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MASTER'S THESIS

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MODELING OF DIRTY SANDS AND CLAY ZONES WITH POOR PRODUCTION CHARACTERISTICS

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ABSTRACT

The Statfjord field is one of the oldest and largest oil and gas producing fields on the Norwegian continental shelf. It is currently at its late life production period with pressure depletion as the main production mechanism. Gas released from the residual oil contributes a large portion to the field reserves. At this period of production, all sources of pressure support are important and should be included in modeling of pressure drop in reservoir.

Non productive zones, which contain "dirty sand" and clay, are traditionally not included in numerical reservoir simulation models as they are believed to have a negligible impact on the production performance. However, in this project, when the pressure reduction is large and over a long time, the non productive zones can act as an external pressure support by produce water into the reservoir. Additionally, the gas dissolved in such water will be released as pressure of the reservoir drops. The gas is liberated under the form of small bubbles and the bubbles are believed to be immobile – they block the pore and act as a factor of pore volume reduction. This helps increasing effective compressibility of the formation. Both of the mentioned effects can contribute significantly to total reservoir pressure drop. The objective of this thesis is to evaluate the pressure contribution from non productive zone to total pressure drop by calculating induced water volume from the zone into reservoir and to develop methods for including the impact of such zones in conventional reservoir simulation models.

The thesis involves in building reservoir simulation models with basic fluid and rock properties data from Brent formation of Statfjord field and different combinations of parameters of non productive zone permeability, thickness, compressibility, field depletion time and reservoir pressure drop to evaluate the correlations between those parameters with induced water volume from the zone into reservoir. Reservoir simulator Eclipse is utilized for simulating the flow of fluids and pressure inside the zone and reservoir. For the impact of dissolved gas in water liberation on effective compressibility of rock, ROCKTAB keyword, which traditionally used for rock compaction/expansion scenario, is utilized.

It has been observed in the simulation results that for a specific combination of parameters for non productive zone, there is a value of thickness such that no matter how thicker than that value the non productive zone is, the volume of induced water does not change dramatically. For a specific zone, optimum grids thickness should be used in building simulation models to save time and resources for having to run with finer grid sizes. Grids

thickness distribution for the non productive zone seems not to have a large impact on the simulating results.

Different correlating equations between induced water volume and the other parameters have been found for the cases where the thickness of non productive zone is higher than the effective value and that of non productive zone less than the effective value. The equations may generally be used to estimate induced water volume for other formation rather than for Brent formation only.

ROCKTAB keyword is useful when being used to simulate the impact from dissolved gas releasing. The result data fit well with the data calculated from correlating equation mentioned above.

This thesis is merely a primary study on the matter. More works on running simulation models which integrate combinations of parameters should be carried out in order to confirm the obtained correlating equations as well as the application of such equations on general formation cases.

ACKNOWLEDGEMENTS

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Stavanger, June 2011,
Pham Gia Minh

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NOMENCLATURE AND ABREVIATION

NP zone	Non Productive zone
SFLL	Statfjord Late Life
RDP	Reservoir Development Plan
h_{NP}	Non Productive zone thickness, m
t	Depletion time, day
tD	Dimensionless time
WI	Induced water volume from NP zone to reservoir, m^3
WId	Dimensionless volume
$R_{ws,salt}$	Gas solubility in saline water (Sm^3/Sm^3)
R_{ws}	Gas solubility in pure water (Sm^3/Sm^3)
SRR_{ws}	Gas solubility ratio ($R_{ws,salt}/ R_{ws}$)
$B_{w,un.sat}$	Under saturated water formation volume factor (Rm^3/Sm^3)
$B_{w,sat}$	Saturated water formation volume factor (Rm^3/Sm^3)
$B_{w,sat,salt}$	Saturated water with dissolved salt formation volume factor (Rm^3/Sm^3)
$V_{g,released}$	Volume of dissolved gas released from water at pressure P, Rm^3
$V_{dissolved\_gas,Pi}$	Volume of dissolved gas in water at initial pressure, m^3
$V_{dissolved\_gas,P}$	Volume of dissolved gas in water at pressure P, m^3
$B_{g,Pi}$	Gas formation volume factor at initial pressure, Rm^3/Sm^3
ΔR_{ws}	$R_{ws,Pi}-R_{ws,P}$
B_g	Gas formation volume factor at pressure P, Rm^3/Sm^3
P_i	Initial pressure, bar
P	Pressure, bar
ΔP	Pressure drop in reservoir, bar
μ	Fluid viscosity, cP
φ	Porosity

C_t Total compressibility, bar^{-1}

$V_{w,sat}$ Saturated water volume for 1 unit volume of water at standard condition, Rm^3

M_{pore} Pore volume multiplier

V_{rock} Volume of rock at pressure P, Rm^3

$V_{rock,i}$ Volume of rock at initial pressure, Rm^3

$V_{t,g+w}$ Total volume of gas and water at pressure P, Rm^3

$V_{t,w+g,i}$ Total volume of gas and water at initial pressure P, Rm^3

$C_{t,av}$ Average compressibility, bar^{-1}

Subscript

i: initial condition

w: water

g: gas

rock: rock

sat: saturation

un.sat: undersaturation

t: total

1 INTRODUCTION

1.1 General

Statfjord is one of the oldest producing fields on the Norwegian continental shelf. It was discovered by Mobil in 1974 and began to produce from November 1979. The field is located on the western side of the North Viking Graben; location of the field is described in Figure 1-1. The field is also one of the largest oil and gas discoveries in the North Sea with STOIIP of 1006 MSm3 oil and 179.6 GSm3 gas.

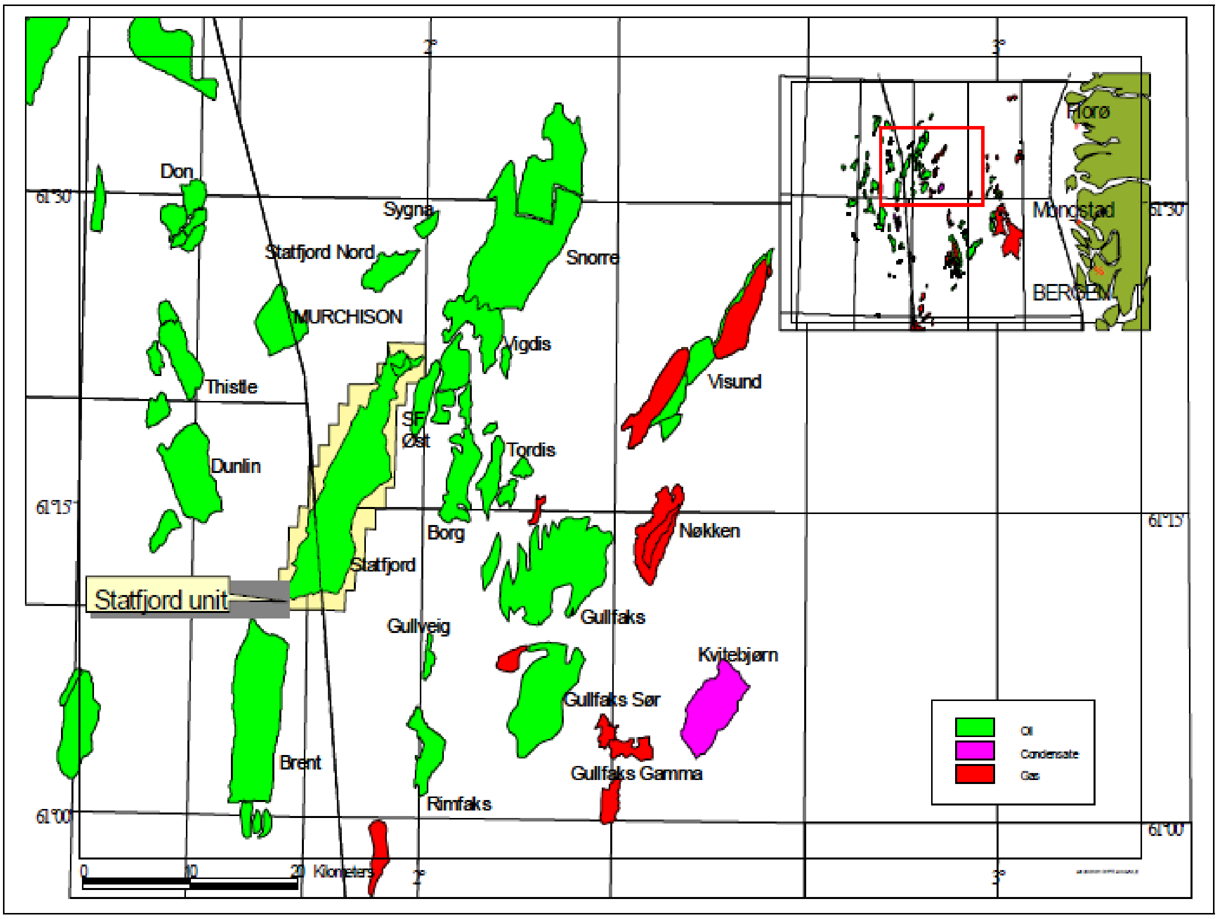

Figure 1-1. Location of Statfjord Field (Statfjord RDP 2007)

In June 2005, Statfjord Late Life Project (SFLL Project) was approved and new production strategy was implemented with the goal of converting the field from an oil field in to a gas field (with associated oil) by reducing reservoirs and platform pressure. The oil and gas production rates are declining. The field is expected to produce up until 2020 with recovery factor for oil and gas are expected to be 66% and 72% respectively (22).

In the late life of the field production, one of the technical challenges for the implementation of drainage strategy is: "Monitor and predict reservoir behaviour during SFLL" (22). In order to overcome the challenge, "mastering the mechanisms of pressure decline, gas generation and migration is essential to succeed in the depletion phase". Full field simulation model has been built and updated to monitor the reservoir activities.

One important factor which has certain impact on the supporting pressure of the reservoir, especially at low reservoir pressure, but not yet been investigated in any simulation model, is the released water from non-productive zones (NP - "dirty" sands and clay) and dissolved gas from such water, which occupies the pore and thus, reduces the pore voluem. This thesis will investigate the pressure contribution from the non productive zone (NP zone) by the means of induced water from that zone into reservoir and pore volume reduction by dissolved gas in the water, and develop a method of including the impact from such zones into conventional reservoir simulation models.

1.2 Methodology

The thesis involves in simulating Statfjord reservoir models, together with non-productive zones using Eclipse software as simulator. Various approaching options related to changing inputs of the model as well as reservoir properties are investigated by the models. This is accomplished by building and running many reservoir simulating cases for an imaginary reservoir (with rock and fluids parameters taken from Brent formation - Statfjord fields). The following steps are carried out for the purposes of the project:

- *General:* build simulation models with various reservoir and model parameters. In the models, NP zone is located on top of the reservoir. The pressure drop is controlled by limiting maximum production rate from reservoir. The thickness and properties of reservoir below the NP zone are kept unchanged for all scenarios. The NP zone is assumed to contain only water while the reservoir contains only oil with properties the same as oil from Brent formation of Statfjord field.
- *Finding the effective thickness of NP zone:* simulate the flow of fluid process from NP zone into the reservoir with various NP zone thicknesses and permeability to find the effective NP zone thicknesses corresponding to different values of permeability – the thicknesses above which there would be little changes in volume of induced water into reservoir. The effective NP zone thickness estimations are carried out with reservoir

pressure drop of 250 bar, 12 years of depletion time, total compressibility of 8.12×10^{-5} bar^{-1} and grids thickness of NP zone of 1m.

- *Investigating the correlation between NP zone thickness, reservoir pressure drop, NP zone permeability, field depletion time and total compressibility with induced water volume:*
    - NP zone with thickness less than the effective value: scenarios with different values of NP zone thickness, compressibility, permeability, depletion time and reservoir pressure drop are built and simulated. Correlating equations for dimensionless values of induced water volume and time are investigated by plotting graphs and using SOLVER function in Microsoft Excel. The correlating equation is expressed under dimensionless values of volume and time. Graphs between parameters are plotted to find the correlating equations between parameters.
    - NP zone with thickness equal or greater than the effective value: because of the existence of the effective value, for any thickness of NP zone is higher than the effective thickness, induced water volume does not change significantly (even when the thickness of NP zone goes to very high value). Therefore, correlations between all the parameters, except the NP zone thickness, have been investigated. Different models with various parameters are simulated; some parameters are fixed while changing the others to see the relationship between them. Graphs between parameters are plotted to find the correlating equations between parameters.
- *Investigating the effect of releasing dissolved gas in water to the induced water volume*: gas dissolved in water, when being released can act as a pore volume occupier (assuming it is immobile), which reduced the pore volume of NP zone. The phenomenon is similar to the compaction/expansion of rocks when reducing pressure and therefore, ROCKTAB keyword can be used in simulation program for Eclipse. Average total compressibility is then calculated from initial and final condition. Correlation between dimensionless volume and time then are investigated.
- *Finding optimum grid thickness:* for the obtained effective thickness of the NP zone corresponding to different values of permeability, each model is tested with various

values of grid thicknesses to find an optimum value, the value where the induced water volume would not change significantly even if finer grids utilized in the model.

- *Investigating the effect of various grid thickness on the induced water volume:* for one effective thickness value of a specific NP zone, the grid thicknesses of the simulation layers are varied and the obtained induced water volumes for each scenario is compared to each other to see the if the changes in the induced water volumes are significant with the changes of grid thicknesses or not; and if there are any correlation between parameters.

More details of the methodology and working process will be discussed in following chapters.

1.3 Structure of the thesis

The thesis contains 5 chapters. Following the introduction, chapter 2 discusses about theoretical aspects of the thesis, which includes induced water from rocks, total compressibility and effects of dissolved gas in water on it; geological setting of Statfjord field; reservoir modelling and simulation related knowledge etc. Chapter 3 and 4 describes more details of working process together with the simulating results and analysis of the results. Discussions of the results are also included in chapter 4. The final chapter summarizes the entire thesis with some conclusions and statement about future works on the matters relating to the project.

2 THEORY

2.1 Depressurization process of a oil field

For a mature field, depressurisation of waterflooded reservoirs can economically increase recovery and extend the life of the field (Drummond. A. et al), especially for fields with reservoirs contain high solution gas oil ratio. In other words, depressurisation is an option to enhance the late life reserves of the field. According to Beecroft, waterflooding and other conventional recovery processes can result in large quantities of residual oil in a reservoir. In addition, oil may also be trapped in unswept regions of reservoir with significant volume. The depressurisation process results in releasing gas from unswept and swept oil in the reservoir. The gas gained from the process is potentially large in volume and can be put on sales to contribute to the field's economical values.

The depressurisation of an oil field relates to several processes, for which the main challenge is to manage the field to maximise oil recovery while maintaining gas sales at plateau. As pressure in the reservoirs depleted, unswept oil would liberate gas; the gas, after reaching a critical saturation, becomes mobile and migrates vertically to a shale layer and begins to move up-dip towards the crest of the field (Braithwaite). The reservoir depressurisation process for one geological layer can be showed in the below figure.

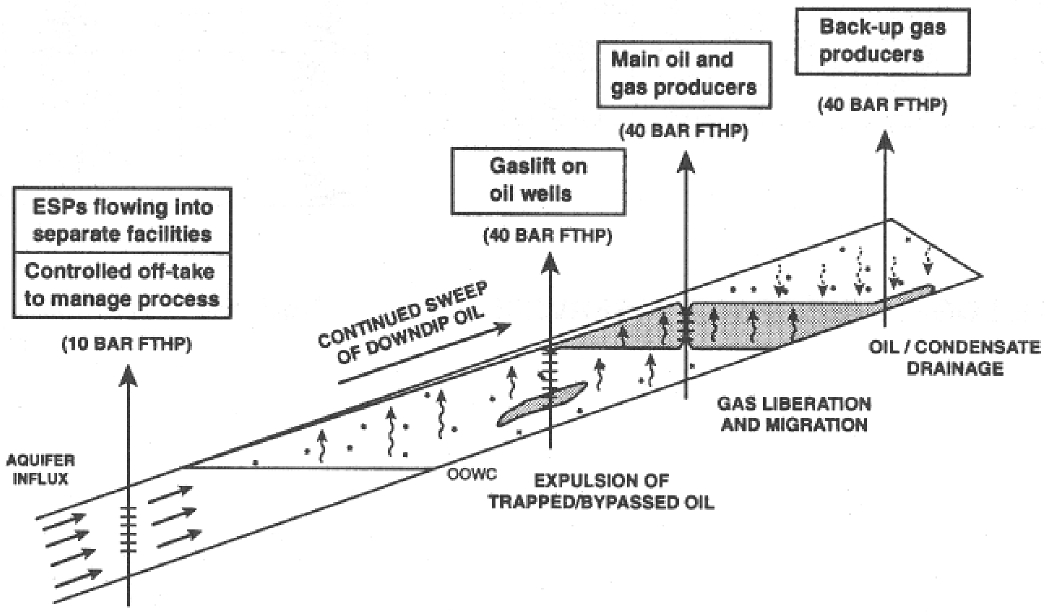

Figure 2-1: Reservoir depressurisation process within one geological layer (6)

The growth of the gas cap during depressurisation in reservoir depends on the rate of pressure decline. It is expected that more gas would be liberated than required to sustain the gas contract. The excess gas would be stored in a number of selected reservoir units. The gas cap would be allowed to expand in those units to a certain volume, which has been predetermined. Additional oil recovery could be gained by a gravity drainage process in those reservoir units. The drainage of both oil and condensate helps sustain the oil-rim size and by careful planning of well locations, additional oil recovery may be possible (6). In order to maximize oil recovery, special attention would be paid to oil-rim management. The oil rims should remain at the crest during depressurization so that wells continue to produce from the oil-rims, without interruption because of workover and side-tracks campaigns. The gas caps should be kept as much as possible and maintained during depressurisation to ensure requirement of free gas supplying in the gas contract.

The depressurisation of Brent Gp in Statfjord field involves in the reduction of pressure in reservoir for about 230 bar within a period of 18 years. Gas production will be from existing, secondary gas caps, created as a result of gas injection. Similar to other depressurisation process of other fields, the overall goals and challenges for reservoir management of the Statfjord Field are to maximise the net present value for the lifetime of the field and optimise the hydrocarbon recovery (22 & 2). The main risks encountered during the depressurisation process for the field are critical gas saturation, which will be bases to predict when gas will start to accumulate at the crest and available for sales and how easy it will be to stay on gas plateau; aquifer influx, which influences the success of the depressurisation project by its strength and size; reservoir compaction, which can result to subsidence and affects the wellbore integrity and platform wave height safety margins; sand failure during large pressure drop inside reservoir and H_2S formed and released during the depressurisation (7 & 6 & 2). The new drainage strategy in Statfjord field is expected to increase the ultimate recovery of gas from 53% to 74% (2). Oil recovery increases slightly due to prolonged economical life of the field.

2.2 Induced water from non-productive zones

Non productive zone is defined as shale/shaly sand with some water filled porosity and non-zero permeability. During depletion of the field, non productive zone may also deplete. Water is released as result of depletion and the releasing water acts as pressure support to the reservoir.

Bourgoyne, in both of his articles, stated that shale water influx is a possible mechanism for pressure support in a superpressure gas reservoir. In his research, he indicated that shale water influx should be considered in material balance calculations for it can contribute significantly to pressure support. The influx or induced water from shale is controlled by shale permeability, shale porosity, shale compressibility and shale water viscosity. Bobek (1961) and other in their experiments also found out that shale water influx can affect recovery for oil wet and water wet porous medium at different scales: recovery decreased with decreasing rate of induced water from shale. Bourgoyne concluded in his literature that shale water influx is approximately proportional to the square root of the permeability-compressibility product and for superpressure gas reservoirs, significant quantities of water can move into it and contribute to pressure support.

Fetkovich (1997), in his general material balance equation obtained from series of mathematical derivations, also accounted for the impacts of water from non pay and total water compressibility on pressure support of a high pressure gas reservoir.

Even though the induced water volume from shale to reservoir is small, it can still contribute significantly to total pressure support during the late life period. Higher permeability non productive zone will have higher impact on the total pressure support.

2.3 Water contribution from non productive zone

Not many literatures on how much water coming from certain part of NP zone into reservoir are found. However, in common sense, due to low permeability and porosity of the NP zone, the water at positions far way from boundaries between NP zone and reservoir would take longer time to reach the boundary than the water at closer points.

Bourgoyne expressed the reaction of pressure in shale against time and distance from reservoir in the Figure 2-3 below. It can be seen from pressure profiles that pressure decreasing from high value to reservoir pressure when approaching the boundary between shale and reservoir. This means that the water at further points from reservoir responses slower than the closer point.

Statoil in its internal studies also found similar effect when investigating various pressure profiles with different NP zone thickness. One example of the pressure distribution inside shale layers are showed in Figure 2-2.

It is therefore expected that for a specific NP zone within certain depletion time, only part of the zone will contribute most of the support to the pressure (or water mostly comes from this part), impacts from the other part far away from the boundary may be neglected.

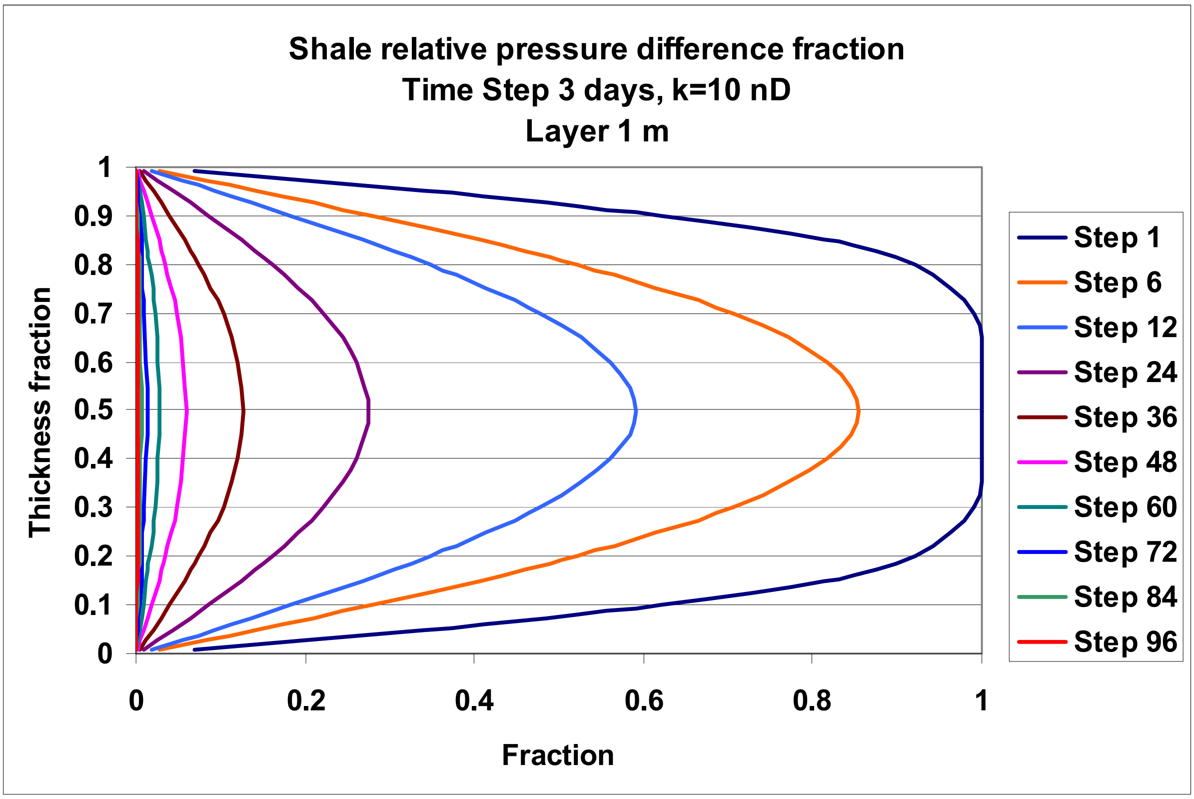

Figure 2-2: Shale pressure profile vs time (STATOIL)

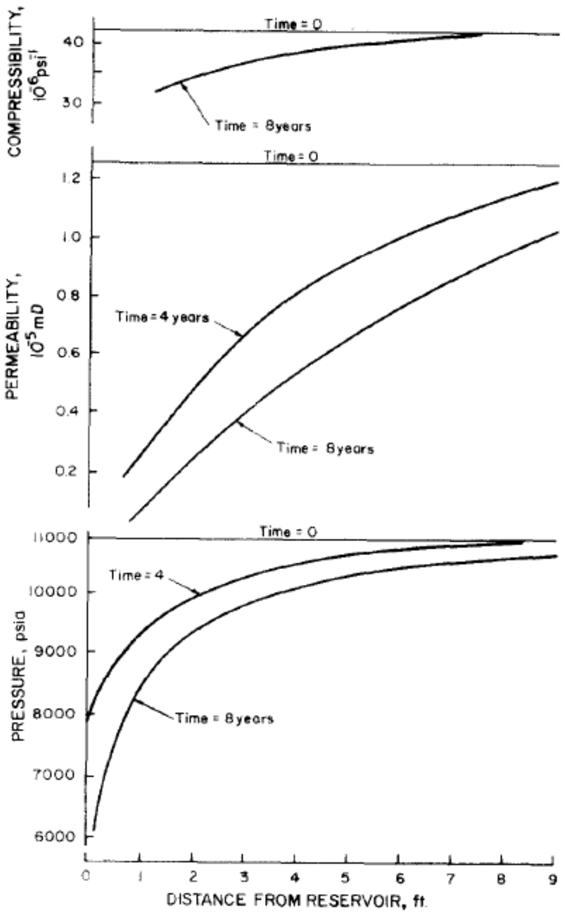

Figure 2-3: Shale properties as a function of distance and time (4)

2.4 *Effect of dissolved gas on effective compressibility*

Dissolved gas in water, when being released will form gas bubbles inside the pore. The gas bubbles are blocked in pore space of NP zone and most likely not mobile due to capillary pressure. It does, however, have significant impact on the system compressibility by expanding when pressure drop and contributing to the pore volume reduction in NP zone. Therefore, the released gas acts as an extra energy source in the aquifer.

This part of the thesis involves in derivation of pore volume multiplier caused by the presence of gas in water inside NP zone.

It is observed that the amount of gas dissolved in water is dependent on pressure and salinity of the water. Taken value of R_{ws} from Figure 2-4, the solubility of gas in saline water can be calculated using the equation:

$$R_{ws,salt} = R_{ws} * SRR_{ws}$$

The solubility ratio can be read from Figure 2-5.

The salt when dissolved in water can change the water formation volume factor. Given values of undersaturated and saturated formation volume factor from Figure 2-6, the saturated water formation volume factor when dissolving salt in it can be computed from following equation:

$$B_{w,sat,salt} = B_{w,un.sat} + SRR_{ws} * (B_{w,un.sat} - B_{w,sat})$$

For calculation purpose, assuming 1 unit volume of water at standard condition, we can calculate the gas released from water at reservoir condition using the formula by Fetkovich (12):

$$V_{g,released} = (V_{dissolved\_gas,P_i} - V_{dissolved\_gas,P}) * B_{g,P_i} = \Delta R_{ws} * B_{g,P}$$

Because of assumption of 1 unit volume of water at standard condition, at reservoir condition we have:

$$V_{w,sat} = B_{w,sat}$$

Total volume of water with dissolved gas in it at reservoir pressure is:

$$V_{t,w+g} = V_{w,sat} + V_{g,released}$$

Taken into account the effect of rock expansion due to rock compressibility, the pore volume multiplier can be computed using followign equation:

$$M_{pore} = 1 - (\frac{\Delta V}{V})_t = 1 - \frac{\Delta V_{rock}}{V_{rock,i}} - \frac{\Delta V_{t,g+w}}{V_{t,g+w,i}} = 1 - \frac{\Delta V_{rock}}{V_{rock,i}} - \frac{V_{t,g+w,i} - V_{t,g+w}}{V_{t,g+w,i}}$$

The average compressibility or effective compressibility of NP zone with gas saturation water in it can be calculated from normal compressibility estimating formula:

$$C_{t,av} = \frac{\Delta V_t}{\Delta P * V} = \frac{1 - M_P}{P_i - P}$$

Pore volume multiplier is used in the simulation models to simulate the impact of rock compaction of the NP zone (using keyword ROCKTAB) while average compressibility value corresponding to that multiplier value is used in dimensionless volume and dimensionless time calculations in the next chapters. The dimensionless quantities are defined as following:

$$WId = \frac{WI}{WI_{Ultimate}} = \frac{WI}{V_W * C_t * \Delta P}$$

$$tD = \frac{k * t}{C_t * h_{NP}^2 * \phi * \mu * 10^8}$$

The thesis will try to find an equation describing the dependence between the dimensionless values. The equation can be used in general cases rather than for Brent Fm only.

In case of shale water not 100% saturated with gas, all the calculations are similar except that the gas bubbles can be released only when the pressure reach the bubbles point and therefore, the pore volume reduction caused by the gas released happens only from pressure less than bubble point pressure.

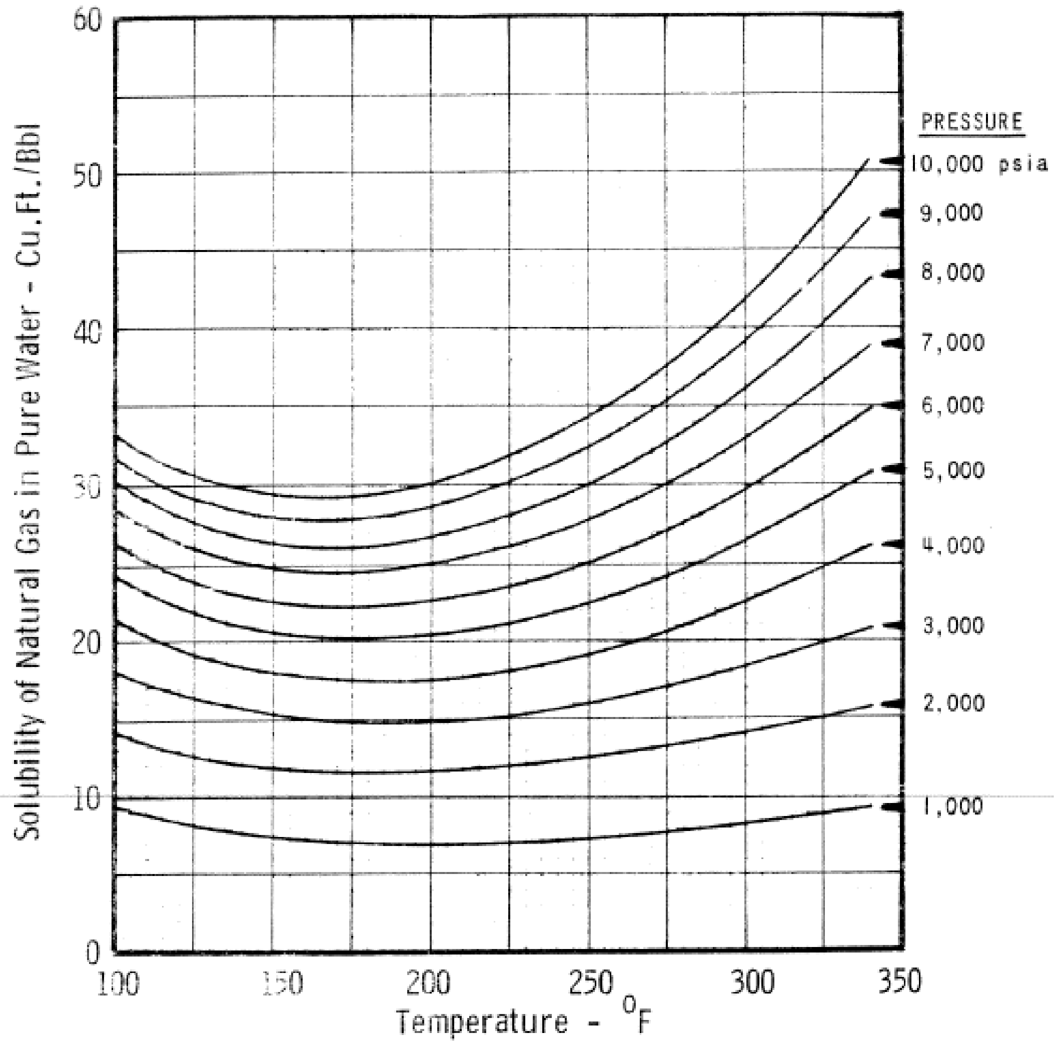

Figure 2-4: Solubility of 0.65 gravity natural gas in pure water (9)

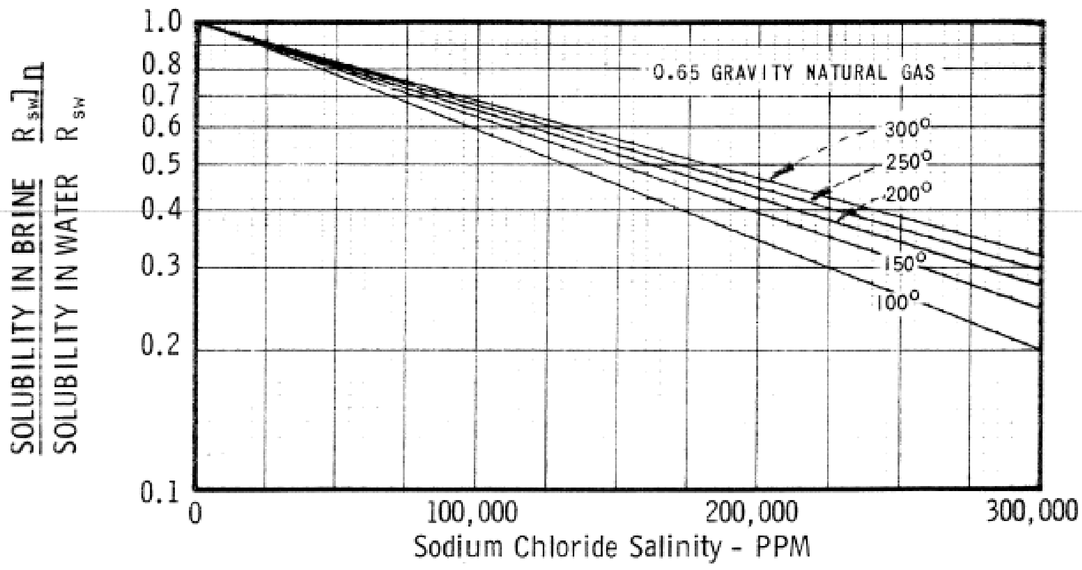

Figure 2-5: Reduction in gas solubility due to dissolved salt content (9)

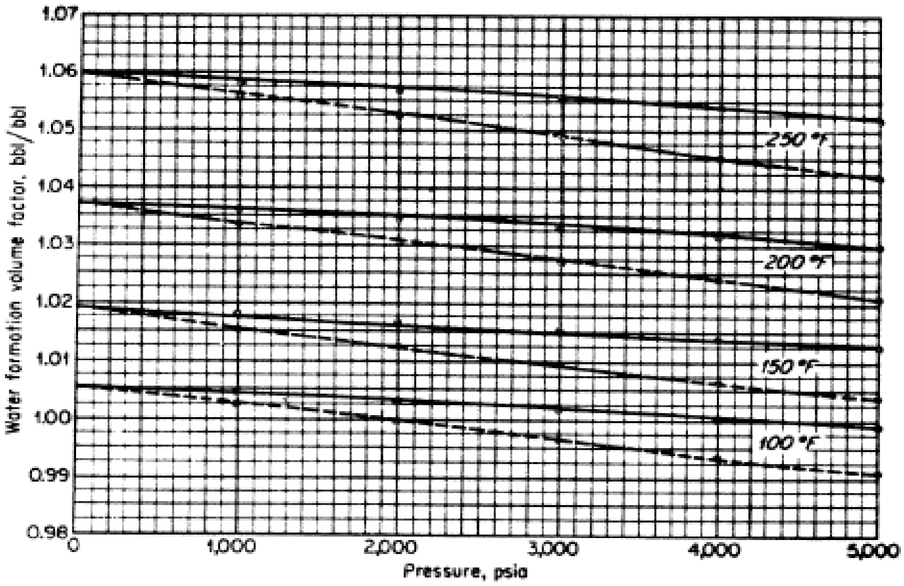

Figure 2-6: Water formation volume factor for pure water (dashed lines) and pure water saturated with natural gas (solid lines) as function of pressure and temperature (9)

2.5 Geological setting of Statfjord Field and Brent Group

The Statfjord Field is situated on the western margin of the North Sea Rift System, on the crest of a SW – NE trending tilted fault block and on the footwall of one of the major faults on the western side of the North Viking Graben (Tampen Spur area); its area is of approximately 26 x 5 km (Statfjord RDP 2007). The field contains of two parts: a relatively uniform Main Field fault block, which reservoirs consist of sandstones ranging in age from Late Triassic – Mid Jurassic, and East Flank gravitational collapse zone, which reservoirs formed with reworked Mid - Upper Jurassic reservoir sandstones.

The Main Field of Statfjord consists of 5 main reservoirs:

- The Lower Statfjord Formation, comprising the Raude Member
- The Upper Statfjord Formation, comprising the Eiriksson and Nansen Members
- The Dunlin Group, comprising of the Cook Formation
- The Lower Brent Group, comprising the Etive, Rannoch and Broom Formations
- The Upper Brent Group, comprising the Ness and Tarbert Formations

The East Flank, on the other hand, consists of reservoirs belong to Reworked Brent (and Dunlin) sediments and fault blocks of Brent, Dunlin and Statfjord sediments.

The typical stratigraphy and permeabilities for the different reservoir units of the Statfjord Field are shown in Figure 2-7.

Lithostrat.			LITHO_Statfjord
Viking		Rew. Brent	Rew. Brent
BRENT	Upper Brent	Tarbert	Tarbert
		Ness	Ness 2
			Ness 1
	Lower Brent	Etive	Etive
		Rannoch	Rannoch 2
			Rannoch 1
		Broom	Broom
DUNLIN		Drake	Drake
		Cook	Cook2
			Cook 1B
			Cook 1A
		Burton	Burton
		Amundsen	Amundsen 2
			Amundsen 1
STATFJORD	Upper Statfjord	Nansen	Nansen
		Eiriksson	Eiriksson
	Lower Statfjord	Raude	Raude 2
			Raude 1

Figure 2-7. Lithostratigraphic Column of Statfjord Field (Statfjord RDP 2007)

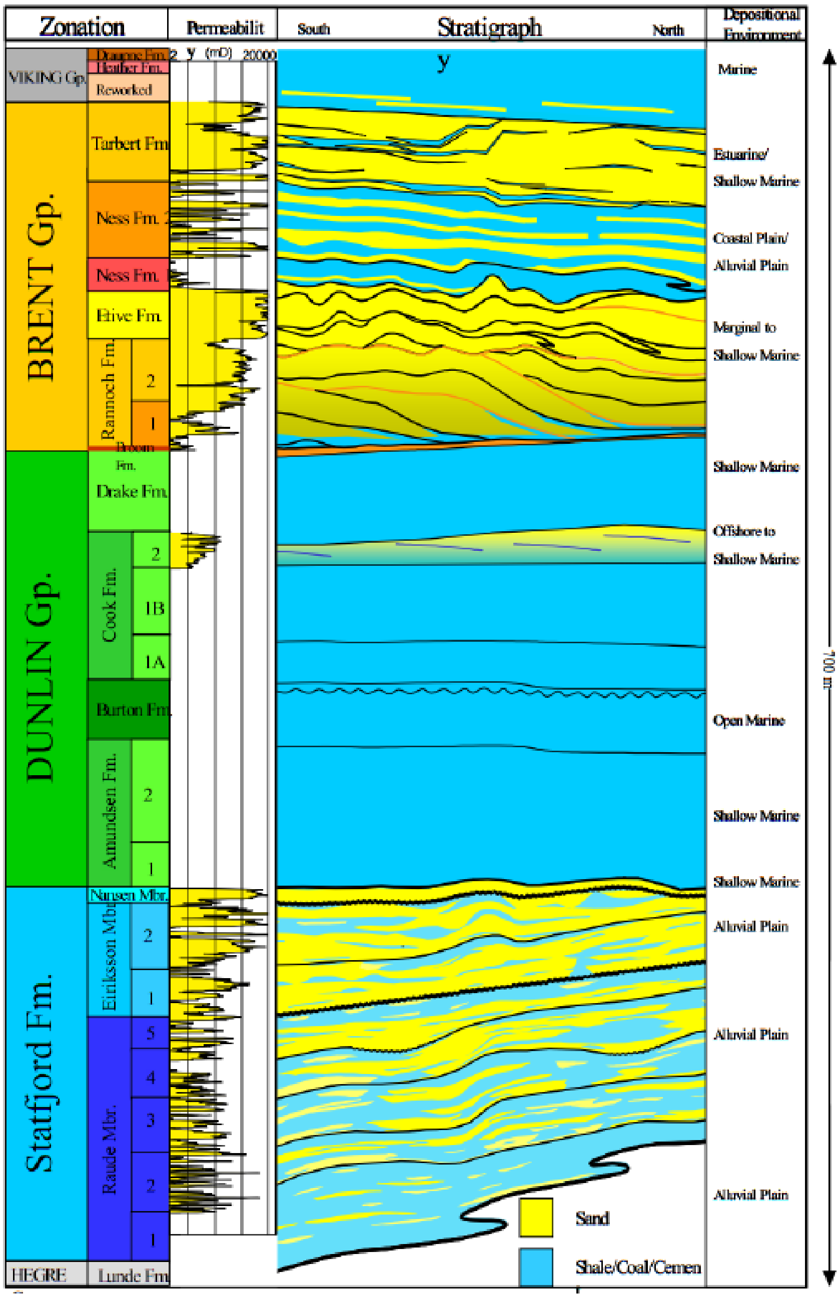

Figure 2-8. Lithostratigraphic Column of Statfjord Field (Statfjord RDP 2007)

The input data of this project is taken from Brent formation in Statfjord field. The Brent formation group consists of Upper Brent and Lower Brent.

Upper Brent: the Tarbert Fm lays on top of Ness 1 & 2 Fm. It composed of several wedges of shallow marine sand along the total Brent system. In the northern part of the field, Tarbert is very homogeneous as a result of a more wave/storm dominated shore face environment while moving further to southern part, Tarbert is heterogeneous, including numerous coal beds. On the Statfjord field, the Tarbert Fm varies in thickness, generally ranging from 40m to 55m. This formation is subdivided into 8 zones. The Ness Fm is wide spread throughout the Brent depositional province. Its maximum thickness is in Central Viking Graben and the thickness decreasing northwards. As described in RDP of Statfjord field, The Ness Fm in the Statfjord Field is characterized by highly layered mudrocks, coals and sandstones of coastal plain to shallow marine depositional origin. In the Statfjord Field, the lower Ness Fm (Ness Fm 1) shale represents a major pressure barrier, that divides the Brent Gp into Upper Brent and Lower Brent. Within the Statfjord Field, the Ness Fm is lithostratigraphically subdivided in two main zones.

Lower Brent: lays below the Upper Brent and consists of the Etive Fm, Rannoch Fm and Broom Fm. The Etive Fm represents the marginal marine environment and Rannoch Fm the prograded, storm dominated delta front. Lithological differences between the lower and upper part of the Rannoch Fm leads to distinctly different reservoir behaviour, and hence the Rannoch Fm is subdivided into Rannoch 1 and Rannoch 2. Broom Fm is sheet sand, which was deposited as storm deposits and small distal bar buildups on a shallow marine platform. The Broom Fm marks the base of the Brent delta complex and lays on top of Dunlin Gp.

2.6 Reservoir simulation

2.6.1 Reservoir models and simulation

Reservoir modelling is a part of reservoir engineering study. The process involving in the construction of a computer model of a petroleum reservoir, based on available data collected from geological survey, geophysic, petrophysic measurement and well testing results, their interpretations etc. The data employed for the reservoir modelling covers rock & fluids characteristics, reservoir structures, quality of reservoir, pressure, and temperature regimes of the reservoir. Lots of mathematical equations for the properties are solved using sophisticated computer programs in order to describe the processes inside the reservoir. The reservoir model then can be utilized in supporting decisions related to field development planning, reserves estimation, reservoir management and production & reservoir behaviour forecasts…

It is dependent on the purposes of tasks and applications of the results that how the models are built. The finer the grids and simulation steps, the more precise the results are. However, the time consumption and complexity of the models also increase, consequently increasing the cost and punctuality of the project and therefore, may not be suitable for some specific goals. Availability of input data also plays an important role in getting high quality of the models. The more data is provided, the closer to reality the models are. However, similar to the previous situation, high availability of data may effect time and cost effectiveness of the project and should be optimized in order to achieve the best results. Input data for the simulation model can be taken from following sources:

Property	Sources
Permeability	Pressure transient testing, core analyses, correlations, well performance
Porosity, Rock compressibility	Core analyses, Well logs
Saturations	Well logs, core analyses pressure cores, single-well tracer test
Relative permeability and capillary pressure	Laboratory core flow test
Fluid property (PVT) data	Laboratory analyses of reservoir fluid samples
Faults, boundaries, fluid contacts	Sesmic, pressure transient testing
Aquifers	Seismic, material balance calculations, regional exploration studies
Fracture spacing, orientation, connectivity	Core analyses, well logs, seismic, pressure transient tests, interference testing, wellbore performance
Rate and pressure data, completion and workover data	Field performance history

Figure 2-9. Input data for simulation and sources of data (Fanchi, J. R)

In this project, the Black Oil model is used for reservoir simulations of a simple model based on data from Brent formation of Statfjord field. The Black Oil model is the simplest and most used for reservoir simulation. The model based on following assumptions:

- Three phases in reservoir: water, oil and gas.
- Three components: water, oil and gas
- The water component exists in the water phase only. No phase transfer between water and hydrocarbons.
- The oil component exists in the oil phase only.
- The gas component can exists in both the oil and gas phase. This means that gas can be dissolved in oil and come with oil when it is produced; the gas produced at the surface therefore comes from both the reservoir oil and reservoir gas.
- Reservoir temperature is constant.

In this project, in the case of evaluating impact of dissolved gas in water, the effect of the gas is not simulated but it is utilized as source of modifying effective compressibility for the simulation. The effect is similar to the pore volume reduction by rock compaction. The Rock compaction option models the collapse of pore channels as the fluid pressure decreases. The process may be reversible, irreversible or hysteretic as required. (ECLIPSE Technical Description).

2.6.2 Reservoir simulator

A simulator is a computer program written to solve the equations for flow of fluids in a reservoir. The simulator integrates mathematical formulas and geological, geophysical, petrophysical, drilling, production, testing… data, processes and giving out the results on fluid flows, production forecasts, pressure regimes… of reservoir. The outcome from the simulator is very useful in reservoir management and development.

In this project, a reservoir simulator owned by Schlumberger Information Solutions called ECLIPSE is used to model and simulate the flow of fluids. ECLIPSE can solve Black Oil models with ECLIPSE 100 module and compositional and thermal models with ECLIPSE 300 module. In addition, ECLIPSE also provides means for visualizing and processing result data. This project employs ECLIPSE 100 module only.

Main structure of an input data file for ECLIPSE to run contains several sections that are in specific order, recognized by a keyword at beginning of each section. Some sections are compulsory and some of them can be optional. A typical structure of an input data file is as following (in their appeared orders) (ECLIPSE Reference Manual):

- RUNSPEC: declares title of the simulation run, start date, option switches, numbers of grid blocks and wells, dimension of tables, number of pressure nodes etc.
- GRID: defines basic geometry of the simulation grid and rocks properties for each grid block such as porosity, absolute permeability etc. Grid block pore volumes, mid-point depths and inter block transmissibilities can be calculated from those properties.
- EDIT: is an optional section that contains instructions for modifying data computed by the program in the grid section.
- PROPS: is a required section that contains pressure and saturation dependent properties of the reservoir fuids and rocks.
- REGIONS: is an optional section that divides the grid into sections/regions in order to compute different properties separately for different segments of the reservoir. The divided regions can be for segments with different rock properties, saturation functions, PVT properties, fuids in place etc.. If there is only one segment in reservoir, the REGIONS section can be omitted.

- SOLUTION: this section contains data that is base for computation of the initial state of the reservoir or defines the initial state of the reservoir. The initial state concerning pressure, saturations and fluid compositions for all grid blocks of reservoir.
- SUMMARY: is an optional section that specifies variables those will be written to Summary files for each simulation time step. The outcome data can be graphically plotted and displayed after simulation.
- SCHEDULE: specifies operations to be controlled and constraint and the controlling parameters. The operations can be production and injection. Also in this section, the times at which output reports are created are specified. In addition to that, vertical flow performance curves and simulation tuning parameters can be included in this section.

Keywords are special simulation coded commands those are used in the sections of input file to specify the input data, give control order to output files etc. Keywords are bases for any input file and they have to follow strictly pre-defined programming syntax.

2.7 Application of Microsoft Excel SOLVER function

Microsoft Excel SOLVER function is very useful function in Microsoft Excel that utilizes iteration to solve for variables in equations. The process involves in the setting up of an error value between actual data and guessed solution. By specifying which parameters in equations should be changed to get minimum possible error value, the solutions for the equations can be found.

In this project, given the values of WId and tD and a guessed equation under the form:

$$WId = 1 - \frac{1}{1 + a * tD^n}$$

SOLVER is used to find values of a and n. It is carried out by setting up initial guessed values of a and n and calculate corresponding values of WId based on the guessed parameters. Sum of squares of ratios of error values (between guessed and actual WId) and actual values are set to be target. The SOLVER function computes and changes values of a and n to get minimum value of the target. Values of a and n corresponding to minimum value of target cell are constant parameters for the guessed equation. The agreeability between the predicted values and actual values can be visualized when the data are plotted in a same graph.

3 NON PRODUCTIVE ZONE MODELLING

In order to investigate the dependences of induced water volume on reservoir properties, simple reservoir models are built. The input parameters for the models then are varied and the outcome results are analysed in order to find relationships between induced water from NP zone to reservoir volumes and reservoir properties. Details of the modelling process are described in following sections.

3.1 Input data

The simple reservoir models are built with two separate regions: a NP zone is located above a reservoir layer. For the purpose of investigating the induced water from NP zone only, the properties of reservoir region are kept unchanged for all the investigated models. One production well is included in the model.

3.1.1 Reservoir

The reservoir is built with dimension of 10x10x10 grids corresponding to dimensions of 1000x1000x50m. The properties of rock and fluids from the reservoir are taken from real Brent reservoir of Statfjord field without any modification. Some of the main input parameters are showed in the following table:

Table 3-1: Input parameters for reservoir region

Vertical permeability (mD)	Horizontal permeability (mD)	Porosity (%)	Rock compressibility (1/bar)	Water viscosity (cP)	Oil density (kg/m^3)	Gas density (kg/m^3)	Water density (kg/m^3)
333	333	30	4.12E-05 (@ 383 bars)	0.36 (@344.83 bars)	842.3	0.942	1001.1

The vertical production well is located at the corner of the reservoir and perforated for whole thickness of the reservoir section.

The depletion time of reservoir, pressure drop of the reservoir are changed for different reservoir simulation scenarios.

3.1.2 Non productive zone (NP zone)

Different cases are built with different input parameters for the NP zone, to fit the purposes of investigation. Some of the common input parameters of NP region for all the cases are showed in the following table:

Table 3-2: Some common parameters for NP region

Porosity (%)	Water viscosity (cP)	Water density (kg/m^3)
12	0.36 (@344.83 bars)	1001.1

Other properties of the NP zone such as zone thickness, simulation grids thickness, permeability, compressibility of rock and water are varied differently from different scenarios.

An imaginary water saturation table for the NP zone is utilized in the simulation models. The capillary pressures are adjusted so that there will be no fluids from reservoir will get into the NP zone. Only water from NP zone can go to reservoir as reduction of pressure in reservoir during the production period.

3.2 Reservoir modelling process

In order to investigate the correlations between parameters of NP zone, it is necessary to build many different modelling scenarios which integrated various input values. The outcomes from such modelling scenarios then will be processed and analysed using Microsoft Excel spread sheets and graphs. Details of the modelling projects are listed in the parts below.

3.2.1 Finding effective thickness for non-productive zone

Induced water coming from NP zone has to move through a medium with very low permeability. The water at positions far away from the NP zone-reservoir contact will therefore requires certain time to reach to the boundary. Thus, it is predicted that for a specific time, permeability, compressibility of NP zone and certain pressure drop of reservoir, only water from partial thickness of NP zone will contribute mostly to the pressure support of production. The partial thickness that contributes mostly to the pressure support of reservoir is defined as effective thickness of NP zone.

Finding effective thickness is important because it can save simulation time and computer resources: in case of encountering a very thick NP zone, it is more effective if we just take one section of it and integrate into the model without effecting the final results.

In order to find the effective thickness, the work flow for modelling is designed as the figure below:

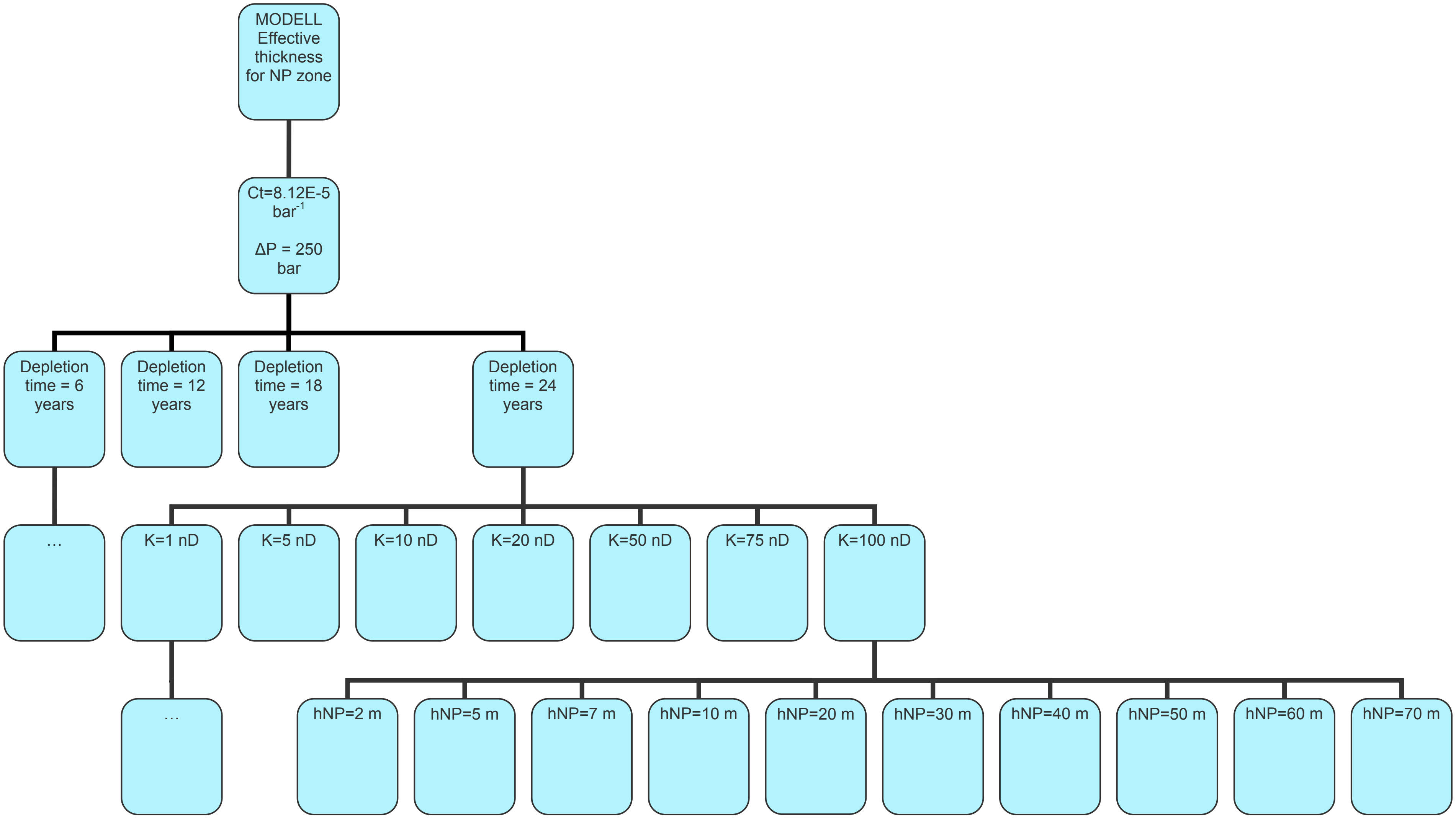

Figure 3-1: Work flow for finding the effective thickness of NP zone

In this thesis, the effective thickness of the NP zone is investigated for the cases where the total compressibility of the zone is 8.12E-5 bar^{-1} and reservoir pressure drop of 250 bar. For simplification, grids thickness of NP zone of 1m is used for all models.

The depletion times for the reservoir are set for the values from 6 to 24 years. The reservoir pressure drop of 250 bar within the depletion time period of the field is controlled by field production rates.

For the NP zone with the above input parameters, different values of permeability are integrated into the models. The models run with values of permeability from 1nD up to 100nD. Each value of permeability then will be the base to build different scenarios of NP zone thickness. The thickness of the zone ranges from 2m up to 80m. Induced water volumes from NP region into the reservoir are recorded. Values of induced water volume and NP zone thickness are plotted against each other with every value of permeability in order to see their correlations. For the studying purposes of this thesis, the values of induced water volumes of two NP zone thicknesses are considered to be negligibly changed when the difference between them less than 0.1% with the thickness difference of 1m. The starting point where the changes in induced water volumes are negligible defines the effective thickness of NP zone.

Summary of all values of effective thickness is plotted together in one graph for comparison.

More cases of combination from compressibility and pressure drop parameters can be studied for more corresponding values of effective thickness. Correlation between the effective thickness and other parameters may be found.

3.2.2 Induced water volume for NP zone with thickness less than effective value

Due to the existence of the effective thickness values, when studying the dependence of induced water volume on other parameters, it is necessary to divide the situation into two scenarios: one correlation including NP zone thickness (dimensionless correlation) and one correlation without NP zone thickness (dimensional correlation). The dimensionless correlation is applied for the NP zone thickness less than the effective thickness values.

The work flow for this case of study is described in the following figure:

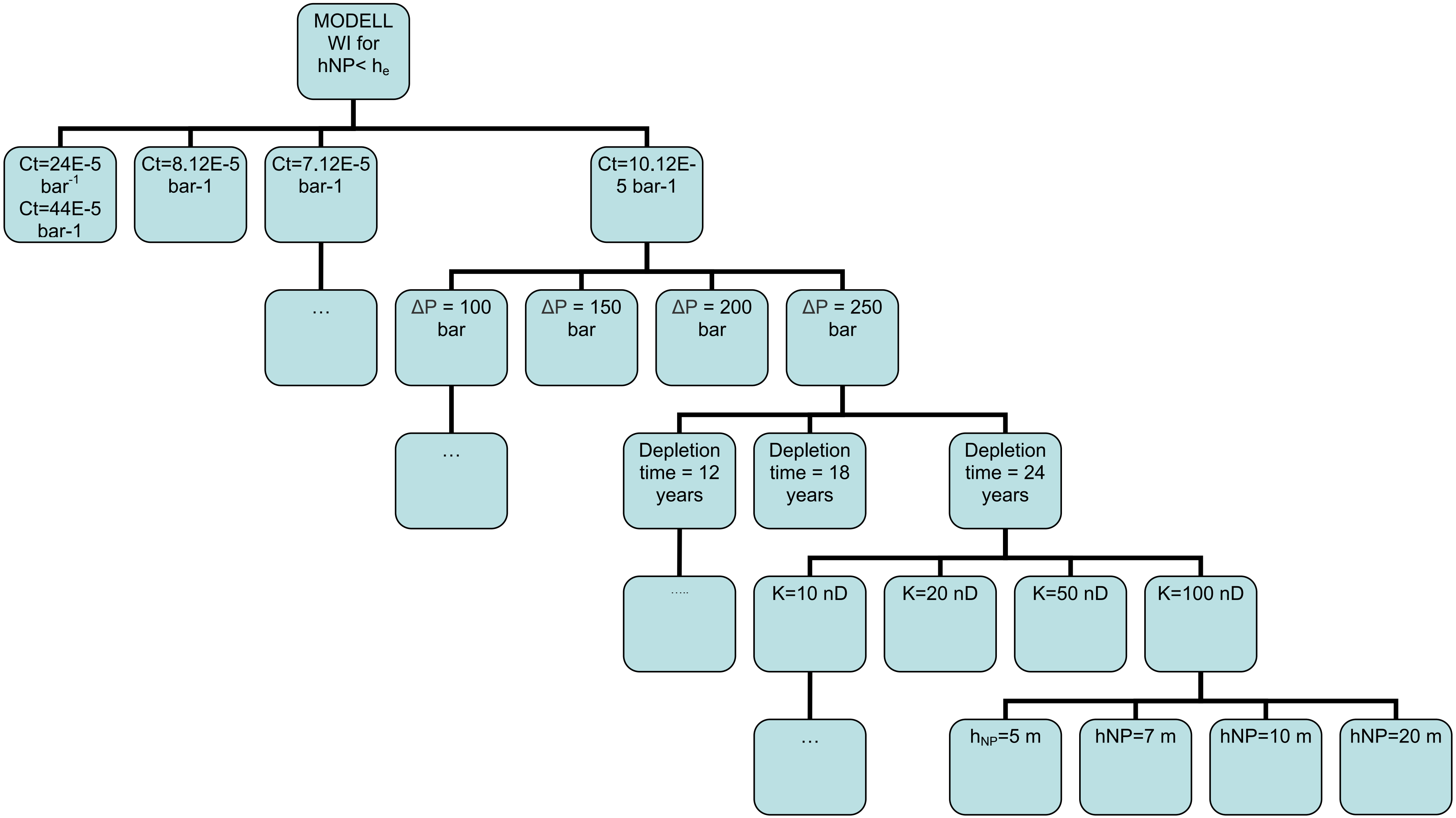

Figure 3-2: Work flow for finding correlation between induced water volume and other parameters for NP zone with thickness less than effective value

In this case, the models are built with different combinations of values of compressibility, reservoir pressure drop, NP zone permeability, depletion time and NP zone thickness. For each combination, one value of induced water volume is recorded from simulation result. Grids thickness for the NP zone is 1m for all the runs.

The correlation between dimensionless values is also checked with extreme values of water and rock compressibility (total compressibility of 24.12E-5 bar^{-1} with water compressibility increasing 5 times comparing to base case and 44.12E-5 bar^{-1} with rock compressibility increasing 10 times comparing to base case). This can be done by running simulation models with above parameters and plot the obtained dimensionless values in the same graph with the data points from previous normal scenarios of total compressibility.

The dimensionless volume and dimensionless time values are calculated using the equations in chapter 2. These values are plotted against each other in order to see their distribution in the graphs. Microsoft Excel function SOLVER is utilized to adjust and find the constants in predicted equation, which fits the trend for the data points in the plots.

3.2.3 Induced water volume for NP zone with thickness higher/equal to effective value

For the NP zones with thickness values equal to or higher than the effective values, the induced water volumes from those zones into the reservoir are almost independent on their thickness (the induced water volume depends only on the effective thickness in this case). Therefore, in these scenarios, the correlating relationships can only be established between other parameters than the NP zone thickness.

In all of investigating cases, the models are built with fixed total compressibility of NP zone (8.12E-5 bar^{-1}) and thickness equal to effective values while changing other parameters. The work flow of this part is described by the figure below:

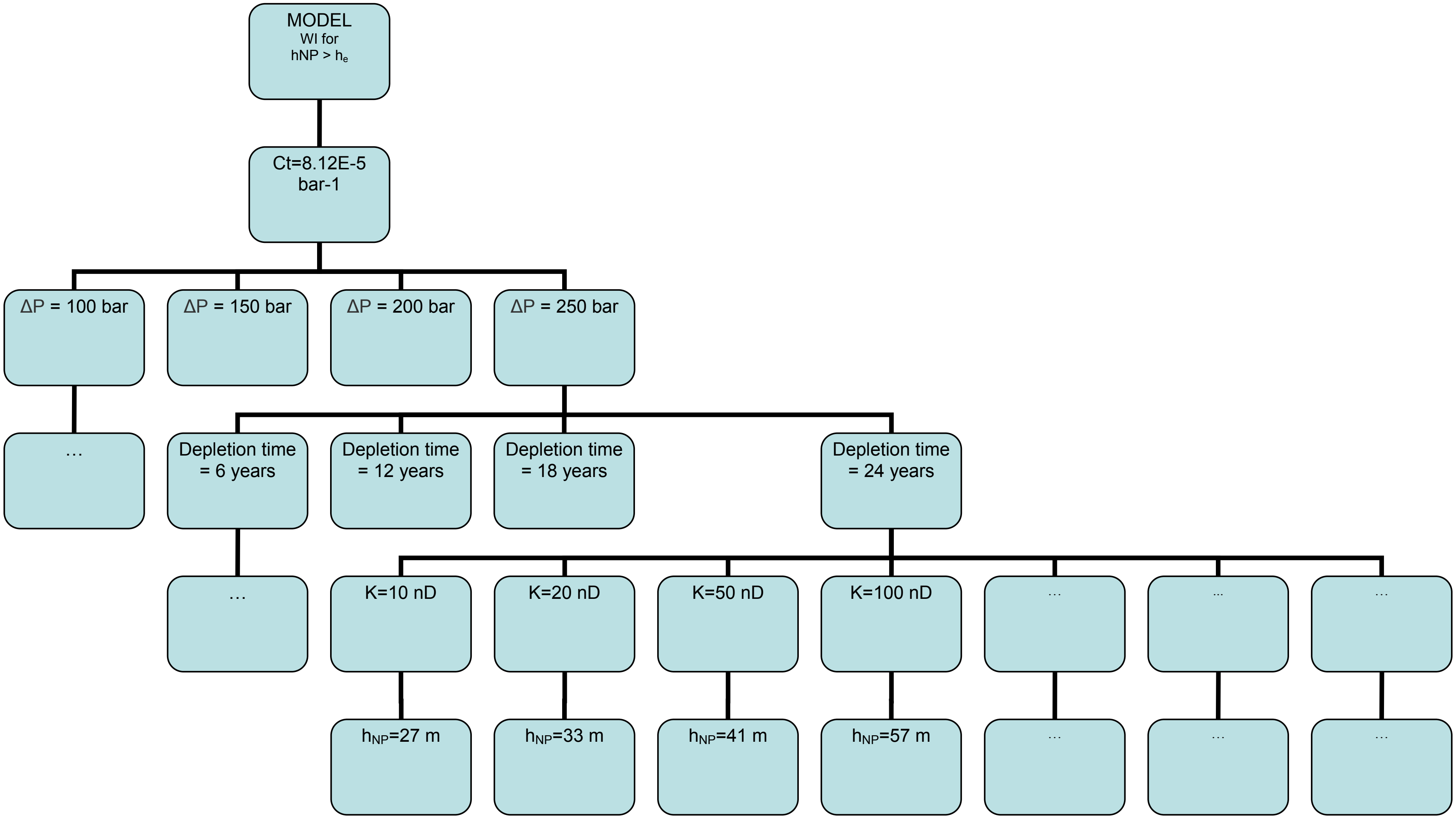

Figure 3-3: Work flow for finding correlation between induced water volume and other parameters for NP zone with thickness larger than effective value

In order to find relationships between the parameters in this scenario, the obtained data are analysed to obtain following targets:

- Correlation between NP zone permeability and induced water volume: the induced water volume values from models with the same depletion time and pressure drop are plotted against values of NP zone permeability. Adding trend lines and equations to the plots in order to find common factor which is dependent only on permeability.
- Correlation between reservoir depletion time and induced water volume: the induced water volume values from models with the same NP zone permeability and pressure drop are plotted against values of depletion time. Adding trend lines and equations to the plots in order to find common factor which is dependent only on depletion time.
- Correlation between reservoir pressure drop and induced water volume: the induced water volume values from models with the same NP zone permeability and depletion time are plotted against values of pressure drop. Adding trend lines and equations to the plots in order to find common factor which is dependent only on pressure drop.
- Correlation between induced water volume and all parameters: the induced water volume values from all the simulation models are plot with data combined all variable parameters with all the common factors in previous steps to find constant for the correlating equation. Setting up a final equation integrating all parameters is the most important objective of this scenario.

It is suggested to test the obtained correlating equation with different scenarios where the input parameters for total compressibility being varied.

3.2.4 Effect of dissolved gas in water on the pore volume multiplier and using of ROCKTAB keyword

It is assumed that when pressure decreases, the water releases the dissolved gas in it (mostly methane); the liberated bubbles are blocked in the pore space and will not move. The gas bubbles will therefore, occupy part of pore space and reduce the total pore volume. The effect created by this process is similar to the effect of rock compaction/expansion when changing the reservoir pressure. In Eclipse simulation, the keyword ROCKTAB is utilized to input the pore volume multiplier for simulating with the case of rock compaction. For this project, with dissolved gas liberation from NP zone, the ROCKTAB keyword is also used to describe the similar effect.

Pore volume multipliers are calculated using the equations in Chapter 2 and Microsoft Excel calculating sheets. The transmissibility multiplier is assumed to be 1 and fixed for the simulation. For the reservoir layer, due to much lower water saturation, the effect of pore volume reduction from immobile gas can be neglected. Thus, for the reservoir, the rock and water compressibility are used as normal simulation model.

Two main cases are studied using the ROCKTAB keyword in simulation. One with the water in NP zone saturated with 100% gas and the other case where the gas saturation in water is only 70%. Both of the cases have the depletion time of 12 years and pressure drop of 250 bar. The grid thickness for the NP zone using in the models is 1m. The work flow of building simulation models and corresponding parameters for this study is demonstrated in the following figure:

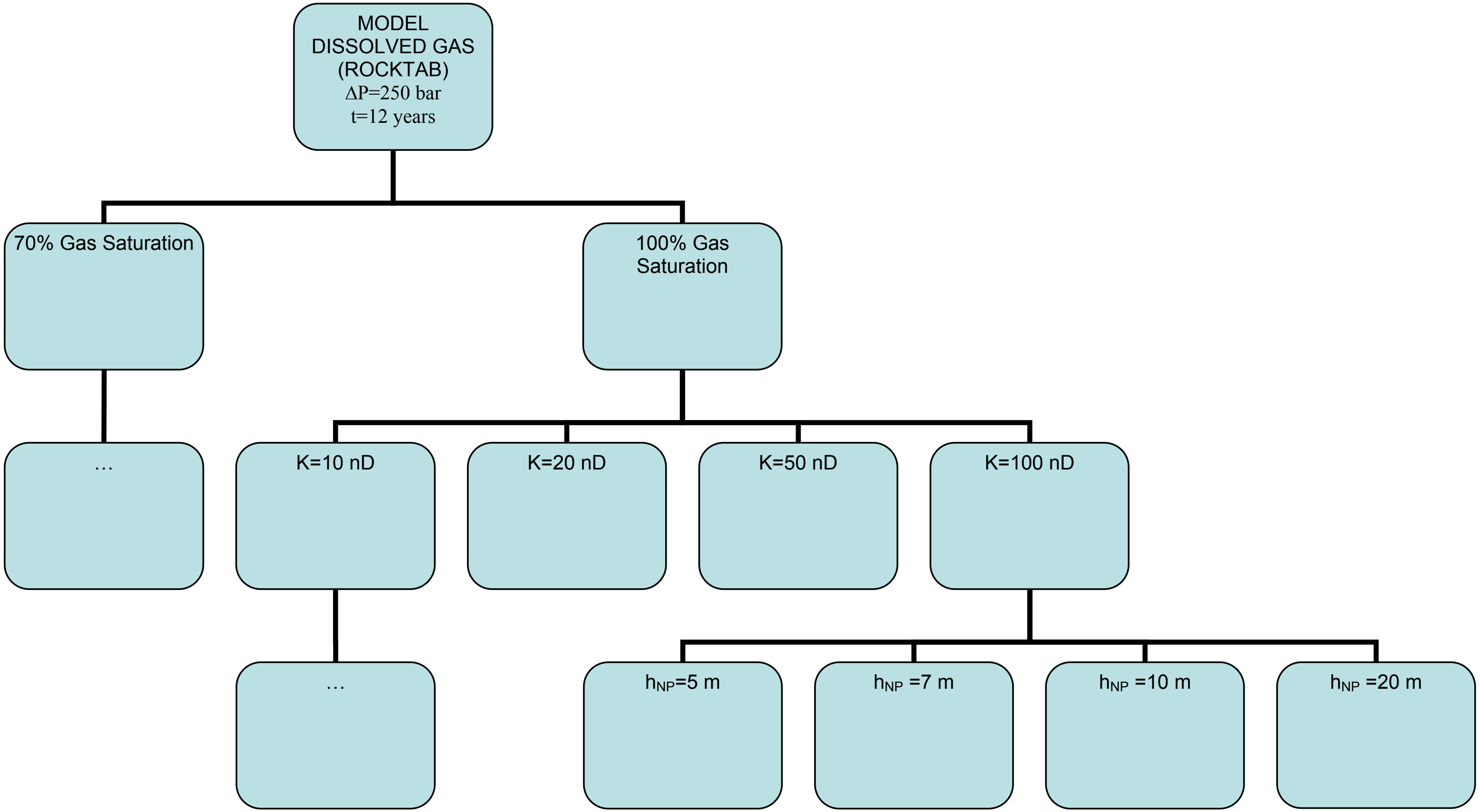

Figure 3-4: Work flow for finding correlation between induced water volume and other parameters taken into account the dissolved gas effect

Induced water volume values from the simulations are used to calculate the values of dimensionless volume by the equations in chapter 2. Average values of compressibility for 100% saturated and 70% saturated cases are estimated using following equation:

$$C_{t,av} = \frac{\Delta V}{\Delta P} = \frac{1 - M_f}{P_i - P_f}$$

Dimensionless volume values are to be plotted against dimensionless time values to find the correlation between them and compare the plots with the plots of scenarios where the dissolved gas effects are not taken into account.

Different cases with different values of pressure drop and depletion time may also be inspected to confirm the solidity of the correlation between dimensionless quantities.

3.2.5 Finding optimum grids thickness for simulating non-productive zone

For a reservoir simulation model, the finer the grids, the more details of reservoir can be described and therefore, the better quality of the results can be obtained. However, more computer resources will be needed for higher resolution models. Time and cost for projects will be higher. Finding optimum grids thickness for simulation therefore plays an important role in a project cost and time reduction.

In this project, for studying purposes, only some values of effective thickness corresponding to three different values of NP zone permeability (1nD, 10nD and 100nD) are used in building simulation models. The models are built with common input parameters of 12 years field depletion, 250 bar pressure drop and 8.12E-5 bar^{-1} compressibility for NP zone. The grids thickness for NP zone to be studied ranges from 1m up to 40m (in case of 100nD). Detail of the layer divisions of NP zone is showed in the below table:

Table 3-3: Number and thickness of grid layers input for investigating optimum grid size

Permeability (nD)	Thickness (m)	No. of layers	Thickness of layers (m)
100	40	1	40
		2	20
		5	8
		10	4
		20	2
		40	1
10	20	1	20
		2	10
		5	4
		10	2
		20	1
1	5	2	2.5
		5	1
		10	0.5

The values of induced water volume from NP zone to reservoir obtained from the simulations then are plotted against number of grids layers to find the optimum values of number of layers corresponding to different values of permeability. Optimum grids thickness thus, can be easily calculated from optimum values of number of grid layers.

More scenarios with different values of parameters such as compressibility, pressure drop… can be built to have better understanding of the problem and may be able to find correlations between parameters and optimum grids size.

3.2.6 Investigating effects of variations of non productive zone grids thickness on induced water volume

In a simulation model, pressure of a cell is at the centre of the cell. Different cell thickness therefore can affect simulating results on the distribution of pressure in NP zone. In this project, the effects of different grids thickness distribution in NP zone are studied for the case of 100nD permeability, 12 years field depletion, 250 bar pressure drop and 8.12E-5 bar^{-1} compressibility, where the response from pressure within each grid layer is considered to be of higher sensitive (comparing to other cases with the properties above).

The thickness of NP zone in this case is the effective thickness corresponding to above parameters, which is 40m. The NP zone is divided into regions; each region contains one grid layer and total number of regions equal to optimum values of grid layers (5 regions). By changing the thickness of the regions while keeping the same total thickness of NP zone, it is possible to investigate how the pressure in each layer changes with time, how it is distributed in regions and how total induced water volume changes. The different cases for the region thickness are as following:

Table 3-4: Different grids thickness distributions

Case	Region 1 (m)	Region 2 (m)	Region 3 (m)	Region 4 (m)	Region 5 (m)
1	8	8	8	8	8
2	12	10	8	6	4
3	14	12	8	4	2
4	12	12	8	4	4

The induced water volume from each case is compared to the base case (grids being equally distributed) to see if there are changes in the results and how significant the changes are.

In order to get more information on the matter and have better understanding about the effects of grids thickness variations, it is necessary to build and analyse data from additional models with different NP zone and different grids thickness distributions.

4 RESULTS AND DISCUSSION OF RESULTS

Result data from simulation of the models following working steps in Chapter 3 are analysed to achieve correlations between the parameters. Details of the results are showed in the following articles.

4.1 Effective thickness

As stated in Chapter 3, the effective thickness values for NP zone are estimated for the case where total compressibility is 8.12E-5 bar^{-1} and reservoir pressure drop is 250 bar only.

The plots of induced water volumes against NP zone thickness in figures below showed clear trends of the data for any depletion time and permeability. The water volumes increase rapidly from 0 m^3 at thickness of NP zone is 0 m to a certain value of thickness. Within this interval, the relation between the water volume and the thickness of the zone is almost linearly related. After that point, volume of induced water from NP zone increases slowly and reaches a fairly stable value. This “stable value” changes negligibly as the NP zone thickness increasing, even when the thickness value is very large. However, it is difficult to detect the exact stable values because it requires the difference between permeability of two adjacent data points to be small enough to see significance of the changes. In this project, the stable values or effective thickness are roughly estimated by looking at the plots and on the percentage differences between two adjacent data points. For the situations where the NP zone permeability is very small, the induced water volume from the zone to reservoir is really small and therefore, the differences between two adjacent data points can hardly see on the plots. It is suggested that the effective thickness can be taken just for references only. Higher resolution of data is required to have more precise values of effective thickness.

It can be seen from Figure 4-1 to Figure 4-7 that with the same value of permeability, total compressibility and reservoir pressure drop, the effective thickness values are strongly dependent on the depletion time of the field. The longer depletion time, the higher the induced water volume is. Data plots in Figure 4-8 is a combination of all the results data from simulation models. Even though it can be seen from this figure that the effective thickness of NP zone increasing with depletion time, no equation for their correlation can be found.

Effective thickness of NP zone is also plotted against permeability in Figure 4-9. The dependences between these two quantities can be seen from the graph: the effective thickness higher for the zone with higher permeability. No equation is found for this dependence between two values.

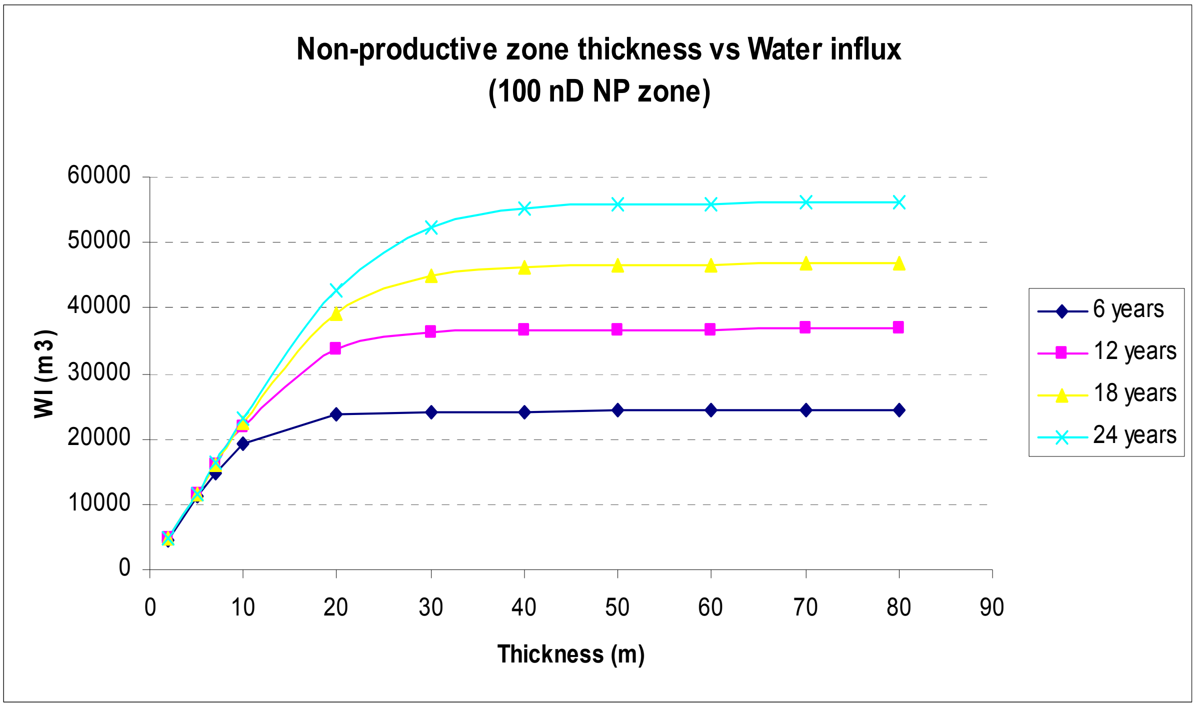

Figure 4-1: 100 nD NP zone thickness against induced water volume for different depletion time

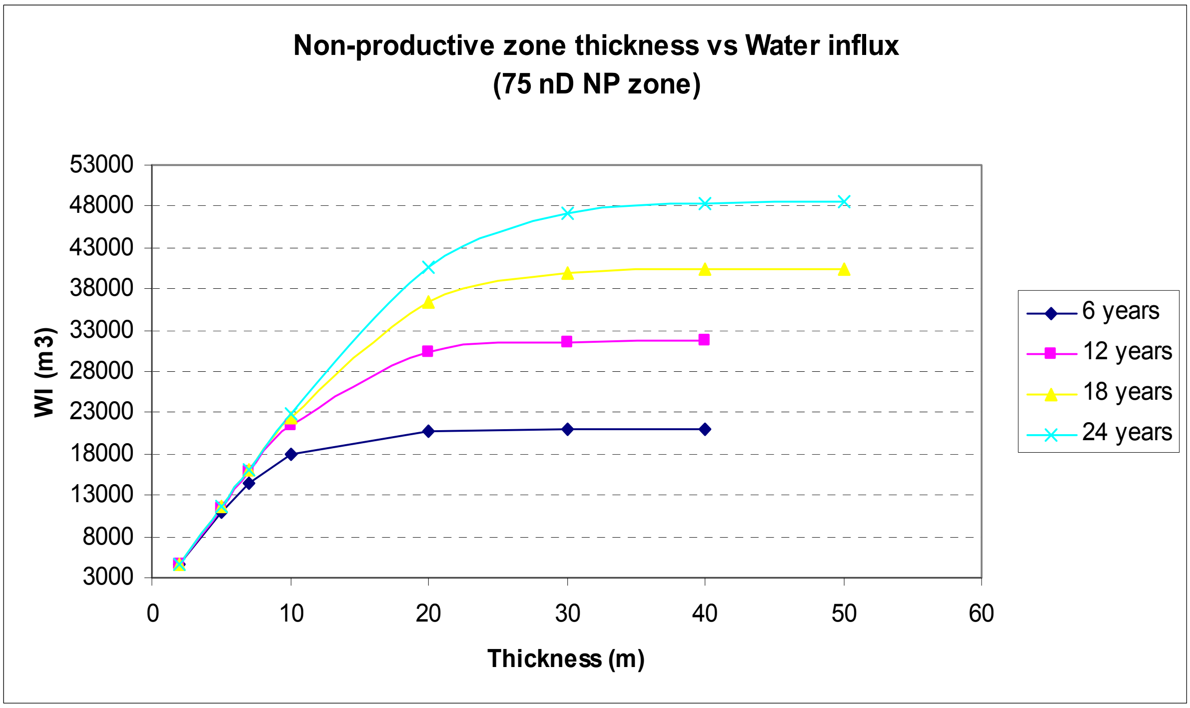

Figure 4-2: 75 nD NP zone thickness against induced water volume for different depletion time

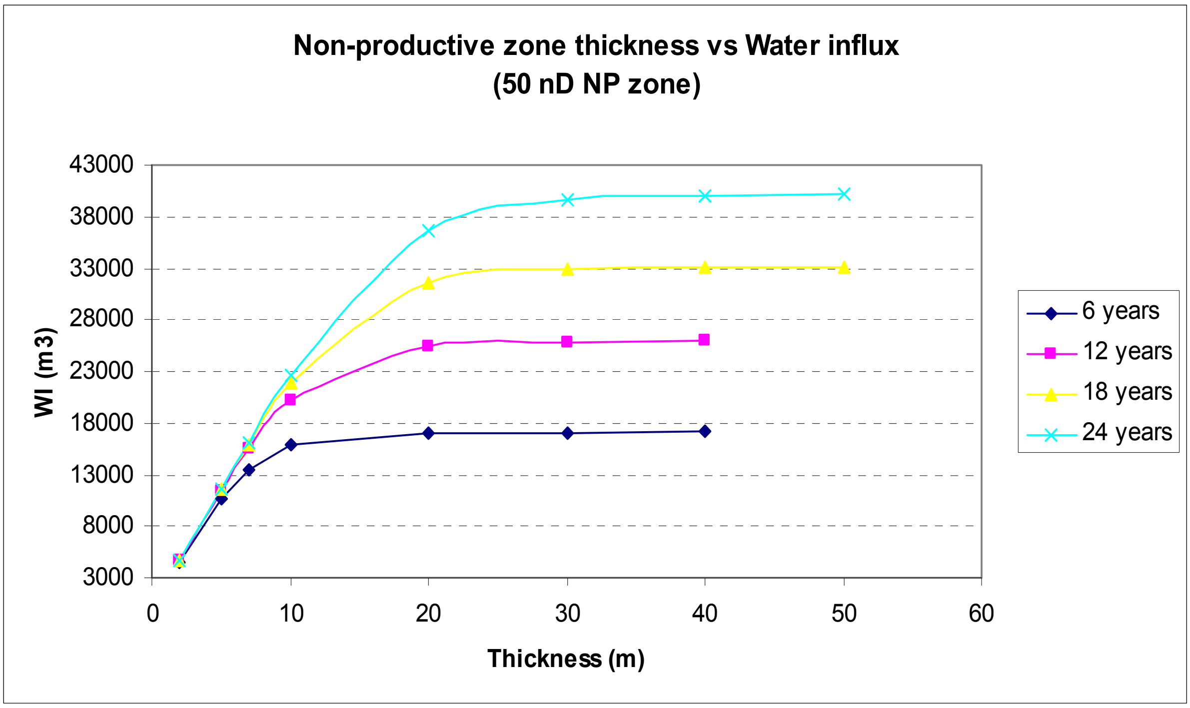

Figure 4-3: 50 nD NP zone thickness against induced water volume for different depletion time

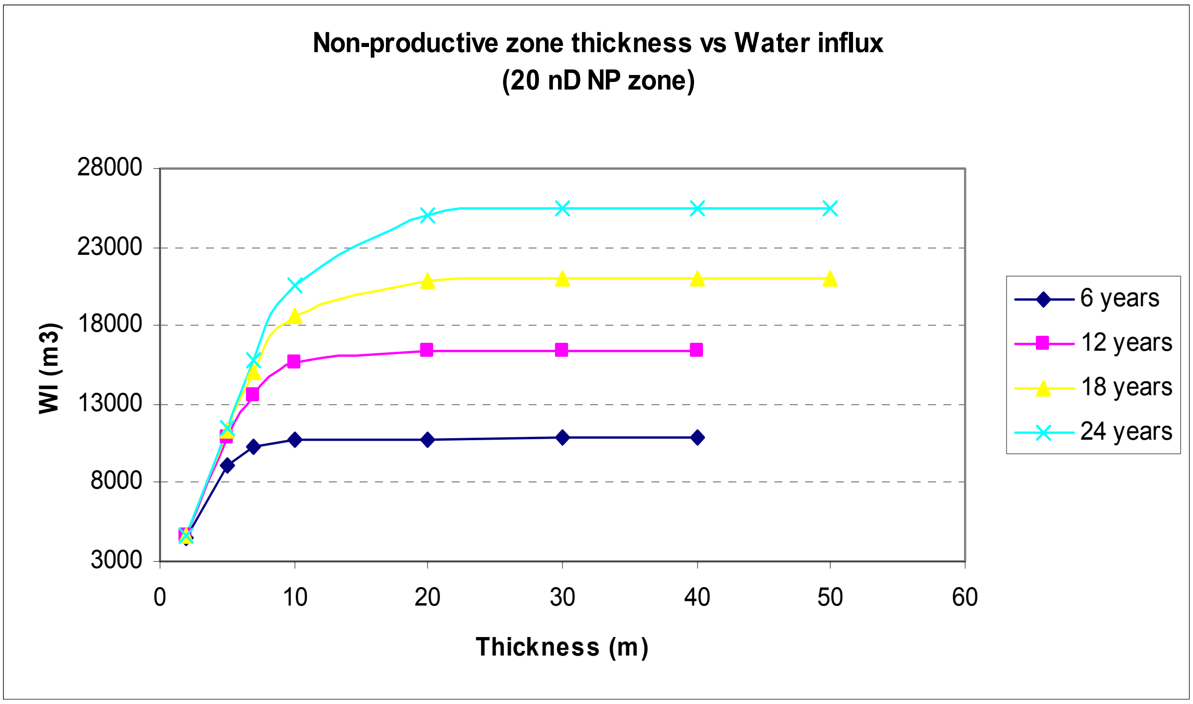

Figure 4-4: 20nD NP zone thickness against induced water volume for different depletion time

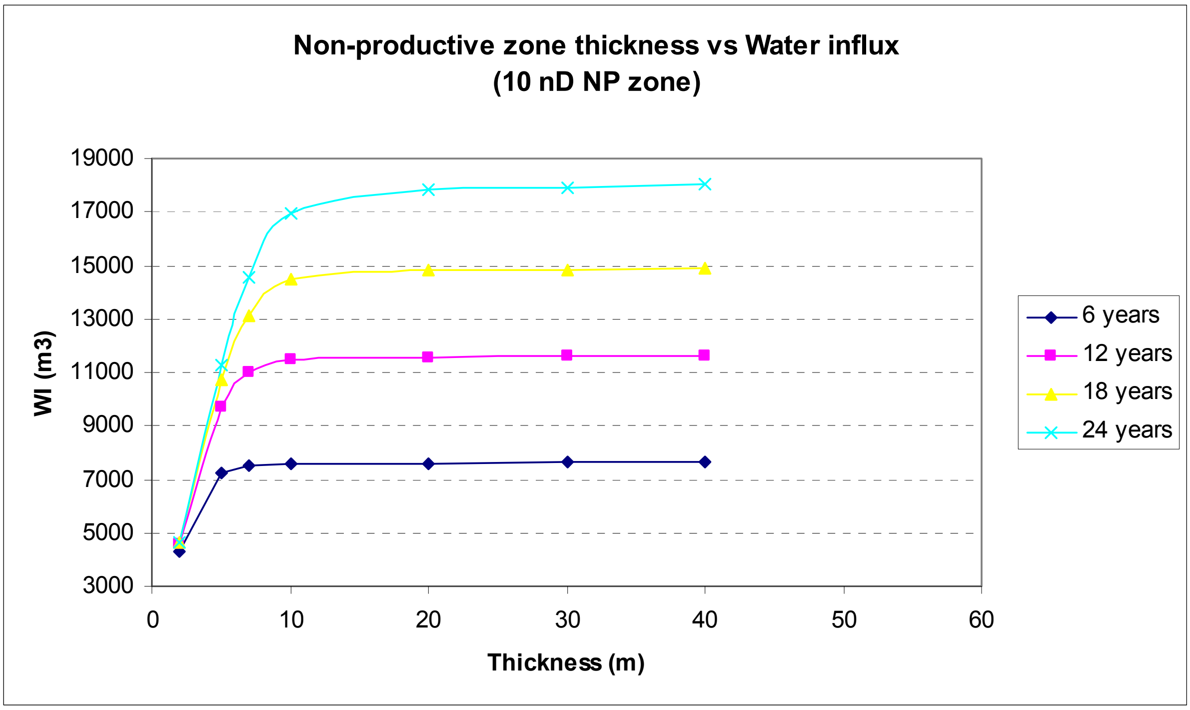

Figure 4-5: 10nD NP zone thickness against induced water volume for different depletion time

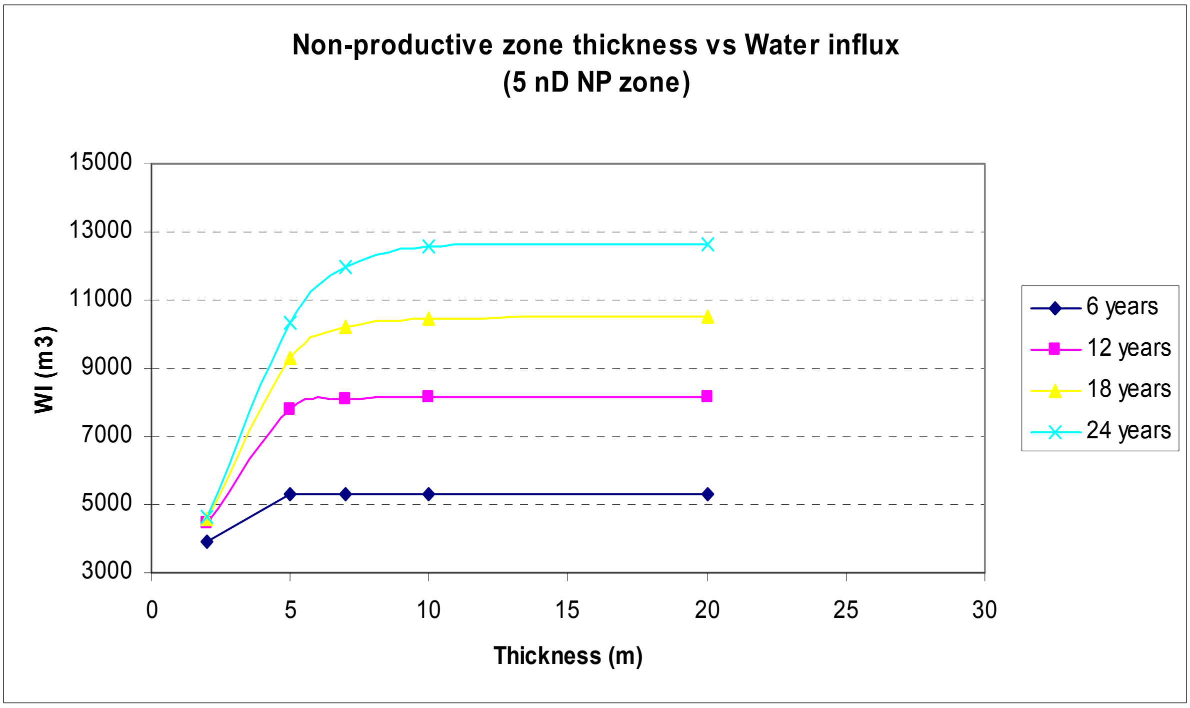

Figure 4-6: 5nD NP zone thickness against induced water volume for different depletion time

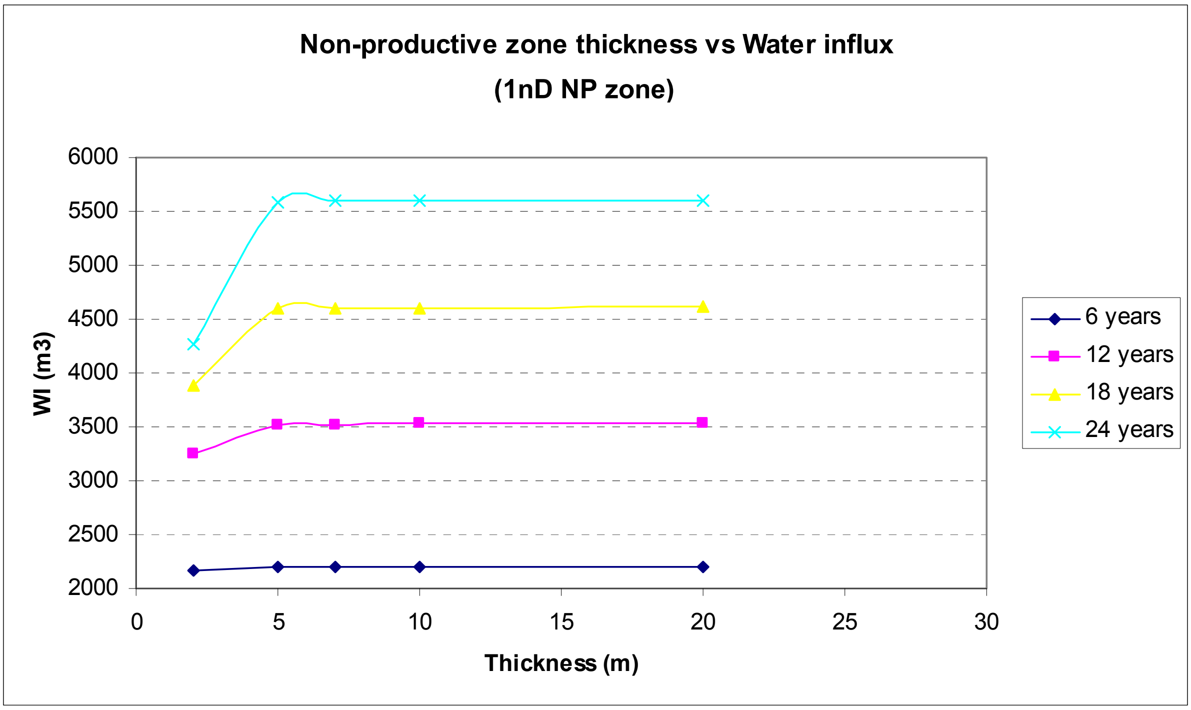

Figure 4-7: 1nD NP zone thickness against induced water volume for different depletion time

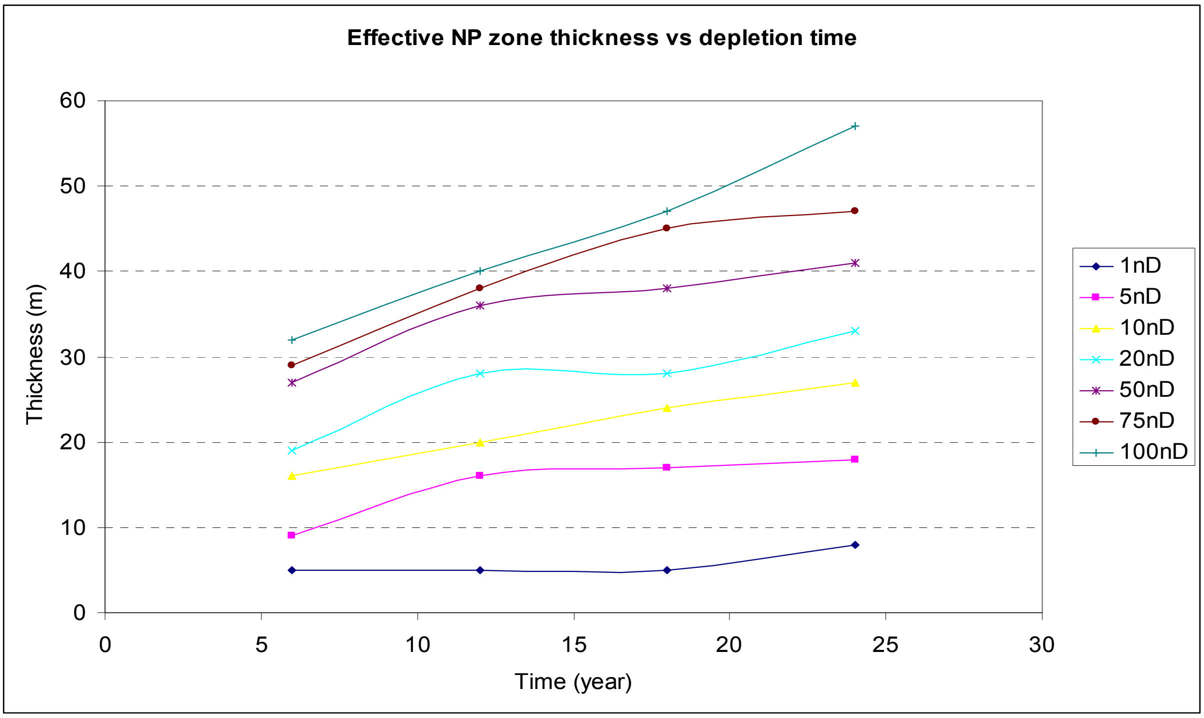

Figure 4-8: Effective NP zone thickness against field depletion time

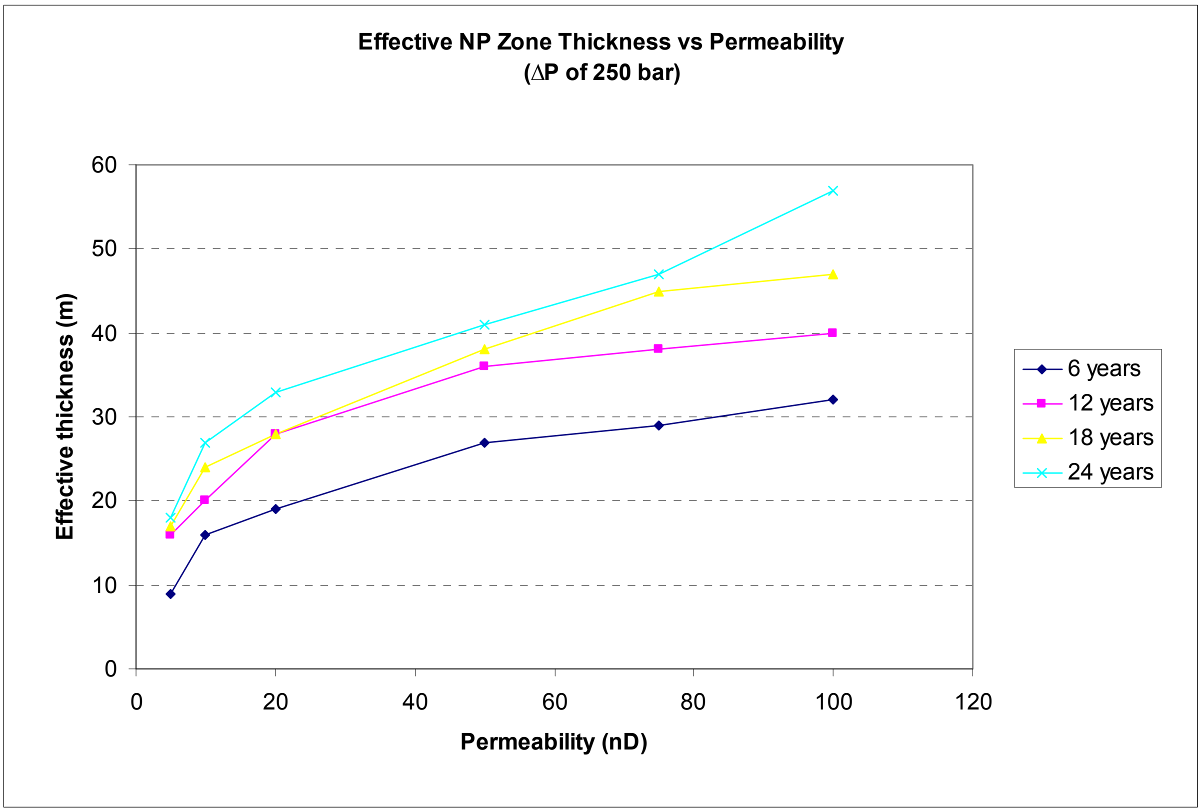

Figure 4-9: Effective thickness of NP zone for different values of permeability

It can be seen from the above graphs that in every investigated case, there is a value for NP zone thickness such that all the values higher than that, the change in induced water volume from this zone to reservoir is negligible. This can be explained that for a specific period of depletion, most of water transferred to reservoir comes from the interval near the reservoir; the points in NP zone far from the boundary contribute little to the pressure support of reservoir depletion process. The pressure profile of the regions within the NP zone clearly confirms this argument. The regions far from the boundary have pressure drop less than the ones close to the reservoir.

It is, however, difficult to pick the exact points for decision of the effective thickness values. The transition between the zone where induced water volume rapidly increasing with thickness and the zone where the changing being slow requires increment differences between the data points to be small in order to select more precise value of effective thickness.

Precision of the effective thickness value is also necessary if a mathematical correlation between it and other parameters such as permeability, depletion time, pressure drop and total compressibility is to be established. This project, however, can only roughly estimate the effective values for some scenarios and the effective values obtained are used for other part of the thesis. Details of the result data are showed by a table in Appendix B.

4.2 Correlation for input parameters

It has been indicated in Chapter 3 that because of existence of the effective thickness of NP zone, the correlation for the input parameters is divided into 2 cases: for NP zone with lower thickness than the effective values and for NP zone with higher thickness than effective values.

4.2.1 Correlation for NP zones with thickness less than effective values

Total of almost 500 simulation runs, which combine all variations of parameters, are carried out for the purpose of setting up a relationship between dimensionless volume and dimensionless time values. The dimensionless quantities are defined in Chapter 2 as followings:

$$WId = \frac{WI}{WI_{Ultimate}} = \frac{WI}{V_W * C_t * \Delta P}$$

$$tD = \frac{k * t}{C_t * h_{NP}^2 * \phi * \mu * 10^8}$$

The dimensionless values are calculated from the input data and outcomes of the simulations and they are plotted against each other as in the below figures (Figure 4-10 to Figure 4-18). The figures present correlation between values of WId and tD for different parameters of depletion time, pressure drop and total compressibility. It can be seen that in any figure, the discrepancy between any plots of data is negligible. This can be explained by an assumption that there is a common correlation equation for all the dimensionless quantities.

The assumption about correlation between the dimensionless values is furthermore confirmed when all the data are plotted in the same graph (Figure 4-19). Different data point collected from simulation models running with different combination of parameters lie on the very same line. The variations in the values of the point can be seen as very small and negligible. In order to test the consistency of the results in cases of extreme values of total compressibility, the models are built for a scenario where the water compressibility increasing 5 times and a scenario where rock compressibility increasing 10 times comparing to the base case. The data points for the cases when the models are built with very high values of total compressibility above are plotted in Figure 4-20 against the data point for the base cases. The discrepancy between the lines of data is negligible.

Base on the shapes of the plots, assuming a correlating equation with its unknown constants under the form of:

$$WId = 1 - \frac{1}{1 + a * tD^{n}}$$

** a, n: constants to be found*

By using Microsoft Excel SOLVER function and looking at adjustment of the predicted graph in Figure 4-21 to fit the data points, the correlation between dimensionless values of volume and time can be expressed as below equation:

$$WId = 1 - \frac{1}{1 + 0.921 * tD^{0.965}}$$

The graph based on the above equation fits well with the data points obtained from the simulation models. Because the left hand side of the equation is the ratio between the induced volume water and maximum water can move to reservoir from NP zone, this dimensionless correlation is useful for estimating the induced water when knowing other parameters. The volume of induced water can be compared to total volume of produced fluid from reservoir in order to see if the pressure contribution from NP zone to total pressure drop is significant.

Obtaining exact effective values of NP zone thickness are very important in applying the equation to calculate the water volume. If the actual thickness is higher than the effective value and we still apply the equation, the results will not be correct. Other equation should be applied in this case.

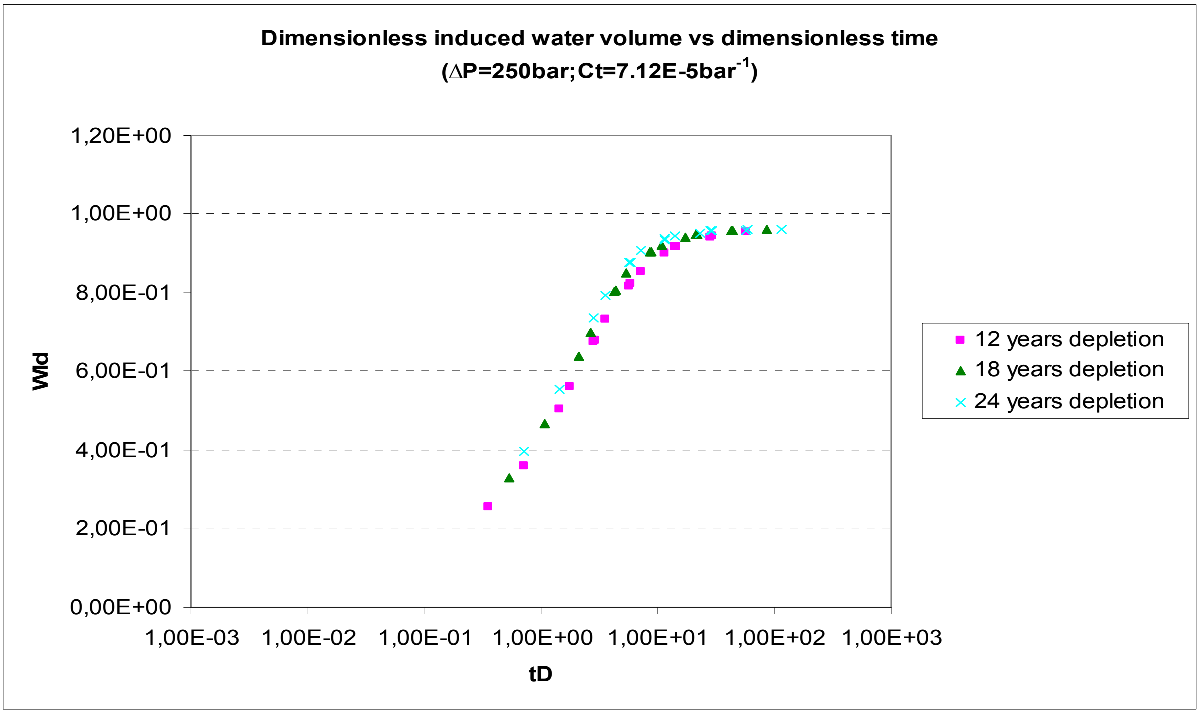

Figure 4-10: Dimensionless volume against dimensionless time: pressure drop of 250 bar and total compressibility of 7.12E-5 bar^{-1}

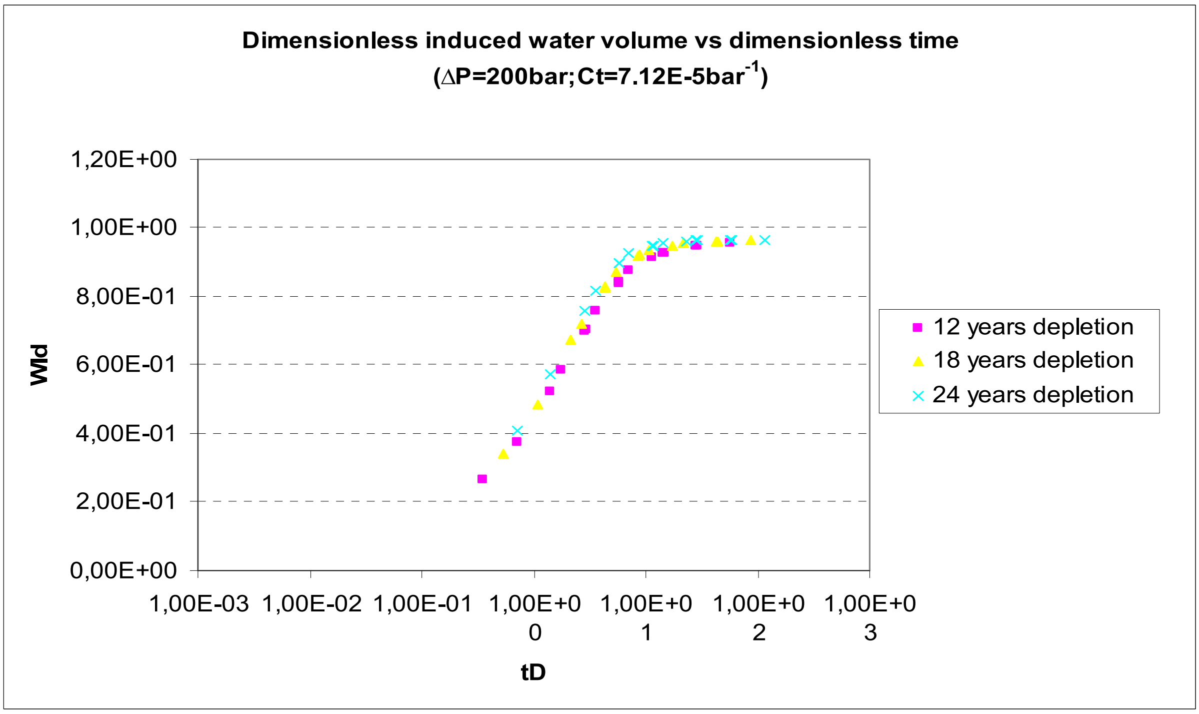

Figure 4-11: Dimensionless volume against dimensionless time: pressure drop of 200 bar and total compressibility of 7.12E-5 bar^{-1}

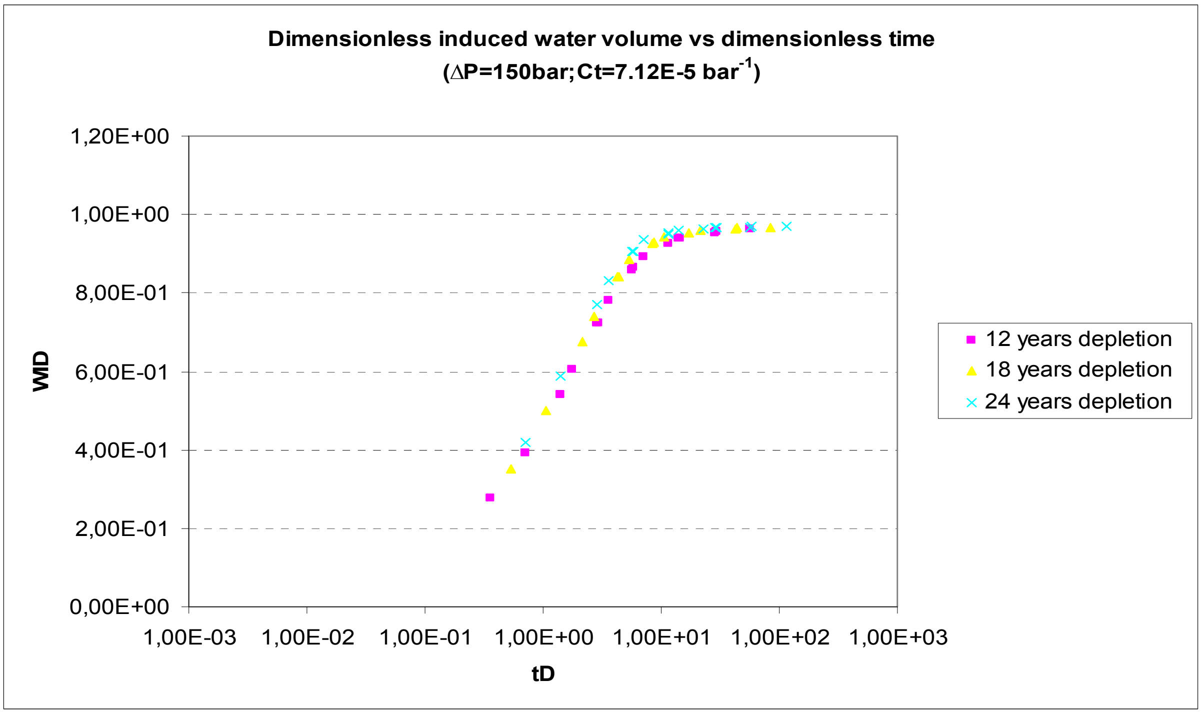

Figure 4-12: Dimensionless volume against dimensionless time: pressure drop of 150 bar and total compressibility of 7.12E-5 bar^{-1}

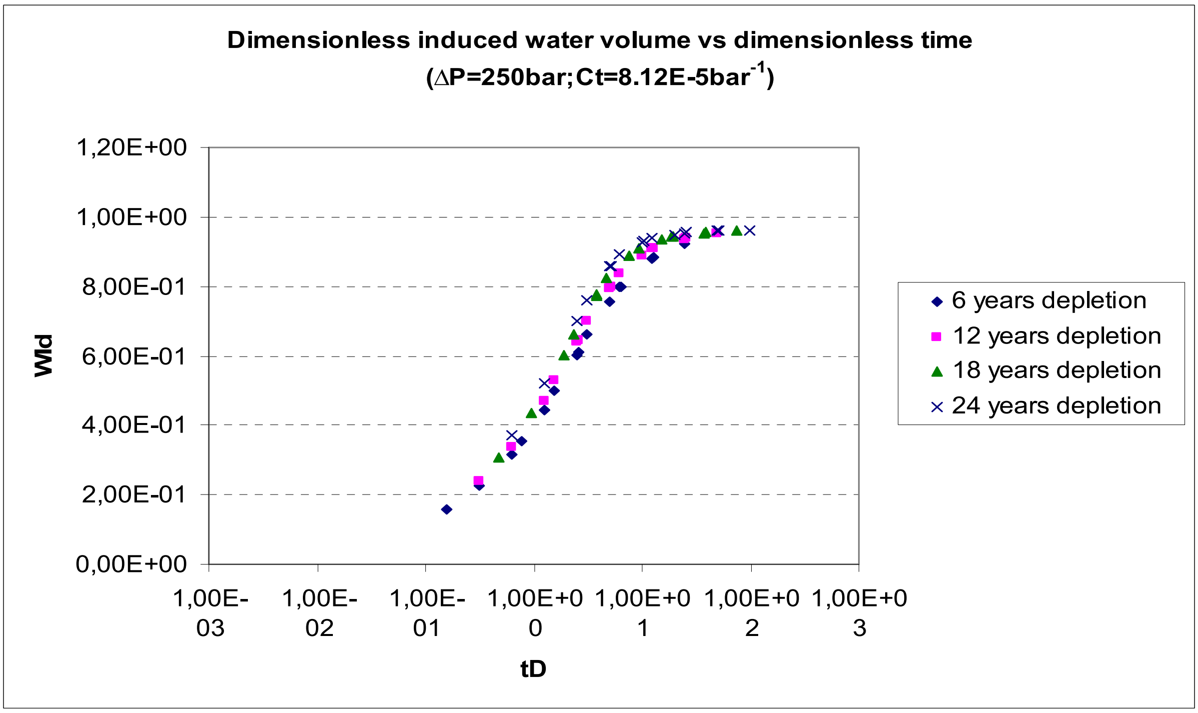

Figure 4-13: Dimensionless volume against dimensionless time: pressure drop of 250 bar and total compressibility of 8.12E-5 bar^{-1}

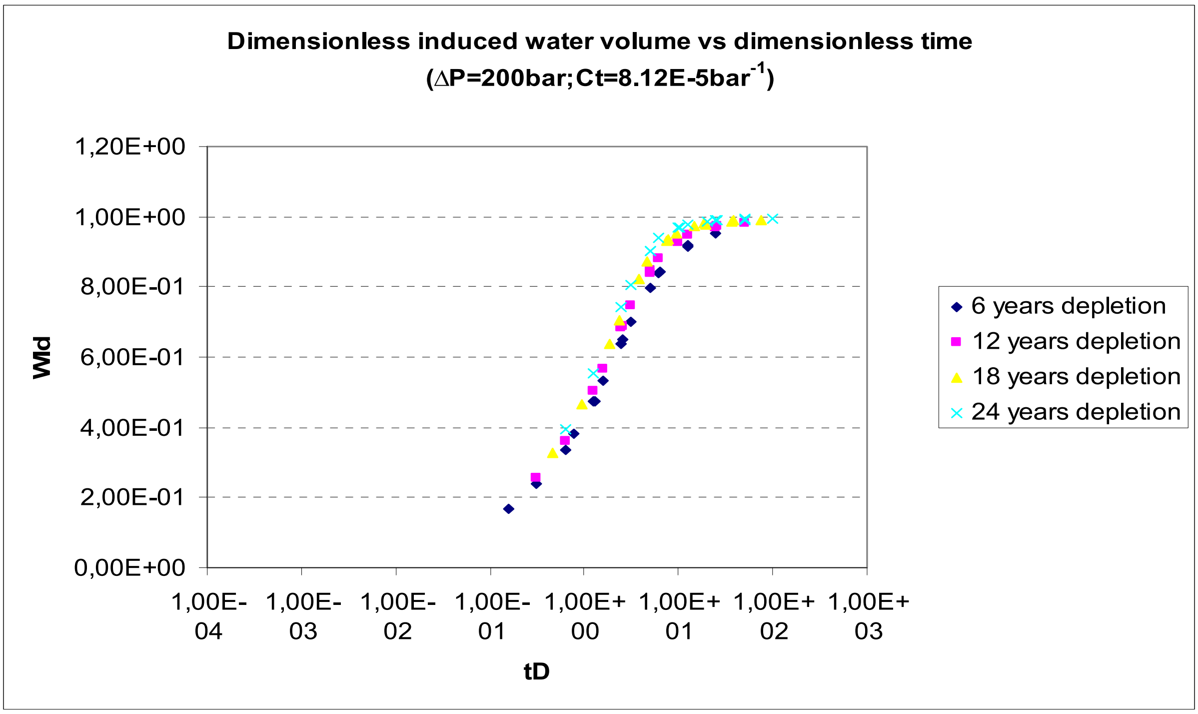

Figure 4-14: Dimensionless volume against dimensionless time: pressure drop of 200 bar and total compressibility of 8.12E-5 bar^{-1}

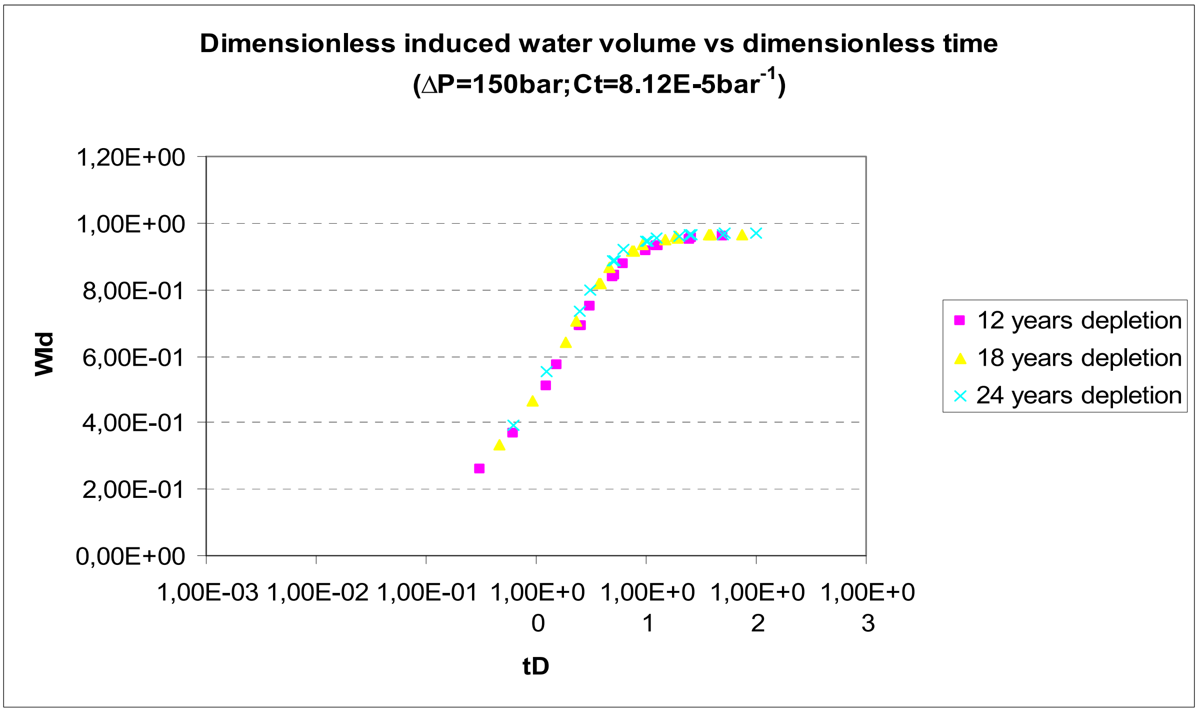

Figure 4-15: Dimensionless volume against dimensionless time: pressure drop of 150 bar and total compressibility of 8.12E-5 bar^{-1}

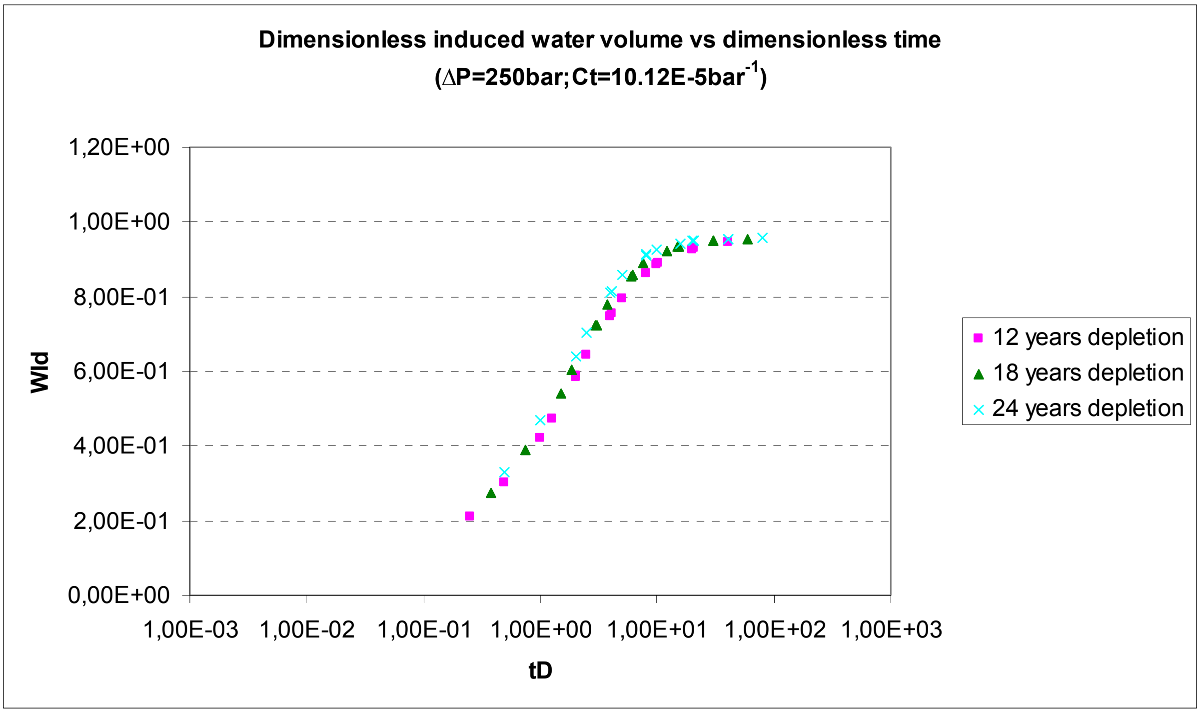

Figure 4-16: Dimensionless volume against dimensionless time: pressure drop of 250 bar and total compressibility of 10.12E-5 bar^{-1}

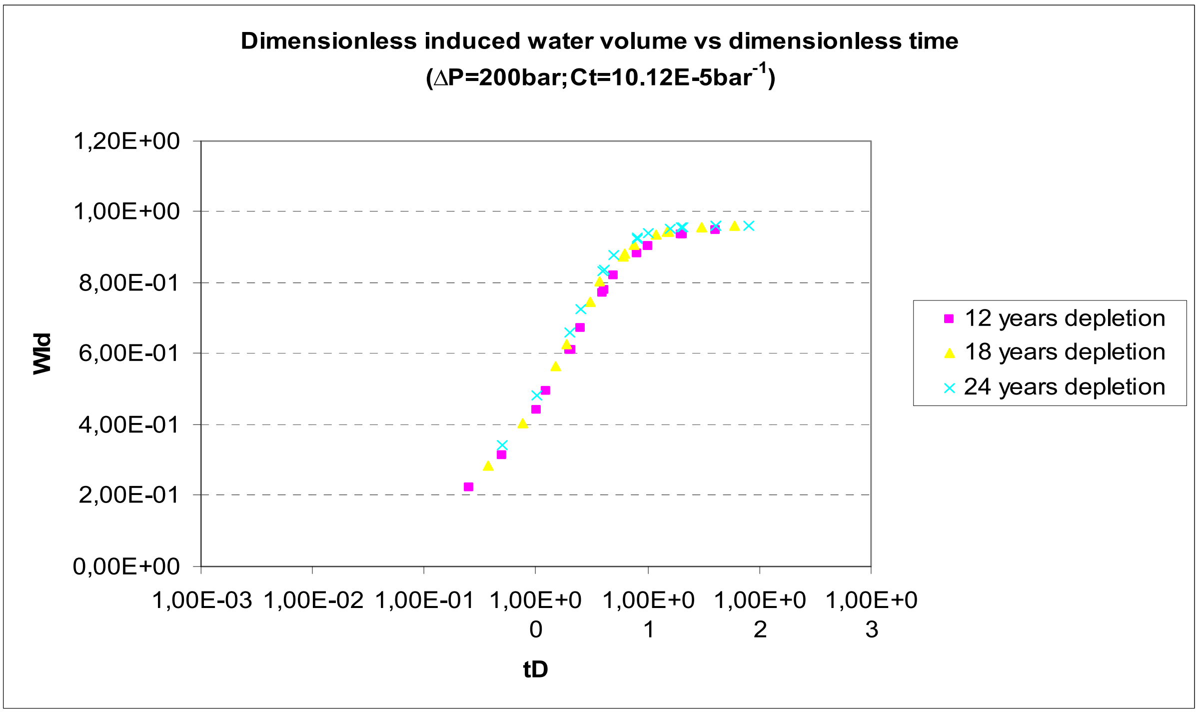

Figure 4-17: Dimensionless volume against dimensionless time: pressure drop of 200 bar and total compressibility of 10.12E-5 bar^{-1}

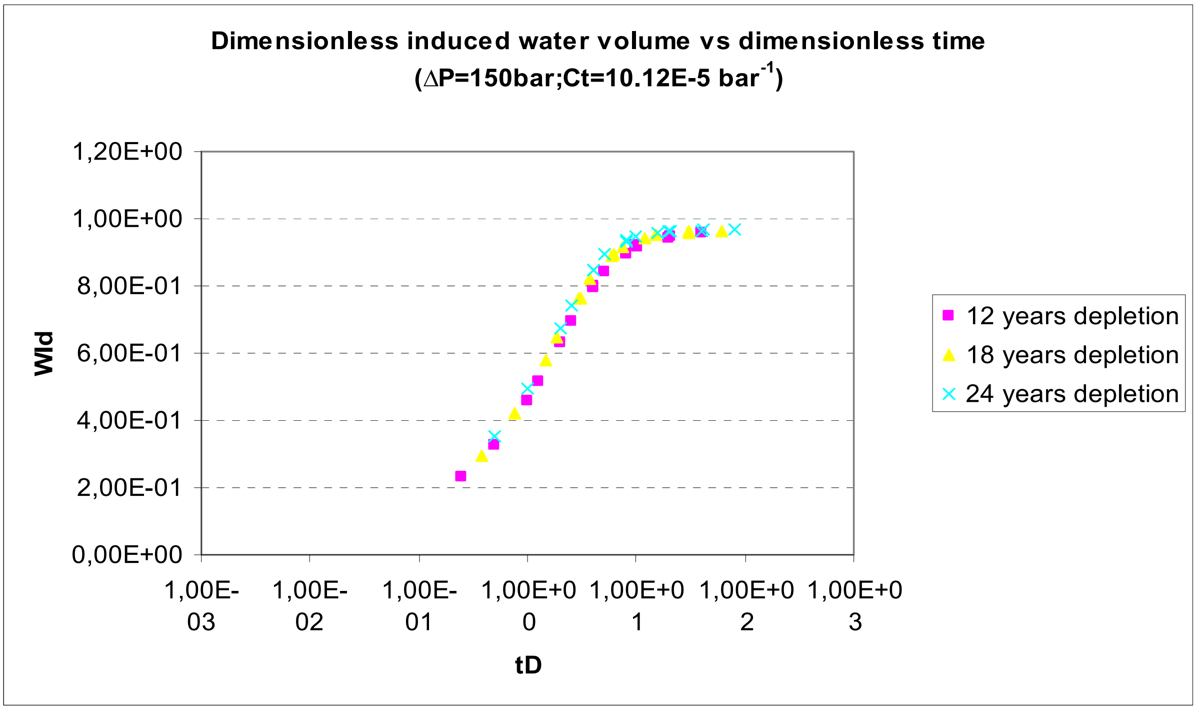

Figure 4-18: Dimensionless volume against dimensionless time: pressure drop of 150 bar and total compressibility of 10.12E-5 bar^{-1}

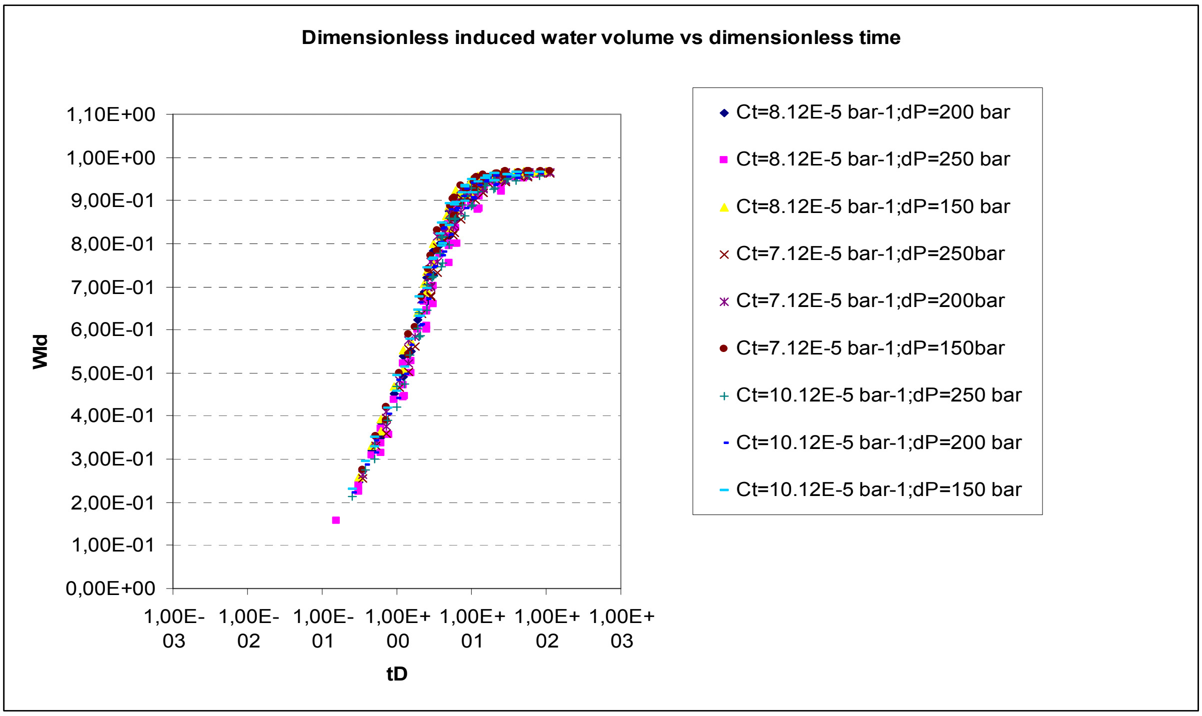

Figure 4-19: Dimensionless volume against dimensionless time: all cases

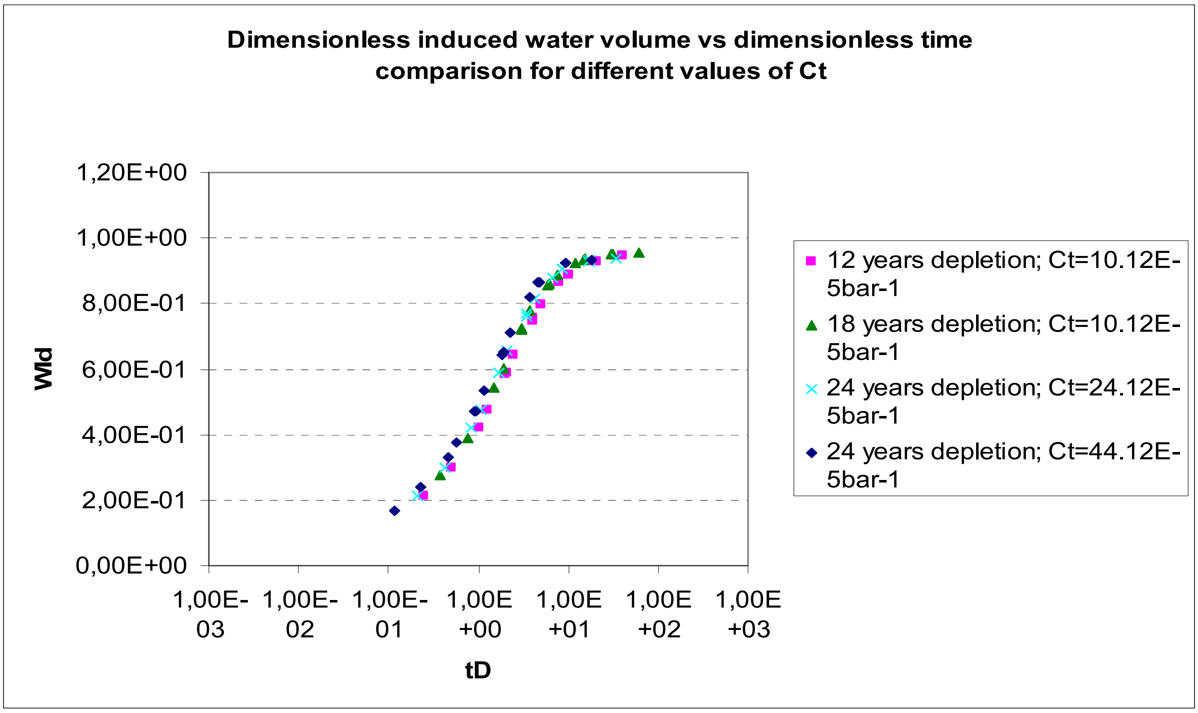

Figure 4-20: Dimensionless volume against dimensionless time: pressure drop of 250 bar and values of total compressibility

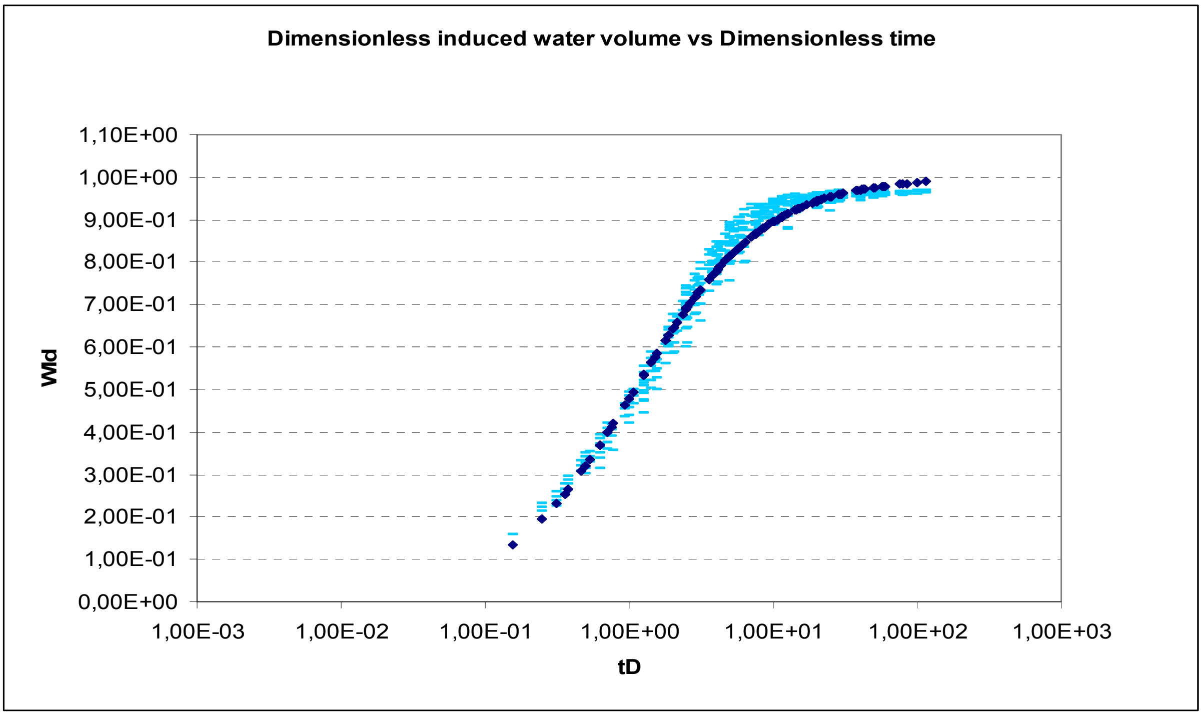

Figure 4-21: Dimensionless volume against dimensionless time: actual data in comparison with correlating equation

4.2.2 Correlation for NP zones with thickness higher than effective values

The thickness of NP zones, when increasing higher than effective values, give no significant different from volume of induced water by the effective thickness. For this situation, the correlation between the parameters in simulation models and induced water volume is excluded the thickness of NP zone. Due to time limitation, only one value of total compressibility of 8.12E-5 bar^{-1} is used for all models.

As can be seen from Figure 4-22 to Figure 4-28, where the values of permeability and depletion time for each data line are kept unchanged, the induced water volume is almost linearly proportional to power 0.82 of pressure drop. That is:

$$WI = f(C_t, k, t) * \Delta P^{0.8}$$

With similar method, by keeping reservoir pressure drop and time constant while changing values of NP zone permeability; plotting the values of induced water volume against the values of permeability in Figure 4-29 to Figure 4-32. The dependence between two quantities can be expressed by the equation:

$$WI = f(C_t, \Delta P, t) * k^{0.5}$$

Using the similar method to investigate the dependences between induced water volume and other parameters, from Figure 4-33 to Figure 4-36, the correlation between induced water volume and depletion time is found to be:

$$WI = f(C_t, \Delta P, k) * t^{0.6}$$

Combining all three above equations, we can express the value of induced water volume under the equation of other parameters as following:

$$WI = f(C_t) * \Delta P^{0.8} * k^{0.5} * t^{0.6}$$

In this part of project, because only one scenario of total compressibility is studied, the function of compressibility has value of a constant. Plot of the above equation is a straight line with the gradient is the dependent constant. Figure 4-37 shows that the data points fit very well with the estimated equation's graph and the gradient of the graph is 0.291 in this case.

Final expression for the dependence between induced volume water from NP zone to reservoir is:

$$WI = 0.291 * \Delta P^{0.8} * k^{0.5} * t^{0.6}$$

It should be noted that the above equation can be applied for the model with lateral area of 1 km^2 and constant compressibility of 8.12E-5 bar^{-1} only. The results can be scaled up for Brent formation in Statfjord field.

This part of the project is just a primary study of the relationship between the induced water volume and other parameters for NP zones with thickness higher than effective values. In order to find correlation between those values for more general cases, more studies should be carried out with models integrate combinations of different values of total compressibility, depletion time, permeability, pressure drop and area of contact surface between NP zone and reservoir.

For this specific case, the data points fit very well with the estimated equation. The equation is also tested with more models with different values of permeability, pressure drops and depletion time. All the result data are consistent with the above equation when plotted in the same graph.

As can be seen from the figures, the most variations in the data points are when the data values are at very extreme ends, for example when very low permeability NP zone is simulated with very long depletion time and very low pressure drop. In this situation, the above equation may only be used to roughly estimate the values of water volume when knowing other parameters; more precise results should be taken from simulation models.

In addition, values of effective thickness of NP zone are also critical in application of the equation. The water volume can only be correctly estimated by the equation if the actual thickness is higher than the effective value. Otherwise, dimensionless equation in previous part must be utilized.

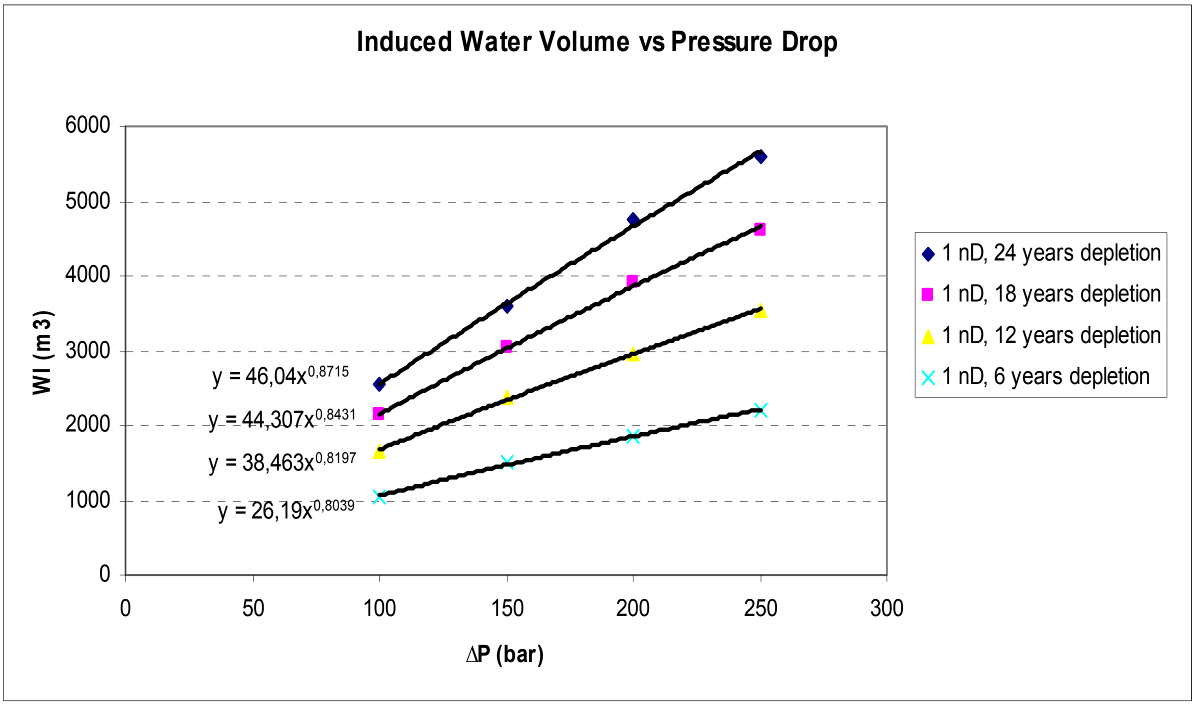

Figure 4-22: Induced water volume against pressure drop – 1nD NP zone

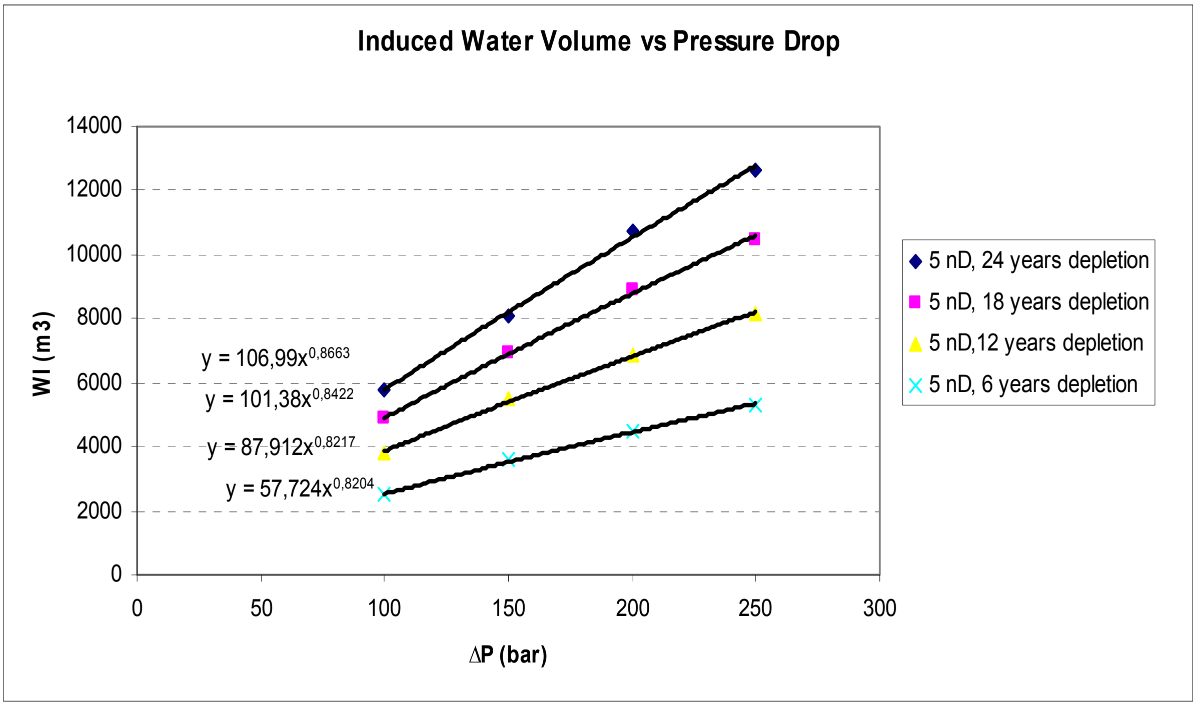

Figure 4-23: Induced water volume against pressure drop – 5nD NP zone

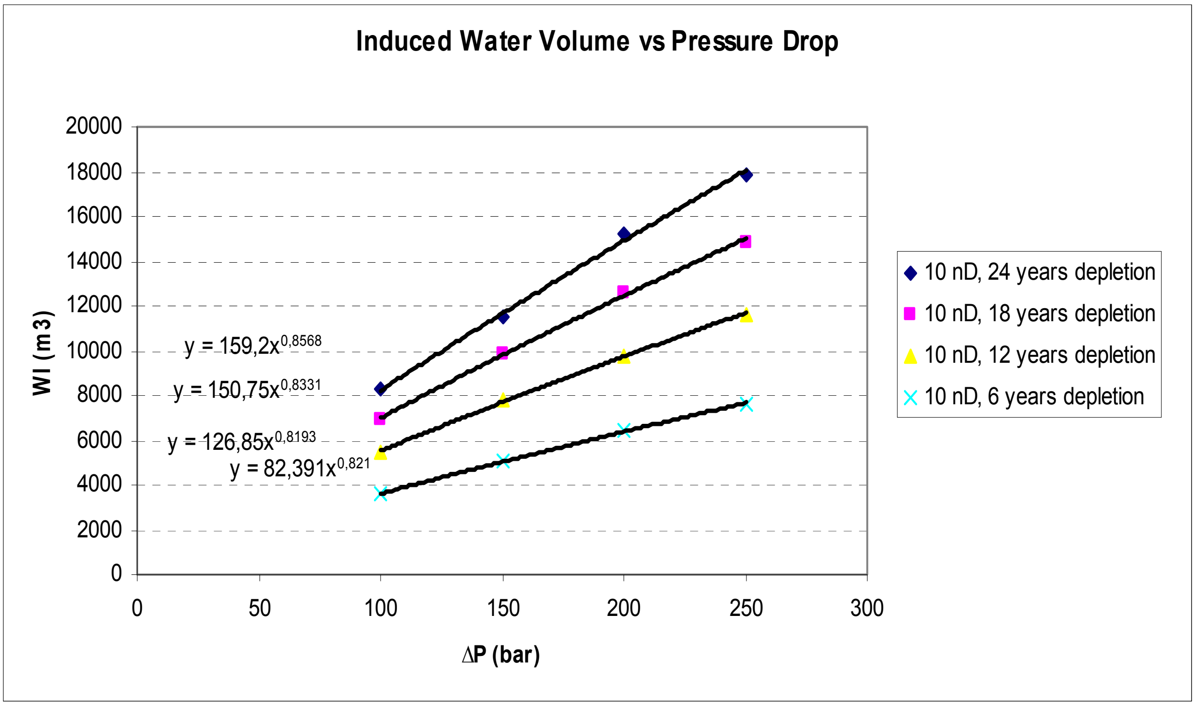

Figure 4-24: Induced water volume against pressure drop – 10nD NP zone

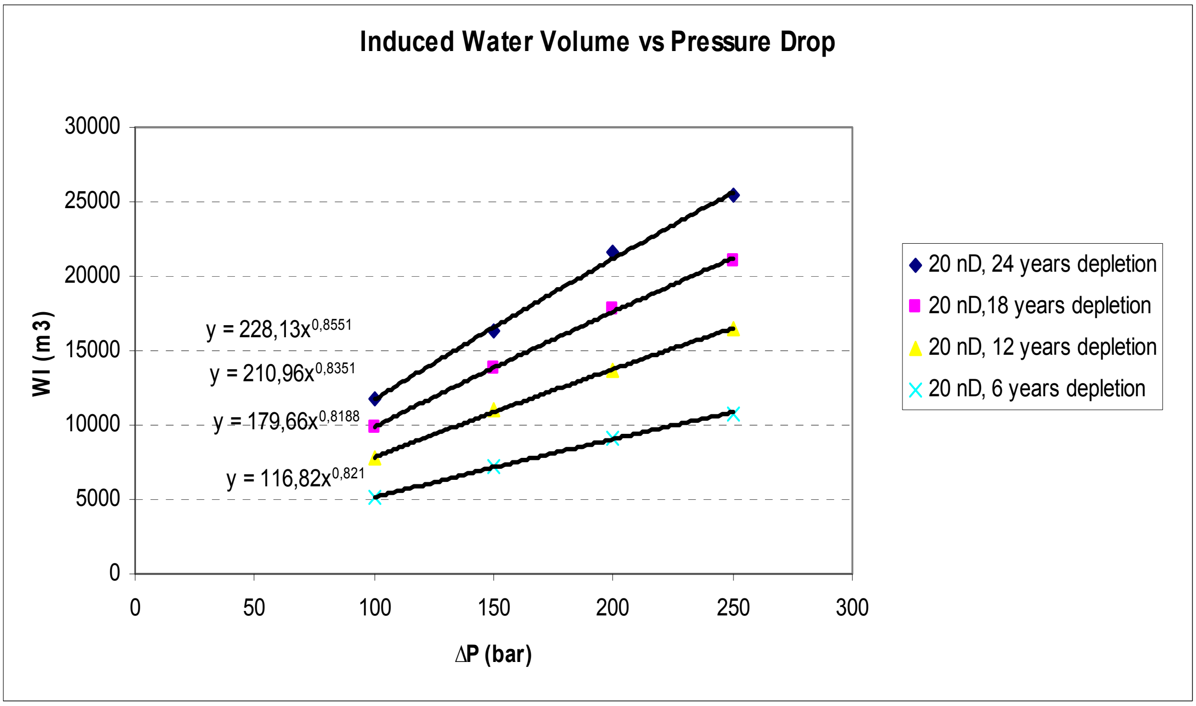

Figure 4-25: Induced water volume against pressure drop – 20nD NP zone

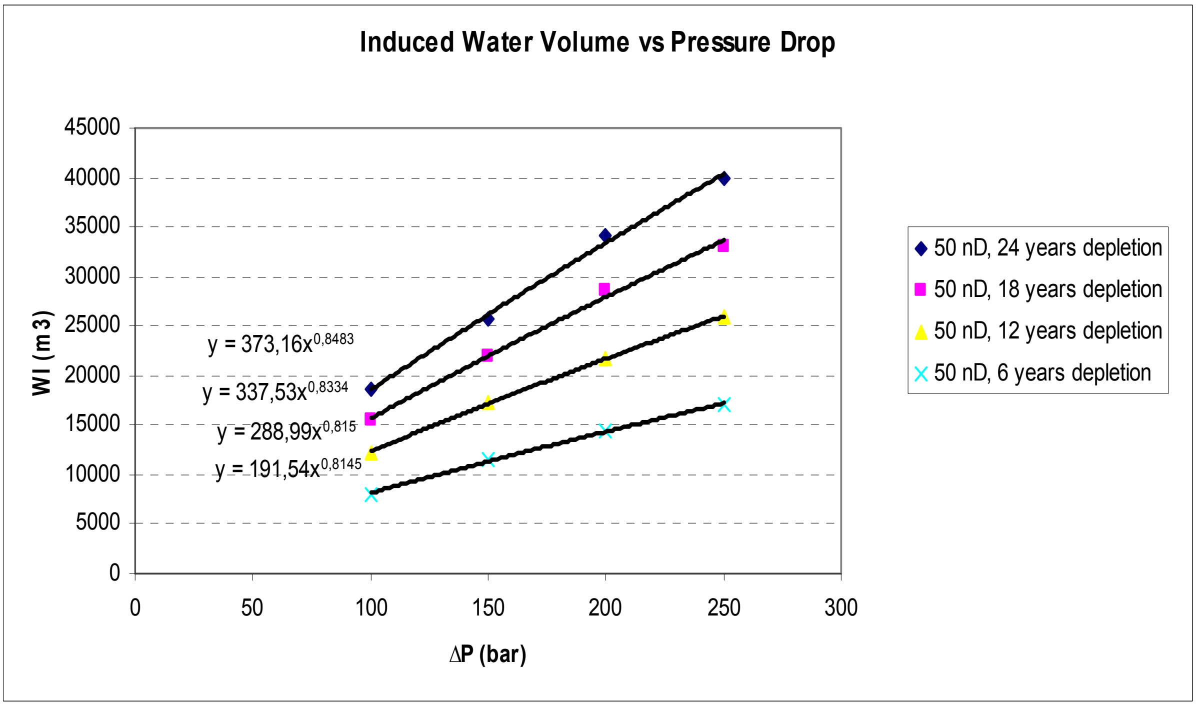

Figure 4-26: Induced water volume against pressure drop – 50nD NP zone

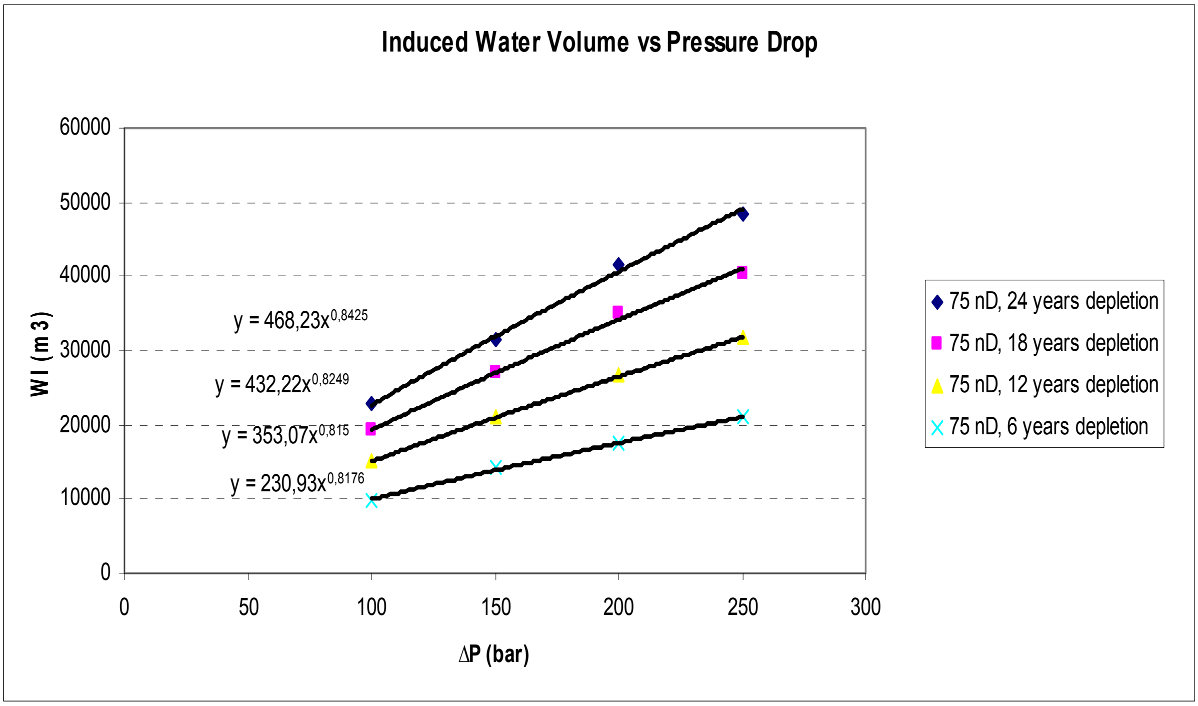

Figure 4-27: Induced water volume against pressure drop – 75nD NP zone

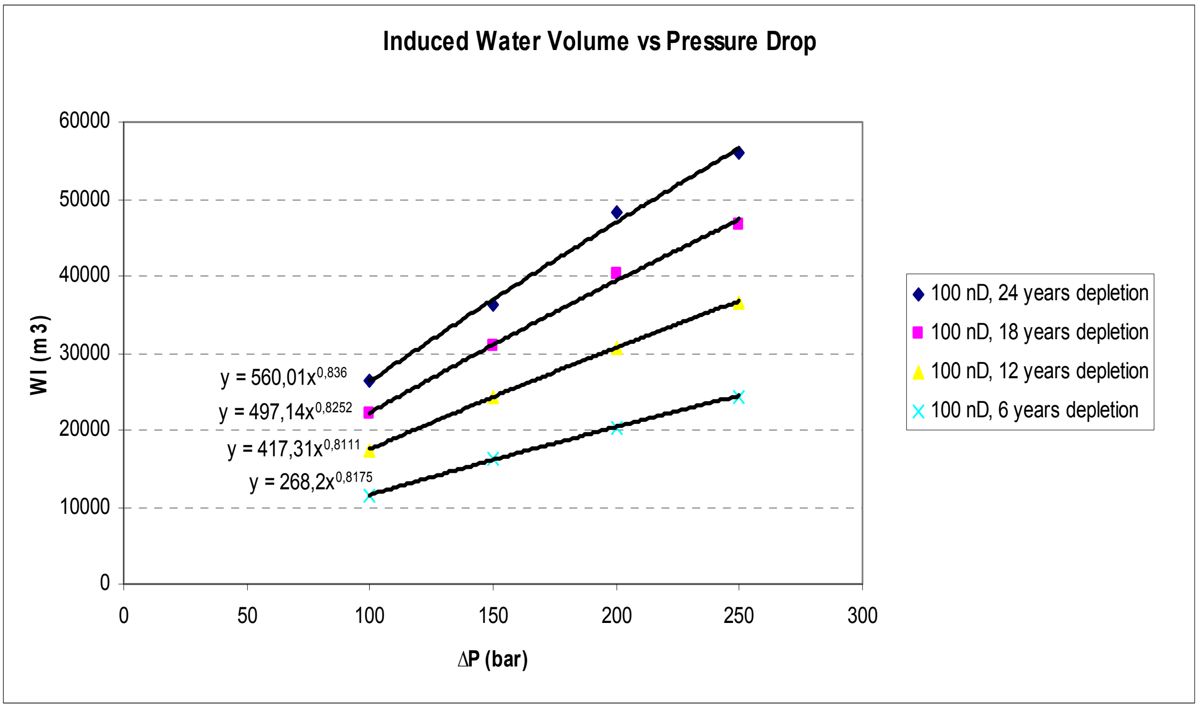

Figure 4-28: Induced water volume against pressure drop – 100nD NP zone

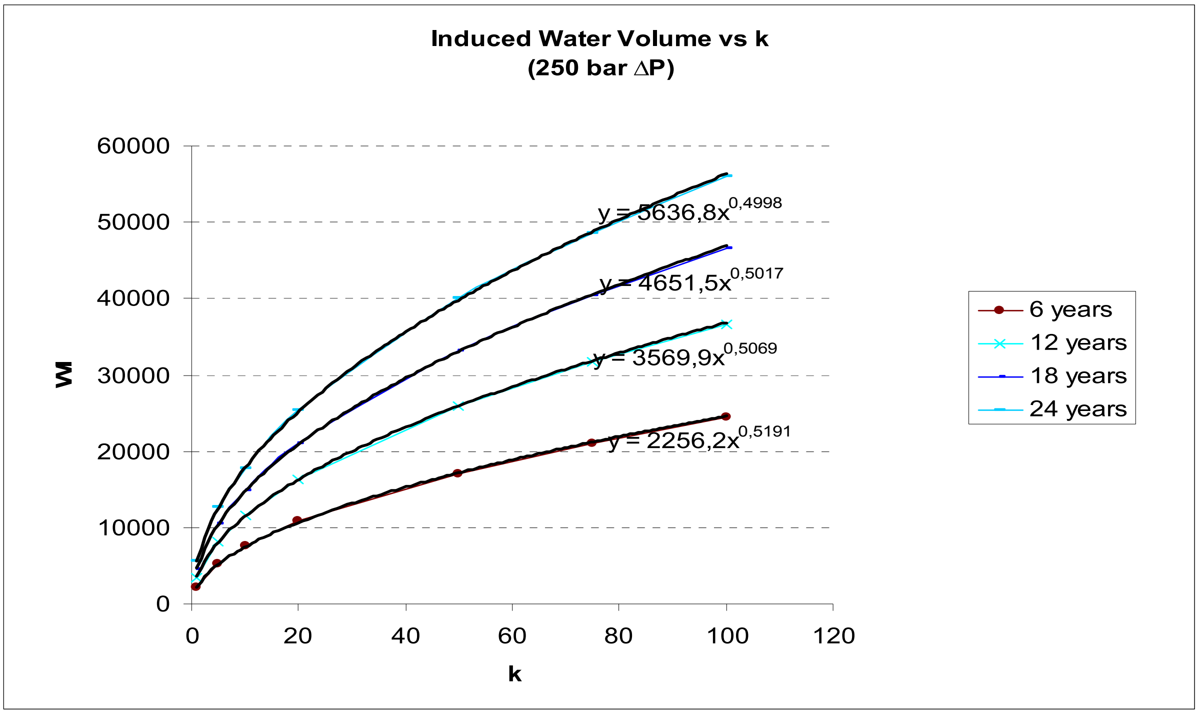

Figure 4-29: Induced water volume against permeability – 250 bar reservoir pressure drop

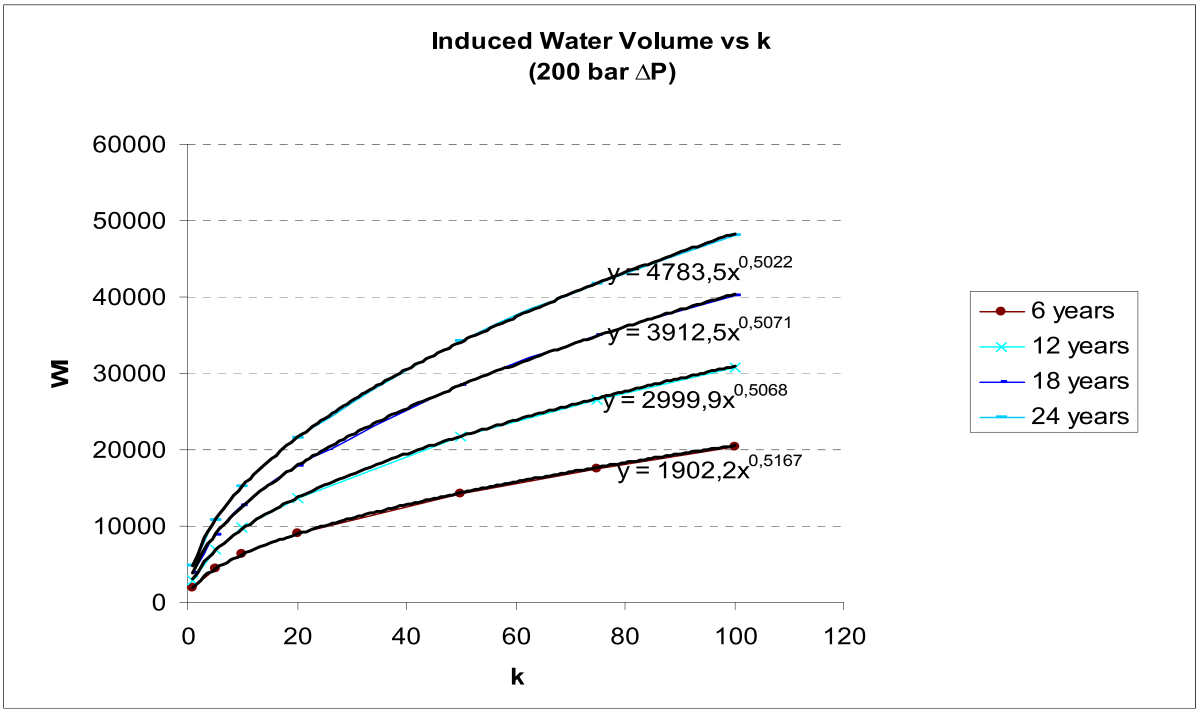

Figure 4-30: Induced water volume against permeability – 200 bar reservoir pressure drop

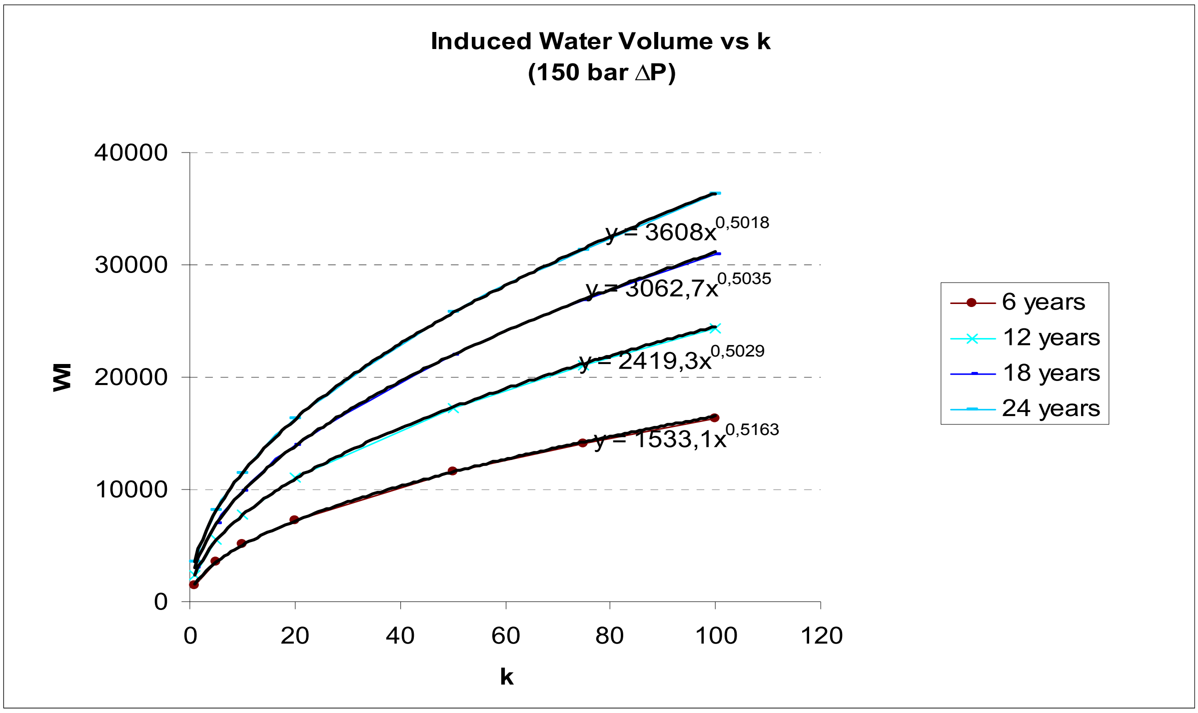

Figure 4-31: Induced water volume against permeability – 150 bar reservoir pressure drop

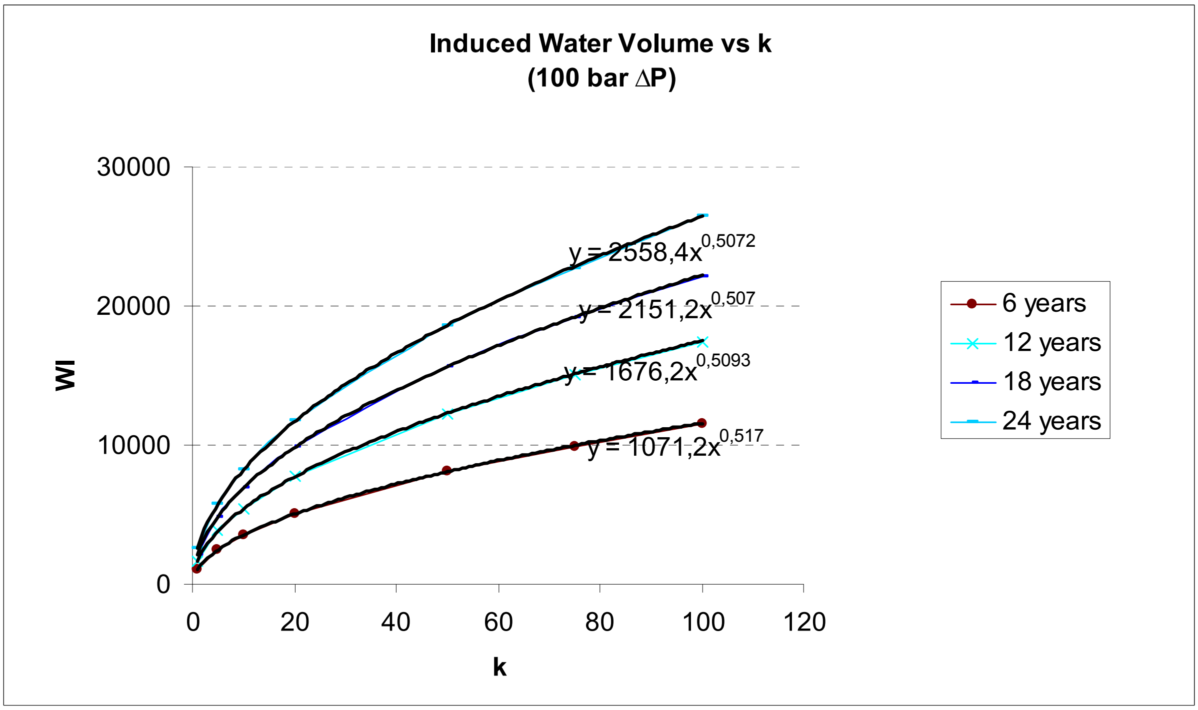

Figure 4-32: Induced water volume against permeability – 100 bar reservoir pressure drop

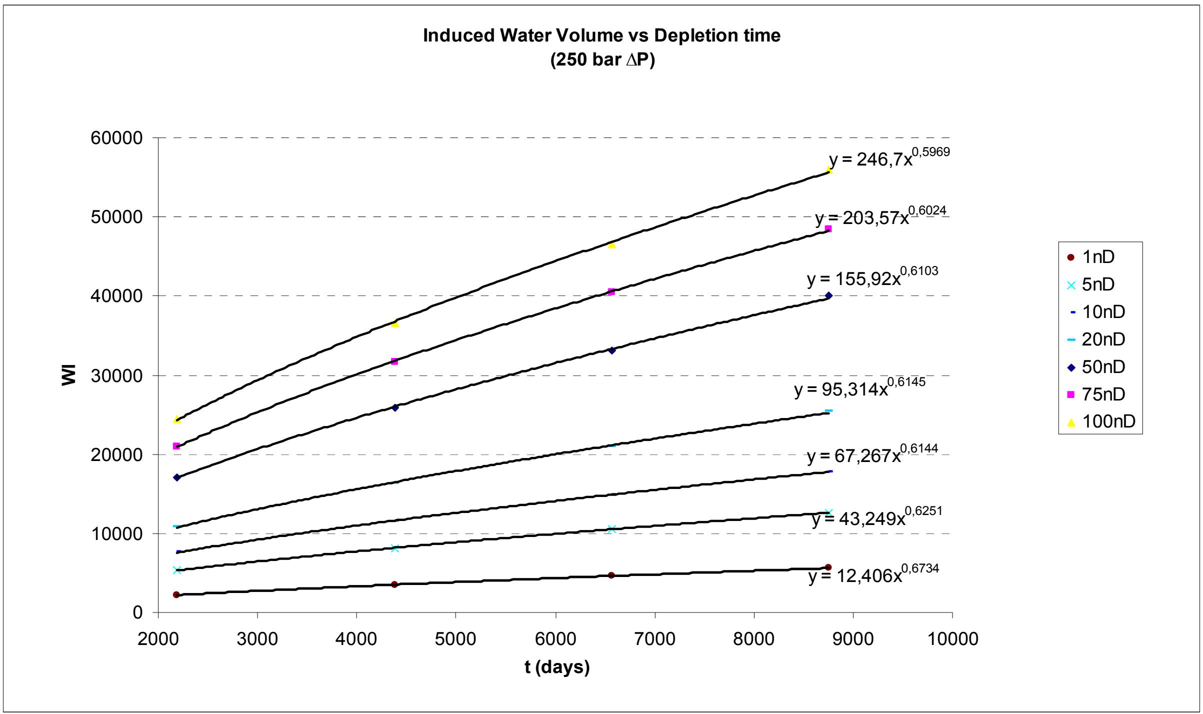

Figure 4-33: Induced water volume against depletion time – 250 bar reservoir pressure drop

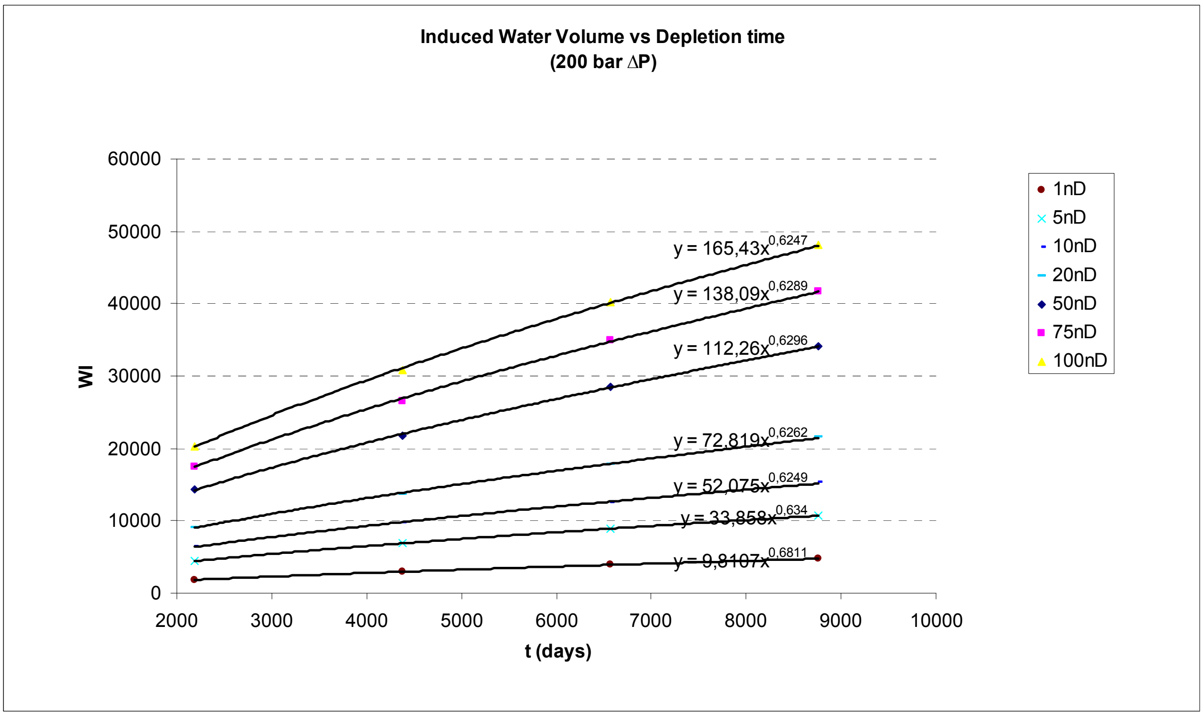

Figure 4-34: Induced water volume against depletion time – 200 bar reservoir pressure drop

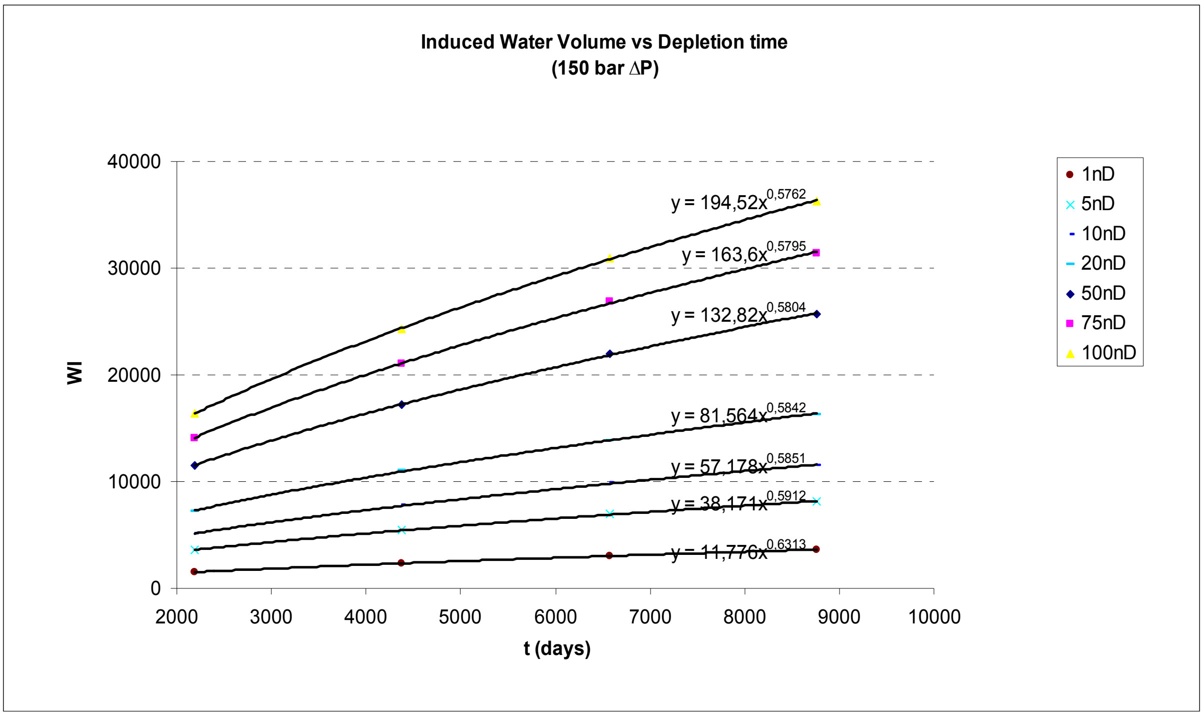

Figure 4-35: Induced water volume against depletion time – 150 bar reservoir pressure drop

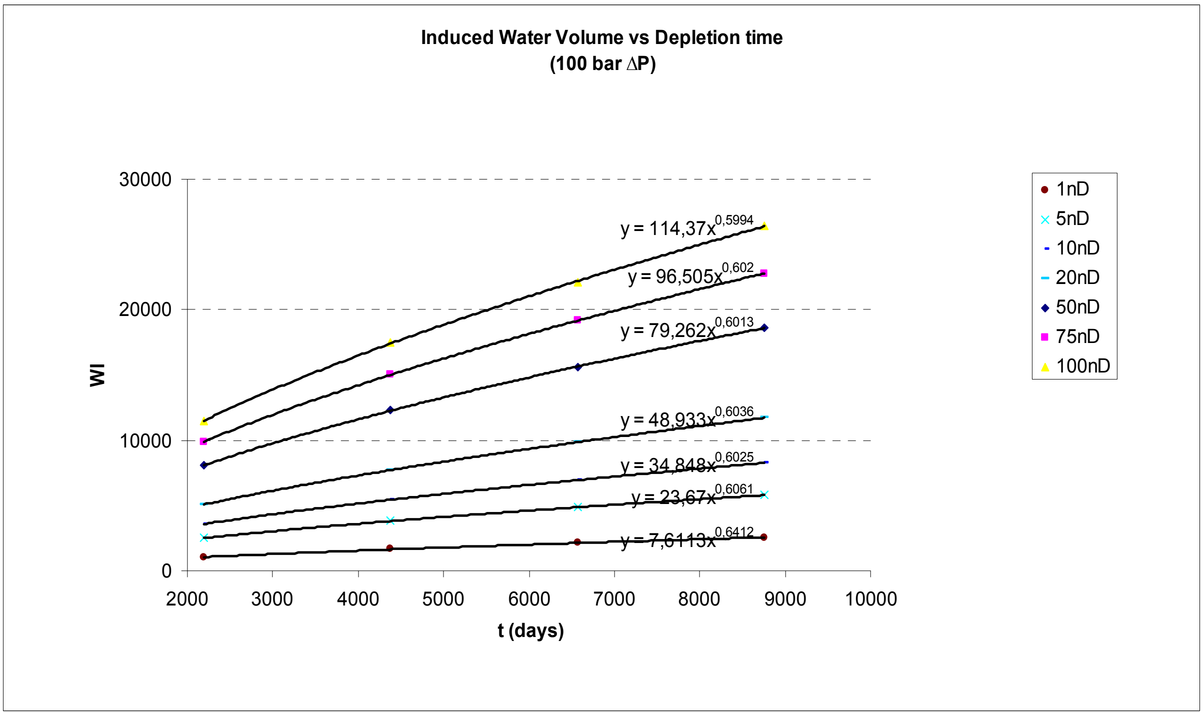

Figure 4-36: Induced water volume against depletion time – 100 bar reservoir pressure drop

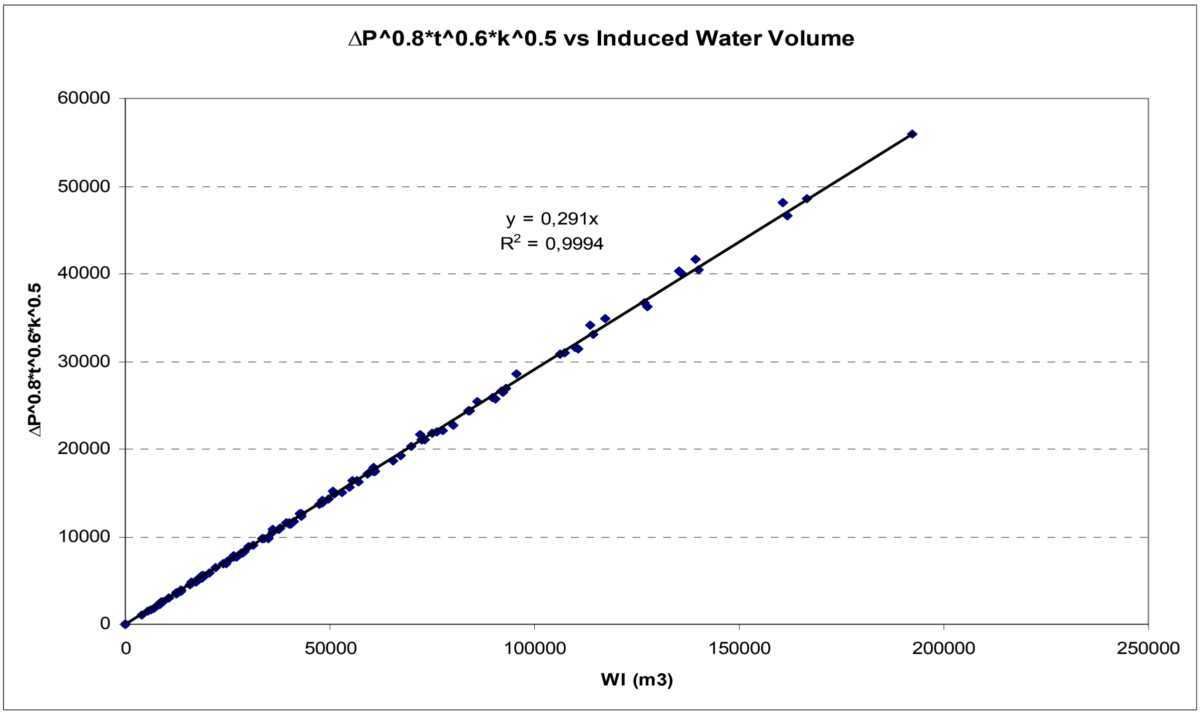

Figure 4-37: Correlation between induced water volume and other parameters

4.3 Effects of dissolved gas in water: ROCKTAB keyword application

In previous chapter, it has been assumed that the dissolved gas in water when being liberated will form immobile bubbles, which block the pore and contribute to pore volume reduction. The effects caused by the gas bubble are similar to effects of rock compaction/expansion. The pore volume multipliers used together with the ROCKTAB keyword are in following tables:

Table 4-1: Pore volume and transmissibility multipliers for water 100% saturation with gas

Pressure (bar)	Pore volume multiplier	Transmissibility multiplier
50	0,91836	1,0
80	0,94470	1,0
110	0,95963	1,0
140	0,96947	1,0
170	0,97571	1,0
200	0,98083	1,0
230	0,98488	1,0
260	0,98848	1,0
290	0,99163	1,0
320	0,99452	1,0
350	0,99727	1,0
380	1,00000	1,0

Table 4-2: Pore volume and transmissibility multipliers for water 70% saturation with gas

Pressure (bar)	Pore volume multiplier	Transmissibility multiplier
50	0,94010	1,0
80	0,95821	1,0
110	0,96869	1,0
140	0,97584	1,0
170	0,98051	1,0
200	0,98447	1,0
230	0,98742	1,0
260	0,98994	1,0
290	0,99245	1,0
320	0,99497	1,0
350	0,99748	1,0
380	1,00000	1,0

Average compressibility for the full saturated and 70% saturated cases are 1.58E-4 bar^{-1} and 1.22E-4 bar^{-1} respectively.

Dimensionless values are calculated using equations in chapter 2 and above average values of total compressibility. The obtained data are plotted against each other in the graph below. The graphs of data points in the cases of gas content are compared with the graph of data points where the effect of dissolved gas is not taken into account.

There is almost no difference between the graph for the cases of 70% gas saturation and 100% gas saturation. The discrepancy between the lines where gas effects are taken into account and the line without dissolved gas is about 10% maximum and can be acceptable for the purpose of roughly estimate the induced water volume in case of gas presence. The equation can be used in this case is similar to the equation for the case where there is no dissolved gas and NP zone thickness less than effective thickness:

$$WId = 1 - \frac{1}{1 + 0.921 * tD^{0.965}}$$

It should be noted that in this project, effect of dissolved gas in water is investigated for the case of NP zone thickness less than effective one. For more general application of the equation, more data for different values of parameters should be obtained.

ROCKTAB keyword application for the case of dissolved gas in water is reasonably acceptable. The results are consistent with the case where no dissolved water is taken into account. The obtained equation therefore can be used to roughly estimate the volume of induced water from NP zone into the reservoir.

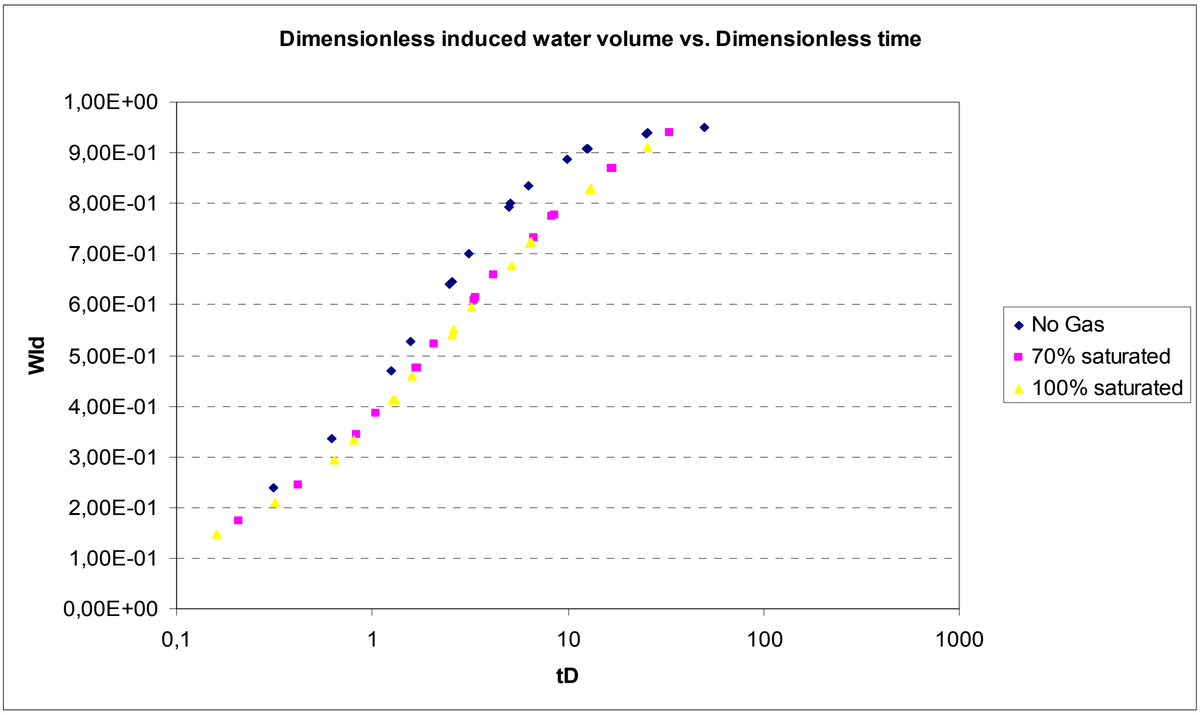

Figure 4-38: Correlation between dimensionless volume and dimensionless time for non dissolved gas and dissolved gas water

4.4 Optimum grid thicknesses

For a specific value of effective thickness, it can be observed that number of layers in the simulation model can effect significantly to the outcome of the model, especially induced water volume from NP zone into reservoir. The more layers (or the finer the grids), the higher values of volume water is.

It has also been observed from the simulation results that the increasing of water volume with higher model's resolution does not go to infinity. The volume increases faster at the beginning and then comes to a quite stable value when certain thickness of grids is reached. By looking at the below plots of water volume against number of grid layers, we can see that for the zone with higher permeability, the grids thickness required for stable value of water volume is higher than that for zones of lower permeability. For the case of 1nd NP zone, very thin grid should be used for the better results.

The optimum thickness of cell grids is defined as the thickness of grid layer where the induced water volume from simulation being relatively stable even when the simulation runs with higher resolution grid cells. In this project, the area of the model is quite small. The simulation does not take much computer resources and time. However, in the cases when the models are much more complicated, the application of the optimum grid thickness is really useful in saving time and resources for simulation.

This project only studies some cases for the value of optimum grid thickness due to time limitation. For references, it is roughly estimate from below figures that for an effective thickness of NP zone, 5 layers of grids can be used as optimum value.

Future works should be carried out with models integrating different combination of parameters for better understanding of this matter and obtain more values of optimum grid thickness. Correlating equations or plots between the optimum values and other parameters may be found if more data being available.

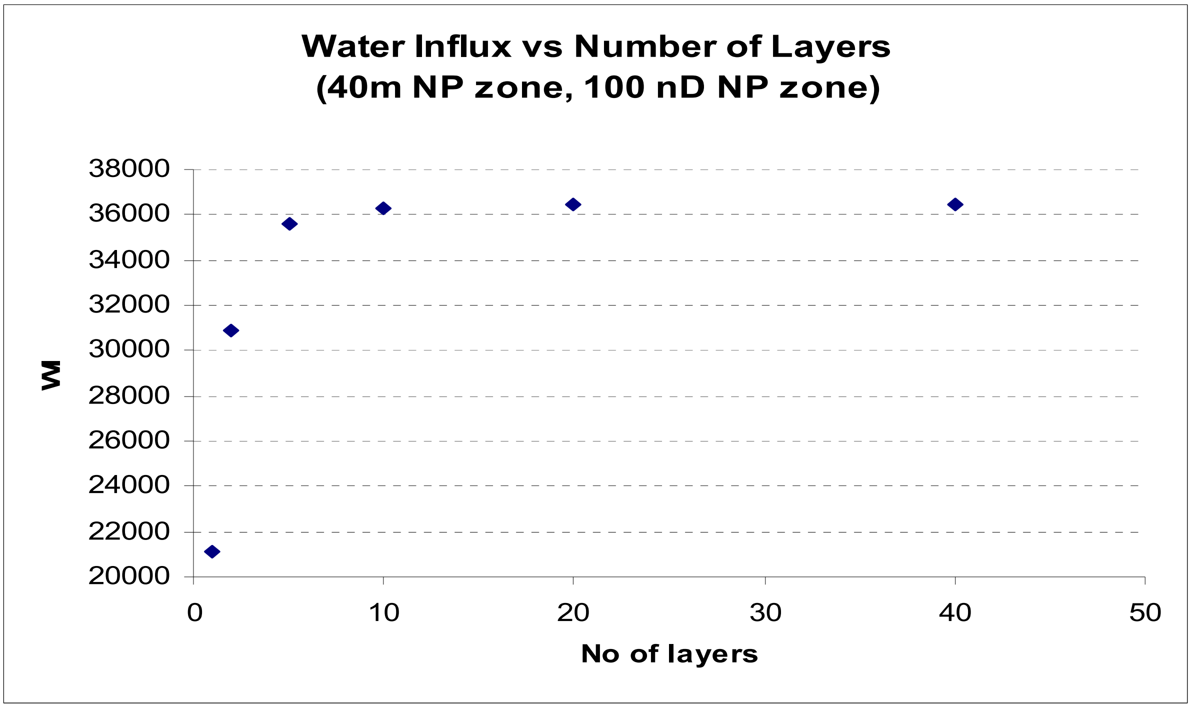

Figure 4-39: Correlation between induced water volume and number of grid layers (40m – 100nD NP zone)

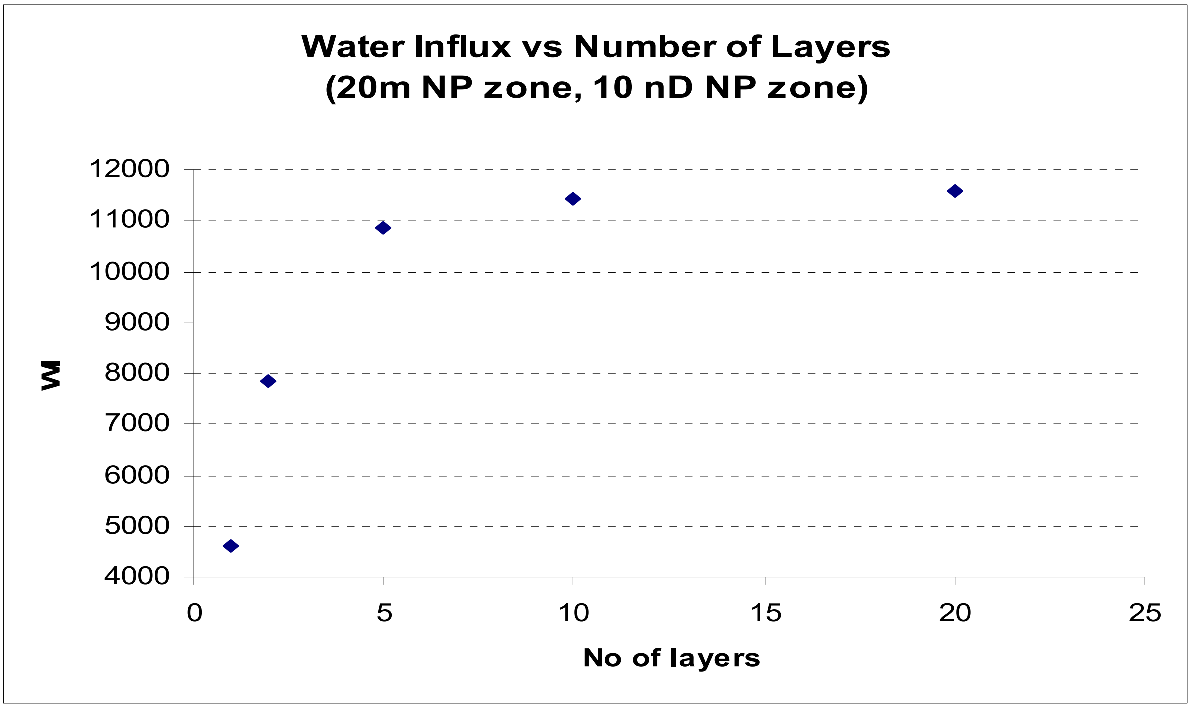

Figure 4-40: Correlation between induced water volume and number of grid layers (20m – 10nD NP zone)

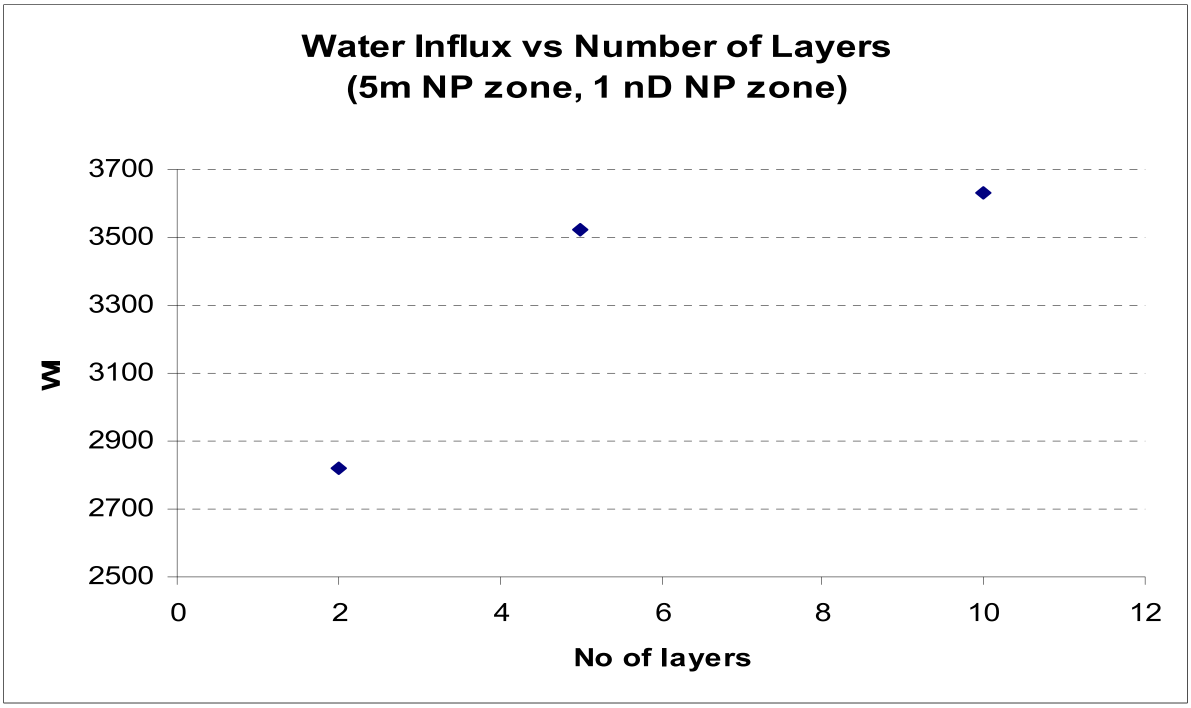

Figure 4-41: Correlation between induced water volume and number of grid layers (5m – 1nD NP zone)

4.5 Effects of different grid thicknesses distribution on induced water volume

In this part of project, models are built with basic parameters: permeability of NP zone is 100nD, total compressibility of 8.12E-5 bar^{-1}, 12 years field depletion, NP zone thickness equal to effective thickness of 40m and 5 grid layers.

It can be seen from Table 4-3 that even there is large variation in the thickness of regions, the induced water volumes do not change significantly from each other. Pressure profiles of each region inside the NP zone indicated that for equal grid thickness case, the pressure drop in the region far away from contact boundary is less than pressure drop of zones closer to the boundary. It changes for the cases where the grid layers thickness distribution between regions is not equal. If layers far away from the boundary are thicker than the ones near it, the pressure drop can be higher and vice versa. However, total pressure drop of all the regions does not change significantly.

This combination of parameters is assumed to be sensitive with the grids thickness due to high permeability of NP zone. For lower permeability of NP zone, the dependence between the induced water volume and the distributions of grid layers thickness is less sensitive.

Table 4-3: Effects of grids thickness variation on total induced water volume from NP zone

Case	Region 1 (m)	Region 2 (m)	Region 3 (m)	Region 4 (m)	Region 5 (m)	WI (m3)
1	8	8	8	8	8	35617
2	12	10	8	6	4	35828
3	14	12	8	4	2	35580
4	12	12	8	4	4	35729

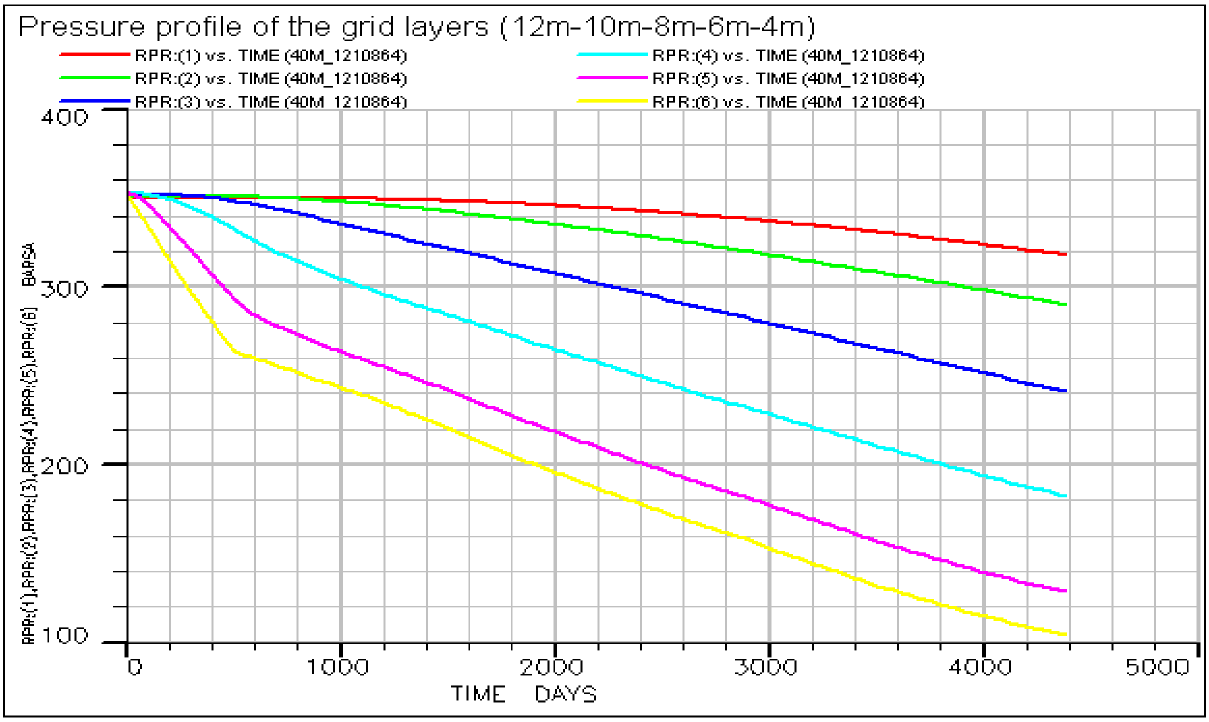

Figure 4-42: Pressure profile of the grid layers (12m-10m-8m-6m-4m)

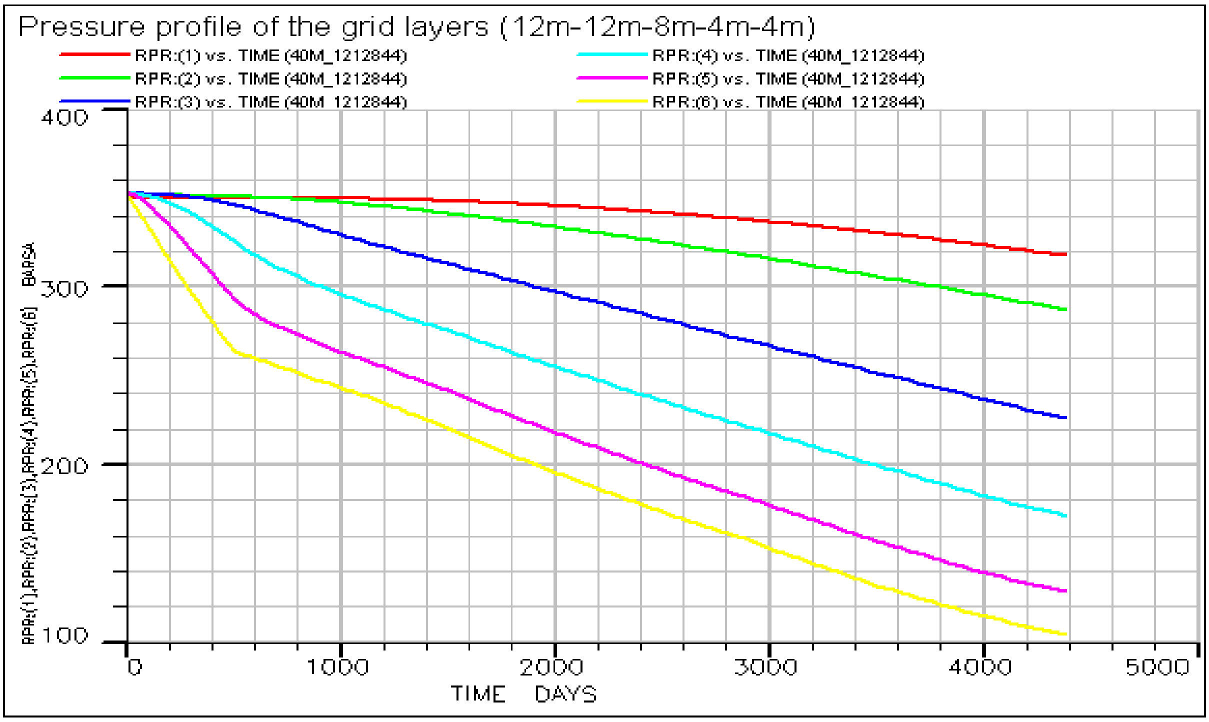

Figure 4-43: Pressure profile of the grid layers (12m-12m-8m-4m-4m)

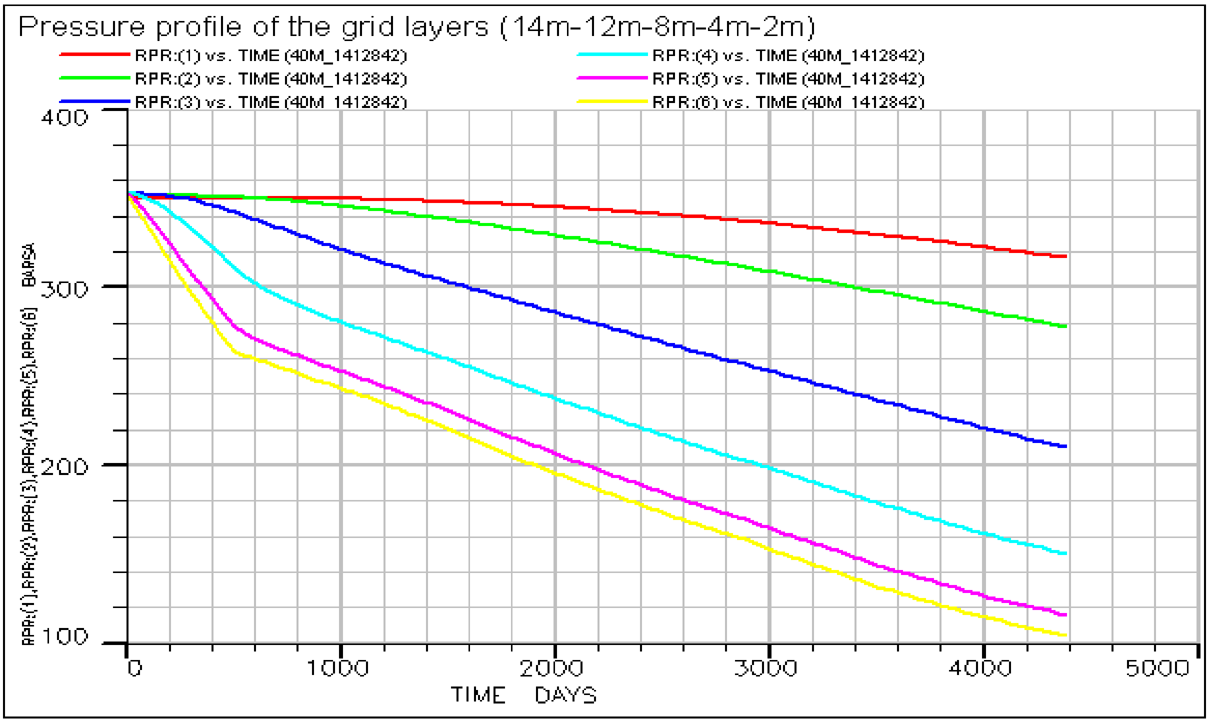

Figure 4-44: Pressure profile of the grid layers (14m-12m-8m-4m-2m)

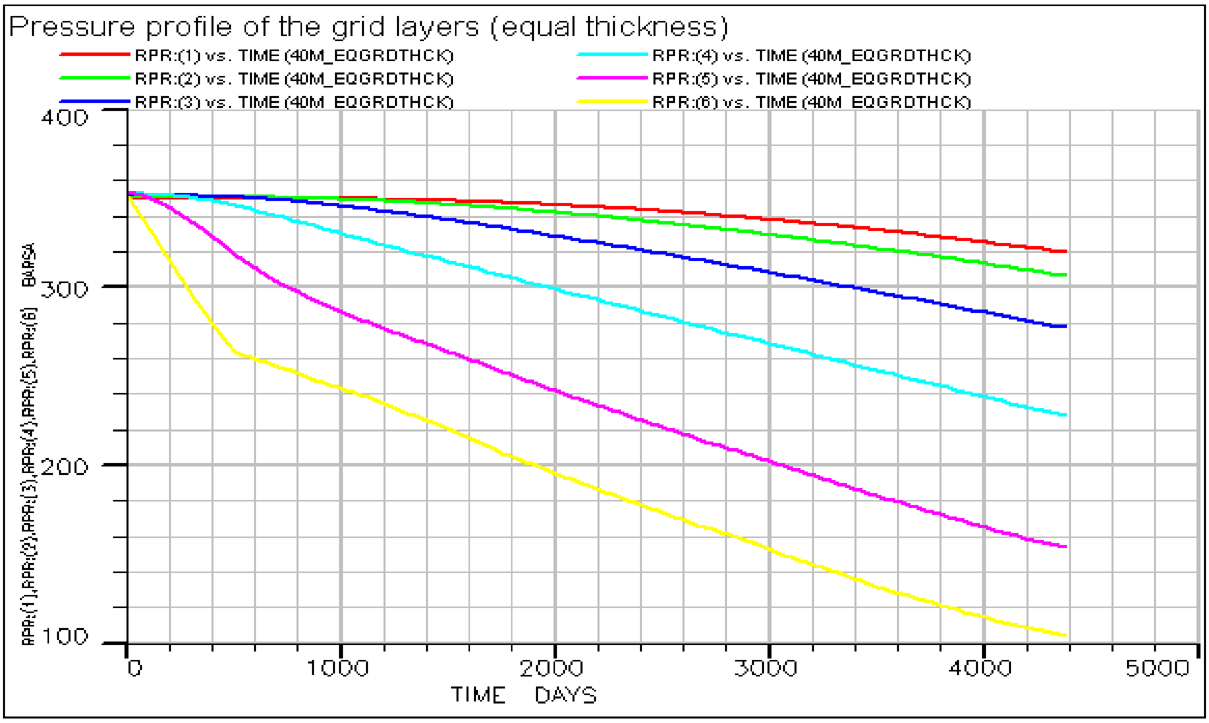

Figure 4-45: Pressure profile of the grid layers (equal thickness)

5 CONCLUSION

Lots of models have been built and many cases have been investigated to achieve final results of the project. More than 500 simulation runs with various modelling scenarios, those integrate combinations of different parameters have been carried out. It can be concluded from the modelling results and discussions as followings:

- The induced water volume from NP zone into reservoir is dependent on the NP zone thickness, simulation grids thickness, NP zone permeability, total compressibility, reservoir's depletion time and pressure drop.
- For a specific NP-zone, there is an effective thickness such that there is little change in induced water volume if the thickness value is higher the effective value. The effective thickness of a NP-zone is dependent on the permeability, reservoir depletion time and compressibility of the zone. It is also expected that the reservoir pressure drop can also affect the effective thickness of NP zone. Picking up the right effective thickness of NP zone plays an important role in studying the correlating between induced water volume and other parameters. However, this task is difficult because the transition between quick changes of water volume and stable water volume is not clear in all runs. Selections of high precise effective thickness points require differences between adjacent steps of input parameters to be very small so that the transition of the values can be detected easier. More models with inputs are combinations from different parameters should be studied in order to find relationship between the effective thickness and NP-zone's properties. However, due to time limitation and scope of the project, only part of the studies have been carried out. The effective thicknesses of NP-zones with reservoir depletion time of 12 years, reservoir pressure drop of 250 bars, total compressibility of 8.12E-5 bar^{-1} and various values of permeability are investigated and showed in this thesis. The obtained results are used for references to take the relevant thickness in the next parts of the project.
- Correlation between induced water volume and other parameters:
    - For thickness of NP zone equal or less than effective values: the correlation between values of induced water volume with NP zone permeability, thickness, compressibility, field depletion time and reservoir pressure drop is expressed in a correlating equation:

$$WId = 1 - \frac{1}{1 + 0.921 * tD^{0.965}}$$

where WId and tD are dimensionless quantities of volume and time. The data points from simulation models fit very well with the obtained equation. The equation is very useful in estimating the induced water volume from NP zone into reservoir when having other parameters. The volume of water can be compared to total fluid volume to investigate the pressure contribution from NP zone to production of reservoir. This equation can be applied not only for Brent formation of Statfjord field but also for other formations as well.

- For thickness of NP zone equal or higher than effective values: for the area of 1km^2 of Brent formation, the correlation between induced volume water from NP zone into reservoir and NP zone permeability, field depletion time and reservoir pressure drop is expressed with the equation:

$$WI = 0.291 * \Delta P^{0.8} * k^{0.5} * t^{0.6}$$

the thickness of NP zone is excluded from the formula as long as it is higher than the effective value. The equation is applied for specific case of Brent formation with total compressibility of 8.12E-5 bar^{-1} and reservoir pressure drop of 250 bar. For other scenarios of parameters, more studies should be carried outl.

- Gas dissolved in water, when being released can act as a factor for reduction of pore volume in the zone (assuming that the released gas bubbles are not mobile). In the simulation model, the reduction of pore volume due to the gas released can contribute significantly to the volume of induced water from NP zone to reservoir. The phenomenon is similar to the phenomenon of rock compaction/expansion and is modelled using keyword ROCKTAB in the simulation. In comparison to the simulating results without considering the effects of dissolved gas in water, by using average value of total compressibility, it can be seen that the dimensionless correlation between induced water volume and time for both cases are quite similar.
- The thickness of the simulation grids (and therefore the number of the grid layers) is a factor that affects the computer resources consumption and time to run the simulation models. It is also a factor effecting on the value of induced water volume from NP-zones to reservoir. The finer the grids are, the closer the results to the actual values.

However, for each NP-zone, there is an optimum grid thickness such that for grids with thickness less that the value, the changes in the induced water volume values are negligible. In this thesis, within the effective thickness of the NP zone, the optimum grids thicknesses for the case of NP zone with depletion time of 12 years, reservoir pressure drop of 250 bar and total compressibility of 8.12E-5 bar^{-1} have been studied with various values of NP zone permeability. It can be concluded that in this specific cases, the optimum grid thickness for the simulation is greatly dependent on the permeability of the NP zone: lower permeability of NP zone required finer grid thickness to have highest value of induced water volume (closer to the real value). In case of NP zone permeability of 1nD, it is really difficult to pick reasonable optimum grid thickness. It seems that grid with thickness of less than 1m should be used in this situation for high accuracy of the model. Further development of this primary study should be carried out to find general formulas for optimum grids thickness of NP zone.

- The distribution of grid thickness in NP zone can affect the value of induced water volume from the zone to reservoir. However, it has been observed from the simulation results that the changes of the values while changing the distribution and equality of the grids thicknesses are negligible.

Within the limitation of time, the scope of work of the project has also been limited to some extends. There will be further works those can be done to improve the project results:

- Build simulation models with small discrepancy between parameters in adjacent steps in order to find precise values of effective thickness of NP zones. Different combinations of parameters should be integrated into the models so that the result can be general and used for other rock formations.
- Optimum grids thickness values are important and should be evaluated with more simulation models with various input parameters of compressibility, permeability, depletion time and pressure drop.
- In order to make correlating equations between induced volume water and other parameters such as compressibility, permeability, depletion time and pressure drop to be generalized and can be used for other formations, more modelling scenarios with different input parameters should be studied. The differences between parameters of models should be reasonably small to have better results. Similar tasks should be

carried out to confirm the impact of dissolved gas when released on the pressure distribution.

- In case of NP zones have thickness larger than the effective values, it is necessary to investigate the effect of lateral contact area between the zones and reservoir and integrating that parameter into the correlating equations between induced water volume and other input parameters.

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APPENDIX A: A SIMPLE RESERVOIR MODEL

Below is a typical simulation model for the project. The parameters in the model change for different scenarios depending on the purposes of the investigations.

```
RUNSPEC     ======================
TITLE
   SIMPLE MODEL

DIMENS
      10    10    60  /

NONNC

WATER

OIL

GAS

VAPOIL

DISGAS

METRIC

REGDIMS
      2     2     0     2     /

WELLDIMS
      2    20    2   2 /

TABDIMS
      2 1 50 50 2 5* 2 /

EQLDIMS
      2 /

UNIFOUT

RPTRUNSP

START
      1 'NOV' 1979  /

GRID        ======================

INIT

DUMPFLUX

FLUXNUM
      5000*1
      1000*2  /

EQUALS
     'DX'     100    /
     'DY'     100    /
/
```

```
DZ
      5000*1
      1000*5/


PERMX
      5000*0.35e-4
      1000*333
/

COPY
      PERMX PERMY /
      PERMX PERMZ /
/

PORO
      5000*0.12
      1000*0.3
/

TOPS
  100*2511 /
/

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

SWFN

      0.0          0      2
      0.7          0.0    2
      1            0.3    2
/

    0.000000     0.000000      2.000000
    0.050000     0.000125      0.715732
    0.100000     0.001000      0.636497
    0.150000     0.003375      0.562249
    0.200000     0.008000      0.492941
    0.250000     0.015625      0.428522
    0.300000     0.027000      0.368937
    0.350000     0.042875      0.314132
    0.400000     0.064000      0.264045
    0.450000     0.091125      0.218614
    0.500000     0.125000      0.177769
    0.550000     0.166375      0.141436
    0.600000     0.216000      0.109537
    0.650000     0.274625      0.081982
    0.700000     0.343000      0.058674
    0.750000     0.421875      0.039502
    0.800000     0.512000      0.024340
    0.850000     0.614125      0.013038
    0.900000     0.729000      0.005409
    0.950000     0.857375      0.001202
    1.000000     1.000000      0.000000
/

SGFN

      0      0    0
      0.2    0    0
      0.3      0.1  0
```

```
/
    0.000000     0.000000     0.000000
    0.050000     0.011180     0.000000
    0.100000     0.031623     0.000000
    0.150000     0.058095     0.000000
    0.200000     0.089443     0.000000
    0.250000     0.125000     0.000000
    0.300000     0.164317     0.000000
    0.350000     0.207063     0.000000
    0.400000     0.252982     0.000000
    0.450000     0.301869     0.000000
    0.500000     0.353553     0.000000
    0.550000     0.407891     0.000000
    0.600000     0.464758     0.000000
    0.650000     0.524047     0.000000
    0.700000     0.585662     0.000000
    0.750000     0.649519     0.000000
    0.800000     0.715542     0.000000
    0.850000     0.783661     0.000000
    0.900000     0.853815     0.000000
    0.950000     0.925945     0.000000
    1.000000     1.000000     0.000000
/

SOF3

      0     0       0
      0.2     1.0E-6   0.0
      0.3     0.1     0.1
/
    0.000000     0.00000000     0.000000
    0.050000     0.00002795     0.000125
    0.100000     0.00031623     0.001000
    0.150000     0.00130713     0.003375
    0.200000     0.00357771     0.008000
    0.250000     0.00781250     0.015625
    0.300000     0.01478851     0.027000
    0.350000     0.02536519     0.042875
    0.400000     0.04047715     0.064000
    0.450000     0.06112851     0.091125
    0.500000     0.08838835     0.125000
    0.550000     0.12338700     0.166375
    0.600000     0.16731288     0.216000
    0.650000     0.22140975     0.274625
    0.700000     0.28697439     0.343000
    0.750000     0.36535447     0.421875
    0.800000     0.45794672     0.512000
    0.850000     0.56619527     0.614125
    0.900000     0.69159012     0.729000
    0.950000     0.83566578     0.857375
    1.000000     1.00000000     1.000000
/

--         ***   G A S   D A T A   ***
--    BAR                                (CP)
--
PVTG

     20.00    0.00002448   0.061895     0.01299
              0.00001224   0.061810     0.01300
              0.00000000   0.061725     0.01300 /
```

40.00	0.00000628	0.030252	0.01383
	0.00000314	0.030249	0.01383
	0.00000000	0.030245	0.01383 /
60.00	0.00000585	0.019844	0.01450
	0.00000292	0.019845	0.01450
	0.00000000	0.019846	0.01449 /
80.00	0.00000728	0.014686	0.01520
	0.00000364	0.014689	0.01519
	0.00000000	0.014692	0.01518 /
100.00	0.00001017	0.011627	0.01596
	0.00000509	0.011633	0.01595
	0.00000000	0.011638	0.01593 /
120.00	0.00001485	0.009619	0.01682
	0.00000743	0.009627	0.01679
	0.00000000	0.009635	0.01676 /
140.00	0.00002182	0.008213	0.01780
	0.00001091	0.008224	0.01774
	0.00000000	0.008235	0.01767 /
160.00	0.00003155	0.007184	0.01890
	0.00001577	0.007198	0.01878
	0.00000000	0.007212	0.01866 /
197.66	0.00006327	0.005820	0.02160
	0.00003164	0.005840	0.02122
	0.00000000	0.005860	0.02086 /
231.13	0.00010861	0.005042	0.02477
	0.00005431	0.005061	0.02389
	0.00000000	0.005082	0.02306 /
261.31	0.00016781	0.004561	0.02844
	0.00008391	0.004571	0.02672
	0.00000000	0.004584	0.02515 /
288.87	0.00024205	0.004255	0.03272
	0.00012103	0.004243	0.02976
	0.00000000	0.004241	0.02711 /
314.34	0.00033405	0.004062	0.03783
	0.00016703	0.004017	0.03311
	0.00000000	0.003990	0.02893 /
338.20	0.00044866	0.003953	0.04410
	0.00022433	0.003860	0.03693
	0.00000000	0.003797	0.03065 /
360.83	0.00059341	0.003915	0.05210
	0.00029670	0.003756	0.04150
	0.00000000	0.003644	0.03227 /
382.58	0.00077814	0.003947	0.06273
	0.00038907	0.003698	0.04725
	0.00000000	0.003518	0.03382 /
403.60	0.00100943	0.004048	0.07723
	0.00050471	0.003683	0.05472
	0.00000000	0.003413	0.03529 /
423.77	0.00127517	0.004207	0.09631
	0.00063758	0.003705	0.06418
	0.00000000	0.003325	0.03664 /
500.00	0.00127517	0.004050	0.10409
	0.00063758	0.003516	0.07013
	0.00000000	0.003069	0.04052 /
600.00	0.00127517	0.003894	0.11351
	0.00063758	0.003335	0.07714
	0.00000000	0.002836	0.04510 /
700.00	0.00127517	0.003775	0.12226
	0.00063758	0.003200	0.08353
	0.00000000	0.002672	0.04923 /
800.00	0.00127517	0.003679	0.13052

```
              0.00063758   0.003096     0.08947
              0.00000000   0.002548     0.05303 /
    900.00    0.00127517   0.003601     0.13838
              0.00063758   0.003011     0.09505
              0.00000000   0.002450     0.05656 /
   1000.00    0.00127517   0.003535     0.14589
              0.00063758   0.002942     0.10034
              0.00000000   0.002372     0.05987 /
/


--         ***   O I L   D A T A   ***

--   RSO    PRESSURE     B-OIL     VISCOSITY
--           (BAR)                   (CP)

PVTO

   17.81     20.00    1.117     1.02620
             59.00    1.111     1.09836
             98.00    1.106     1.17156
            137.00    1.101     1.24557
            176.00    1.097     1.32017
            215.00    1.093     1.39516
            254.00    1.089     1.47036
            293.00    1.085     1.54562
            332.00    1.082     1.62081
            371.00    1.079     1.69584
            410.00    1.076     1.77064
            449.00    1.073     1.84514
            488.00    1.070     1.91932 /

   29.68     40.00    1.150     0.91278
             79.00    1.144     0.97366
            118.00    1.138     1.03530
            157.00    1.133     1.09753
            196.00    1.128     1.16017
            235.00    1.123     1.22309
            274.00    1.119     1.28612
            313.00    1.115     1.34916
            352.00    1.111     1.41210
            391.00    1.108     1.47487
            430.00    1.105     1.53739
            469.00    1.102     1.59962
            508.00    1.099     1.66153 /

   40.55     60.00      1.178     0.83726
             99.00      1.171     0.89054
            138.00      1.165     0.94438
            177.00      1.160     0.99866
            216.00      1.154     1.05325
            255.00      1.150     1.10801
            294.00      1.145     1.16283
            333.00      1.141     1.21762
            372.00      1.137     1.27228
            411.00      1.133     1.32676
            450.00      1.130     1.38099
            489.00      1.126     1.43493
            528.00      1.123     1.48855 /
--
   50.88     80.00      1.206     0.77872
```

```
            119.00      1.199     0.82613
            158.00      1.192     0.87398
            197.00      1.186     0.92216
            236.00      1.180     0.97055
            275.00      1.175     1.01905
            314.00      1.170     1.06757
            353.00      1.166     1.11603
            392.00      1.162     1.16435
            431.00      1.158     1.21247
            470.00      1.154     1.26035
            509.00      1.151     1.30795
            548.00      1.147     1.35524 /
--
   61.40    100.00      1.233     0.73080
            139.00      1.226     0.77347
            178.00      1.219     0.81647
            217.00      1.212     0.85972
            256.00      1.206     0.90311
            295.00      1.201     0.94658
            334.00      1.196     0.99002
            373.00      1.191     1.03339
            412.00      1.186     1.07661
            451.00      1.182     1.11964
            490.00      1.178     1.16243
            529.00      1.175     1.20496
            568.00      1.171     1.24719 /
--
   72.24    120.00      1.261     0.69022
            159.00      1.253     0.72895
            198.00      1.246     0.76792
            237.00      1.239     0.80706
            276.00      1.233     0.84631
            315.00      1.227     0.88559
            354.00      1.222     0.92484
            393.00      1.216     0.96399
            432.00      1.212     1.00300
            471.00      1.207     1.04183
            510.00      1.203     1.08044
            549.00      1.199     1.11879
            588.00      1.195     1.15688 /
--
   83.48    140.00      1.290     0.65247
            179.00      1.282     0.68877
            218.00      1.274     0.72493
            257.00      1.267     0.76097
            296.00      1.260     0.79694
            335.00      1.254     0.83283
            374.00      1.248     0.86861
            413.00      1.243     0.90427
            452.00      1.238     0.93978
            491.00      1.233     0.97509
            530.00      1.229     1.01020
            569.00      1.224     1.04507
            608.00      1.220     1.07968 /
--
   95.16    160.00      1.320     0.6070
            199.00      1.311     0.6332
            238.00      1.302     0.6604
            277.00      1.295     0.6894
            316.00      1.288     0.7224
            355.00      1.281     0.7572
```

```
            394.00      1.275     0.7970
            433.00      1.270     0.8398
            472.00      1.264     0.8838
            511.00      1.260     0.9272
            550.00      1.255     0.9692
            589.00      1.250     1.0093
            628.00      1.246     1.0477 /
--
  123.98    197.63      1.397     0.5109
            236.63      1.387     0.5307
            275.63      1.377     0.5503
            314.63      1.369     0.5696
            353.63      1.361     0.5888
            392.63      1.353     0.6077
            431.63      1.346     0.6264
            470.63      1.340     0.6449
            509.63      1.334     0.6631
            548.63      1.328     0.6811
            587.63      1.323     0.6988
            626.63      1.318     0.7163 /
--
  152.82    231.06      1.474     0.4419
            270.06      1.462     0.4581
            309.06      1.452     0.4741
            348.06      1.442     0.4899
            387.06      1.433     0.5055
            426.06      1.425     0.5210
            465.06      1.417     0.5362
            504.06      1.410     0.5513
            543.06      1.403     0.5662
            582.06      1.397     0.5809
            621.06      1.391     0.5954
            660.06      1.386     0.6097 /
--
  181.67    261.19      1.550     0.3900
            300.19      1.537     0.4037
            339.19      1.526     0.4171
            378.19      1.515     0.4304
            417.19      1.505     0.4436
            456.19      1.496     0.4565
            495.19      1.488     0.4694
            534.19      1.480     0.4820
            573.19      1.473     0.4945
            612.19      1.466     0.5069
            651.19      1.459     0.5191 /
--
  210.55    288.69      1.626     0.3499
            327.69      1.612     0.3617
            366.69      1.599     0.3732
            405.69      1.588     0.3847
            444.69      1.577     0.3960
            483.69      1.567     0.4071
            522.69      1.558     0.4182
            561.69      1.550     0.4291
            600.69      1.541     0.4398
            639.69      1.534     0.4505 /
--
  239.46    314.12      1.701     0.3181
            353.12      1.686     0.3284
            392.12      1.673     0.3386
            431.12      1.660     0.3486
```

```
           470.12      1.649     0.3585
           509.12      1.638     0.3683
           548.12      1.628     0.3779
           587.12      1.619     0.3875
           626.12      1.610     0.3969 /
--
  268.39   337.92      1.776     0.2923
           376.92      1.760     0.3015
           415.92      1.745     0.3106
           454.92      1.732     0.3195
           493.92      1.720     0.3284
           532.92      1.708     0.3371
           571.92      1.698     0.3456
           610.92      1.688     0.3541
           649.92      1.678     0.3625 /
--
  297.35   360.49      1.850     0.2712
           399.49      1.833     0.2795
           438.49      1.818     0.2877
           477.49      1.804     0.2958
           516.49      1.790     0.3037
           555.49      1.778     0.3115
           594.49      1.767     0.3193
           633.49      1.756     0.3269 /
--
  326.33   382.18      1.923     0.2537
           421.18      1.906     0.2612
           460.18      1.889     0.2687
           499.18      1.874     0.2760
           538.18      1.861     0.2833
           577.18      1.848     0.2904
           616.18      1.836     0.2974
           655.18      1.824     0.3052 /
--         655.18      1.906     0.2612 /
--
  355.35   403.26      1.996     0.2389
           442.26      1.977     0.2459
           481.26      1.960     0.2527
           520.26      1.945     0.2595
           559.26      1.930     0.2661
           598.26      1.917     0.2727
           637.26      1.904     0.2791 /
--
  384.39   423.86      2.067     0.2264
           462.86      2.048     0.2329
           501.86      2.030     0.2392
           540.86      2.014     0.2454
           579.86      1.999     0.2516
           618.86      1.985     0.2576
           657.86      1.972     0.2636 /
--
  650.00   600.00      2.785     0.1645
           850.00      2.694     0.1985 /
--
 1310.00  1000.00      4.600     0.1220
          1250.00      4.550     0.1540 /
/

--*******************************************************
--*  PVT WATER
--*******************************************************
```

```
PVTW
   344.83   1.0292   4.002E-05   0.36000    0.00E+00 /

--P(DATUM)        CR
ROCK
      383.0    4.12E-05 /
      383.0    4.12E-05 /

DENSITY
      842.3   1001.1  0.942 /

REGIONS    =======================

COPY
      FLUXNUM     FIPNUM   /
      FLUXNUM     SATNUM   /
      FLUXNUM     EQLNUM   /
/

RPTREGS
      FIPNUM      ROCKNUM     SATNUM   /

SOLUTION    =============================

--   DATUM  DATUM   OWC    OWC    GOC    GOC   RSVD   RVVD   SOLN
--   DEPTH  PRESS  DEPTH   PCOW  DEPTH   PCOG  TABLE  TABLE  METH

EQUIL
      2538        350   2511   0.0   1*    0.0      1      1       20 /
      2538        350   2611   0.0   1*    0.0      2      2       20 /

RVVD
      2000   0.0
      4000   0.0  /
      2000   0.0
      4000   0.0  /

RSVD
      1500 184.0
      4000 184.0  /
      1500 184.0
      4000 184.0  /


SUMMARY      ============================

INCLUDE
      SUMMARY_MASTER.INC  /

FORMR RORMR
FORMW RORMW
FORMG RORMG
FORME RORME
FORMS RORMS
FORMF RORMF
FORMX RORMX
FORMY RORMY
FORFR RORFR
FORFW RORFW
FORFG RORFG
FORFE RORFE
```

```
FORFS RORFS
FORFF RORFF
FORFX RORFX
FORFY RORFY
/

SCHEDULE     ============================

RPTRST
      BASIC=3
      FREQ=4   /

RPTSCHED
      RESTART=1
      FIP=2 /

WELSPECS
 'PROD'  'G'   1   1   1*  'LIQ'  /
  /

COMPDAT
  'PROD'  1  1  51  60  'OPEN'  2*  0.25  /
  /


WCONPROD
  'PROD'  'OPEN'  LRAT  3*    350   /
  /
TSTEP
      12*36.5 /

WCONPROD
  'PROD'  'OPEN'  LRAT  3*    330   /
  /
TSTEP
      12*36.5 /

WCONPROD
  'PROD'  'OPEN'  LRAT  3*    256   /
  /
TSTEP
      12*36.5 /

WCONPROD
  'PROD'  'OPEN'  LRAT  3*    205   /
  /
TSTEP
      12*36.5 /

WCONPROD
  'PROD'  'OPEN'  LRAT  3*    164   /
  /
TSTEP
      12*36.5 /

WCONPROD
  'PROD'  'OPEN'  LRAT  3*    131   /
  /
TSTEP
      12*36.5 /
```

```
WCONPROD
  'PROD'  'OPEN'  LRAT  3*    105   /
  /
TSTEP
      12*36.5 /

WCONPROD
  'PROD'  'OPEN'  LRAT  3*    84    /
  /
TSTEP
      12*36.5 /

WCONPROD
  'PROD'  'OPEN'  LRAT  3*    67    /
  /
TSTEP
      12*36.5 /

WCONPROD
  'PROD'  'OPEN'  LRAT  3*    54    /
  /
TSTEP
      12*36.5 /

WCONPROD
  'PROD'  'OPEN'  LRAT  3*    43    /
  /
TSTEP
      12*36.5 /

RPTPRINT
      1 2 1 1 0 0 0 1 0 0 1 1 /
END
```

APPENDIX B: CHANGING OF NP ZONE EFFECTIVE THICKNESS WITH DEPLETION TIME AND PEMEABILITY

Time (year)	k (nD)	h_{NP} (m)
6	1	5
6	5	9
6	10	16
6	20	19
6	50	27
6	75	29
6	100	32
12	1	5
12	5	16
12	10	20
12	20	28
12	50	36
12	75	38
12	100	40
18	1	5
18	5	17
18	10	24
18	20	28
18	50	38
18	75	45
18	100	47
24	1	8
24	5	18
24	10	27
24	20	33
24	50	41
24	75	47
24	100	57

APPENDIX C: ROCKTAB KEYWORD – SIMULATION CODE

```
ROCKTAB
--Pressure  PV multiplier     Transmissibility multiplier

50    0.91836     1.0
80    0.94470     1.0
110   0.95963     1.0
140   0.96947     1.0
170   0.97571     1.0
200   0.98083     1.0
230   0.98488     1.0
260   0.98848     1.0
290   0.99163     1.0
320   0.99452     1.0
350   0.99727     1.0
380   1.00000     1.0  /

50    0.97150     1.0
80    0.97431     1.0
110   0.97705     1.0
140   0.97973     1.0
170   0.98234     1.0
200   0.98490     1.0
230   0.98742     1.0
260   0.98994     1.0
290   0.99245     1.0
320   0.99497     1.0
350   0.99748     1.0
380   1.00000     1.0  /

ROCKTABW
--Increased Sw    PV multiplier     Transmissibility multiplier
      0.0   1.0   1.0
      0.3   1.0   1.0
      0.4   1.0   1.0
      1.0   1.0   1.0 /

      0.0   1.0   1.0
      0.3   1.0   1.0
      0.4   1.0   1.0
      1.0   1.0   1.0 /
```

APPENDIX D: PROPERTIES OF WATER 100% SATURATED WITH GAS

Salinity	ppm	22000
Pres	bar	380
Temp	C	90
$R_{sw}/ R_{sw, salt}$		0,92
Gas Gravity		0,65

Pressure	R_{sw} (Fresh water)	R_{sw} (Water with salt)
Bara	Sm^3/Sm^3	Sm^3/Sm^3
689,655	5,343	4,915
551,724	4,898	4,506
413,793	4,096	3,768
344,828	3,651	3,359
275,862	3,206	2,949
206,897	2,671	2,458
137,931	2,048	1,884
68,966	1,247	1,147
34,483	0,819	0,754

Presure	B_w	B_w	B_w	C_w	C_w
Bara	Sat. incl. Salt	Under. Sat no salt	Sat no salt	Saturated	Under sat
413,79	1,0274	1,0180	1,0282	2,68E-05	4,27308E-05
344,83	1,0293	1,0210	1,03	2,28E-05	4,26053E-05
275,86	1,0309	1,0240	1,0315	2,28E-05	4,24805E-05
206,90	1,0325	1,0270	1,033	2,28E-05	4,23564E-05
137,93	1,0341	1,0300	1,0345	2,31E-05	4,64563E-05
68,97	1,0358	1,0333	1,036	1,70E-05	5,1921E-05

APPENDIX E: PROPERTIES OF WATER 70% SATURATED WITH GAS

Salinity	ppm	22000
Pres	bar	380
Temp	C	90
R_{sw}/ $R_{sw,\ salt}$		0,92
Gas Gravity		0,65
Saturation Pressure	bar	212,7

Pressure	R_{ws}	Maximum $R_{ws,salt}$	$R_{ws,actual}$
bar	Sm^3/Sm^3	Sm^3/Sm^3	Sm^3/Sm^3
689,7	5,3	4,92	2,50
551,7	4,9	4,51	2,50
413,8	4,1	3,77	2,50
344,8	3,7	3,36	2,50
275,9	3,2	2,95	2,50
206,9	2,7	2,46	2,46
137,9	2,0	1,88	1,88
69,0	1,2	1,15	1,15
34,5	0,8	0,75	0,75
1	0	0	0,00

Presure	B_w	B_w	Degree of Sat.	C_w
Bara	Saturated incl. salt	Fresh	Both un. sat and sat	Saturated
413,793	1,027	1,018	1,00	2,68E-05
344,828	1,029	1,021	1,00	2,28E-05
275,862	1,031	1,024	1,00	2,28E-05
206,897	1,033	1,027	0,92	2,28E-05
137,931	1,034	1,030	0,92	2,31E-05
68,966	1,036	1,033	0,92	1,73E-05

APPENDIX F: LIQUID RATES FOR DIFFERENT SCENARIOS OF DEPLETION TIME AND PRESSURE DROP

250bar Pressure drop							
6 years		**12 years**		**18 years**		**24 years**	
Step	Liquid rate (m^3/d)	Step	Liquid rate (m^3/d)	Step	Liquid rate (m^3/d)	Step	Liquid rate (m^3/d)
1	580	1	380	1	350	1	330
2	464	2	360	2	330	2	315
3	371	3	288	3	256	3	252
4	297	4	230	4	205	4	202
5	238	5	184	5	164	5	161
		6	147	6	131	6	129
		7	118	7	105	7	103
		8	94	8	84	8	83
		9	75	9	67	9	66
		10	60	10	54	10	53
				11	43	11	42

200bar Pressure drop							
6 years		**12 years**		**18 years**		**24 years**	
Step	Liquid rate (m^3/d)	Step	Liquid rate (m^3/d)	Step	Liquid rate (m^3/d)	Step	Liquid rate (m^3/d)
1	500	1	340	1	310	1	300
2	400	2	310	2	290	2	280
3	320	3	248	3	232	3	224
4	256	4	198	4	186	4	179
5	205	5	159	5	148	5	143
		6	127	6	119	6	115
		7	102	7	95	7	92
		8	81	8	76	8	73
		9	65	9	61	9	59

		10	52	10	49	10	47
				11	39	11	38
				12	31	12	30
				13	25	13	24
				14	20	14	19
				15	16	15	15
						16	12
						17	10
						18	8
						19	6
						20	5

150bar Pressure drop							
6 years		**12 years**		**18 years**		**24 years**	
Step	Liquid rate (m^3/d)	Step	Liquid rate (m^3/d)	Step	Liquid rate (m^3/d)	Step	Liquid rate (m^3/d)
1	390	1	260	1	240	1	230
2	312	2	240	2	220	2	210
3	250	3	192	3	176	3	168
4	200	4	154	4	141	4	134
5	160	5	123	5	113	5	108
		6	98	6	90	6	86
		7	79	7	72	7	69
		8	63	8	58	8	55
		9	50	9	46	9	44
		10	40	10	37	10	35
				11	30	11	28
				12	24	12	23
				13	19	13	18
				14	15	14	14
				15	12	15	12

						16	9
						17	7
						18	6
						19	5
						20	4

100bar Pressure drop							
6 years		**12 years**		**18 years**		**24 years**	
Step	Liquid rate (m^3/d)	Step	Liquid rate (m^3/d)	Step	Liquid rate (m^3/d)	Step	Liquid rate (m^3/d)
1	190	1	150	1	130	1	140
2	170	2	130	2	115	2	120
3	136	3	104	3	100	3	96
4	109	4	83	4	80	4	77
5	87	5	67	5	64	5	61
		6	53	6	51	6	49
		7	43	7	41	7	39
		8	34	8	33	8	31
		9	27	9	26	9	25
		10	22	10	21	10	20
				11	17	11	16
				12	13	12	13
				13	11	13	10
				14	9	14	8
				15	7	15	7
						16	5
						17	4
						18	3
						19	3
						20	2

Dissolved gas - 250bar Pressure drop	
12 years	
Step	Liquid rate (m^3/d)
1	410
2	380
3	304
4	243
5	195
6	156
7	125
8	100
9	80
10	64