Evaluation of the Pore Volume Multiplier Method to Quantify Field Production Uncertainty

By

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in collaboration with Statoil ASA:

A report submitted in partial fulfilment of the requirements for the MSc and/or the DIC.

September 2013
DECLARATION OF OWN WORK

I declare that this thesis *Evaluation of the pore volume multiplier method to quantify field production uncertainty* is entirely my own work and that where any material could be construed as the work of others, it is fully cited and referenced, and/or with appropriate acknowledgement given.

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ABSTRACT

Incorporating structural uncertainty into the dynamic uncertainty phase was, only a decade ago, a very difficult and time consuming task. The difficulty was with automatically gridding new reservoir models, parameterising subsurface structures and ensuring that the reservoir simulates production in reasonable time. However recent software development has made it easier to update models according to uncertainty in the horizons, and it is becoming more and more common. Nevertheless dynamic uncertainty analysis, to incorporate structural uncertainty, is often performed with a simplified approach using pore volume multipliers (PVM). It is therefore useful to see what difference there is between the rigorous method and simplified approach.

This paper compares the two approaches for the simple case of an oil field with one gas injector in the top layer, to simulate a gas drive, and one producer 9m above the oil water contact (with approximately 30m of oil column). The finding is that an increased thickness causes a greater recovery as gas stays at the top of the reservoir and pushes oil down, providing more of a gas drive and therefore higher production. This effect is not observed for the case of using a PVM because the thickness remains constant. The recommendation is therefore not to use the PVM method to quantify field production uncertainty in cases where the recovery is dependent on reservoir thickness, such as when gravitational effects are significant, as the PVM method does not account for this.
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# TABLE OF CONTENTS

**ABSTRACT** ........................................................................................................................................... ii

**ACKNOWLEDGEMENTS** ......................................................................................................................... iii

**TABLE OF CONTENTS** ............................................................................................................................... iv

**LIST OF FIGURES** .................................................................................................................................... v

**LIST OF TABLES** ...................................................................................................................................... v

**LIST OF FIGURES IN APPENDICES** ......................................................................................................... vi

**LIST OF TABLES IN APPENDICES** ........................................................................................................... vi

**Abstract** ................................................................................................................................................... 1

**Introduction** ............................................................................................................................................. 1

**Description of the base model** .................................................................................................................. 2

**Methodology used to assess the pore volume multiplier method** ............................................................ 3

  1) Building several models to represent structural uncertainty to quantify field production .................. 3
  2) Using the base model with pore volume multiplier to quantify production uncertainty .................. 4

**Simulation results – comparing the methods of quantifying field production uncertainty** ..................... 4

  **Analysis of gas production** ...................................................................................................................... 5
  **Analysis of gas propagation** .................................................................................................................. 5
  **Results for different horizon movements** ............................................................................................. 6
  **Localising horizon movement** .............................................................................................................. 8
  **Modication of the PVM method to improve the results** .......................................................................... 9

**Other sensitivities** ................................................................................................................................... 12

**Discussion** .............................................................................................................................................. 12

**Conclusions** ......................................................................................................................................... 12

**Acknowledgements** ............................................................................................................................... 13

**Nomenclature** ....................................................................................................................................... 13

**Acronyms** .............................................................................................................................................. 13

**Conversion Factors & Units** .................................................................................................................... 13

**References** ............................................................................................................................................ 13

**Appendix** ............................................................................................................................................. 15

**APPENDIX A1: CRITICAL LITERATURE REVIEWS** .............................................................................. 15

**APPENDIX A2: MILESTONES IN PORE VOLUME MULTIPLIER STUDY** .................................................. 22

**APPENDIX B: RESERVOIR DESCRIPTION** .............................................................................................. 23

**APPENDIX C: OIL RATE AND WATER CUT PLOTS** ................................................................................ 24

**APPENDIX D: FIELD OIL PRODUCTION PROFILE FOR PORE VOLUME MULTIPLIER HEIGHT SENSITIVITY** 25

**APPENDIX E: POLYGON HORIZON MOVEMENT – TABLE VALUES OF PRODUCTION AFTER 60 YEARS** .... 26

**APPENDIX F1: OIL RATE SENSITIVITY** .................................................................................................. 27

**APPENDIX F2: POLYGON SENSITIVITY WHERE PVM HAS BEEN APPLIED IN HIGHER LOCATION** ........ 28
LIST OF FIGURES

Figure 1. A schematic of the base model showing the oil producer and gas injector location in 3 different views: a) top map, b) 3D view of the initial water saturation and, c) cross section view taken through the oil producer and gas injector..........................................................2

Figure 2. An example of the horizon movement operation to represent structural uncertainty, shown for movement of horizon i) 10m up, and ii) 10m down. The lower limit of the stretch operation is shown as a blue line. ........................................3

Figure 3. A comparison of the field production, for 60 years of simulation, of the pore volume multiplier method (dotted lines) vs. the ‘correct’ horizon movement method (solid red and blue line) for the case of a structural 10m movement of the top horizon up and down.................................................................4

Figure 4. Well gas-oil-ratio plot for the case of a 10m up movement of the horizon (10m up ) and for the case where a pore volume multiplier has been used to represent the horizon 10m up movement (10m up PVM) in order to compare the two different methods of quantifying field production uncertainty due to structural uncertainty. ........5

Figure 5. Gas saturation plot of a cross section through the producer for the case of a top horizon movement 10m up (left) and for the case where a pore volume multiplier has been used to reproduce the same stock tank oil originally in place (right). The snapshot is for the simulation year 11 of 60. ........................................................................................................6

Figure 6. Map view of layer 5, half way between the top surface and the well, to map gas saturation in order to compare the two different methods of field production uncertainty due to horizon uncertainty. The top left shows the spread of gas for the case where the horizon is moved up 10m in year 10, and top right an equivalent snapshot but using the pore volume method. The bottom two show the two different methods for the spread of gas for year 17 of simulation. .................................................................5

Figure 7. Plot of total field production after 60 years of simulation for moving horizons vs. using pore volume multiplier method for the different horizon movement cases. The pore volume multiplier was applied to the entire grid, as shown in the bottom image. ........................................................................................................7

Figure 8. Shows: a) map view of area of localised horizon adjustment and b) cross sectional view of where pore volume multiplier has been applied to the base model (applied to volume below polygon surface). .........................8

Figure 9. Comparing the field production of the pore volume multiplier method vs. the ‘correct’ horizon movement method for a localised horizon movement. The comparison is made for moving the localised polygon 10m up (red lines) and 10m down (blue lines) for the two different methods. .................................................................8

Figure 10. Plot of total field production after 60 years for localised movement of horizon vs. equivalent pore volume multiplier applied on base model for 2m, 4m, 6m, 8m and 10m; up and down horizon movements. .................9

Figure 11. Total field production after 60 years of simulation for moving horizons vs. using pore volume multiplier method for different horizon movement cases, where the pore volume multiplier has been applied to the whole grid (shown on bottom left) and just above the oil water contact (1760m – shown on bottom right). ..............................................10

Figure 12. Total field production after 60 years of simulation for moving horizons vs. pore volume multiplier method for the different horizon movement cases, where the pore volume multiplier has been applied above the well (1749m – Shown on the image directly below the graph), above 1740m (bottom left) and above 1735m (bottom right). ..............................................11
LIST OF TABLES

Table 1. Total field production values after 60 years of simulation for the two different methods of quantifying the impact of structural uncertainty on field production; horizon movement and pore volume multiplier. The percentage difference between the methods for the different horizon movement cases is also shown.

LIST OF FIGURES IN APPENDICES

Figure A 1. A plot of total field production oil rate for i) the base model, ii) the movement in horizon 10m up and also with the equivalent pore volume multiplier applied (10m up PVM), and iii) the model with the movement of horizon 10m down and with the equivalent pore volume multiplier applied (10m down PVM).

Figure A 2. Producer water production rate plot for the different cases: i) base model, ii) 10m up and 10m up pore volume multiplier, and iii) 10m down and 10m down pore volume multiplier.

Figure A 3. Plot of total field oil production for different locations where the pore volume multiplier has been applied: i) on the whole grid, and ii) in the volume above 1740m. This shows that applying the pore volume multiplier closer to where the change has been made on the grid gives a closer approximation to the 'correct' case.

Figure A 4. Plot of total field production for cases i) base model, ii) 10m up and equivalent 10m up pore volume multiplier, and iii) 10m down and equivalent 10m down PVM. This is shown for two different rates: a) 3000 Sm3/Day and b) 1000 Sm3/Day. This shows the result that the pore volume multiplier method gives a smaller recovery range, than the 'correct' method of adjusting horizons, is still true for different rates.

Figure A 5. Total field production after 60 years of simulation, for moving a polygon area of the top horizon vs. using pore volume multiplier method for different horizon movement cases, where the pore volume multiplier has been applied to the entire volume under the polygon area (shown as 'WholeGrid' on graph) and also applied to the volume only above 1735m under the polygon area (shown as 'Above 1735m' on the graph).

LIST OF TABLES IN APPENDICES

Table A 1. Total field production values after 60 years of simulation, for a polygon movement in the horizon, for the two different methods of quantifying the impact of structural uncertainty on field production; horizon movement and pore volume multiplier. The percentage difference between the methods for the different horizon movement cases is also shown.
Evaluation of the Pore Volume Multiplier Method to Quantify Field Production Uncertainty

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Abstract
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This paper compares the two approaches for the simple case of an oil field with one gas injector in the top layer, to simulate a gas drive, and one producer 9m above the oil water contact (with approximately 30m of oil column). The finding is that an increased thickness causes a greater recovery as gas stays at the top of the reservoir and pushes oil down, providing more of a gas drive and therefore higher production. This effect is not observed for the case of using a PVM because the thickness remains constant. The recommendation is therefore not to use the PVM method to quantify field production uncertainty in cases where the recovery is dependent on reservoir thickness, such as when gravitational effects are significant, as the PVM method does not account for this.

Introduction
In the quantification of field production for a field development project, uncertainty analysis is a key component to enable more robust decisions. These uncertainties can be categorised into two stages. The first stage is the static uncertainty phase where an initial estimate of the inplace volumes is obtained. Uncertainty parameters included in this phase generally consist of:

i) Geophysics - seismic time interpretation and time-to-depth conversion, described in Samson et al. (1996).
ii) Petrophysics – evaluation of well log measurements and interpretation, in addition to mapping petrophysical properties between wells (net-to-gross, porosity, saturation and sometimes permeability) etc.
iii) Geology – hydrocarbon column (including contacts), facies fraction, sedimentology etc.
iv) Fluid properties – oil formation volume factor, gas formation volume factor, gas oil ratio etc.

Each uncertainty parameter is assigned an uncertainty distribution range, and subsequently, usually through Monte Carlo methods (Stoian 1965), a range for the in place volumes is obtained.

Subsequent to the static uncertainty phase, a list of all factors affecting the dynamic flow characteristics and recovery is listed to be taken through to the second uncertainty stage – dynamic uncertainty quantification. The parameters in this stage are in two categories:

i) Reservoir factors - horizontal and vertical barriers to fluid flow, size of aquifer, relative permeability, all parameters contributing to in-place volumes uncertainties i.e. gross-rock-volume, contacts, net-to-gross, porosity, saturation, expansion factors, etc.
ii) Operational factors – well placement, well performance, process design, well capacity change, cost etc.
The most important of these factors are subsequently fed through to repeat a Monte Carlo simulation which quantifies the dynamic field production uncertainty.

In this process of quantifying field production uncertainty for a field development project, uncertainty in the seismic horizons is very often a key uncertainty in determining in place volumes. These uncertainties in the geophysical domain are caused by data acquisition, processing and interpretation. The main factors that contribute to this uncertainty are twofold; i) uncertainty in horizon picking and ii) uncertainty in time-to-depth conversion. Following processing, given that the structural uncertainty is important in determining fluid flow characteristics and recovery, best practice would involve taking through several stochastic realisations of the horizons and running dynamic simulations. However, this whole process is very time consuming, as it requires the building of several models, gridding the models, parameterising subsurface structures, and running simulations; but it is becoming more and more common with recent software developments. This process may be required to quantify field production uncertainty due to structural variation accurately - as shown by Vincent et al. (1999). Their work showed that having different horizon realisations for models with the same Stock Tank Oil Initially In Place (STOIIP) can produce significantly different field production values. Several other authors have recognised the influence of horizon uncertainty on field production values. The first work seems to have been published by Palatnik et al. (1994) where history matching was attempted through changing the grid geometry (using the grid corner points as a matching parameter). In
Evaluation of the Pore Volume Multiplier Method to Quantify Field Production Uncertainty

A more recent study Rivanæs et al. (2005) provides a technique to plan a well accounting for the horizon uncertainty by simulating several realisations but with the use of an elastic stretching grid operation. A similar method proposed by Rivanæs et al. (2005) is used in Seiler et al. (2009) and Irving and Robert (2010). In another study Schaaf et al. (2009) presents a workflow involving rebuilding the geomodel to achieve a history match. Finally, in a very recent study Ahmadi et al. (2013) makes use of the immersed interface method to account for structural uncertainty in order to history match for a 2D reservoir model.

In other studies where horizon variation has not been the focus of the study, a low, mean and high ‘structural’ parameter is varied where 3 models are constructed representing these cases. For example Costa and Schiozer (2005) discuss simplifying risk analysis procedures used in the industry and Ligero et al. (2007) compares risk methodologies used in the industry; both make use of constructing these 3 models to represent structural uncertainty. This method of representing horizon uncertainty may not capture the full range of stochastic uncertainty in the horizon, as flow characteristics may vary depending on the realisation.

In the industry, there is therefore a good understanding that building several models is the most accurate way to represent horizon uncertainty. However, in a fast-paced industry where companies are often faced with fast approaching deadlines and time constraints, this could be impractical. So there are two other common approaches by which industry projects account for this structural variation. The first method involves introducing a variation in the oil water contact to produce the same effect as having a horizon variation. The second involves using a pore volume multiplier (PVM) to account for the difference in STOIIP. It is the second method that is the focus of this study. An example of the use of the PVM in a gas reservoir is shown in Rivera et al. (2007) and an example of its use for a history match is presented in Maschio et al. (2009). Furthermore, it is apparent in an earlier study, Steagall et al. (2001) who proposed the decision tree method of quantifying production uncertainty, that the PVM method was an acceptable form of representing horizon uncertainty. The study made use of the PVM as an approximation to represent structural uncertainty in order to quantify field production uncertainty using the proposed decision tree method.

The PVM method of quantifying field production uncertainty does indeed account for the variation in STOIIP owing to structural uncertainty. However, what is geologically uncertain is that the reservoir is thinner or thicker in some locations, and the PVM method does not account for this.

The extent to which this has a significant impact on the recovery range of a reservoir will clearly depend on the recovery process. The objective of this study is to give a methodology of how to address this issue. A specific case of a real oil field has been chosen; where a sector model was populated with geological properties and gas drive implemented as the recovery mechanism.

Description of the base model

The following section describes the field and base model used for the study.

![Figure 1. A schematic of the base model showing the oil producer and gas injector location in 3 different views: a) top map, b) 3D view of the initial water saturation and, c) cross section view taken through the oil producer and gas injector.](image-url)
The field used in this study is a heavy oil field with an oil viscosity of 10 cP. There is a relatively small amount of water in the system and so the water drive is not significant; nevertheless there is a constant oil water contact at a depth of 1760m. The main drive mechanism of the field is a gas drive, with gas injectors being used to create a gas cap and consequently supply pressure support. Seismic data quality was considered to be good over most of the area and the uncertainty of the seismic interpretation was considered to be low. This translates to a standard deviation of approximately 10m in the top horizon.

This study revolves around a geological description of a sector of this real field, which will hereafter be known as the base model. Within the base model, there are two horizontal wells; one oil producer 9 m above the oil water contact at a depth of 1751m, and one gas injector in the top layer. The gas injector has been placed in the top layer to simulate the field gas gravity drainage. A schematic of the base model and where the injector and producer are located is shown in Figure 1.

The base model has been homogenised in order to explain physical processes without the additional complication of heterogeneous properties. The permeability in all directions and all grid cells is 7000 mD and the porosity in all grid cells is 0.33. The value of STOIIP is 39.2 million Sm$^3$ (additional information on reservoir and well controls in Appendix B).

**Methodology used to assess the pore volume multiplier method**

There are two methods presented in this study which can be used to represent structural uncertainty in order to quantify field production uncertainty. The first method involves creating a series of entirely new models with a top horizon with varying depths. For this study, only the top horizon was varied. The operation effectively shifts the entire horizon up or down. Another representation of the horizon uncertainty could use a stochastic approach conditioned to available well data. However, for an understanding of the concept the method presented here clearly identifies the uncertainty. The second method presented here makes use of a pore volume multiplier which multiplies all the pore volumes in the base model by a constant factor. This is the quick way the industry may use. The two methods as applied to this study are described below.

![Figure 2. An example of the horizon movement operation to represent structural uncertainty, shown for movement of horizon i) 10m up, and ii) 10m down. The lower limit of the stretch operation is shown as a blue line.](image)

**1) Building several models to represent structural uncertainty to quantify field production**

In order to build several models, an elastic horizon movement operation was performed. This takes the top horizon and a layer above the well, using these as the reference. It then stretches all layers between these two reference surfaces, with all layers below the well remaining unchanged. An example for moving the horizon 10m up and 10m down is shown in Figure 2. The operation effectively increases/decreases the STOIIP by a fraction and is performed in this way to avoid redefining the well paths according to the grid.

Constructing several of these models with varying depths, and simulating production for 60 years for each of the models will quantify the structural impact on the field production uncertainty. The process of building these models was repeated for...
both moving the horizon up and down for cases: 2m, 4m, 6m, 8m and 10m. These were chosen as the standard deviation in the uncertainty of the top horizon for the field is approximately 10m. This provides a total of 11 models, including the base model, to quantify production uncertainty and investigating the first method.

2) Using the base model with pore volume multiplier to quantify production uncertainty

Building several models to quantify production uncertainty as described can be laborious and time consuming, so the industry may use a pore volume multiplier to reproduce the same effect. Therefore in order to make a realistic comparison, a pore volume multiplier of varying values was applied to the base model to match the hydrocarbon volumes of each of the models built with horizons moved.

Moving the horizon 10m up can be taken as an example. The STOIIP in this case is 51 million Sm$^3$ which is an increase of 30% as compared to the base model of 39.2 million Sm$^3$. A comparison of this same 10m up case with the PVM method involves taking the base model and multiplying the pore volumes by that same fractional increase. In this case pore volumes would be multiplied by 1.3 in all grid cells. This includes the water zone, but is acceptable as the water drive is not significant.

It is very important that the initial STOIIP values remain the same for the two different methods for a realistic comparison.

In this way, the base model was simulated for 60 years of production, but each time with a PVM of a different value which matches the STOIIP of the same cases as before: up and down for 2m, 4m, 6m, 8m and 10m. This totals 11 simulations using the PVM method, without a change in model structure, to quantify production uncertainty and investigate the second method.

Simulation results – comparing the methods of quantifying field production uncertainty

The aim is to compare the PVM method with the ‘correct’ method of moving horizons to quantify the impact of structural uncertainty on field production uncertainty. To this effect, a comparison of the field production using the two different methods is shown in Figure 3 for an example where the top horizon is moved up/down by 10m (oil rate plot and water cut plot in Appendix C). An important note is that the ‘10m up’ (red line) and ‘10m up PVM’ (dotted red line) have the same initial STOIIP, and similarly the ‘10m down’ (blue line) and ‘10m down PVM’ (dotted blue line) also have the same initial STOIIP. The only difference is the methods used to achieve the increase/decrease in STOIIP.

Figure 3 shows that the base model (green line) has a total field production of 8.2 million Sm$^3$ at end of simulation. If it is assumed that the uncertainty range is produced via the PVM method, the range obtained is +2.4 million Sm$^3$ and -2.5 million Sm$^3$. However with the use of the correct method of quantifying total field production, this range is +6.5 million Sm$^3$ and -4.4 million Sm$^3$. The PVM method of quantifying uncertainty is therefore giving the minimum range for field production uncertainty in this example.

This is a significant and unacceptable difference in uncertainty range between the two methods; and using the PVM method to quantify the impact of structural uncertainty on field production uncertainty leads to an inaccurate estimation. This difference can be explained if the 10m up case is taken as an example. Moving the horizon 10m up effectively increases the thickness of the reservoir, whereas, with the use of the PVM method, the thickness of the reservoir remains the same as the base model. This increased thickness causes a greater recovery, for the 10m up case, because gas stays at the top of the reservoir and pushes oil down, providing more of a gas drive and therefore higher production. This effect is not observed for the case of using a PVM because the thickness remains constant.

![Figure 3. Comparison of the field production, for 60 years of simulation, of the pore volume multiplier method (dotted lines) vs. the 'correct' horizon movement method (solid red and blue line) for the case of a structural 10m movement of the top horizon up and down.](image)
Analysis of gas production

The difference between the two methods of quantifying field production uncertainty due to structural uncertainty is caused by gas segregation effects; therefore an analysis of the gas production is presented. As there is only one gas injector and one producer in the model, a plot of well gas-oil ratio (WGOR) is shown in Figure 4 to confirm the analysis. There is a lower GOR for the 10m up case, as compared to the case where a PVM is applied to the base model, as gas stays at the top of the reservoir.

![Figure 4. Well gas-oil-ratio plot for the case of a 10m up movement of the horizon (10m up ) and for the case where a pore volume multiplier has been used to represent the horizon 10m up movement (10m up PVM) in order to compare the two different methods of quantifying field production uncertainty due to structural uncertainty.](image)

Analysis of gas propagation

A visual representation of where the gas is moving for the two different methods shows that gas indeed does stay up for the 10m up case and therefore provides a higher gas drive than the case where a PVM is applied to the base model. A cross section through the producer, for simulation year 11 of 60, is shown in Figure 5. A red oval shows that there is higher gas saturation in the upper layers.

A map view of layer 5, which is half way between the top surface and the well, is shown in Figure 6. The observation is that there is a wider spread of gas in this layer for the case where the top horizon is moved up 10m as oppose to where a PVM has been applied to the base model. The implication is that gas is staying up to provide a stronger driving force, leading to higher production for the 10m up case. However, as the 10m up model has been stretched, the same layer in the ‘10m up’ model has a higher vertical depth than the ‘10m up PVM’ case. Nevertheless, Figure 5 clearly shows gas staying near the top of the field.

![Figure 5. Gas saturation plot of a cross section through the producer for the case of a top horizon movement 10m up (left) and for the case where a pore volume multiplier has been used to reproduce the same stock tank oil originally in place (right). The snapshot is for the simulation year 11 of 60.](image)
Evaluation of the Pore Volume Multiplier Method to Quantify Field Production Uncertainty

Results for different horizon movements

The analysis for comparing the two methods of quantifying field production uncertainty due to structural uncertainty has thus far concentrated on the case where the top horizon has been moved 10m up or down. However, the uncertainty for a horizon can have a range of values depending on the quality and quantity of the seismic data. A plot has therefore been made, in Figure 7, of the total field production after 60 years of simulation for each top horizon movement case vs. PVM case. This was done for each of the different cases for 2m, 4m, 6m, 8m and 10m for both the up and down movement of the top horizon. The vertical distance from the points to the straight line shows the deviation from the ‘correct’ production value. The percentage difference in production values for the different cases and the two different methods, along with the field production values is given in Table 1. The table shows that if the uncertainty in the top horizon is 10m, the field production uncertainty values obtained will be inaccurate by up to 50%.

Therefore Figure 7 and Table 1 shows that regardless of the uncertainty range in the reservoir, the PVM method never approximates the field production to the ‘correct value’. This indicates that if the recovery process is sensitive to reservoir thickness, as in the case of a gas drive, then the PVM method of quantifying field production uncertainty is inaccurate and should not be used.
Figure 7. Plot of total field production after 60 years of simulation for moving horizons vs. using pore volume multiplier method for the different horizon movement cases. The pore volume multiplier was applied to the entire grid, as shown in the bottom image.

Table 1. Total field production values after 60 years of simulation for the two different methods of quantifying the impact of structural uncertainty on field production: i) horizon movement and ii) pore volume multiplier. The percentage difference between the methods for the different horizon movement cases is also shown.

<table>
<thead>
<tr>
<th>Horizon movement (M Sm$^3$)</th>
<th>Pore volume multiplier method (M Sm$^3$)</th>
<th>Percentage difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10m down</td>
<td>3.8</td>
<td>5.7</td>
</tr>
<tr>
<td>8m down</td>
<td>4.4</td>
<td>6.2</td>
</tr>
<tr>
<td>6m down</td>
<td>5.3</td>
<td>6.7</td>
</tr>
<tr>
<td>4m down</td>
<td>6.1</td>
<td>7.1</td>
</tr>
<tr>
<td>2m down</td>
<td>7.0</td>
<td>7.8</td>
</tr>
<tr>
<td>base</td>
<td>8.2</td>
<td>8.2</td>
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<tr>
<td>2m up</td>
<td>9.4</td>
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<td>6m up</td>
<td>12.0</td>
<td>9.7</td>
</tr>
<tr>
<td>8m up</td>
<td>13.4</td>
<td>10.2</td>
</tr>
<tr>
<td>10m up</td>
<td>14.7</td>
<td>10.6</td>
</tr>
</tbody>
</table>
Localising horizon movement

To further compare the two different methods of quantifying the impact of structural uncertainty on field production uncertainty, a localised horizon movement was completed. There are several reasons for localising the horizon movement:

i) For the case of drilling a new well, localised changes in horizon are often required, in order to match newly acquired data.

ii) Horizon movement operations are often performed for history matching purposes.

iii) Confirmation of previous analysis. If the analysis that a thicker reservoir has a higher production because of gas staying up and driving the oil down is correct, then a localised adjustment in the horizon only above the producer should produce a similar trend.

The polygon area where this localised adjustment was made is shown in Figure 8 a) as a top map view. The PVM was applied only to the volume below the polygon area. A cross section where the PVM was applied to the base model to reproduce the same STOIIP values as the horizon movement is shown in Figure 8 b).

![Figure 8. Shows: a) map view of area of localised horizon adjustment and b) cross sectional view of where pore volume multiplier has been applied to the base model (applied to volume below polygon surface).](image)

The total field production result of moving the top horizon in only the polygon area 10m up and 10m down, together with the 10m up PVM and 10m down PVM case is shown in Figure 9. The same trend is observed as with the case where the entire top horizon is moved. However the difference in total field production between the methods here is not as much as before, and that is because there is only a smaller volume of space for gas to occupy near the top, as the reservoir has been made thicker only in a localised area. This analysis gives a strong indication that the reason for the difference in recovery between the two methods is due to reservoir thickness differences.

To further qualify the localised horizon movement analysis, the total field production after 60 years has been plotted for the localised horizon movement vs. the PVM method for cases 2m, 4m, 6m, 8m and 10m; up and down. This is shown in Figure 10 (exact values are shown in Appendix E). The difference between the total field production after 60 years for these methods can be up to 7%. The trend observed is exactly the same as with the movement of the entire horizon. Therefore the thickness of reservoir, especially above the producer, is having a significant impact on recovery.
Figure 9. Comparing the field production of the pore volume multiplier method vs. the ‘correct’ horizon movement method for a localised horizon movement. The comparison is made for moving the localised polygon 10m up (red lines) and 10m down (blue lines) for the two different methods.

In reality, good industry practice would involve building multiple models with stochastically varied horizons, to account for well picking uncertainty, and also conditioned to available well data. Therefore this polygon analysis is extremely useful, as it indicates that any variation of the top horizon is not properly represented with the use of the PVM method of quantifying production uncertainty. The recommendation is therefore not to use the PVM method to quantify production uncertainty for the case where the recovery process is a gas drive.

Figure 10. Plot of total field production after 60 years for localised movement of horizon vs. equivalent pore volume multiplier applied on base model for 2m, 4m, 6m, 8m and 10m; up and down horizon movements.

Modification of the PVM method to improve the results

Although the finding of this study is that the PVM does not properly account for the horizon variation uncertainty, it is nevertheless useful to determine if it has validity when applied to different locations in the reservoir model. A sensitivity study has therefore been completed to establish where best to apply the PVM.
The methodology involved repeating the same top horizon movement as before for cases of 2m, 4m, 6m, 8m and 10m; up and down. The STOIIP value will change accordingly for each of the cases, then a pore volume multiplier is applied to the base model to reproduce the same STOIIP value for each case. However, in this sensitivity, instead of applying the multiplier to the whole model, it was applied to 5 different locations. The total field oil production after 60 years comparison for the two methods is shown in Figure 11 for a PVM application to the whole grid, and then to the volume only above the oil water contact. Then in Figure 12 the comparison is made for a PVM application above the well location (1749m), 1740m and also 1735m. In addition to these plots, more information is given in Appendix D with the plot of field production through time for the cases where the PVM was applied to the whole grid and above 1740m.

Of these 5 cases, the best PVM application can be identified according to which cases most closely reproduce the ‘correct value’ of when the horizon is moved. This can be seen from the graphs as the points with the least vertical distance to the ‘correct value’ line. The general trend is that the vertical distance between the points and the line is reduced if the PVM is applied higher up.

This analysis suggests that the PVM should be applied closer to where the horizon modification should be made. However, caution should be exercised before proceeding, as this may only be valid for this specific case, and it is difficult to determine exactly where the PVM should be applied. With this in mind, the most sensible approach is not to use the PVM to quantify production uncertainty due to structural uncertainty for a gas drive production mechanism. Structural uncertainty should be accounted for directly, by building several models, as the recovery process in this case is sensitive to reservoir thickness and the PVM method fails to account for this.

Figure 11. Total field production after 60 years of simulation for moving horizons vs. using pore volume multiplier method for different horizon movement cases, where the pore volume multiplier has been applied to the whole grid (shown on bottom left) and just above the oil water contact (1760m – shown on bottom right).
Figure 12. Total field production after 60 years of simulation for moving horizons vs. pore volume multiplier method for the different horizon movement cases, where the pore volume multiplier has been applied above the well (1749m – Shown on the image directly below the graph), above 1740m (bottom left) and above 1735m (bottom right).
Other sensitivities

The following sensitivities were performed in order to obtain additional information:

1) Oil rate sensitivity shown in Appendix F1. The result shows that a lower target oil rate of 1000 Sm$^3$ still results in the same conclusion as using an oil rate of 3000 Sm$^3$ used in this study.

2) A sensitivity where the pore volume multiplier has been applied in a higher location for the polygon movement in horizon, shown in Appendix F2. The result from this is that it is difficult to determine exactly which volume location to apply the pore volume multiplier in order to reproduce the ‘correct’ method.

Discussion

The convenience of the pore volume multiplier method of quantifying production uncertainty, due to structural uncertainty, is that it is quick and easy to use. All that is required is to multiply the pore volumes of the base model by a multiplier factor greater than 1, and then also by a multiplier factor less than 1. Then subsequently include this as a parameter in the dynamic simulation. This method is effectively being used to represent structural uncertainty in top and bottom horizons, which is due to horizon picking and time to depth conversion. The more rigorous and best practice method of quantifying production uncertainty involves building several stochastic realisations of the base model conditioned to well data and running dynamic simulations (one way of doing this is shown in Ridha et al. (2012). Only a decade ago, this was very time intensive and impractical. However, due to recent software developments, this is becoming more and more common.

Nevertheless, in a fast-paced industry where project deadlines are often fast approaching, engineers will often use the PVM method to quantify production uncertainty. This was apparent in an earlier study where Steagall et al. (2001) proposed the decision tree method of quantifying production uncertainty with several uncertain parameters and makes use of the PVM method to represent structural uncertainty.

This paper compares the two different methods of quantifying production uncertainty. However practicing engineers should be very clear about whether the PVM method correctly reproduces the same production uncertainty values as the ‘correct method’ of building several models. A field may very well result in unexpectedly producing too much or too little oil in the future. However, this should not be because of poor reservoir management based on misleading models, which have not properly considered the structural uncertainty in a reservoir. Therefore it is of paramount importance that engineers understand the limitations of using the PVM method of quantifying the impact of structural uncertainty on field production uncertainty.

In this study, a geological description of a sector of a real oil field has been used. A gas injector has been placed in the top layer, and a producer 9m above the oil water contact (approximate 30m oil column). The comparison of the two methods of quantifying the impact of structural uncertainty on field production uncertainty was achieved through building several models with the top horizon of a base model moved up and down. The operation will increase/decrease the STOIIP by a fraction and represents the ‘correct method’ to quantify field production uncertainty. A pore volume multiplier is subsequently applied to the base model to achieve the same fractional increase/decrease in STOIIP. The important condition is that the STOIIP remains the same for each comparison made.

Based on this study, given that the recovery process is a gas drive where the recovery is dependent on reservoir thickness, using the PVM method to represent changes in structure can lead to misleading and inaccurate results. The reason for this is that the correct representation of the reservoir involves having thicker and thinner realisations. With these there will be a stronger/weaker gas drive depending on the thickness of the reservoir. This gravity effect is completely unaccounted for with the PVM method. The result is that the PVM method gives a much lower recovery production uncertainty range.

The base model considered here was selected so that controlled experimentation could be performed to prove the concept. The same concept is applicable to other problems. The recommendation of this study is therefore not to use the PVM method of quantifying the impact of structural uncertainty on field production uncertainty in the case where the recovery process is dependent on reservoir thickness, as the PVM method does not account for reservoir thickness. Structural uncertainty should be accounted for directly, where several models should be built.

Conclusions

If the recovery process is sensitive to the thickness of the reservoir, the pore volume multiplier method to quantify the impact of structural uncertainty on field production uncertainty is not accurate and should not be used.

For the example where gas gravity drainage is the recovery mechanism, the uncertainty range found using the PVM method gives a much lower range of recovery, as compared to building several models to make the reservoir thicker/thinner. The physical reason for the difference in recovery values is because of gravity effects where there is a stronger gravity drainage for a thicker reservoir, and the PVM method does not account for this. The recommendation of this study is therefore to deal with structural uncertainty directly and build several models to quantify field production uncertainty for cases where the recovery process is sensitive to reservoir thickness.
Acknowledgements
I would like to express my gratitude to my supervisor, Professor Martin Blunt for his support, encouragement and advice throughout the duration of the project.

I would also like to thank Statoil ASA for sponsoring my MSc programme and having suggested an extremely interesting topic for this project. Many thanks to all the Statoil employees who have contributed to shaping the project, in particular to Frank Hovland, Daniel Knowles, Roger Nybo, Cecelie Otterlei, Olujure Oyeniran, Junior Chukwudi, Abdulmecit Araz, Maria Antonia Santacreul Llovera and Stephani Agostini for their invaluable discussions, advice and encouragement.

Nomenclature
\[\text{SWATINIT} = \text{saturation of water at initial time, dimensionless}\]
\[S_{\text{gas}} = \text{saturation of gas, dimensionless}\]

Acronyms
\[\text{PVM} = \text{pore volume multiplier}\]
\[\text{STOILP} = \text{stock tank oil initially in place}\]
\[\text{Sm}^3 = \text{standard cubic metres}\]
\[\text{FOPT} = \text{field oil production total}\]
\[\text{WGOR} = \text{well-gas-oil-ratio}\]

Conversion Factors & Units
\[\text{Bbl} \times 0.159 = \text{Cubic Metres (m}^3\text{)}\]

References


Evaluation of the Pore Volume Multiplier Method to Quantify Field Production Uncertainty


Appendix

APPENDIX A1: CRITICAL LITERATURE REVIEWS

JCPT65-0-02 (1965)
Fundamentals and Applications of the Monte Carlo Method

Authors: Stoian, E.

Contribution to the PVM method and dynamic structural uncertainty quantification
Significant as it was the first paper to propose that Monte Carlo methods should be included as a distinct component in a company's repertoire of tools.

Objective of the paper:
To explain the Monte Carlo method and demonstrate its application in areas related to the oil and gas industry.

Methodology used:
Thorough explanation of Monte Carlo methods and applied to a reservoir to obtain in place volumes.

Conclusion reached:
The Monte Carlo method is well understood and is advantageous to use in the oil and gas industry as the industry is concerned with stochastic environments. However, the method requires multidisciplinary collaboration.

Comment:
A numerical simulator was not used and dynamic flow characteristics were not considered.
EAGE (1994)
New Technique to Improve the Efficiency of History Matching of Full-Field Models

Authors: Palatnik, B.N.; Aanonsen, S.I.; Zakirov, I.S.; Zakirov, E.S.

Contribution to the PVM method and dynamic structural uncertainty quantification
Significant as it was the first paper to history match a reservoir by using the horizon depth as a matching parameter, as oppose to only use a pore volume multiplier or a permeability multiplier.

Objective of the paper:
To obtain a more accurate description of static field data by using the structure as a history matching parameter

Methodology used:
A multiplier was used to control the corner point depths within different zones to minimise an objective function and get a better history match. The method was applied to a synthetic field based on data from a North Sea Oil Field – production is through gas injection.

Conclusion reached:
It is possible to obtain a history match with the use of varying the corner point geometry. However the relationship between the corner point depth and the objective function is more complicated than between porosity or permeability multipliers – which can result in a non convex objective function.

Comment:
Only corner point depth was used as a matching parameter - there was no stochastic variation in the horizon, which would represent a more elaborate case. Also the reason why the corner point depth would work as a history matching parameter as opposed to using only a pore volume multiplier was not explained.
SPE 57468 (1999)
Managing Structural Uncertainty in a Mature Field for Optimal Well Placement

Authors: Vincent, G.; Corre, B.; Thore, P.

Contribution to the PVM method and dynamic structural uncertainty quantification
Showed for an example case that same reservoir with different horizon realisations but the same STOIIP can lead to significantly different productions. This shows that horizon uncertainty affects flow characteristics, and therefore the PVM may not be a representative method to use.

Objective of the paper:
To determine whether or not an additional well should be drilled for a nondrained zone for which 3D seismic survey showed a structural high.

Methodology used:
200 simulations of the top reservoir map were made. The probability field technique generates an error at each position. Flow simulations were run for all 200 structural maps, along with the original reference map. All other geological and dynamic parameters were frozen.

Conclusion reached:
1. The structural map is a possible matching parameter
2. Models with different top horizons but identical STOIIP can generate extremely different production figures.
3. Identical production curves can be obtained with different STOIIP and horizons, which will influence the chosen development plan.

Comment:
This was based on a specific case study where a thick aquifer provided pressure support for production. Conclusions may not be general. In addition to this, only structural variation was accounted for and all other geological and dynamic parameters were frozen.
SPE 66399 (2001)
Uncertainty Analysis In Reservoir Production Forecasts During Appraisal And Pilot Production Phases

**Authors:** Steagall, D.E.; Schiozer, D.J.

**Contribution to the PVM method and dynamic structural uncertainty quantification**
Proposed the decision tree method of dealing with dynamic uncertainty. Has made use of the PVM method to quantify uncertainty due to structure, which may be the cause of future publications and industry using the method.

**Objective of the paper:**
To present the application of a methodology to obtain the impact of uncertainties in production forecasts. An alternative to the Monte Carlo method.

**Methodology used:**
The decision tree analysis was presented and applied to an adapted data set on an offshore field of Campos Basin, Brazil.

**Conclusion reached:**
The methodology presented for production forecasting uncertainty and risk, with the use of numerical simulation, can be applied and is adaptable for simple and complex reservoir cases

**Comment:**
This method fails to account for horizon variation in the dynamic simulation, but makes use of the PVM. This should be questioned.
EAGE (2005)

A 3D stochastic model integrating depth, fault and property uncertainty for planning robust wells, Njord Field, offshore Norway

Authors: Rivenæs, J.C.; Otterlei, C.; Zachariassen, E.; Dart, C.; Sjøholm, J.

Contribution to the PVM method and dynamic structural uncertainty quantification

Established a technique to represent horizon uncertainty dynamically using software to provide 3D grid realisations that reflect uncertainty in horizons, faults and properties. A move forward away from using the PVM method.

Objective of the paper:

To summarise IOR work for Njord Central Area by applying unconventional technology for structural modeling, along with advanced 3D modeling.

Methodology used:

Build a base case 3D grid model with expected top and bottom reservoir surfaces. Then subsequently generate multiple realisations of the surfaces and apply to the base case 3D model by applying an elastic grid stretch. Finally run simulations on different models with a variation in dynamic parameters for each model.

Conclusion reached:

1. Model supported that at least one well target would be economically feasible.
2. Modelling structural uncertainty is difficult with current tools which presents a challenge to the software vendors

Comment:

Different models were built with a stretch of an original grid. This may have an impact on the dimensions of facies objects and properties.
SPE 121899 (2009)

Joint Structural and Petrophysical History Matching Leads to Global Geological Stochastic Reservoir Models

**Authors:** Schaaf, T.; Coureaud, B.; Labaune, F.

**Contribution to the PVM method and dynamic structural uncertainty quantification**

Demonstrated an automatic workflow to history match taking account of horizon uncertainty, involving rebuilding the geomodel. A move away from the PVM method.

**Objective of the paper:**

To propose a history matching workflow that automatically updates structural, petrophysical and fluids related parameters. This is done through a single optimisation process

**Methodology used:**

1. Define initial history matching variables, then run a simulation.
2. Then read the simulation results and compare with an objective function.
3. Subsequently update the variables with the use of an optimisation algorithm.
4. Then update model and
5. Repeat steps 1 to 4 until a satisfactory match is obtained.

**Conclusion reached:**

1. The proposed history matching method showed promising results on a synthetic reservoir application.
2. The structural and petrophysical aspects were considered simultaneously in the history matching process.

**Comment:**

Rebuilding the geomodel each time for a simulation means that the time for a simulation run increases significantly.
SPE 163606 (2013)
Structural Uncertainty Quantification with Immersed Interface Methods

Authors: Ahmadi, M.; Christie, M.; Gerritsen, M.

Contribution to the PVM method and dynamic structural uncertainty quantification
New approach known as the immersed interface method has been applied to reservoir engineering for structural uncertainty quantification. Another move away from the PVM method.

Objective of the paper:
To modify Cartesian gridding in order to adapt to general structures without the need to regrid the model, in addition to maintaining accurate higher order flow characterisation

Methodology used:
A Cartesian cut cell method is the concept. The idea behind this is to deform cells which intersect with a boundary that is not aligned to the grid lines. Any cells located outside of the immersed boundary are then disregarded. This method was used for a 2D example case.

Conclusion reached:
The method was able to accurately represent geological structures in a dynamic simulation and use the horizons as a matching parameter.

Comment:
Study has been completed on 2D grid. Extension to 3D grid may be challenging.
# APPENDIX A2: MILESTONES IN PORE VOLUME MULTIPLIER STUDY

<table>
<thead>
<tr>
<th>SPE Paper No.</th>
<th>Year</th>
<th>Title</th>
<th>Authors</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>JCPT65-0-02</td>
<td>1965</td>
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<td>Stoian, E.</td>
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<td>First paper to history match a reservoir using horizon depth as a matching parameter as opposed to only using a pore volume multiplier or a permeability multiplier.</td>
</tr>
<tr>
<td>SPE 57468</td>
<td>1999</td>
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<td>Steagall, D.E.; Schiozer, D.J.</td>
<td>Proposed the decision tree method of dealing with dynamic uncertainty. Made use of the pore volume multiplier method to quantify uncertainty due to structure, which may be part of the cause of such wide usage in the industry.</td>
</tr>
<tr>
<td>EAGE</td>
<td>2005</td>
<td>“A 3D stochastic model integrating depth, fault and property uncertainty for planning robust wells, Njord Field, offshore Norway”</td>
<td>Rivenæs, J.C.; Otterlei, C.; Zachariassen, E.; Dart, C.; Sjøholm, J.</td>
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<td>Schaaf, T.; Coureauad, B.; Labaune, F.</td>
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<td>“New approach known as the immersed interface method has been applied to reservoir engineering for structural uncertainty quantification. Another move away from the PVM method.”</td>
<td>Ahmadi, M.; Christie, M.; Gerritsen, M.</td>
<td>First to apply the immersed interface method to to quantify structural uncertainty, which may lead to a quicker way of quantifying field production uncertainty due to horizon uncertainty. A move away from the pore volume multiplier method.</td>
</tr>
</tbody>
</table>
APPENDIX B: RESERVOIR DESCRIPTION

Reservoir description
- Permeability = 7000 mD
- Porosity = 0.33
- Approximately 2.5 Km by 1.5 Km by 30 m (oil column)
- 42000 grid cells (50 x 75 x 4m)
- 20 layers 21 rows and 101 columns
- Reservoir Pi = 178 bar
- Oil viscosity = 10 cP
- Oil density = 937 kg m$^{-3}$
- Gas density = 0.771 kg m$^{-3}$
- Oil-water-contact depth = 1760 m
- Base case STOIIP = 39.2 million Sm$^{3}$
- Oil-water-contact = 1760m
- Drive mechanism = gas drive

Well controls
- BHP control = 70 bars
- Oil rate target = 3000 Sm$^{3}$/day
- Gas rate upper limit = 1M m$^{3}$/day
- Gas voidage replacement = 0.9
- No water limit control (no water injector)
- No VFP
APPENDIX C: OIL RATE AND WATER CUT PLOTS

Figure A 1 shows an oil rate plot of the cases presented in the study, whereas Figure A 2 shows a water cut plot. The purpose of these plots is to present additional information related to the models presented in the study.

Figure A 1. A plot of total field production oil rate for i) the base model, ii) the movement in horizon 10m up and also with the equivalent pore volume multiplier applied (10m up PVM), and iii) the model with the movement of horizon 10m down and with the equivalent pore volume multiplier applied (10m down PVM).

Figure A 2. Producer water production rate plot for the different cases: i) base model, ii) 10m up and 10m up pore volume multiplier, and iii) 10m down and 10m down pore volume multiplier.
APPENDIX D: FIELD OIL PRODUCTION PROFILE FOR PORE VOLUME MULTIPLIER HEIGHT SENSITIVITY

Figure A3 shows a field production plot of the pore volume multiplier height sensitivity presented in the study. The graph shows clearly that applying the pore volume multiplier to a higher depth reproduces a closer approximation to the ‘correct’ case. However it also shows that it is not possible to easily approximate the ‘correct’ case therefore the recommendation is ultimately not to use the pore volume multiplier for the case of a gas drive mechanism, where the recovery process is sensitive to reservoir thickness as the pore volume multiplier does not account for this.

Figure A3. Plot of total field oil production for different locations where the pore volume multiplier has been applied: i) on the whole grid, and ii) in the volume above 1740m. This shows that applying the pore volume multiplier closer to where the change has been made on the grid gives a closer approximation to the ‘correct’ case.
APPENDIX E: POLYGON HORIZON MOVEMENT – TABLE VALUES OF PRODUCTION AFTER 60 YEARS

Table A1 shows the values for field production after 60 years of simulation for a polygon movement in the horizon for the two different method of quantifying the impact of structural uncertainty on field production; horizon movement and pore volume multiplier. The difference between the two methods can be up to 7%. The reason why this value is small is because the polygon is relatively local. The difference can be up to 50% for the case where the entire horizon is adjusted as shown in the study (Table 1). Therefore this difference is unacceptable and therefore a direct method should be used, where horizon uncertainty is modeled directly, to quantify the impact of structural uncertainty on field production.

Table A1. Total field production values after 60 years of simulation, for a polygon movement in the horizon, for the two different methods of quantifying the impact of structural uncertainty on field production; horizon movement and pore volume multiplier. The percentage difference between the methods for the different horizon movement cases is also shown.

<table>
<thead>
<tr>
<th>Horizon movement (M Sm³)</th>
<th>Pore volume multiplier method (M Sm³)</th>
<th>Percentage difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10m down</td>
<td>7.01</td>
<td>7.43</td>
</tr>
<tr>
<td>8m down</td>
<td>7.22</td>
<td>7.69</td>
</tr>
<tr>
<td>6m down</td>
<td>7.34</td>
<td>7.74</td>
</tr>
<tr>
<td>4m down</td>
<td>7.71</td>
<td>8.01</td>
</tr>
<tr>
<td>2m down</td>
<td>7.69</td>
<td>8.02</td>
</tr>
<tr>
<td>base</td>
<td>8.19</td>
<td>8.19</td>
</tr>
<tr>
<td>2m up</td>
<td>8.53</td>
<td>8.44</td>
</tr>
<tr>
<td>4m up</td>
<td>8.90</td>
<td>8.59</td>
</tr>
<tr>
<td>6m up</td>
<td>9.10</td>
<td>8.71</td>
</tr>
<tr>
<td>8m up</td>
<td>9.37</td>
<td>8.74</td>
</tr>
<tr>
<td>10m up</td>
<td>9.68</td>
<td>9.06</td>
</tr>
</tbody>
</table>
APPENDIX F1: OIL RATE SENSITIVITY

Figure A4 shows an oil rate sensitivity for the cases presented in this study. The oil rate has been changed from 3000 Sm³/Day (a) used in the study, to 1000 Sm³/day (b). The plots show that the conclusion of the study is still valid for different rates.

Figure A4. Plot of total field production for cases i) base model, ii) 10m up and equivalent 10m up pore volume multiplier, and iii) 10m down and equivalent 10m down PVM. This is shown for two different rates: a) 3000 Sm³/Day and b) 1000 Sm³/Day. This shows the result that the pore volume multiplier method gives a smaller recovery range, than the 'correct' method of adjusting horizons, is still true for different rates.
APPENDIX F2: POLYGON SENSITIVITY WHERE PVM HAS BEEN APPLIED IN HIGHER LOCATION

Figure 5 shows a sensitivity study. This sensitivity was performed on the study where a polygon area of the base model was taken and the horizon adjusted in that local area. The figure plots the field production after 60 years for moving a polygon area of the top horizon vs. using the pore volume multiplier for the different cases 2m, 4m, 6m, 8m, and 10m movement up and down. The difference between the green triangle and the blue diamond data labels are that the green triangles represents the case where the pore volume multiplier has been applied to the entire volume under the polygon area. Conversely for the blue diamond data labels, the pore volume multiplier has been applied to a volume under the polygon area and only above a depth of 1735m. The result of this plot is that it is difficult to determine what volume the pore volume multiplier should be applied to. Therefore the recommendation of the study is not to use the pore volume multiplier for the case where the recovery process is sensitive to reservoir thickness, as the pore volume multiplier does not account for reservoir thickness.