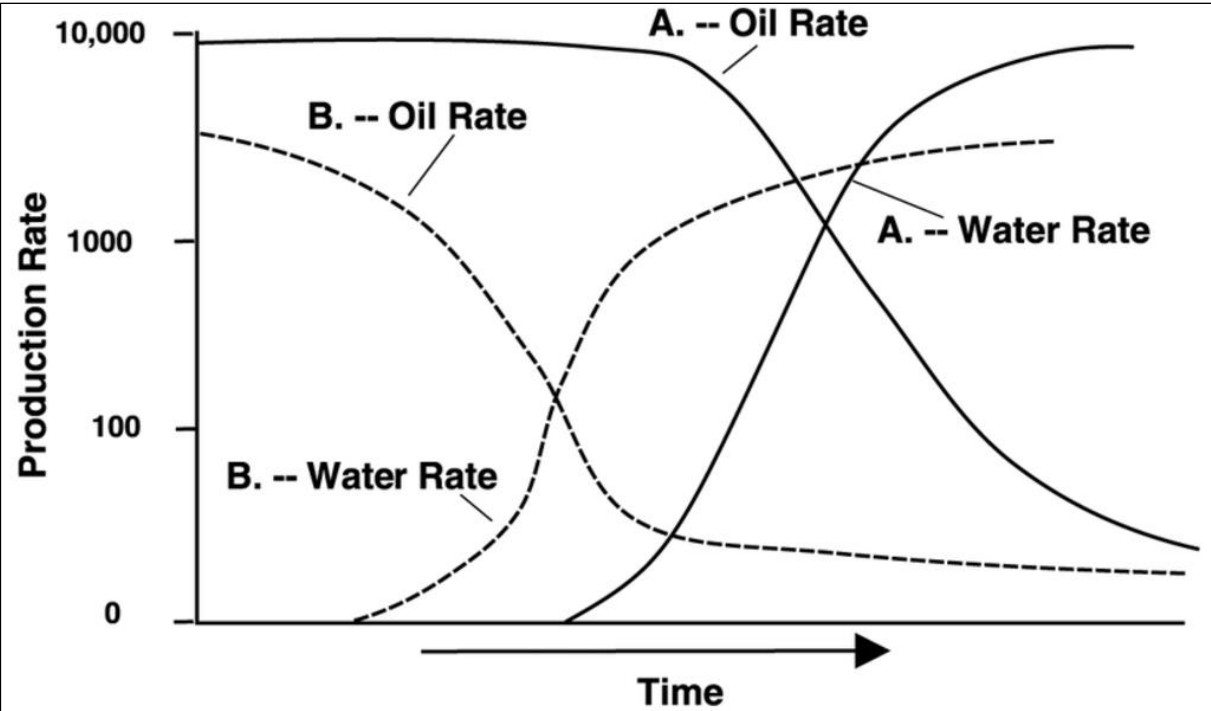


Figure 3 Typical decline curves for a wellbore draining a reservoir system with a strong water drive (A) and partial water drive (B) (AAPG WIKI, 2016)

Furthermore, it is possible to have a reservoir-aquifer system with combination of the categories. For example, an aquifer in which water encroaches into the reservoir from the bottom can be of significant larger size to be regarded as an infinite.

## **2.2 Factors Causing Water Influx into the Reservoir**

In response to the pressure drop due to production, and when the reservoir is hydraulically connected with an aquifer and the size of the aquifer is larger enough with high permeability, water in the aquifer begins to expand and moves into the reservoir to offset the pressure decline. Apart from expansion of water in the aquifer, there are other factors causing water influx into the reservoir. These include expansion of other known or unknown accumulation of hydrocarbon in the aquifer rock, compressibility of the aquifer rock and artesian flow especially when the water bearing formation is located structurally high than the pay zone (Craft, Hawkins, & Terry, 1991; Ahmed, 2006).

## **2.3 Significance of Estimating Water Influx into the Reservoir**

The accurate estimation of water influx into the petroleum reservoir is very important in various applications such as material balance calculations, reservoir simulation studies, production scheduling and setting up development strategies to optimize hydrocarbon recovery (Alghanim, Nashawi, & Malallah, 2012). For example, in water drive reservoir, estimation of initial oil in place or amount of oil produced at specific interval of time requires amount of water influx into the reservoir to be known. Likewise, in reservoir simulation studies, inclusion of aquifer into reservoir simulation model can help to reduce model uncertainties in case when water influx into the reservoir is significant.

## **2.4 Models Applied in Estimating Water Influx into the Reservoir**

Water influx models are mathematical models that simulate and predict cumulative water influx into the reservoir. Various researchers have proposed models that estimates cumulative water influx into the reservoir. To mention some of them: (Schilthuis, 1936; van Everdingen & Hurst, 1949; Cater & Tracy, 1960; Fetkovich, 1971; Allard & Chen, 1988). Out of them three models are considered more realistic to date: the van Everdingen-Hurst model, Carter-Tracy model and Fetkovich model (Petrowiki, 2015). The following are some of models applied in estimating water influx into the reservoir listed based on authors.

- Pot Aquifer model
- Schilthuis' steady-state model
- Hurst's modified steady-state model
- van Everdingen and Hurst unsteady-state model
- Coats model or Allard and Chen model
- Carter Tracy water influx model and

- Fetkovich water influx model

### 2.4.1 Pot Aquifer model

In this model, the aquifer pressure is assumed to be at equilibrium with the boundary pressure. The model is valid when the size of the aquifer is very small compared with the size of the reservoir and when the fluid transmissibility between the aquifer and the reservoir is very large. In addition, when the size of the aquifer is larger than the size of the reservoir the model becomes unrealistic (Leung, 1986). The model is simple and uses the basic definition of compressibility with time independent material balance as shown in Equation 2.1 (Dake, 1978; Ahmed, 2006). Considering the following definitions for the symbols.

$\bar{c}$  is the total aquifer compressibility (water and rock) in  $psi^{-1}$

$W_i$  is initial volume of water in the aquifer in *bbl*

$p_i$  is initial aquifer/reservoir pressure in *psi*

$p$  is current reservoir pressure in *psi*

$W_e$  is cumulative water influx into the reservoir in *bbl*

$$W_e = \bar{c} W_i (p_i - p) \quad (2.1)$$

It should be noted that, Equation 2.1 suggests water influx is coming radially from all direction. This condition becomes unrealistic in case the reservoir is not circular in nature. Equation 2.3 shows modification made to Equation 2.1 to account the flow mechanism by adding fractional influx angle (Ahmed, 2006). It could be suggested that for larger aquifers, a mathematical model should be used that include time dependent variable to account the fact that it takes a finite time for aquifer to respond to the pressure changes into the reservoir (Dake, 1978). The definition of the fractional influx angle ( $f$ ), is shown in Equation 2.2.

$$f = \frac{\text{Influx angle in degree}}{360^\circ} = \frac{\theta}{360^\circ} \quad (2.2)$$

$$W_e = \bar{c} W_i f (p_i - p) \quad (2.3)$$

## 2.4.2 Schilthuis' steady-state model

The model hold the steady state condition, that is the rate of change of pressure is equal to zero, and assumes the aquifer volume is very large than the reservoir volume such that the pressure at the external boundary of aquifer remains constant at initial pressure throughout the entire field life (Craft, Hawkins, & Terry, 1991; Fekete, 2014; Petrowiki, 2015). The rate of water influx into the reservoir is proportional to the pressure drawdown,  $(p_i - p)$  and can be determined by using Darcy equation as shown in Equation 2.5 (Craft, Hawkins, & Terry, 1991; Ahmed, 2006). Considering the following definitions for the symbols.

$\frac{dw_e}{dt}$  is the rate of water influx in *bbl/day*

$C$  is the water influx constant in *bbl/day /psi*

$k$  is permeability of the aquifer in *md*

$h$  is thickness of the aquifer in *ft*

$r_a$  is the radius of the aquifer in *ft*

$r_0$  is the radius of the reservoir in *ft*

$\mu_w$  is the viscosity of water in *cP*

The parameter  $C$ , can be defined as shown in Equation 2.4

$$C = \left[ \frac{0.00708kh}{\mu_w \ln\left(\frac{r_a}{r_0}\right)} \right] \quad (2.4)$$

$$\frac{dw_e}{dt} = C (p_i - p) \quad (2.5)$$

In addition to that, one of the weakness of the Schilthuis' steady-state model is that as water is drained from the aquifer, the aquifer radius,  $r_a$  increases with time or in other word the length of invading water to reach to the reservoir increases with time (Craft, Hawkins, & Terry, 1991; Ahmed, 2006).

### 2.4.3 Hurst's modified steady-state model

Hurst's in 1943 proposed a method to eliminate problem encountered in Schilthus's steady-state model by replacing dimensionless radius,  $r_a/r_0$  with time dependent function,  $at$ . The Hurst's modified steady-state model is shown in Equation 2.6 (Ahmed, 2006).

$$\frac{dw_e}{dt} = \left[ \frac{0.00708kh}{\mu_w \ln(at)} \right] (p_i - p) \quad (2.6)$$

By defining the parameter C as shown in Equation 2.7, Equation 2.6 is reduced to Equation 2.8.

$$C = \frac{0.00708kh}{\mu_w} \quad (2.7)$$

$$e_w = \frac{dw_e}{dt} = \frac{C}{\ln(at)} (p_i - p) \quad (2.8)$$

Equation 2.8 can be re-arranged as shown in Equation 2.9 - 2.10 and a plot of  $\left(\frac{p_i - p}{e_w}\right)$  versus  $\ln(t)$  in log-log scale can be constructed provided that historical water influx rates,  $e_w$  are available, for example determined separately using another technique such as material balance method. The trendline will give a slope of  $\frac{1}{C}$  and y-intercept a value of  $\frac{\ln(a)}{C}$  estimated when time  $t = 1$  as shown in Figure 4. In addition, (Craft, Hawkins, & Terry, 1991) pointed that Hurst's method is infrequently used because of limited application.

$$\left(\frac{p_i - p}{e_w}\right) = \frac{\ln(at)}{C} \quad (2.9)$$

$$\left(\frac{p_i - p}{e_w}\right) = \frac{\ln(t)}{C} + \frac{\ln(a)}{C} \quad (2.10)$$

The parameter C is a group of variables as shown in Equation 2.7 which represent an overall driver for water influx into the reservoir. For example, when the parameter C is large the rate of water influx into the reservoir will increase and vice versa hold.

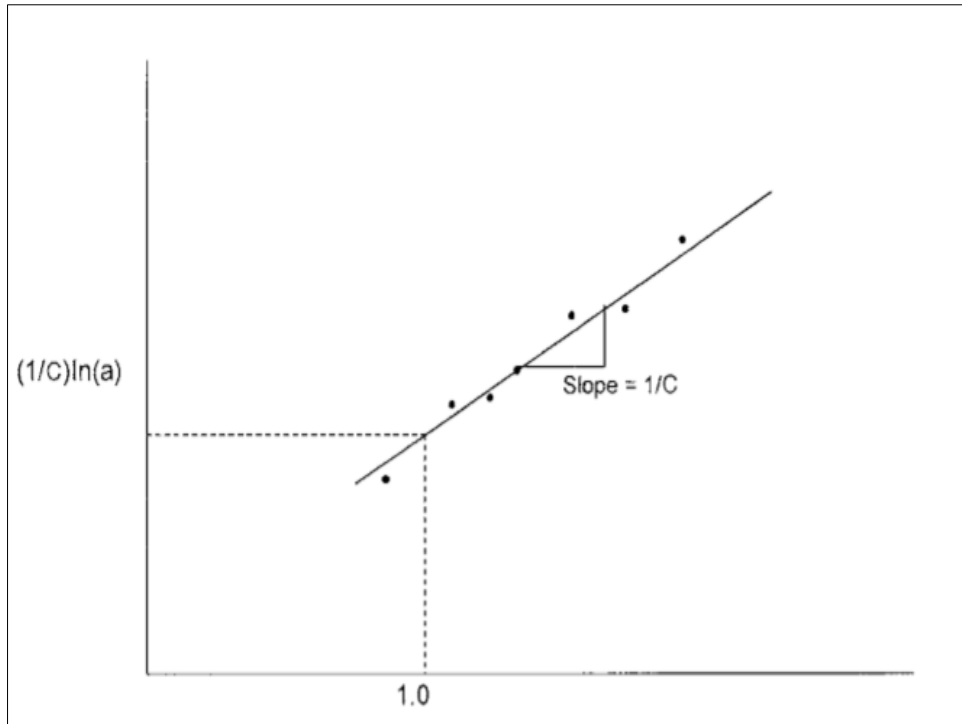


Figure 4 Graphical determination of constants  $C$  and  $a$  in the Hurst's modified steady-state model (Ahmed, 2006)

#### 2.4.4 van Everdingen and Hurst unsteady-state model

The van Everdingen and Hurst model represents a mathematical model that estimate the cumulative water influx into the reservoir by using superposition principle. The authors solved the radial diffusivity equation for water influx into the reservoir by applying Laplace transformation. The detail of radial diffusivity equation and its derivation of the solution can be found through the following paper (van Everdingen & Hurst, 1949). The model is applicable for determining water influx of the following systems: edge water-drive system, bottom water-drive system and linear water-drive system as shown in Figure 5. The authors proposed solutions to the dimensionless diffusivity equation shown in Equation 2.14 for constant terminal rate and constant terminal pressure boundary conditions (Klins, Bouchard, & Cable, 1988; Ahmed, 2006).

In constant terminal rate boundary condition, the rate of water influx at the reservoir-aquifer boundary is assumed to be constant and pressure drop at the interface of the reservoir-aquifer system is calculated as a function of time.



While, for constant terminal pressure boundary condition, the constant pressure drop is assumed over finite period and water influx is calculated. In addition, various researchers recommend calculation of water influx into the reservoir-aquifer boundary rather than pressure (Dake, 1978; Klins, Bouchard, & Cable, 1988; Craft, Hawkins, & Terry, 1991; Ahmed, 2006). This is because water influx into the reservoir is a function of time and pressure drop at the inner boundary condition of reservoir-aquifer system.

The following definitions for symbols can be considered.

$k$  = aquifer permeability, md;  $t$  = time, hours;  $r_o$  = outer reservoir radius, ft;  $\phi$  = porosity, fraction;  $\mu$  = water viscosity, cp;  $c_t$  = aquifer compressibility,  $psi^{-1}$ ;  $r$  = distance from centre of well, ft;  $p_i$  = initial reservoir pressure, psi;  $p$  = current reservoir pressure, psi and  $p_{wf}$  = bottom hole flowing pressure, psi.

The dimensionless parameters are defined in Equation 2.11-2.13 (Craft, Hawkins, & Terry, 1991).

$$\text{Dimensionless time: } t_D = 0.0002637 \frac{kt}{\phi \mu c_t r_o^2} \quad (2.11)$$

$$\text{Dimensionless radius: } r_D = \frac{r}{r_o} \quad (2.12)$$

$$\text{Dimensionless pressure: } p_D = \frac{p_i - p}{p_i - p_{wf}} \quad (2.13)$$

$$\frac{\partial p_D}{\partial r_D^2} + \frac{1}{r_D} \frac{\partial p_D}{\partial r_D} = \frac{\partial p_D}{\partial t_D} \quad (2.14)$$

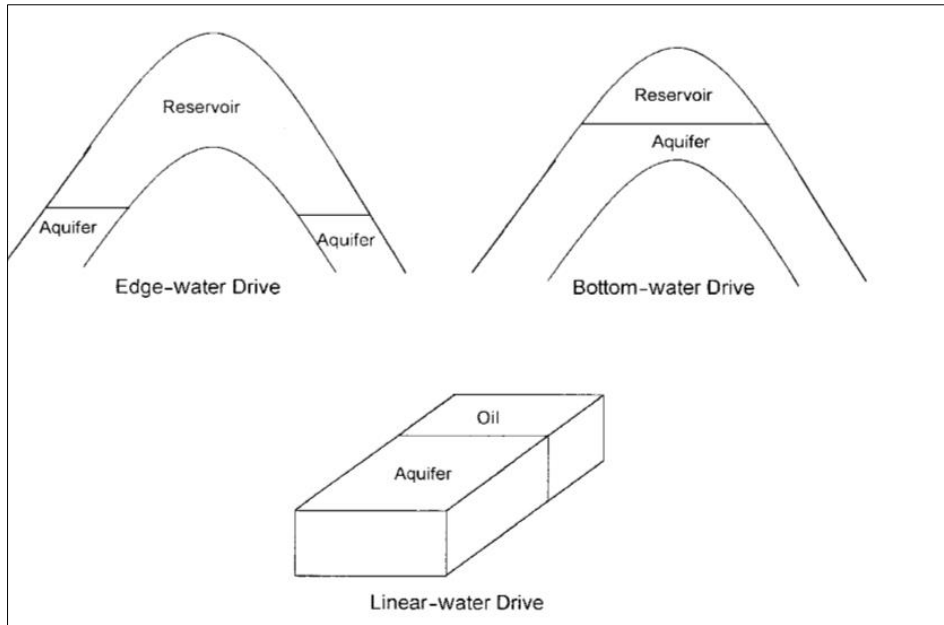


Figure 5 Flow geometries describing water influx into the reservoir (Ahmed, 2006)

Equation 2.15 shows the cumulative water influx into the reservoir due to instantaneous pressure drop at the outer boundary. The value of water influx constant,  $U$ , and dimensionless time,  $t_D$  depends on the geometry of the reservoir- aquifer system. For example, for the radial aquifer geometry as shown in Figure 6, the equations for determining water influx constant and dimensionless time are shown in Equation 2.16 and Equation 2.17 respectively. Likewise, for a linear aquifer geometry as shown in Figure 7, water influx constant and dimensionless time can be determined using Equation 2.18 and Equation 2.19 respectively (Dake, 1978). Further, considering the following definitions for the symbols.

$W_D$  is dimensionless cumulative water influx

$\Delta p$  is a pressure-drop at the reservoir-aquifer boundary in  $psi$

$U$  is the water influx constant in  $bbl/psi$ ; its value depends on the geometry (radial or linear)

$L$  = length of the aquifer in  $ft$

$W$  = width of the aquifer in  $ft$

$W_e$  is cumulative water influx in  $bbl$

$$W_e = U\Delta p W_D(t_D) \quad (2.15)$$

For radial aquifer in field units;

$$U = 1.119f\phi h c_t r_o^2 \text{ (bbl/psi)} \quad (2.16)$$

$$t_D = \text{Constant} * \frac{kt}{\phi \mu c_t r_o^2} \quad (2.17)$$

The constant = 0.000264 (t in hours)

= 0.006634 (t in days)

= 2.309 (t in years)

For linear aquifer in field units;

$$U = 0.1781WLh c_t \text{ (bbl/psi)} \quad (2.18)$$

$$t_D = \text{Constant} * \frac{kt}{\phi \mu c_t L^2} \quad (2.19)$$

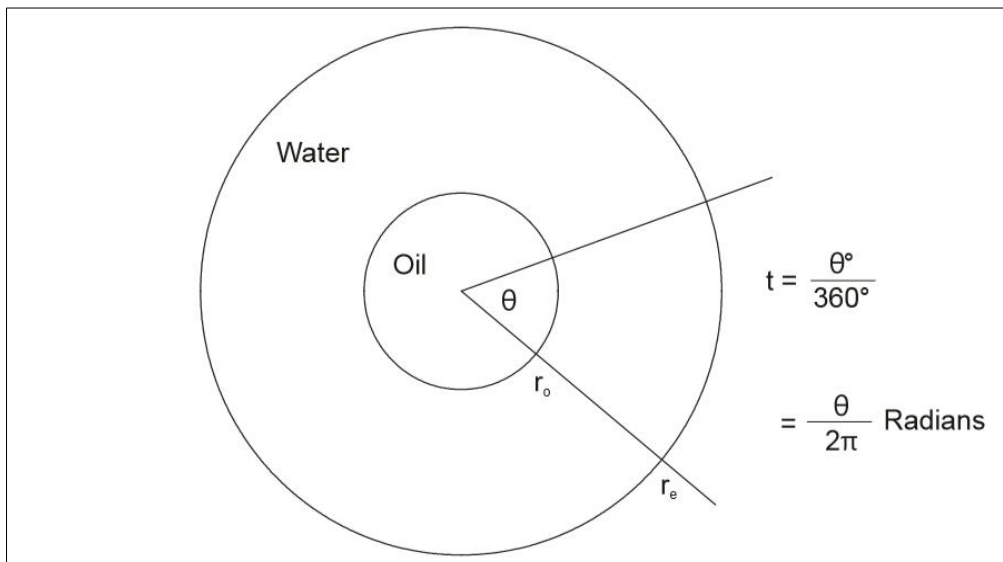


Figure 6 Radial aquifer geometry (Dake, 1978)

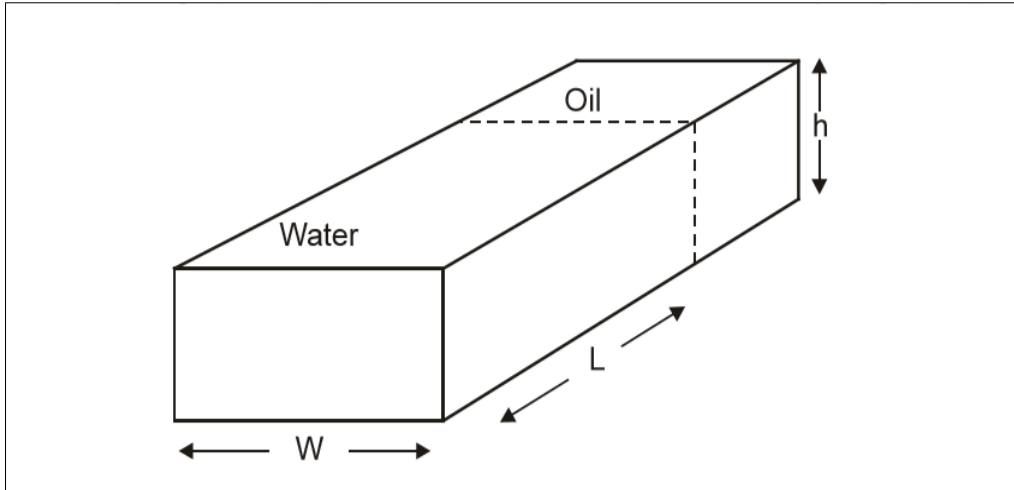


Figure 7 Linear aquifer geometry (Dake, 1978)

Since Equation 2.15 is usually used to calculate the cumulative water influx into the reservoir due to instantaneous pressure drop at the outer boundary; it is necessary to establish a relationship for calculating the total water influx at any given time during depletion stage. van Everdingen and Hurst proposed a concept of superposition which enables calculation of water influx at each successive pressure drop in the reservoir-aquifer system. Equation 2.20 shows the application of superposition principle (Dake, 1978; Ahmed, 2006).

$$W_e(T) = U[\Delta p_0 W_D(T_D) + \Delta p_1 W_D(T_D - t_{D1}) + \Delta p_2 W_D(T_D - t_{D2}) + \dots + \Delta p_j W_D(T_D - t_{Dj}) + \dots + \Delta p_{n-1} W_D(T_D - t_{Dn-1})] \quad (2.20)$$

By considering the following definition for the symbols:

$T$  is the selected arbitrary time corresponding to the end of  $n^{\text{th}}$  time step.

$\Delta p_j$  is pressure drops corresponding to time 0,  $t_1, t_2, t_3$ , etc.

Equation 2.20 can be written in general form as shown in Equation 2.21.

$$W_e(T) = U \sum_{j=0}^{n-1} \Delta p_j W_D(T_D - t_{Dj}) \quad (2.21)$$

Few things to note regarding to Equation 2.21. The term  $W_D(T_D - t_{Dj})$  does not represent two separate functions instead it stands for dimensionless cumulative water influx as a function of dimensionless time. The definition of dimensionless time has been presented in Equation 2.17 and is applicable for both early time influx, once the aquifer boundary effect has been felt and as well as for infinite aquifer case. The illustration on determining values of  $W_D(t_D)$  at different

aquifer-reservoir radius ratio,  $r_{eD}$  can be obtained by considering the use of Figure 9. For more details, the following book can be consulted (Dake, 1978). Furthermore, the method of determining values of pressure drops,  $\Delta p_j$  was initially suggested by van Everdingen, Timmerman and McMahon by matching the continuous historical pressure decline at the reservoir-aquifer boundary by a series of discrete pressure step function as shown in Figure 8.

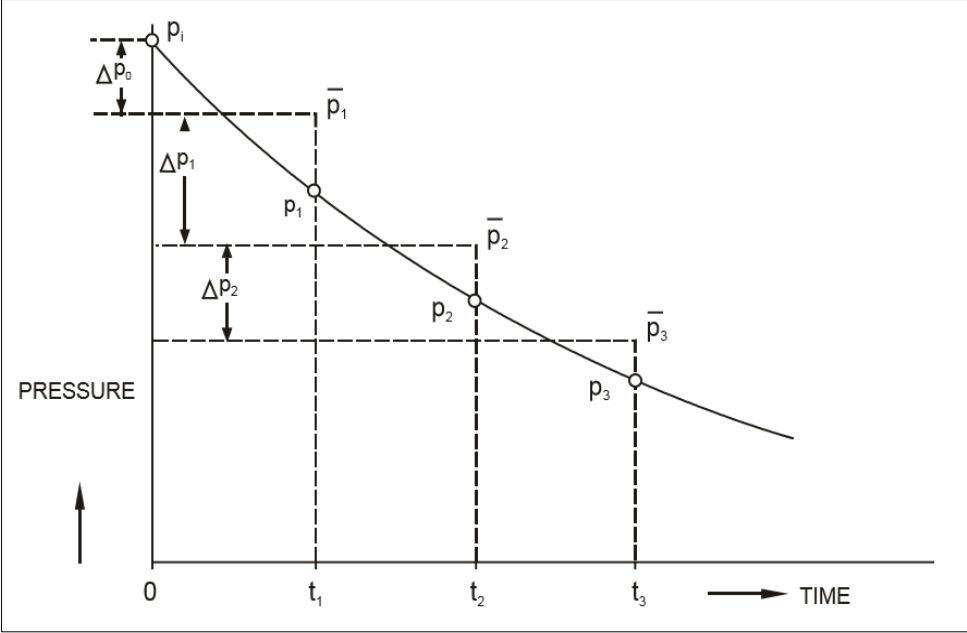


Figure 8 Matching a continuous pressure decline at the reservoir-aquifer boundary by a series of discrete pressure step function (Dake, 1978)

Equation 2.22 shows the calculations procedure for boundary pressure at the interface of the reservoir-aquifer system as an emphasize of Figure 8.

$$\bar{p}_n = \frac{p_{n-1} + p_n}{2} \tag{2.22}$$

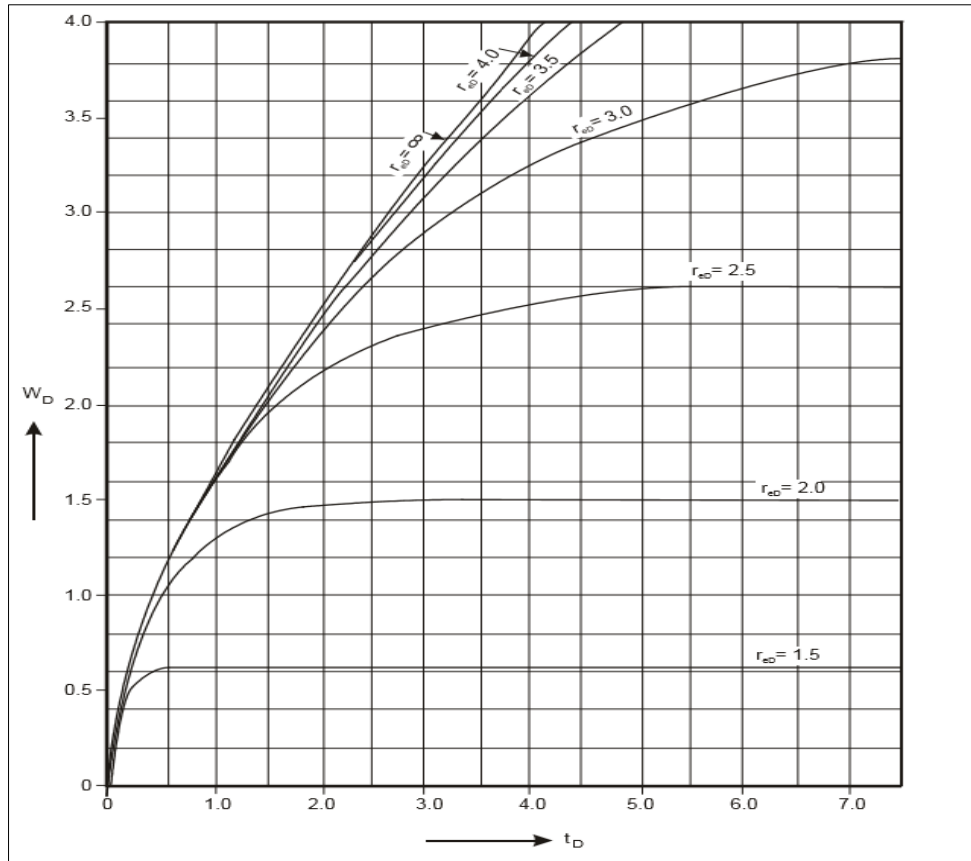


Figure 9 Dimensionless water influx for constant terminal pressure case, radial (Dake, 1978)

#### 2.4.5 Coats model or Allard and Chen model

Although, the van Everdingen and Hurst (VEH) model is considered the most exact water influx model for benchmarking available in the literature due to its faithfulness in describing the radial diffusivity equation of fluid flow in the reservoir or aquifer (Klins, Bouchard, & Cable, 1988; Marques & Trevisan, 2007; Al-ghanim, Nashawi, & Malallah, 2012); it is not adequately used to describe significant vertical water influx in bottom water drive system. To account the effect of vertical water movement into the reservoir, Coats in 1962 and later Allard and Chen in 1988 developed a mathematical model specifically for bottom water drive by modifying the diffusivity equation to consider the vertical flow in reservoir-aquifer system as shown in Equation 2.23-2.24 (Craft, Hawkins, & Terry, 1991; Ahmed, 2006). Considering the following definition of the symbols.

$F_k$  is the ratio of vertical to horizontal permeability.

$\mu$  is viscosity of water in  $cP$

$\emptyset$  is the porosity of aquifer in fraction

$c_t$  is the total compressibility (rock and water) in  $psi^{-1}$

$k$  is the aquifer permeability in  $md$

$$F_k = \frac{\text{vertical permeability}}{\text{horizontal permeability}} \quad (2.23)$$

$$\frac{\partial^2 p}{\partial r^2} + \frac{1}{r} \frac{\partial p}{\partial r} + F_k \frac{\partial^2 p}{\partial z^2} = \frac{\mu \emptyset c_t}{k} \frac{\partial p}{\partial t} \quad (2.24)$$

The solution developed by Allard and Chen for bottom-water drive system is identical to van Everdingen and Hurst as shown in Equation 2.27 (Ahmed, 2006). Furthermore, considering the following definition for symbols.

$z_D$  = dimensionless vertical distance as shown in Equation 2.25.

$B$  = water influx constant as shown in Equation 2.26.

$W_{eD}$  = dimensionless cumulative water influx

$$z_D = \frac{h}{r_o \sqrt{F_k}} \quad (2.25)$$

$$B = 1.119 \emptyset h c_t r_o^2 \text{ (bbl/psi)} \quad (2.26)$$

$$W_e = B \Delta p W_{eD}(r_D, t_D, z_D) \quad (2.27)$$

It is important to note that, water influx constant,  $B$  in Equation 2.26 does not include water influx angle,  $\theta$  as in VEH model. In addition, the actual values of dimensionless cumulative water influx,  $W_{eD}$  are different from those of VEH model as now,  $W_{eD}$  is the function of three parameters:  $r_D$ ,  $t_D$  and  $z_D$ . Meanwhile, dimensionless cumulative water influx in VEH model is the function of only two parameters:  $r_D$  and  $t_D$ .

## 2.4.6 Carter Tracy water influx model

In 1960 Cater and Tracy developed a simplified method of calculating direct water influx into the reservoir without using superposition principle. The method assumes constant water influx rate into the reservoir for each finite interval of time rather than constant terminal pressure as assumed by van Everdingen and Hurst method (Cater & Tracy, 1960). The cumulative water influx at any time,  $t_n$  are calculated using values obtained at previous time step,  $t_{n-1}$  as shown in Equation 2.28 (Ahmed, 2006). The following definition for the symbols can be considered.

$B$  = water influx constant in *bbl/psi*. The same as in VEH model in Equation 2.16.

$t_D$  = dimensionless time, same as in Equation 2.17.

$\Delta p_n$  = total pressure drop,  $p_i - p_n$  in *psi*

$n$  = current time step in *years*

$n - 1$  = previous time step in *years*

$p_D$  = dimensionless pressure

$p_D'$  = dimensionless pressure derivative

$$(W_e)_n = (W_e)_{n-1} + [(t_D)_n - (t_D)_{n-1}] * \left[ \frac{B\Delta p_n - (W_e)_{n-1}(p_D)_n'}{(p_D)_n - (t_D)_{n-1}(p_D)_n'} \right] \quad (2.28)$$

The values of  $(p_D)_n$  and  $(p_D)_n'$  are function of  $t_D$  and  $r_D$  and can be estimated by using polynomial equations developed by (Klins, Bouchard, & Cable, 1988).



### 2.4.7 Fetkovich water influx model

The Fetkovich model represents a simplified model to unsteady-state model of van Everdingen-Hurst which eliminates the use of superposition. The method utilizes the stabilized or pseudosteady-state aquifer productivity index and aquifer material balance in calculation of water influx into the reservoir as shown in Figure 10. Fetkovich presented a generalized rate equation for an aquifer as shown in Equation 2.29 (Fetkovich, 1971; Craft, Hawkins, & Terry, 1991). Considering the following definition for the symbols.

$q_w$  = aquifer influx rate in *bbl/day*

$J$  = aquifer productivity index which is the function of aquifer geometry in *bbl/psi/day*

$\bar{p}$  = average aquifer pressure in *psi*

$p_R$  = reservoir-aquifer pressure boundary in *psi*

$n = 1$  for Darcy flow and pseudosteady-state condition

$\bar{p}$  = Average aquifer pressure in *psi*

$p_i$  = initial aquifer pressure in *psi*

$W_{ei}$  = initial encroachable water in place in *bbl*

$W_e$  = cumulative water influx into the reservoir in *psi*

$$q_w = J(\bar{p} - p_R)^n \quad (2.29)$$

Fetkovich also wrote the aquifer material balance equation for constant compressibility system as shown in Equation 2.30. Equations 2.29 and 2.30 can be combined to obtain Equation 2.31 (Craft, Hawkins, & Terry, 1991).

$$\bar{p} = -\left(\frac{p_i}{W_{ei}}\right)W_e + p_i \quad (2.30)$$

$$W_e = \frac{W_{ei}}{p_i}(p_i - p_R)\left(1 - e^{\frac{-Jp_it}{W_{ei}}}\right) \quad (2.31)$$

Fetkovich noted that Equation 2.31 was derived at constant reservoir-aquifer boundary pressure,  $p_R$  and constant average aquifer pressure,  $\bar{p}$  and cannot handle a practical problem where the reservoir-aquifer boundary pressure is changing with time. Previous researchers such as van Everdingen and Hurst handled this problem by using superposition principle. Fetkovich handled this problem by re-evaluation of aquifer shut in pressure at each time and eliminate the need of superposition. Equations 2.32-2.38 represents the calculation of water influx by considering the use of Fetkovich method (Craft, Hawkins, & Terry, 1991). Considering the following definition for the symbols.

$\bar{p}_{n-1}$  = average aquifer pressure at the end of  $n - 1$  time interval in *psi*

$\bar{p}_{Rn}$  = average reservoir-aquifer boundary pressure during interval  $n$  in *psi*

$\Delta t_n$  = time interval in *days*

$\Delta W_{en}$  = incremental water influx for a short period,  $\Delta t_n$  in *bbl*

$W_{ei}$  = initial encroachable water in place in *bbl*

$W_e$  = cumulative water influx into the reservoir in *bbl*

$W_i$  = Cumulative water injection in *bbl*

$W_p$  = Cumulative water produced in *bbl*

$B_w$  = Water formation volume factor in *resevoir bbl/stocktank bbl*

$\sum_2^j W_{ej}$  = Summation of cumulative water influx from other reservoirs sharing a common aquifer in *bbl*

$$\Delta W_{en} = \frac{W_{ei}}{p_i} (\bar{p}_{n-1} - \bar{p}_{Rn}) \left( 1 - e^{-\frac{J p_i \Delta t_n}{W_{ei}}} \right) \quad (2.32)$$

$$\bar{p}_{n-1} = p_i \left( 1 - \frac{W_e}{W_{ei}} \right) \quad (2.33)$$

In case the aquifer is supported with injections, Equation 2.33 is modified to consider the interference due to injections into the aquifer as shown in Equation 2.34 (Fetkovich, 1971).

$$\bar{p}_{n-1} = - \left[ \frac{W_e + \sum_2^j W_{ej} + (W_p - W_i) B_w}{W_{ei}} \right] p_i + p_i \quad (2.34)$$

$$\bar{p}_{Rn} = \frac{p_{Rn-1} + p_{Rn}}{2} \quad (2.35)$$

$$\Delta t_n = t_n - t_{n-1} \quad (2.36)$$

$$W_{ei} = \frac{c_t \left( \frac{\theta}{360} \right) \pi (r_a^2 - r_o^2) h \phi p_i}{5.615} \quad (2.37)$$

$$W_e = \sum \Delta W_{en} \quad (2.38)$$

The aquifer productivity index, J can be determine as shown in Table 1.

*Table 1 Determination of aquifer productivity index, J (Craft, Hawkins, & Terry, 1991)*

<b>Type of Outer Aquifer Boundary</b>	<b>Radial Flow<sup>a</sup></b>	<b>Linear Flow<sup>b</sup></b>
Finite - no flow	$J = \frac{0.00708kh \left( \frac{\theta}{360} \right)}{\mu [\ln(r_a/r_o) - 0.75]}$	$J = \frac{0.003381kwh}{\mu L}$
Finite – constant pressure	$J = \frac{0.00708kh \left( \frac{\theta}{360} \right)}{\mu [\ln(r_a/r_o)]}$	$J = \frac{0.001127kwh}{\mu L}$

**a** Units are in normal field units with k in millidarcies

**b** w is width and L is length of linear aquifer

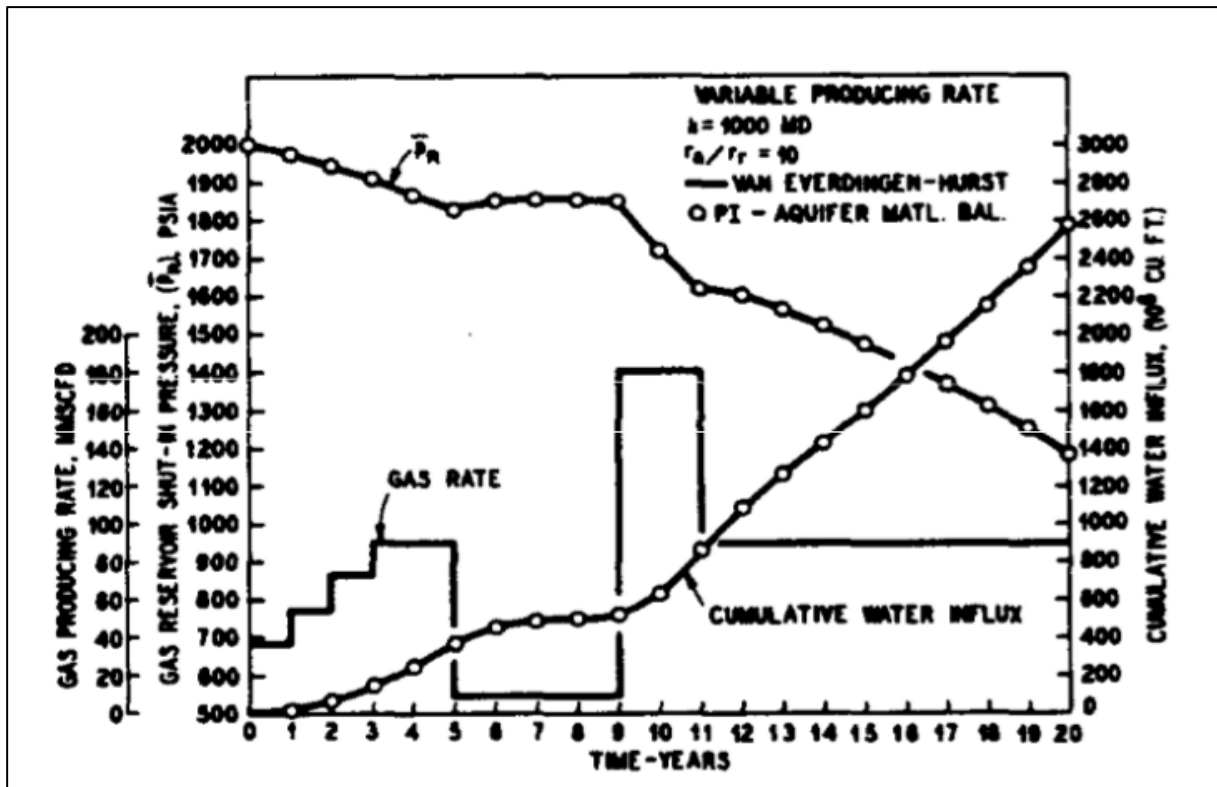


Figure 10 Comparison between PI-Aquifer material balance and van Everdingen-Hurst method for variable producing rate case (Fetkovich, 1971).

## 2.5 Aquifer Modelling Facilities in Eclipse

There are various ways to model an aquifer in Eclipse software. These include numerical aquifer, analytical aquifer (such as Fetkovich and Carter-Tracy aquifers), constant flux aquifer and constant head aquifer (Schlumberger, 2015).

### 2.5.1 Numerical aquifer

Numerical aquifer is created by nominating one-dimension row of cells within a simulation grid by using the keyword AQUNUM. The keyword AQUNUM contain information about properties of the aquifer such as length, cross-section area, porosity, permeability, initial pressure, depth, PVT, and saturation table numbers. A non-neighbour connections (NNCs) to the reservoir faces are specified by using keyword AQUCON. Both keywords AQUNUM and AQUCON are specified in GRID section. The dimensions of the aquifer are specified by using the keyword AQU DIMS in RUNSPEC section (Schlumberger, 2015). Figure 11 shows the definition of a numerical aquifer in Eclipse software.

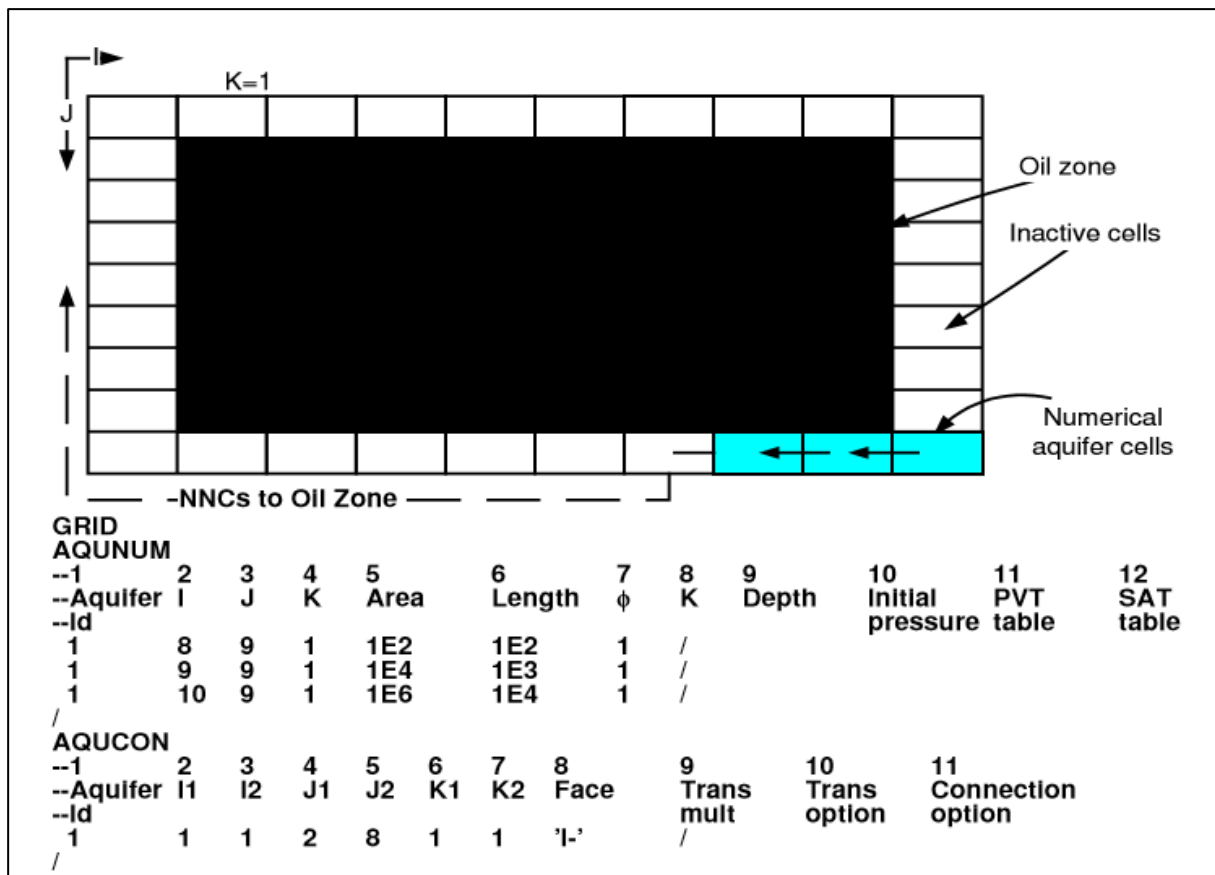


Figure 11 Numerical Aquifer Definition (Schlumberger, 1999)

### 2.5.2 Analytical aquifer

Analytical aquifer is created by computed source terms in the reservoir grid cells with which they join by using the keyword AQUCT (for Carter-Tracy aquifer) or AQUFET or AQUFETP (for Fetkovich aquifer). The aquifer is connected to the reservoir by using the keyword AQUANCON. Both keywords AQUCT, AQUFET and AQUANCON are specified in SOLUTION section. The dimensions of the aquifer are specified by using the keyword AQUADIMS in RUNSPEC section (Schlumberger, 2015).

### 2.5.3 Constant flux aquifer

A constant flux aquifer is defined by using the keyword AQUFLUX. It is joined to the reservoir grid by non-neighbour connection defined in the keyword AQUANCON. Both keywords AQUFLUX and AQUANCON are specified in SOLUTION section. The user directly specifies the flow rate of flux aquifer. The negative rate means the flux is out of the reservoir. In RUNSPEC section, flux aquifer is treated the same as analytical aquifer (Schlumberger, 2015).

#### **2.5.4 Constant head aquifer**

A constant head aquifer is defined by the keyword AUCHWAT for water aquifer and AUCHGAS for gas aquifer. The aquifer connection to the reservoir faces is made by using the keyword AQUANCON or AQANCONL. The difference between the latter two keywords is the connection to a global cell or local grid cell. The keywords AUCHWAT, AUCHGAS, AQUANCON and AQANCONL are specified in SOLUTION section. In RUNSPEC section, the keyword AQUUDIMS should be set to define the parameters NANAQU (maximum number of analytical aquifers) and NCAMAX (maximum number of grid blocks connected to aquifer) for the facility to function ([Schlumberger, 2015](#)).

#### **2.6 Conclusion**

In the literature, there are various models for estimating water influx into the reservoir. But, the following three models are frequently used. These include the van Everdingen and Hurst (VEH) model, Carter-Tracy model and Fetkovich model. These models will be investigated specifically to describe the Norne aquifer. Further, Eclipse software has various options to model an aquifer such as numerical aquifer, Carter-Tracy aquifer, Fetkovich aquifer, constant flux aquifer and constant head aquifer. The next chapter will explain the Norne field as the case study.

## CHAPTER 3

### NORNE FIELD AS A CASE STUDY

The study area of this research is the Norne field. This chapter will cover the description of the Norne field such as its location, the current operator and its licensee's partners, segments in the field and the development plan. Further, it will cover the geological and petrophysical information of the Norne field, the drainage strategy of the field, in place volumes, recoverable and remaining reserves, Norne field hydrocarbon composition.

#### 3.1 The Description of Norne Field

The Norne field is located at blocks 6608/10 and 6508/1 in the southern part of the Nordland II area in the Norwegian Sea. The currently operator of the Norne field is Statoil Petroleum AS company although there are three licensee's partners as shown in Table 2. The horst block dimension is approximately 9 km \* 3 km. The Norne field is 200 km from Norwegian continental shelf and 80 km north of Heidrun field with 380 m water depth, see Figure 12 (Lind, 2004; IO center NTNU, 2008).

The field is divided into two separate oil compartments. The main structure (which consists of segments C, D, and E) and the northeast segment (Norne G-segment), see Figure 13. Oil in the main structure was discovered in December 1991 and consists of 97% of oil in place. The oil production started in November 1997 and until this report is written in 2017, the field is under production (Lind, 2004; IO center NTNU, 2008).

The field is being developed with six templates (B, C, D, E, F, and K) and all templates are connected to the floating production and storage vessel through risers (Lind, 2004; IO center NTNU, 2008). Figure 14 shows development of the Norne field, platform structure and associated templates.

*Table 2 Norne field licensee's partners (NPD, 2016)*

<b>Company name</b>	<b>Company share (%)</b>
Petoro AS	54.00
Statoil Petroleum AS	39.10
Eni Norge AS	6.90

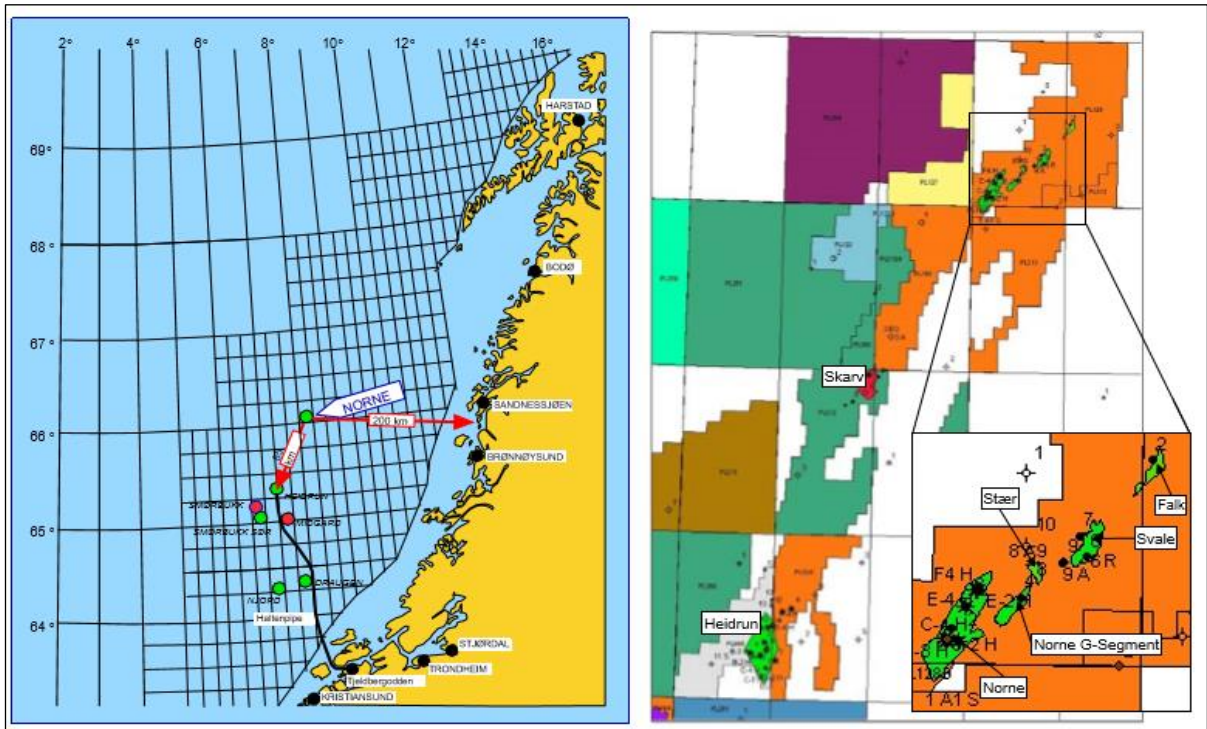


Figure 12 Location of the Norne field (Lind, 2004; IO center NTNU, 2008)

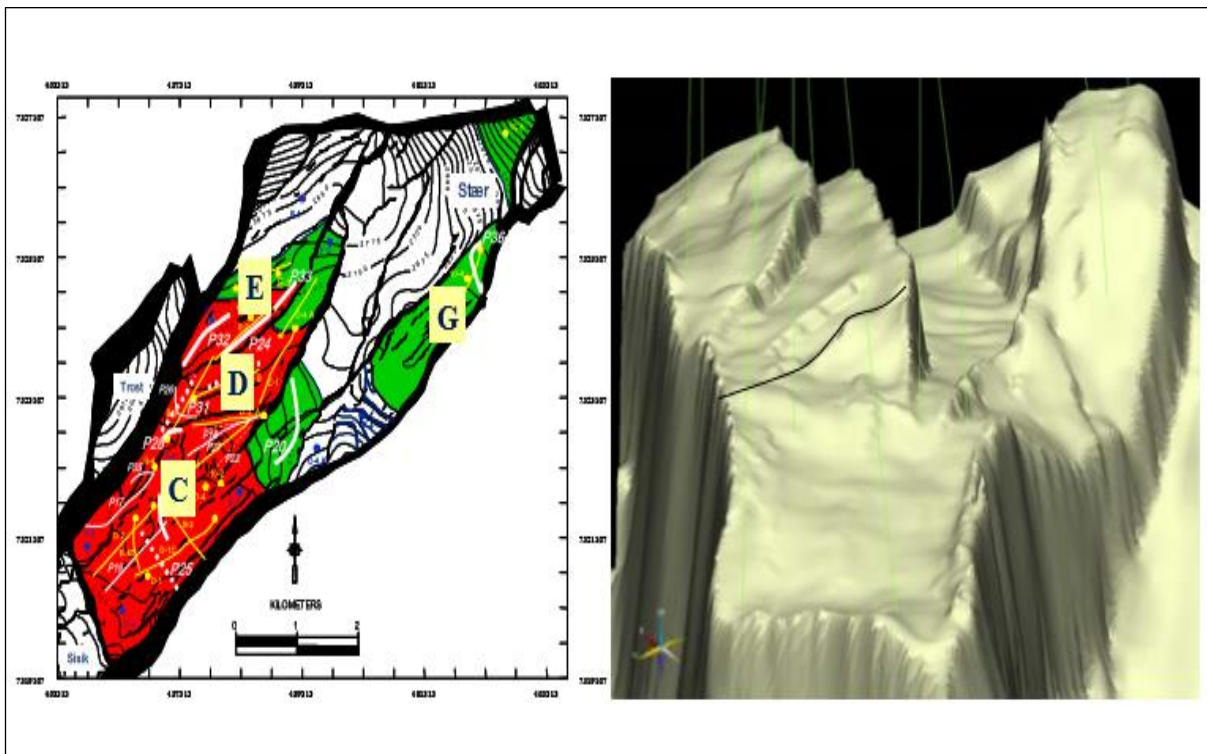


Figure 13 Segments and wells in the Norne field (Lind, 2004; IO center NTNU, 2008)



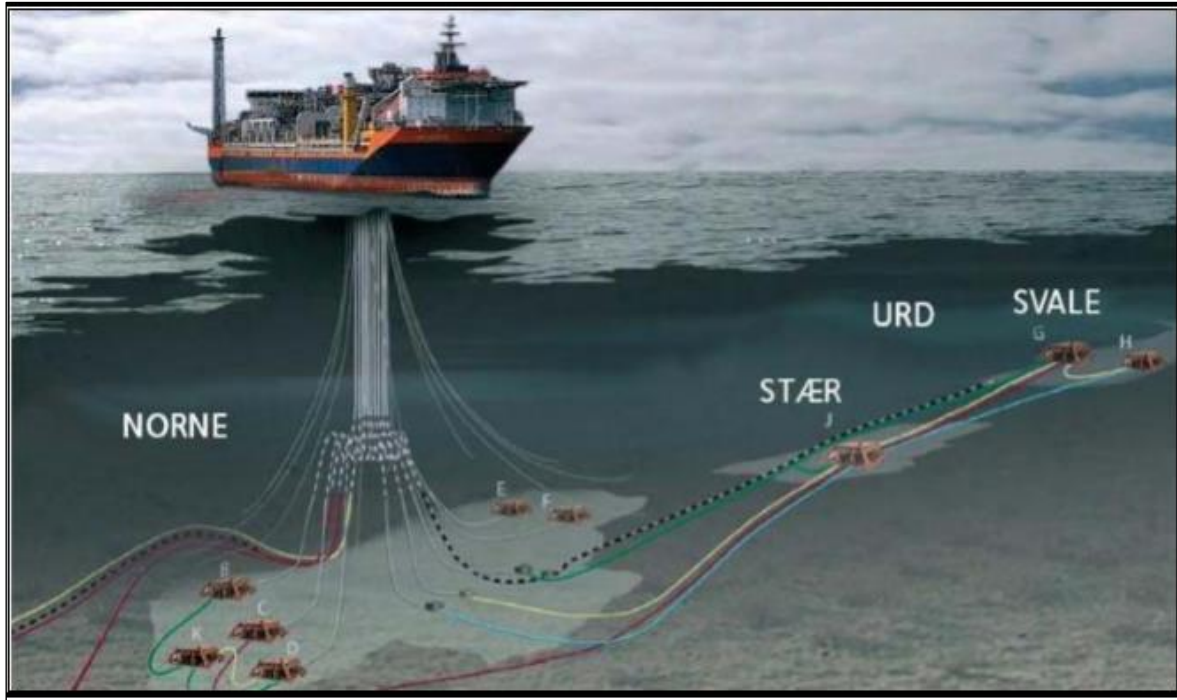


Figure 14 Development of Norne field (Lind, 2004; IO center NTNU, 2008)

### 3.2 Geological and Petrophysical Information of the Norne Field

The Norne field is subdivided into five geological formations from top to base. These formations are Garn, Not, Ile, Tofte and Tilje. The Garn formation contain approximately 25 m of gas column and on top of Gan formation there is a cap rock called Melke formation which seals the reservoir and keeps oil and gas in place. The Not is a claystone formation isolating Garn from Ile formation. This makes the gas in the Norne field being isolated from oil rather than a gas cap. The Ile and Tofte formation contain oil column of approximately 110 m thus making a total of hydrocarbon bearing column in the Norne field being 135 m based on well 6608/10-2. The water zone is mainly covered at the bottom of the Tilje formation. Therefore, most of oil production comes from Ile and Tofte formation (IO center NTNU, 2008).

The age of the reservoir rocks in the Norne field is of lower to middle Jurassic sandstones as shown in Figure 15. The top sand and lower sand are of interval 2500-2700 m respectively and are affected by diagenetic process. The reservoir is of good quality with average porosity ranging from 25-30 percent and permeability from 20-2500 millidarcy (IO center NTNU, 2008) The reservoir has 22 layers as shown in Table 3.

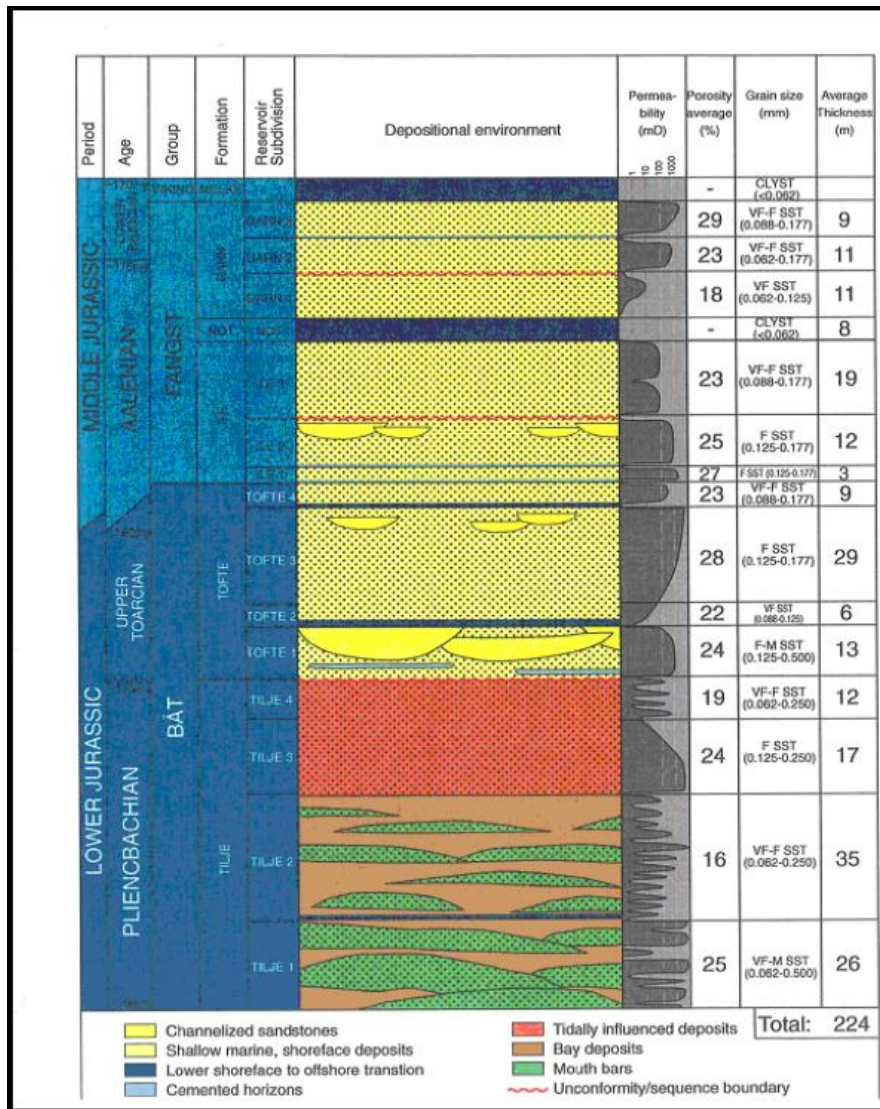


Figure 15 Stratigraphical sub-division of the Norne reservoir (IO center NTNU, 2008)

Table 3 Norne reservoir zonation (Rwechungura, et al., 2010; Abrahamsen, 2012)

Layer Number	Layer Name	Layer Number	Layer Name
1	Garn 3	12	Tofte 2.2
2	Garn 2	13	Tofte 2.1.3
3	Garn 1	14	Tofte 2.1.2
4	Not	15	Tofte 2.1.1
5	Ile 2.2	16	Tofte 1.2.2
6	Ile 2.1.3	17	Tofte 1.2.1
7	Ile 2.1.2	18	Tofte 1.1
8	Ile 2.1.1	19	Tilje 4
9	Ile 1.3	20	Tilje 3
10	Ile 1.2	21	Tilje 2
11	Ile 1.1	22	Tilje 1

### 3.3 The Drainage Strategy of Norne Field

The pre-start drainage strategy of the Norne field was to maintain reservoir pressure through up flank re-injection of the produced gas in the gas cap and down flank water injection in the water zone. However, during the first year of production, it was experienced that a Not shale formation is sealing the main structure and completely isolate what was described earlier as a gas cap (In fact is an isolated gas). Following that scenario, the drainage strategy in the Norne field was changed by re-injection of produced gas into water zone. Since gas is less dense than water, it then bubbles upward until it encounters a sealing Not shale formation at the top and form what is called a secondary gas cap. This secondary gas cap aids oil production by gravity displacement. In 2005, gas injection in Norne field was ceased, and the main drive mechanism for oil production was only by water injection. However, injection of gas from C-wells started again in 2006 for an extended period to avoid pressure depletion in gas cap (IO center NTNU, 2008). Figure 16 and Figure 17 shows the drainage strategy of Norne field.

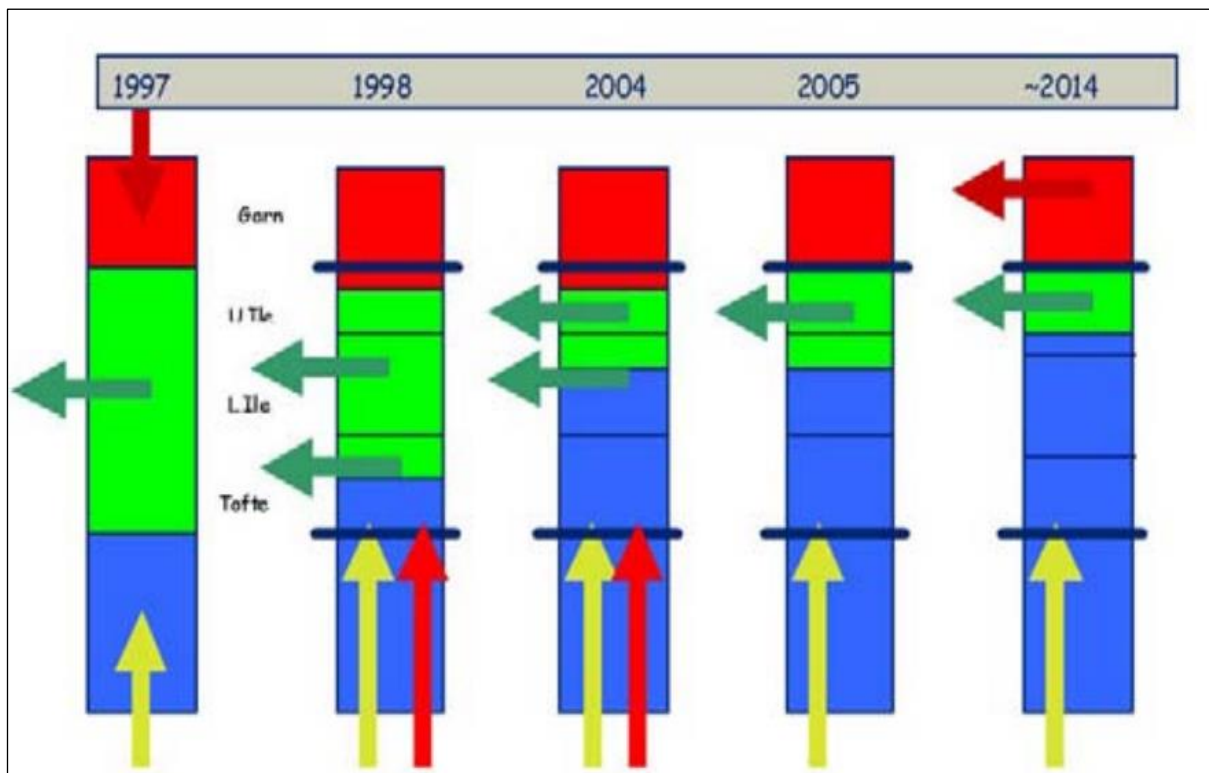


Figure 16 Drainage strategy of the Norne field from pre-start to 2014 (IO center NTNU, 2008)

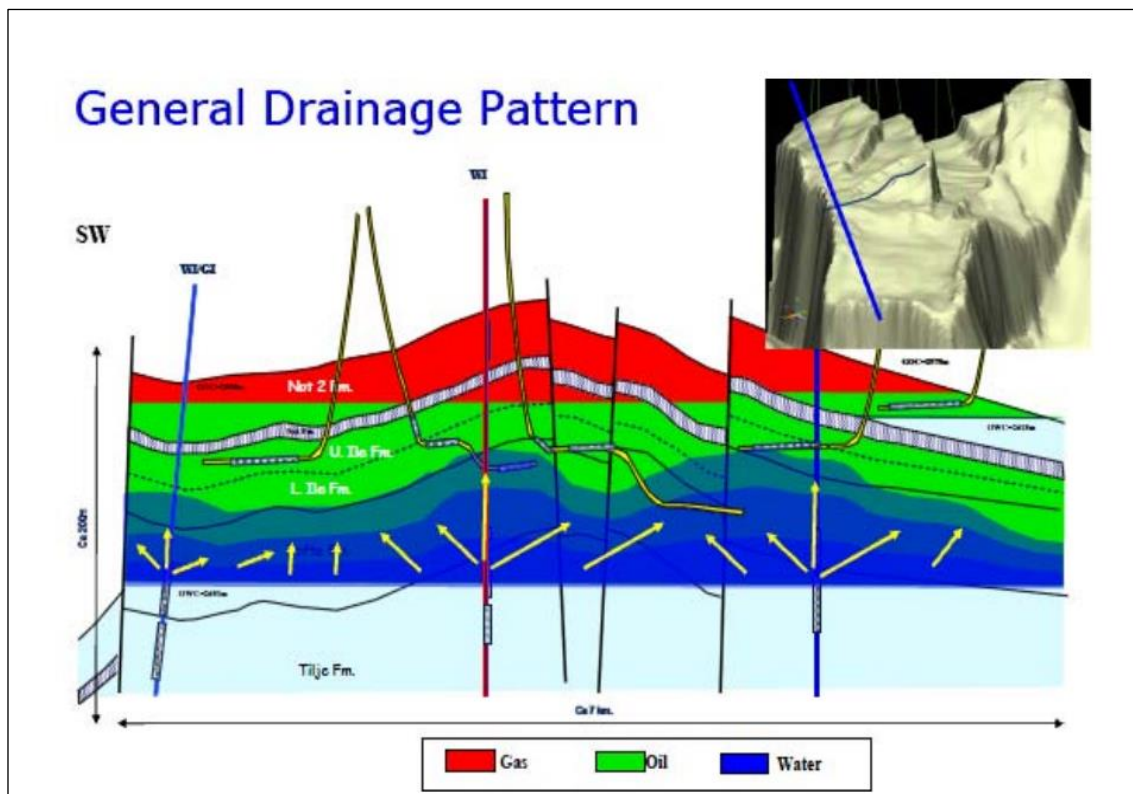


Figure 17 General drainage pattern of Norne field (IO center NTNU, 2008)

### 3.4 Norne Field in Place Volumes, Recoverable and Remaining Reserves

Table 4 shows the Norne field in place volumes, recoverable and remaining reserves. In approximation 80 percent of oil reserves in the Norne main structure is in Ile and Tofte formations. This indicates the potential area of concentration when setting drainage strategies of Norne reservoir. The free gas is in Garn formation and is completely isolated from oil column by an impermeable Not formation (Lind, 2004). The remaining oil and gas reserves are approximated  $2 * 10^6 Sm^3$  and  $3 * 10^9 Sm^3$  respectively. Following that situation, the Norne field production vessel is currently tied back with a satellite field called Urd for economic reason.

*Table 4 Norne field in place volumes, recoverable and remaining reserves updated until December 2016. (NPD, 2016)*

<b>Item</b>	<b>Value</b>	<b>Unit (Sm<sup>3</sup>)</b>
Original oil in place	157.00	*10 <sup>6</sup>
Original in place associated liquid	1.80	*10 <sup>6</sup>
Original in place associated gas	18.30	*10 <sup>9</sup>
Original in place free gas	11.50	*10 <sup>9</sup>
Original recoverable oil	90.50	*10 <sup>6</sup>
Original recoverable gas	10.20	*10 <sup>9</sup>
Original recoverable condensate	0.00	*10 <sup>6</sup>
Remaining oil	2.00	*10 <sup>6</sup>
Remaining gas	3.00	*10 <sup>9</sup>
Remaining condensate	0.00	*10 <sup>6</sup>

### **3.5 Norne Field Hydrocarbon Composition**

The Norne reservoir consist of both oil and gas hydrocarbon fluid. The oil in Norne reservoir is considered light with specific gravity of 0.86 (32.97° API). The molecular weight of gas is 19.31 *kg/kgmol*. The composition of oil and gas in the Norne field is presented in Figure 18.

Component	Norne Main Structure		Norne G-Segment Reservoir oil (mol%)
	Reservoir oil (mol%)	Reservoir gas (mol%)	
	N2	0,272	
CO2	0,874	1,306	0,69
C1	47,749	91,174	43,90
C2	3,921	3,869	3,96
C3	2,085	1,371	2,19
iC4	0,445	0,219	0,47
nC4	0,878	0,369	0,93
iC5	0,429	0,131	0,44
nC5	0,467	0,128	0,48
C6	0,871	0,161	0,88
C7	2,505	0,282	2,55
C8	4,071	0,319	4,16
C9	2,992	0,185	3,08
C10+	32,441	0,459	35,96
Molvekt C10+	282 g/mol	171 g/mol	281 g/mol
Tetthet C10+	876 kg/m3	816 kg/m3	877 kg/m3
Fluidprøve	TS-61-06	TS-03-07, A-16745	814700
Prøvetype	bunnhull	separator	bunnhull

Figure 18 Norne field hydrocarbon composition (Nielsen, 2012)

### 3.6 Conclusion

The Norne field is of good reservoir quality. The gas and oil in the reservoir are completely isolated by impermeable Not shale formation. The field is divided into two separate oil compartments: the main structure which consists of segments C, D, and E and the northeast Norne G-segment. Approximately 97 percent of the original oil in place is in the main structure. The field began production in November 1997 and until this report is written in 2017, the field is still under production and is tied up with a satellite field called Urd for economic reason. The main drive mechanism for production of oil in the Norne field is by injection of water in the water zone. The next chapter will cover aquifer characterization, model ranking, aquifer modelling in Eclipse and economic analysis.

## **CHAPTER 4**

### **AQUIFER CHARACTERIZATION, MODEL RANKING, AQUIFER MODELLING IN ECLIPSE AND ECONOMIC ANALYSIS**

The methodology of this research will cover the following areas: Data collection, data processing, determination of water drive strength, estimation of aquifer properties, model ranking, aquifer modelling in Eclipse and economic analysis.

#### **4.1 Data Collection**

The following data has been collected from the Norne field database at an Integrated Operation Center of NTNU. These data include but not limited to:

- The full field reservoir simulation model of Norne field based on geological model of 2004.
- The production and Injection data of Norne field from 1997 to 2006.
- Annual reservoir development plan of 2004.
- Average reservoir pressure data and PVT properties extracted from the reservoir simulation model.
- Annual WTI crude spot oil prices from 1997 to 2006.

In addition to the mentioned data, the following tools has been used in this thesis;

- Non-linear regression tool in material balance software (MBAL) from Petroleum Experts for estimating Norne aquifer properties and model ranking.
- Eclipse software (from Schlumberger) for integrating aquifer with reservoir simulation model to compare oil recovery factor with and without aquifer model included.
- Eclipse office and FloViz for visualization of results.

## **4.2 Data Processing**

The historical data (production and injection volumes) in Norne field were first processed to identify outliers that might affect the analysis process. Outliers are values in the data set that are extremely higher or lower compared to other data. The methodology used to identify outliers in this research is called quartile method.

The quartile method starts with computation of first and third quartile of the given data set. Then followed by calculation of interquartile range which is the difference between third and first quartile. Further, the lower and upper bound of the data set were computed using interquartile range. The identification of outliers was done by using conditional formatting in excel by considering that every data point that was lower than the lower bound or greater than the upper bound was regarded as an outlier. The practical procedure is presented in appendix A by using Equations 4.1-4.6.

## **4.3 Determination of Water Drive Strength in the Norne Field**

The strength of the water drive in the Norne field has been determined by considering the use of diagnostic plots. These plots include the production decline curve of oil rates versus time in semi-logarithm scale, and drive indices plot. The results of a plot of oil rates versus time drawn in semi-logarithm scale are presented in chapter 5 through Figure 23. In the case of drive indices plot, various sources of energy available in the Norne reservoir are drawn in a single plot as a function of time by using MBAL software as shown in chapter 5 through Figure 24.

## **4.4 Estimation of Norne Aquifer Properties**

A non-linear regression technique in material balance software (MBAL) was used to estimate Norne aquifer properties such as aquifer size, aquifer porosity, aquifer permeability and water encroachment angle ( $\theta$ ). This was done by matching the historical average reservoir pressure data sometimes called tank pressure data with van Everdingen-Hurst model, Carter-Tracy model and Fetkovich aquifer model. On each model, the uncertain parameters in the aquifer were regressed starting with arbitrary selected initial values within the range until the best match was obtained after 100 number of iterations. The best match parameters were accepted and the model captures the improvement of the trend of pressure matching after regression. Figure 25 to Figure 33 shows the results of the pressure matching before regression, after regression and regressed parameters for VEH, Carter-Tracy and Fetkovich model.



#### 4.5 Model Ranking and Parameter Selection

The purpose of model ranking was to obtain a model that best describe the Norne aquifer in accuracy. This was achieved by using standard deviation of the pressure matching points after regression analysis. The model with small standard deviation was considered as the best model to describe the Norne aquifer. The results of the model ranking and parameter selection are presented in chapter 5 through Table 6 and Table 7 respectively.

#### 4.6 Carter-Tracy Aquifer Modelling in Eclipse

To model an aquifer in Eclipse by using Carter-Tracy model, three keywords were added in Eclipse data file. These include AQUODIMS, AQUUCT and AQUANCON. The AQUODIMS keyword specifies dimensions for aquifer such as maximum number of analytical aquifer in the model and maximum number of grid blocks connected to the aquifer. The keyword is specified in RUNSPEC section. The screenshot of the implementation of AQUODIMS keyword in Eclipse data file is presented in Figure 19 and shows the maximum number of influence table for Carter-Tracy aquifer is 1, the maximum number of rows in Carter-Tracy aquifer influence table are 36, the maximum number of analytical aquifer in the model is 1 and the maximum number of grid blocks connected to aquifer are 450.

```
AQUODIMS
-- MXNAQN MXNAQC NIFTBC NRIFTBL NANAQU NCAMAX
0 0 1 36 1 450/
```

*Figure 19 Implementation of AQUODIMS keyword in Eclipse data file*

The next keyword that follow is AQUUCT. This keyword is responsible for specifying property data for Carter-Tracy aquifers. These data are such as aquifer identification number, datum depth, initial aquifer pressure at datum depth, permeability of the aquifer, porosity of the aquifer, total compressibility of the aquifer, external radius of the reservoir or inner radius of the aquifer, thickness of the aquifer and angle of influence. The keyword is specified in SOLUTION section. The screenshot of the implementation of AQUUCT keyword in Eclipse data file is shown in Figure 20.

```
AQUUCT
1 2668 273.2 2495 0.2004 9.51e-5 2932 171 51.9133 1 1 0 1 /
/
```

*Figure 20 Implementation of AQUUCT keyword in Eclipse data file, units are in metric*

The last keyword used in aquifer modelling by Carter-Tracy is AQUANCON. This keyword is responsible for specifying aquifer connection to the reservoir. It includes items such as aquifer identification number, lower and upper I, J, K indices of reservoir grid cells connected to aquifer and reservoir face. The keyword is specified in SOLUTION section. The screenshot of the implementation of AQUANCON keyword in Eclipse data file is shown in Figure 21.

```
AQUANCON
1 6 29 11 11 5 22 'I+' / Western face on C seg
/
```

*Figure 21 Implementation of AQUANCON keyword in Eclipse data file*

Further, the results of aquifer modelling by Carter-Tracy with respect to cumulative water influx into the Norne reservoir and additional oil recovery factor with aquifer model included in reservoir simulation model are presented in chapter 5 through Figure 34 and Figure 35 respectively.

#### **4.7 Economic analysis**

In this section, the main deliverable is the total additional revenue based on additional oil produced due to the influence of aquifer as shown in Equation 4.8. This revenue is computed by using two main parameters, additional volume of oil produced due to the influence of aquifer and the average crude oil price during the historical period (From November 1997 to December 2006). The additional volume of oil produced due to the influence of aquifer is computed by using Equation 4.7 with the inputs from Table 5 meanwhile the average crude oil price is calculated by using the annual WTI crude spot oil prices as shown in Figure 22. The results of economic analysis are presented on Table 8 on chapter 5.

*Table 5 Summary of simulation runs in terms of oil recovery factor and their corresponding field oil production total (FOPT) with and without aquifer model included.*

<b>Scenario</b>	<b>Oil recovery factor (%)</b>	<b>FOPT (Sm<sup>3</sup>)</b>
Base case for historical period	42.6	6.86 * 10 <sup>7</sup>
Carter-Tracy simulation for historical period	43.6	7.01 * 10 <sup>7</sup>
Base case for prediction period	45.7	7.36 * 10 <sup>7</sup>
Cater-Tracy simulation for prediction period	47.3	7.60 * 10 <sup>7</sup>

Consider the following definitions for symbols.

$\Delta V$  is additional volume of oil produced due to the influence of aquifer,  $Sm^3$

$V_1$  is volume of oil produced with aquifer model included,  $Sm^3$  and

$V_2$  is volume of oil produced without aquifer model included,  $Sm^3$

$$\Delta V = V_1 - V_2 \quad (4.7)$$

By considering the use of Equation 4.7 and Table 5, additional volumes of oil produced due to the influence of aquifer are calculated as follows:

**Case 1.** At the end of historical period (From November 1997 to December 2006)

$$\Delta V = 7.01 * 10^7 - 6.86 * 10^7 = 1.5 * 10^6 Sm^3$$

Likewise, for **case 2** when the model is predicted until December 2010,

$$\Delta V = 7.60 * 10^7 - 7.36 * 10^7 = 2.4 * 10^6 Sm^3$$

Further, Equation 4.8 shows the formula for calculating the total additional revenue due to influence of aquifer.

Consider the following definitions for symbols.

$TR$  is the total additional revenue, USD

$\Delta V_i$  is additional volume of oil produced due to the influence of aquifer in  $Sm^3$ , the subscript index  $i$  stands for year 1 to N.

$P_a$  is average WTI crude oil price in USD per barrel

$$TR = \sum_i^N \Delta V_i * P_a \quad (4.8)$$

### Basic assumption

Average WTI crude oil price = 46.11 USD/bbl computed from annual WTI crude spot oil prices as shown in Figure 22.

Therefore, for **case 1.** At the end of historical (From November 1997 to December 2006)

$$TR = 1.5 * 10^6 Sm^3 * \frac{6.29 bbl}{1 Sm^3} * \frac{46.11 USD}{1 bbl} = 435.0 * 10^6 USD$$

For **Case 2.** At the end of prediction period (From January 2007 to December 2010)

$$TR = 2.4 * 10^6 Sm^3 * \frac{6.29 bbl}{1 Sm^3} * \frac{46.11 USD}{1 bbl} = 696.1 * 10^6 USD$$

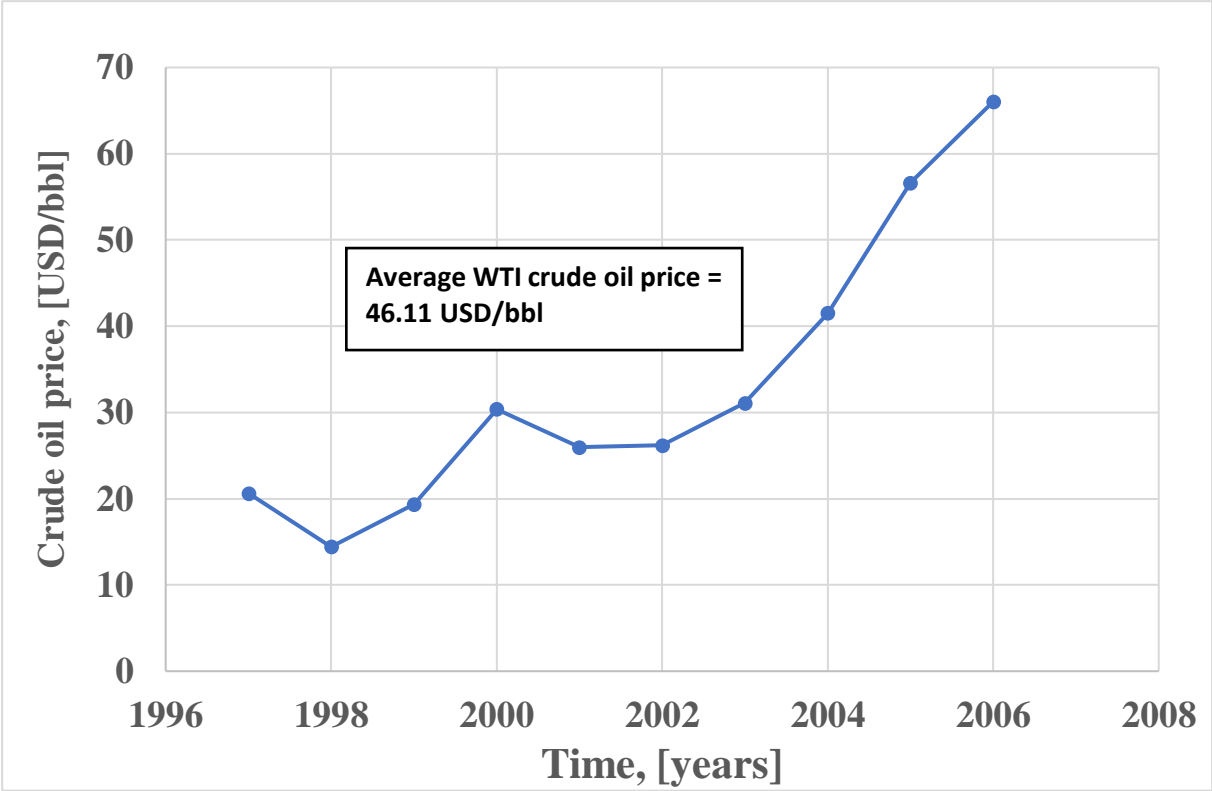


Figure 22 Annual WTI crude spot oil prices for historical period (EIA, 2017)

# CHAPTER 5

## RESULTS AND DISCUSSION

### 5.1 Results

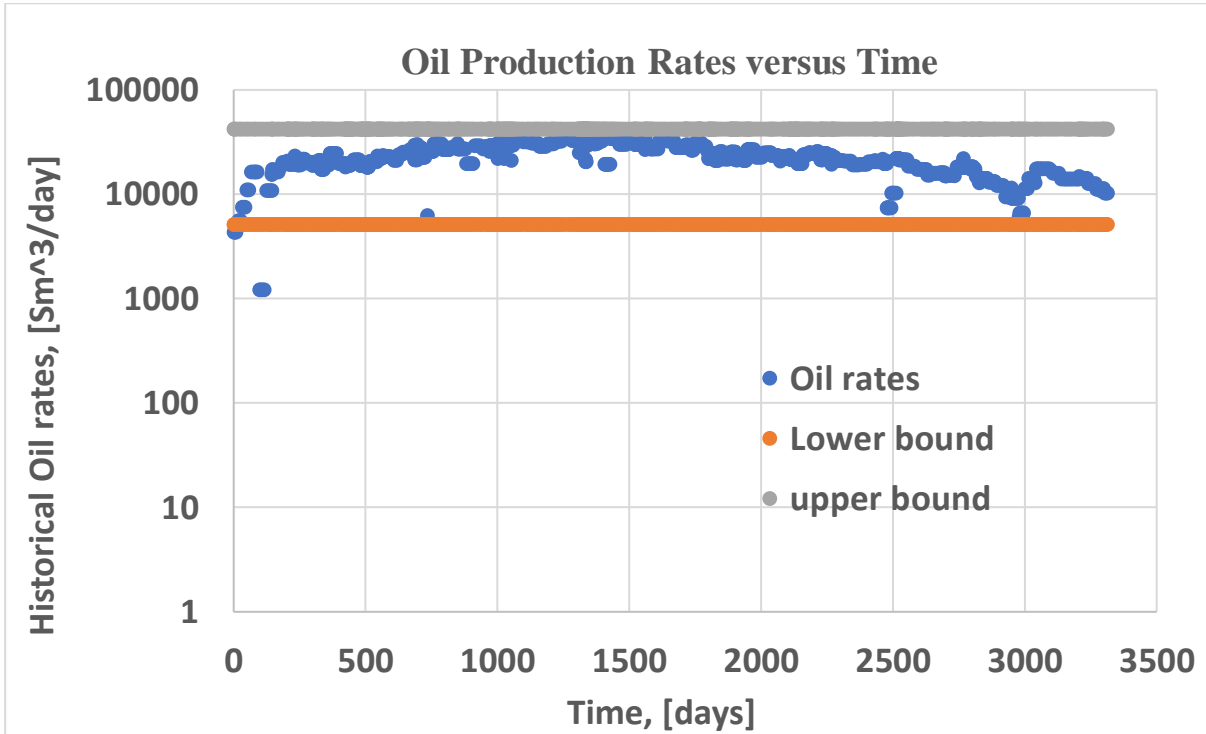


Figure 23 Determination of water drive strength in Norne field by using a plot of oil rate versus time in semi-logarithm scale

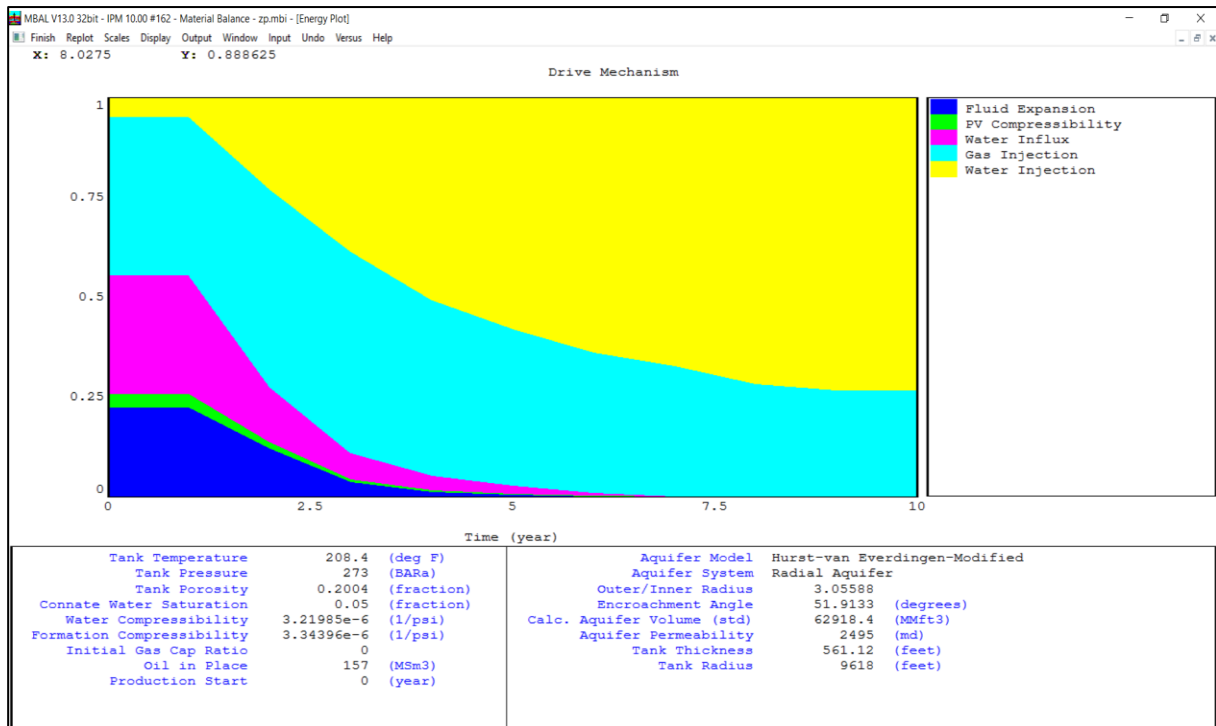


Figure 24 Drive indices showing dominant energies that drives oil production in the Norne reservoir

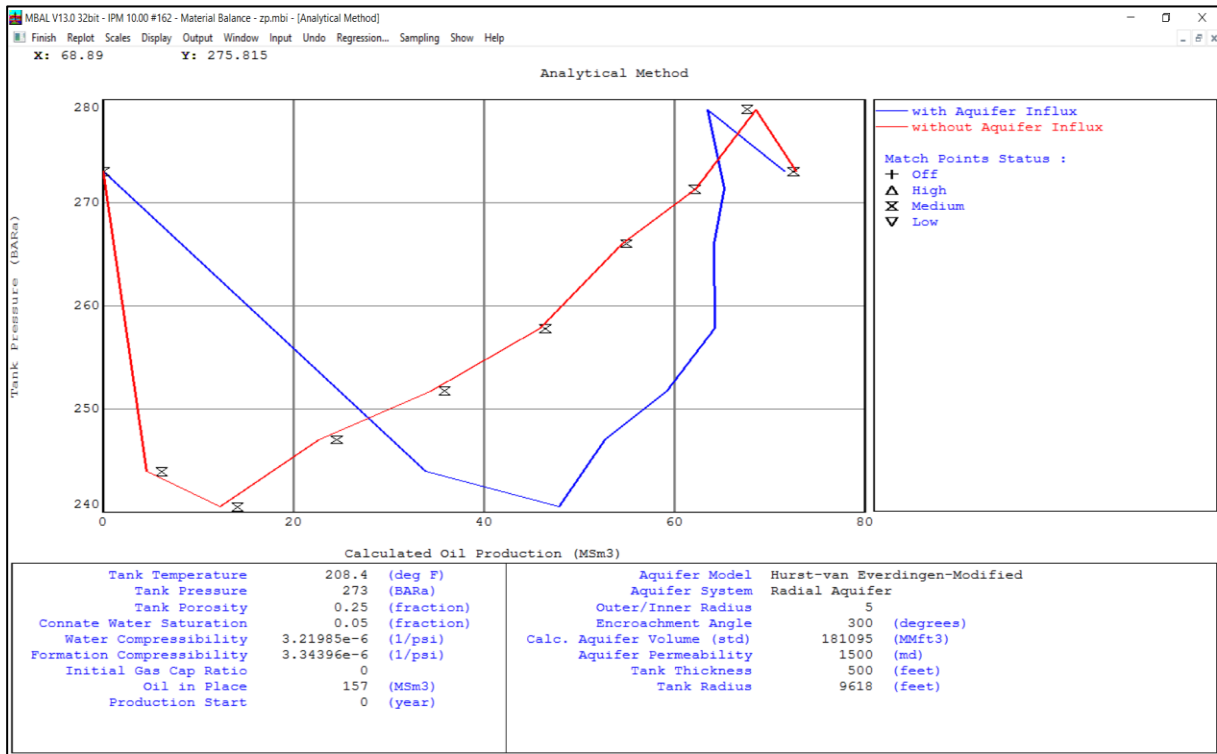


Figure 25 Average reservoir pressure matching in Norne field before regression by using VEH model

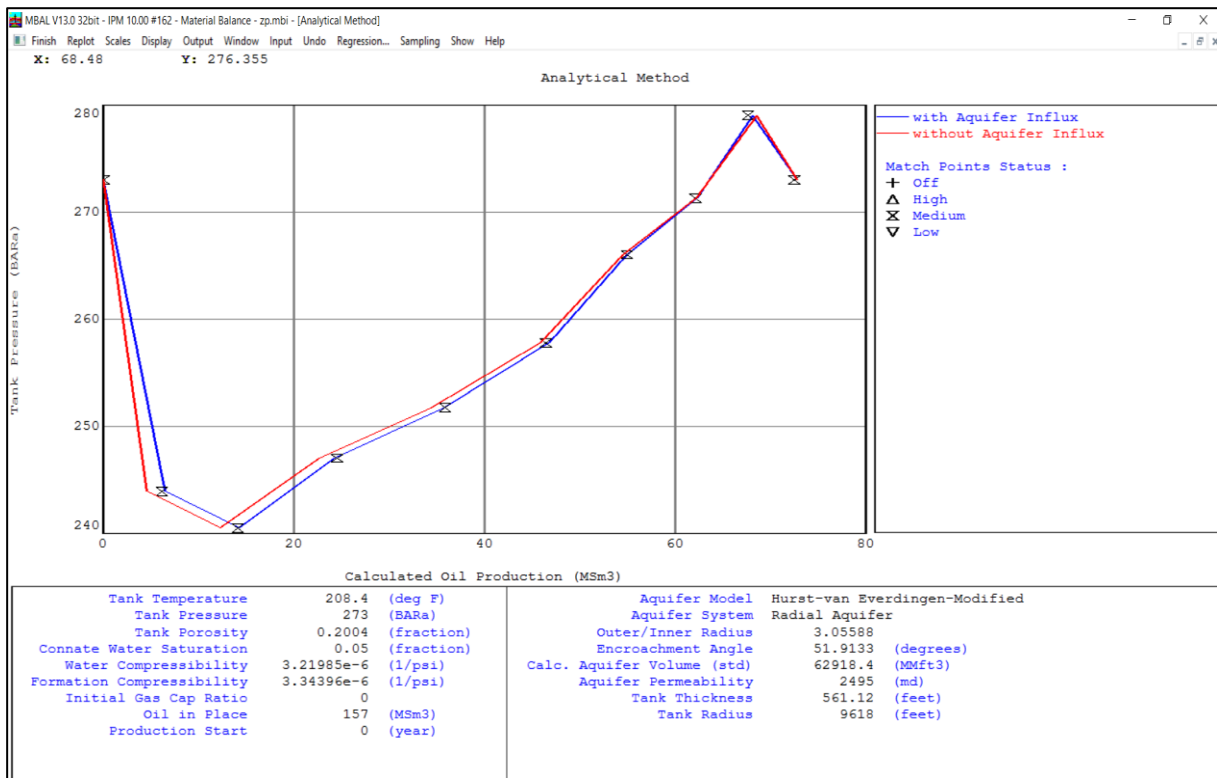


Figure 26 Average reservoir pressure matching in Norne field after regression by using VEH model

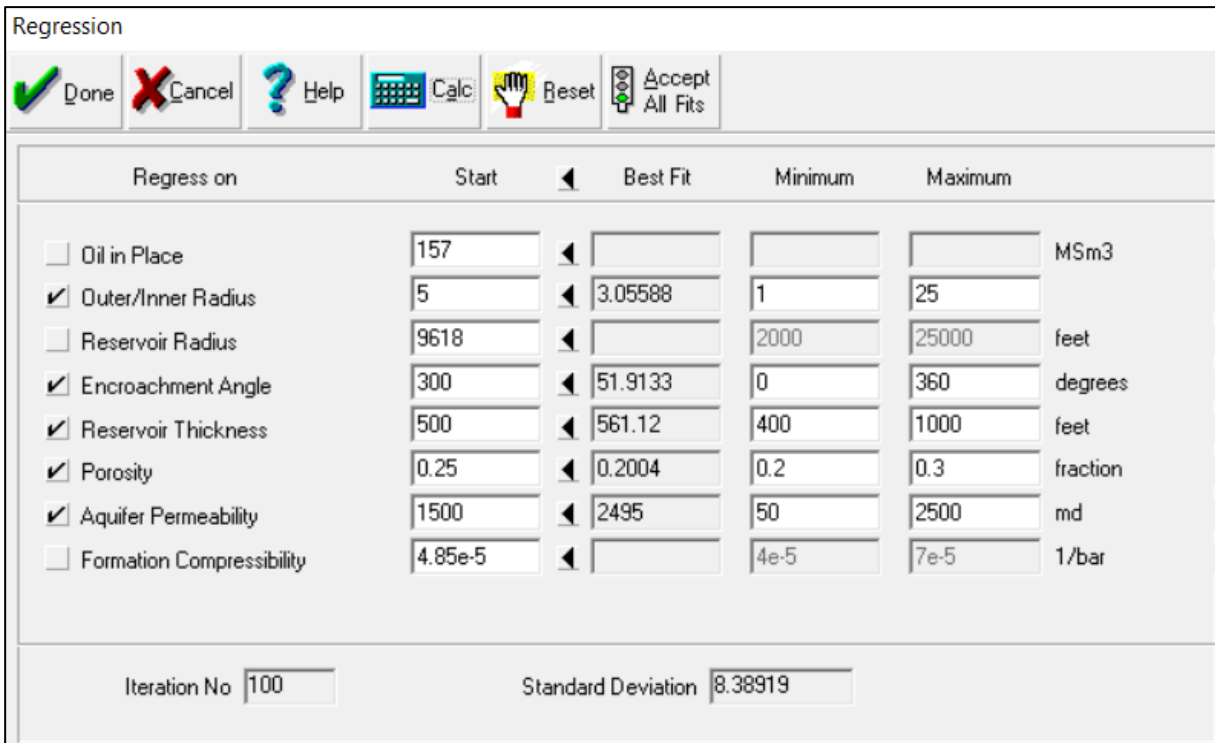


Figure 27 Regressed parameters and standard deviation of the matching points achieved after regression with VEH model

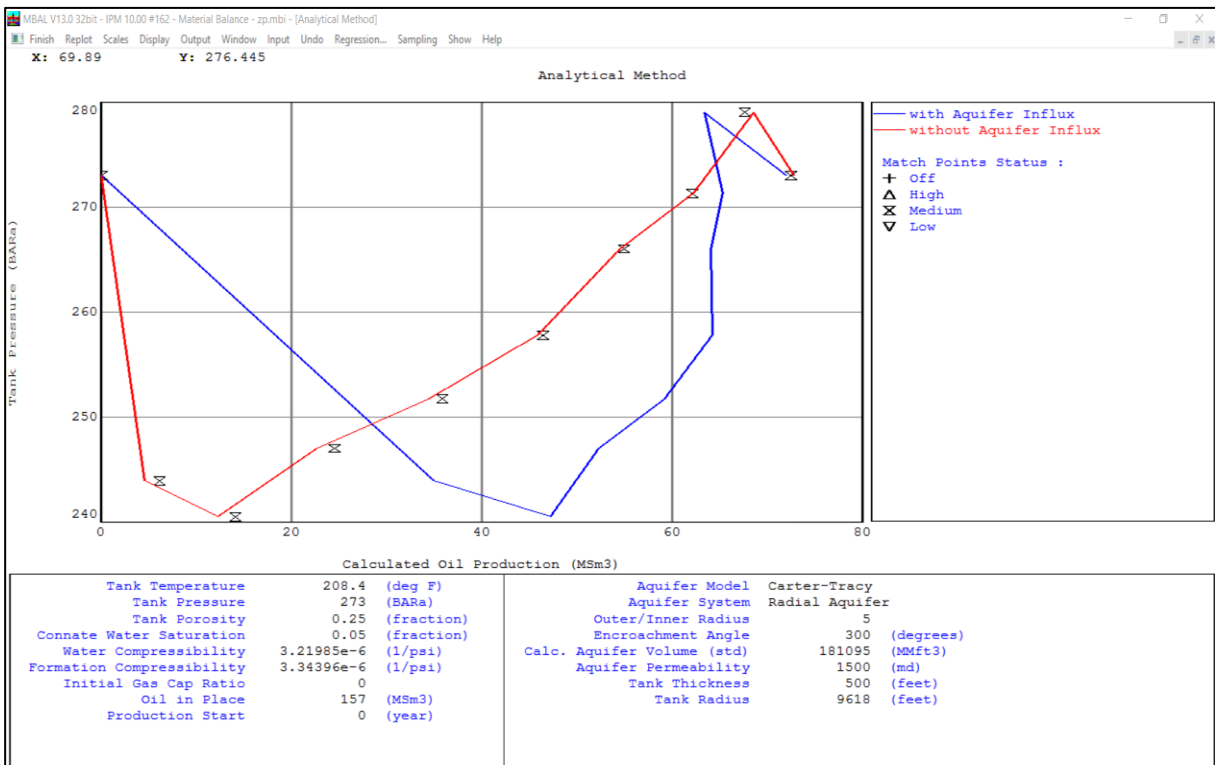


Figure 28 Average reservoir pressure matching in Norne field before regression by using Carter-Tracy model

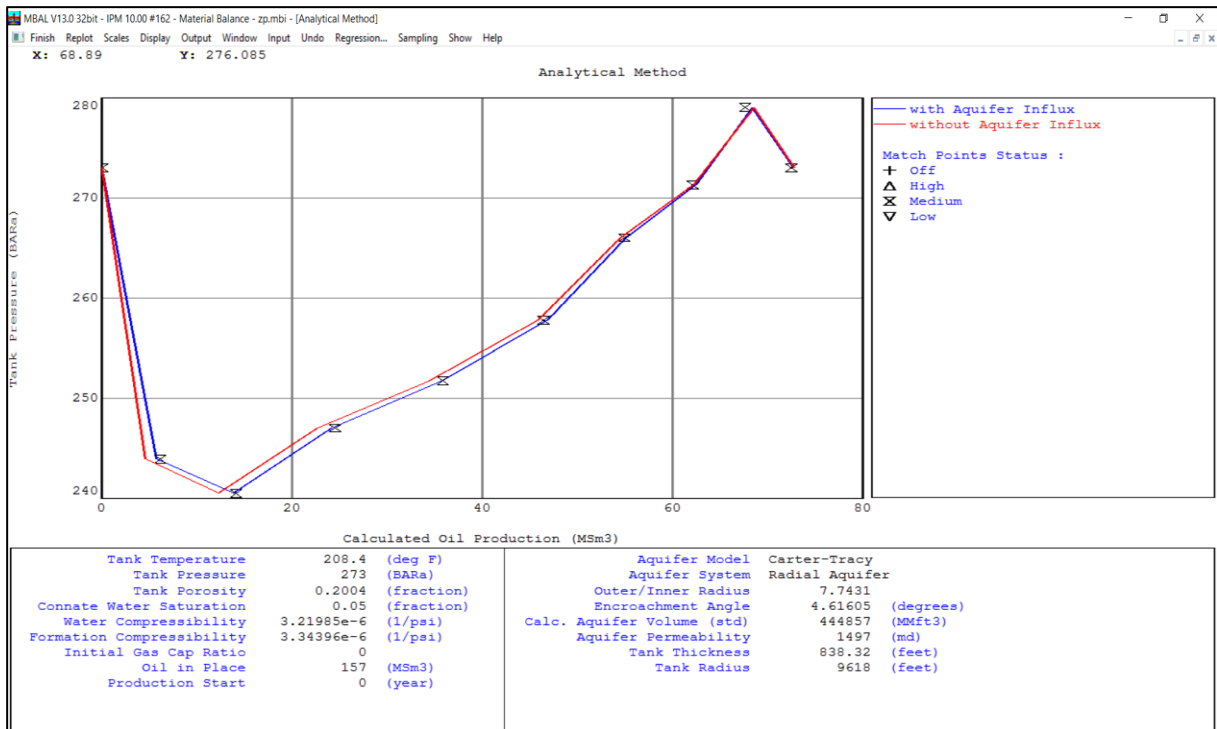


Figure 29 Average reservoir pressure matching in Norne field after regression by using Carter-Tracy model

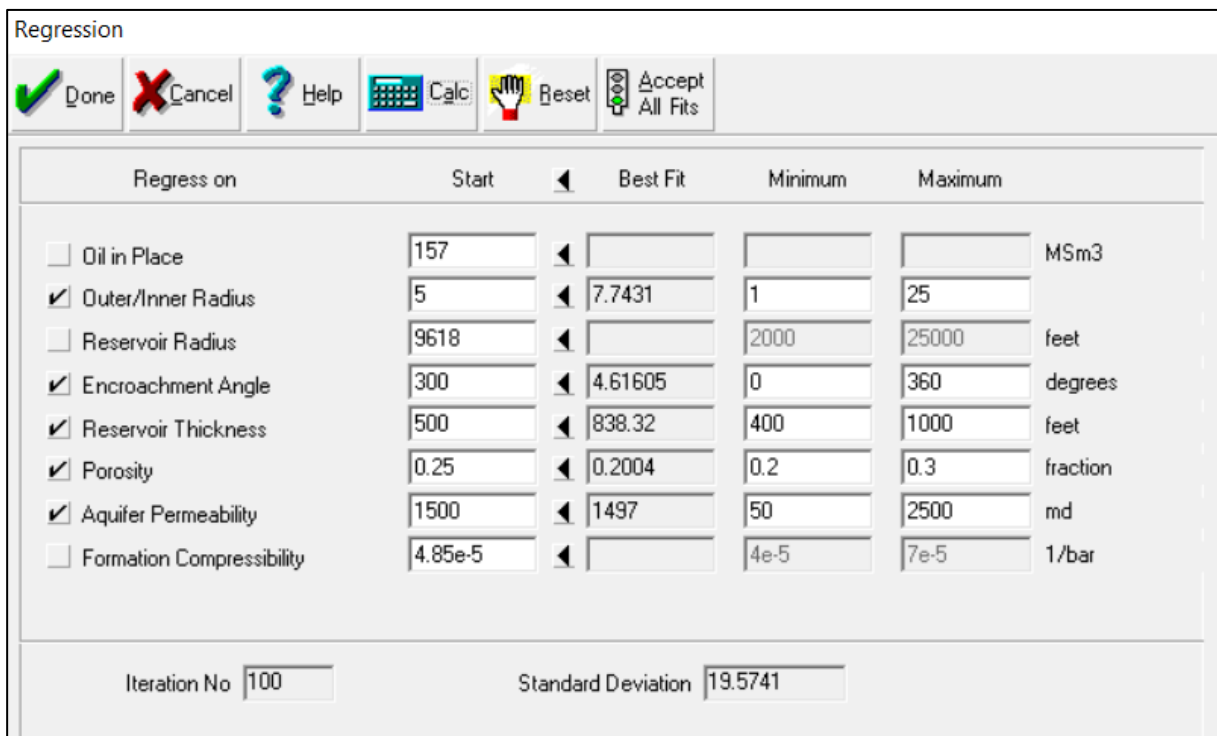


Figure 30 Regressed parameters and standard deviation of the matching points achieved after regression with Carter-Tracy model



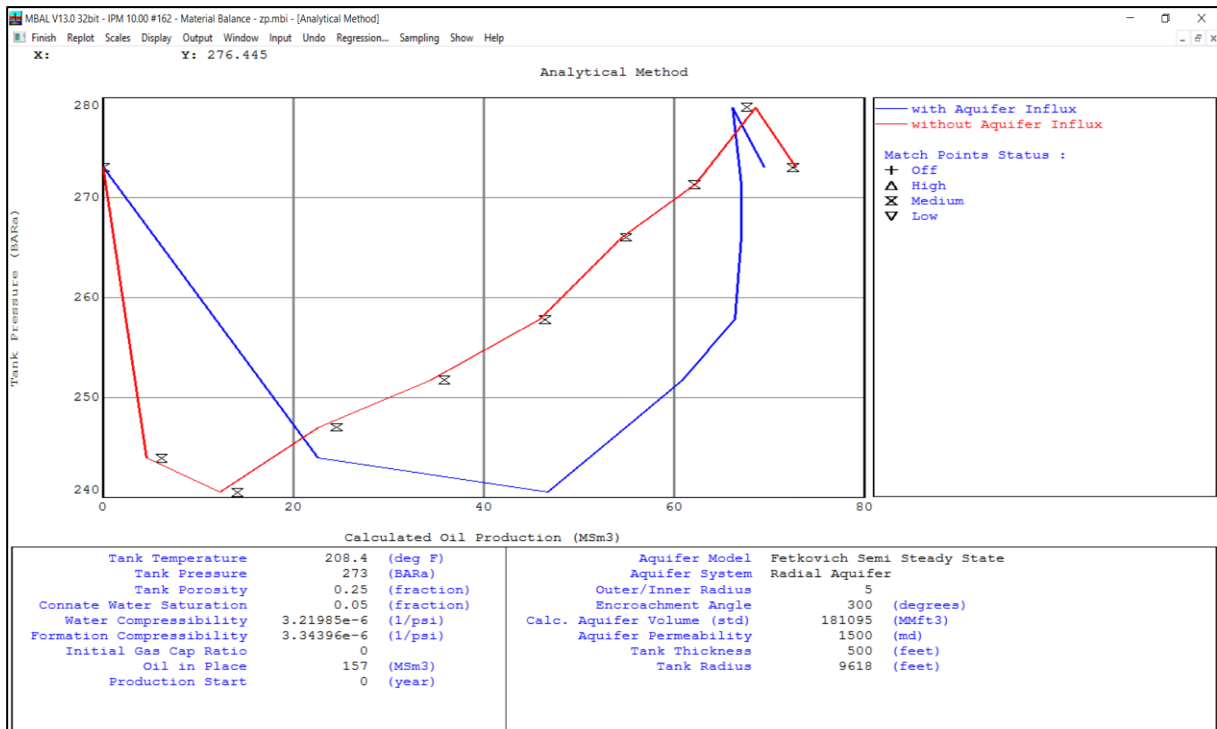


Figure 31 Average reservoir pressure matching in Norne field before regression by using Fetkovich model

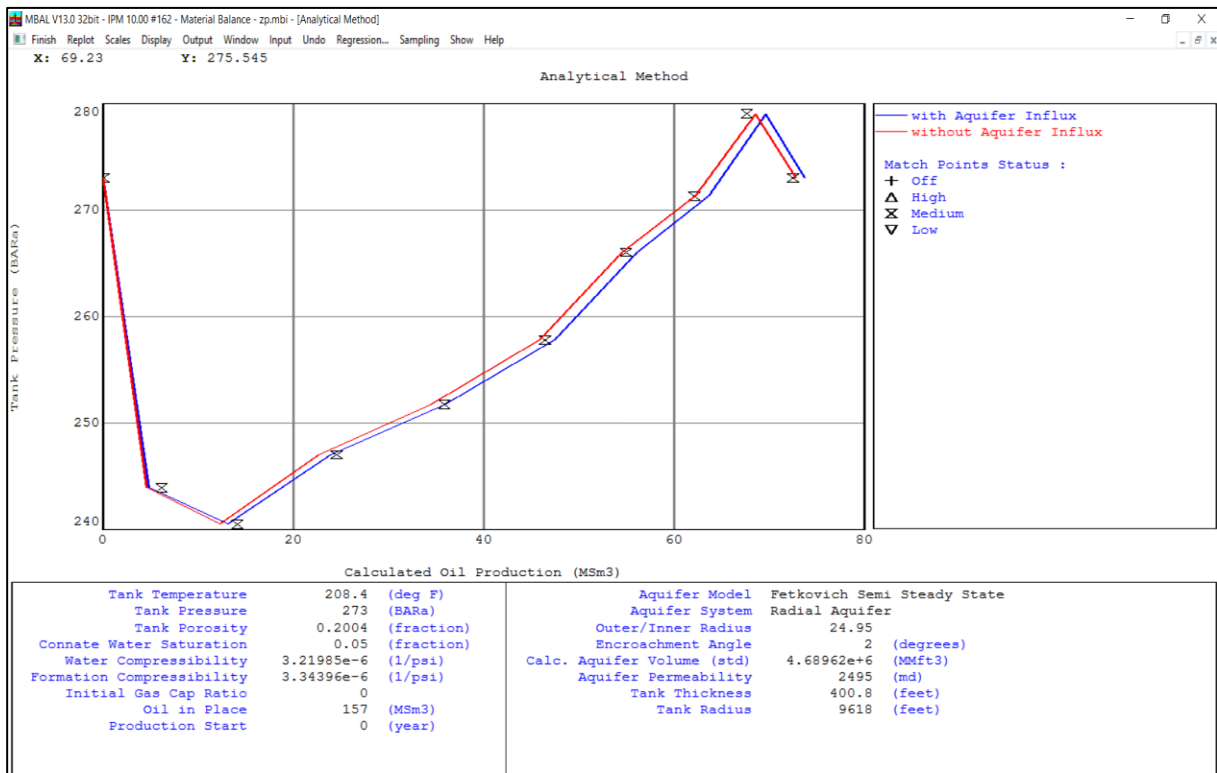


Figure 32 Average reservoir pressure matching in Norne field after regression by using Fetkovich model

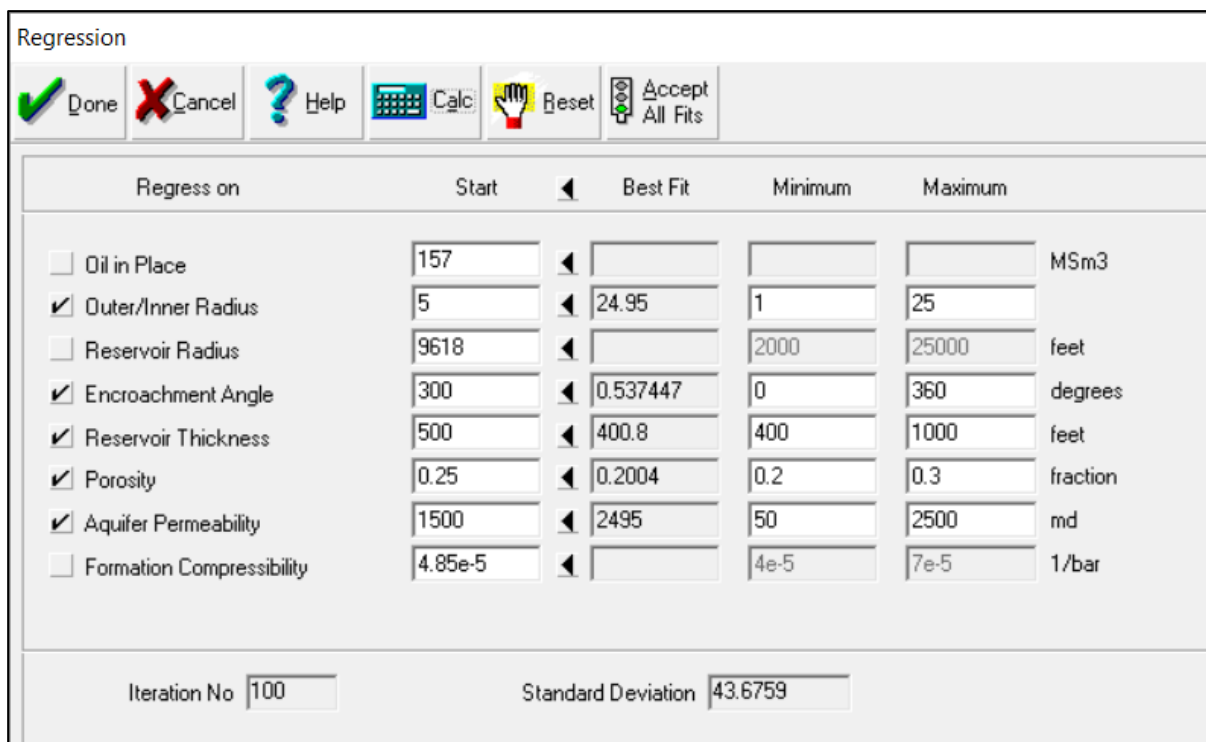


Figure 33 Regressed parameters and standard deviation of the matching points achieved after regression with Fetkovich model

Table 6 Model ranking based on standard deviation after regression analysis on average reservoir pressure of Norne field for 100 iterations.

Model	Standard deviation	Ranking
VEH	8.38919	1
Carter-Tracy	19.57410	2
Fetkovich	43.67590	3

Table 7 Norne aquifer properties selected based on model with small standard deviation (Radial VEH model). Red color are estimated parameters.

Property/parameter	Value	Units
Aquifer permeability, $k_a$	2495	[md]
Dimensionless aquifer radius, $r_D$	3.05588	[-]
Aquifer porosity, $\phi_a$	0.2004	[fraction]
Water influx angle	51.9133	[degree]
Aquifer thickness, $h_a$	561.12	[ft]
Total compressibility, $C_t$	$6.56 \cdot 10^{-6}$	[1/psi]
Viscosity of water	0.318	[cp]
Reservoir radius, $r_o$	9618	[ft]

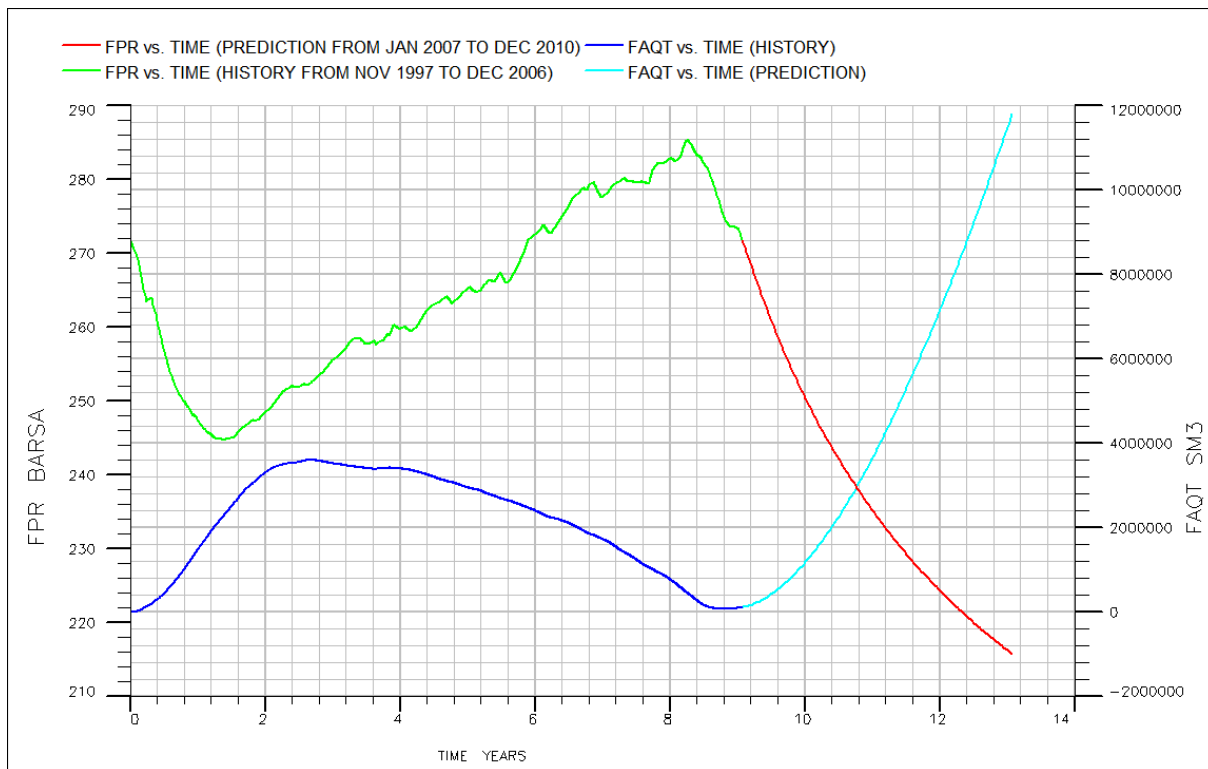


Figure 34 Correlation behaviour between average reservoir pressure and cumulative water influx in Norne field for historical period (Nov 1997 to Dec 2006) and prediction period (Jan 2007 to Dec 2010) by using Carter-Tracy model in Eclipse software

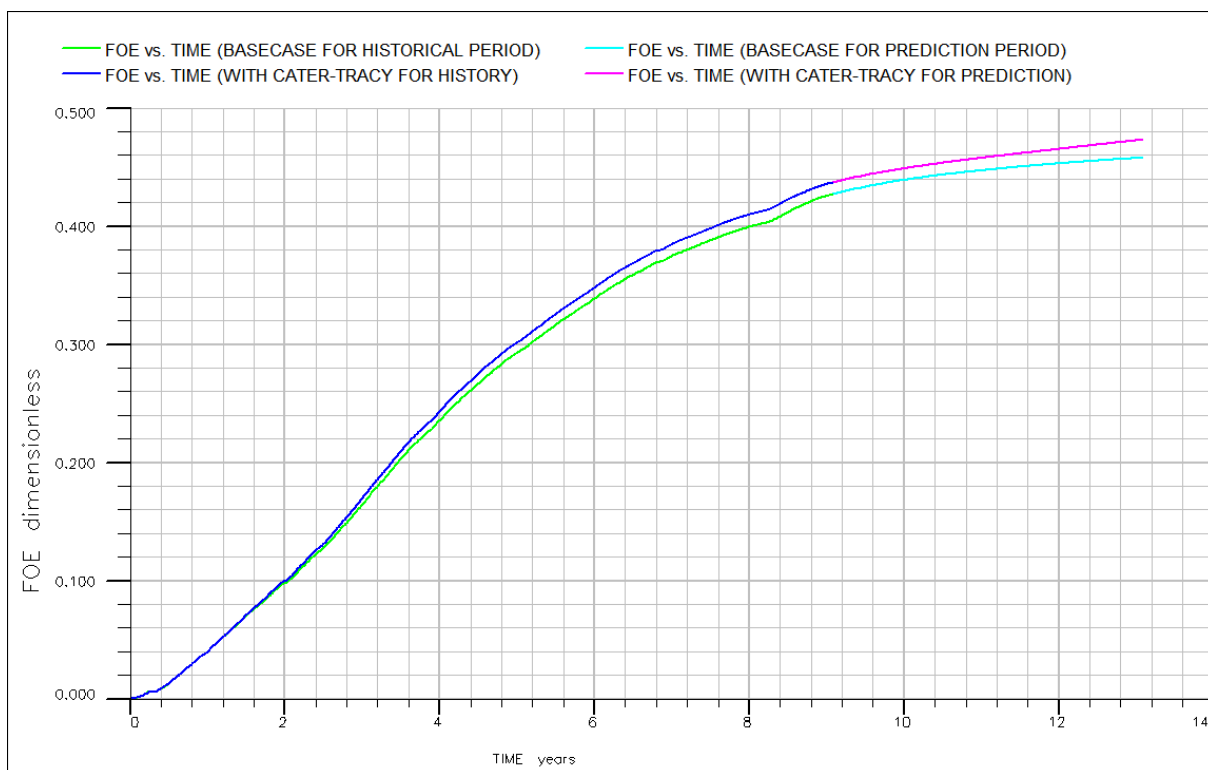


Figure 35 Comparison of oil recovery factor in Norne field during historical period (Nov 1997 to Dec 2006) and prediction period (Jan 2007 to Dec 2010) with and without aquifer model included within the simulation model

Table 8 Total additional revenues when the aquifer model is included in reservoir simulation model of Norne field (WTI crude oil price = 46.11 USD per barrel)

Case	Runs	Increment in volume of oil produced (* 10 <sup>6</sup> Sm <sup>3</sup> )	Additional Revenues (* 10 <sup>6</sup> USD)
1	Simulation with aquifer model for historical period (November 1997 to December 2006)	1.5	435.0
2	Simulation with aquifer model for prediction period (January 2007 to December 2010)	2.4	696.1

## 5.2 Discussion of Results

### 5.2.1 Water Drive Strength in the Norne Field

The strength of the water drive in the Norne field is considered strong. This is because of the flat trend of the oil production rate versus time drawn in a semi-logarithm scale for the whole historical period from November 1997 to December 2006 as shown in Figure 23. The results in Figure 23 are supported very well by the literature through Figure 3 (AAPG WIKI, 2016), in the sense that if the flat trend is observed in a plot of oil rate versus time in a semi-logarithm scale is an indication of strong water drive system. On other hand, the declining trend from the beginning of production is an indication of either partial water drive system, gravity drainage drive, gas expansion drive or dissolved gas drive depending on the nature of the decline curve. Further, the analysis of the energy plot in the Norne field as shown in Figure 24 tells that during the historical period from November 1997 to December 2006, water injection was the main energy driving oil production towards wellbores in the Norne reservoir followed by gas injection, natural water influx, fluid expansion, and pore volume compressibility. Furthermore, results in Figure 34 shows that after historical period, the average reservoir pressure continues to decline and the significant amount of natural water influx is observed to encroaches the Norne reservoir.

### **5.2.2 Aquifer Properties in the Norne Field**

The aquifer properties such as aquifer size, water encroachment angle, aquifer porosity and permeability in the Norne field are very well described by using van Everdingen-Hurst (VEH) model. This is because the VEH model can describe the reality of the Norne aquifer with standard deviation error of 8.38919 as shown in Figure 26 and Figure 27 after regression analysis. The other models such as Carter-Tracy and Fetkovich describes the reality of the Norne aquifer with standard deviation of 19.57410 and 43.67590 respectively. Figure 29 shows the improved pressure match by using Carter-Tracy model while Figure 30 shows the corresponding standard deviation when the Carter-Tracy model is used. Similarly, for Fetkovich aquifer model as shown in Figure 32 and Figure 33 in chapter 5 of results section.

Further, Table 6 shows the summary of model ranking based on the standard deviation after regression analysis on the average reservoir pressure of the Norne field for 100 number iterations. Table 7 shows the list of selected aquifer properties to describe the Norne aquifer with small standard deviation error of 8.38919. Few things to note about the Norne aquifer properties in Table 7, the aquifer permeability is high, estimated to be 2495 millidarcy. This means the fluid transmissibility between the aquifer and reservoir is significant. In addition, the aquifer size is approximately three times larger than the reservoir size, and the water influx angle is 52 degrees meaning that water from the aquifer is encroaching the reservoir from edge direction into reservoir. Furthermore, due to limitation of VEH model facility in Eclipse, the Carter-Tracy model will be used with some redundancy in accuracy to show the contribution of the aquifer in reservoir simulation model in terms of additional oil recovery factor.

### **5.2.3 Effect of Aquifer in Reservoir Simulation Model**

The effect of aquifer in reservoir simulation model of Norne field is discussed in two ways. First based on the amount of cumulative water influx into the reservoir and second based on additional oil recovery factor expressed in terms of additional revenues.

Figure 34 in chapter 5 shows that during the first year of production the reservoir pressure seems to decline dramatically and the same time aquifer is observed to react by encroaches water into the reservoir to offset the reservoir pressure from declining. One of the main reason of declining in the reservoir pressure is because of the void left as fluid is drained while the gas injected in the gas cap did not provide any pressure support due to the presence of a sealing layer called Not formation which separates gas zone from oil zone. After the first year of

production the drainage strategy was changed by injecting gas in the water zone and the reservoir begin to be energized and water outflux is observed. After year 8 of production in 2005, gas injection was ceased and the reservoir pressure begin to drop and the aquifer seems to react to retard the pressure from declining. This correlation behaviour between average reservoir pressure and cumulative water influx is also supported by the literature through Figure 10 (Fetkovich, 1971).

Further, Figure 35 in chapter 5 shows that adding an aquifer in reservoir simulation model of Norne field improves the oil recovery factor from 1.0-1.6 percent at the end of historical period in December 2006 and at the end of prediction period in December 2010 respectively. This means total additional revenues between 435.0-696.1 million USD are generated when the aquifer model is included during historical and prediction simulation periods respectively as shown in Table 8.

## CHAPTER 6

### CONCLUSION AND RECOMMENDATION

Aquifer characterization is an important step during aquifer modelling. This is because various information such as aquifer strength and properties can be determined and used in aquifer modelling. This research has employed various techniques to characterize the Norne aquifer. These includes diagnostic plots for determination of aquifer strength and non-linear regression tool in MBAL software to estimate Norne aquifer properties.

Further, the estimated aquifer properties were tested in reservoir simulation model by using Eclipse software to determine its impact in terms of additional oil recovery factor with aquifer model included in reservoir simulation model.

Furthermore, the research provides findings of objectives formulated, contribution to scientific knowledge and suggestions for further research to improve knowledge of aquifer characterization and modelling in Norne field.

#### 6.1 Findings of Research Objectives

The following are the findings covered based on the research objectives.

- The van Everdingen-Hurst model is the best model to describe the Norne aquifer with the standard deviation of 8.38919, followed by Carter-Tracy model with standard deviation of 19.57410 and Fetkovich model is the least with standard deviation of 43.67590 as illustrated in Table 6.
- The size of the aquifer in Norne field is approximately three times the size of the reservoir (as reservoir radius is 9618 feet) meanwhile the aquifer permeability is 2495 millidarcy, aquifer porosity is 20.04 percent, aquifer thickness is 561.12 feet and water influx angle is 51.9133 degree. Table 7 illustrate in detail. In addition, the water drive strength in Norne field is strong. The evidence is found in Figure 23 and Figure 24.
- The behaviour of cumulative water influx into the Norne reservoir correlate with average reservoir pressure trend for historical period from November 1997 to December 2006 and prediction period from January 2007 to December 2010. Figure 34 illustrate.
- Adding an aquifer model in reservoir simulation model increase the oil recovery factor in the Norne reservoir by 1.0-1.6 percent at the end of historical and prediction period respectively. Figure 35 illustrate. This means the corresponding total additional revenues between 435.0-696.1 million USD are generated when the aquifer model is

included during the historical and prediction simulation periods respectively as shown in Table 8.

## **6.2 Research Contribution to Scientific Knowledge**

The following are research contributions to scientific knowledge.

- First, the research intended to bridge the knowledge gap exist in None reservoir simulation model of 2004 by including the aquifer model. This will help to improve the Norne reservoir simulation model and better describes the Norne field.
- Second, the candidate has gained practical skills of aquifer characterization and modelling by using MBAL and Eclipse software's. These skills may be useful in other fields producing under aquifer influence.

## **6.3 Suggestions for Further Research**

The following are suggestions for expanding knowledge about the research topic which has not been covered in this research.

- The influence of Norne aquifer in oil production of satellite field such as Urd which is tied back to the Norne field's production vessel. The Urd field comprises of three deposits: Staer, Svale and Svale Nord.
- Aquifer modelling in reservoir simulator that has a facility of VEH aquifer model. The results may be compared with this research.

## **6.4 Recommendation**

The candidate recommends expanding the Norne reservoir description by including the aquifer in reservoir simulation model. This will not cause any additional cost to the company rather than using internal technical staff and their time.



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## APPENDICES

### APPENDIX A

#### Quartile Method to Identify Outliers

**Step 1:** Calculation of first quartile (Q1) and third quartile (Q3) using Equations 4.1-4.2 inbuilt in excel.

$$Q_1 = \text{QUARTILE}(\text{array}, 1) \quad (4.1)$$

$$Q_3 = \text{QUARTILE}(\text{array}, 3) \quad (4.2)$$

**Step 2:** Calculation of interquartile range (IQR) using Equation 4.3.

$$IQR = Q_3 - Q_1 \quad (4.3)$$

**Step 3:** Calculation of the lower bound and upper bound using Equations 4.4 and 4.5 respectively.

$$\text{Lower bound} = Q_1 - 1.5 * IQR \quad (4.4)$$

$$\text{Upper bound} = Q_3 + 1.5 * IQR \quad (4.5)$$

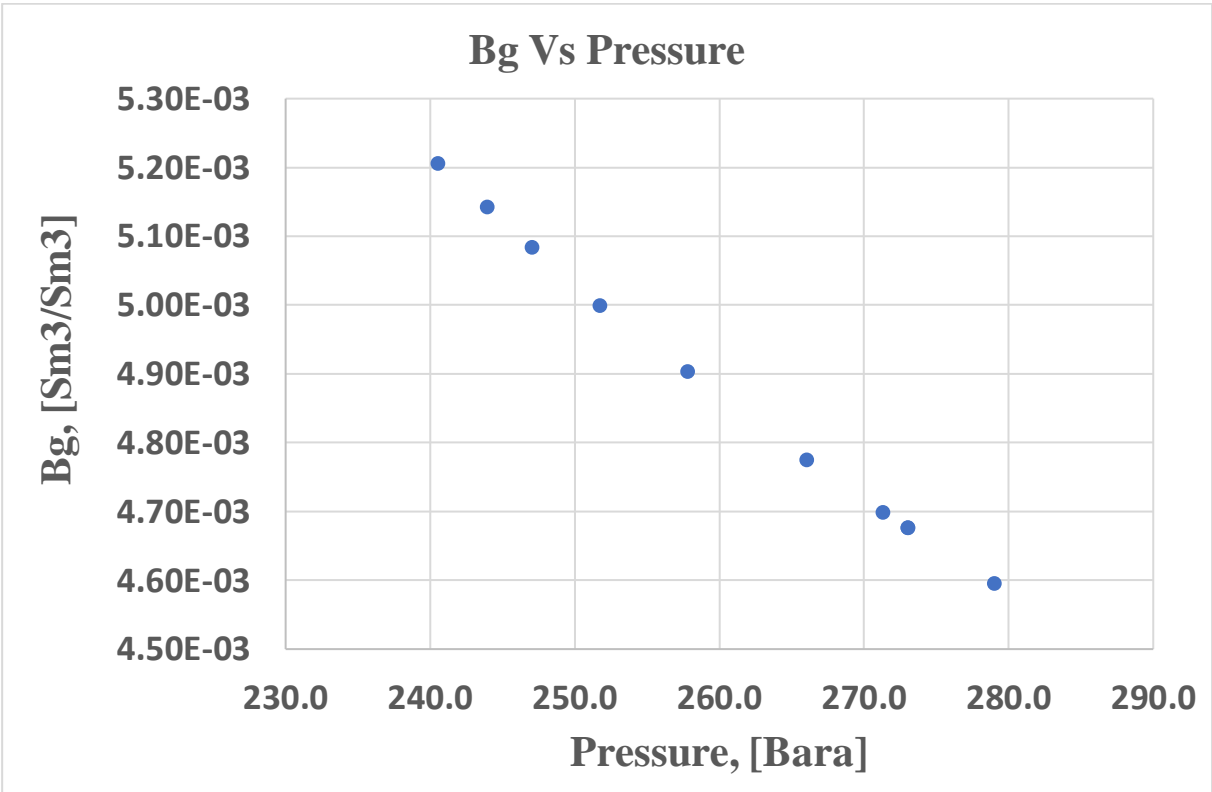
**Step 4:** Identification of outliers using conditional formatting

In this case, every data point that was lower than the lower bound or greater than the upper bound was regarded as an outlier and marked with a special colour to differentiate from other set of data. The condition formatting equation in excel was constructed as shown in Equation 4.6.

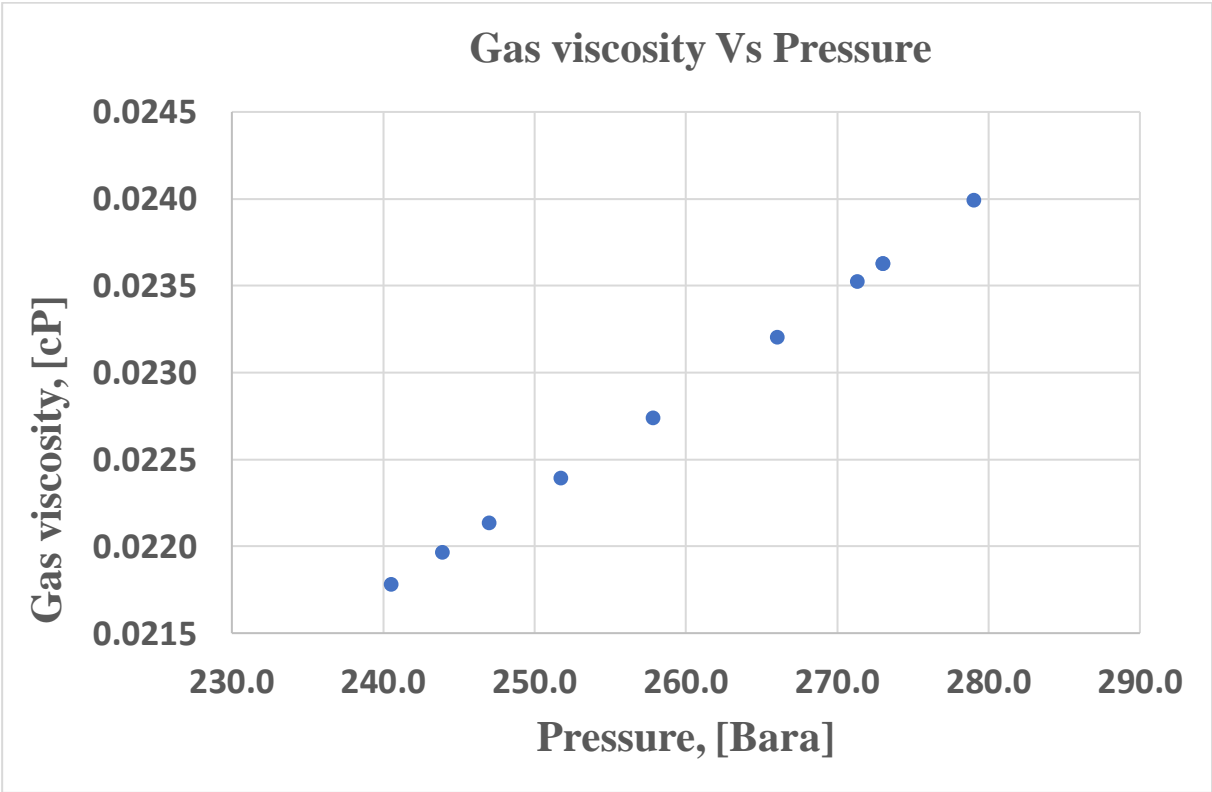
$$\text{Outlier} = \text{OR}(\text{target cell} < \text{lower bound}, \text{target cell} > \text{upper bound}) \quad (4.6)$$

**APPENDIX B**

**Norne Field PVT Properties**



*Figure 36 Gas formation volume factor as a function of pressure in the Norne field*



*Figure 37 Gas viscosity as a function of pressure in the Norne field*

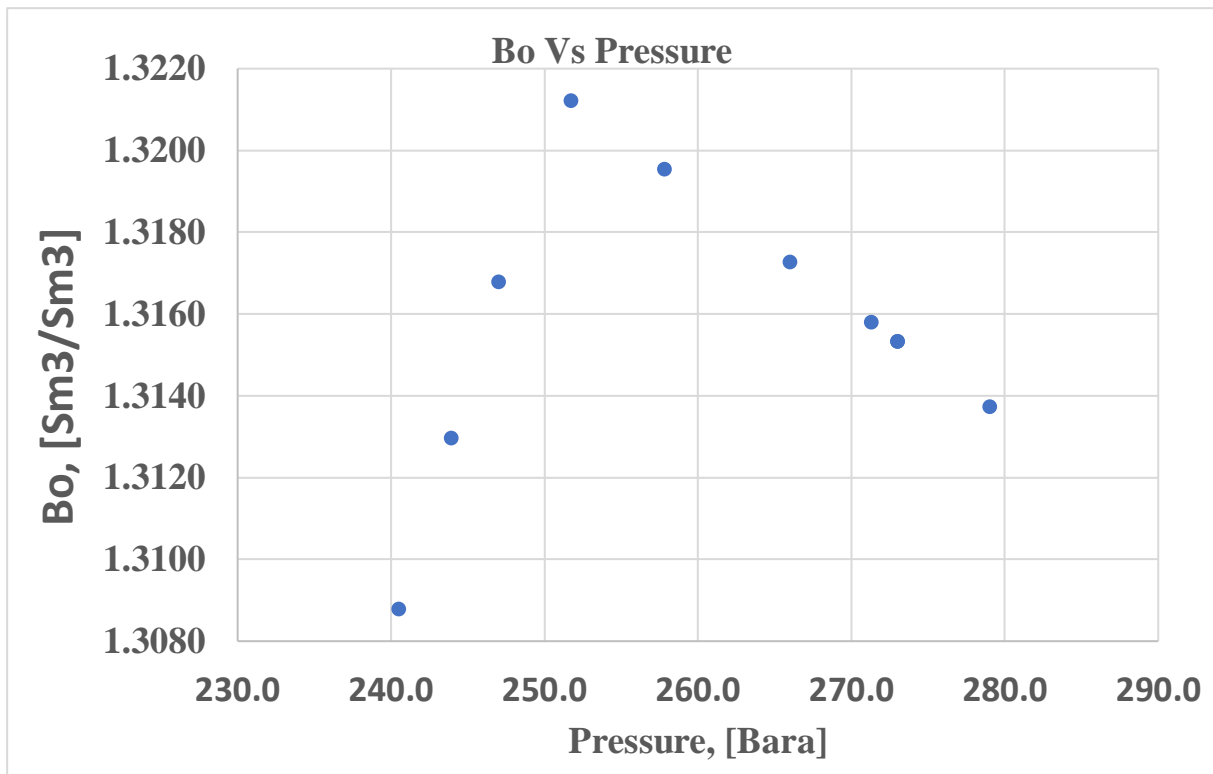


Figure 38 Oil formation volume factor as a function of pressure in the Norne field

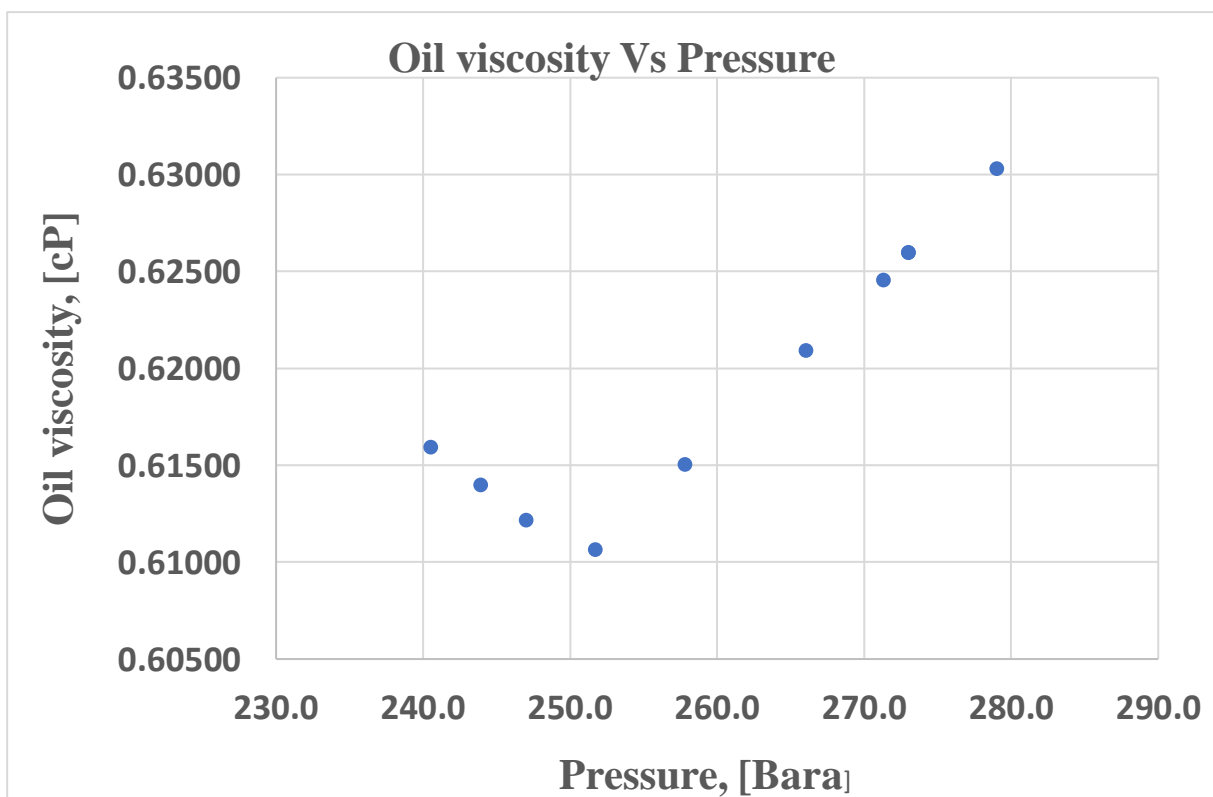
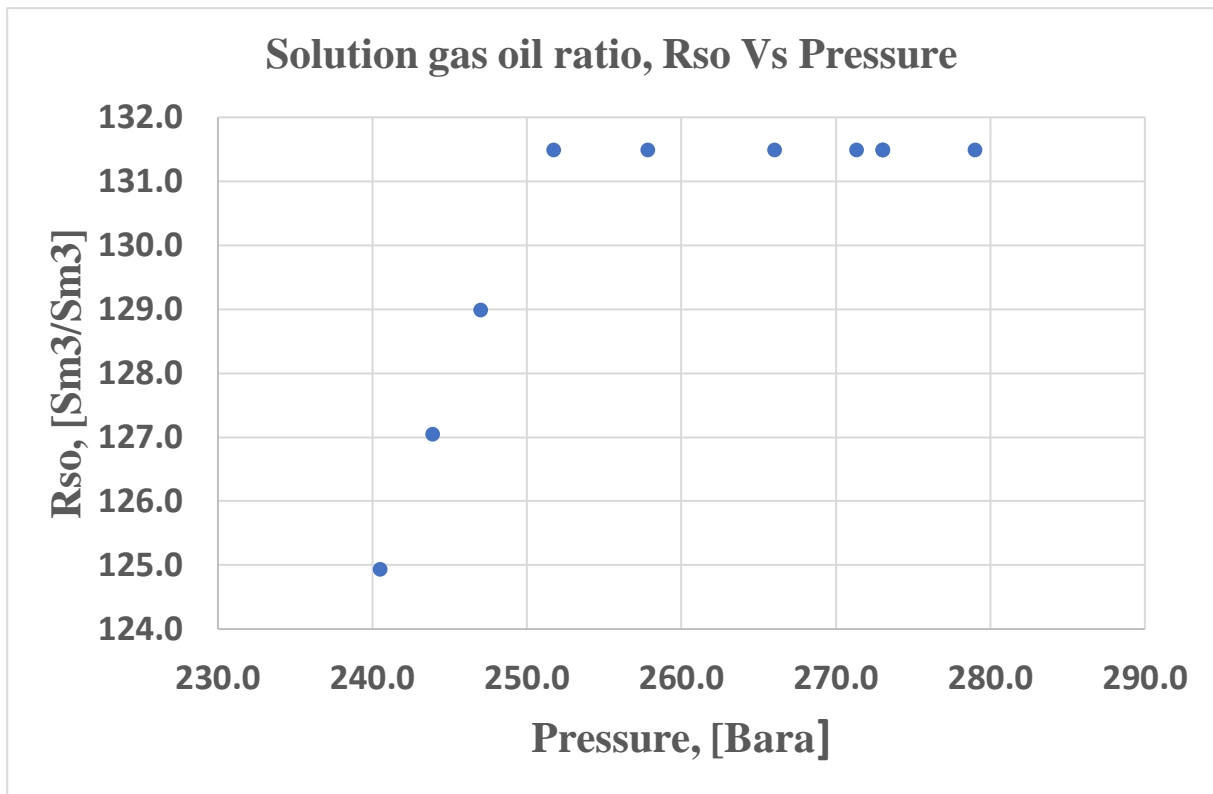
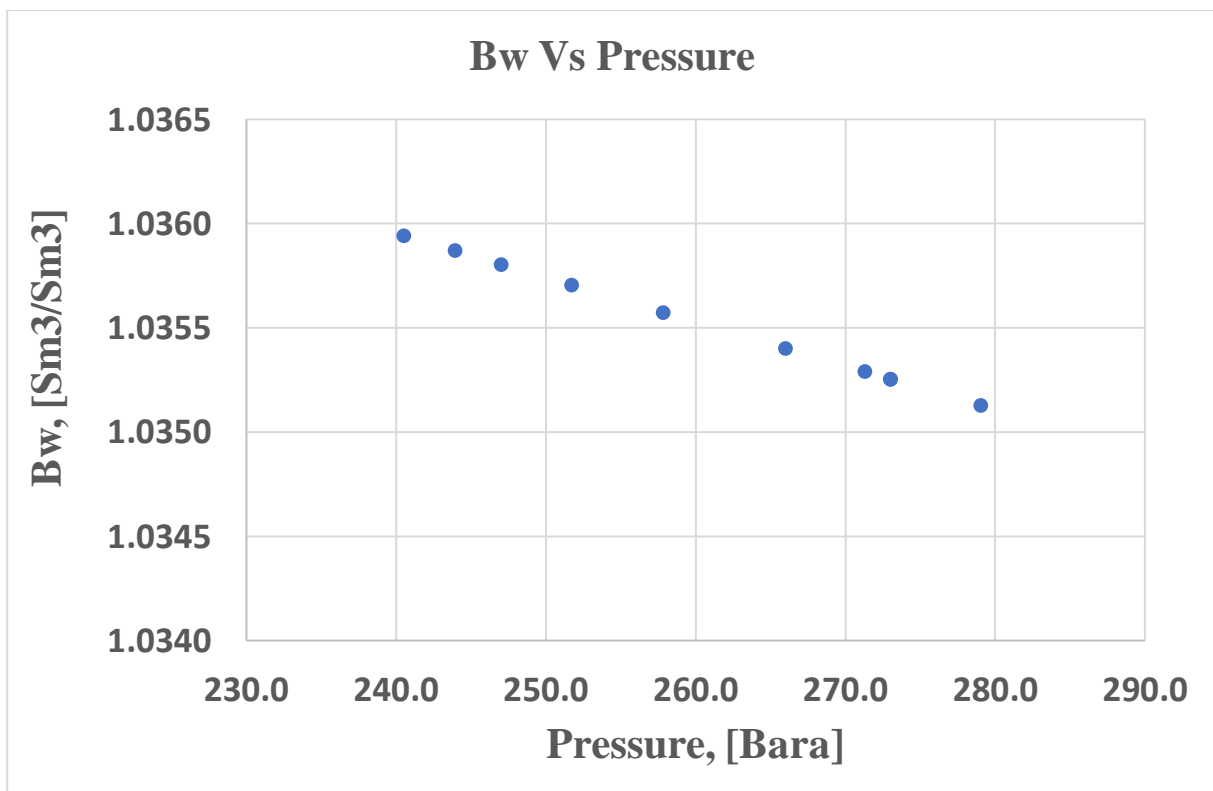


Figure 39 Oil viscosity as a function of pressure in the Norne field



*Figure 40 Solution gas oil ratio as a function of pressure in the Norne field*



*Figure 41 Water formation volume factor as a function of pressure in the Norne field*

## APPENDIX C

### Tank Input Data for Norne Field

Tank Input Data - Tank Parameters

Done
  Cancel
  Help
  Import

Tank Parameters	Water Influx	Rock Compress.	Rock Compaction	Pore Volume vs Depth	Relative Permeability	Production History
Tank Type: Oil		<input checked="" type="checkbox"/> Monitor Contacts				
Name: Tank01		<input type="checkbox"/> Gas Coning				
Temperature: 208.4 deg F		<input type="checkbox"/> Water Coning				
Initial Pressure: 273 BARa		<input type="checkbox"/> Use Fractional Flow Table (instead of rel perms)				
Porosity: 0.2004 fraction		<input type="checkbox"/> Enter Gas Cap as Surface Volume				
Connate Water Saturation: 0.05 fraction		<input type="button" value="Calculate Pb..."/>				
Water Compressibility: 4.67e-5 1/bar						
Gas Cap (downhole ratio): 0						
Original Oil In Place: 157 MSm3						
Start of Production: 0 year						
Reference Date: 01/01/1900 date d/m/y						

Figure 42 A snapshot of tank input parameters in MBAL

Tank Input Data - Water Influx

Done
  Cancel
  Help

Tank Parameters	Water Influx	Rock Compress.	Rock Compaction	Pore Volume vs Depth	Relative Permeability	Production History
Model: Hurst-van Everdingen-Modified						
System: Radial Aquifer						
Reservoir Thickness: 561.12 feet						
Reservoir Radius: 9618 feet						
Outer/Inner Radius ratio: 3.05588						
Encroachment Angle: 51.9133 degrees						
Aquifer Permeability: 2495 md						

Figure 43 A snapshot of natural water influx parameters in Norne field



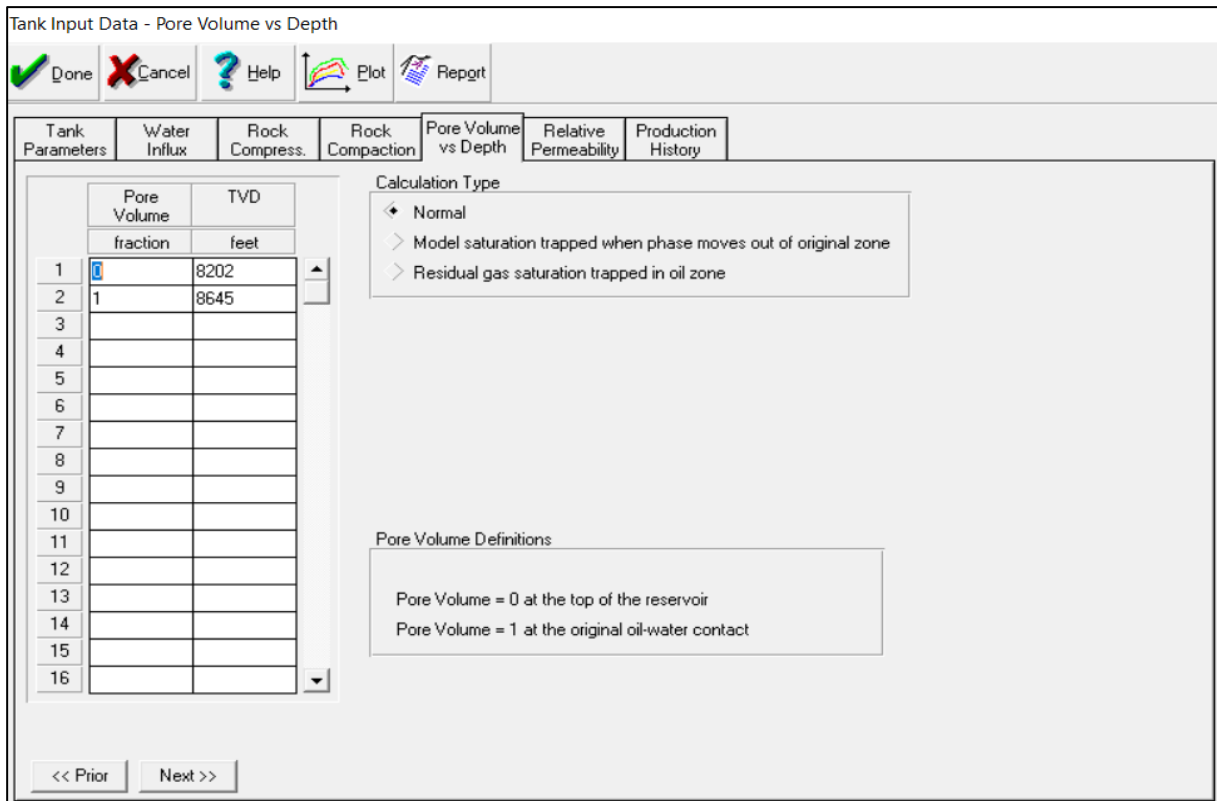


Figure 44 A snapshot of pore volume versus depth input data in Norne field

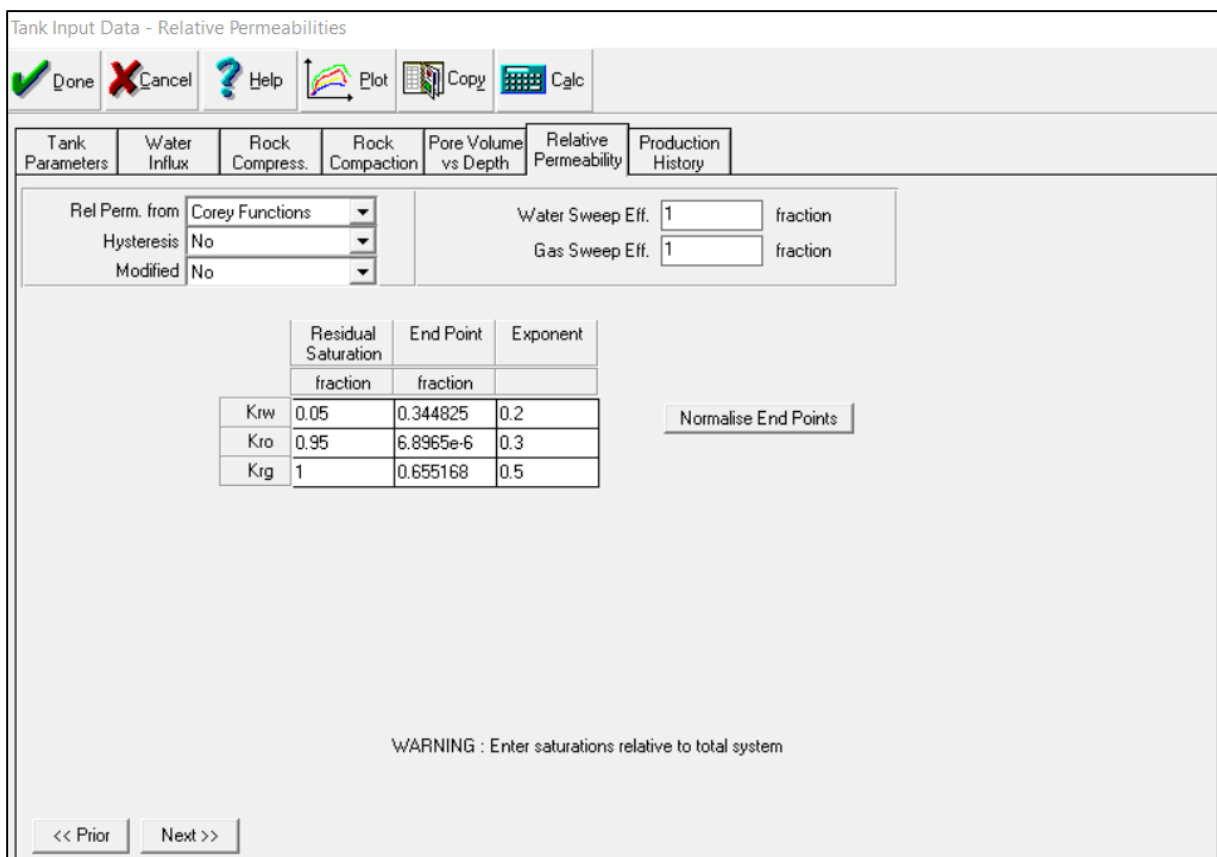


Figure 45 A snapshot of relative permeability data in Norne field

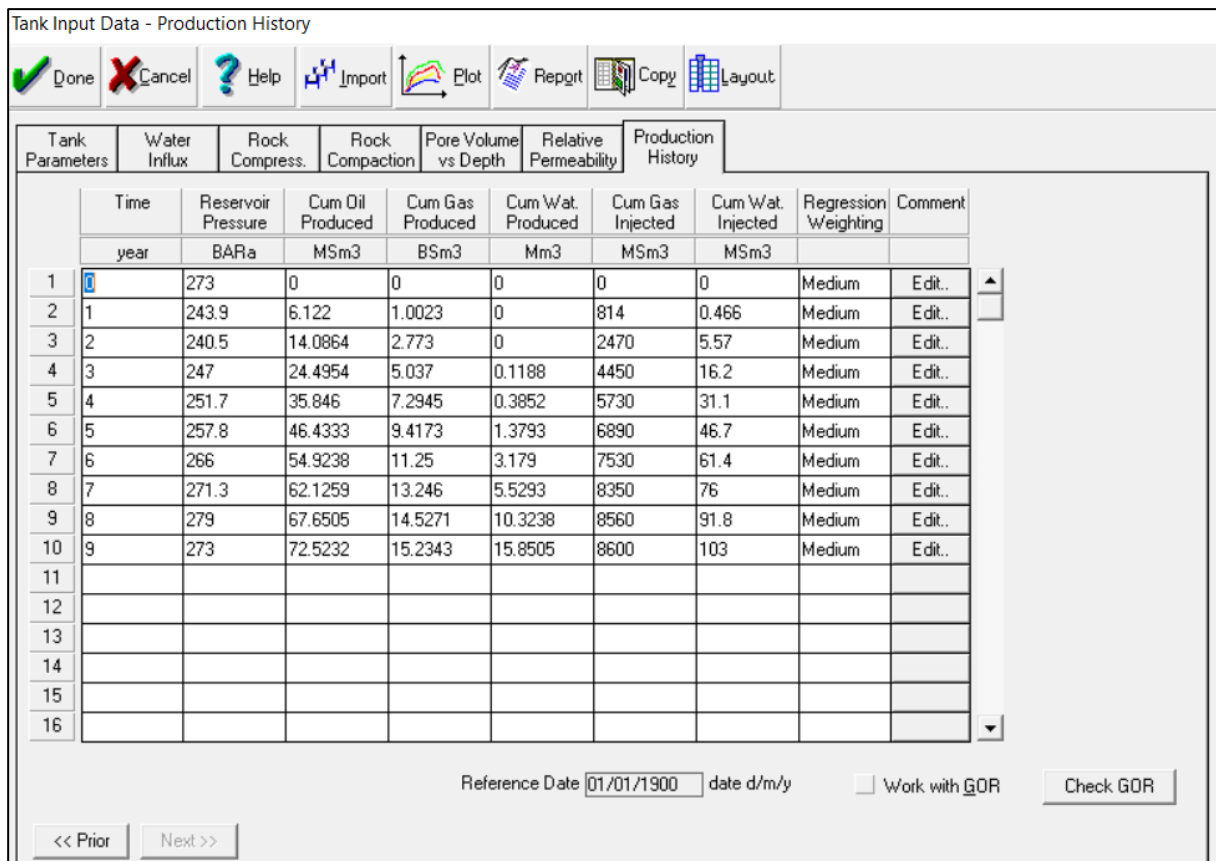


Figure 46 A snapshot of production history data in Norne field