The Effect of Permeability towards Coalbed Methane (CBM) Production

By

Ahmad Hisyam Rosaimi Bin Hassim

11870

This Dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Engineering (Hons.)

(Petroleum Engineering)

September 2012

Supervisor: Saleem Qadir Tunio

Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Effect of Permeability towards Coalbed Methane (CBM) Production

by

Ahmad Hisyam Rosaimi Bin Hassim

This project dissertation submitted to the

Petroleum Engineering Programme

Universiti Teknologi PETRONAS

in partial fulfilment of the requirement for the

BACHELOR OF ENGINEERING (Hons)

(PETROLEUM ENGINEERING)

Approved by,

____

(Mr. Saleem Qadir Tunio)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 2012

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.

____

AHMAD HISYAM ROSAIMI BIN HASSIM

ABSTRACT

Coalbed methane (CBM) reservoirs have generated large and unerring interest in the last 20 years or so due to its potential as one of the most efficient unconventional source of energy. Hydrocarbon reservoirs are known to react to changes in their properties, particularly permeability. Therefore, it is important to study the effect of permeability changes towards primary production of CBM. The production rates of two CBM fields outside Malaysia and one coal field from Sarawak will be simulated and analysed, with permeability being the manipulated variable. Simulation will be performed using the ECLIPSE E100 model, with several assumptions made. The corresponding results will then be analysed. From the result, it is clear to see that permeability enhances the production of methane gas from CBM fields. An increase in permeability leads to higher production rates and a prolonged maximum production time. High reservoir pressure, Langmuir pressure, and permeability are favourable for CBM production.

ACKNOWLEDGEMENT

First and foremost, it is appropriate to firstly thank God Almighty for giving me the will to complete this Final Year Project dissertation. Without His blessings, then surely this project would just go to waste. Secondly, I would like to thank my Supervisor, Mr Saleem Qadir Tunio. His expertise, particularly in the field of Coalbed Methane, has enabled me to carry out this project with complete confidence and his willingness to teach and guide me into unchartered territories have definitely given me a positive attitude. Thirdly, I would like to thank my friends and family for giving me constant motivating in carrying out this project. Lastly, I would like to thank the FYP coordinator, Dr Abdelaziz for organising this FYP and making things run smoothly for all.

Contents

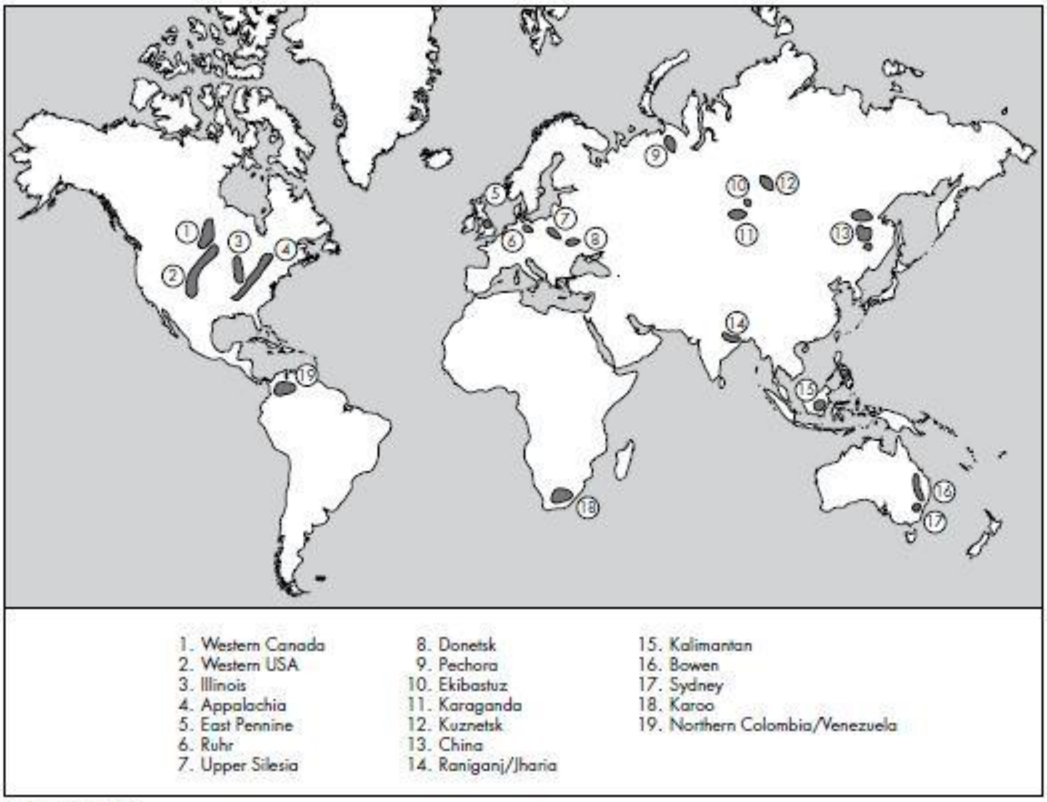
List of Figures

1.0 INTRODUCTION

1.1 Background

Coal bed Methane (CBM) is becoming an increasingly interesting field in the petroleum industry. In fact, gas from coalbeds were among the first gas reservoirs to be discovered and among the most recent to be exploited. Indeed it is relatively a new branch of petroleum engineering and the potential of harvesting the natural gasses found in coal beds is looking ever more likely. There continues to be a large interest in developing coal beds and extracting the natural gas contained within it, hence providing us with yet another source of energy. Coal bed methane has emerged as a significant source of energy from new discoveries of coal beds, not only in Malaysia, but also all over the world, especially in the United States of America and Canada.

To put this into perspective, total coal gas production is estimated to be more than 256 trillion cubic meters, whereas worldwide proven natural gas reserves are 185 trillion cubic meters. Recovery of one-half the global coal gas resource would increase global natural gas reserves by 128 trillion cubic meters, a gain of about two-thirds (Seidle, 2011). With production of over 31 billion cubic meters of CBM gas in the United States alone, and over 13 trillion cubic meters of proven reserves in Indonesia, CBM is set to be a large contributor to world gas resources as natural gas resources deplete. With more and more coal bed fields being discovered, and demand of energy ever increasing, the need to produce this unconventional gas seems more of a necessity. In 2009, CBM gas accounted for about 9% of total natural gas produced in the USA (Wang & Economides, 2009). Below is a graphical representation of the major coalbed methane resources around the world.



Source: IEA 1993.

Figure 1: Major coal basins around the world

Coal bed methane started out as a safety hazard when miners accidently tapped into methane resources when trying to mine out coal. This has resulted in several explosions, caused by unwanted production of methane (Fanchi, 2006). To counter this, pockets of methane which has been accidently produced are trapped using a bladder. Mining of coal beds also resulted in the release of methane gas, which is a greenhouse gas, into the atmosphere, thus contributing to global warming and negative environmental consequences. The benefits of coal gasses were not taken seriously until William Murdoch from Scotland recognized its usefulness as a combustible source of energy in the 1700's.

Coal bed methane can be classed as an unconventional source of hydrocarbons, in which the natural gasses are produced from seams and cleats of the coal. But it is only in the last generation or so that coal bed gasses, along with shale gas and tight formation gas, has been regarded as a useful source of hydrocarbons, albeit unconventional. Prior to gas production, the CBM reservoir porosity is water-filled and permeability to gas remains zero. When enough water is produced, gas saturation increases and hence permeability of gas increases. It is only at this stage that the gasses in CBM reservoirs can be produced (Dacy, 2010).

This research aims to deduce whether or not the coal bed methane in Sarawak should be produced or not based on the petrophysical properties of the coal alone. Petrophysical properties of the coal include its porosity and permeability.

1.2 Problem Statement

Malaysia does have potential coal fields which can be developed to be CBM fields. However, there hasn't been much research regarding the producibilty of the coalfields. In general, more research has to be done regarding the effect of permeability towards production rates, and this can be significant since hydraulic fracturing of any reservoir has an enhanced effect on permeability. To gauge on this potentiality for a CBM field, the production rates should be comparable to that of renowned CBM producing fields.

1.3 Project Objectives and Scope

The objectives of this project will be the following:

i. To study the changes in gas production rate when permeability of the reservoir changes
ii. To compare and contrast between the production rates of two CBM fields which are outside Malaysia, and one coalfield from Sarawak.

The CBM location in question are the San Juan Basin and the Powder River Basin, whereas the coalfield is a Sarawakian coalfield, Malaysia. The scope of study is limited to using only one simulation software and only published data will be used.

2.0 LITERATURE REVIEW

2.1 Formation of coal

Coal is a dual porosity organic sedimentary rock which mainly comprises of matrices and natural fractures and cleats. It is composed of solid matrix blocks bounded by a well-defined network of natural fractures, also known as cleats (Grattoni et al., 2006). Coals are the preserved remains of organic materials that have been metamorphosed over geologic time by temperature and pressure into complex organic rocks. Coalbeds constitute both source rock and reservoir rock (Worthington, 2011). Coal is a form of fossil fuel, in which plants and trees decay in marshy terrain and swampy areas millions of years ago by anaerobic thermal degradation of the cellulosic materials in the plants and trees (Shukla, n.d.). Layers upon layers of peat are compacted over time. As the coalification process continues, water is gradually compressed out of the peat. Physical and chemical processes brought about by compaction and elevated temperatures with prolonged burial at depths of up to several kilometers and over periods of up to several hundred million years then change the peat into coal through a process referred to as coalification or rank advance (Suárez-Ruiz & Crelling, 2008; Speight, 2008).

2.2 Geologic Parameters of Coal

The properties of a given coal can be related to three independent geological parameters, each of which is determined by some aspect of the coal's origin. There are three parameters into which coal can be classified, which are *Rank, Type and Grade.*

Rank is the degree of which the coal has undergone metamorphism, from plant debris to coal itself. This depends on the maximum temperature to which it has been exposed. Rank plays a direct role when determining how much methane can be stored within the coal. Darling (2011) explained that the higher the rank of the coal, the more methane it is able to store. Rank also plays an important role for gas content, permeability, and mechanical and physical properties of the coal (Rogers et al., 2007)

Coal rank	Reflectance (%)	Volatile matter (%)	Carbon (% dry ash-free, vitrinite)	Bed moisture (%)	Calprific Value; Btu/lb moist, mmf
Peat		64	60	75	<6,300
Lignite	0.3	60, 56		35	6,300 - 8,300
Sub-bituminous C	0.4	52			8,300 - 9,500
Sub-bituminous B		48	71	25	9,500 - 10,500
Sub-bituminous A	0.5				10,500 - 11,500
High-volatile bituminous C	0.6	44	77	8-10	11,500 - 13,000
High-volatile bituminous B	0.7	40			13,000 - 14,000
High-volatile bituminous A	0.8, 1.0	36, 32			> 14,000
Medium-volatile bituminous	1.2, 1.4	28, 24	87		
Low-volatile bituminous	1.6, 1.8	20, 16			
Semi-anthracite	2.0	12, 8	91		
Anthracite	3.0, 4.0	4			
Meta-Authracite	> 4.5	< 2	> 91	0	

Source: Seidle, 2011

Figure 2: Coal Rank

Type of coal reflects the nature of the plant debris from which the original peat was derived, including the mixture of plant components (wood, leaves, algae, etc.) involved and the degree of degradation to which they were exposed before burial.

Lastly, grade of a coal reflects the extent to which the accumulation of plant debris has been kept free of contamination by inorganic material (mineral matter), including the periods before burial. Therefore, a high grade coal would be relatively free of mineral matter, and hence a high organic content (Ward, 2008, as cited in Suárez-Ruiz & Crelling, 2008)

2.3 Formation of methane in coal beds

There are several ways in which methane is produced within the beds of coal. Methane is naturally produced when the peats were first laid and compacted, prior to becoming and transforming into coal. There are two methods in which gasses, particularly methane, are produced within the coal seams.

2.3.1 Biogenic methane

Biogenic gasses are produced by anaerobic microorganism at low temperatures. After the oxygen has been depleted by aerobic microorganisms, sulfate reduction is the main form of respiration. Methane generation and accumulation in the coal seams and cleats become dominant only after sulfate in pore water sediment is depleted. Methane is produced by the anaerobic oxidation of organic matter (Rice and Claypool, 1981). However, in fresh water environments, methane is produced directly after the oxygen has been depleted (Rice and Claypool, 1981).

2.3.2 Thermogenic methane

As the temperature at which the microorganisms are being exposed increases to above 122°F, thermogenic methane begins to be produced. The temperature increase can be attributed by increased burial depth or increased geothermal gradient. At the same time, additional water, carbon dioxide and nitrogen are produced as coalification continues. As the temperature continues to increase up to 210 °F, generation of carbon dioxide exceeds the production of methane. However, at about 250°F, generation of methane is superior to the production of carbon dioxide, hence; more methane occupies the cleats of the coal. It is only at 300°F when maximum generation of methane occurs. At temperatures higher than 300°F, production of methane is lower than the maximum rate (Rightmire, 1984).

2.4 Storage of methane in coalbeds

Gas in the coal can be present as free gas within the pores or just as an adsorbed layer in the internal surfaces of the coal micropores. Methane gas is adsorbed to the internal surface area of the coal due to the high pressure. Coalbed methane exists as a monomolecular layer on the internal surface of the coal matrix (Fanchi, 2006). The only way to produce these gasses is by reducing the pressure within the coal matrix until the gas can be desorbed. Coal has an immense structure of micropores and macropores, along with natural fractures or cleats where the methane gas can be stored. In a coal bed methane reservoir, the amount of gas that can be stored is usually much more than typical, conventional reservoirs. Although the porosity of coal may be small, the network of cleats can easily make for storage capacity. Most of the gas is stored by adsorption in the coal matrix. Hence, production is based on pressure depletion (Aminian, n.d.). The amount of gas stored in coals can be estimated using Langmuir's equation:

$$G_s = \frac{V_L\, P}{P_L + P} \qquad \text{(Eq. 1)}$$

Where:

G_s= Gas storage capacity, SCF/ton

P = Pressure, psia

V_L= Langmuir volume constant, SCF/ton

P_L= Langmuir pressure constant, psia

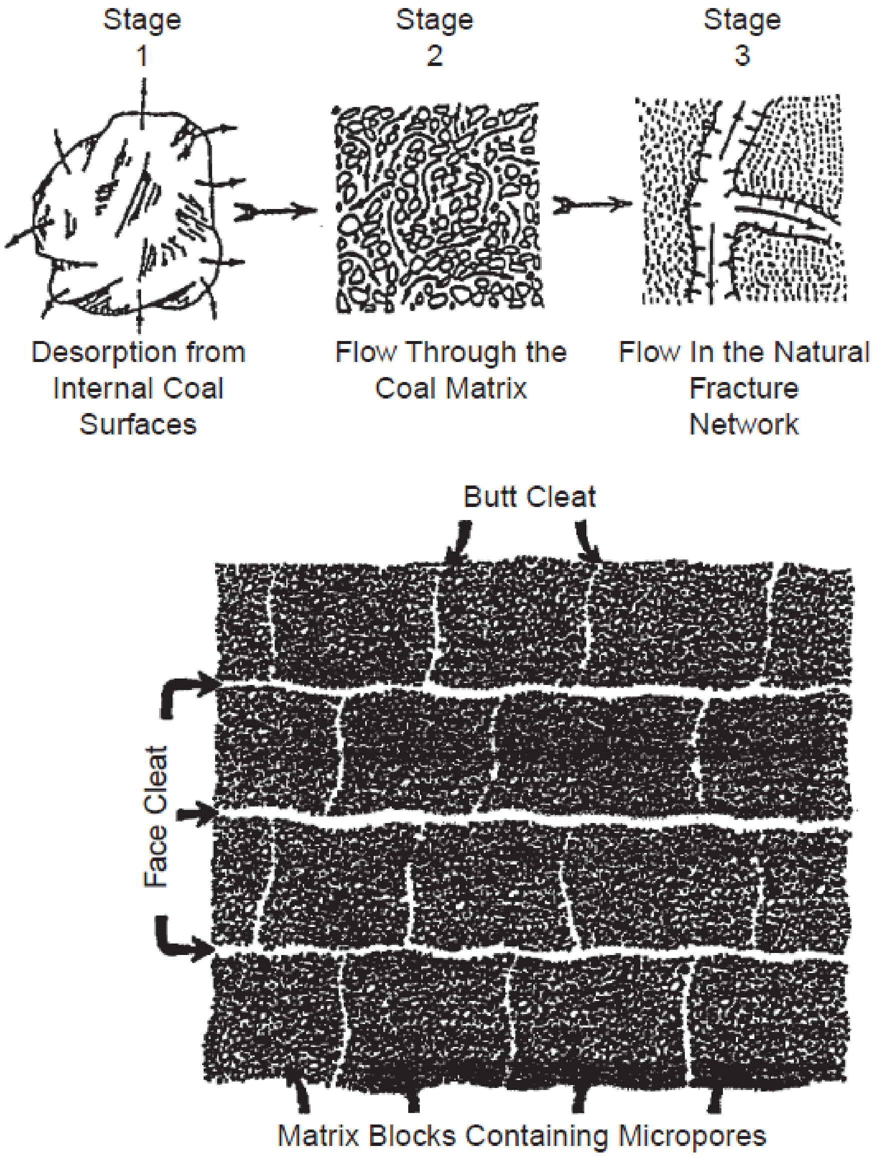
Meng et al (1996) also suggested that primary and secondary cleats are also a means for gas storage within the coal. Gas derived from coal is generally pure and required little or no processing.

2.5 CBM reservoir and coal properties

Unlike conventional reservoirs where there exist a source rock and cap rock, CBM differs in that the coal is both the source and cap rock. In fact, the gasses are produced within the coal itself and stored directly in it. Coal fails the definition of reservoir rock since pore volumes are much less than those normally accepted in conventional reservoirs. The main properties of the coal that describes it's suitability to be produced is porosity and permeability. Micropores are the cavities and capillaries within the coal matrix, essential for gas storage in the adsorbed state (Singh, K.N., 2010).

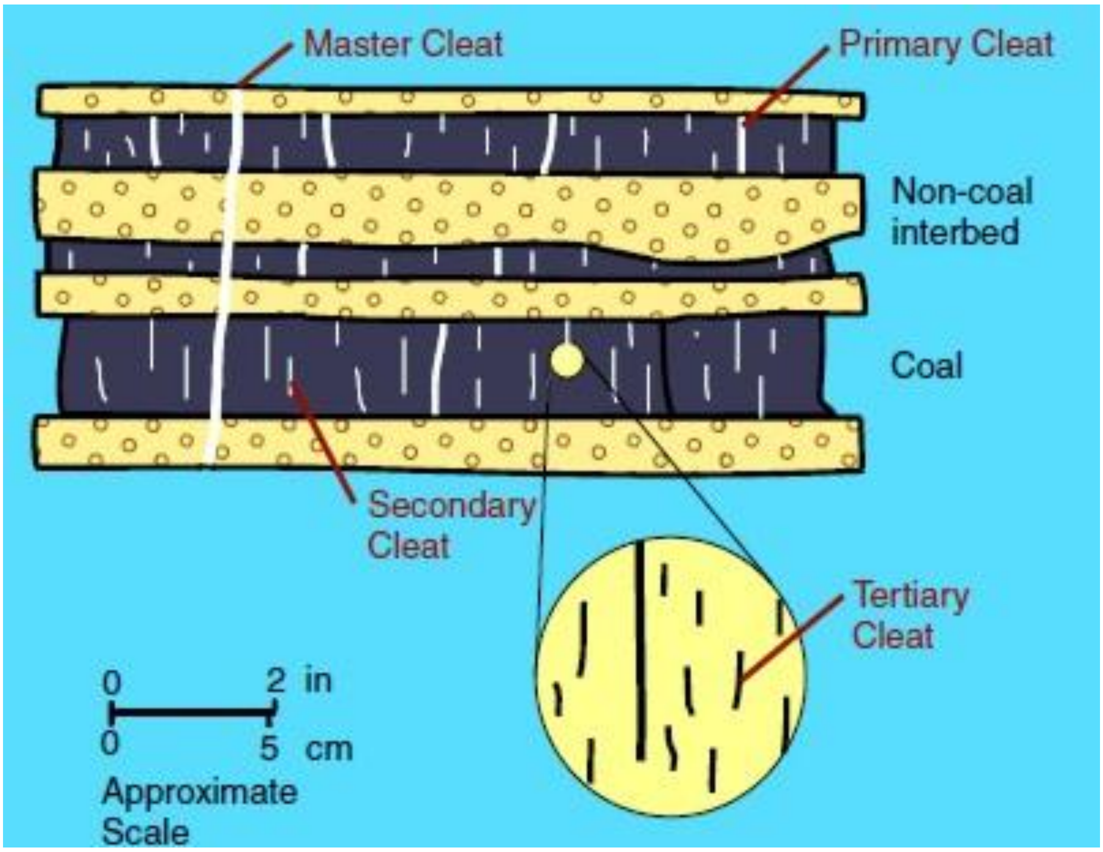
Furthermore, Tarek and Nathan (2012) stated that there are two main porosity systems, which are primary and secondary. The primary porosity is composed of micropores. These micropores are the main sites in which the methane gas is adsorb and stored. It should be noted that the surface area of these micropores can be astonishingly large. Secondary porosity is the system of macropores or coal seams, which consists of the natural fracture network of cracks and fissures which are inherent in all coals. Secondary porosity does not hold much gas as compared to the primary porosity. However, secondary porosity is important because it provides the permeability for fluid flow. They act as conduits for fluid flow. Macropores also indicates the natural space available in the cleat system. Macropores are insignificant when it comes to gas storage. An important property in gas storage is the micropores.

Permeability is the other important property of the coal to determine its potentiality. It is also an important economic indicator. The flow rate of gas from coal is determined by the complete network of natural cleats and fractures, whether natural of artificial. Coal beds have two major cleat systems, which are face cleats and butt cleats (Singh, K.N, 2010) as shown in the figure below.



Source: Tarek & Nathan, 2012

Figure 3: Methane Flow Dynamics



Source: http://spec2000.net/17-speccbm.htm

Figure 4: Primary and Secondary Cleats system

Furthermore, coal fractures can be classified into two types, which are endogenetic fractures and exogenetic fractures. Endogenetic fractures are created from tension due to the dewatering of the coal and causing shrinkage. On the other hand, exogenetic fractures are due to natural plate movements of the earth and tectonism (faults and folds). Worthington (2011) further stated that one of the main challenges in evaluating coal formations is the effectiveness of the cleats system, hence stressing the importance of the natural network of cleats and fractures when it comes to producing gasses from coal beds. Optimum CBM production from coal should be higher than 3.0 millidarcy. However, Chow et al (2011) reported that permeability in the range of 1md to 10 md is considered fairly good, whilst anything above 10md is considered excellent.

The measurement of permeability can be fairly difficult to determine due to the compressible nature of the gas itself during conduction of the experiment. Gas is a compressible fluid, hence during experimentation gas compression can somewhat distort the data. At low gas pressures, there can be few molecules of gas occupying some of the smaller pores. When this happens, there can be a noticeable overestimation of the permeability. This is known as gas slippage, or Klinkenburg effect. This can be corrected by constructing a simple graph of Permeability vs. 1/p , whereby the y-intercept is the Klinkenburg Permeability (Glover, P., nd.). If the input P_i and the output pressure is P_o then the permeability can be plotted as a function of:

$$\frac{1}{P_{av}} = \frac{2}{P_i+P_o} \qquad \text{(Eq. 2)}$$

The points should lie on a straight line and the intercept of this straight line with the y-axis should be the Klinkenburg Permeability, and hence giving us a more accurate reading of the permeability. Klinkenburg permeability, in simple terms defines the permeability at which the gas is compressed by infinite pressure and hence becomes a near perfect liquid.

Ham & Kantzas (2010) discussed that coal is the hardest reservoir rock to evaluate. This is because:

i. Coal is friable
ii. Low porosity in the connected fracture network, which can cause issues when conducting lab experiments
iii. Permeability of coal is stress-dependent, hence care must be taken when handling the coal samples
iv. There can be a variety of gasses adsorbed on coal, which can be difficult to obtain the true value of its permeability, hence can cause disparities in obtained data between samples.

When coal samples are obtained, complex interactions of stress and chemistry have a strong effect on the properties of coal (Chen, D. et al, 2010)

The quantity of stress applied to core samples can also have drastic effect on the properties of the coal. The rise in effective stress can lead to a decrease in permeability which is counteracted by coal shrinkage due to gas desorption (Connell et al, 2010). Wang (2010) also stated that when pore pressure is kept constant, increasing effective stress cause a reduction in permeability attributed to cleat closure.

Coal matrix is also elastic and deformable; hence changes in its volume can affect the dimensions of the natural fractures. Existence of CO_2 can have an effect on the coal in that it induces swelling or shrinkage, hence affecting the porosity and permeability of the coal (Grattoni et al, 2006).

2.6 CBM Production

Gas production from CBM wells will not initiate until coal reservoir pressure falls below the point where the actual gas content of the coal is in equilibrium with the isotherm (Koenig et al, 1990). In other words, no gas will be produced when a certain minimum reservoir pressure is reached. Furthermore gas content of the reservoir will produce only water initially. Gas will then start to be produced when the reservoir pressure reaches the saturation point on isotherm, eventually expelling gas from the coal, or desorption of coal. Therefore, it is important to produce CBM gas at as low a pressure as possible (Schraufhagel, 1990).

3.0 METHODOLOGY

The basic flow of the research would be:

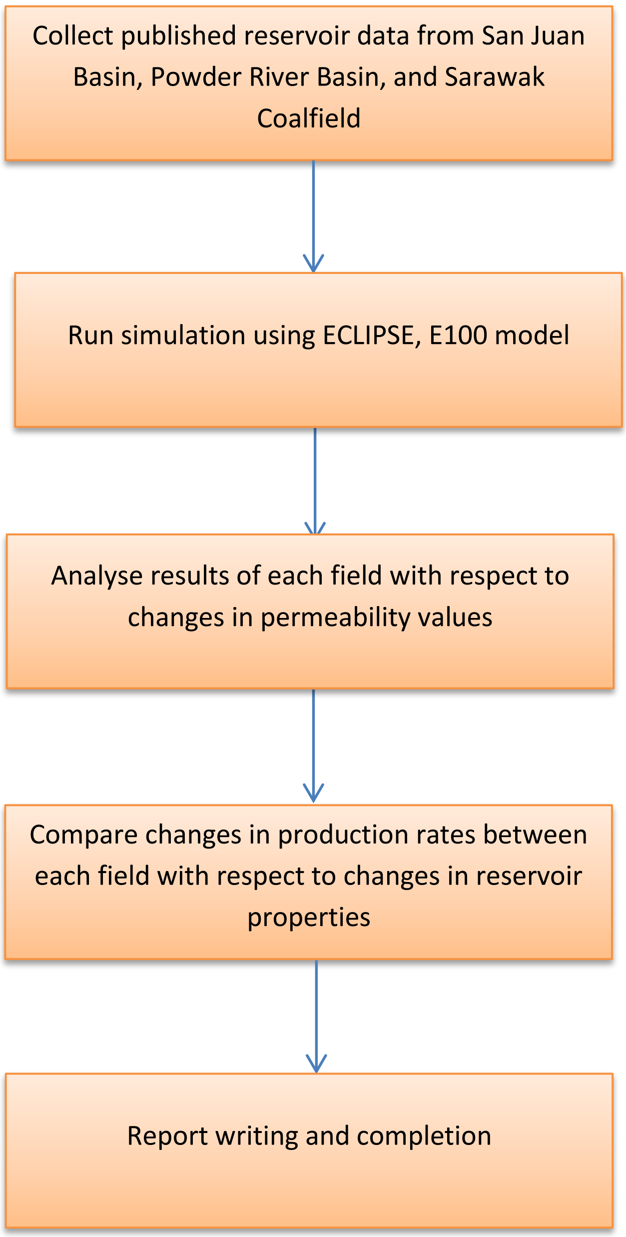


Figure 5: Project activities and flow

The effect of permeability towards CBM production will be studied and simulated using ECLIPSE software, using the E100 model. It should be noted that only primary production will be simulated. Three different fields will be selected for this simulation, in which two fields are CBM fields outside of Malaysia, and one field is a coalfield from Sarawak. It should also be noted that the coalfield in Sarawak is not yet classified as a CBM producing field. However, research is still underway to determine if it has the potential to be a CBM field. The two CBM locations outside Malaysia are the San Juan Basin and the Powder River Basin. These two basins are currently undergoing Enhanced CBM (ECBM) production.

For this study, it is solely concentrated on primary CBM and how petrophysical properties of the coal itself affect production of methane gas. For this simulation, there will be no injection of any fluid into the well for pressure maintenance, hence only primary CBM is considered for all three wells. To ensure that the data obtained from these simulations are comparable, a few constant variables were identified. The variables that are kept equal for all fields are as below:

i. Target production rate of 500 Mscf/d

ii. Bottomhole pressure limit at 40 psia

iii. No skin taken into consideration, with wellbore diameter of 1 ft

Furthermore, the model will be of size 165ft x 165ft x coal seam thickness, as shown in figure 6. The production well is positioned at the center of the model for maximum and equal coverage. The model also contains independent zones with separate initial conditions and employs non-equilibrium initialization. The only data that are changed are the reservoir characteristics itself which differ from field to field.

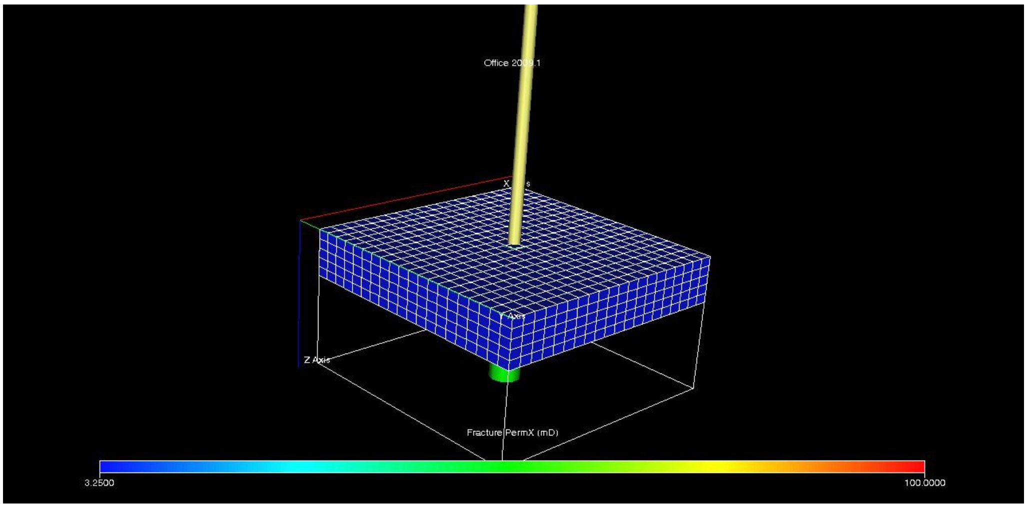


Figure 6: Simulation Model on ECLIPSE

Simulation is run several times for each field with different permeability values (manipulated variable), which will differ from case to case. The results will then be compared, first within the same field and the analysis of how permeability affects production of CBM. Secondly, the fields will be inter-compared.

To further ease the simulation process, a few assumptions were made. Firstly, it is assumed that only methane gas exists and no injection fluids were injected, hence, no injector well. Secondly, it is assumed that gas diffusion between the coal matrix and the natural fracture system occurs instantaneously. Thirdly, it is assumed that the reservoir pressure is uniform throughout; hence the model would also have equal pressure everywhere. Fourth, coal matrix shrinkage effects which are due to the production of the gas are completely neglected.

The simulation will be divided into three different cases, where case 1 is the San Juan Basin, case 2 is the Powder River Basin, and case 3 is the Sarawak Coalfield. The properties of each location are given in tables 1, 2 and 3.

Case 1: San Juan Basin

Table 1: Case 1; Base Case Data, San Juan Basin

Coal seam thickness	29.527 ft.
Top of coal seam	4112.8 ft.
Permeability	3.65md
Porosity of natural fracture system	0.1 %
Effective coal compressibility	1.0 x 10^{-6} $psia^{-1}$
Reservoir temperature	113 F
Reservoir pressure	1109.5 psia
Water saturation	59.2%
Coal density	89.5 lb/ft^3
Coal moisture content	6.72 %
Coal ash content	15.6 %
Langmuir pressure	4688.5 psia
Langmuir volume	486 scf/ton

Source: (Syahrial & Lemigas, 2005)

The permeabilities will be the manipulated variable with values ranging from 3.65md to 100md.

Case 2: Powder River Basin

Table 2: Case 2; Base Case Data, Powder River Basin

Coal seam thickness	64 ft
Top of coal seam	557 ft.
Permeability	632md
Porosity of natural fracture system	2 %
Effective coal compressibility	1.0 x 10^{-6} $psia^{-1}$
Reservoir temperature	65 F
Reservoir pressure	152.5 psia
Water saturation	50%
Coal density	83.34 lb/ft^3
Coal moisture content	27.49 %
Coal ash content	4.40 %
Langmuir pressure	394 psia
Langmuir volume	116.8 scf/ton

(Source: Mavor et. al, 2003)

The permeability values used for this case will range from 632md to 750md. Furthermore, since coalbed compressibility data was not available for this field, the value was assumed to be equal to 1.0 x 10^{-6} $psia^{-1}$. The same can be said with water saturation; hence it is estimated to be at 50 % saturated with water.

<u>Case 3: Sarawak coalfield</u>

Table 3: Case 3; Base Case Data, Sarawak Coalfield

Coal seam thickness	24.25 ft
Top of coal seam	660 ft
Permeability	14.42md
Porosity of natural fracture system	3.6 %
Effective coal compressibility	1.0 x 10^{-6} $psia^{-1}$
Reservoir temperature	75 F
Reservoir pressure	200 psia
Water saturation	050%
Coal density	83.34 lb/ft^3
Coal moisture content	23.25%
Coal ash content	5.95%
Langmuir pressure	1024.5 psia
Langmuir volume	714.29 scf/ton

(Source: Chen et. al, 2011)

Due to unavailability of published data regarding initial reservoir pressure and temperature, the values used are estimates. Furthermore, water saturation data for the coal was also unavailable, hence it is assumed to be 50% saturated with water. The permeabilities will be manipulated from 14.42 md to 100md.

3.1 Gantt Chart

Table 4: Project Gantt Chart

No.	Details/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
									Midterm Break								
1	Continue consultation with Supervisor																
2	Research for published reservoir data to be used in Simulation																
3	Perform simulation using ECLIPSE, E100																
4	Consult supervisor regarding obtained results																
5	Start work on Progress Report and Submission																
6	Conduct further simulation work if needed																
7	Preparation for Pre-Sedex																
8	Start write-up of Draft Report and consultation with supervisor																
9	Submission of draft report																
10	Make necessary amendments to draft report																
11	Start write-up of technical paper																
12	Submission of Dissertation (Soft Bound) and Technical Paper																
13	Oral Presentation																
14	Submission of Dissertation (Hard Bound)																

Key Milestones: Week 3 – Find published CBM reservoir data

Week 5 – Perform Simulation

Week 12 – Submission of Dissertation and Technical Report

Week 13 – Oral Presentation

Week 15 – Submission of Dissertation (Hard Bound)

Tools and material needed for research:

i. ECLIPSE software

4.0 RESULTS AND DISCUSSION

4.1 Case 1: San Juan Basin

<u>Case 1a: San Juan Basin (Base Case, k=3.65md)</u>

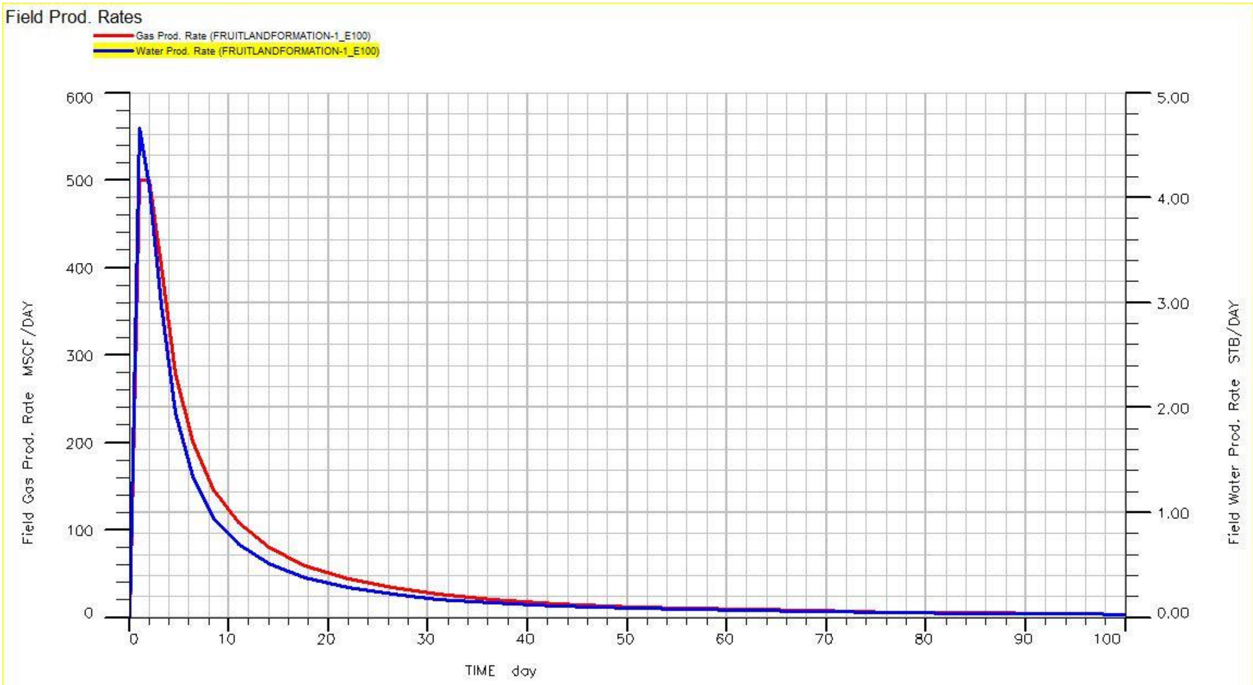


Figure 7: Field production rates, Permeability 3.65md

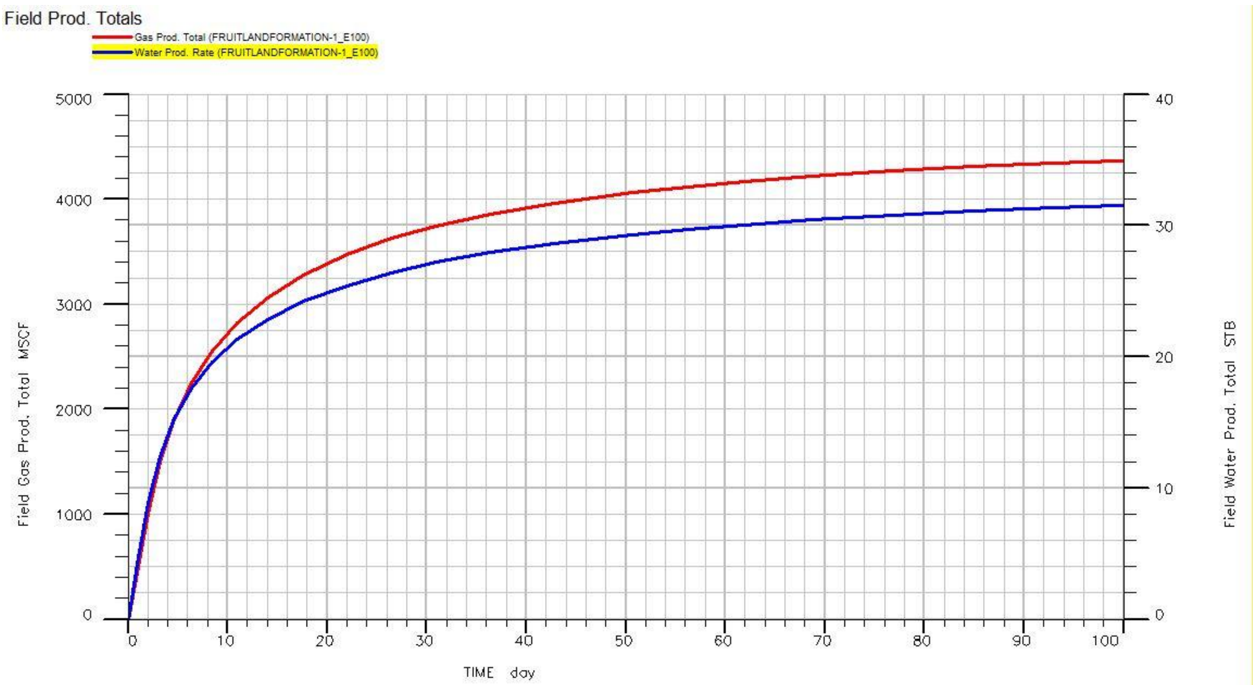


Figure 8: Field production totals, Permeability 3.65md

Case 1b: San Juan Basin (k=20md)

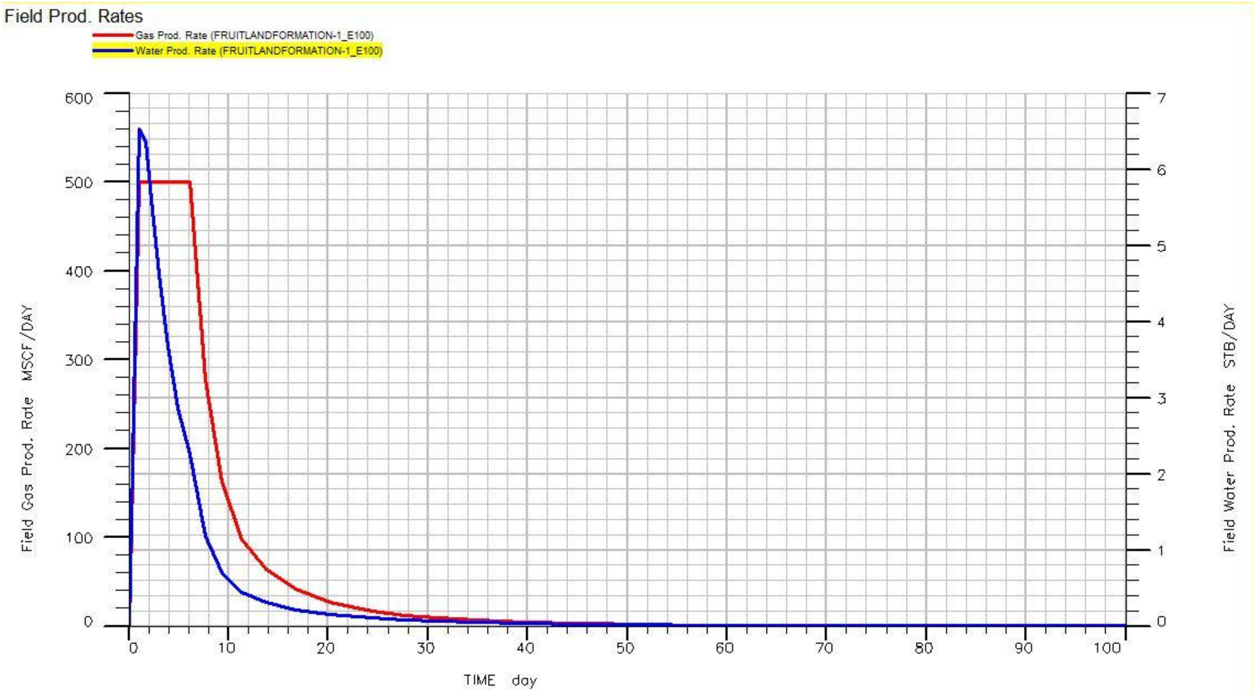


Figure 9: Field production rates, permeability 20md

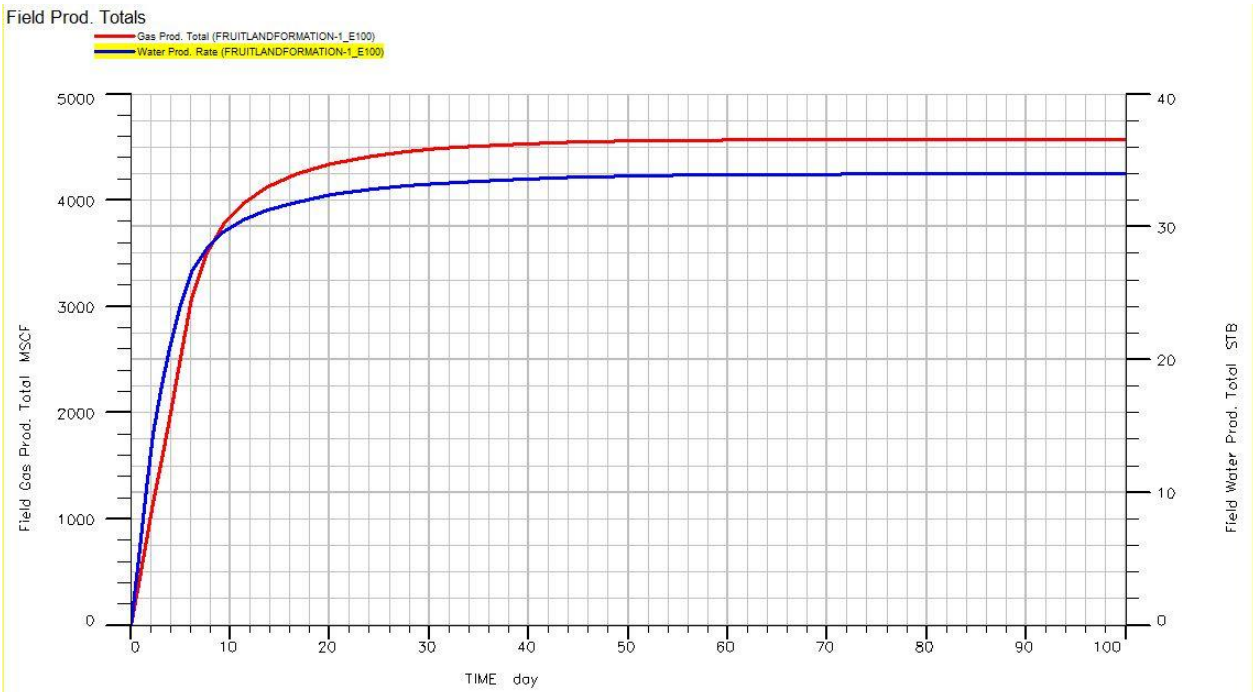


Figure 10: Field production totals, permeability 20md

Case 1c: San Juan Basin (k=40md)

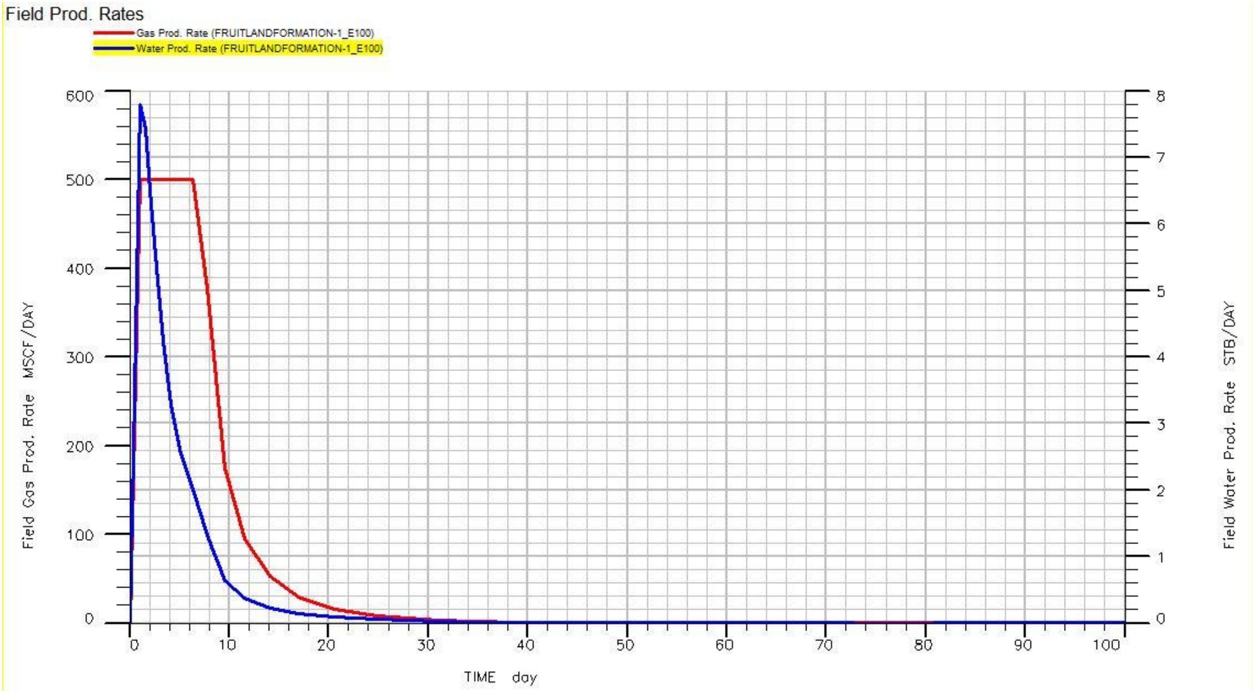


Figure 11: Field production rates, permeability 40md

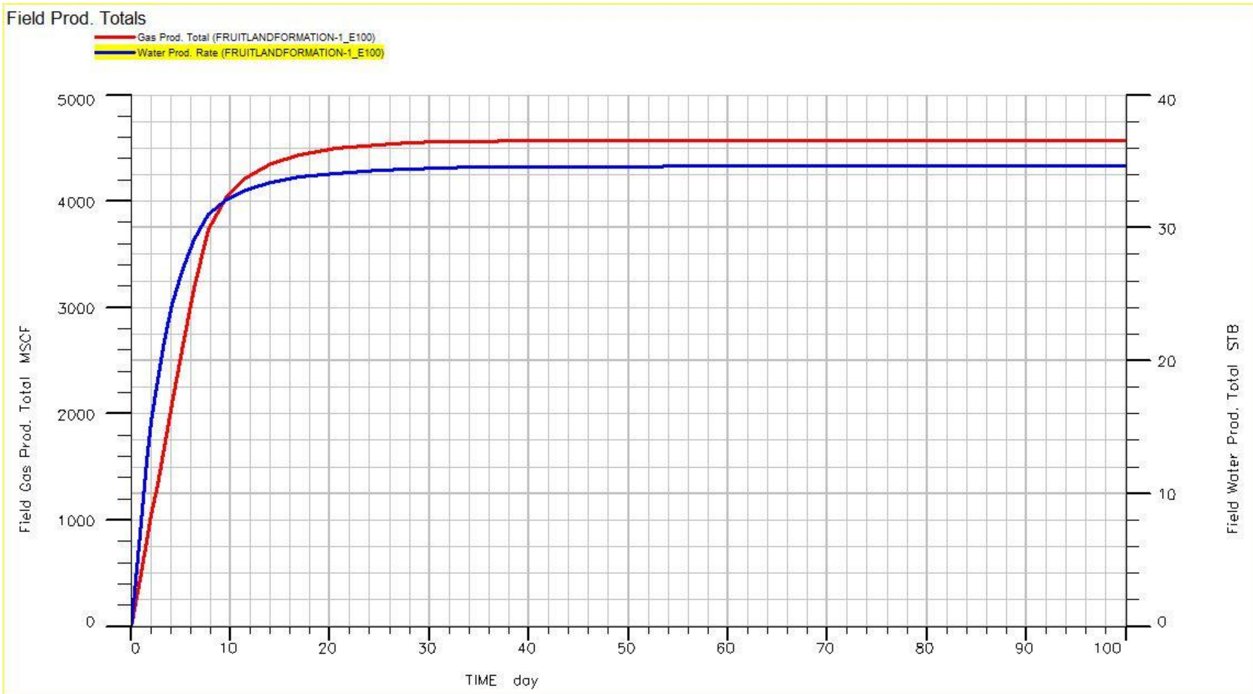


Figure 12: Field production totals, permeability 40md

Case 1d: San Juan Basin (k=60md)

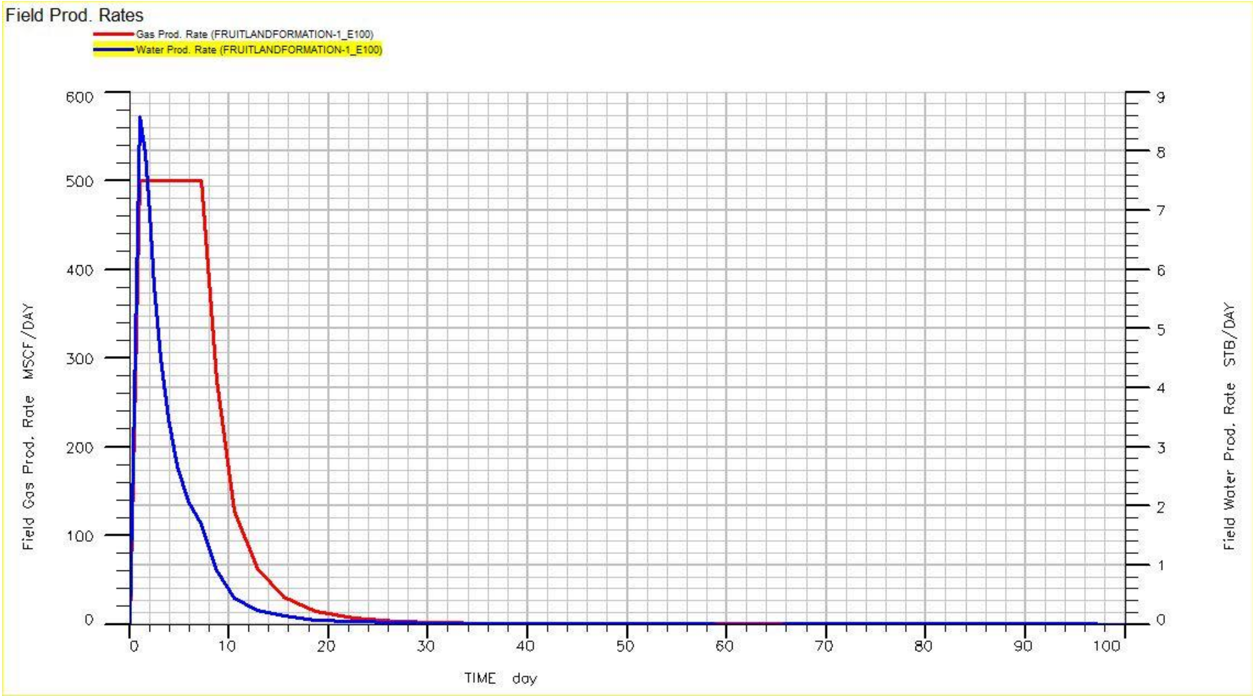


Figure 13: Field production rate, permeability 60md

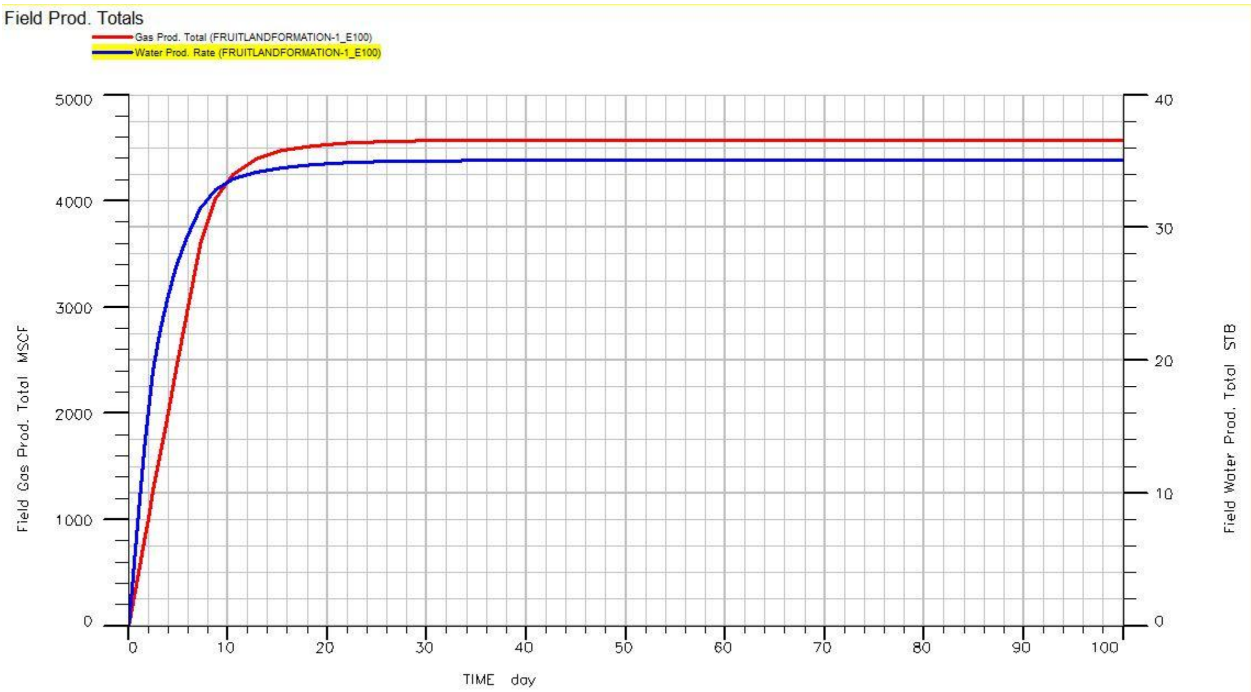


Figure 14: Field production totals, permeability 60md

Case 1e: San Juan Basin (k=80md)

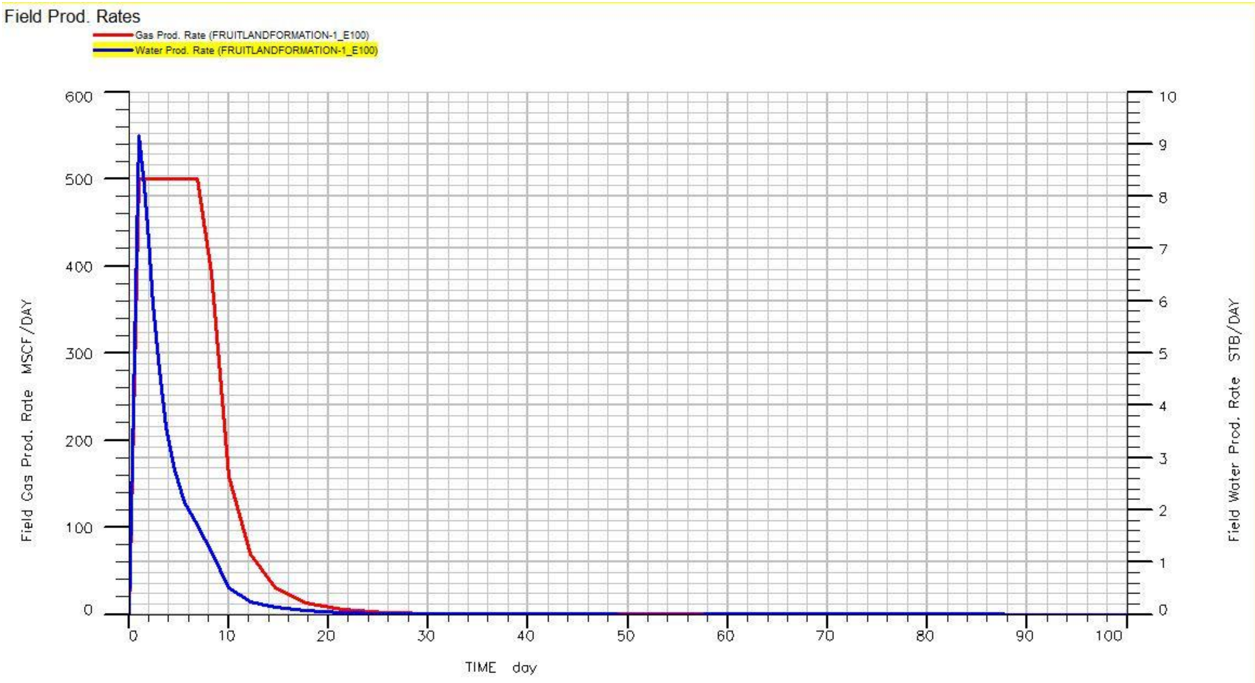


Figure 15: Field production rates, permeability 80md

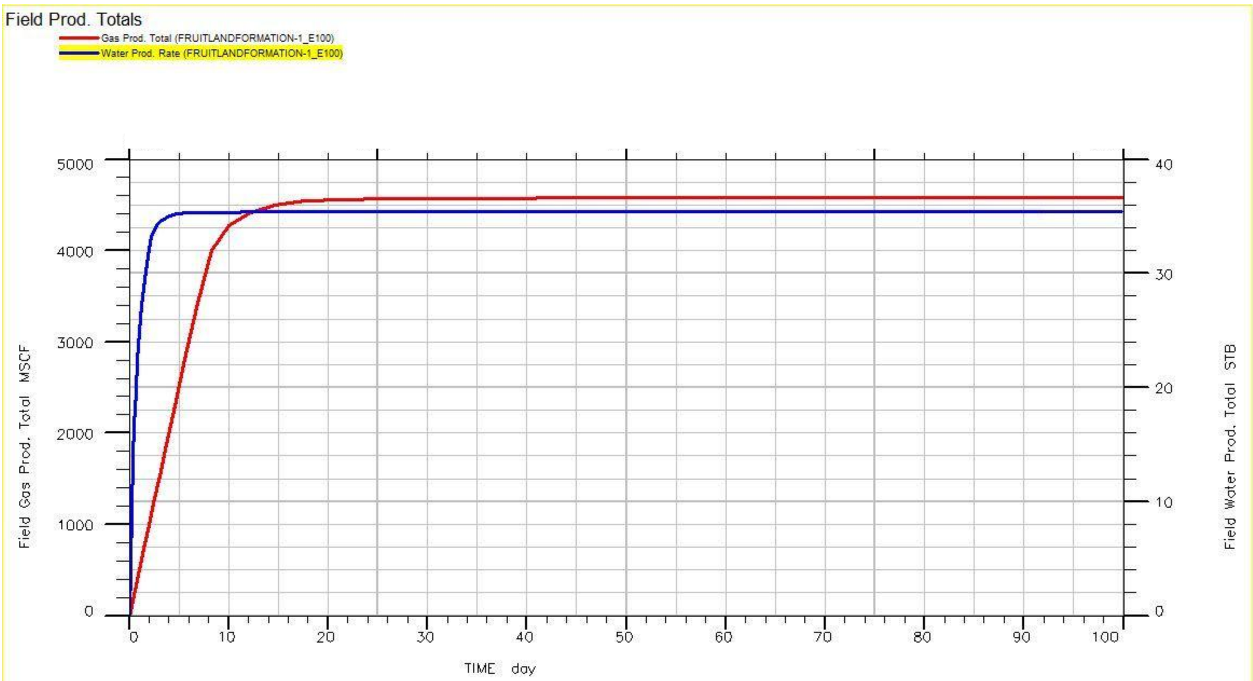


Figure 16: Field production totals, permeability 80md

Case 1f: San Juan Basin (k=100md)

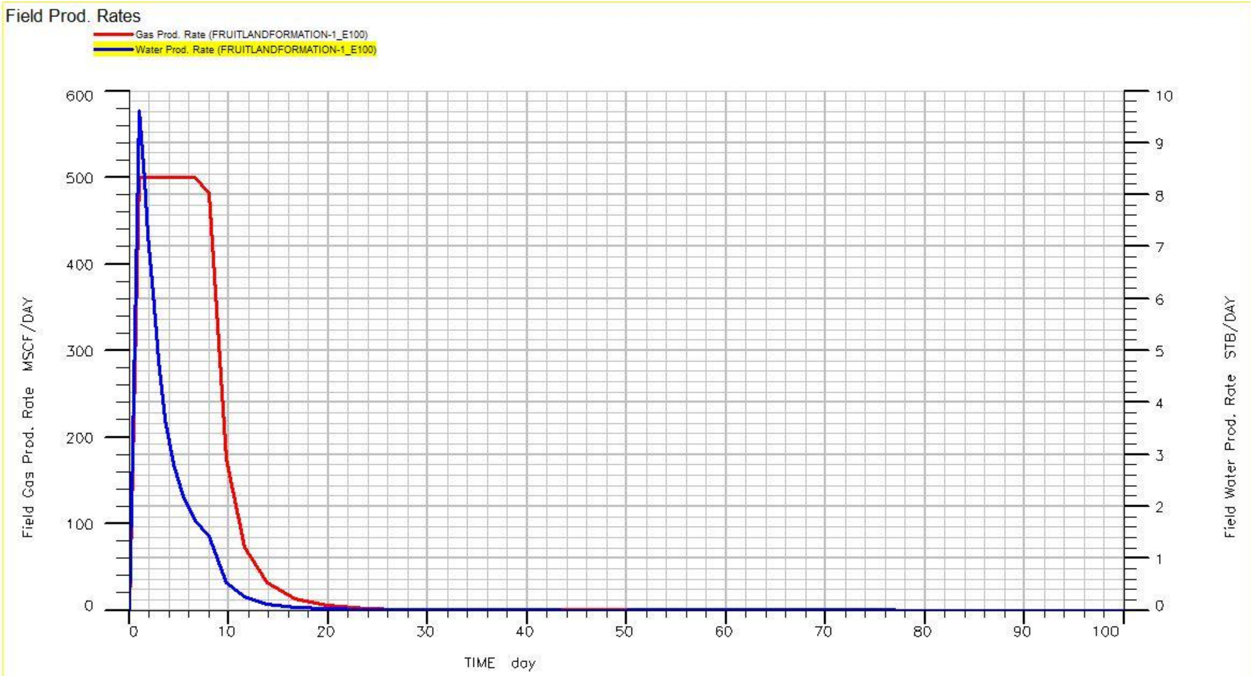


Figure 17: Field production rates, permeability 100md

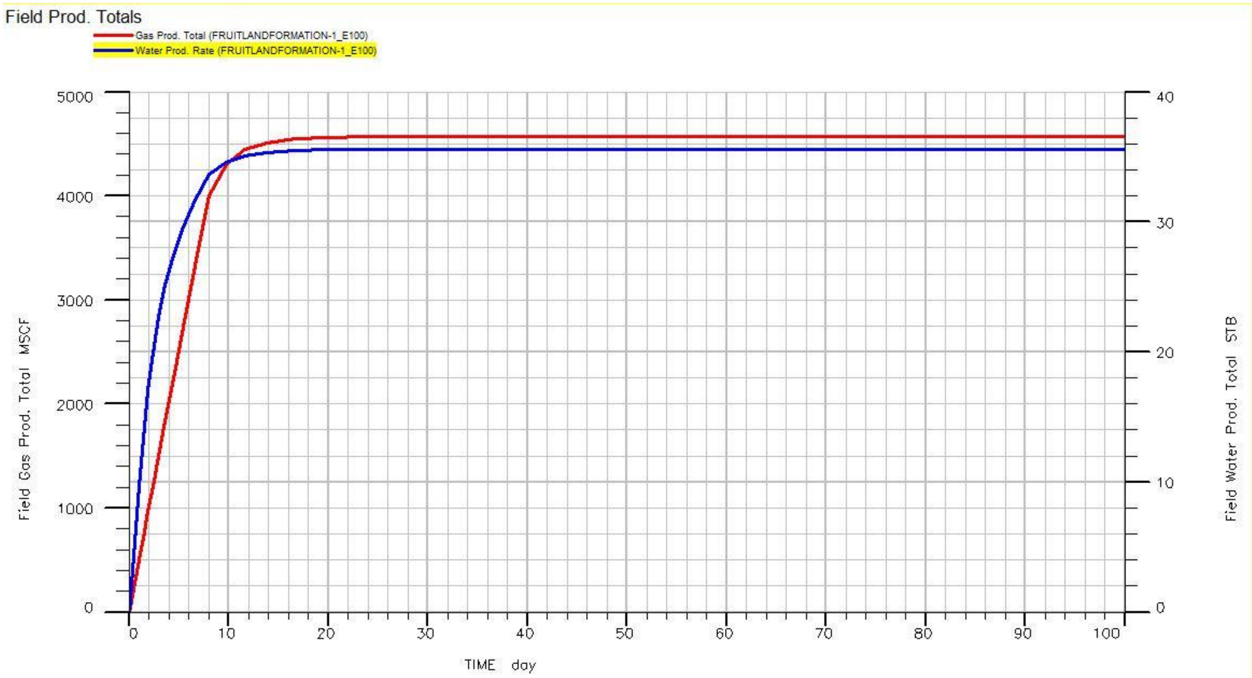


Figure 18: Field production totals, permeability 100md

Table 5: Analysis of results, San Juan Basin

No.	Permeability (md)	Analysis
1	3.65	i. Maximum water production rate of 5 STB/day at one day, thereafter water production decreases rapidly. At about 10 days, rate of decline of water production decreases, resulting in a more leveled production rate ii. Gas production reached a plateau of 500 Mscf/day which continued for two days. This is due to the maximum production limit set during running of the simulation. Production decline rate reduces after about 12 days where it starts to leveled out due to reduction in reservoir pressure iii. Initial rapid water production rate can be attributed to the water saturation of the coal formation iv. Cumulative water and gas production is rather steep in the first ten days of production v. After 10 days, cumulative production slows down. After 100 days, cumulative production for gas is at 4300 Mscf, whereas cumulative water production is almost 32 STB.
2	20	i. Water production peaked at about 6.6 STB/day and then drops after one day. The water production rate decreases steeply until about 10 days. Thereafter, water production rates starts to level out. ii. Production of methane gas peaked and plateaued for a longer period, which is about six days compared to only two days in the previous case. After this plateau period, gas production dropped immediately and rather steeply, similar to the water production rate. iii. Gas production decline rate reduces at the critical time of 14 days, which is two days longer than the previous case. iv. Both water and gas cumulative production is substantial in the first 10 days. v. Water cumulative production is at 34 STB whereas gas production is at 4600 Mscf after 100 days.

3	40	i. Maximum water production rate increases to 7.8 STB/day. After this maximum production, water production rate rapidly decreases until it reaches a critical point at 11 days, at which point, rate of decline reduces. ii. Gas production at 500 Mscf/day is also prolonged to 6.5 days, after which it decreases in production rate. Critical point is about 14 days iii. Cumulative production of gas remains unchanged at 4600 Mscf, whereas for water, it increases slightly to 34.2 STB
4	60	i. Water production rate peaked at 8.6 STB/day, thereafter decreases rapidly until about 10 days when the production rate starts to level out. ii. Methane gas production at 500 Mscf/day continued for over 7 days. Critical point of production is at 13 days where rate of production eventually starts to level out. iii. Initial rapid water and gas cumulative production can be seen from the graph as both have higher saturations and higher reservoir pressure. After 8 days, water cumulative production starts to slow down, whereas for gas it is after 11 days. iv. Total water production after 100 days is 35 STB and for gas it is 4600 Mscf, which is equal as in the previous case.
5	80	i. Water production rate maximizes at 1 day at a rate of 9.2 STB/day. After this period, water production reduces. Rate of production decline eventually reduces at 10 days ii. Methane gas production continued at a rate of 500 Mscf/day for 7 days and then reduces in production rate. After 14 days, rate of decline reduces and eventually ends at zero production rate. iii. Cumulative production of gas remains unchanged, at 4600 Mscf. On the other hand, water total production increases slightly to 35.3 STB.
6	100	i. Maximum water production rate is at 9.6 STB/day and after

		one day, production rapidly decreases. After a critical point of 10 days, water production starts to level out and eventually ends at zero production. ii. For methane gas, the plateau period of production remains unchanged at 7 days, whereas the critical point is at 14 days. iii. Cumulative production of water increases to 35.5 STB and for gas, total production remains unchanged at 4600 Mscf.

It can be seen that there are common trends with all the graphs. Firstly, both water and gas production rate spiked very quickly. This can be attributed to the instantaneous diffusion of fluids from coal matrix into the fractures of the coal. After this spike, all results showed a decline in production ate and then eventually evened off to zero production. Furthermore, when permeability increases, the period of which maximum gas production occurs in prolonged. In other words, the higher the permeability, the longer the maximum production period.

From the cumulative production graphs, it can be said that when permeability rises, total production also raises. However, there is an exception for the gas production in which at 20md and above, the total production remains constant at 4600 Mscf. At permeabilities of 20md and above, the gas diffuses out of the coal and into the well more quickly, hence resulting in faster depletion of the total gas content of the coal, resulting in greater cumulative gas production. Due to this, the limiting factor is the Langmuir volume, which is the maximum gas content of the coal. The high permeability results is faster production of gas, which in turn results in faster depletion of the gas content, hence resulting in equal production totals of coal reservoirs at permeabilities of 20md and above.

To see the trends of gas production rate and cumulative volume as permeability increases, the sequences of production rates and cumulative production with increasing permeability is illustrated in figure 19, 20 and 21.

Case 1: San Juan Basin Trends

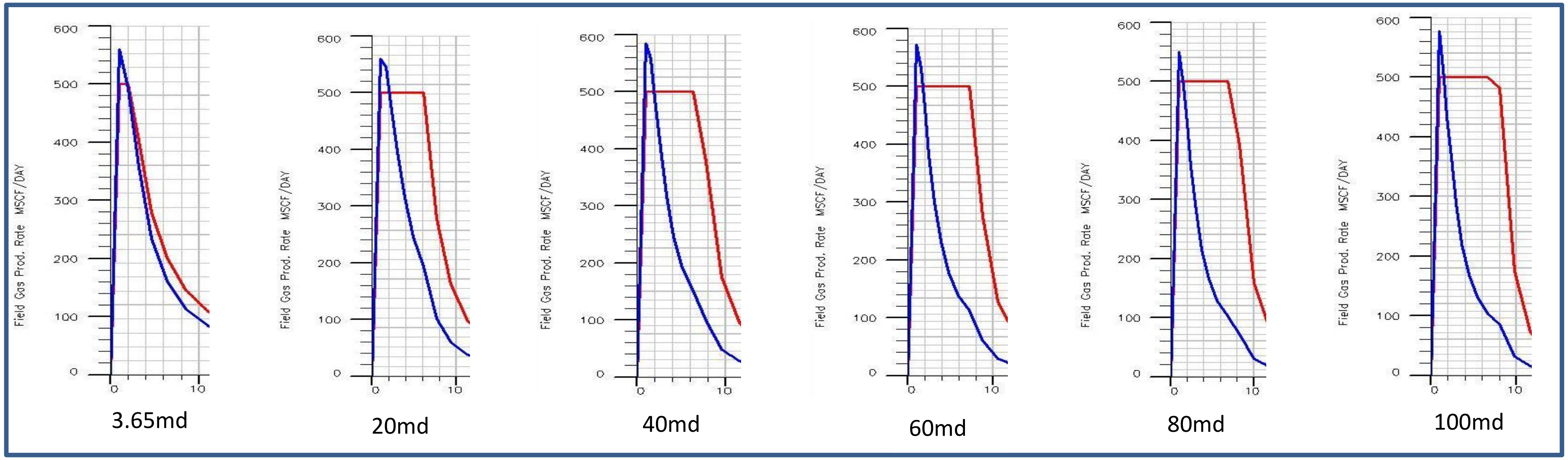


Figure 19: Production rate trends, (Early Production)

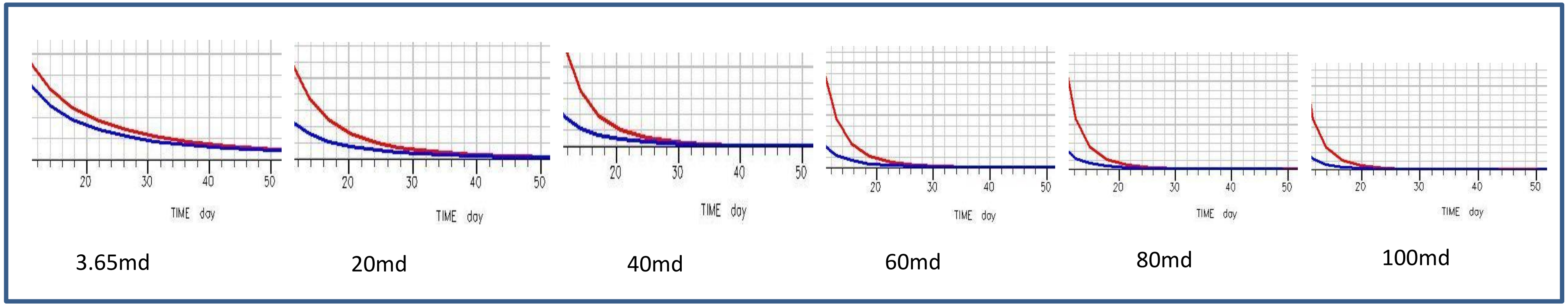


Figure 20: Production rate trends, (Decline)

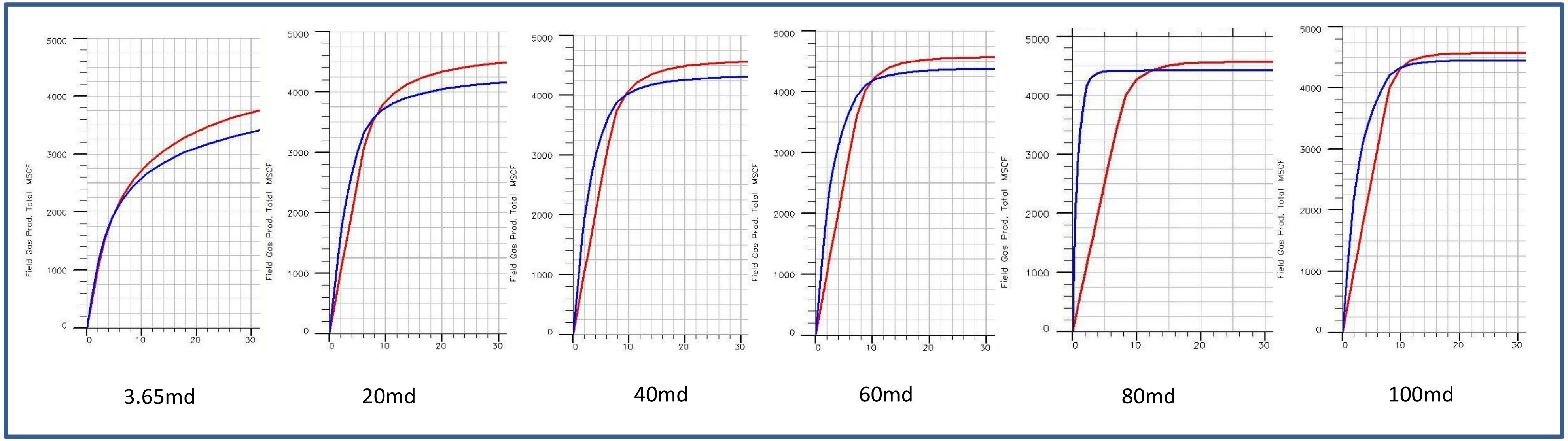


Figure 21: Cumulative gas production trends

4.2 Case 2: Powder River Basin

Case 2a: Powder River Basin (Base Case, k=632md)

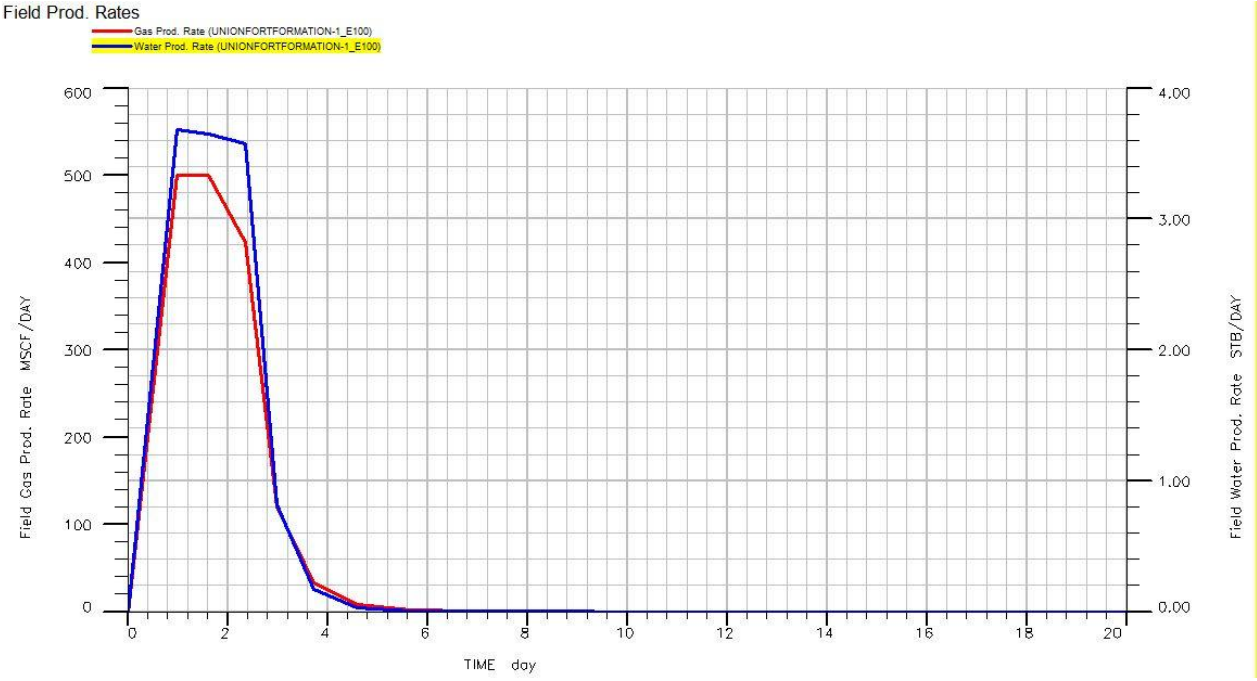


Figure 22: Field production rate, permeability 632md

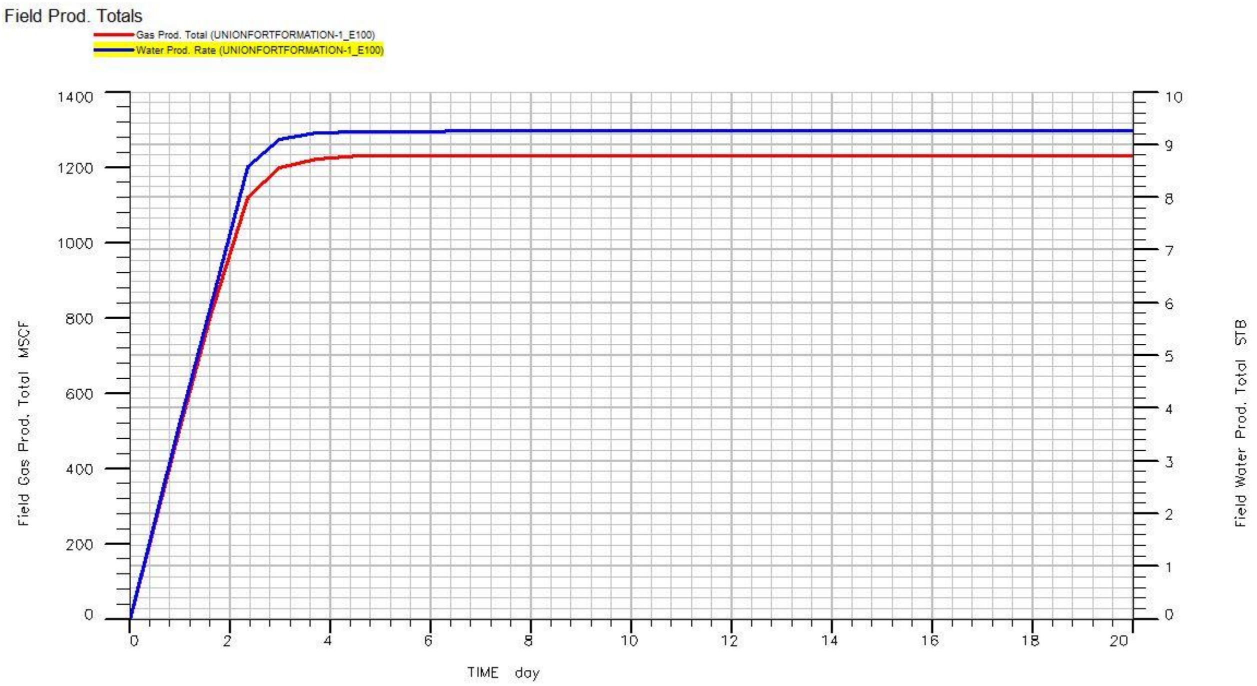


Figure 23: Field production totals, permeability 632md

Case 2b: Powder River Basin (k=650md)

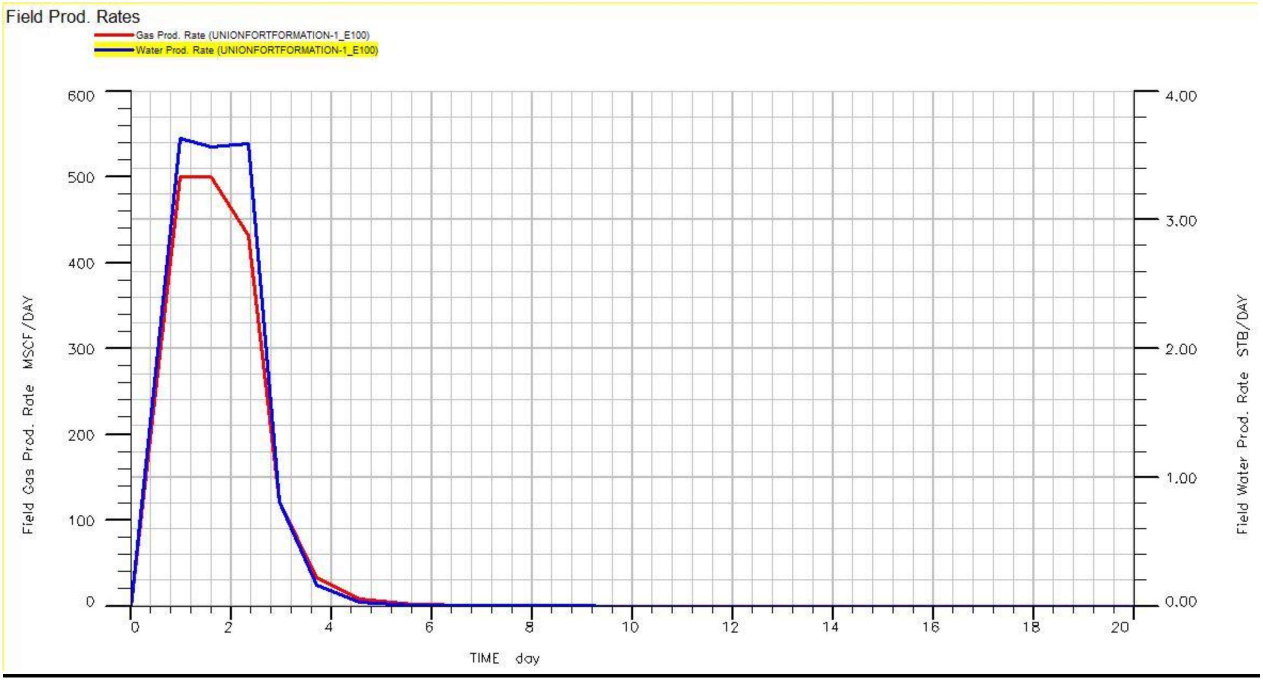


Figure 24: Field production rates, permeability 650md

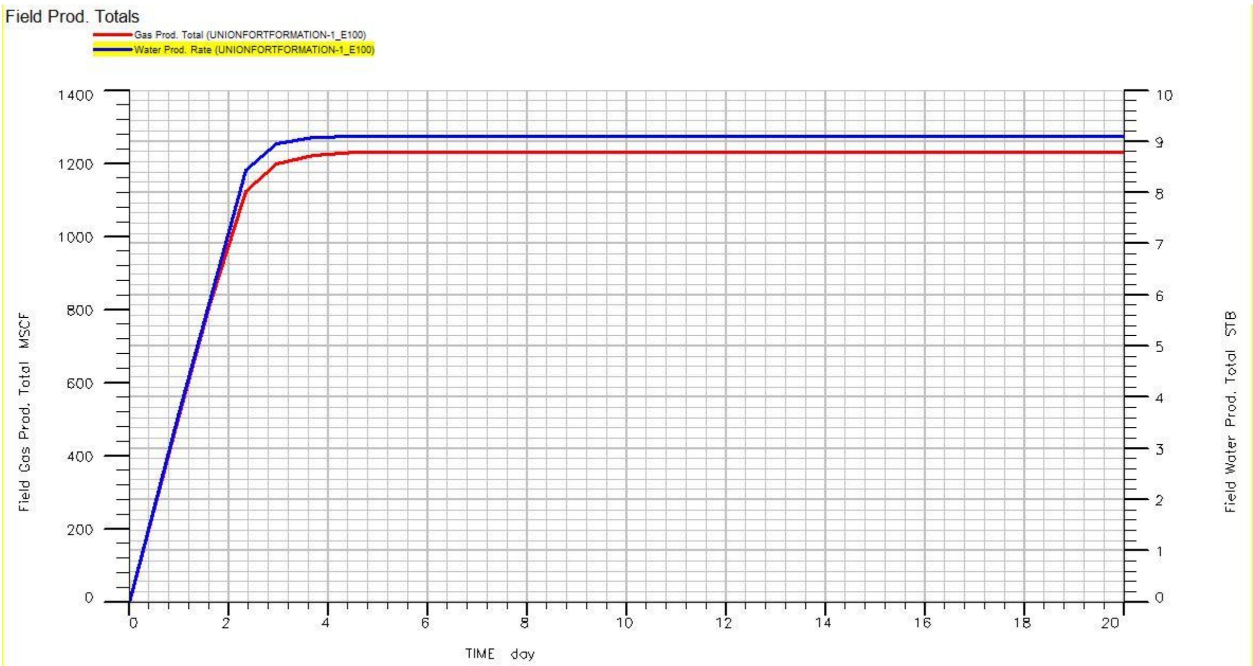


Figure 25: Field production totals, permeability 650md

Case 2c: Powder River Basin (k=670md)

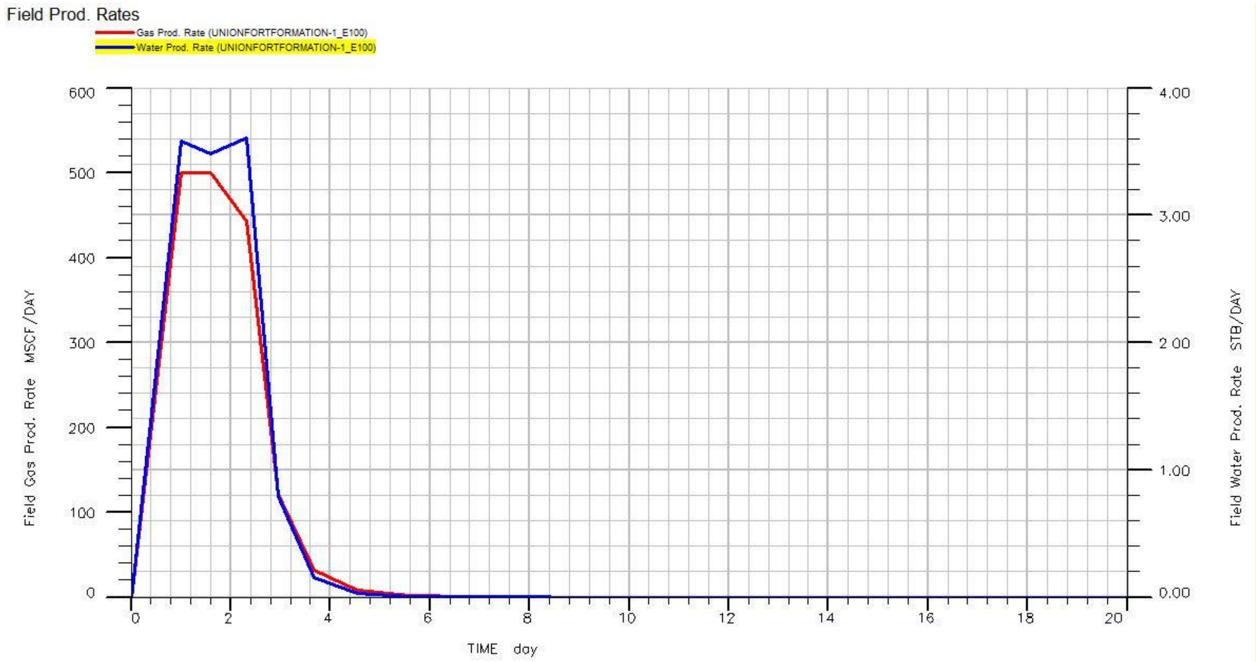


Figure 26: Field production rates, permeability 670md

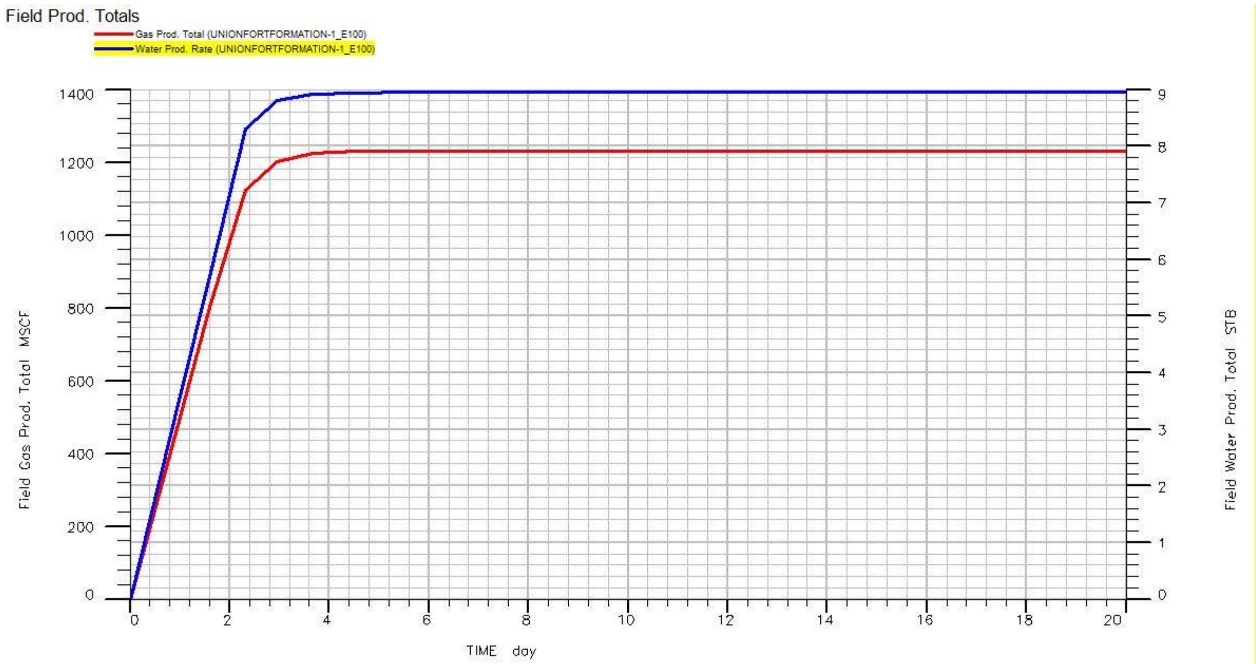


Figure 27: Field production totals, 670md

Case 2d: Powder River Basin (k=700md)

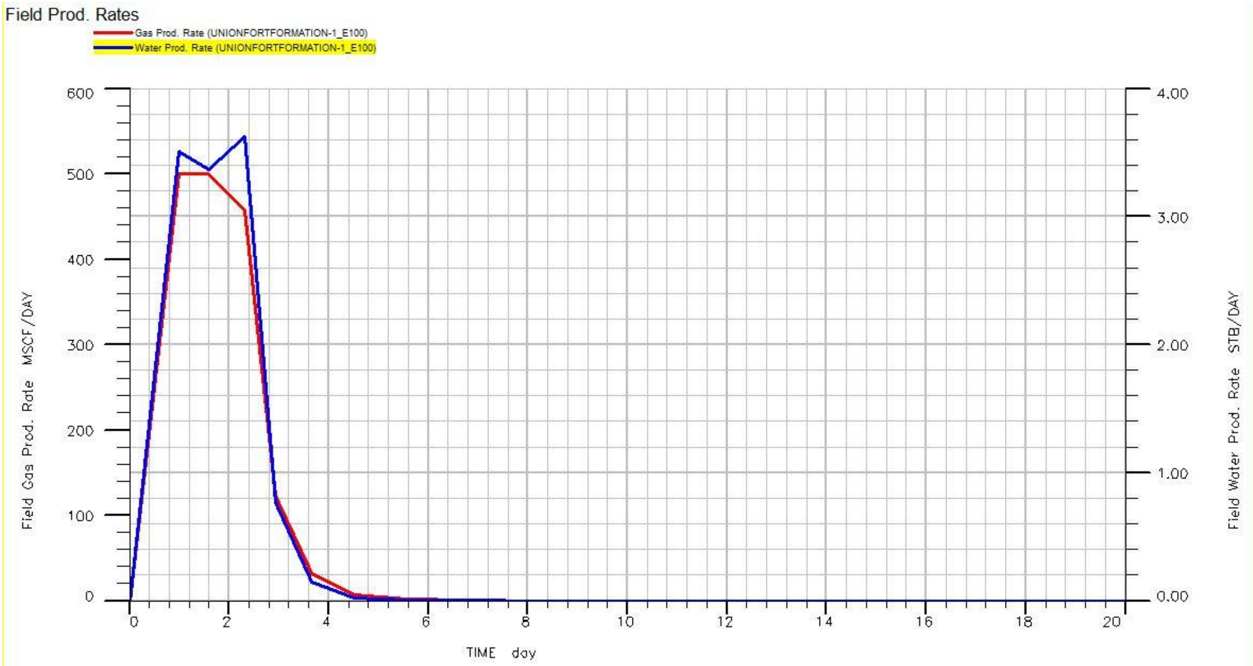


Figure 28: Field production rates, permeability 700md

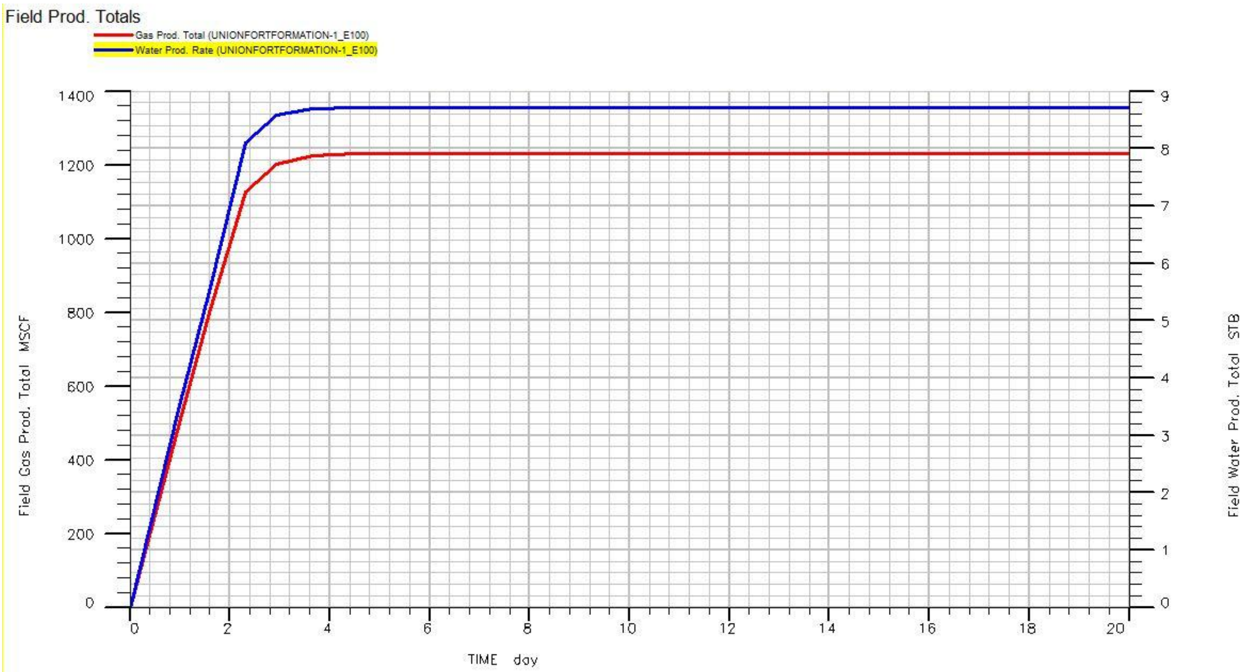


Figure 29: Field production totals, permeability 700md

Case 2e: Powder River Basin (k=720md)

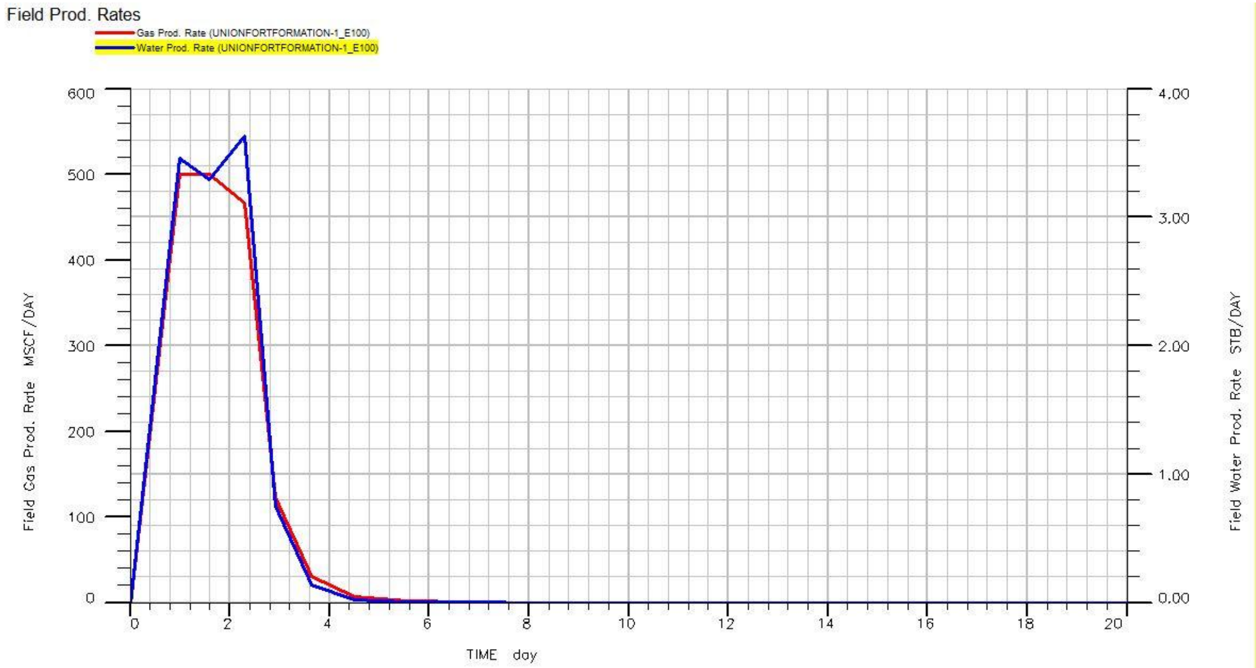


Figure 30: Field production rates, permeability 720md

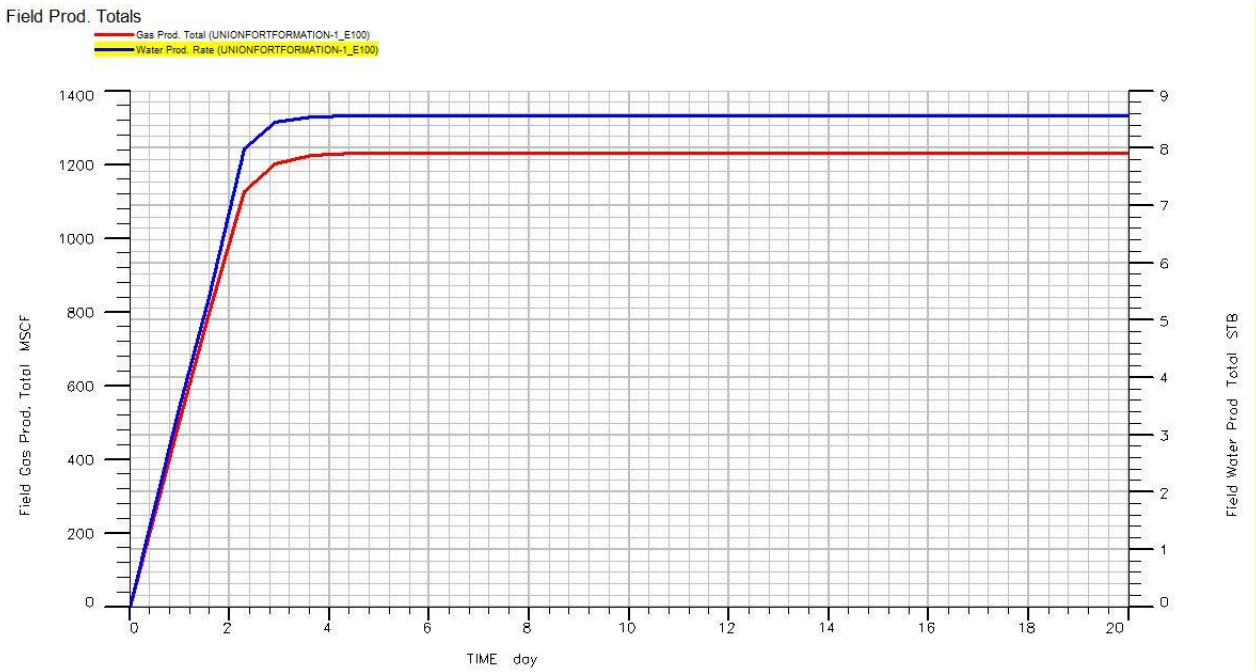


Figure 31: Field production totals, permeability 720md

Case 2f: Powder River Basin (k=750md)

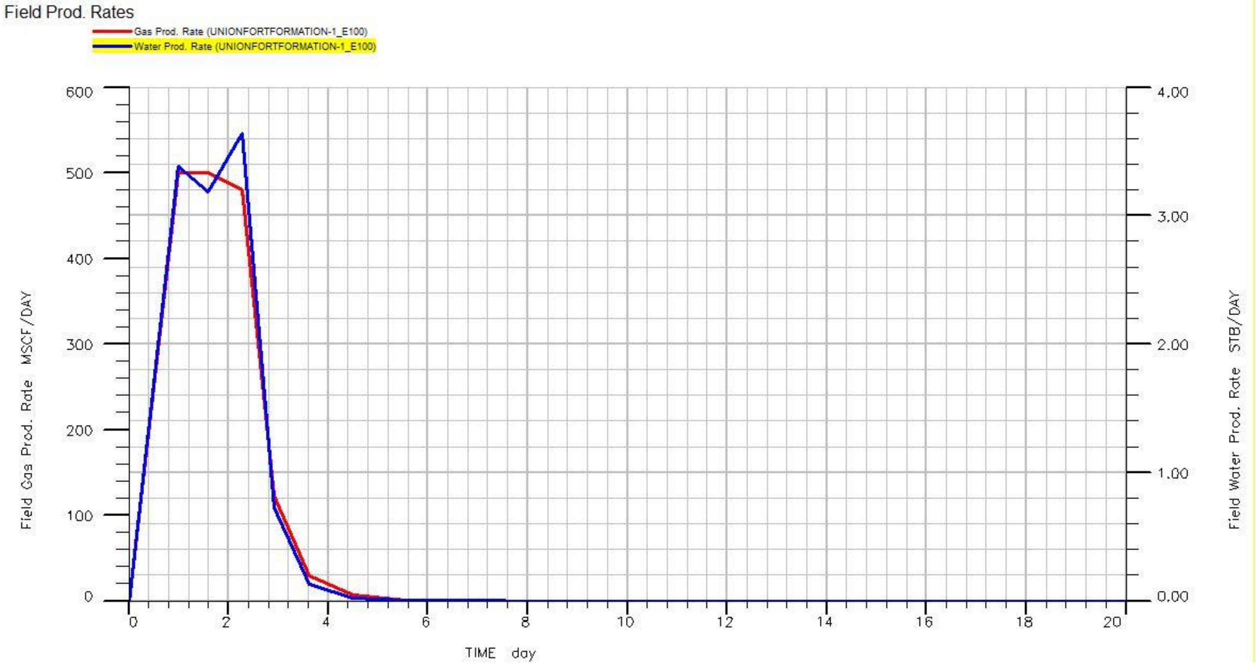


Figure 32: Field production rates, permeability 750md

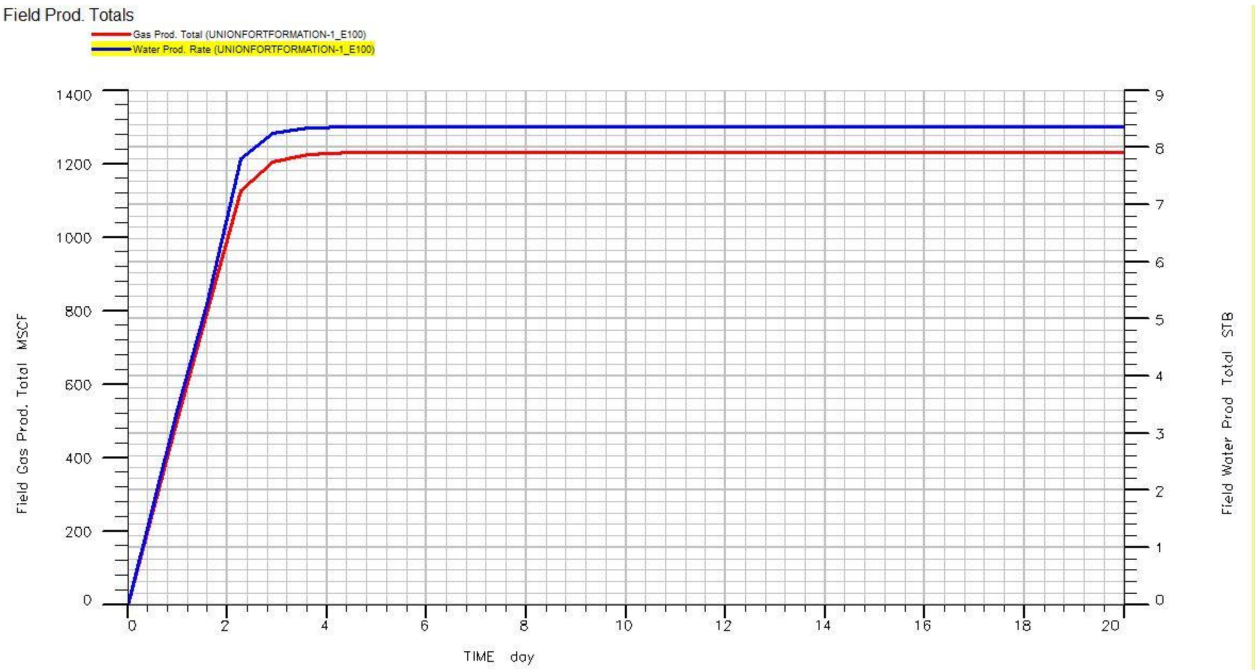


Figure 33: Field production totals, permeability 750md

Table 6: Analysis of results, Powder River Basin

No.	Permeability (md)	Analysis
1	632	i. Both water and gas production increases very rapidly. Water production reached a maximum rate of 3.7 STB/day. After this maximum production, production rate decreases gradually, until about 2.4 days, where water production rate drops rapidly. This goes on for one day, after which point water production rate reduces in its rate of decline. ii. Methane gas production reaches maximum production and continues for about 0.8 days, thereafter decreasing in production rate rapidly. Gas rate eventually starts to level off at 3.7 days. iii. Total water production is about 9.25 STB after 20 days, whereas total gas production is 1240 Mscf.
2	650	i. Both water and gas production rate peaked at one day. Maximum water production rate is around 3.62 STB/day. On the other hand, the maximum gas production rate of 500 Mscf/day continued for about 0.8 days, similar as in the previous case. ii. From closer observation, water production rate drops slowly during the plateau production rate of gas. Water production rate then increases slightly when gas production rate reduces rapidly. This can be attributed to the relative permeabilities of each fluid. As the rate at which the gas bubble reduces, the relative permeability of water to gas increases, hence water is the preferred production fluid, therefore resulting in a slight increase in the water production rate. iii. At 2.4 days, both water and gas production rates drop rapidly, after a mild drop of methane gas production. Zero production occurs at 6.4 days. iv. Cumulative production of water drops to 9.1 STB, whereas cumulative gas production remains unchanged at 1240

		Mscf.
3	670	i. Water production maxed at 3.62 STB/day, same as in the previous case. Gas production also remains unchanged, both in production rate and plateau period. ii. However, the dip in production rate of water after one day is greater than the previous case. The subsequent temporary rise of water production is also steeper as compared to the previous case. This is also caused by the changes in the relative permeability of water and gas phase. As gas production rate drops, the relative permeability of water increases, causing a short rise in production rate of water. The higher permeability of the coal formation also plays a role in this phenomenon. iii. Total water production drops to 8.9 STB, so does the total gas production which drops to just under 1240 Mscf.
4	700	i. Both water and gas production rates starts of according to the trend in which both fluids spiked rapidly. However, one major difference that can be observed is that water production only peaked at almost 2.4 days, that is after the methane gas production rate has dropped to below its maximum production rate. ii. When methane gas production rate drops, this paves the way for more water to be produced, hence the slight increase at 2.2 days. iii. Maximum production rate is still 3.62 STB/day, however it took a longer time to reach that point. iv. At almost 2.4 days, both production rates drop rapidly. v. Total production of water drops to 8.7 STB and total water production drops to 1200 Mscf.
5	720	i. The production rates follow the trend of the previous case, where maximum water production rate only occurs after the methane gas production rate has dropped. However, the difference from the previous result is that water production

		rates actually drops below the gas production rate, which occurred at 1.6 days. The causes of this is the same as the previous case where relative permeability of water is higher at this point, with the addition of the higher permeability of the coal formation. ii. Maximum water production rate increases slightly. Both water and gas production rate drops rapidly at 2.4 days and zero production occurs at 7.6 days. iii. Cumulative production of water drops to just under 8.6 STB whereas gas total production is at 1220 Mscf.
6	750	i. The final case with permeability 750md is similar to the previous two results, where maximum production rate of water occurs when methane gas producing rate is dropping. ii. After one day, water production rate drops as gas production rate is maintained at 500 Mscf. However, water production rate rises again when gas rate drops. Again, this is due to the relative permeability of water which rises when gas production rate drops. The water is somewhat released from the formation when methane production rate reduces, hence an increase in the relative production of water. iii. After almost 2.4 days, both fluids drop in production rate and zero rate is at 5.4 days. Maximum water production rate is 3.62 STB/day. iv. Maximum water produced drops to 8.4 STB and total produced gas remains unaltered.

It can be observed that for all permeability values, both gas and water is initially produced at high rates, until a certain point is reached, thereafter production rate drops. However, as permeability values rises, water production rates drops slightly, and starting at 650md until 750md, water production rate does not change at all. This can be attributed to the extremely high permeability values of the coal formation. Furthermore, relative permeability of water to gas plays a large role in this case. When the gas production rate starts to drop, relative permeability of the water rises, hence water production rate starts to increase again. This can be seen for all cases except for the base case (k=632md).

Another unusual characteristic of this high permeability coal formation is that water cumulative production drops as the permeability values increases. This can be attributed to the relative permeability of the fluids. For example, at 670md, the drop in water production rate is small as compared to the drop in water production rate at 750md during the plateau period of methane gas production. At lower permeabilities, i.e. 650md, water relative permeability drops when methane production rate is at a plateau. As relative permeability of gas reduces, production rate of the gas also drops and relative permeability of water rises, hence an increase in production rate of water. At higher permeabilities, i.e. 750md, this has a magnified effect on the producibility of the fluid with higher relative permeabilities. So, using the 750md case as an example, when methane gas is produced at a plateau rate, water production rate decreases due to lower relative permeability of water. Coupled with the higher permeability of the reservoir, the reduction in production rate is magnified, therefore, resulting in less cumulative production of water when permeability is higher.

To give a clearer insight into the trends of production rate and cumulative production with respect to changes in permeability, the following figures are presented.

Case 2: Powder River Basin Trends

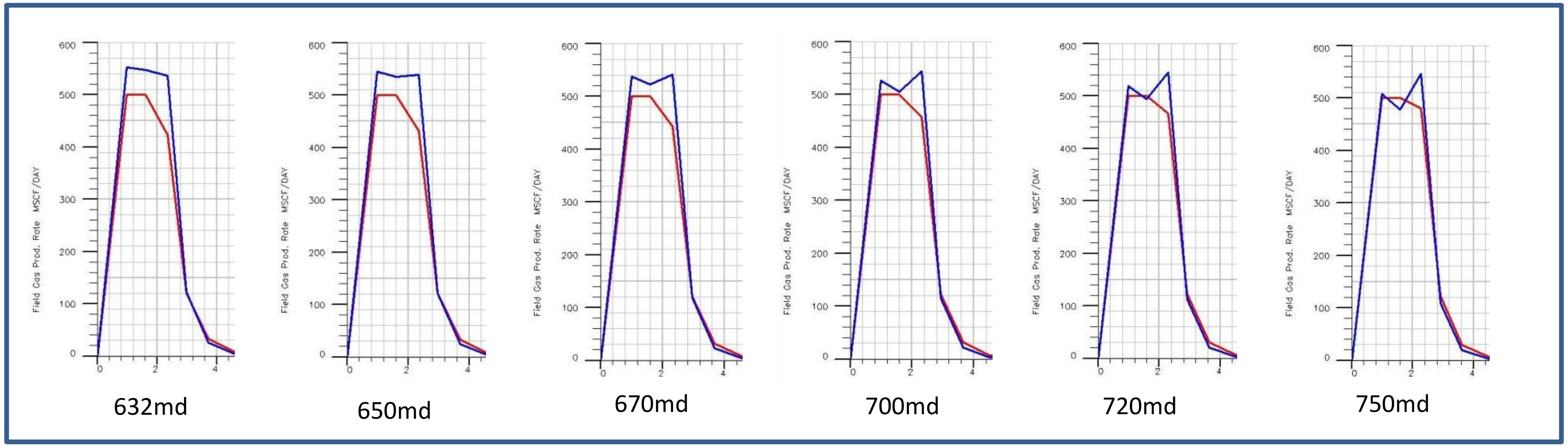


Figure 34: Production rates trend, (Early Production)

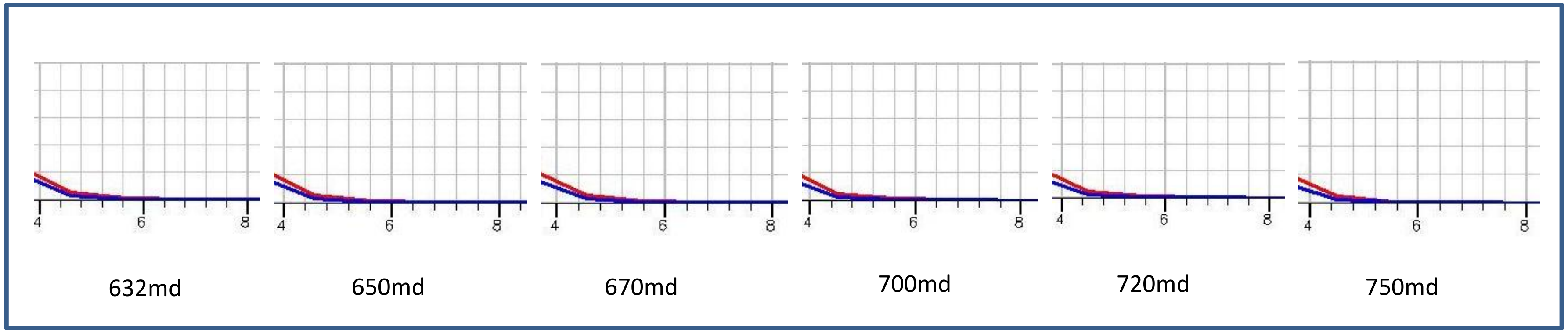


Figure 35: Production rate trends, (Decline)

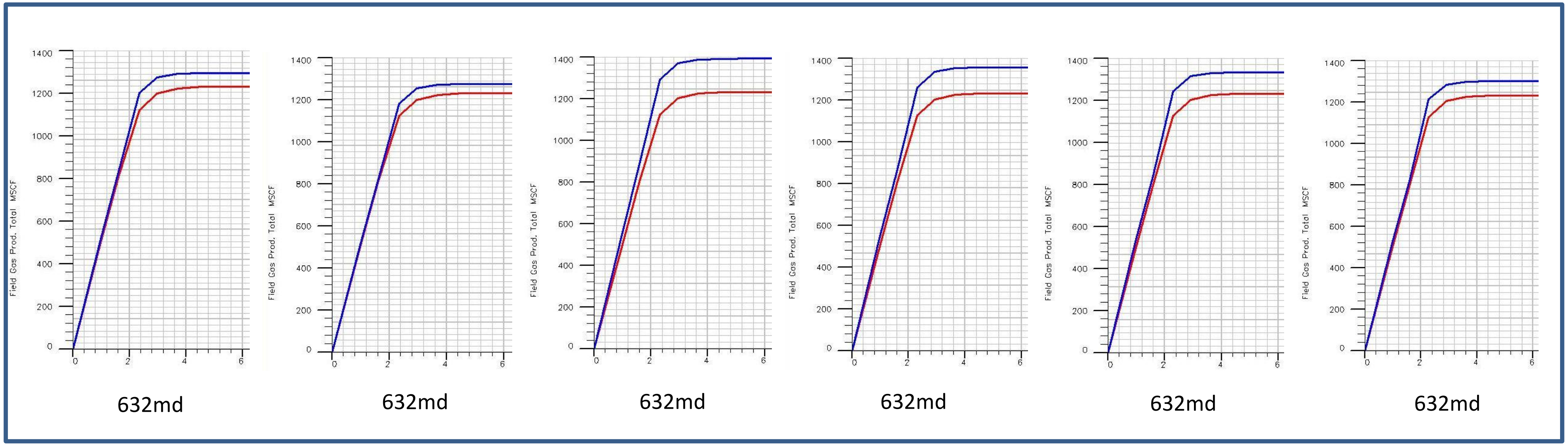


Figure 36: Cumulative gas production trend

4.3 Case 3: Sarawak Coalfield

<u>Case 3a: Sarawak Coalfield (Base Case, k=14.42md)</u>

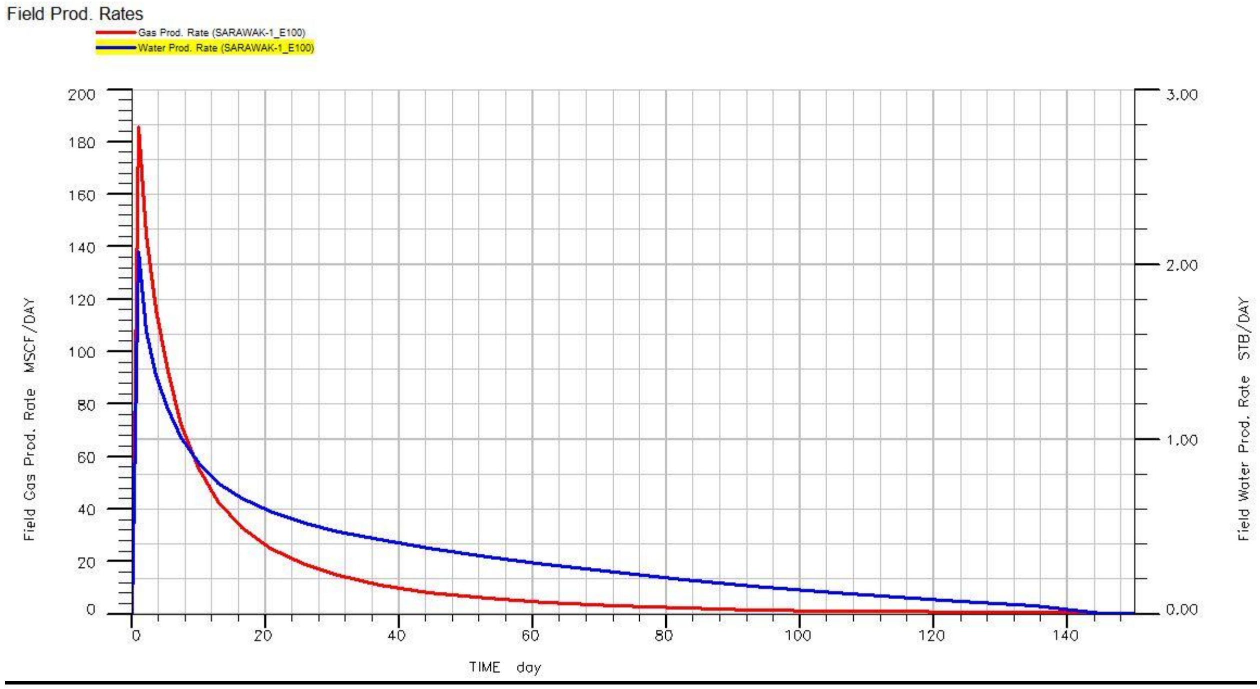


Figure 37: Field production rates, Permeability 14.42md

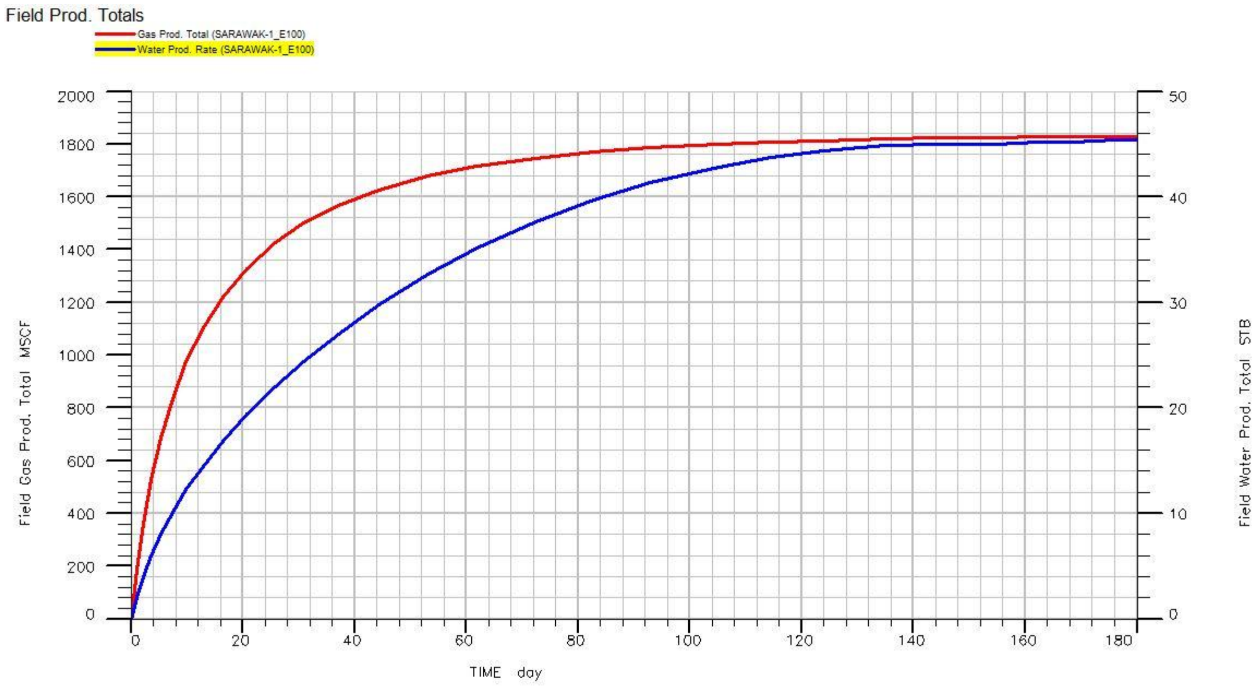


Figure 38: Field production totals, Permeability 14.42md

Case 3b: Sarawak Coalfield (k=20md)

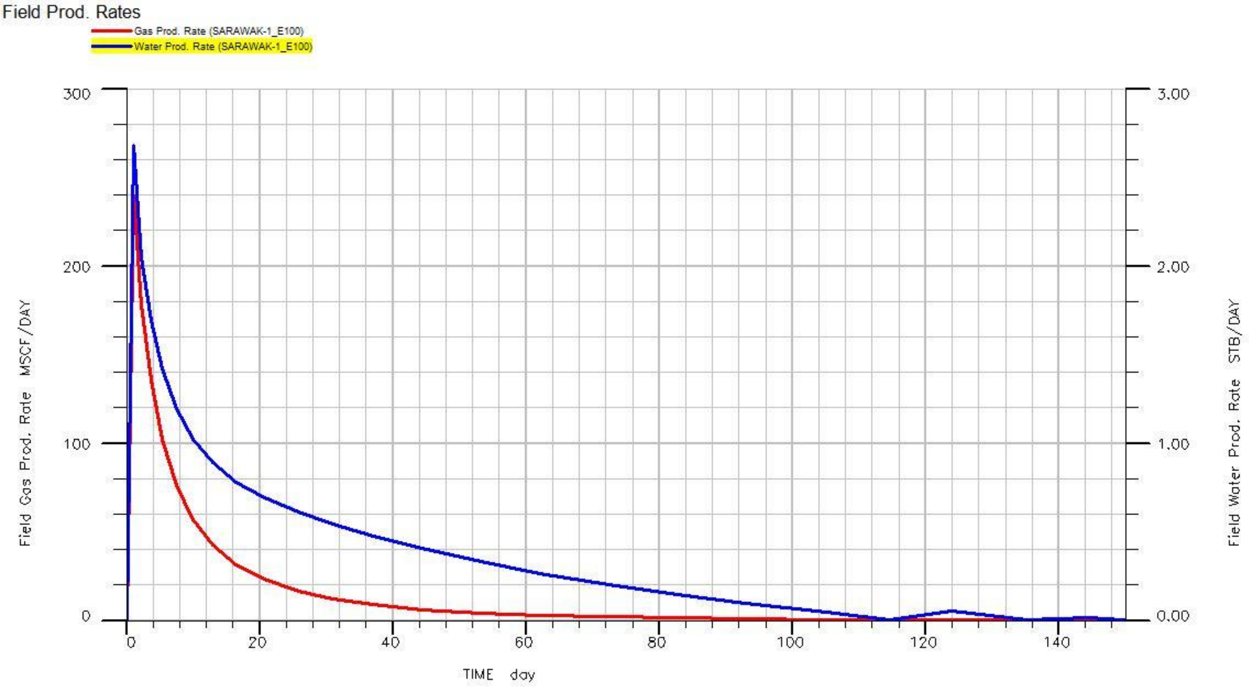


Figure 39: Field production rates, Permeability 20md

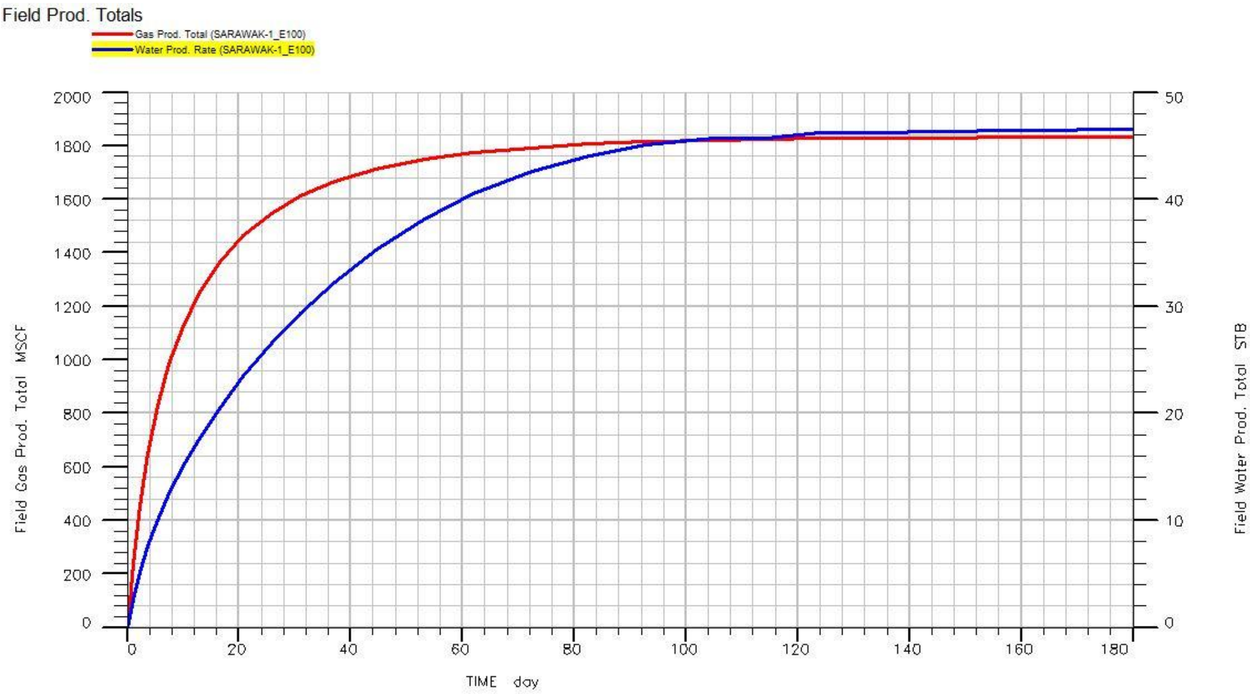


Figure 40: Field production totals, Permeability 20md

Case 3c: Sarawak Coalfield (k=40md)

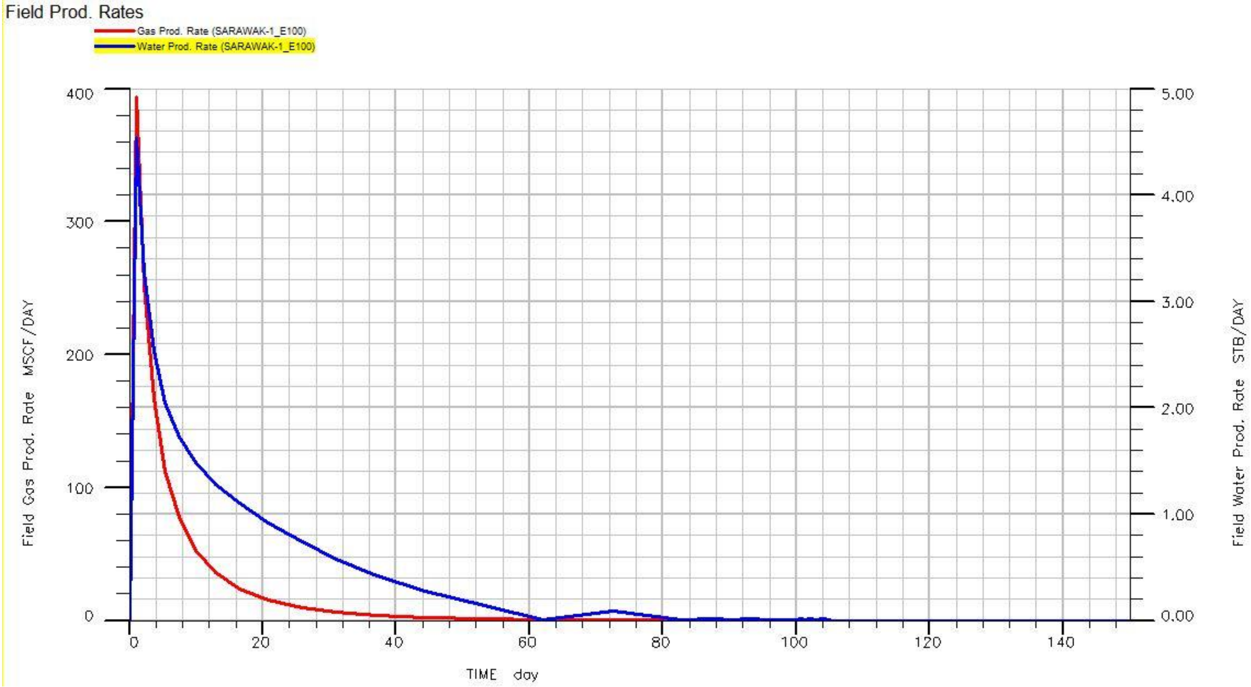


Figure 41: Field production rates, Permeability 40md

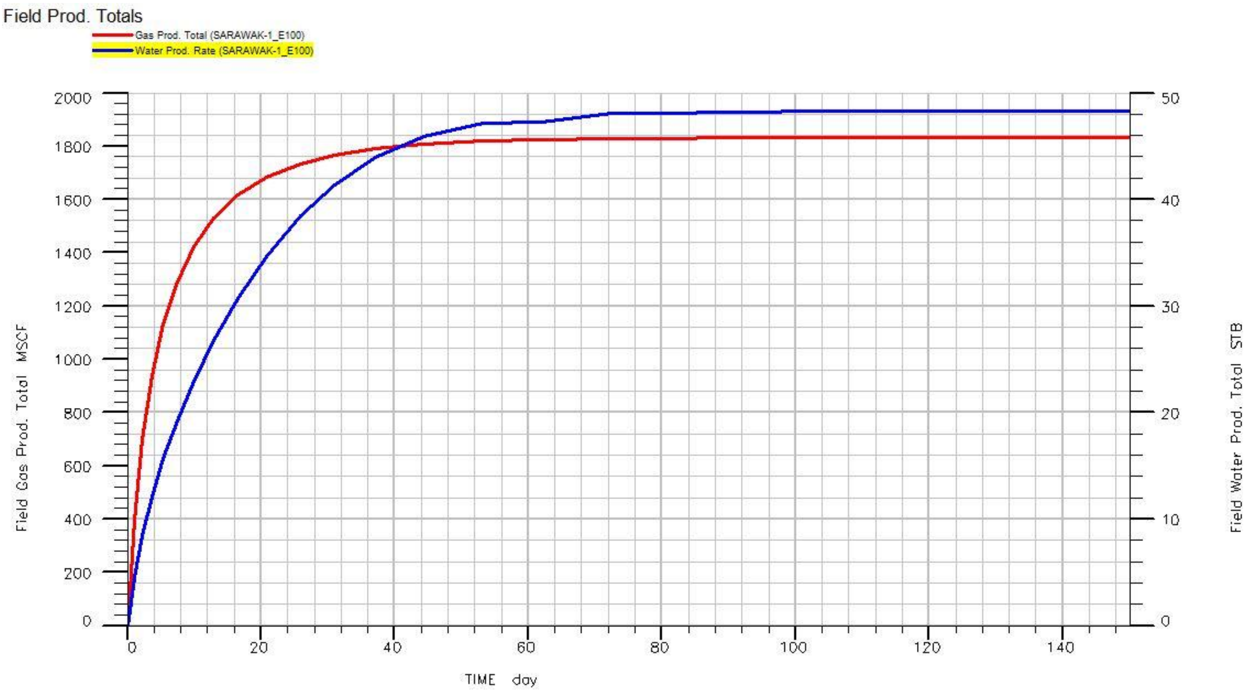


Figure 42: Field production totals, Permeability 40md

Case 3d: Sarawak Coalfield (k=60md)

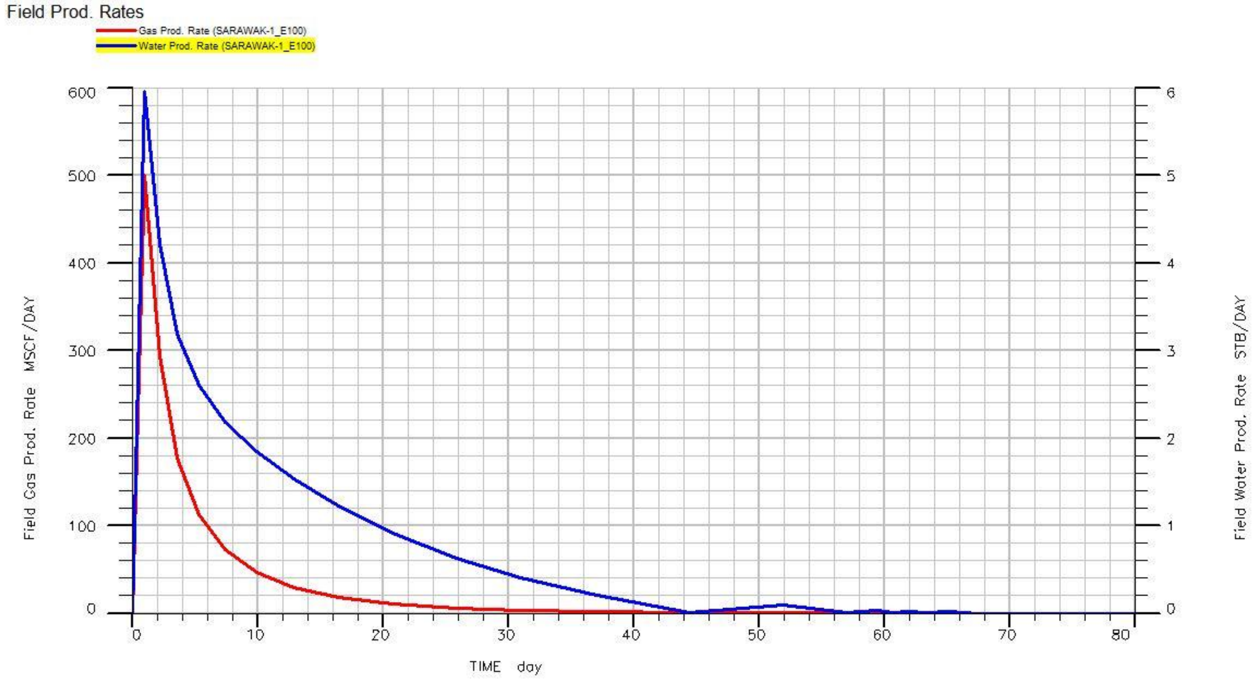


Figure 43: Field production rates, Permeability 60md

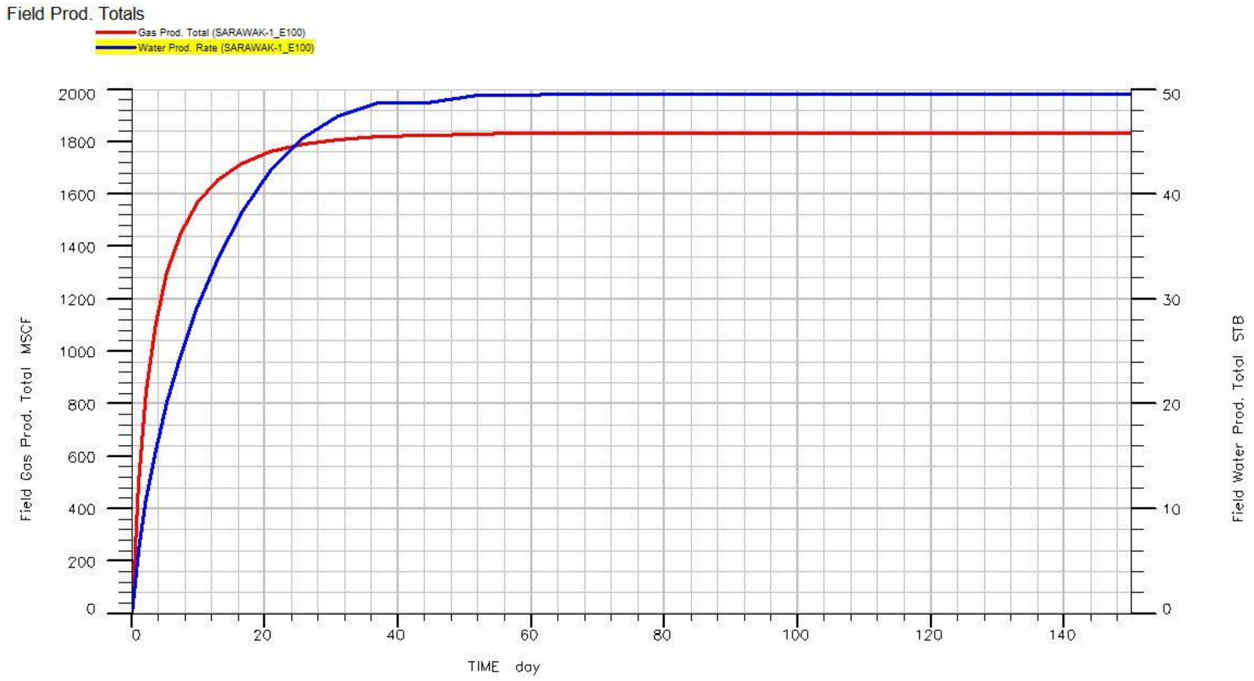


Figure 44: Field production totals, Permeability 60md

Case 3e: Sarawak Coalfield (k=80md)

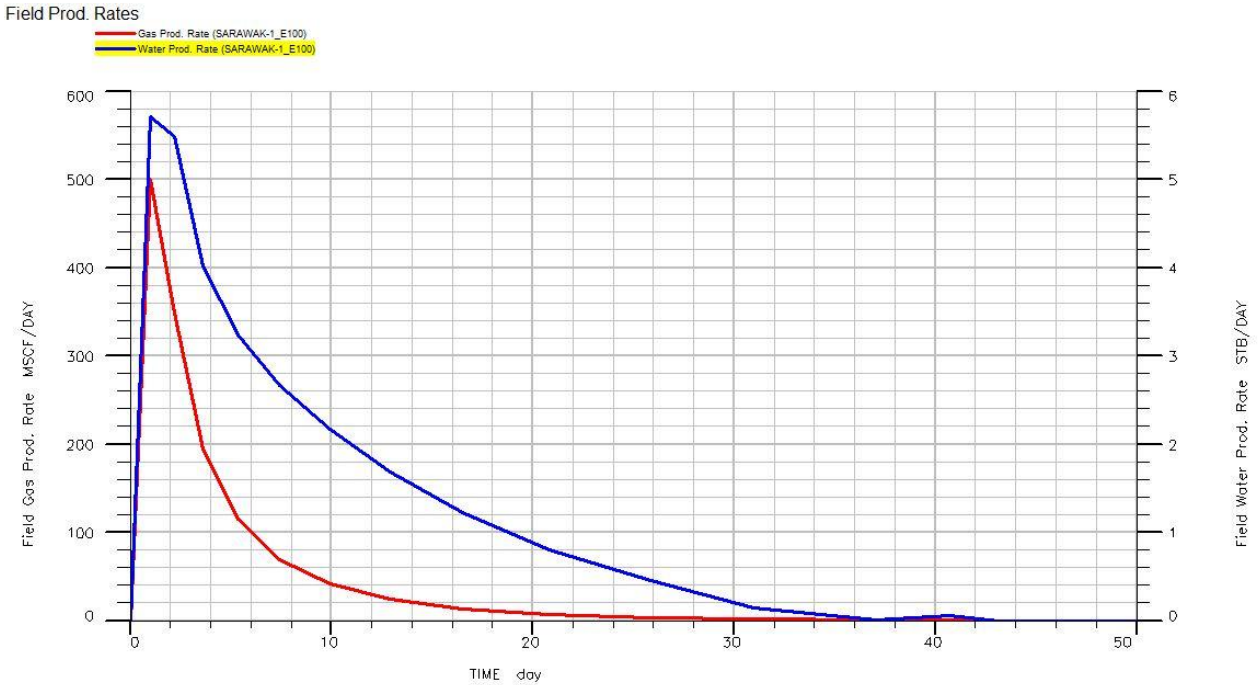


Figure 45: Field production rates, Permeability 80md

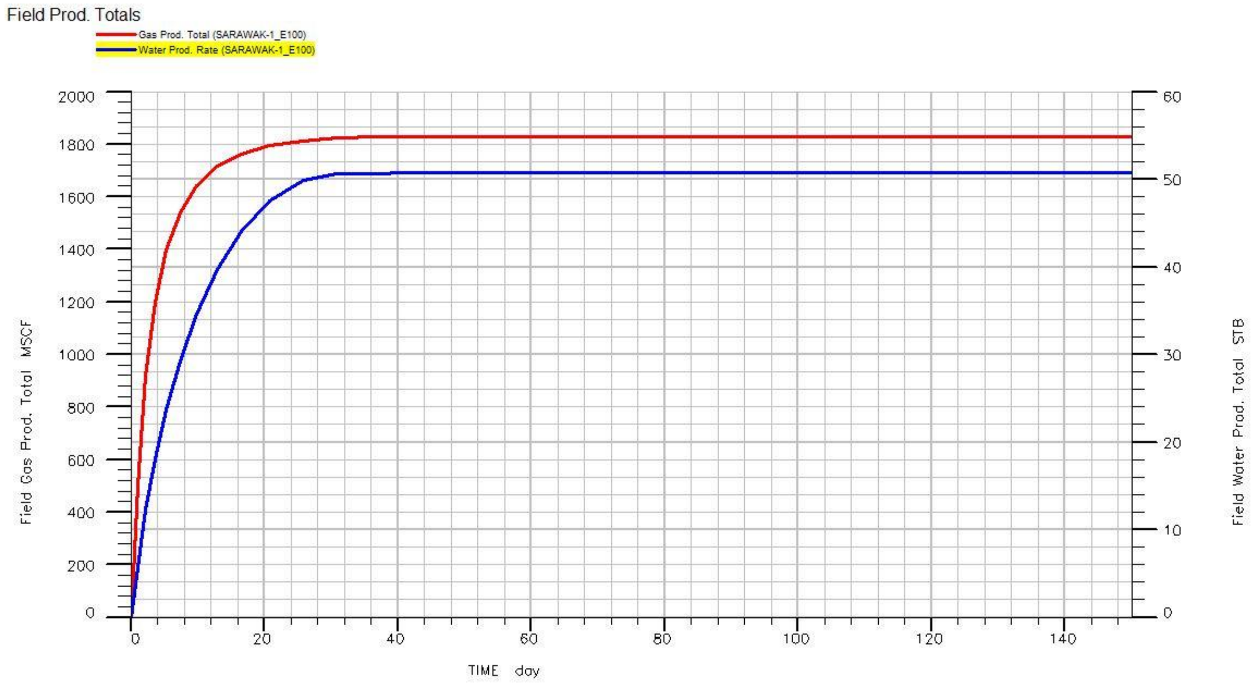


Figure 46: Field production totals, Permeability 80md

Case 3f: Sarawak Coalfield (k=100md)

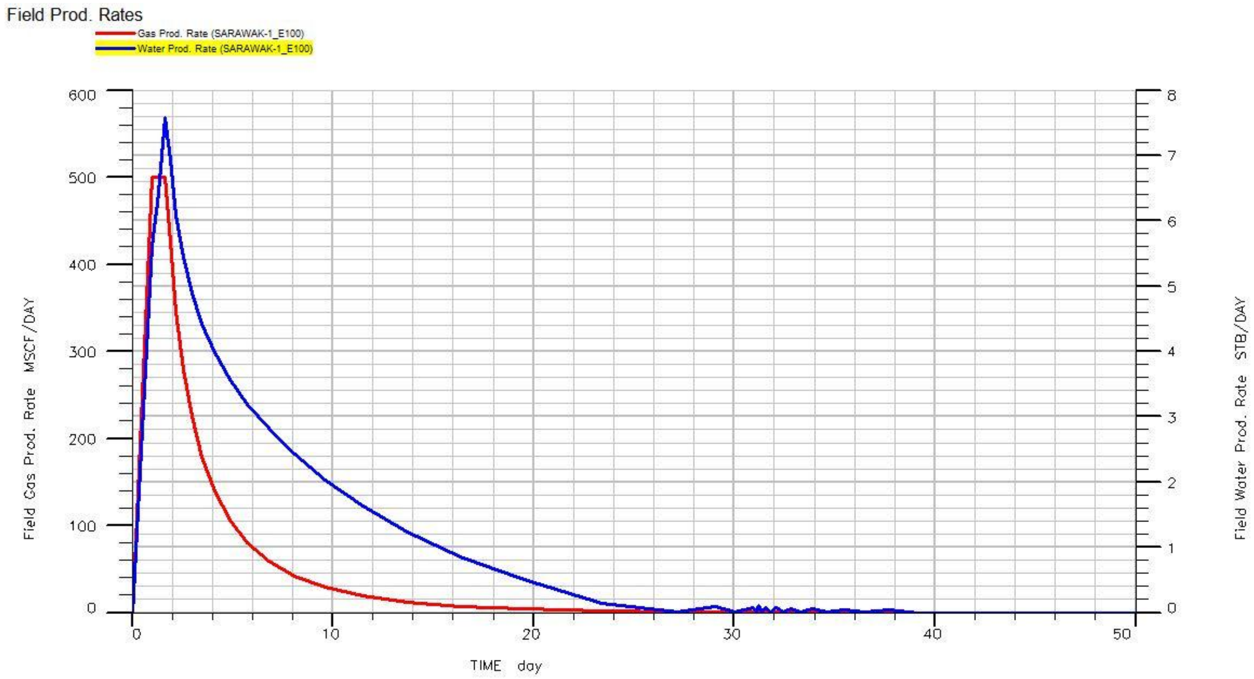


Figure 47: Field production rates, Permeability 100md

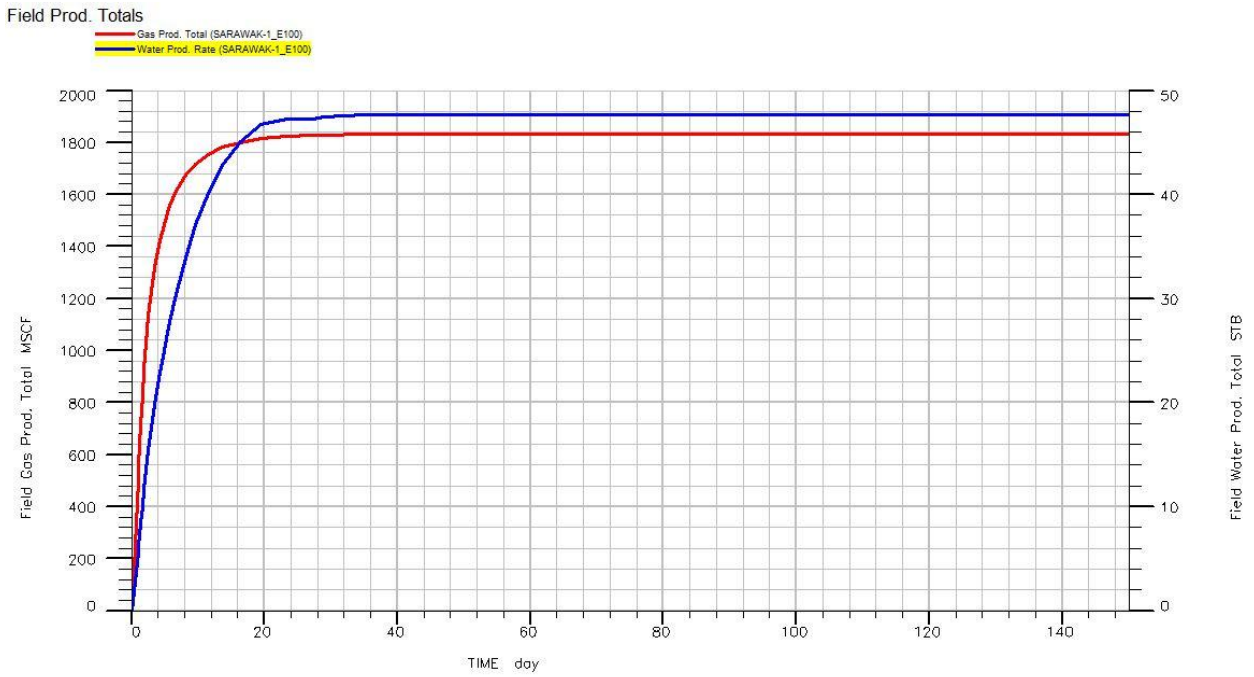


Figure 48: Field production totals, Permeability 100md

Table 7: Analysis of results, Sarawak Coalfield

No.	Permeability (md)	Analysis
1	14.42	i. As with other production rates from previous fields, both water and gas production rates increases rapidly over a one day period. This can be attributed by the instantaneous diffusion rates between coal matrix to the natural fractures of the coal. However, one major difference of this coalfield to other fields mentioned above is that the target production rate of 500 Mscf/day is not reached. Instead, the maximum gas production rate is only at 186 Mscf/day. This is due to the low initial reservoir pressure and the high Langmuir Pressure. ii. Maximum water production rate is at 2.1 STB/day. iii. After the initial spike in production rates, both fluids drop in rate dramatically. For water, the decline rate reduces at about 10 days, after which point the production rate starts to level off. iv. The same can be said for the gas production rate, however, the leveling-off period is at 14 days. v. Maximum produced gas is just under 1800 Mscf, whereas maximum produced water is 45.5 STB.
2	20	i. A rise in the permeability of the coal formation results in a rise of the gas production rate, albeit still well below the target production of 500 Mscf/day. Gas production rate reached a peak of 240 Mscf/day, likewise, maximum water production rate increases to 2.7 STB/day. ii. As time goes by, both production rates dwindled down significantly until it reaches zero production rate as the reservoir pressure declines. However, at around 114 days, there is a slight raise in the production of water. Due to the low reservoir pressure at this point, the

			relative permeabilities of each fluid plays a role in the production rates. The reduction in the gas saturation and the subsequent rise in the water production rate can be due to the increase of the relative permeability of water.
		iii.	Total produced gas remains unchanged at just under1840 Mscf. For water, totals production increased to 46.5, which can be attributed to the slight rise in production rate at the latter stages of production.
3	40	i.	When permeability is increased to 40 md, the target rate of gas production of 500 Mscf/day is almost met. Maximum gas production rate reached 395 Mscf/day. The increase in permeability allows more transport of gas through the coal fractures, hence an increase in its production rate.
		ii.	Water maximum production rate also increased to 4.5 STB/day
		iii.	The same phenomenon as the previous case can be seen during the latter stages of production, where water production rate increases slightly. A closer look at the graph shows that water production rates alternates between a rise and drop in production rate, as seen between days 62 through 104.
		iv.	Furthermore, gas production rate drops more rapidly than the water production rate from day 4 until day 16.
		v.	Maximum cumulative gas production is still unchanged at just under 1840 Mscf, whereas cumulative water gas production increases to over 48 STB.
4	60	i.	The target gas production rate of 500 Mscf/day can finally be reached when permeability is increased to 60md, which is also the maximum production rate. For water, production rate increases to 6 STB/day. After the peak is reached, both production rates decreased significantly until production rate is zero. However,

		there is a slight increase in the water production rate from day 44 to 52. After this period, production alternates from increasing to decreasing production rates. ii. Total production of gas remains at 1840 Mscf, whereas total production of water is at 49.5 STB.
5	80	i. Target gas production rate is also met when permeability is increased further to 80md. ii. However, water production rate reached a maximum of 5.7 STB/day, a slight decrease from the previous case. It can also be seen that water production initially drops slowly after the peak production. It is only after two days that water production rates declines rapidly. iii. A recognizable trend is that zero production of the fluids is getting earlier as permeability increases. This is logical since the higher permeability allows faster production of the fluids, hence resulting in a faster depletion time. iv. Total gas produced is still at 1840 Mscf, whereas total water produced increases slightly to just under 51 STB.
6	100	i. At a permeability of 100md, the production rate of 500 Mscf continued for about two days, whereas maximum water production rate is at 7.6 STB/day, an increase from the previous case. ii. As a result from the higher permeability, the time to zero production is decreased, this is about 27 days. Again, this is due to the higher permeability of the reservoir which results in a more rapid depletion of the reservoir pressure. iii. However, after 27 days, water production rate is highly unstable. This can be due to the rise and fall of the relative permeability of water as gas saturation decreases.

		iv. Once again, gas production is unchanged at 1840 Mscf, whereas total water production decreases to about 48 STB.

The unavailability of data regarding the reservoir pressure of this Sarawakian coalfield makes this simulation a lot harder to interpret, and the results may not be as reliable as the other two coalfields. The astonishingly high Langmuir pressure also makes this simulation highly debatable. Nevertheless, the results showed that with the base case permeability of 14.42md, the target gas production rate cannot be reached unless the permeability is increased to 60md. A trend among the results is that production rate reaches zero much quicker as the permeability rises. This is understandable since the greater the permeability, the faster the fluids are produced from the reservoir, and without any pressure maintenance, the reservoir pressure depletes much faster.

The trends with respect to increasing permeability can be seen clearly in figures 49, 50 and 51.

Case 3: Sarawak Coalfield Trends

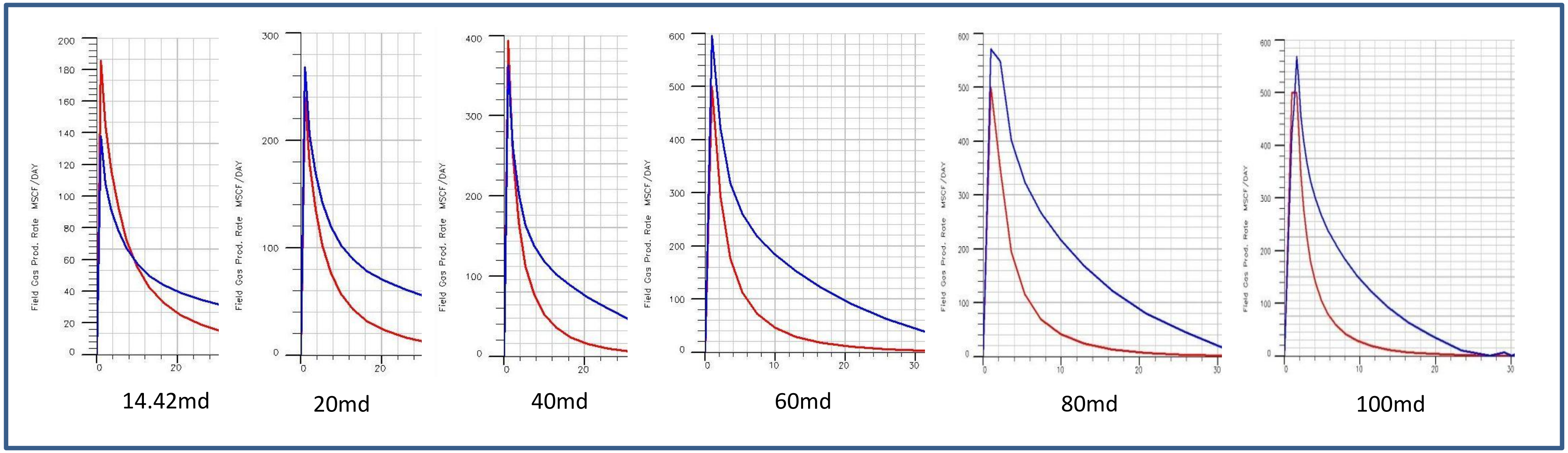


Figure 49: Production rates trend, (Early Production)

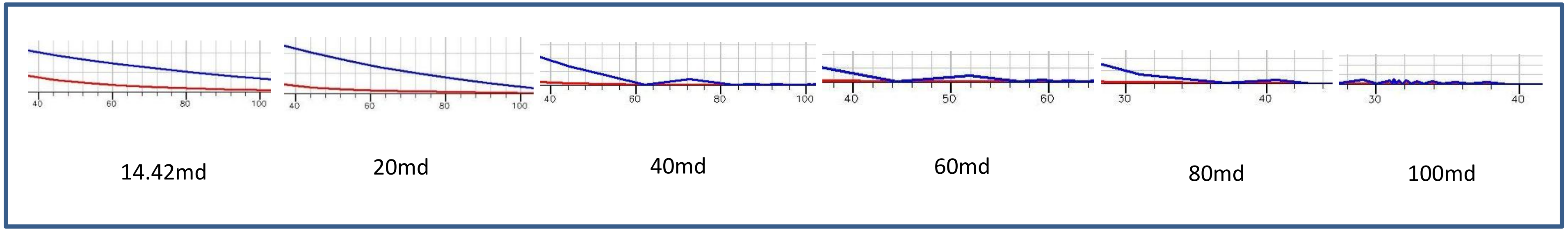


Figure 50: Production rates trend, (Decline)

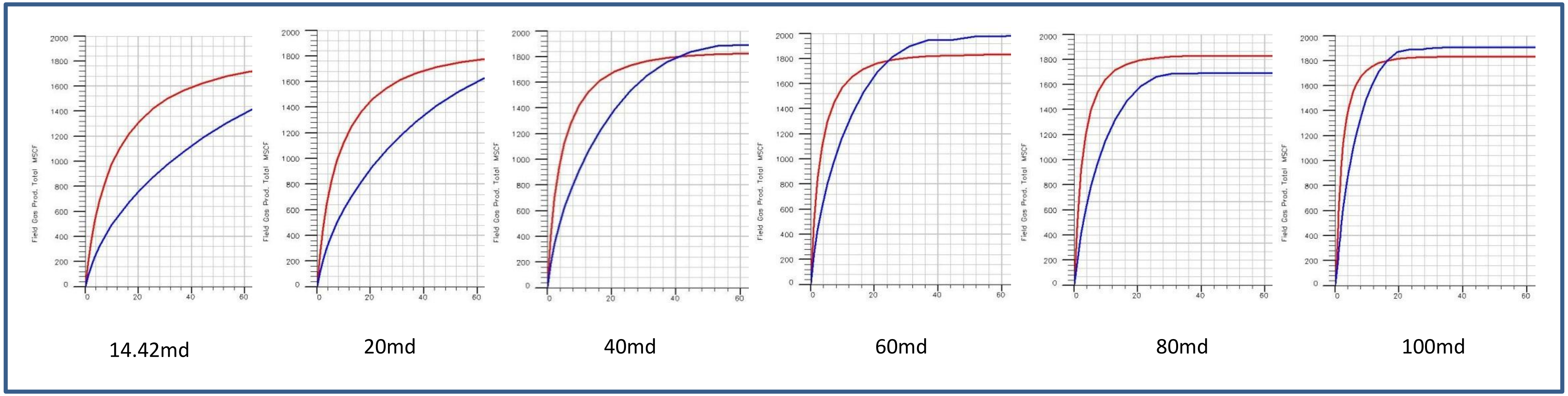


Figure 51: Cumulative gas production trend

Further studies have to be conducted on the reservoir characteristics itself, including in-situ Langmuir pressure and concentration, reservoir pressure and reservoir temperature. Given these data are accurate, then the simulation would be much more reliable to comprehend with.

All three coalfields have specific characteristics which have a direct effect on the production rates and production periods. Permeability, for example, generally gives an improved production rate, or in this case, a prolonged period of production at the target rate of 500 Mscf/day. This is clearly seen between the base cases of the Fruitland formation and the Fort Union formation, where the permeability of the Union Fort formation is 170 times greater than the permeability of the Fruitland formation. Water production also increases when permeability is increased. Indeed, the relative permeabilities of each fluid during each phase in very important during production. The higher the relative permeability of a certain fluid, the higher its tendency to be produced.

Apart from this, initial reservoir pressure and Langmuir volume also plays vital roles in the production profile of the fields. The larger the Langmuir volume, the greater capacity for coal storage. However, Langmuir pressure has an adverse effect of gas production. Higher Langmuir pressure means a high pressure is required for the gas to be adsorbed on the internal surface of the coal. Therefore, in coal with high Langmuir pressure, the methane content is less, and hence production rates will deplete much faster.

All in all, the whole characteristic of the coal formation is important when understanding the production trends and profiles of each field. However, permeability has the most profound effect in production rates since it is permeability that allows the fluids in the reservoir to flow out, into the wellbore and thereafter, up to surface.

5.0 CONCLUSION AND RECOMMENDATION

The research on permeability and its effect towards the production rates of gas in CBM wells have given great insight into the properties of coal and how they relate to pressure. It can be concluded that:

i. Permeability has an enhanced effect on methane gas production rate.

ii. An increase in permeability leads to higher production rate and a prolonged production period at the maximum production rate

iii. Sarawak has the potential to produce CBM, however further research into the coal formation must be conducted

iv. High reservoir pressure, Langmuir volume, and permeability are favorable for CBM production

Among the recommendations that can be made as a follow-up to this project are:

i. Simulation should also be run for higher permeabilities and how they affect production of CBM

ii. More studies should be conducted to see the effect of skin and porosity on production performance

More studies should be conducted to see the effect of skin and porosity on production performance

6.0 REFERENCES

Aminian, K. (n.d.). Coalbed methane- fundamental concepts.

Chen, D., Liu, J., Pan, Z., & Connel, L. D. (2010). Coalbed methane production: why coal permeability matters. *Society of Petroleum Engineers, Conference Paper*, (SPE 133328)

Connel, D., Pan, Z., Lu, M., Heryanto, D., & Camilleri, M. (2010). Coal permeability and its behaviour with gas desorption, pressure and stress. *Society of Petroleum Engineers, Conference Paper*, *SPE 133915*

Dacy, J. M. (2010). Core tests for relative permeability of unconventional gas reservoirs. *Society of Petroleum Engineers, Conference Paper*, *SPE 135427*

Darling, Peter (2011). SME Mining Engineering Handbook (3rd Edition).. Society for Mining, Metallurgy, and Exploration (SME).

Diamond, W. P., & Schatzel, S. J. (n.d.). Measuring the gas content of coal: A review.

Fanchi, John R. (2006). Principles of Applied Reservoir Simulation (3rd Edition).. Elsevier.

Flores, R. M. (1998). Coalbed methane: from hazard to resource. *International Journal of Coal Geology*,*35*(1-4), 3-26.

Grattoni, C. A., Ahsan, M., Durucan, S., & Jing, X. D. (2006). Measurements of petrophysical properties of coal for co2 sequestration.

Guo, R., Mannhardt, K., & Kantzas, A. (2007). Laboratory investigation on the permeability of coal during primary and enhanced coalbed methane production. *Canadian International Petroleum Conference*, *Paper 2007-042*

Ham, Y., & Kantzas, A. (2010). Measurement of relative permeability of coal: approaches and limitations.*Society of Petroleum Engineers, Conference Paper*, (SPE 114994).

Koenig, R. A., et al, “Application of Hydrology to Evaluation of Coalbed MethaneReservoirs”, GRI Topical Report 89/0031, (March 1990) 114.

Kong, C. C., Irawan, S., Chow, W. S., & Tunio, S. Q. (2011). Preliminary study on gas storage capacity and gas-in-place for cbm potential in balingian coalfield, sarawak malaysia. *International Journal of Applied Science and Technology*, 82-94.

Markowski, A. K. (1998). Coalbed methane resource potential and current prospects in pennsylvania.*International Journal of Coal Geology*, *38*, 137-159.

Meng, Y. F., Luo, P. Y., & Jin, L. (1996). Why low permeability and how does it affect coalbed methane supply in coal seams in china. *Society of Petroleum Engineers, Conference Paper, 37382-MS,*

Pusz, S., Krzesinska, M., Pilawa, B., Koszorek, A., & Buszko, R. (2010). The dependence of physical structure of a coal heated in a coking chamber on non-uniform distribution of a temperature.*International Journal of Coal Geology*, *82*(1-2), 125-131.

Rice, D. D., & Claypool, G. E. (1981). Generation, accumlation, and resource potential of biogenic gas.*AAPG Bulletin*, *65*(1), 5-25.

Rightmire, CT., 1984., Coalbed methane resources, in Rightmire, C.T., Eddy, G.E., and Kirr, J.N., editors, Coalbed methane resources of the United States: American Association of Petroleum Geologists Explorer, v. 21, no.4 (April, 2000), p. 16, 18-20, 22-23

Rodrigues, C. F., & Lemos de Sousa, M. J. (2002). The measurement of coal porosity with different gases.*International Journal of Coal Geology*, *48*(3-4), 245-251.

Rogers, R., Ramurthy, M., Rodvelt, G., & Mullen, M. (2007).*Coalbed methane; principles and practices*. (2nd ed.). Starksville: Oktibbeha Publishing.

Schraufhagel, R. A., “Analysis Tecfilques Optimize Coalbed Methane Recovery”, *TheAmerican Oil and Gas Repotier,* (September1990) 33.

Seidle, J. (2011). *Fundamentals of coalbed methane reservoir engineering*. PennWell Books.

Sia, S., & Abdullah, W. H. (2011). Concentration and association of minor and trace elements in mukah coal from sarawak, malaysia, with emphasis on the potentially hazardous trace elements. *International Journal of Coal Geology*, *88*(4), 179-193.

Singh, K. N. (2010). Coal bed methane potentiality – case studies from umaria, korba and ib-valley coals, son-mahanadi basin. *Journal Geological Society of India*, *76*(July 2010), 33-39.

Speight, James G. (2007). Natural Gas - A Basic Handbook.. Gulf Publishing Company.

Suárez-Ruiz, Isabel; Crelling, John C. (2008). Applied Coal Petrology - The Role of Petrology in Coal Utilization.. Elsevier.

Tarek, A., Nathan, D. (2012). Advanced Reservoir Management and Engineering (2nd Edition).. Elsevier.

Wang, S., Elsworth, D., & Liu, J. (2010). Evolution of permeability in coal to sorbing gases – a preliminary study. *ARMA 10-279*

Wang, Xiuli; Economides, Michael (2009). Advanced Natural Gas Engineering.. Gulf Publishing Company.

Wolf, K. (n.d.). Petrophysical properties and image characterisation of sedimentary rock.

Worthington, P. F. (2011). The petrophysics of problematic reservoirs.

7.0 APPENDIX

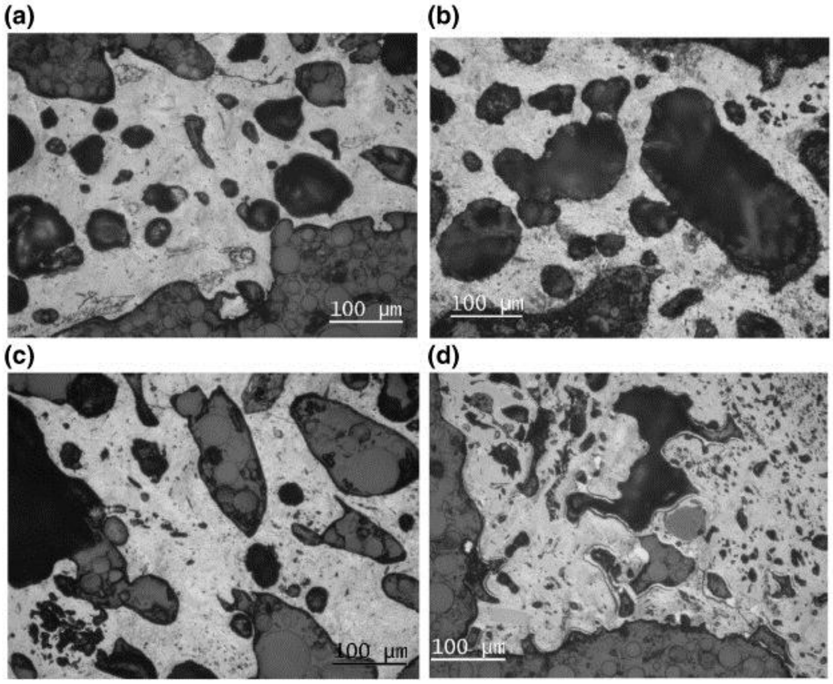


Figure 52: SEM of coal macropores

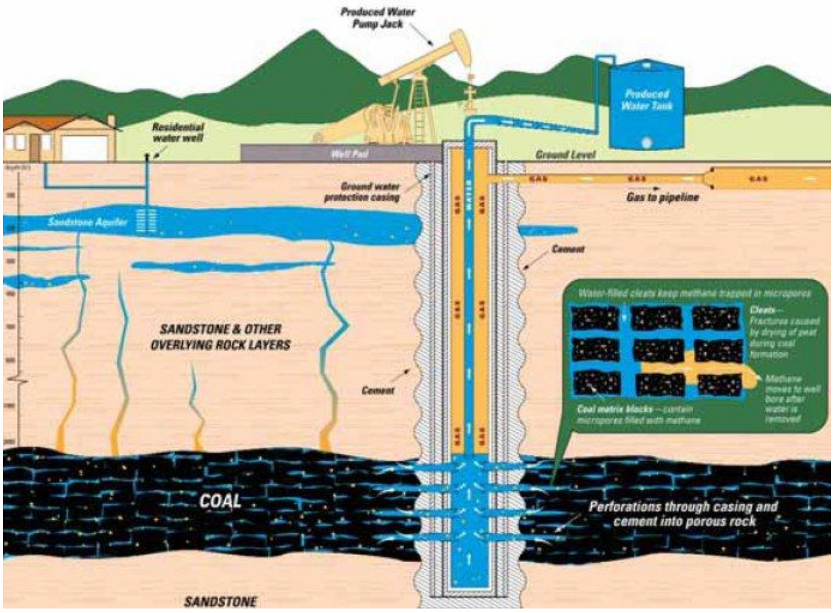


Figure 53: General Schematic of CBM Production