FORECASTING CBM PRODUCTION IN MUKAH-BALINGIAN COALFIELD, SARAWAK MALAYSIA

By

Prashanth Nair s/o Kumaran

Dissertation Submitted to Petroleum Engineering Programme in Partial Fulfillment of the Requirements for the Degree Bachelor of Engineering (Hons)

(Petroleum Engineering)

Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved

13/5/2011

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March 2011

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements and that the original work contained herein have not been undertaken or done by unspecified sources or persons

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(Prashanth Nair s/o Kumaran)

ABSTRACT

Coal-bed methane (CBM) or coal-bed gas is a form of natural gas extracted from coal beds. The term refers to methane adsorbed into the solid matrix of the coal. In order to understand the performance of a CBM reservoir, we need to know the Original Gas in Place, Production Rates and also Recovery Factor. This is mainly on creating a Microsoft Excel ® 2007 with the help of Visual Basic for Application (VBA) based CBM forecast tool. Field data from Mukah-Balingian Coalfield Sarawak is analyzed and forecasted. Original Gas in Place is calculated by multiplying the mass of the coal with the initial gas content of the coal bed. Following from the generated Relative Permeability data, production rates for both water and gas calculated over a specific time range. During the whole production, an abandonment condition which is mainly the pressure will be set by the engineers. Using this abandonment pressure, we can calculate the recovery factor. Using constant values of Langmuir Volume of 714.29 scf/ton, Langmuir Pressure of 1024.5 psia, and reference initial pressure of 2000 psia; flowing pressure of 100 psia which is also the abandonment pressure, various range of skin,permeability, intial gas content as well as porosity tested to predict the field performance. Using the range of initial gas content of 86.286 – 173.36 scf/ton; range of permeability of 1.01e-6 md to 1010 md; porosity, with a range of 0.0001 to 0.5%; Skin ranged from -5 to 4, CBM production is forecasted for the range of 5 years.

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First of all, I would like to place my highest gratitude to my Final Year Project Supervisor, Dr Sonny Irawan, who has been very kind to guide me throughout my entire semester doing this project. Along with this, I would like to take this opportunity to express my gratitude to my Industrial training Supervisor, Mr. Artur Ryba, who has been a big project part of this project and took his time to teach me on the necessary part of the core essentials of Coal Bed Methane production itself and the theory that comes with it.

Secondly, I would like to thank LEAP Energy who had given me chance by doing my internship over there for the past 8 months. Through these 8 months, I have first encountered CBM and fell in love with it. Hopefully the knowledge I gained throughout my training will last till throughout my working years ahead. Apart from that, not forgetting too my friends and family who had helped me during the whole project period by giving me moral and mental support. Hope through this project, I have learned more on Coal Bed Methane as it would surely become the next big thing in the Oil and Gas industry.

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NOMENCLATURE

A = area (ft^2)
B_w = water formation volume factor (ft^3/scf)
B_w = water formation volume factor (bbl/STB)
c_w = water compressibility (/psia)
c_f = formation compressibility (/psia)
G_{ci} = Initial gas content (scf/ton)
$G_{c@abd}$ = Gas content at Abandonment Pressure (scf/ton)
GIP = gas in place (scf)
h = net pay (ft)
k_{rg} = relative permeability to gas,(fraction)
k_{rg0} = endpoint relative permeability to gas,(fraction)
k_{rw} = relative permeability to water,(fraction)
k_{rw0} = endpoint relative permeability to water,(fraction)
k_g = gas effective permeability (md)
k_w = water effective permeability (md)
$m()$ = gas pseudopressure (psi^2/cp)
n_w = exponent of the water relative permeability curve,(fraction)
n_g = exponent of the gas relative permeability curve,(fraction)
P= pressure,(psia)
P_i = initial reservoir pressure (psia)
P_L= Langmuir Pressure constant, (psia)
P_{wf} = bottomhole flowing pressure (psia)
q_g = gas rate (MCFd)
q_w = water rate (STB/day)
r_e = external radius of reservoir (ft)
r_w = wellbore radius (ft)
s = skin
S_g = average gas saturation,(fraction)
S_{gc} = irreducible gas saturation,(fraction)
S_w = average water saturation,(fraction)
S_{wc} = irreducible water saturation,(fraction)
S_{wi} = initial water saturation
T = Temperature (R)
$V(P)$ = amount of gas at pressure P,(scf/ton)
V_L= Langmuir Volume constant,(scf)
W_e = water encroached (bbls)
W_p = water produced (STB)
ϕ = porosity (dimensionless)
μ_w= water viscosity (cp)
ρ_b= bulk density of the coal (lb/ft^3)

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Coal-bed methane (CBM) or coal-bed gas is a form of natural gas extracted from coal beds. The term refers to methane adsorbed into the solid matrix of the coal. Coal is defined as a readily combustible rock that contains more than 50% by weight and more than 70% by volume of carbonaceous material including inherent moisture formed by compaction and induration (hardening of sediment) of various altered plant remains .Coal is a dual porosity rock containing micropores (matrix) and a network of natural fractures knows as cleats. The micropores represents the porosity of the coal where else the cleat provides the permeability of the coal itself. A coal seam is a bed of coal and the natural gas of methane produced from it is referred to as coalbed methane (CBM).

Production from Coalbed Methane, which is the gas desorption from coal, using Langmuir Isotherm ,Gas content vs. Pressure plot, as shown **Error! Reference source not found.**1.1, from the initial pressure, reservoir will constantly be depressurized due to the water production. During this period, process called as "Dewatering" occurs. Once desorption point has been passed, gas will start to desorbs from the surface of the coal in matrix into the cleats and will be produced from the well in the form of mixture with water. Since two phases of fluid are flowing following initially initial single phase flow, relative permeability will change with time to each of the phase.

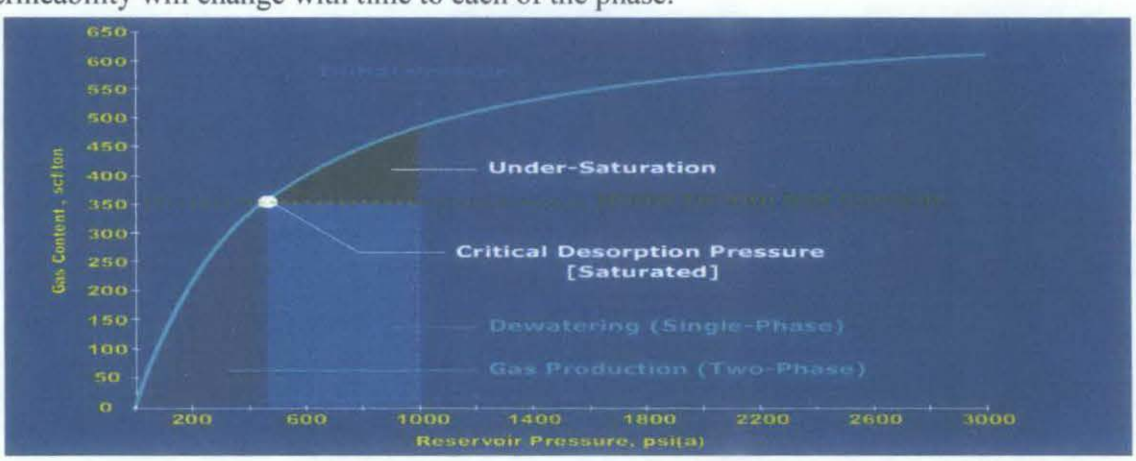


Figure 1.1: Langmuir Isotherm [3]

In order to understand the performance of a CBM reservoir, we need to know the Original Gas in Place which helps the Reservoir Engineer to estimate the deliverability of a known reservoir. It is the amount of gas in the reservoir before any production begins. Production Rates is in need in order to keep track of the production of the reservoir. Based on the abandonment condition, recovery factor can be calculated. Recovery factor of CBM reservoir is the percentage of gas that can be produced from the reservoir

1.2 Problem Statement

1.2.1 Problem Identification

In order to understand and invest in a production from a Coalbed Methane reservoir, one has to know the recovery factor, (RF) and also the Original Gas-In-Place, (OGIP) of the CBM reservoir. This affects the production in the sense that, the duration of the well production can be determine. The higher the OGIP, the higher the methane contained in the reservoir which makes it an economical decision to invest in the particular field. Recovery factor as well helps the reservoir engineer to decide on the future investment of the field. Through the production rate calculated, production is kept under controlled for a known field. Although so, there are always scarcity in data such as the production rates, from both from low-well density and direct measurements [7]. This gives a setback towards CBM production.

1.2.2 Significant Of the Project

Through this project, data such as the production rate, recovery factor and also the Original Gas in Place will be generated using the analytical solutions. Using these values, performance of a producing CBM reservoir can be forecasted. Apart from that, this would become an economical factor in producing any CBM reservoir

1.3 Objectives

- To determine the Gas-In-Place in Coalbed Methane
- To determine the production rate of Coalbed Methane
- To determine the Recovery Factor in a Coalbed Methane Reservoir

1.4 Scope of Study

The scope of study is mainly on creating a Microsoft Excel ® 2007 based CBM forecast tool. The three objectives that forecast tool has to be able to find is the Gas in Place, Production Rates and also the Equations to predict the production of the CBM production are for the gas flow rates, water flow rates, cumulative gas production, cumulative water production as well as the water saturation and the relative permeability related to it. For the first part of the project, research is been done using journal papers and current commercial software in the market (e.g.: F.A.S.T. CBM® by FEKETE Softwares). Equations are studied and tested on sets of data using Microsoft Excel ® 2007 and the commercial software. Once equations are collected, equations are key- in the Microsoft Excel ® 2007 as part of making automated calculations. This is the most crucial part of the whole project as any mistake done during is easier to be detected and modified. An undetected error will cause the whole forecasting to go wrong. Following the development of the calculations in Excel®, equations will be transferred into coding. For this purpose, Visual Basic for Application (VBA) is used. Interface would be created to make it user friendly and more functionality will be added for future usage. Using this software, field data from Mukah-Balingian Coalfield, Sarawak Malaysia is used to forecast its production. Though the field is still new and has not produce, general data from coal properties is recorded and used for forecasting.

1.5 The Relevancy of the Project

Coalbed Methane is becoming a famous in the Oil and Gas Industry. As there were need of a new fuel energy to replace the usage of oil, methane is one of the main replacement seen by the investors. Using this Coalbed methane production Forecast Tool, engineers are able to know the Gas in place, Recovery Factor as well as the production rates as indicator of the CBM performance. This helps in deciding on investment on the particular field.

1.6 Feasibility of the Project

This project is fully computer based. In the time given, the project could be done. This project can be done within 3 months given that everything goes fine. The objective can be achieved if the procedures are closely followed.

CHAPTER 2

BASIC THEORY AND LITERATURE REVIEW

2.1 CBM Parameters

In order to understand the methane gas production from a Coalbed methane reservoir, one has to analyze [5]:

2.1.1 Relative permeability of gas and water

Relative permeability relationship is used to measure the flow in the cleats as gas and water are produced at the same time. Two main relative permeability relationships can be used:

a) Corey (1995)

$$\frac{k_{rg}}{k_{rg0}} = \left(\frac{\bar{S}_g - S_{gc}}{1 - S_{wc} - S_{gc}}\right)^{ng}, \bar{S}_g \geq S_{gc} \ldots\ldots (1)$$

$$\frac{k_{rw}}{k_{rw0}} = \left(\frac{\bar{S}_w - S_{wc}}{1 - S_{wc}}\right)^{nw}, \bar{S}_g \geq (1 - S_{wc}) \ldots\ldots (2)$$

b) Honarpour(1982)

$$k_{rw} = 0.035388\frac{(\bar{S}_w - S_{wc})}{(1 - S_{wc})} - 0.010874\left[\frac{\bar{S}_w}{1 - S_{wc}}\right]^{2.9} + 0.56556{S_w}^{3.6}(\bar{S}_w - S_{wc}) \,..(3)$$

$$k_{rg} = 1.1072\left(\frac{\bar{S}_g - S_{gc}}{1 - S_{wc}}\right)^2_{\bar{S}_g \geq S_g} \ldots\ldots (4)$$

Water saturation for the coalbed methane equation is defined as:

$$\bar{S}_w = \frac{S_{wi}[1 + c_w(P_i - P)] + \frac{5.615(W_e - B_w W_p)}{\phi_i A h}}{[1 - c_f(P_i - P)]} \ldots\ldots (5)$$

2.1.2 Bulk density of the coal

Bulk density of coal is measured from the lab core analysis. Bulk density is usually measured in gram per cubic centimeter. It will be used to calculate the Original Gas In Place of the Coalbed. In order to calculate Original Gas-In-Place (OGIP), following is the calculation used in the forecasting tool using initial gas content (G_{ci}) and Initial Reservoir Pressure (P_i):

$$OGIP = Ah\rho_b G_{ci} \quad \text{...} (6)$$

$$G_{ci} = \frac{V_L * P_i}{P_L + P_I} \quad \text{..} (7)$$

2. 1.3 Porosity

Porosity of the coal is also measured during the core analysis. It ranges from 0.1 to 10%. Porosity is important to calculate the production rates.

2.1.4 Gas content and other Langmuir constants

In order to understand the methane gas production from a coalbed methane reservoir, one has to analyze the Langmuir Isotherm Curve. Langmuir Isotherm assumes that gas adsorbs to the coal surface and covers the as a single layer of gas [1].Nearly all of the gas stored by adsorption coal exists in a condensed, near liquid state. At low pressures, this dense state allows greater volumes to be stored by sorption than is possible by compression. Langmuir Isotherm adsorption derives as:

$$V(P) = \frac{V_L P}{P_L + P}, \text{...} (8)$$

Using the Langmuir Isotherm, with the known abandonment pressure and gas content according to it,

$$Recovery\ Factor, RF(\%) = \left(\frac{G_{ci} - G_{C@abd}}{G_{ci}}\right) * 100\% \text{ ....} (9)$$

2.2 Calculation Flow chart

There are three main calculations involved in creating CBM Forecast Tool. They are the Basic calculations, Pressure drop calculation and Gas/Water Constraint. All of these calculations are related to each other in predicting the performance of a known gas reservoir.

2.2.1 Core calculation Flow Chart

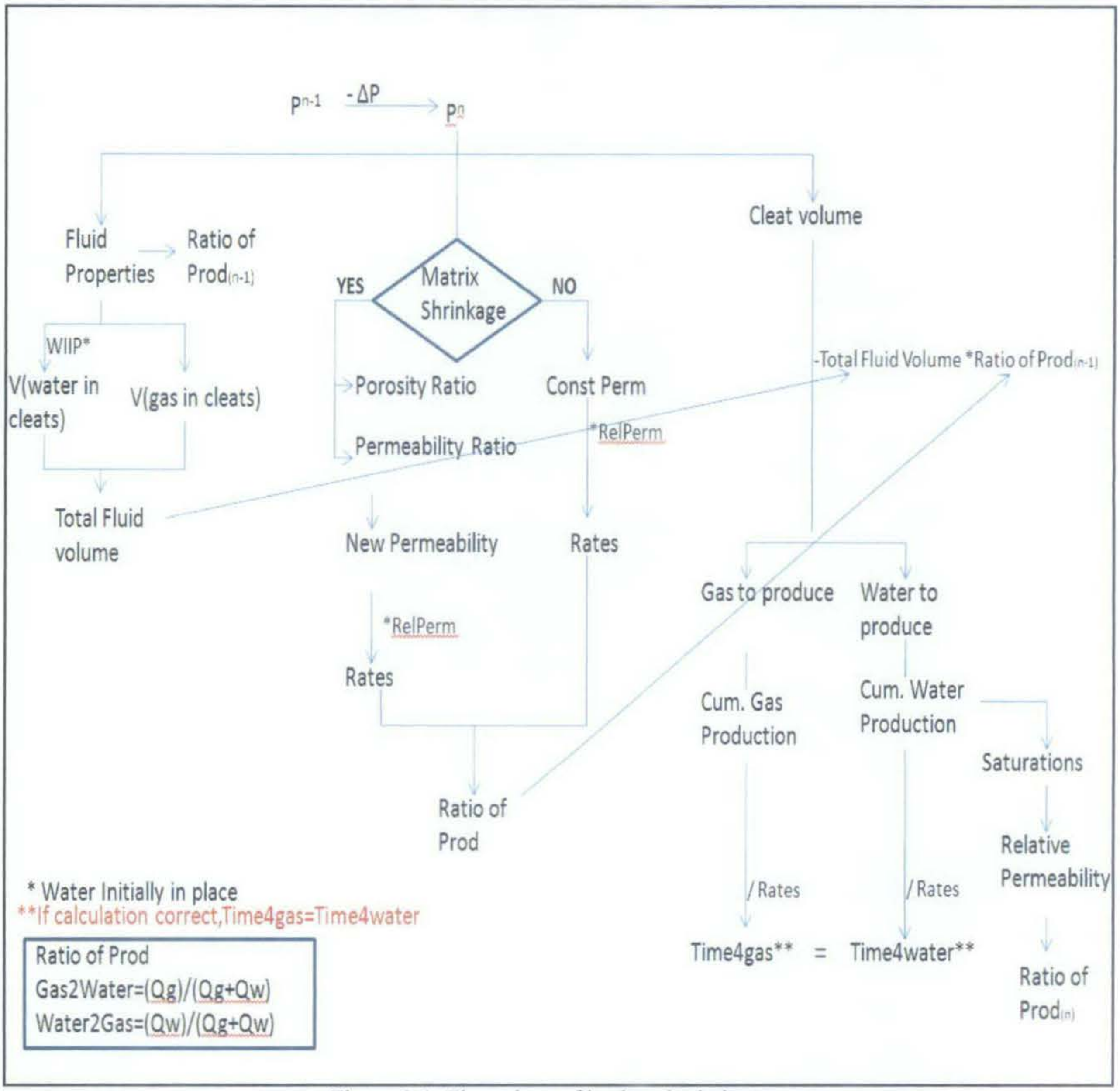


Figure 2.1: Flow chart of basic calculation

CBM Forecast Tool controls the pressure during calculation. As pressure drops from P^{n-1} to P^{n}, fluid properties is calculated using P^{n}. These properties are such as Gas Formation Volume Factor (Bg), Gas compressibility factor (Z), and also Gas density (μ_g). We also can calculate the current cleat volume using its compressibility. Using the properties calculated, we can calculate the volume of water in cleats using the Water Initially in Place (WIIP) together with gas volume in cleats. Both of these add up to give total fluid volume in cleats and they are compared to available pore volume to evaluate production. These properties also will be used to calculate ratio of gas to water and water to gas. The structure used is in Figure 2.1 .

Before calculation, user also specifies whether there is matrix shrinkage and cleat expansion effect in the reservoir. If these are present, permeability and porosity are influenced and a new permeability and porosity needs to be calculated. Using permeability, with or without the matrix shrinkage, gas and water rates are calculated with the help of relative permeability. These rates used are used to find rate ratios to check calculations. Total volume time with the ratio will give the volume of gas and water need to be produced at given pressure difference. With this, we get cumulative gas and water production.

Using cumulative water production, relative permeability for the next pressure step is calculated using the water saturation remaining in the cleat after production. This continues with the rates ratio for the next pressure step. With the current water and gas production, time for both gas and water can be calculated by dividing the cumulative production by the rates subsequently. If the calculation steps were followed accurately, time obtained from gas and water is the same. This is another test of analytical solutions. Once this achieved, CBM Forecast Tool proceeds to next pressure step.

2.2.2 Pressure Drop Calculation

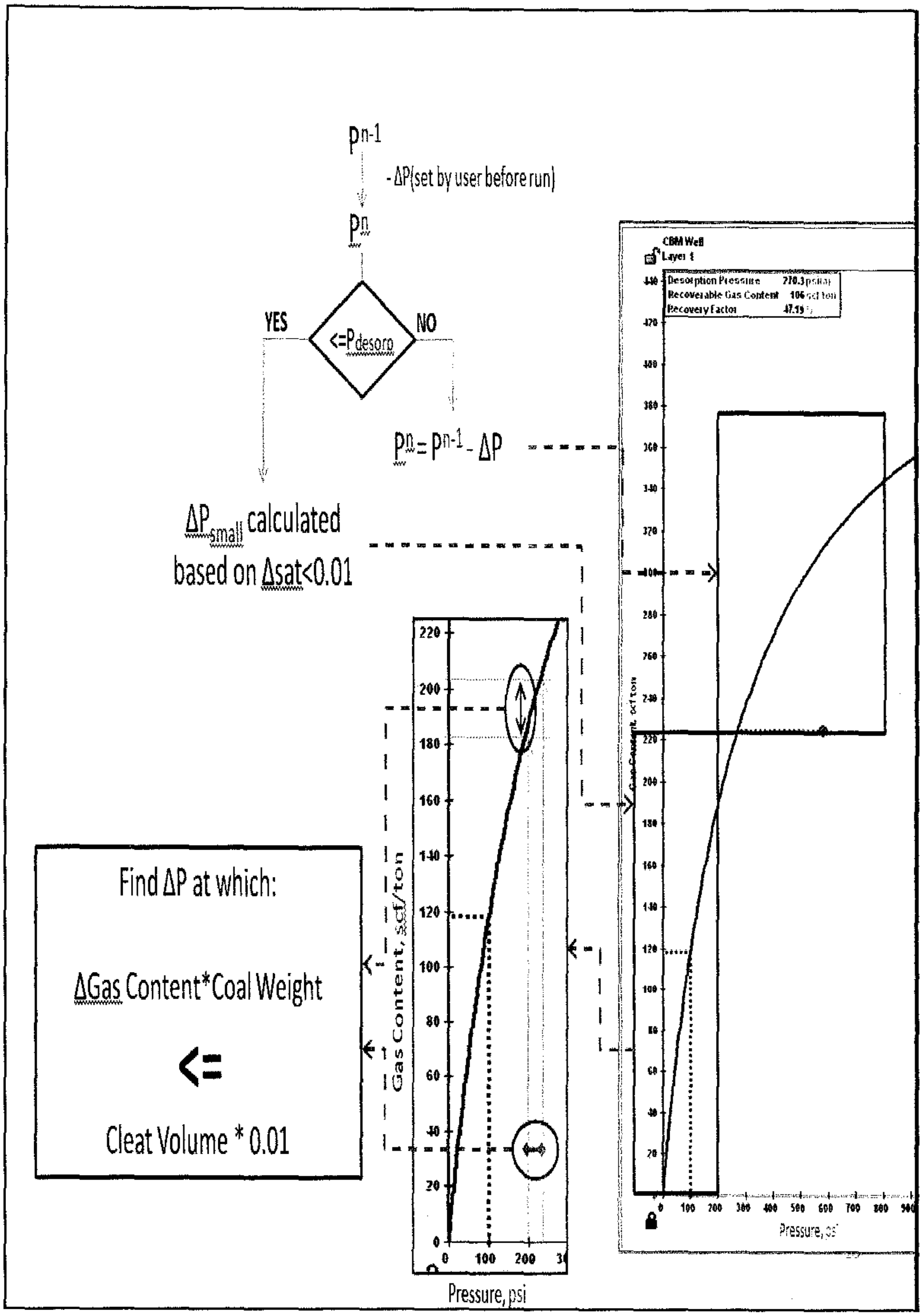


Figure 2.2: Pressure drop calculation

2.2.3 Gas / Water Constraint

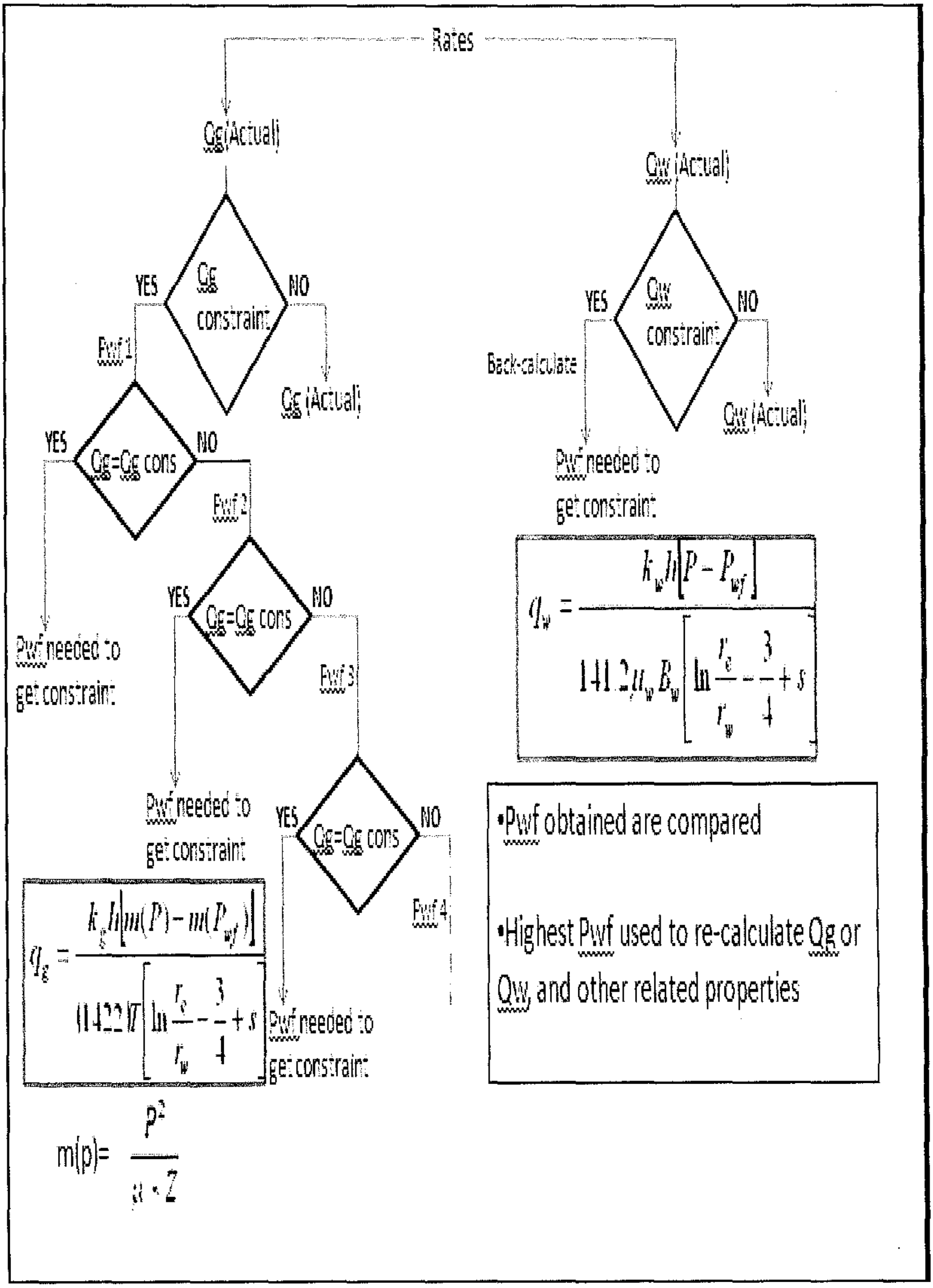


Figure 2.1: Flow chart to calculate based on gas/water constraint

2.3 Literature Review

Coalbed Methane (CBM) reservoir performance is controlled by a complex set of reservoir, geologic, completion and operation parameters and the inter-relationships between those parameters. The best tool to predict CBM reservoirs is a numerical reservoir simulator that accounts for various mechanisms that control CBM production [8]. A few assumptions are taken into consideration when preparing the simulator to convenient the calculations [9]:

1. Coalbed contains two-phase (gas and water)
2. Temperature remains constant
3. Gas volume desorbed from the coal surface is estimated from the available Sorption Isotherm
4. Gas is not soluble in water
5. Gas transport through the coal matrix system is a diffusion process, while gas and water flow to the wellbore via the cleat network obey Darcy's Law
6. Porosity in coal micropore and macropore systems is unchanged with pressure

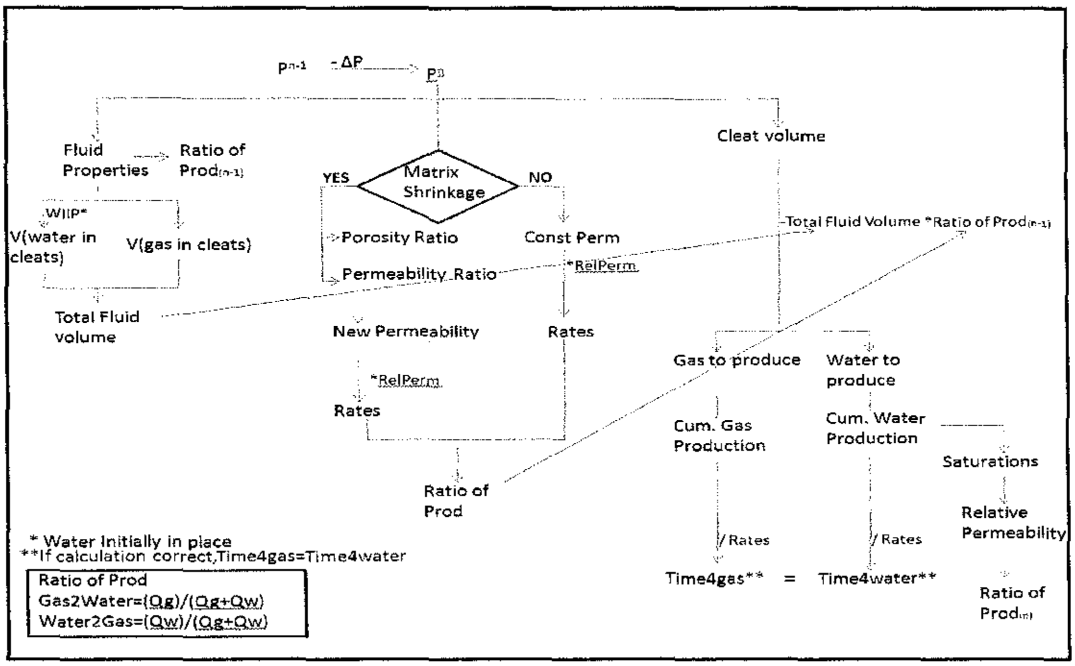
In order to identify, analyze and mitigate risks associated with any CBM prospect, one must first understand the relative importance of each of these parameters, how their relative importance changes under different constraints, and how they interactively affect CBM production [6]. Using these parameters, production of the CBM is analyzed or what we call as Production Data Analysis (PDA). Several key assumptions were used in deriving the PDA techniques including instantaneous desorption (small sorption times), single-layer behavior, and also single-porosity behavior during production are quite important for some producing field [7]. Therefore, through this project it is expected that the production of the Coalbed Methane can be forecasted using analytical solution for the usage of the engineers and the investors.

CHAPTER 3

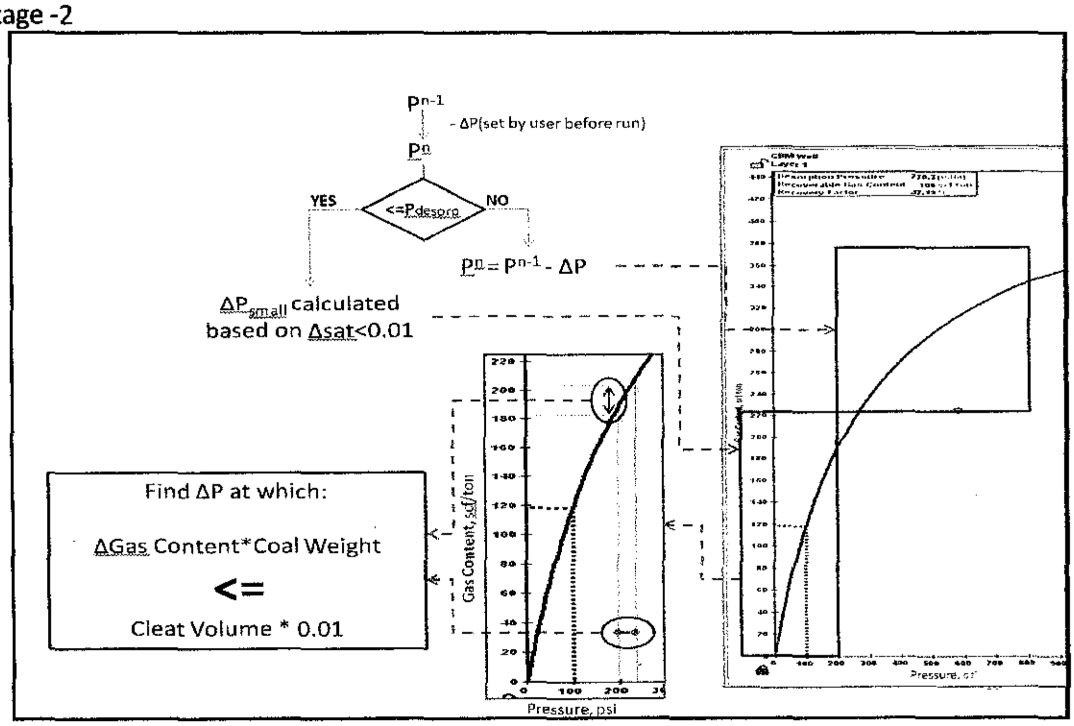
METHODOLOGY

3.1 Introduction (Refer to Calculation Flow Chart)

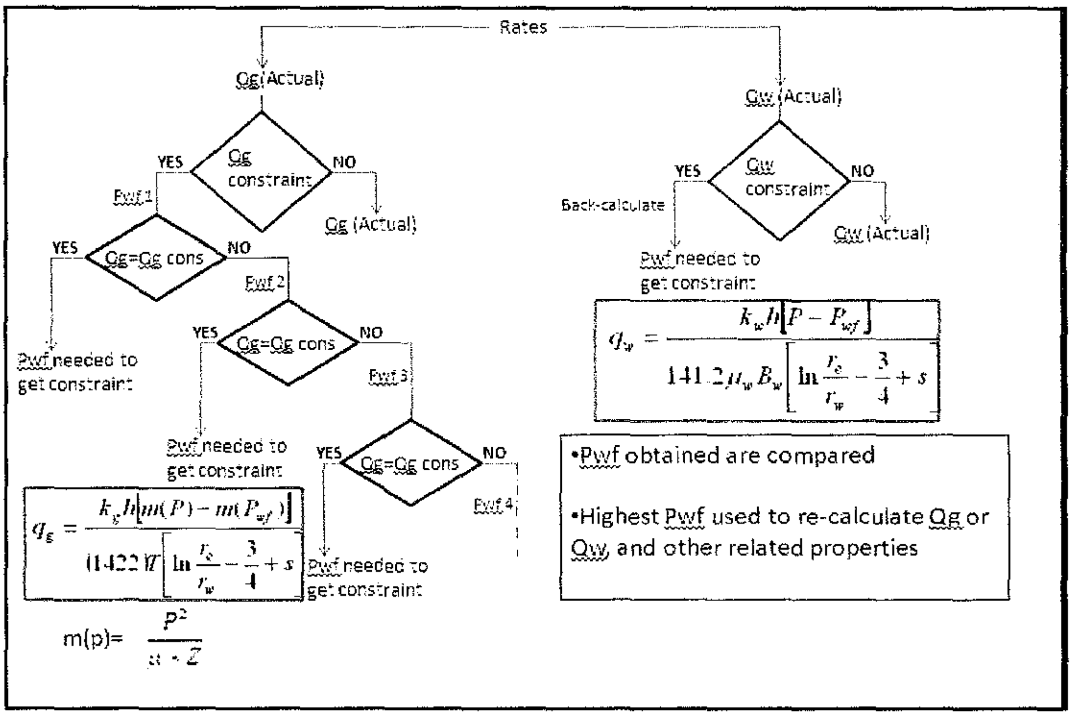
Stage -1:



Stage -2



Stage-3



3.2 Tools and Equipment

In this project, computers are the major tool used. Simulation is done using Microsoft Excel® 2007 and with the help of VBA for the interface. Commercial software is used for comparison purpose which is the F.A.S.T. CBM by FEKETE Softwares.

3.2.1 CBM Forecast Tool

Based on the equations, a Microsoft Excel 2007® and Visual Basic for Application (VBA) based Coal Bed Methane production forecasting tool is created. This forecasting tool is able to generate data for the user such as:

- Recovery Factor
- Peak Water Rate
- Ultimate Recovery of Water
- Initial Gas Rate
- Peak Gas Rate
- Time to Peak

- Original Gas In Place (OGIP)
- Ultimate Recovery of Gas

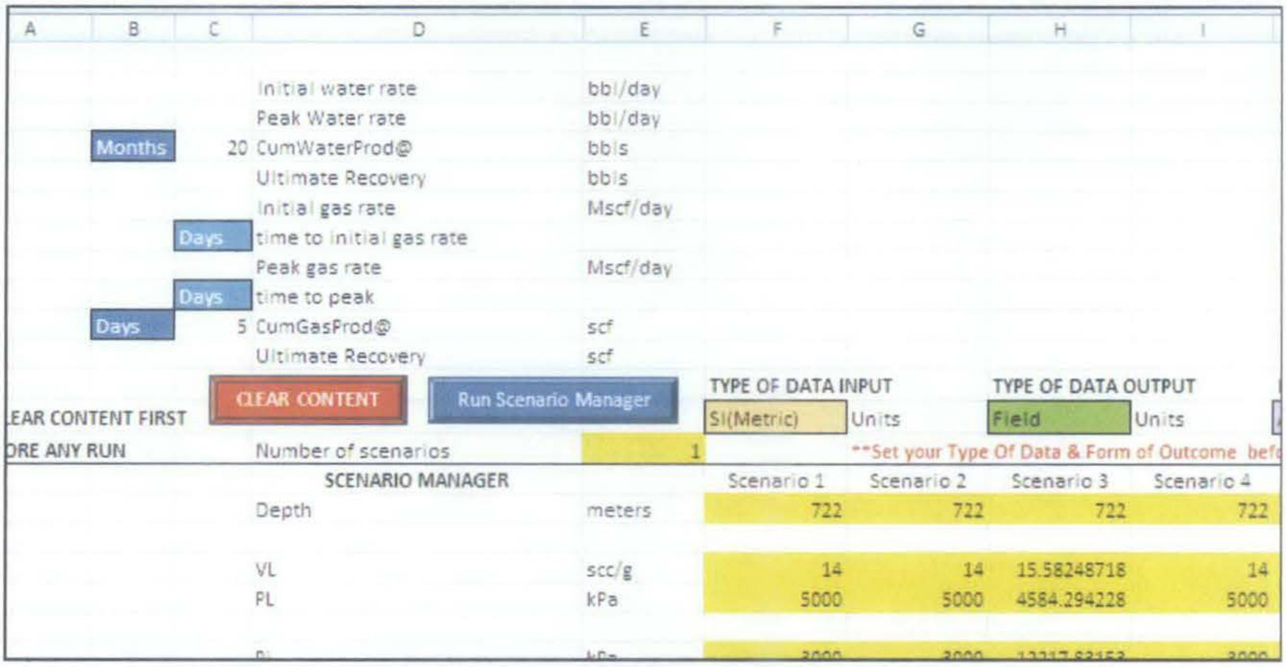


Figure 2.2: CBM Forecast tool Interface

There are a few easy steps to run the CBM forecast tool;

1. Before running the Forecast tool, "CLEAR CONTENT" button need to be pressed to clear out all old result in the forecasting tool.

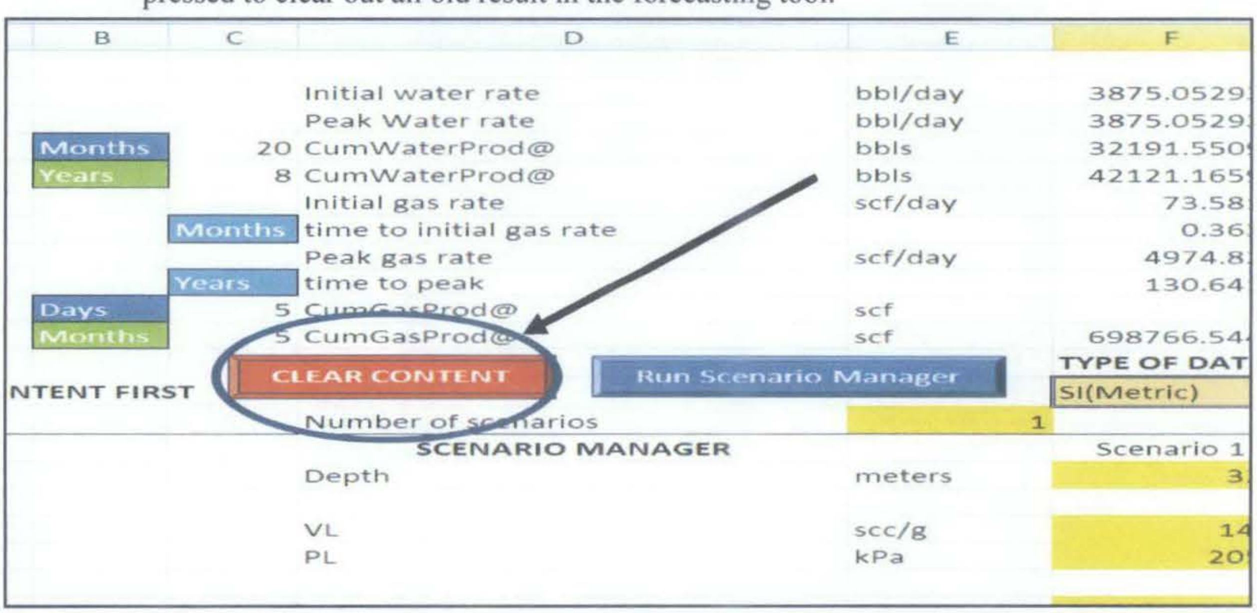


Figure 2.3 : The "CLEAR CONTENT" button

2. Once results cleared, set in the type of data input as well as type of data output. Two choices are given which are the Field Units and SI Units.

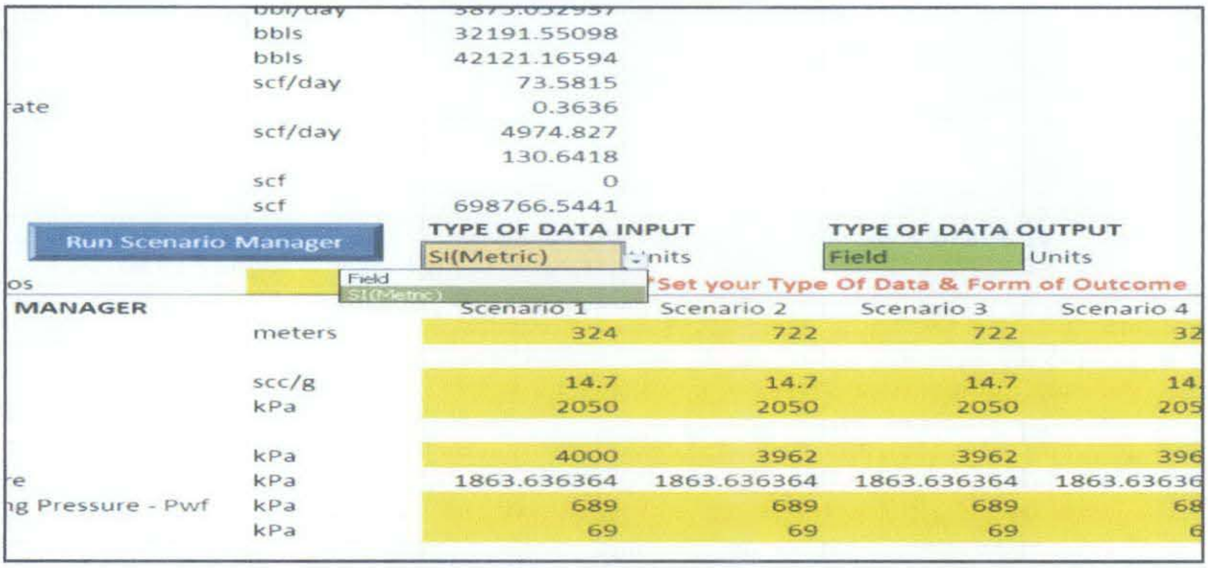


Figure 2.4: Set the type of data input and data output

3. Before running the Forecast Tool, set the correlations and constraints to be used in the calculations, as well as Form of outcome. Input values must be key-in before running the forecast tool.

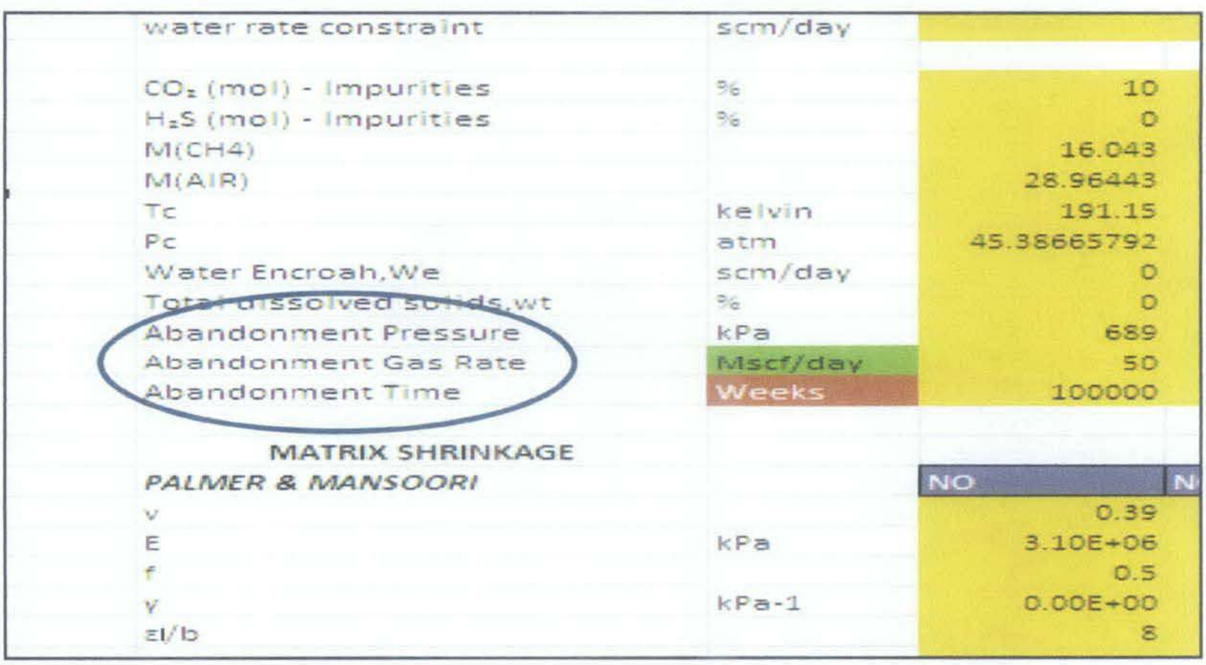


Figure 2.5: Set the Constraints before forecasting

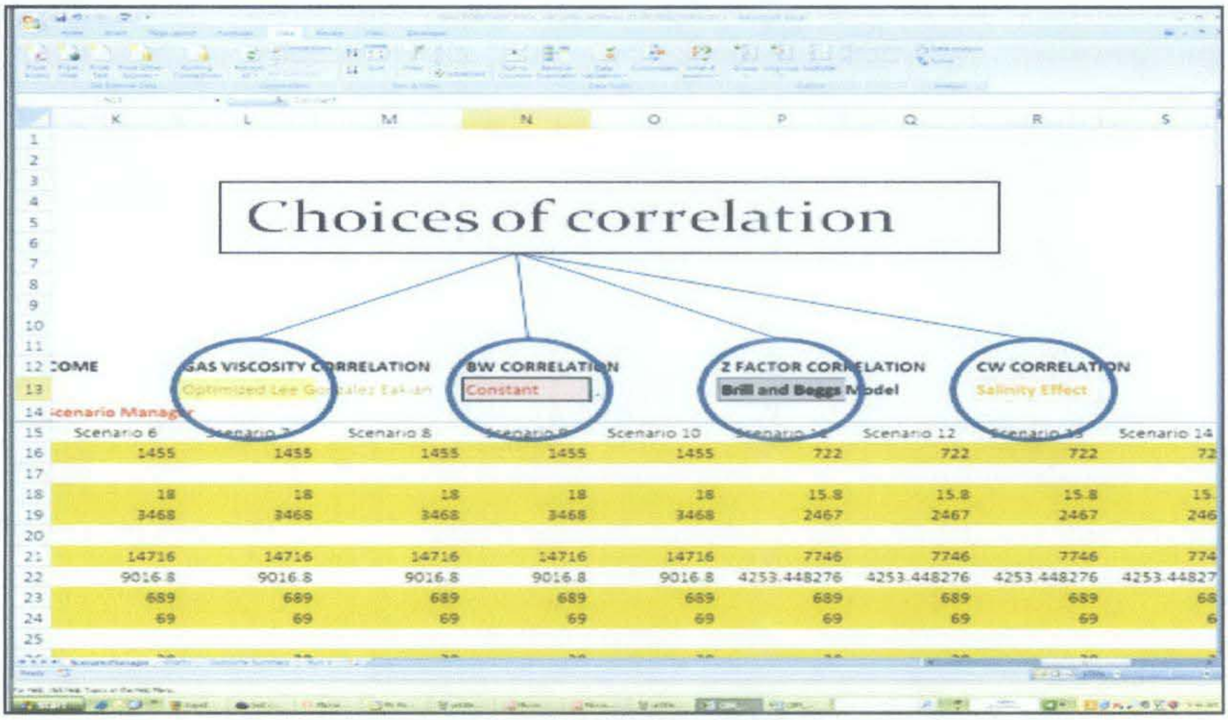


Figure 2.6: Choices of correlations

4. In CBM Forecast Tool, it would be able to choose the data that we want to see. We must choose from the options given in the forecast tool.

Langmuir Isotherm	YES	YES	YES	YES	YES	YES
Rel Perm	YES	YES	YES	YES	YES	YES
Outcome	YES	YES	YES	YES	YES	YES
Rel Perm (Scenario based)	YES	YES	YES	YES	YES	YES
Pwf needed	YES	YES	YES	YES	YES	YES
Ratios(Porosity&Permeability)	YES	YES	YES	YES	YES	YES

Figure 2.7: Choose on what you want the Forecast Tool to display

5. Finally, hit the "Run Scenario Manager" button, and wait for the results to be displayed. Each scenarios would be exported into a new tab named Run

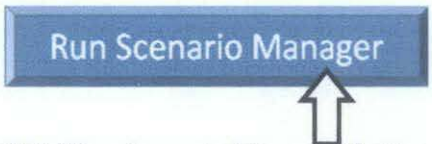


Figure 2.8 :"Run Scenario Manager" button

6. CBM Forecast Tool plots chart based on the need of the user (under the "Outcome Summary" tab"). There are three chart plotters,
   - Single case
   - Selected cases(Sensitivity Plot)
   - Add2chart
7. Add2chart is a unique option in which you get to choose the data you want to be added in the Single case chart only in order to do comparison. It is user-friendly as well

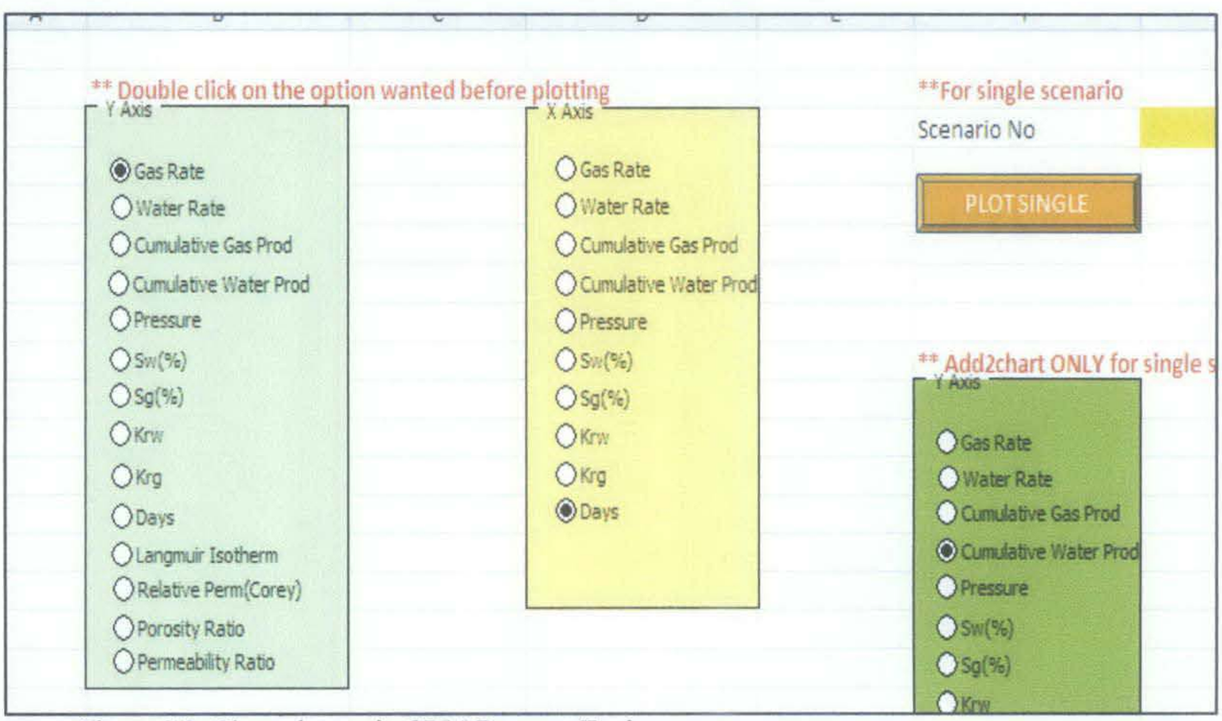


Figure 2.9: Chart plotters in CBM Forecast Tool

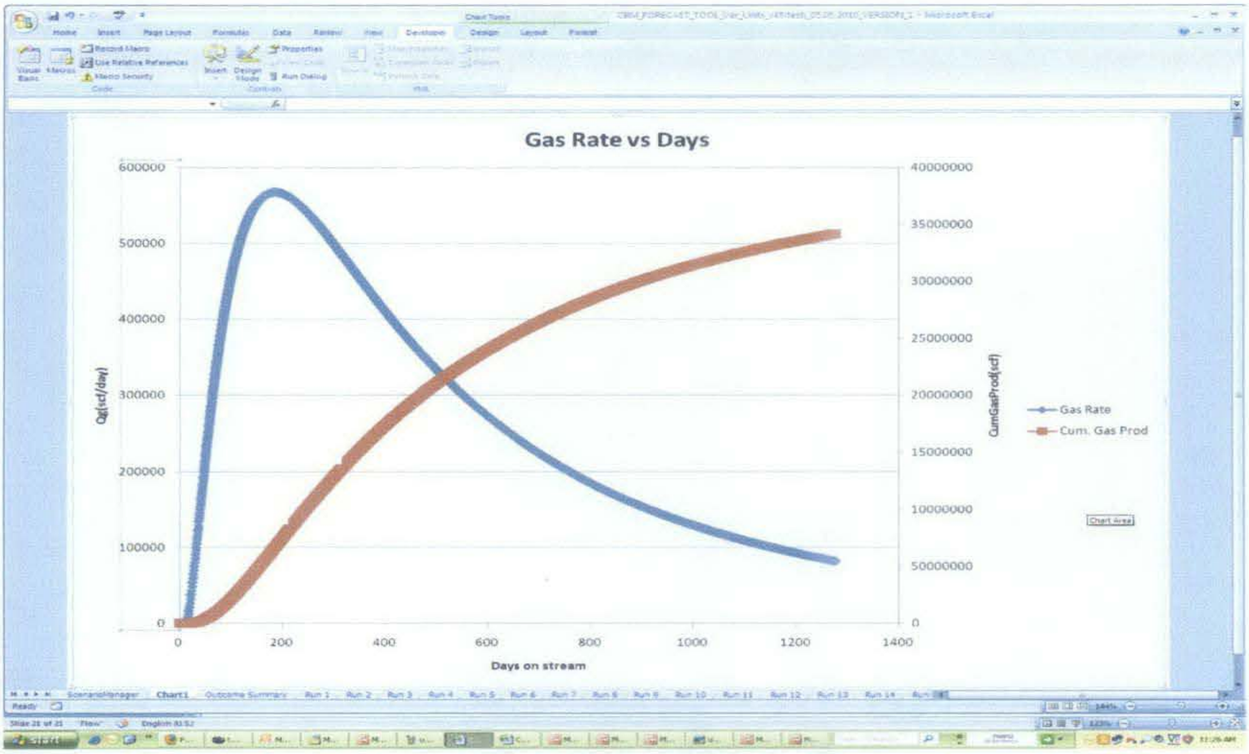


Figure 2.10: Example of the ability of Add2chart

This is a sample of graph plotted by the Chart plotters, whereby it's a single case graph and with the help of Add2Chart, another y-axis is been added for comparison purpose.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Data from Mukah-Balingian Coalfield

Based on the preliminary studies data of Mukah-Balingian Coalfield, a reference input data is prepared for forecasting. Certain values are taken from Pertamina data for the fields in Sumatra [11]. Using this data, a set of range of Skin, Permeability, Porosity as well Initial Gas Content is forecasted to get the Peak Gas Rate, Ultimate Recovery Gas, Ultimate Recovery Water, Recovery Factor and Water Cut. This forecasting was done for the duration of 5 years with the abandonment pressure of 100 psia and abandonment gas rate of 0.1 Mscf/day. (see Appendix 1, **Table A1-1**)

4.2 Assumptions

Throughout the forecasting, certain assumptions need to be considered before running the Forecast Tool.

1. Relative permeability correlation used is Corey's correlation
2. There is no Matrix Shrinkage effect
3. Fluid properties remains constant throughout
4. Physical properties of the coal remains constant throughout
5. No Water Encroach (W_e)
6. No dissolved solids

4.3. Results from CBM Forecast Tool

4.3.1 Range of Initial Gas Content

For this, range of Initial Gas Content from 86.286 to173.36 scf/ton is used for forecasting. Forecasted results are shown in **Appendix 1(Table A1-2)**. Following are the graph plots from CBM Forecast tool.

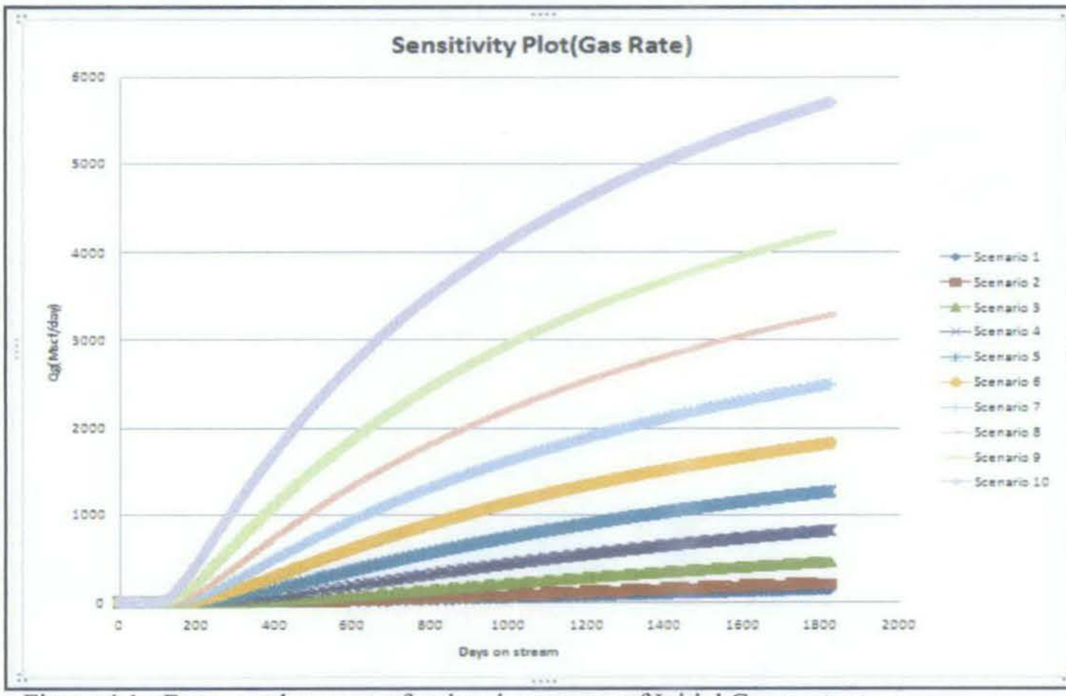


Figure 4.1 : Forecasted gas rates for the given range of Initial Gas content

From the Figure 4.1, we can know that the higher the gas content, the higher is our expected peak gas rate. Given the same properties condition, higher initial gas content gives a smaller duration of "Dewatering" and therefore more gas desorbs into the cleat. Thus, higher peak gas rate is achieved in a shorter duration.

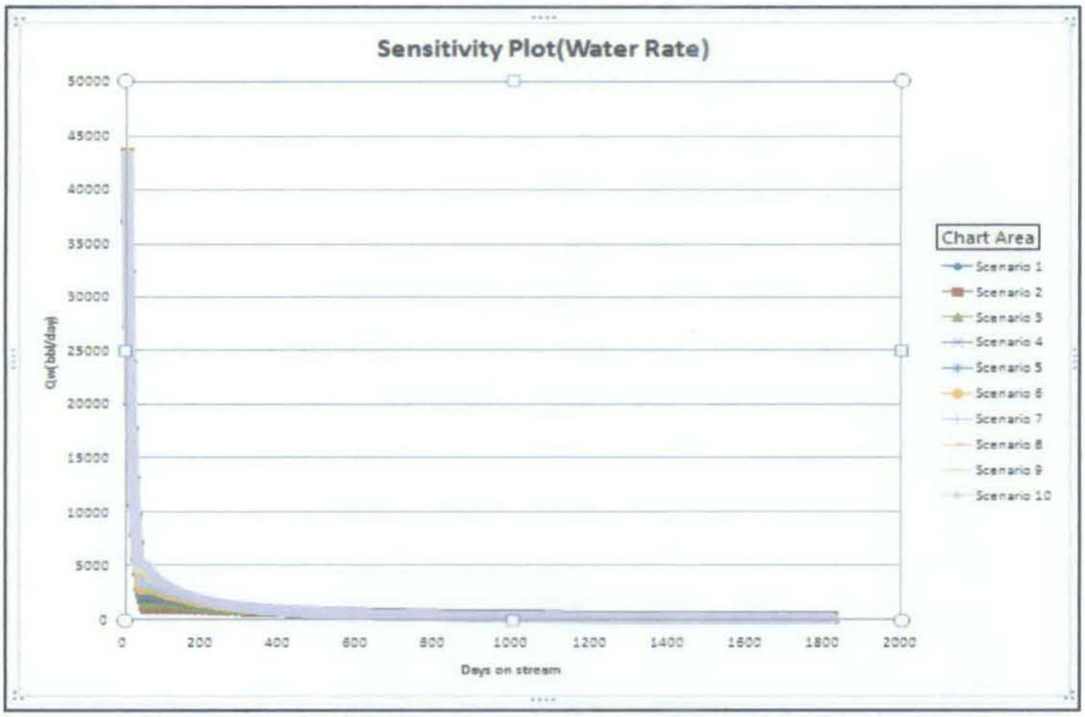


Figure 4.2: Forecasted water rates for the given range of Initial Gas content

For all the cases, the peak water rate is the same. For the highest Initial Gas content case, when the water rate dropped till 5000Bbls/day; gas as began to produce and therefore

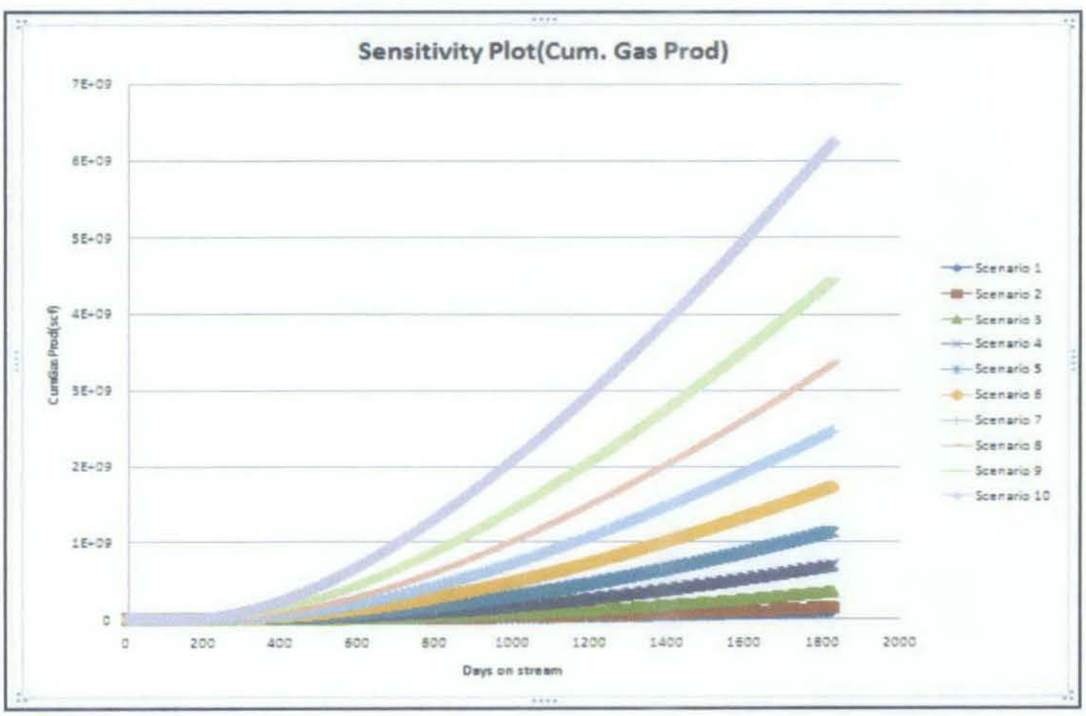


Figure 4.3: Forecasted Cumulative Gas production for the given range of Initial Gas content

This is just the same as the Forecasted Gas rate, whereby the Scenario with the highest Initial Gas content gives the Highest Cumulative Gas Production. Higher Gas content gives shorter dewatering process and more gas is been produced.

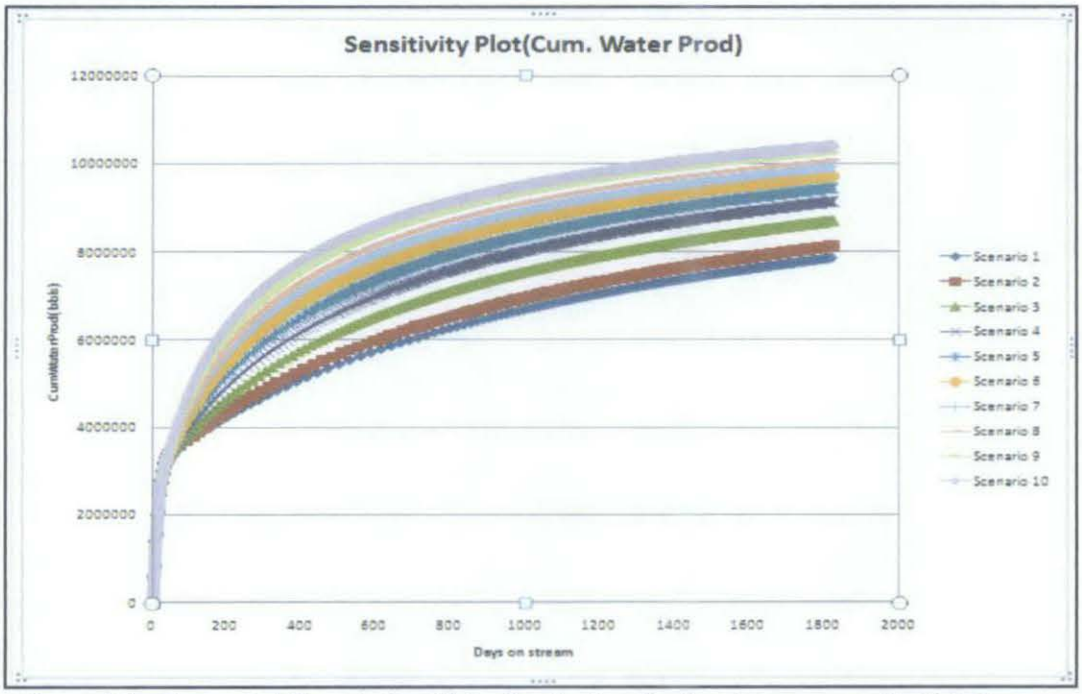


Figure 4.4 : Forecasted Cumulative Water Production for the given range of Initial Gas content

4.3.2 Range of Permeability

For this, range of Permeability from 1.01e-6 to1010 mD is used for forecasting. (see **Appendix 1**, Table A1-**3**)

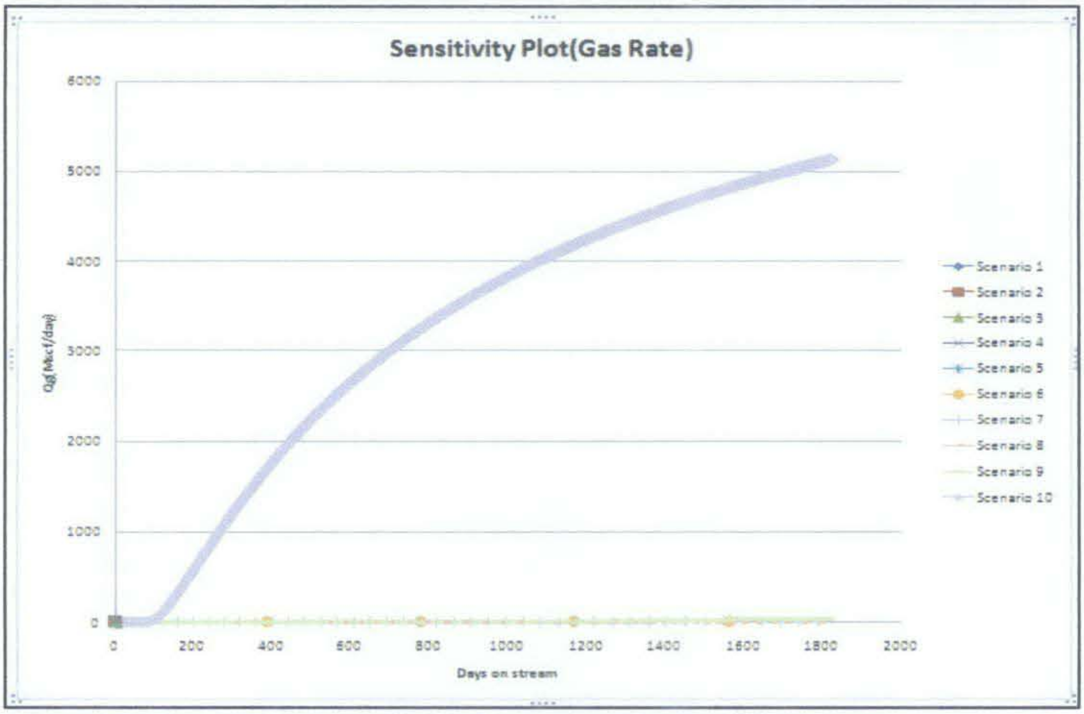


Figure 4.5: Forecasted gas rates for the given range of permeability

This figure clearly proves the effect of permeability to the whole CBM production. The higher the permeability (as we go from Scenario 1 to 10), the higher the methane production from the coal. The highest permeability within the range gives the highest Peak Gas rate.

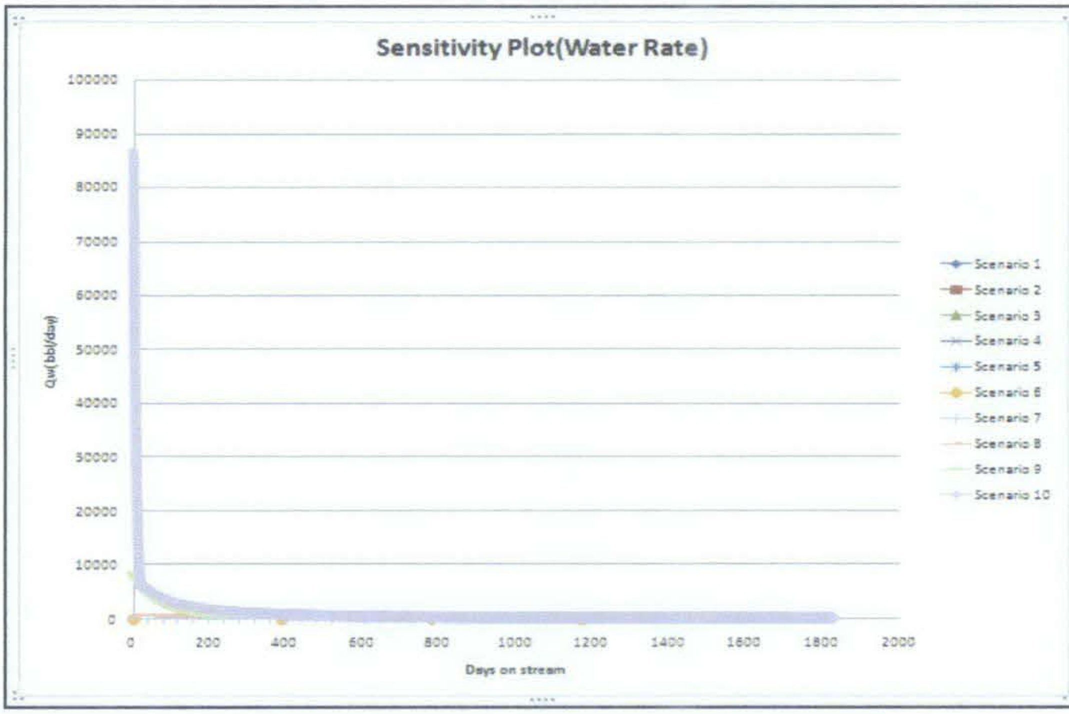


Figure 4.6: Forecasted water rates for the given range of permeability

The effect of permeability on the Water production is the same as it has on gas production. Higher permeability gives higher water production out of the coal reservoir.

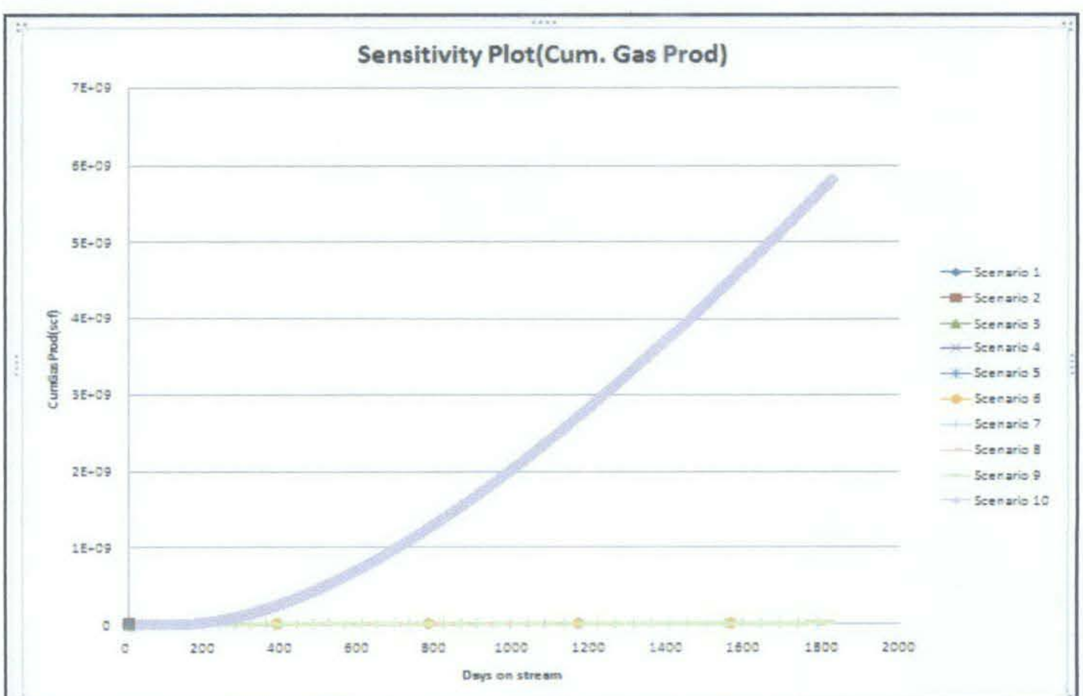


Figure 4.7: Forecasted Cumulative Gas Production for the given range of permeability

Higher the permeability, faster is the duration of dewatering process which eventually gives out more methane from the coalfield during the whole production period of 5years.

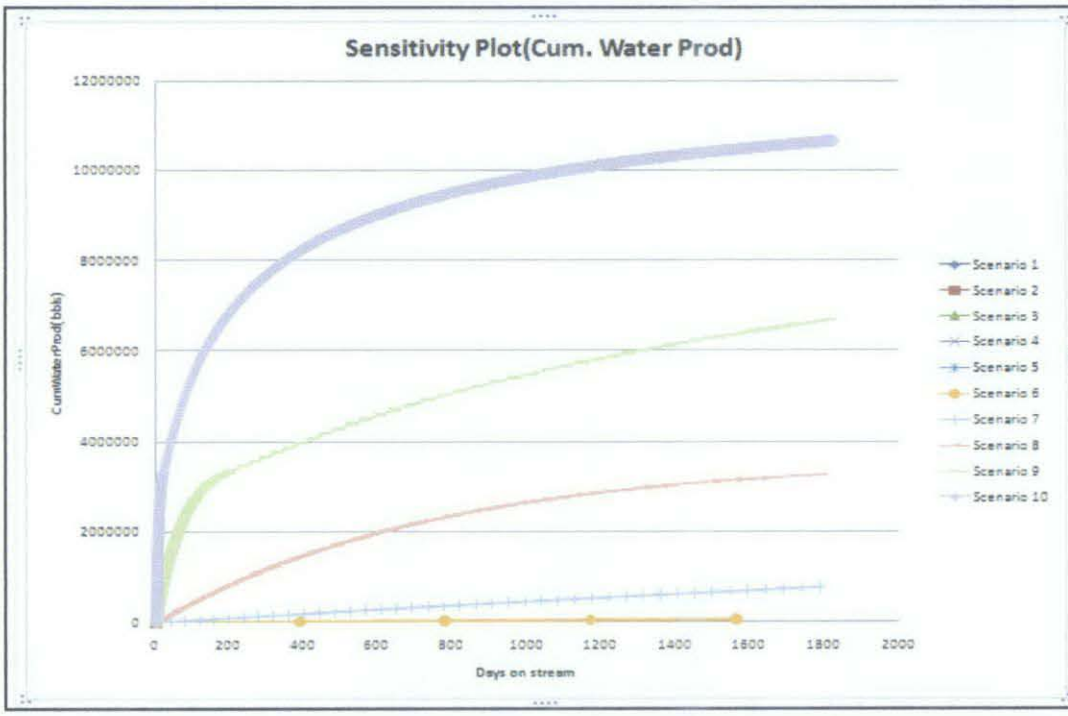


Figure 4.8: Forecasted Cumulative Water Production for the given range of permeability

Higher the permeability also gives more water production as the dewatering process is occurring even faster. Thus, Scenario 10 gives the highest Cumulative Water Production over the period of 5 years.

4.3.3 Range of Porosity

For this, range of Porosity from 0.0001 to 0.5 is used for forecasting. Results of the whole production can be seen in **Appendix 1,Table A1-4**

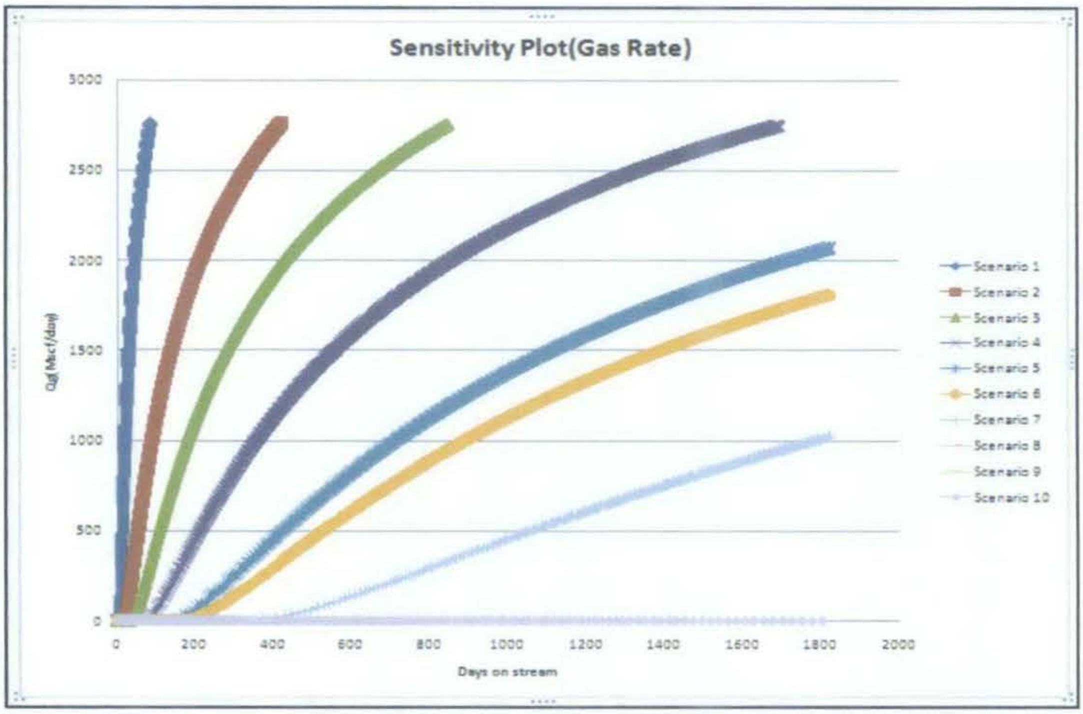


Figure 4.9: Forecasted gas rates for the given range of porosity

The higher porosity of the coal, the lower the methane gas production over a period of time. This is totally opposite for the increase of permeability. This will be further explained in the discussion.

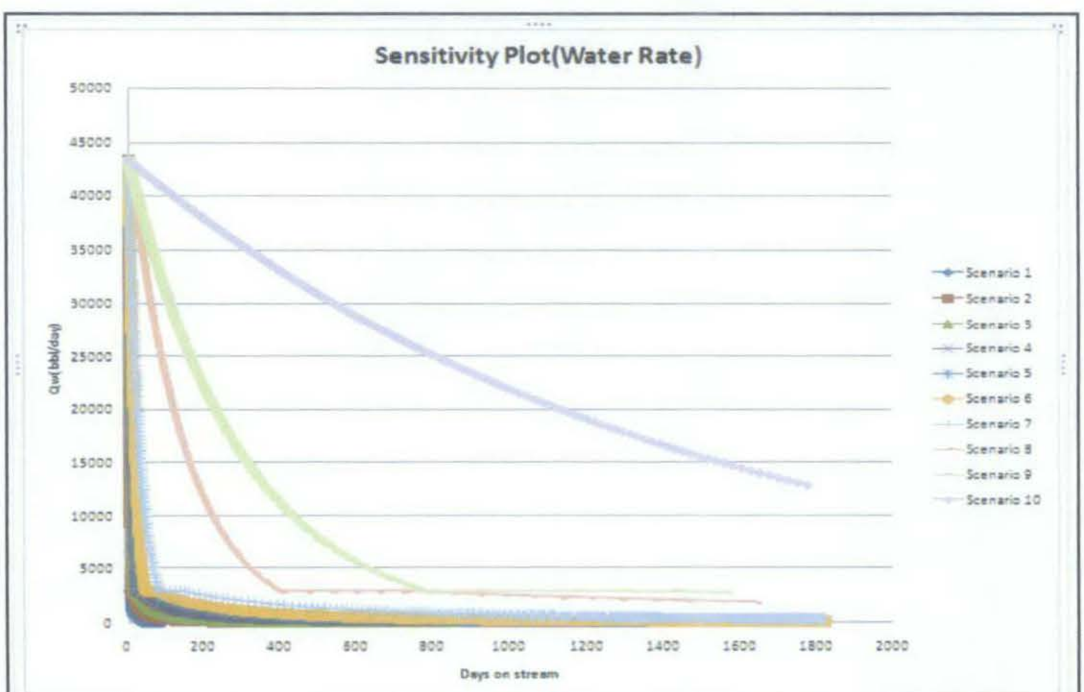


Figure 4.10: Forecasted water rates for the given range of porosity

With the same reservoir size, lower porosity gives faster "dewatering" process. Therefore, it is clearly understandable that the lowest porosity has the fastest decline in water production due to this fastest dewatering process.

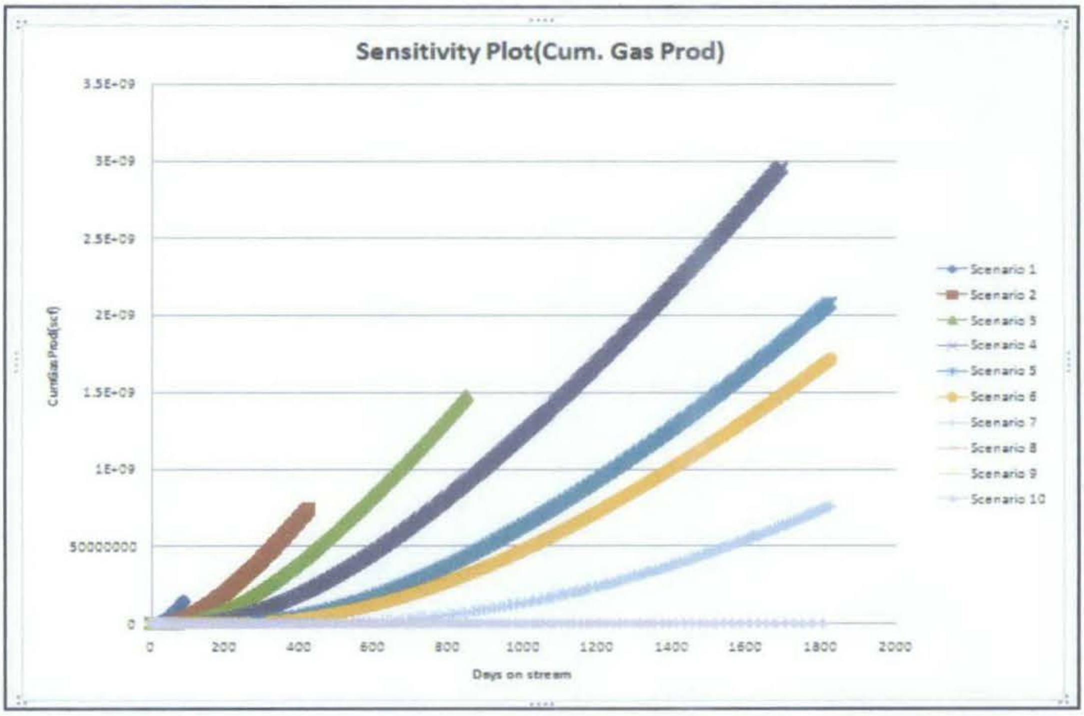


Figure 4.11: Forecasted Cumulative Gas Production for the given range of porosity

The smallest porosity gives the most production, due to the size of array in the CBM Forecast Tool which limits the number of values stored in the forecast tool. This causes the shorter plot for higher porosity.

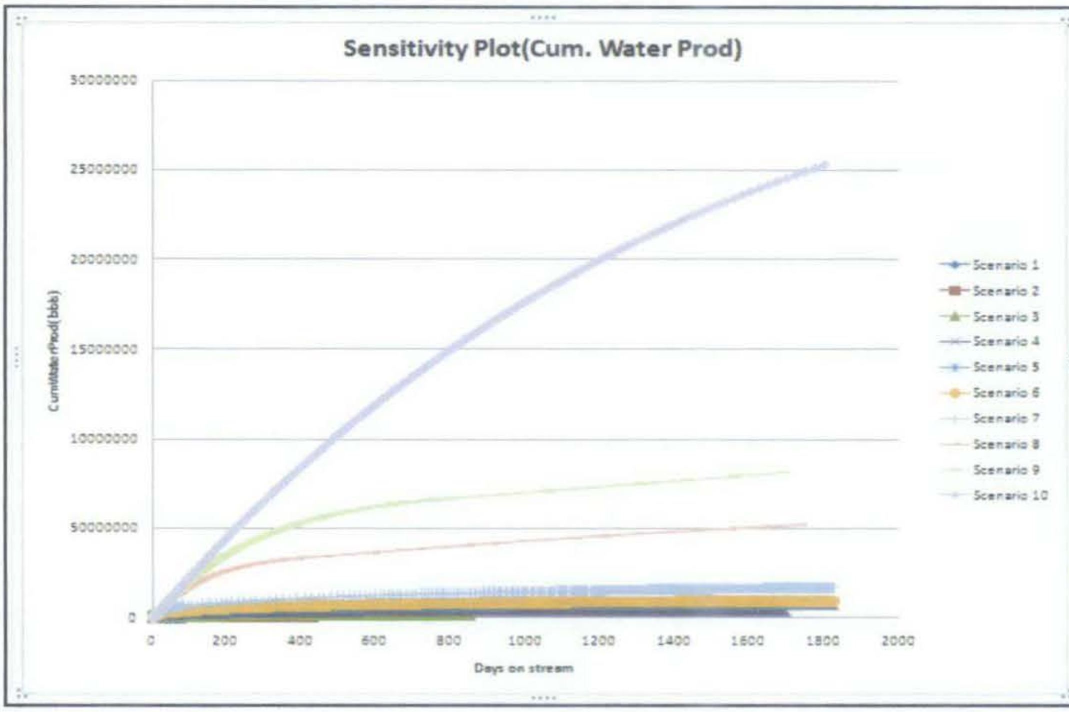


Figure 4.12: Forecasted Cumulative Water Production for the given range of porosity

4.3.4 Range of Skin

For this, range of Porosity from 0 to 9 is used for forecasting. Results are tabulated in **Appendix 1**,Table A1-**5**.

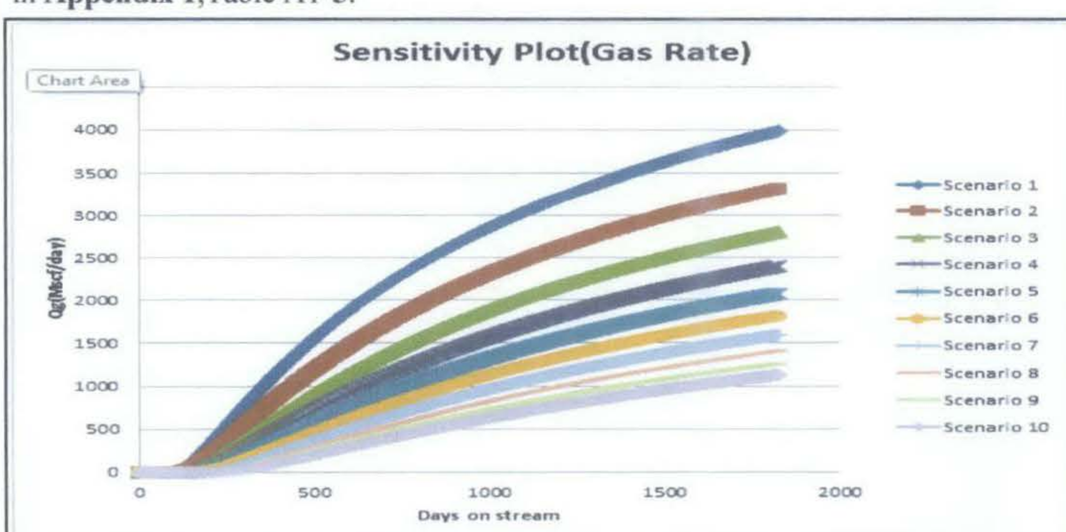


Figure 4.13: Forecasted gas rates for the given range of skin

Negative skin represents the stimulated well and thus gas production is highest comparatively to higher skin values. Lowest skin (Scenario 1) gives the highest peak gas rate.

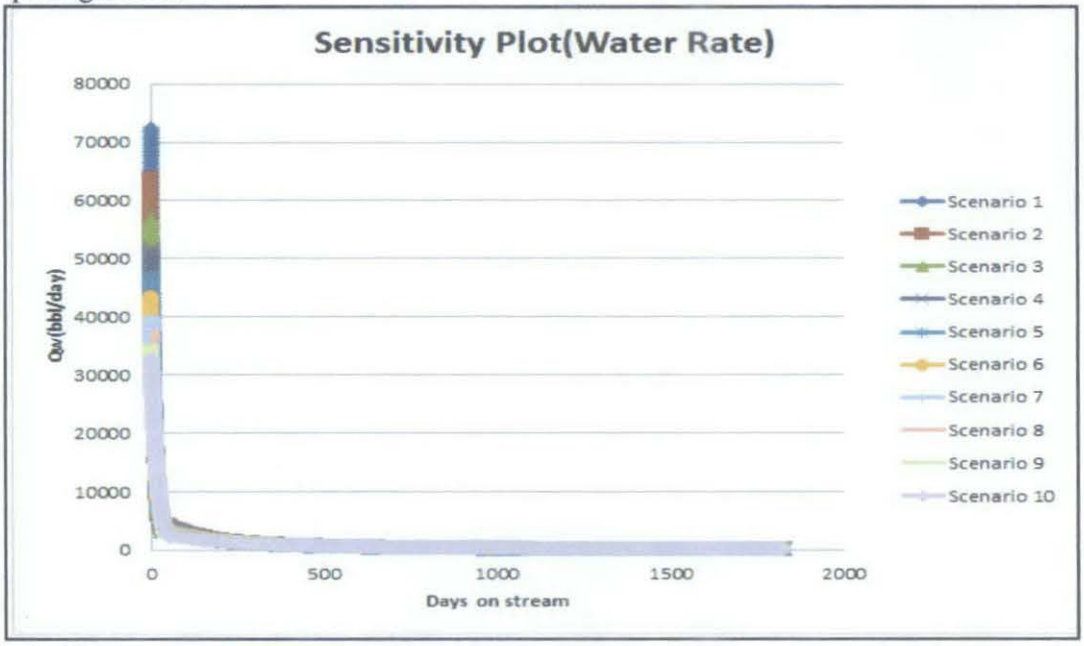


Figure 4.14: Forecasted water rates for the given range of skin

Same goes to water production; the lowest skin gives the highest water production rate. This is clearly shown by the lowest skin value gives the highest water production rate.

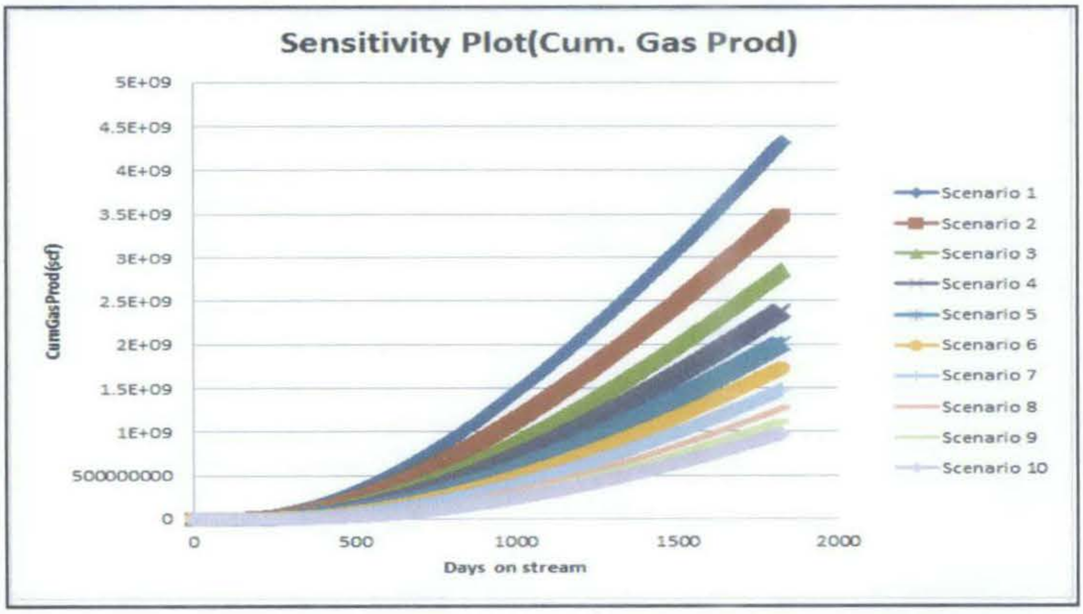


Figure 4.15: Forecasted Cumulative Gas Production for the given range of skin

As mentioned earlier in the discussion of Figure 4.15, the lowest skin value gives the most gas production. Given the same reservoir size and condition, more methane gas is produced over the period of 5 years.

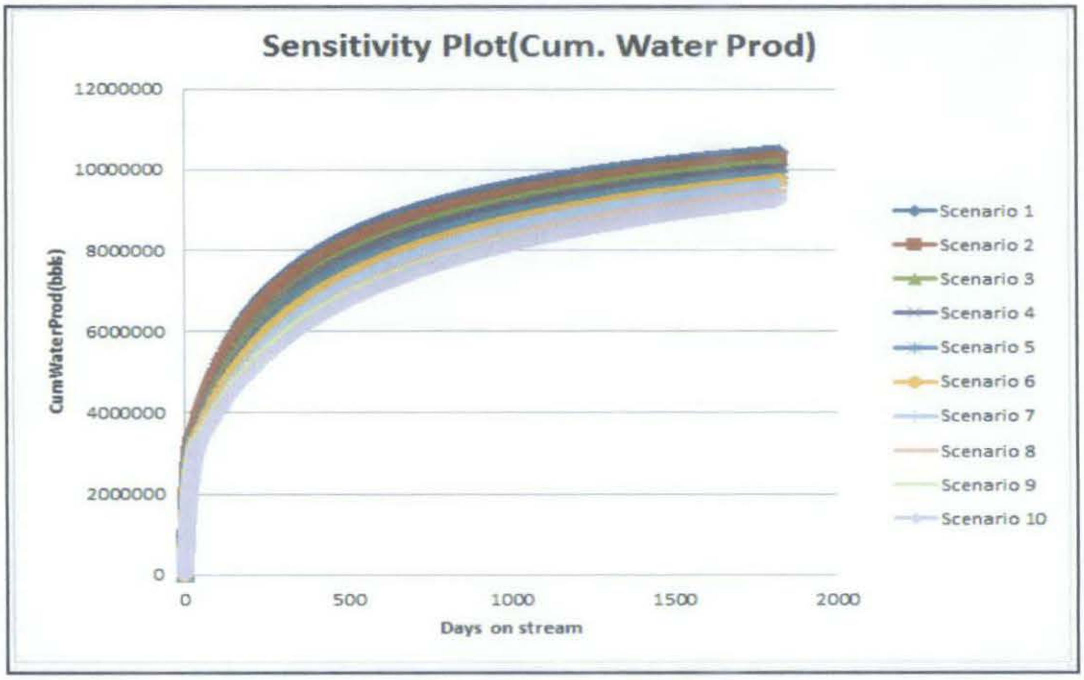


Figure 4.16: Forecasted Cumulative Water Production for the given range of skin

The lower the skin value, "dewatering" process occurs even faster and thus the cumulative water production is also higher. This is clearly shown by Scenario 1 (Skin = -5) giving the highest cumulative water production.

4.4 Discussion

Based on the results obtained through the Forecast tool, result comparison is done to identify the optimum properties of Coal which would give optimum production.

4.4.1 Range of Initial Gas Content

Data from Mukah-Balingian Coalfield shows that the range of Initial gas content from the methane content estimation method, is given from 86.286 to 173.36 scf/ton. Using the Forecast Tool, 10 scenario was forecasted given the initial gas content was within this range. The scenario with the highest Initial Gas Content (Gci = 173.36scf/ton) gives the highest value of Ultimate Gas Recovery (6.23 Bscf) and highest Peak Gas Rate (5714.232 Mscf/day). The scenario with the lowest Initial Gas content gives the opposite.

4.4.2 Range of Permeability

Absolute permeability also effects the production of methane from coal. The range of permeability of coal from a 1.01e-6 to 1010 mD [11] is tested on the forecast tool. The higher the permeability, the higher the methane gas production whereby permeability of 1010 mD gives highest Peak Gas rate (5141.71 Mscf/day) and highest Ultimate Gas Recovery (5.831 Bscf). This permeability helps the mobility of the gas through the fractures and to the well. High Permeability does not affect the gas in place but it affects the time of dewatering. Due to that, gas rate reached peak faster and higher but decline faster too [3].

4.4.3 Range of Porosity

Higher porosity does not mean higher production. In CBM, lowest porosity gives highest Ultimate Recovery. It is very much needed to be noted that for Scenario 1 with the lowest porosity of 0.0001 gives much lower Ultimate Recovery than porosity of 0.0005. This is due to the fact that the reservoir is still producing but the calculation limit of the forecasting tool has been achieved. This is one of the greatest set-back of Microsoft Excel® 2007 and Visual Basic of Application (VBA). Porosity does not affect the gas in place. As in coal, gas is divided to two types which are free gas and adsorbed gas. As the porosity decreases, the amount of free gas reduces until it's negligible. Reduction in porosity also indicates the reduction of cleat volume. Thus, dewatering occurs faster and therefore reaches higher peak gas rate of production [3]. The lowest porosity (ϕ=0.0001) gives highest Peak gas rate of 4208.918 Mscf/day and ultimate recovery of 5.718 Bscf with the recovery factor of 51.07 %.

4.4.4 Range of Skin

Skin is created during the production. Therefore, during forecasting skin =0 is used as the reference value. Positive skin which also damaged well gives lower rates than the negative ones (enhanced well). The lowest skin (S = -5) gives the highest peak gas rate of 3982.843 Mscf/day with the Ultimate recovery of 4.318 Bscf with a recovery factor of 51.07%.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions

- Higher permeability, faster dewatering process, higher peak gas rate
- Lower porosity, lesser free gas with higher adsorbed gas, small cleat volume so faster dewatering process, higher peak gas rate.
- Higher initial gas content, higher adsorbed gas; with the same dewatering process occurring gives higher peak gas rate and more recovery.
- More enhanced the well is (negative skin), the more faster it dewaters and gives higher peak gas rate.
- Using the range given, highest peak gas rate is 5714.232 Mscf/day, highest ultimate recovery value is 6.23 Bscf and finally highest recovery rate is 63.36%.

5.2 Recommendation

In order to increase the CBM production, we can inject Carbon Dioxide (CO_2) or Nitrogen (N_2) into the reservoir. This is called the Enhanced CBM Recovery. Higher affinity gas means, it's more preferable by coal to be adsorbed into its surface. Therefore, when CO_2 or N_2 is injected into the well, the remaining methane is released from the coal surface and thus we could get 100% recovery from a known field. This is due to N_2 and CO_2 reduces the partial pressure of methane which encourages the methane to desorped from the surface of coal. [12]

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APPENDIX 1

Table A1-1: Reference Input data for forecasting

Input data (reference values)		
Depth	ft	167.32
Lagmuir Volume(VL)	scf/ton	714.29
Langmuir Pressure(PL)	psia	1024.5
Initial Pressure (Pi)	psia	2000
Desorption Pressure	psia	227.564
Bottomhole Flowing Pressure (Pwf)	psia	100
Ash Content (a)	%	2.7
Moisture(w)	%	15
Initial Gas Content (Gci)	scf/ton	129.823
Drainage Area (A)	acres	216215
Net Pay (h)	ft	29.69
Bulk Density (rho)	g/cm3	1.4
Reservoir Temperature (T)	Farenheit	98
Fracture Porosity (ø)	%	0.005
Water Compressibility (Cw)	psia-1	2.09E-05
Formation Compressibility (Cf)	psia-1	0.000138
Skin		0
Permeability (k)	md	505
Initial Water Saturation (Swi)		1
Bw	rbbl/stb	1.02
MiuWater (μ)	cp	0.364
Wellbore Radius – rw	ft	0.1

Table A1-2: Range of Initial Gas Content values used for forecasting

Initial gas Content,Gci (scf/ton)	Peak Gas Rate, Mscf/day	UR(gas), Bscf	UR(water), Bscf	Recovery Factor (RF),%
Gci=86.286	147.329	0.092747	0.007851	26.384
Gci=90	217.025	0.147067	0.008137	29.421
Gci=100	469.082	0.362642	0.008720	36.479
Gci=110	817.473	0.689278	0.009138	42.254
Gci=120	1266.905	1.139428	0.009458	47.066
Gci=130	1823.922	1.726104	0.009710	51.138
Gci=140	2496.863	2.464033	0.009916	54.628
Gci=150	3294.869	3.367379	0.010087	57.653
Gci=160	4230.031	4.457539	0.010232	60.300
Gci=173.36	5714.232	6.237660	0.010394	63.359

Table A1-3: Range of Permeability values used for forecasting

Permeability, k (mD)	Peak Gas Rate, Mscf/day	UR(gas), Bscf	UR(water), Bscf	Recovery Factor (RF),%
k=0.000001013	0	0.00	0.00	51.07132
k=0.0000101	0	0.00	0.00	51.07132
k=0.000101	0	0.00	0.00	51.07132
k=0.00101	0	0.00	0.00	51.07132
k=0.0101	0	0.00	0.00	51.07132
k=0.101	0	0.00	0.00007561	51.07132
k=1.01	0.00000	0.00	0.00077500	51.07132
k=10.1	0.00000	0.00	0.00327012	51.07132
k=101	49.11082	0.02036937	0.00666097	51.07132
k=1010	5141.70930	5.81345641	0.01065260	51.07132

Table A1-4: Range of Porosity values used for forecasting

Porosity, ø	Peak Gas Rate, Mscf/day	UR(gas), Bscf	UR(water), Bscf	Recovery Factor (RF),%
ø=0.0001	4208.91824	1.86348	0.00024	51.07132
ø=0.0005	3942.04975	5.71816	0.00120	51.07132
ø=0.001	3449.66034	4.58065	0.00231	51.07132
ø=0.002	2821.08943	3.32737	0.00436	51.07132
ø=0.004	2070.84373	2.08415	0.00803	51.07132
ø=0.005	1812.84218	1.71376	0.00971	51.07132
ø=0.01	1024.97547	0.75914	0.01702	51.07132
ø=0.05	8.01829	0.00045	0.05213	51.07132
ø=0.1	0.00000	0.00000	0.08153	51.07132
ø=0.5	0.00000	0.00000	0.25329	51.07132

Table A1-5: Range of Skin values used for forecasting

Skin	Peak Gas Rate, Mscf/day	UR(gas), Bscf	UR(water), Bscf	Recovery Factor (RF),%
S=-5	3982.843	4.317823	0.010431	51.071
S=-4	3313.013	3.482074	0.010266	51.071
S=-3	2800.146	2.858758	0.010112	51.071
S=-2	2397.894	2.382875	0.009969	51.071
S=-1	2075.742	2.011034	0.009834	51.071
S=0	1812.842	1.713763	0.009706	51.071
S=1	1595.727	1.473982	0.009585	51.071
S=2	1414.121	1.277711	0.009470	51.071
S=3	1260.149	1.114081	0.009359	51.071
S=4	1129.254	0.978410	0.009255	51.071

APPENDIX 2

Testing CBM Forecast Tool

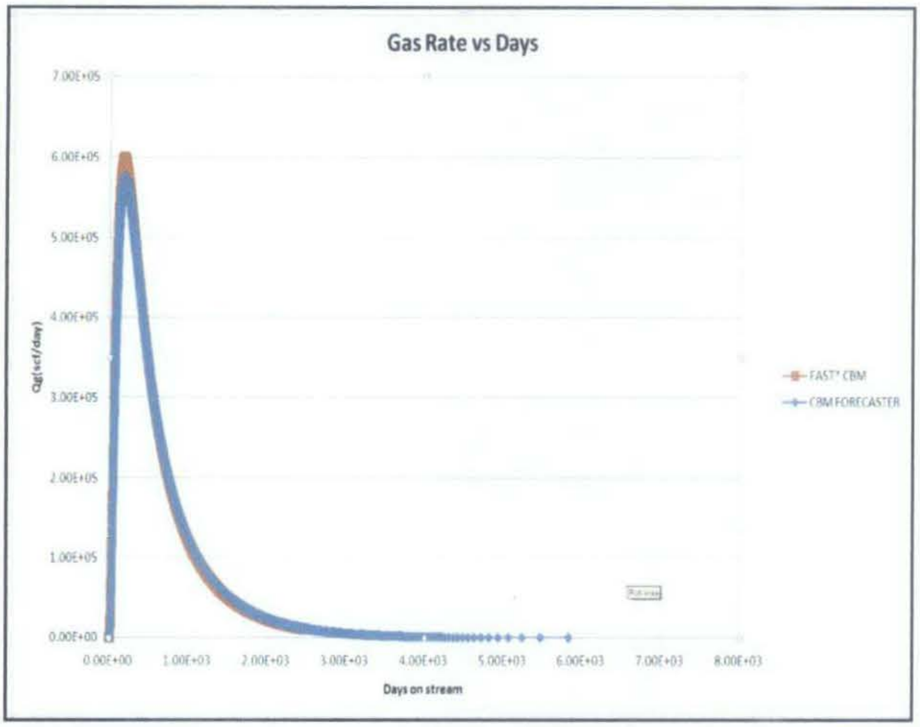
CBM Forecast Tool is been tested using almost 100 various different parameters once it has been known to given similar results with F.A.S.T CBM™. Following is an example of a set of data used to test the Forecast Tool and followed by comparison with the F.A.S.T CBM™.

A) Values of Parameter used:

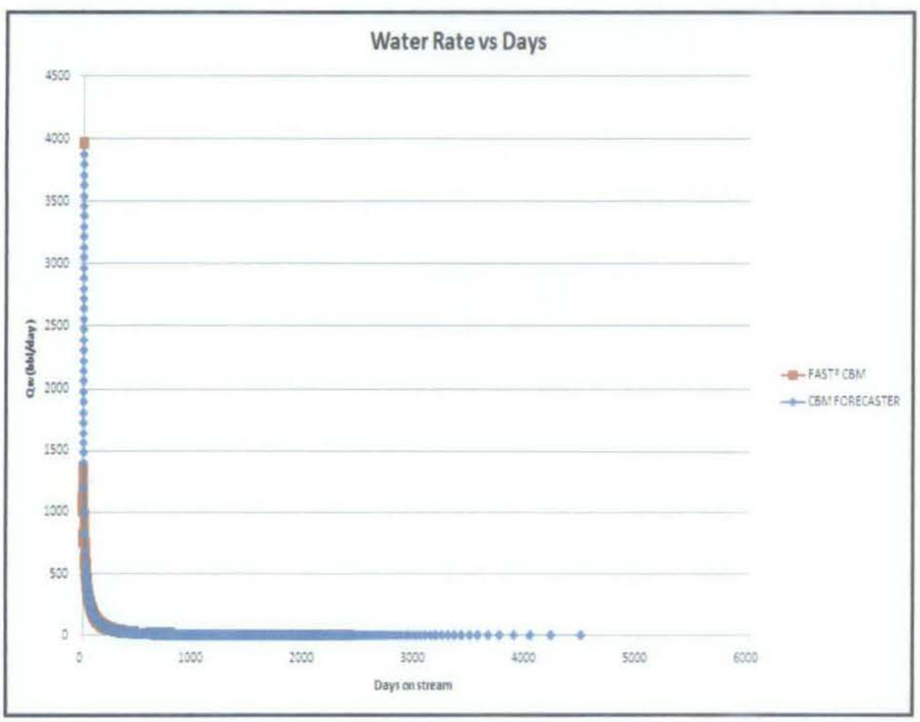
Table A2-1: Values used to test CBM Forecast Tool

PARAMETERS	VALUE
Langmuir Methane Volume, VL	14.7 cm^3 /g
Langmuir Methane Pressure, PL	2050 kPa
Initial Pressure, Pi	4000 kPa
Initial Gas Content, GCi	7 cm^3 /g
Drainage Area, A	12.14 ha
Net Pay, h	22 m
Bulk Density, ρ_{bulk}	1.65 g/ cm^3
Temperature, T	34°C
Porosity, Φ	0.65 %
Ash Content, a	20%
Moisture Content, w_c	2.74%
Permeability, k	100mD
Skin	10
Wellbore Radius	0.091m
Well-flow Pressure, Pwf	689 kPa

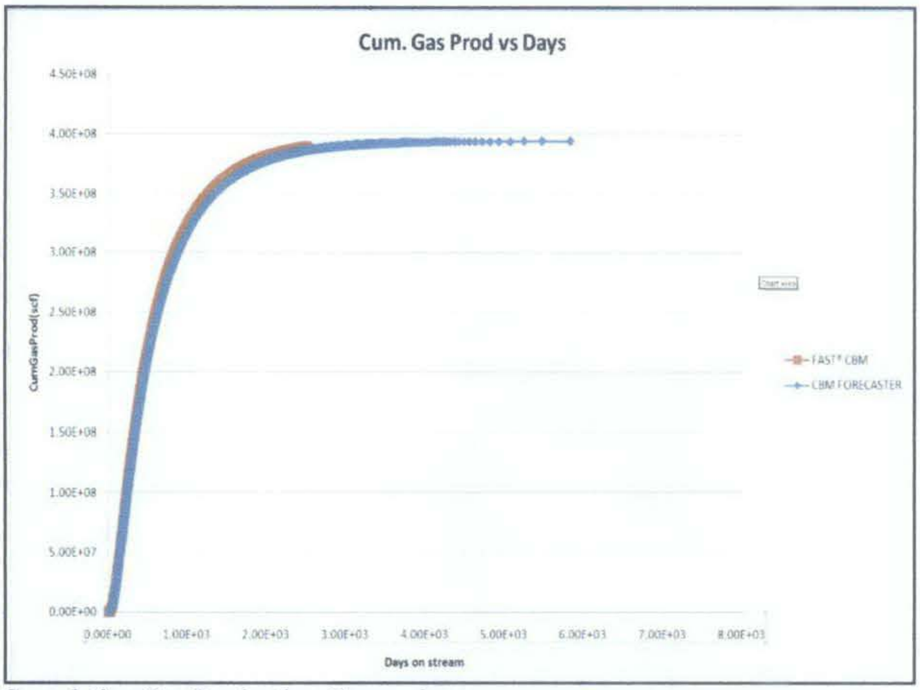
B) Comparison with F.A.S.T CBM™.



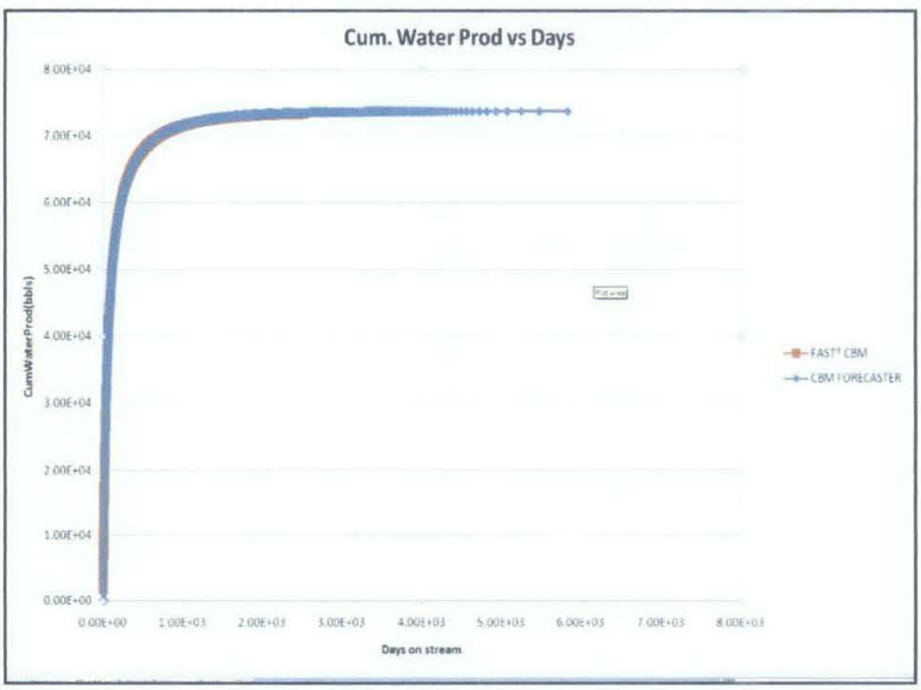
Gas Rate Comparison



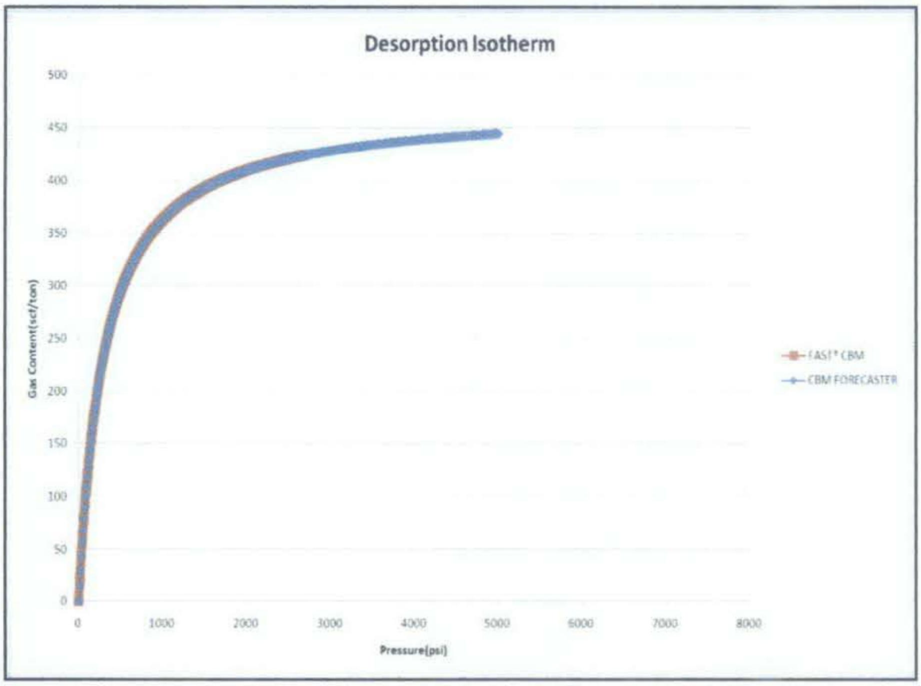
Water Rate Comparison



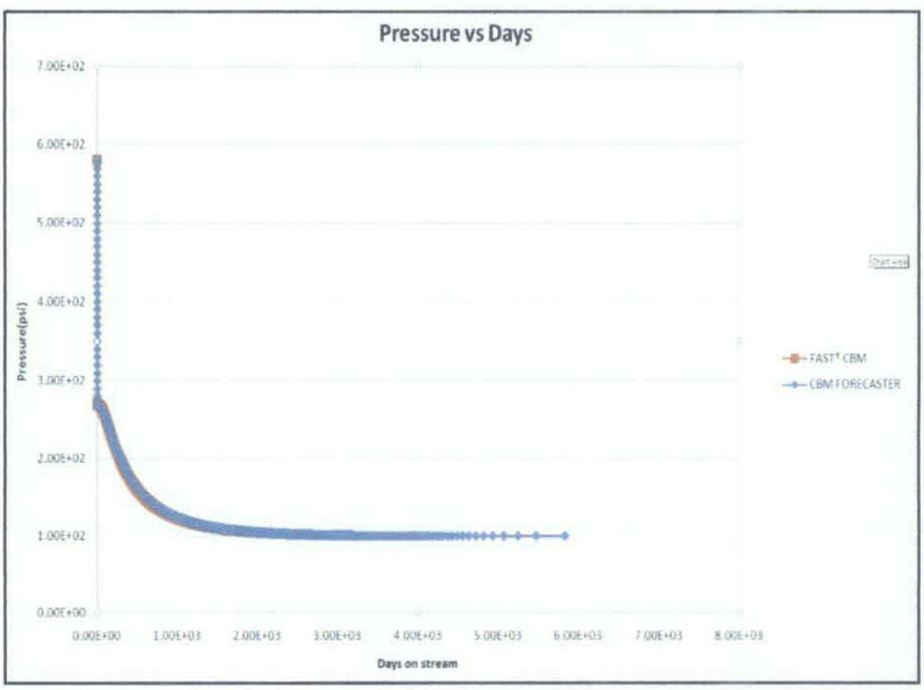
Cumulative Gas Production Comparison



Cumulative Water Production comparison



Desorption Isotherm comparison



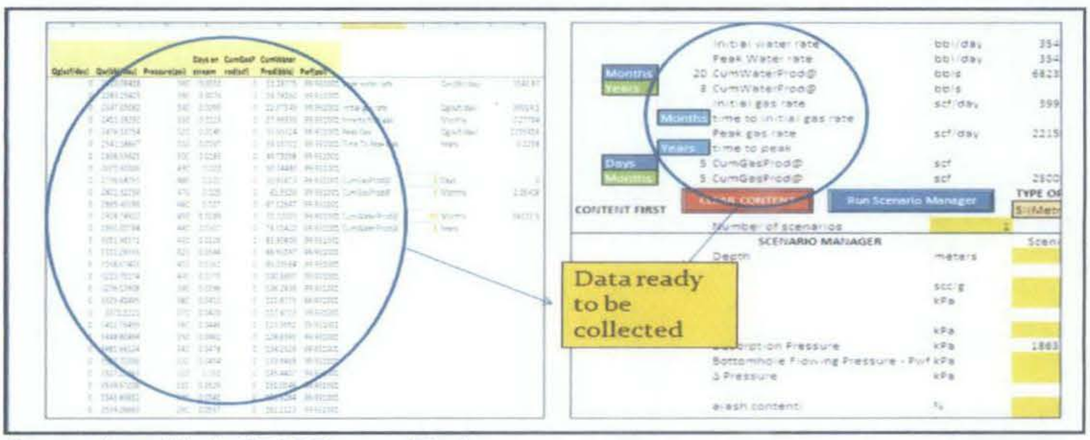
Pressure comparison

Comparison to F.A.S.T CBM™

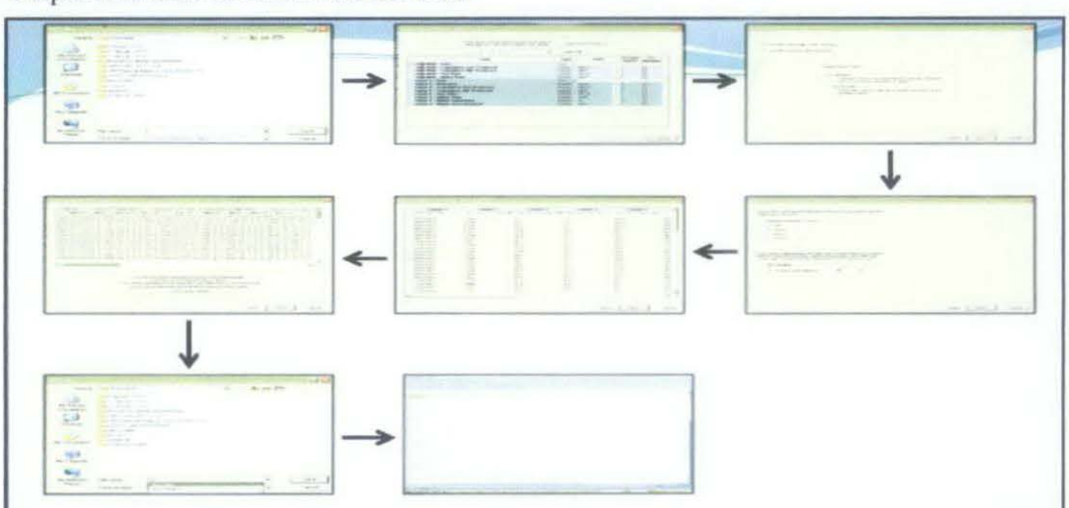
A commercially available tool- Fekete's F.A.S.T CBM™ was selected to investigate the quality of calculations in CBM Forecast Tool and its functionality. CBM Forecast Tool has the ability to forecast production similarly to e.g. F.A.S.T CBM™. But, CBM Forecast Tool has differences and advantages compared to F.A.S.T CBM™. Following are the main comparisons in which are CBM Forecast Tool's advantages over F.A.S.T CBM™ is shown.

a) Easy Data exporting

CBM Forecast Tool gives the user an easy way to export data of the forecasted production compared to F.A.S.T CBM™



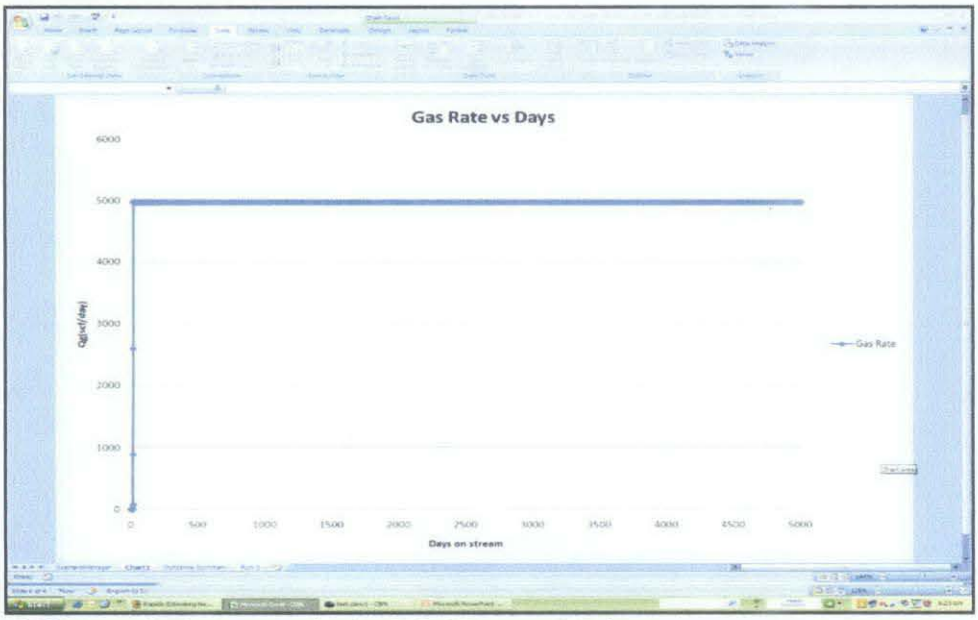
Output data table in CBM Forecast Tool



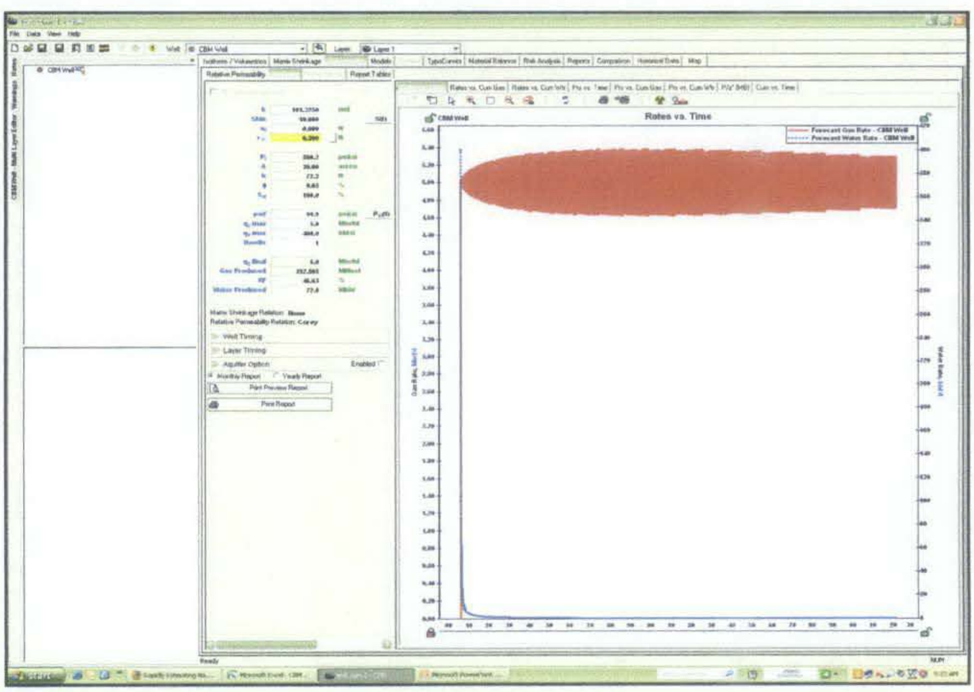
Workflow to export data in F.A.S.T CBM

b) Ability to calculate very low constraints

Compared to F.A.S.T CBM™, CBM Forecast Tool has the ability to calculate rates even when the constraints are very low with much lesser noise. This has been further proven with the test done below.



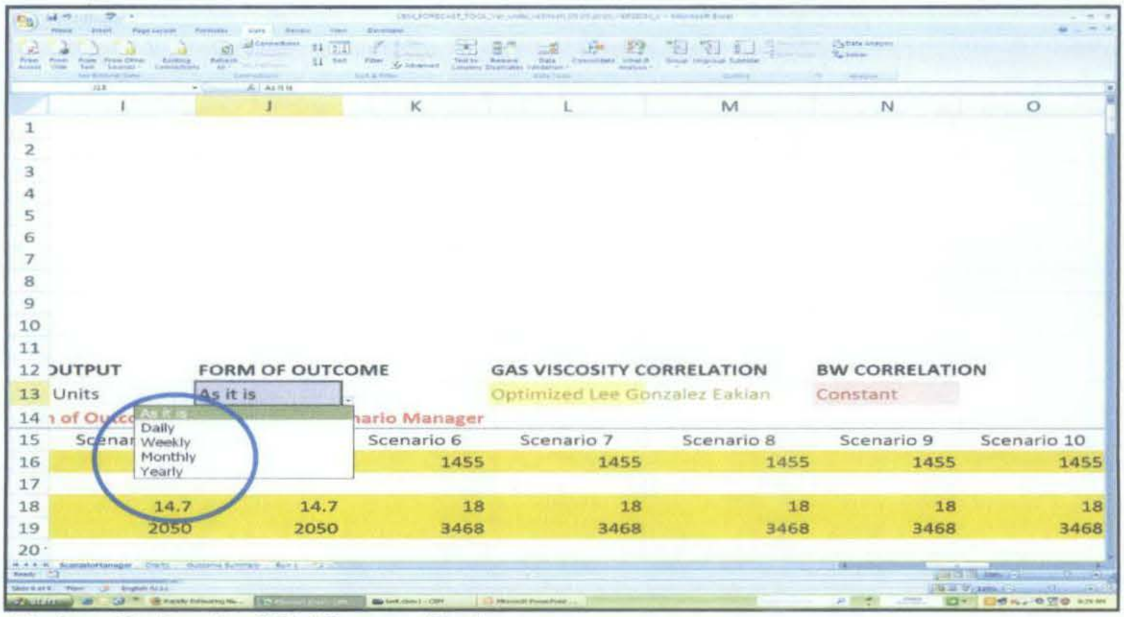
Ability to calculate constraint by CBM Forecast Tool



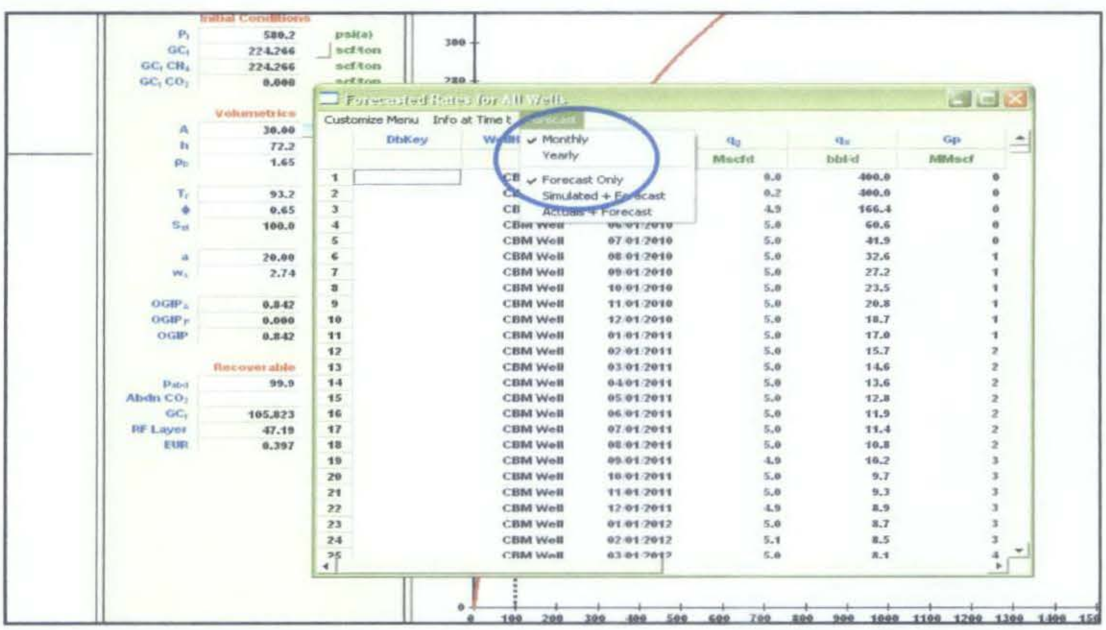
Inability to calculate low constraint by F.A.S.T CBM

c) *High Outcome Granularity*

CBM Forecast Tool gives options to its user on the outcome view. F.A.S.T CBM™ can only give its user to view the forecasted data in monthly and yearly, where else CBM Forecast Tool can forecast in daily, weekly, monthly and also yearly



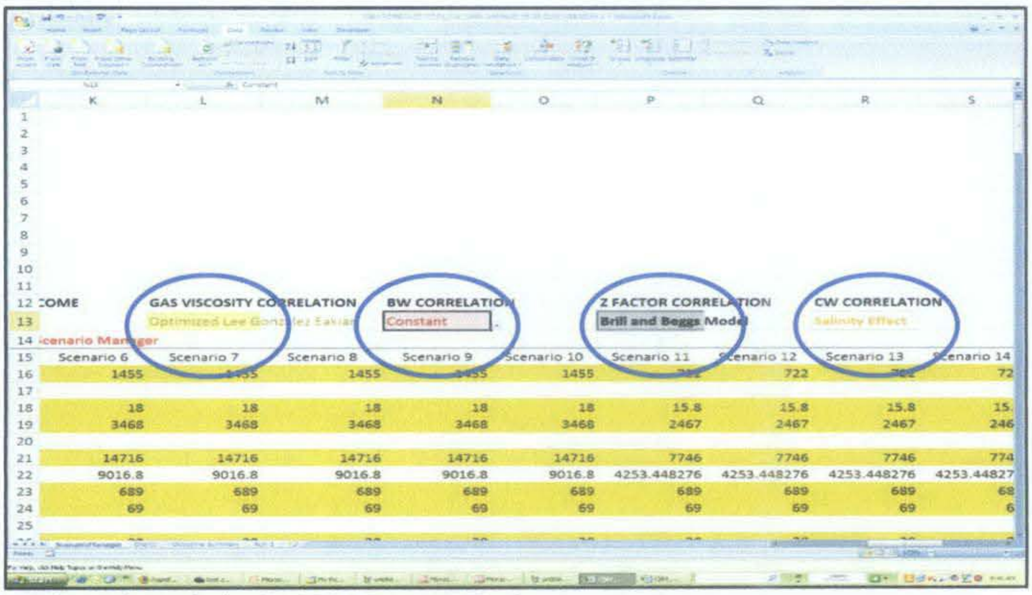
Various Choices for CBM Forecast Tool



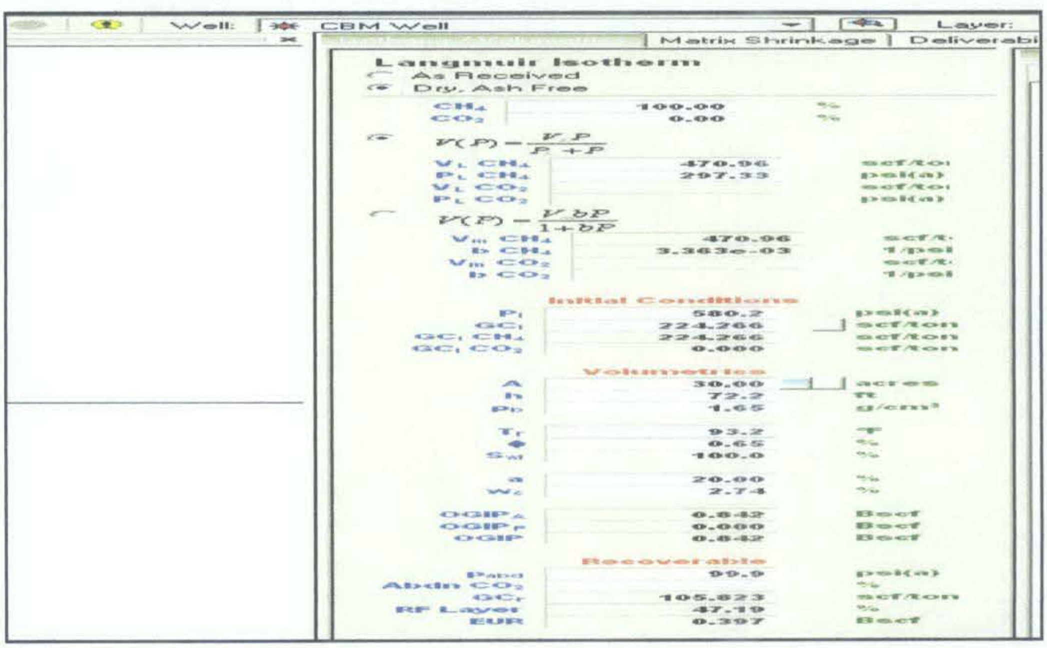
Less choices for F.A.S.T CBM

d) Vast choices of Correlation

One of the main defect in F.A.S.T CBM™ is that user does not the correlation used in his simulation and does not have many options to choose from. This has been overcome in the CBM Forecast Tool whereby the user not only knows his correlation; he also gets to choose as well.



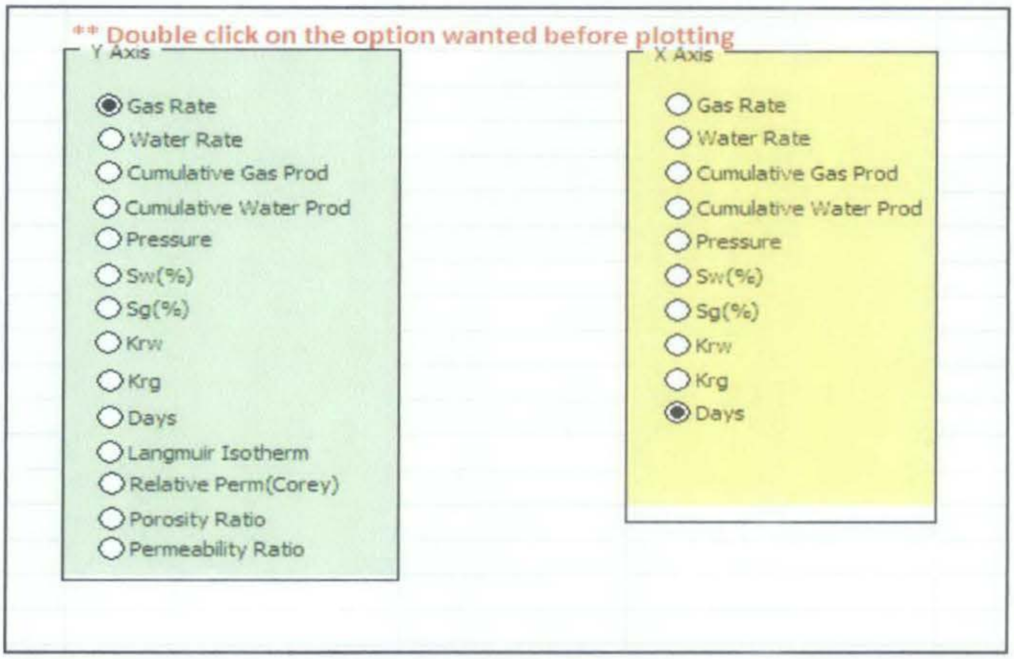
Choices of correlation in CBM Forecast Tool



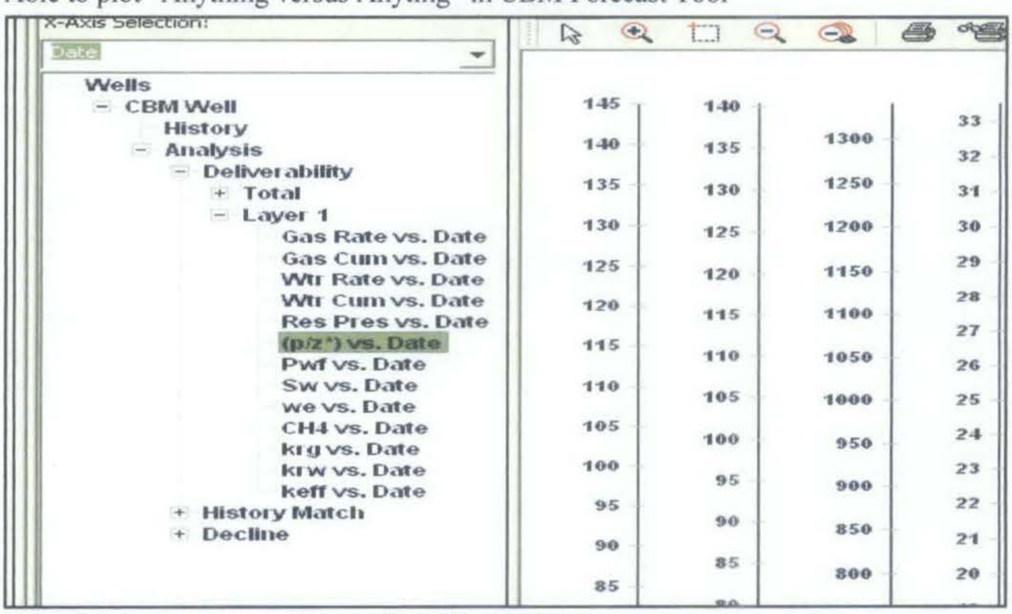
No choices in F.A.S.T CBM

e) Plot "Anything Versus Anything"

One thing that makes CBM Forecast Tool very special is the ability to plot by choosing any values for the y- axis and same goes for x- axis. For comparison purpose, F.A.S.T CBM™ could not do so. It provides a very limited choice where user can only view charts of "versus Time".



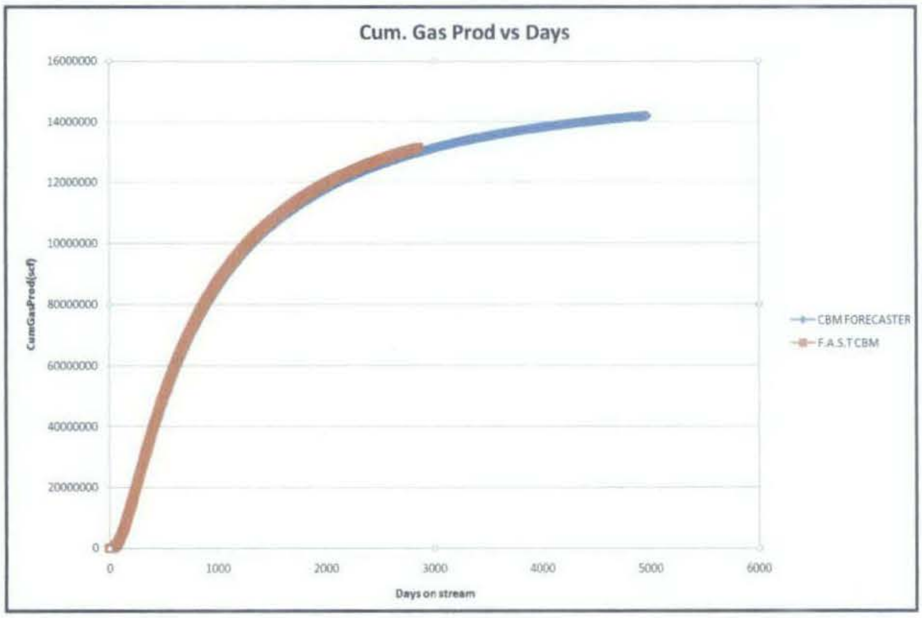
Able to plot "Anything versus Anyting" in CBM Forecast Tool



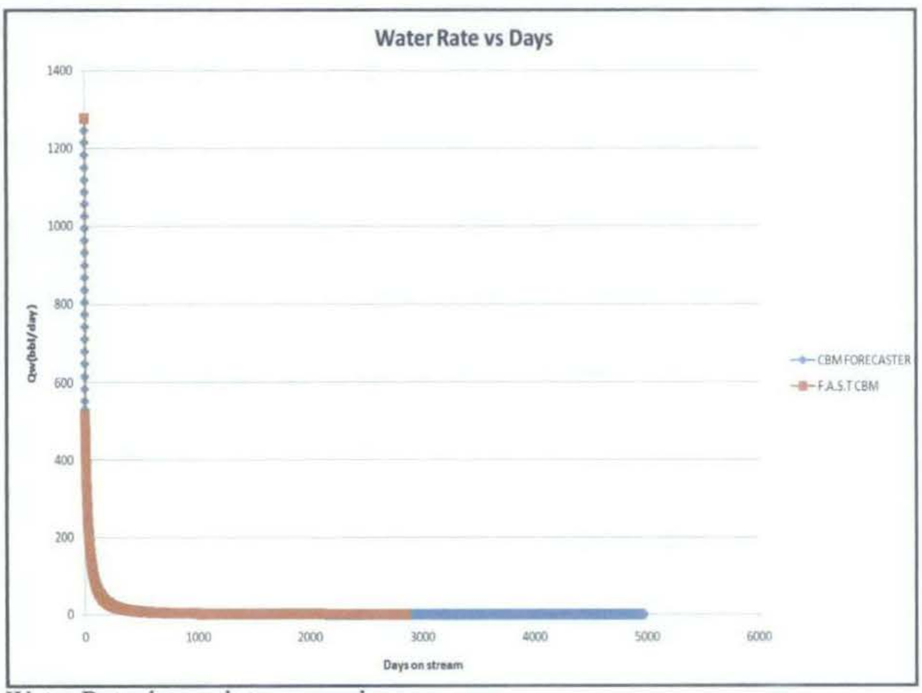
Only able to draw versus time in F.A.S.T CBM

f) More points upfront and higher granularity

Comparatively to F.A.S.T CBM™, CBM Forecast Tool gives more points up front and same time gives higher granularity of points with the given same sets of data.



Cumulative gas production data points comparison



Water Rate data points comparisons

APPENDIX 3

Additional Functionality

There is few new additional functionality which has been added to the CBM Forecast Tool but still under the process of testing. They are Risk Analysis and Tornado Plotting. The functionality will be discussed further in further following sections.

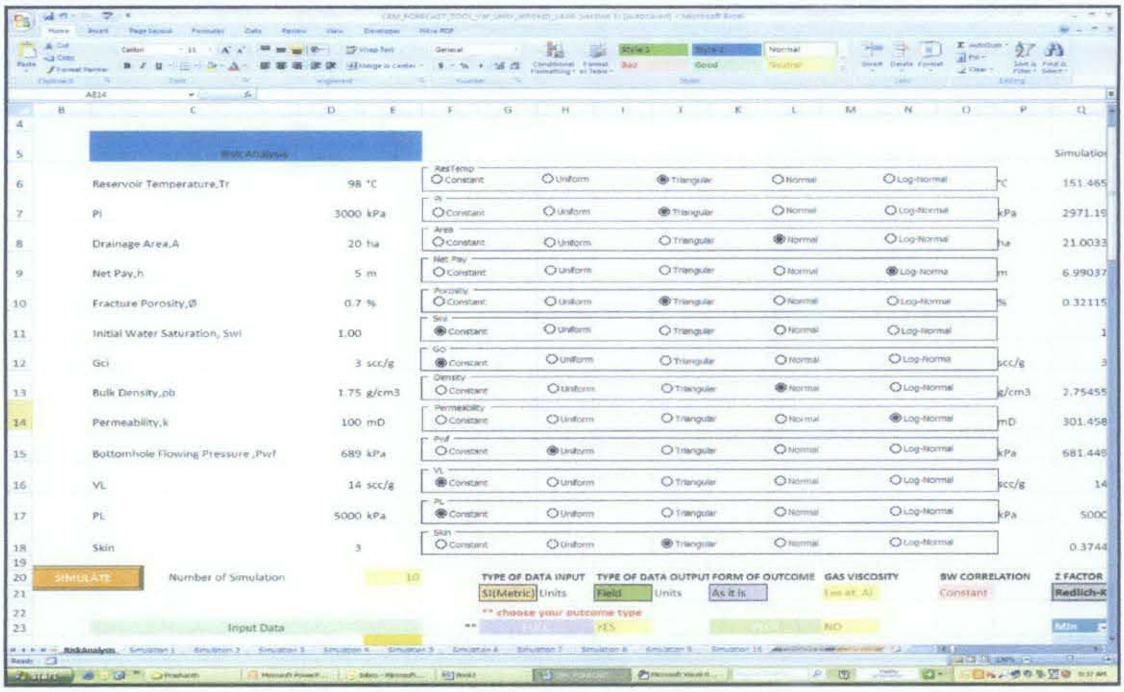
Risk Analysis and Tornado Plots

Development and operation of oil and gas production requires enormous investments which includes mainly time, money and technology. In the same time, engineers works mainly in uncertainty conditions such as the technological constraints, economic and political conditions. Therefore, decisions are made on probabilistic risk assessment and analysis (cited from ***www.goldsim.com)***

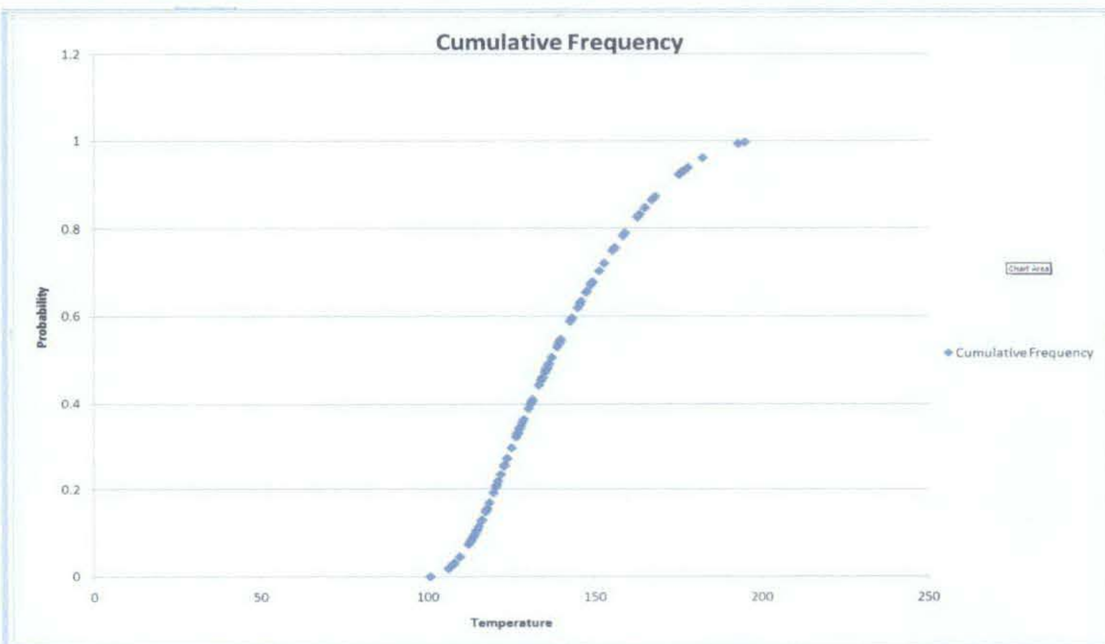
This type of analysis most frequently employs what is known as the Monte Carlo simulation method. This analysis can be accomplished using simple distribution such as the "Normal", "Lognormal", "Triangular", "Poisson" and "Gamma" statistical distribution. CBM Forecast Tool enables its user to do risk analysis with given options of distributions to choose from such as the "Uniform", "Triangular", "Normal" and "Lognormal". Using the known distribution for the selected parameters, series of parameters values are generated and the effect in production profile can be viewed.

CBM Forecast Tool also enables the user to view the cumulative frequency distribution for a selected distribution. Following will be the screenshots from the CBM Forecast Tool of this new functionality.(see and)

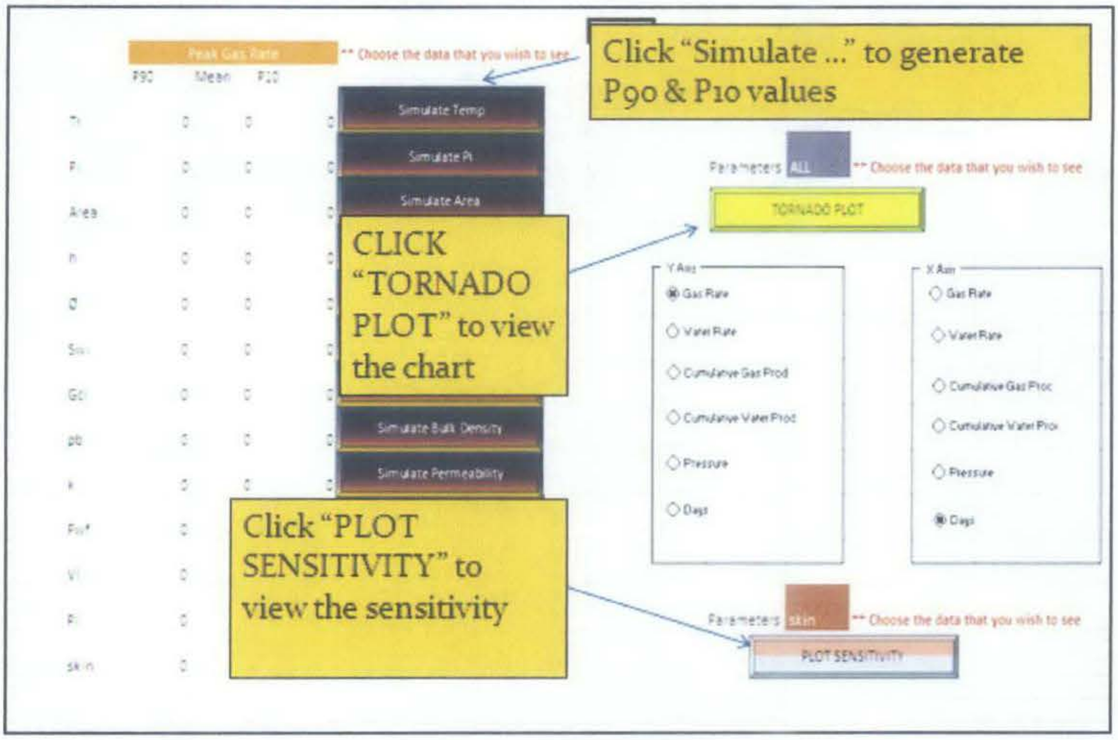
Another new functionality added in the CBM Forecast Tool is Tornado Plotting. A tornado chart is a bar chart commonly used to compare characteristics of two populations (cited from ***http://peltiertech.com/Excel/Charts/tornadochart.html***). Using the distribution selected by the user earlier on, sensitivity of the parameter towards the production profile is important for the engineer to understand how these parameters affect a reservoir production and how production can be controlled. Following are the screen shots from the CBM Forecast Tool and its Tornado plotting capability



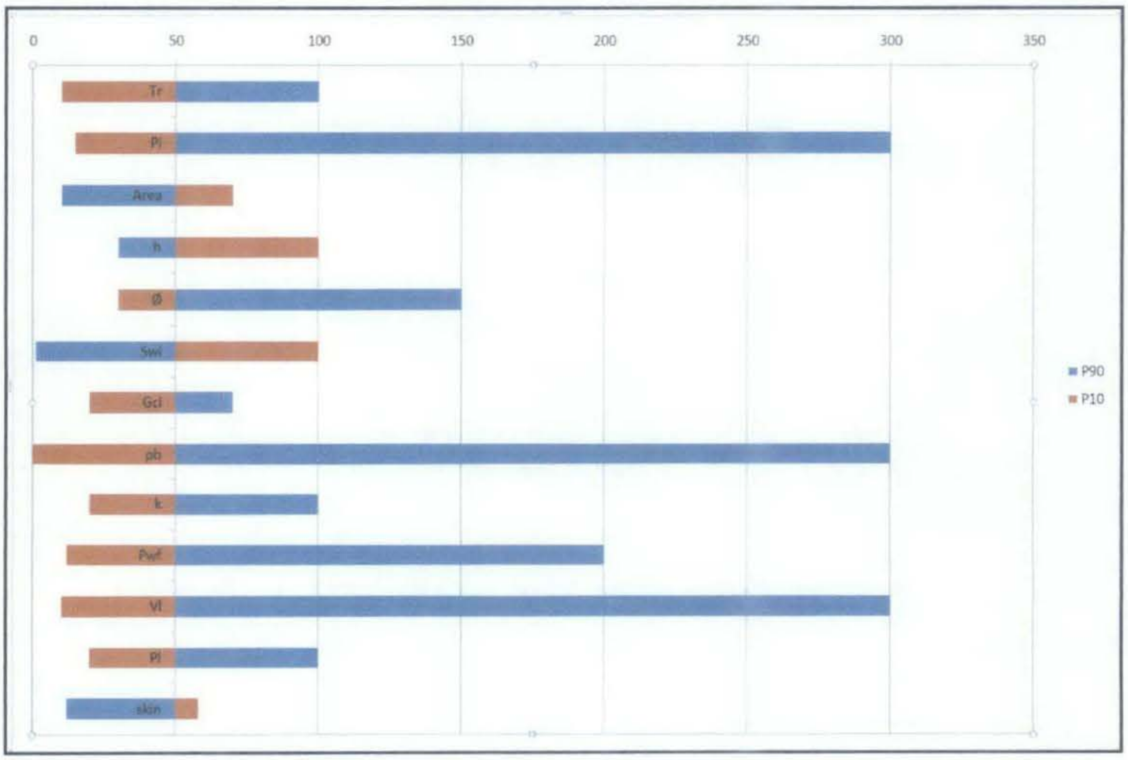
CBM Forecast Tool Risk Analysis Functionality



Example of Cumulative Frequency distribution plot



Tornado plot functionality



Example of a Tornado plot by CBM Forecast Tool

APPENDIX 4

Sample of the coding

```
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        'calculate initial Krg & Krw
        If MatrixShrink = "NO" Then
            Sw = WorksheetFunction.Min(100, ((Swi_i * (1 + cw * (Pi_i - Pi_i)) + ((5.61458333333333 *
We_i - arrayCumWaterRef(0)) / ((Poro_i / 100) * (areaft2) * h_i))) / (1 - cf_i * (Pi_i - Pi_i)) * 100)
)
            arraySw(0) = Sw
        Else
            If PalMan_i = "YES" Then
            Sw = WorksheetFunction.Min(100, ((Swi_i * (1 + cw * (Pi_i - Pi_i)) + ((5.61458333333333 *
We_i - arrayCumWaterRef(0)) / ((Poro_i / 100) * (areaft2) * h_i))) / (1 - cfnew_i * (Pi_i - Pi_i)) * 1
00))
            arraySw(0) = Sw
            Else
            Sw = WorksheetFunction.Min(100, ((Swi_i * (1 + cw * (Pi_i - Pi_i)) + ((5.61458333333333 *
We_i - arrayCumWaterRef(0)) / ((Poro_i / 100) * (areaft2) * h_i))) / (1 - cf_i * (Pi_i - Pi_i)) * 100)
)
            arraySw(0) = Sw
            End If
        End If
        If corey_i = "YES" Then
            If (((Sw / 100 - Swc_i / 100) / (1 - Swc_i / 100)) ^ nw_i) * krw0_i < 0 Then
                arraykrw(0) = 0
            Else: arraykrw(0) = (((Sw / 100 - Swc_i / 100) / (1 - Swc_i / 100)) ^ nw_i) * krw0_i
            End If
                Sg = 100 - Sw
                arraySg(0) = Sg
                If Sg <= Sgc_i Then
                    arraykrg(0) = 0
                ElseIf ((Sg / 100 - Sgc_i / 100) / (1 - Swc_i / 100 - Sgc_i / 100)) ^ ng_i * krg0_i >
krg0_i Then
                    arraykrg(0) = krg0_i
                Else: arraykrg(0) = ((Sg / 100 - Sgc_i / 100) / (1 - Swc_i / 100 - Sgc_i / 100)) ^ ng_
i * krg0_i
                End If
        ElseIf honarpour_i = "YES" Then
            If (0.035388 * (Sw / 100 - Swc_i / 100) / (1 - Swc_i / 100) - 0.010874 * ((Sw / 100) / (1
- Swc_i / 100)) ^ 2.9 + (0.56556 * ((Sw / 100) ^ 3.6) * (Sw / 100 - Swc_i / 100))) < 0 Then
                arraykrw(0) = 0
            Else: arraykrw(0) = (0.035388 * (Sw / 100 - Swc_i / 100) / (1 - Swc_i / 100) - 0.010874 *
((Sw / 100) / (1 - Swc_i / 100)) ^ 2.9 + (0.56556 * ((Sw / 100) ^ 3.6) * (Sw / 100 - Swc_i / 100)))
            End If
                Sg = 100 - Sw
                arraySg(0) = Sg
                If Sg <= Sgc_i Then
                    arraykrg(0) = 0
                Else
                    If arraykrg(0) > 1 Then
                        arraykrg(0) = 1
                    Else: arraykrg(0) = 1.1072 * ((Sg / 100 - Sgc_i / 100) / (1 - Swc_i / 100)) ^ 2
                    End If
                End If
        End If

        'initial gas to water and water to gas ratios
        arrayGas2Water(0) = 0
        arrayWater2Gas(0) = 1

        Tr = (5 / 9 * (Temp_i - 32) + 273) / (Tc_i)
        If viscotype = "Lee et. Al" Then
            k = (9.4 + 0.02 * mCH4_i) * (((Temp_i + 460) ^ 1.5) / (209.2 + 19.3 * mCH4_i + (Temp_i + 4
60)))
            x = (3.5 + (986 / (Temp_i + 460)) + 0.01 * mCH4_i)
            y = 2.4 - 0.2 * x
        ElseIf viscotype = "Lee Gonzalez & Eakin" Then
            k = ((9.379 + 0.01607 * mCH4_i) * (Temp_i + 460) ^ 1.5) / (209.2 + 19.26 * mCH4_i + (Temp_
i + 460))
            x = 3.448 + (986.4 / (Temp_i + 460)) + (0.01009) * (mCH4_i)
            y = 2.447 - (0.2224) * (x)
        ElseIf viscotype = "Optimized Lee Gonzalez Eakian" Then
            k = ((19.9216 + 0.0326212 * mCH4_i) * (Temp_i + 460) ^ 1.38392) / (210.076 + 18.5762 * mCH
4_i + (Temp_i + 460))
            x = 3.84699 + (991.303 / (Temp_i + 460)) + (0.00924455) * (mCH4_i)
```

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Module1 - 12

            y = 2.11068 - (0.136279) * (x)
        End If
        BsqrActual = (Pwf_i ^ 2) / (Zpwf * miupwf)
        arrayBsqr(0) = BsqrActual
        arrayBHP(0) = Pwf_i



        I = 1
        Days_stream = 0
        p = 0

        ' calculate until abandonment constraints reached
         Do Until Days_stream > Day_abd Or I > 60000

                        'calculate Reservoir Pressure
                        If arrayResPres(i - 1) - arraydelPres(i - 1) > Pabd_i Then
                            If arrayResPres(i - 1) - arraydelPres(i - 1) <= PKing_i Then
                                delPresNew = ((PL_i * ((0.01 * arrayCleVol(i - 1)) / (coalweight_i
 * arrayBg(i - 1)) - arrayGC(i - 1))) + (arrayResPres(i - 1) * ((0.01 * arrayCleVol(i - 1)) / (coalwei
ght_i * arrayBg(i - 1)) - arrayGC(i - 1))) + (VL_i * arrayResPres(i - 1))) / (((0.01 * arrayCleVol(i -
 1)) / (coalweight_i * arrayBg(i - 1)) - arrayGC(i - 1)) + VL_i)
                                p = arrayResPres(i - 1) - delPresNew
                                arraydelPres(i) = delPresNew
                            Else:
                                delPresNew = delP_i
                                p = arrayResPres(i - 1) - delPresNew
                                arraydelPres(i) = delPresNew
                            End If
                        ElseIf arrayResPres(i - 1) - arraydelPres(i - 1) < Pabd_i Then
                            p = Pabd_i
                        End If

                        'calculate fluid properties
                        Pr = (p * 0.0680459639) / (Pc_i)
                        Asqr = 0.42747 * (Pr / (Tr ^ 2.5))
                        b = 0.08664 * (Pr / Tr)
                        r = Asqr * b
                        q = (b ^ 2) + b - Asqr
                        If Ztype = "Redlich-Kwong" Then
                            Z = mcroot(1, -1, -q, -r)
                        ElseIf Ztype = "Brill and Beggs Model" Then
                            Z = (1.39 * (Tr - 0.92) ^ 0.5 - 0.36 * Tr - 0.101) + ((1 - (1.39 * (Tr
 - 0.92) ^ 0.5 - 0.36 * Tr - 0.101)) / (Exp((0.62 - 0.23 * Tr) * Pr + ((0.066) / (Tr - 0.86) - 0.037)
* (Pr ^ 2)))) + ((0.132 - 0.32 * WorksheetFunction.Log10(Tr)) * (Pr ^ (10 ^ (0.3106 - 0.49 * Tr + 0.18
24 * (Tr ^ 2)))))
                        End If
                        Bg = 0.0283 * Z * (Temp_i + 460) / p
                        If BWtype = "Constant" Then
                            Bw = Bw_i
                        ElseIf BWtype = "Press&Temp effect" Then
                            Bw = (1 + ((-0.010001) + (0.000133391) * (Temp_i) + (0.00000550654) *
 ((Temp_i) ^ 2))) * (1 + ((-0.00000000195301) * (p) * (Temp_i) - 1.72834E-13 * ((p) ^ 2 * Temp_i) - 0.
000000358922 * (p) - 0.000000000225341 * (p) ^ 2))
                        End If
                        density = (0.0433 * (p) * SGCH4_i / (Z * (Temp_i + 460)))
                        miu = (k * 10 ^ -4) * Exp(x * (density ^ y))
                        Psqr = ((p) ^ 2) / (miu * Z)
                        krg = arraykrg(i - 1)
                        If CWType = "Salinity Effect" Then
                            If wt_i = 0 Then
                                cw = cw_i * 1
                            ElseIf wt_i > 0 Then
                                If p = 0 Then
                                    cw = cw_i * (-0.015 * ((wt_i) / 100) + 0.993)
                                ElseIf p = 10000 Then
                                    cw = cw_i * (-0.013 * ((wt_i) / 100) + 0.997)
                                ElseIf p = 20000 Then
                                    cw = cw_i * (-0.011 * ((wt_i) / 100) + 0.998)
                                ElseIf p > 20000 Then
                                    cw = cw_i * 1
                                End If
                            End If
```