Development of New Decline Model for Shale Oil Reserves

A Thesis

Presented to

the Faculty of the Department of Chemical Engineering

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in Petroleum Engineering

by

Samit Shah

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Development of New Decline Model for Shale Oil Reserves

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Abstract

This thesis provides a new methodology to forecast ultimate recovery, based on more reliable production forecast for shale oil wells using historical production data. Compared to available decline curve methods including Arps (AIME: 160, 228-247), Valko (SPE 134231) and Duong (SPE 137748), this method is more accurate and more conservative.

Production forecasts play a vital role in determining the value of oil or gas wells, and improved accuracy enhances management decisions on field development. The new, more accurate method was verified using both field data and numerical simulations. This method can potentially be used in most shale reservoirs producing single-phase liquid.

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Chapter 1 Introduction

Shale oil production has accelerated in the US, growing from 111,000 barrels per day in 2004 to 553,000 barrels per day in 2011. It has been estimated by the US Energy Information Administration (EIA) that shale oil production in the US will increase to about 1.2 million barrels per day by 2035. However, the figure is pretty much conservative as compared to other market analysts who assumes the per day production of shale oil to be 3-4 million bbls. EIA estimates of the scale of total shale oil resources in the US have been revised upwards from 4 billion barrels in 2007 to 33 billion barrels in 2010, providing a significant contribution to increased US energy independence (Fig. 1.1).

It is also assumed that shale oil will make the largest contribution to the total US production growth by 2020, provided the proportion of production from conventional resources remains relatively stable.

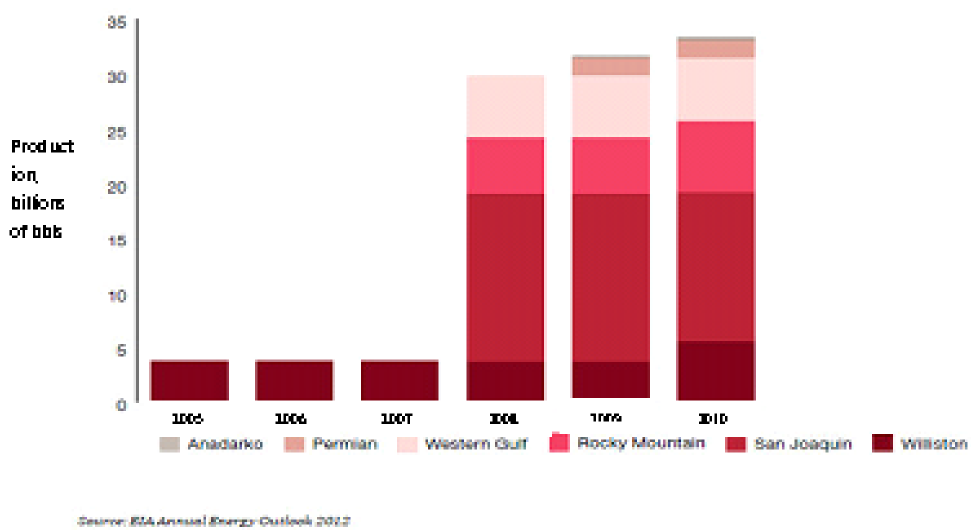

Figure 1.1. EIA assessments of technically recoverable shale oil in the USA.

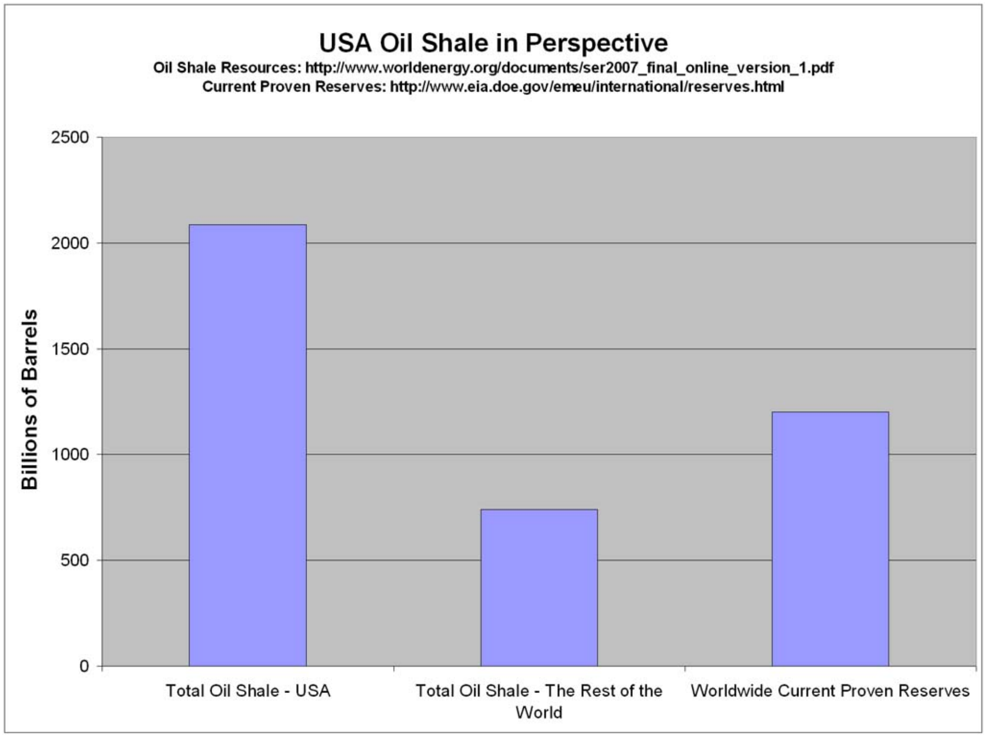

Figure 1.2. Shale oil production in the USA and in the rest of the world.

Though large amount of resources have been discovered globally, the development of shale oil is still at an early stage outside the USA. Global shale oil resources are estimated at between 330 billion and 1,465 billion barrels. Investments have already begun to characterize, quantify and develop shale oil resources outside the US. Since the beginning of 2012, there have been a number of announcements made regarding the discovery of shale oil resources. The exploration and production of shale oil has also been encouraged.

As shown in figure Fig. 1.3, global shale oil production has the potential to rise to up to 14 million barrels of oil per day by 2035, amounting to 12 % of total oil supply at that date (using EIA projections for production other than shale oil).

The investment decisions for unconventional resources depend to a great extent on the ability to accurately forecast ultimate recovery. Conventional methods for forecasting ultimate recovery have generally been a great success for conventional resources. However, estimating reserves in unconventional reservoirs with low permeability is problematic due to the longer transient flow periods. These unconventional wells frequently have bi-linear and linear flow regimes that were absent in traditional wells and these new flow regimes may dominate the production cycle (Freeborn and Russel, 2012).The common industry practice is to use Arps′ empirical rate decline models, but these equations are applicable only during boundary-dominated flow. Using Arps′ relation for unconventional resources can result in significant overestimation of reserves. Recent methods proposed to estimate reserves in unconventional resources include the Stretched Exponential decline model and the Duong model. Each of these methods also has its own shortcomings.

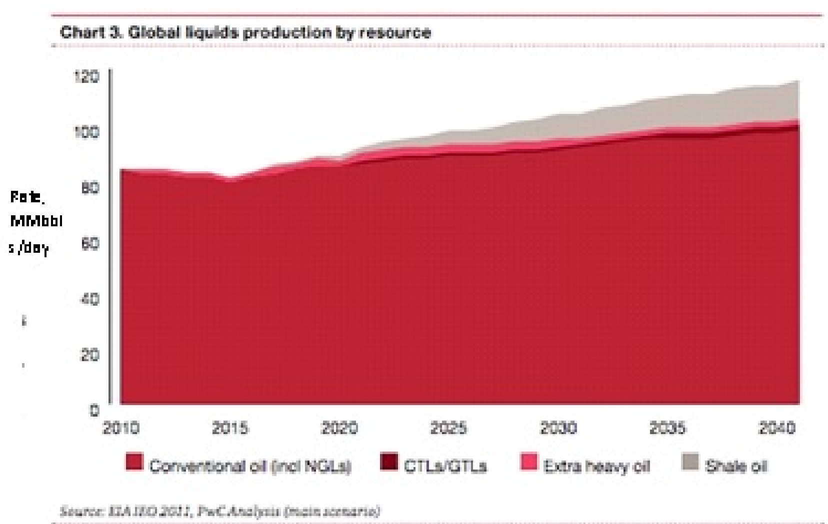

Figure 1.3. Million barrels of oil produced per day from 2010 to 2040, globally.

Chapter 2 Decline Curve Analysis

Production decline curve analysis is one of the oldest methods for predicting oil or gas reserves. Decline curve analysis (DCA) is a means of predicting the future production of oil or gas from a well or series of wells, based on extrapolation of production history. They play a vital role in determining the value of oil or gas wells. If the conditions affecting the rate of production are not changed, the curve will furnish useful knowledge as to the future production of the well. With this knowledge the value of a property may be judged, and proper economic analysis can be made. DCA is one of the most common methods for forecasting of oil and gas production. The main advantage of decline curve analysis is that, it uses historical data which is usually very easy to obtain. The results of decline curve are simple plots and easy to visualize, analyze and understand. To date various methods have been developed for decline curve analysis of which the most common include Arps, Duong and Stretched Exponential Production decline methods.

Chapter 3 Arps Decline Model

Arps decline curve analysis has been broadly used to estimate reserves since 1940s. It is still arguably the major technology to estimate EUR. Arps decline curves are of three basic types: exponential (b = 0), hyperbolic (0 < b < 1), and harmonic (b = 1). The Arps equations are shown below:

Exponential Decline,

$$q_t = q_i exp\left[-Dt\right], \tag{3.1}$$

Hyperbolic Decline

$$q_t = \left[\frac{q_i}{\left(1+bD_i t\right)^{1/b}}\right], \tag{3.2}$$

Harmonic Decline

$$q_t = \left[\frac{q_i}{(1+bt)}\right], \tag{3.3}$$

where q_t represents production rate at time t, q_i represents stabilized rate at t = 0, D_i is the decline rate which is constant for exponential decline, more generally, $D_i$is the decline rate at flow rate q_i, b is Arps decline constant.

Arps derived hyperbolic decline model based on the emperical observation that the decline parameter b is usually constant for most of the wells. The exponential decline model is the special case with b=0. Arps equations are valid only for wells in boundary dominated flow. Unconventional wells, which have permeabilities in the range of micro to nano Darcies, have long duration of transient flow in which b varies (decreases) significantly with time. In horizontal wells with multifracturing completed in unconventional (low permeability) reservoirs, multiple flow regimes may persist for as long as a decade before reservoir boundary dominates flow. During transient flow period, analysis of production indicates that production decline can be adequately represented using values of

Arps decline constant, b, greater than one, although b decreases with time (Lee and Sidle,2010).

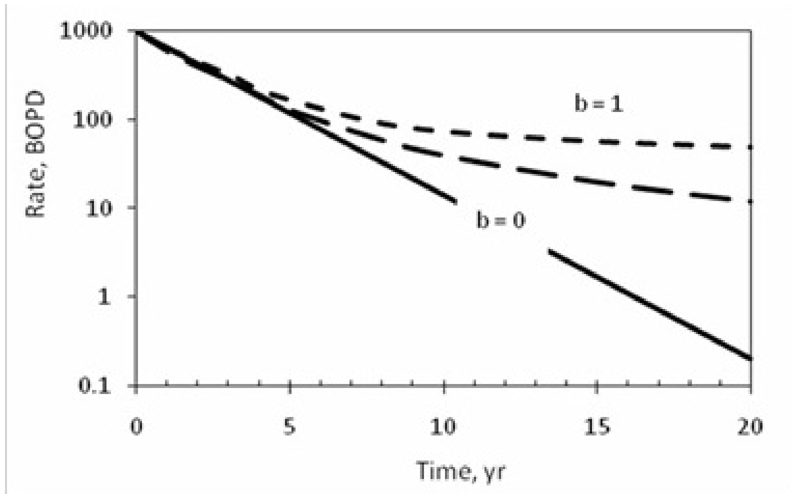

Figure 3.1. Rate vs time variation with respect to b.

Forecasting of wells that have long transient flow periods, using a constant *b* obtained from the early transient flow, over predicts well performance (kurtoglu et al,2011). Fetkovich et al. (1987) have argued that such anomalous behavior, i.e. values of (b > 1) arises when data from the transient flow regime are used to fit the model that is actually appropriate only during Boundary Dominated Flow (BDF).

The decline exponent must be within the range (0 < b < 1) range to apply the Arps curves correctly. The harmonic case (b=1) should be used only with reservation because a forward prediction could result in an infinite cumulative recovery estimate.

Chapter 4 Stretched Exponential Production Decline

To avoid the uncertainty associated with long term reserve estimates from the Arps model, Valko (Valko, 2009) proposed a new method the Stretched Exponential Production Decline. This equation normally tends to fit all the data and it can also handle high initial rates followed by a rapid decline, which are common for wells with multi-stage fracturing. As it tends to fit most of the data, the more historical data, more accurate will be the EUR. Compared to the Arps hyperbolic model, SEPD has a most significant advantage: EUR is bounded for any individual well. The SEPD can be applied using the following equations:

$$q_t = q_i exp\left[\left(-\frac{t}{\tau}\right)^n\right], \tag{4.1}$$

$$Q = \left[-\frac{q_i\tau}{n}\right]\left[\Gamma\left(\frac{1}{n}\right) - \Gamma\left(\frac{1}{n}\right), \left(\frac{t}{\tau}\right)^n\right], \tag{4.2}$$

$$r_{21} = \left[\frac{\left[\Gamma\left(\frac{1}{n}\right) - \Gamma\left(\frac{1}{n}\right), \left(\frac{23.5}{\tau}\right)^n\right]}{\left[\Gamma\left(\frac{1}{n}\right) - \Gamma\left(\frac{1}{n}\right), \left(\frac{11.5}{\tau}\right)^n\right]}\right], \tag{4.3}$$

$$r_{31} = \left[\frac{\left[\Gamma\left(\frac{1}{n}\right) - \Gamma\left(\frac{1}{n}\right), \left(\frac{35.5}{\tau}\right)^n\right]}{\left[\Gamma\left(\frac{1}{n}\right) - \Gamma\left(\frac{1}{n}\right), \left(\frac{11.5}{\tau}\right)^n\right]}\right], \tag{4.4}$$

where q_t is the time-varying production rate, q_i is the initial production rate, Q is the cumulative production, n is the exponent parameter for SEPD model, τ is a characteristic time parameter, r_{21} is the ratio of two year production to one year production; and r_{31} is the ratio of three year production to one year production.

The stretched exponential production decline (SEPD) model acknowledges the heterogeneity of a reservoir in that the actual production decline is determined by a great number of contributing volumes individually in exponential decay, but with a specific distribution of characteristic time constants (Valko and Lee, 2010). SEPD appear to fit field data from various shale plays quite well, thereby providing an effective alternative to Arps model (Lee, 2012). It predicts a lower EUR that would be obtained from extrapolation of Transient flow regime without the transition to exponential decline, as in the case of Arps.

But this method has some serious shortcomings. The equations are very complex and difficult to solve. It relies on complete and incomplete gamma function, for which computer codes are required.The application of this method requires a relatively long production history of the well. Though this equation always obtains a solution, the solutions ability to predict EUR may be too poor or of lesser quality.

Chapter 5 Duong's Production Decline

Duong's method was empirically derived based on a long-term linear flow in a large number of wells in tight and shale gas reservoirs (Duong, 2011). "A log-log plot of rate over cumulative production vs. time is observed to fit a straight line in most unconventional reservoir cases studied. The slope and intercept are related to reservoir rock characteristics, fracture stimulation practice, operational conditions and possibly liquids content" (Duong, 2011). Duong's equations are described below,

$$q_t = q_1 t^{-n}, \tag{5.1}$$

$$\frac{Q}{q_t} = \left[\frac{1}{a}\right] t^m, \tag{5.2}$$

$$t_D = t^{-m} exp\left[\frac{a}{1-m}(t^{1-m} - 1\Big)\right], \tag{5.3}$$

$$q_t = q_i t_D + q_{inf}, \tag{5.4}$$

where q_t represents production rate at time t, q_1 represents stabilized rate at t = 1,a and m are emperical constants, t_D is dimensionless time, Q is cumulative porduction and q_{inf} is the intercept of the plot of q_t vs. t_D

The Duong equation differs from the previously mentioned methods due to the simplicity and ease with which the equation is solved. This method is easy and simple to use for predicting future rate and EUR. The equation can be solved in a simple spreadsheet. This equation was formulated for the use for unconventional resources.

Duong equations can be solved in just two steps: the first step is plotting ratio of production rate, q, and cumulative production, Q, vs.t on log - log coordinates.

The parameters a and m can be obtained from intercept and slope respectively. The second step is to plot dimensionless time vs rate, to solve for q_1 and q_{inf}. However, the derivation of equation 5.4 does not include q_{inf}, so the trend line should be obtained in such a way so as to force the q_{inf} to be zero.

Duong′s method appears to fit production data from both vertical and horizontal wells. The EUR is not based on the traditional concept of drainage area (BDF) but on the constraints of the latest trends with both time and economic rate limits (Duong, 2011).

The Duong equation models transient flow, so it assumes prolonged production within this flow regime. Duong model is suitable for a single flow regime but currently has not been proved and is questionable for wells with transitions from linear to boundary-dominated flow (Freeborn and Russell, 2012). The equation is useful only for a transient flow regime and maybe a poor estimator of EUR. But it gives accurate estimates so long as the transient flow regime persists. In addition, the solution is quite sensitive to small variations in data.

Chapter 6 Comparison of methods

Arps is the most common method used in the industry currently. It produces accurate results for conventional resources, which have limited duration transient flow regimes. Most of the data for wells in conventional resources are in the boundary dominated flow regime. But because the transient flow regime may last for more than a decade in unconventional resources, there came a need to formulate new methods. The Arps model doesn′t work well in the transient regime as the b value is usually greater than one, i.e., super hyperbolic, and decrease with time. In addition, production continues for infinitely long. However, Arps is still used as a complement to the other methods.

SEPD and Duong were developed to overcome the problem that develops when the transient flow regime lasts for a long time. SEPD always provides a solution. The solution of SEPD requires specialised software or complex computer code. The Duong method is easy to understand and visualize. It can be applied using a simple spreadsheet. But this equation is valid for a single transient flow regime only. It is neither expected to work across flow regimes nor to predict accurately outside the flow regime being analyzed.

When historical field data is long enough to include a moderate to large amount of boundary dominated flow data, then it may be preferable to use the Arps models rather than using the SEPD equations (Freeboen and Russell, 2012)

In summary, SEPD and Duong fail to perform in BDF and Arps fail to provide accurate results if a long transient flow regime is present.

Chapter 7 New Method

As stated above, Arps is inaccurate in the transient flow regime, Duong is inaccurate in boundary dominated flow (BDF). Hence there is a need to develop a new decline model or a new method to predict more accurately the recovery in unconventional resources. The new method is basically the combination of above mentioned methods. As SEPD and Duong model the transient flow regime well and Arps are widely used for BDF regime, the new method combines the two methods to achieve our objectives and eliminate the shortcomings.

First we plot rate (or normalised rate) vs material balance time (or time) to identify the flow regimes in well history and the current flow regime. Material balance Time (MBT) is the ratio of cumulative production to the production rate. Then we try to match the given data with the methods stated above and calculate the parameters from rate vs time plots. If the data has not reached the BDF the onset of BDF is unknown. The b value in Arps decline model decreases during a long transient flow period. So Kurtoglu et al. (Kurtoglu et al., 2011) suggested using Arps standard decline rate equation until the decline rate reaches a minimum decline and thereafter, use the exponential decline equation with decline exponent equal to terminal decline. In an analogous way, we assume in our new method that BDF will start when the terminal decline rate is 5 percent per annum .When D reaches the Dmin, we switch from the transient model to the Arps model. At the time of switch to Arps, the value of b is assumed to be 0.3, typical for a solution drive reservoir (Fetkovich, 1980). If we know the time of BDF onset from the rate vs MBT plot, we use the time for switch and select the b value such that BDF data is matched. The EUR from the new method is the result of combination of two models: one for transient flow and the other Arps, which is currently the most accurate method to model boundary dominated flow. Thus there are basically three new methods: 1) super Hyperbolic combined with Arps; 2) SEPD combined with Arps; and 3) Duong combined with Arps. Using the field rate data and simulated rates data, we calculate the EUR using six methods discussed above and determine the most appropriate method. Also we will match the output from the above method to analytically simulated rates generated with Fekete Harmony software.

Chapter 8 Field Examples

Two field examples and one simulated example are presented from unconventional shale oil reservoirs to provide a comparative assessment of various decline curve analysis models, and to quantify the uncertainty associated with 30-year EUR estimates. These examples will be analyzed using the six decline curve analysis models described earlier, viz., Arps Hyperbolic model, Stretched Exponential Production Decline Model (SEPD), Duong model and the combined models, Arps + Arps, SEPD + Arps and Duong + Arps.

8.1 Example 1

The first example is from the Elm Coulee Field in Richland County, Montana well Anna 2-3h. Five years of production history are available. Fig. 8.1, a plot of production rate, q, vs Material Balance Time, MBT, shows that a slope of -1 indicating BDF, starts from MBT 90, which is equivalent to the actual time of 45.5 months.

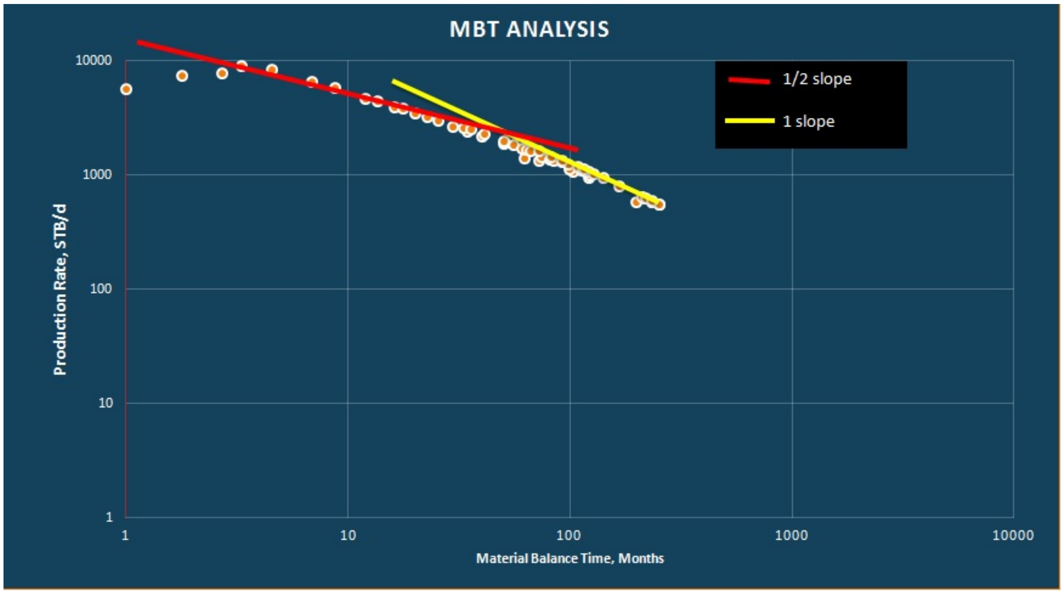

Figure 8.1. Rate vs material balance time for field example 1.

8.1.1 Arps Hyperbolic Model

For the Arps model, first we plot the ratio of observed production rate, q, and cumulative production, Q, to estimate the decline exponent, b, and the initial decline rate, D_i. The resulting fit is shown in Fig. 8.2. The resulting best fit parameters are b =1.16 and D_i = 0.198 1/d. Then we plot the production time, t, and cumulative production, Q, as shown in Fig. 8.3. The best fit to the above curve provides an estimate of the third parameter, q_i, the initial production rate. The resulting best fit parameter is q_i = 9710 bbls/month. Using these fitted parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 257,000 bbls.

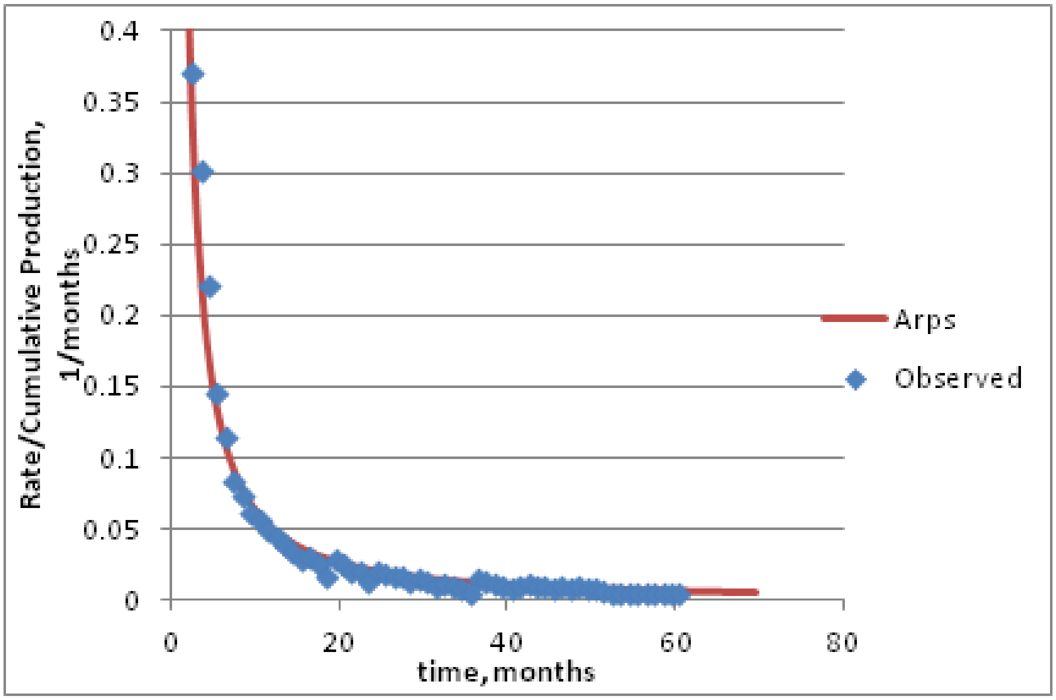

Figure 8.2. Ratio of rate to cumulative production vs time for field example 1.

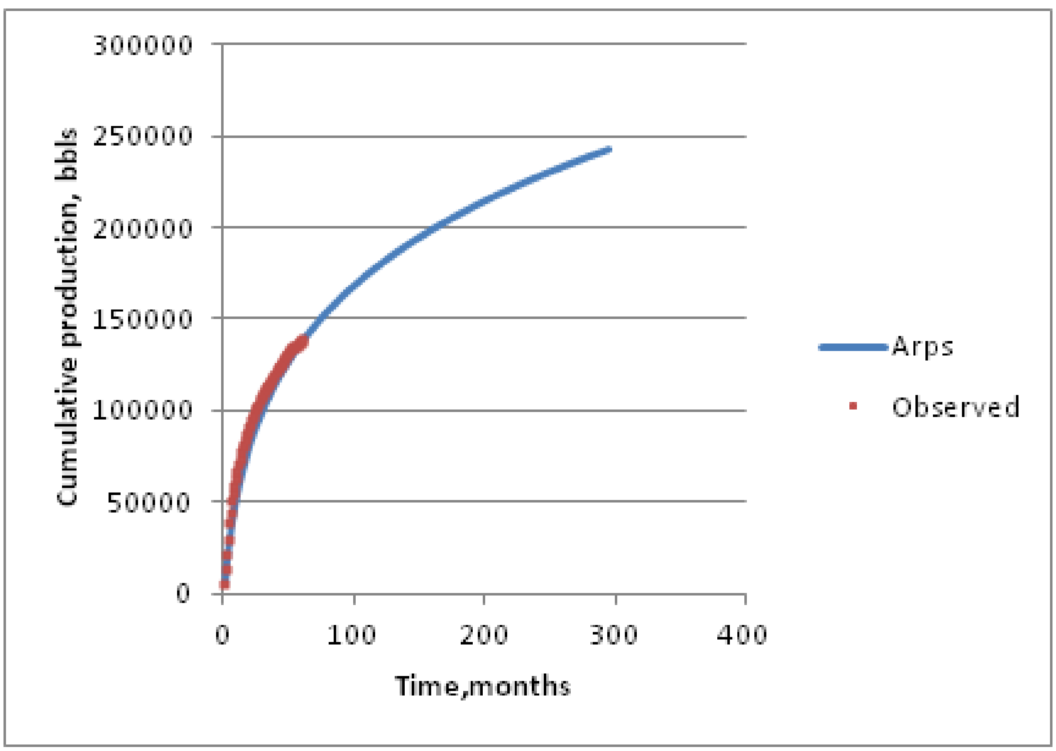

Figure 8.3. Cumulative production vs time for field example 1.

8.1.2 SEPD

For the Stretched Exponential Production Decline, the equations for r_{21} and r_{31}, i.e., the ratio of two year production to one year production and the ratio of three year production to one year production respectively, are used to estimate the characteristic time parameter, τ, and the parameter n. The equations were solved using the VB code in excel. The resulting best fit parameters are τ = 1.2 months and n = 0.32. Then we plot the production time, t, and cumulative production, Q, as shown in Fig. 8.5. The best fit to the above curve gives the answer of the third parameter, q_i, the initial production rate. The resulting best fit parameter is q_i = 25,312 bbls/month. Using these fitted parameters, the 30-year cumulative production (30-year EUR), Q,30, is estimated to be 200,000 bbls.

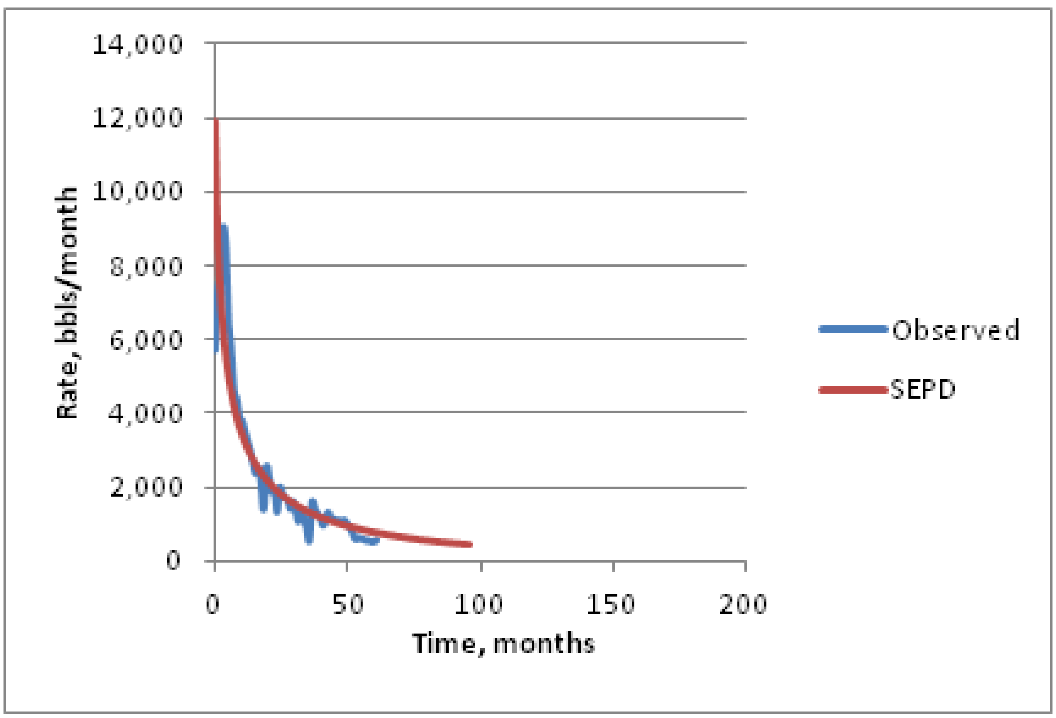

Figure 8.4. Rate vs time for field example 1.

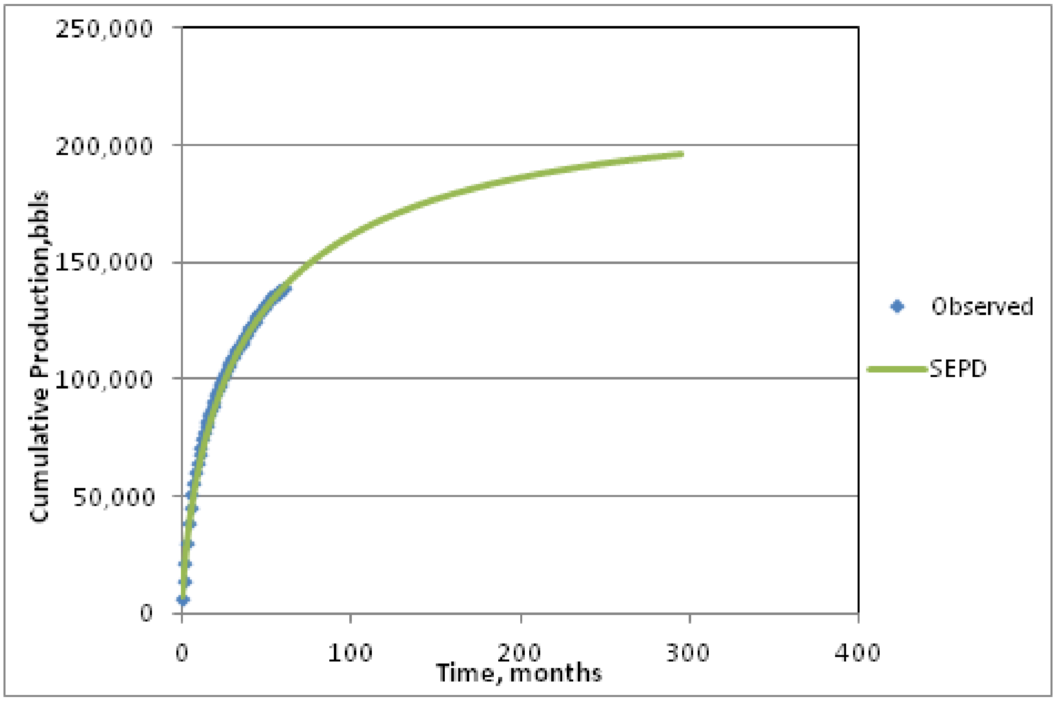

Figure 8.5. Cumulative Production vs time for field example 1.

8.1.3 Duong Model

For the Duong model, the first step is to plot the ratio of production rate, q, and cumulative production, Q, vs. production time, to estimate the intercept, a, and the slope, m Fig. 8.6. The resulting best fit parameters are a = 1.597 1/d and m = -1.409. Then we plot the dimensionless time, t_D, and the production rate as shown in Fig. 8.7. The intercept Q_{inf} is forced to zero. The resulting best fit parameter, based on Fig. 8.7, is q_1 = 9,200 bbls/month. Using these parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 200,000 bbls.

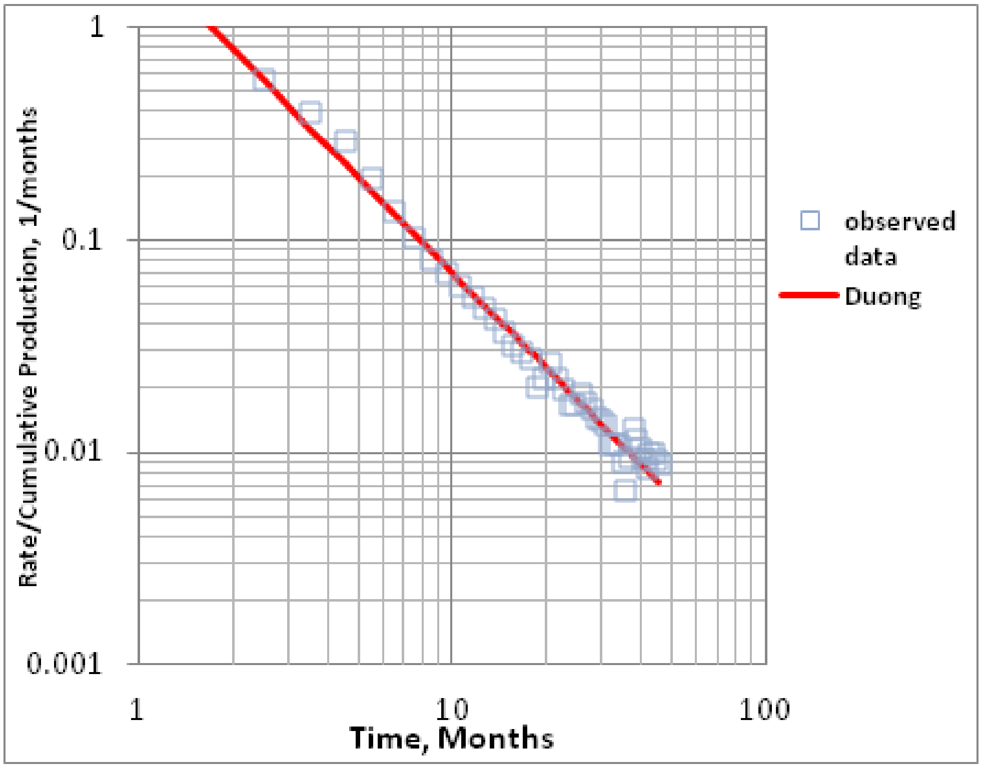

Figure 8.6. Ratio of rate to cumulative production vs time for field example 1.

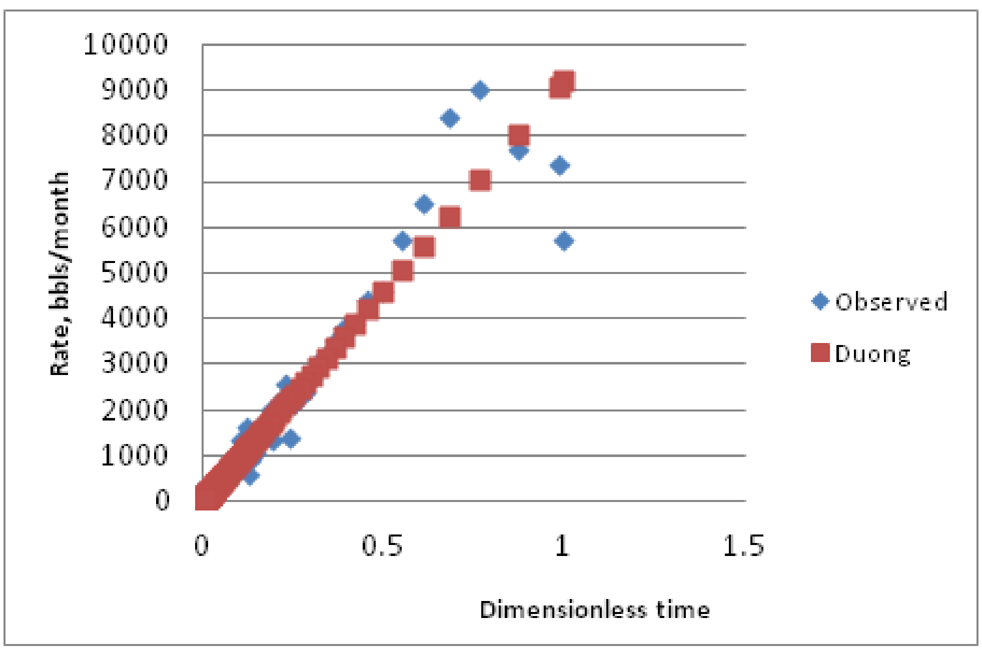

Figure 8.7. Rate vs dimensionless time for field example 1.

8.1.4 Arps+Arps

This is a new method in which Arps super hyperbolic is combined with hyperbolic decline (b<1). At 45.5 months (or when the slope of MBT vs rate becomes 1), we change from the decline exponent b=1.2 to b=0.3. Because insufficient BDF data is available, b= 0.3 has been selected (typically for solution gas drive oil reservoirs). Arps hyperbolic initial decline is 0.017 d^{-1} and initial rate or the rate of switch from Arps super hyperbolic to hyperbolic is 1,187 bbl/month. Using these fitted parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 209,000 bbls.

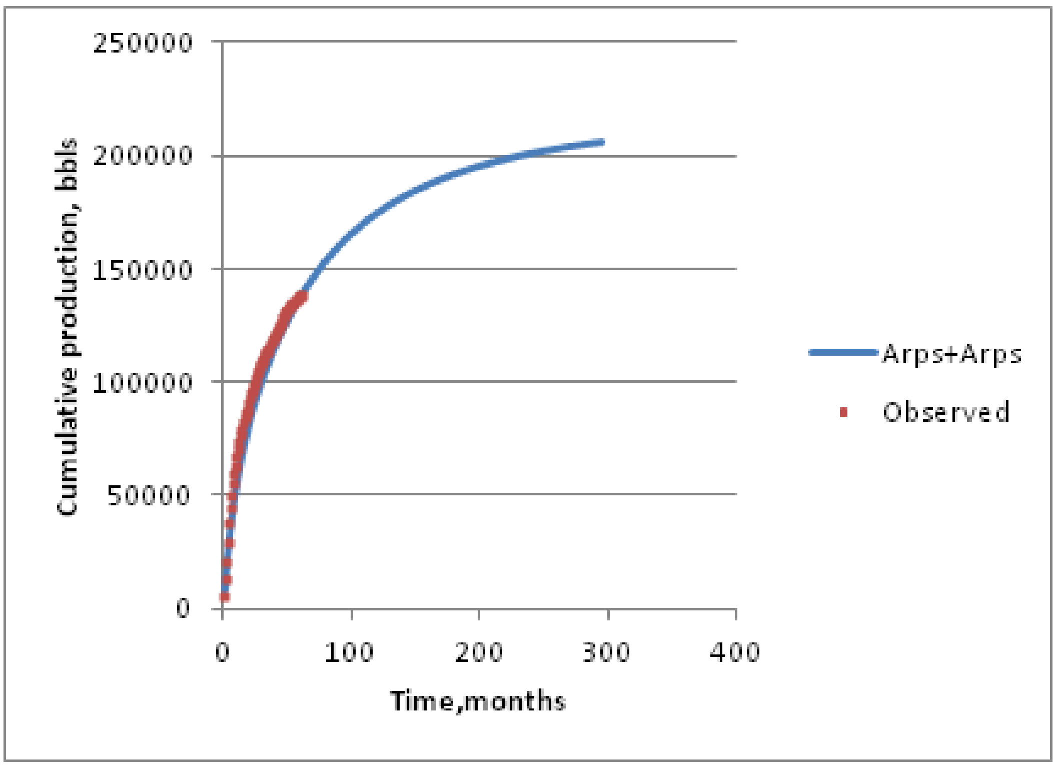

Figure 8.8. Cumulative Production vs time for field example 1.

8.1.5 SEPD+Arps

This is a new method in which Stretched Exponential Production decline is combined with hyperbolic decline (b<1). At 45.5 months (or when the slope of

MBT vs rate becomes 1), we change from from SEPD to Arps hyperbolic decline. Because insufficient BDF data is available, b= 0.3 has been selected (typically for solution gas drive oil reservoirs). Arps hyperbolic initial decline is 0.023 d^{-1} and initial rate or the rate of switch from SEPD to hyperbolic is 1031.2 bbl/month. Using these parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 186,000 bbls.

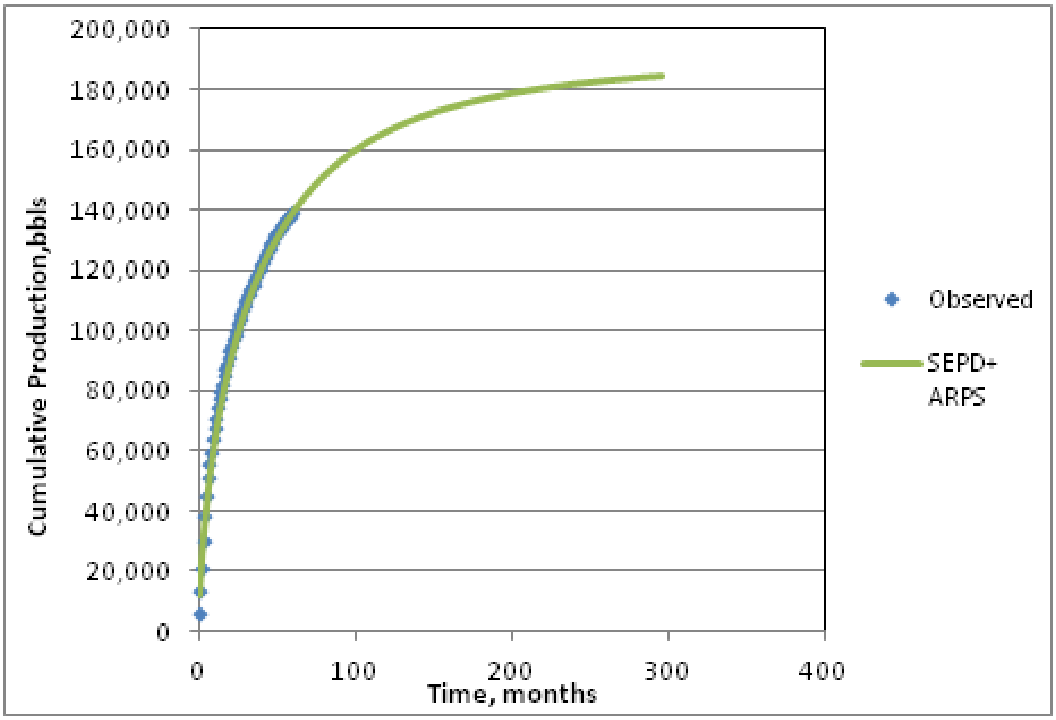

Figure 8.9. Cumulative Production vs time for field example 1.

8.1.6 Duong +Arps

This is a new method in which Duong is combined with hyperbolic decline (b<1). At 45.5 months (or when the slope of MBT vs rate becomes 1), we change from from Duong to Arps hyperbolic decline. Because insufficient BDF data is available, b= 0.3 has been selected (typically for solution gas drive oil reservoirs). Arps hyperbolic initial decline is 0.024 d^{-1} and initial rate or the rate of switch from Duong to hyperbolic is 1,080 bbl/month. Using these parameters, 30-year cumulative production (30-year EUR), Q30, is estimated to be 186,000 bbls.

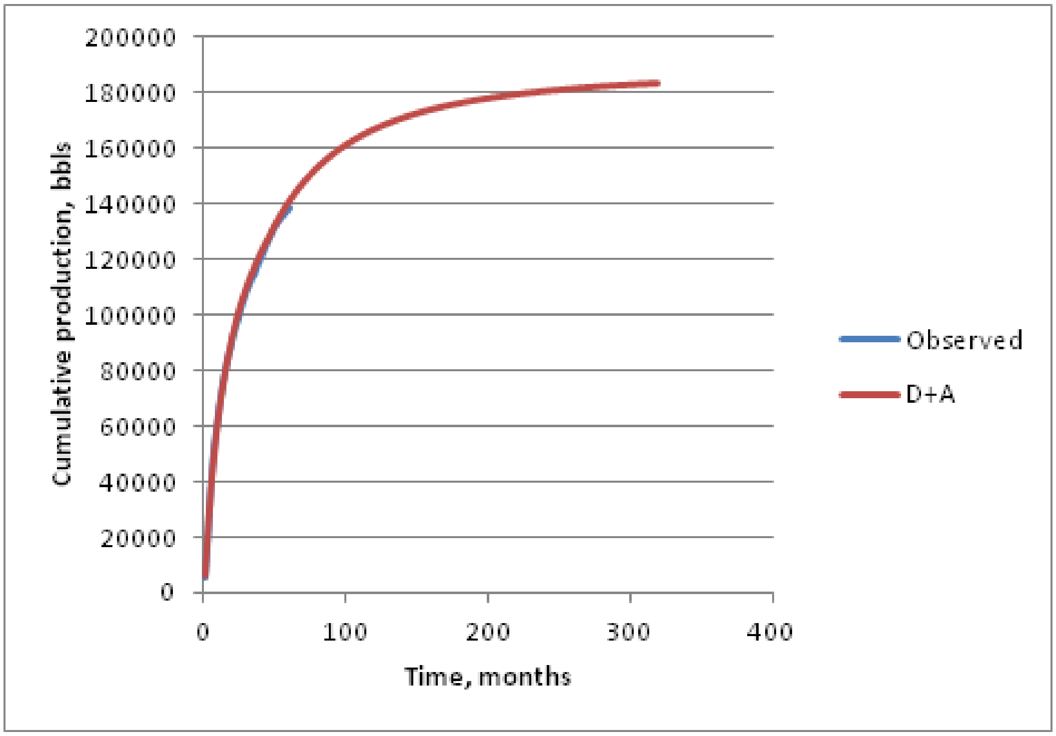

Figure 8.10. Cumulative Production vs time for field example 1.

8.1.7 Summary of methods

Fig. 8.11 below shows the aggregation of 30 year forecasts from all the six models discussed above. Arps hyperbolic model gives the most optimistic projection, while the new developed method SEPD + Arps gives the most conservative projection.Table 8.1 shows the summary of the EUR projection for all the six models.

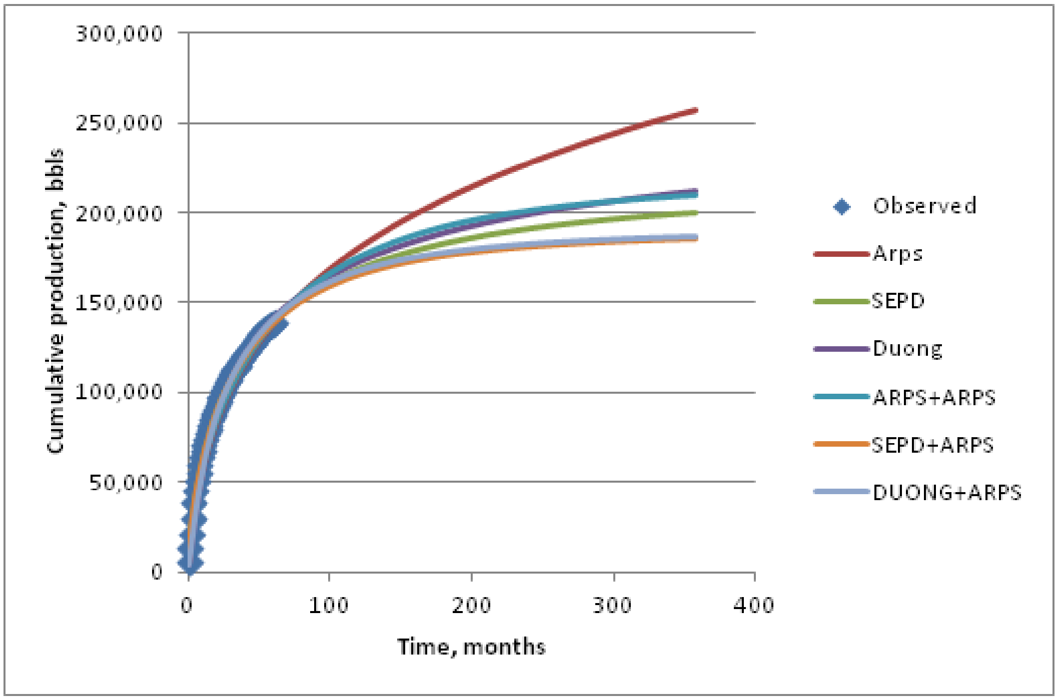

Figure 8.11. Cumulative Production vs time, all methods for field example 1.

Table 8.1. Comparision for all methods, example 1

Methods	EUR (Mbbls)
Arps	257
SEPD	200
Duong	200
Arps + Arps	209
SEPD + Arps	186
Duong + arps	186

8.2 Example 2

This example is of the Woodford Field in Carter County in Oklahama. The well name is Nickel Hill 1h-36. About six years of production data was available. But after 3 years, the well was stimulated. So the available production data for decline analysis was about 3 years. As seen in the Fig. 8.12, of production rate, q, vs Material Balance Time, MBT, we can see that a slope of -1 starts from the MBT 60, which is equivalent to the actual time of 25.5 months.

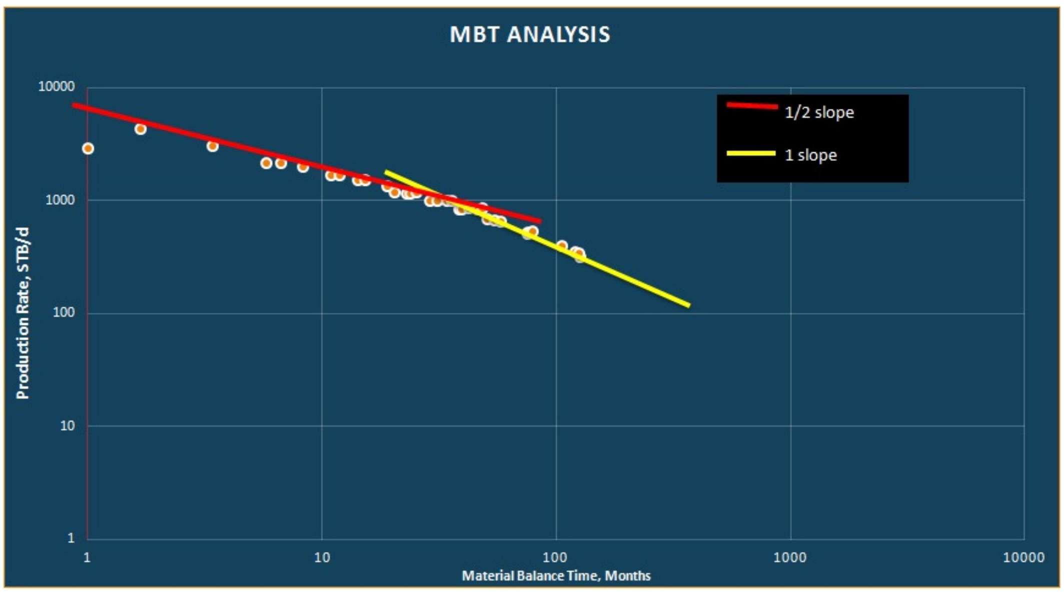

Figure 8.12. Rate vs material balance time for field example 2.

8.2.1 Arps Hyperbolic Model

For the Arps model, first we plot the ratio of observed production rate, q, and cumulative production, Q, to estimate the decline exponent, b, and the initial decline rate, D_i. The resulting fit is shown in Fig. 8.13.The resulting best fit parameters are b =1.11 and D_i = 0.3 1/d. Then we plot the production time, t, and cumulative production, Q, as shown in Fig. 8.14. The best fit to the above curve provides an estimate of the third parameter, q_i, the initial production rate. The resulting best fit parameter is q_i = 9,710 bbls/month. Using these parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 91,900 bbls.

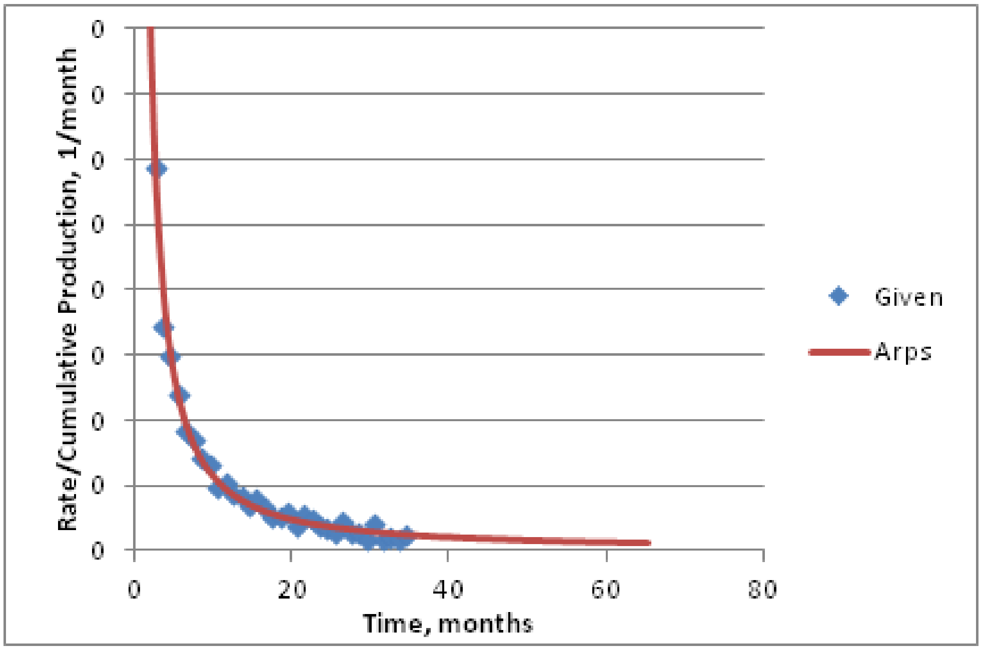

Figure 8.13. Ratio of rate to cumulative production vs time for field example 2.

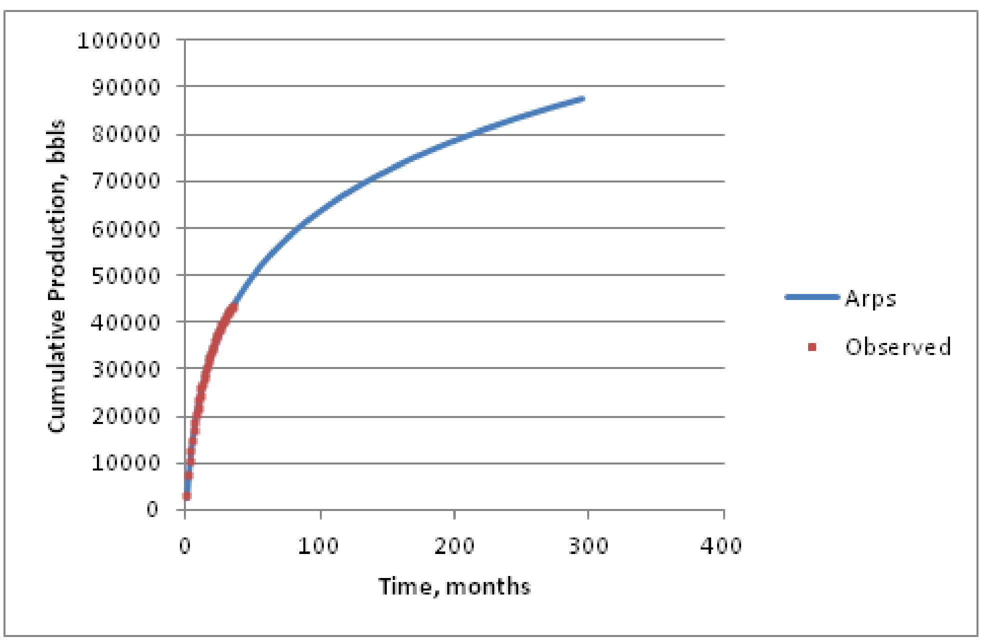

Figure 8.14. Cumulative production vs time for field example 2.

8.2.2 SEPD

For the Stretched Exponential Production Decline, the equations for r_{21} and r_{31}, i.e., the ratio of two year production to one year production and the ratio of three year production to one year production respectively, are used to estimate the characteristic time parameter, τ, and the parameter n. The equations were solved using the VB code in excel. The resulting best fit parameters are τ = 1 months and n = 0.34. Then we plot the production time, t, and cumulative production, Q, as shown in Fig. 8.16. The best fit to the above curve gives the answer of the third parameter, q_i, the initial production rate. The resulting best fit parameter is q_i = 11,774 bbls/month. Using these parameters, the 30-year cumulative production (30-year EUR), Q,30, is estimated to be 64,300 bbls.

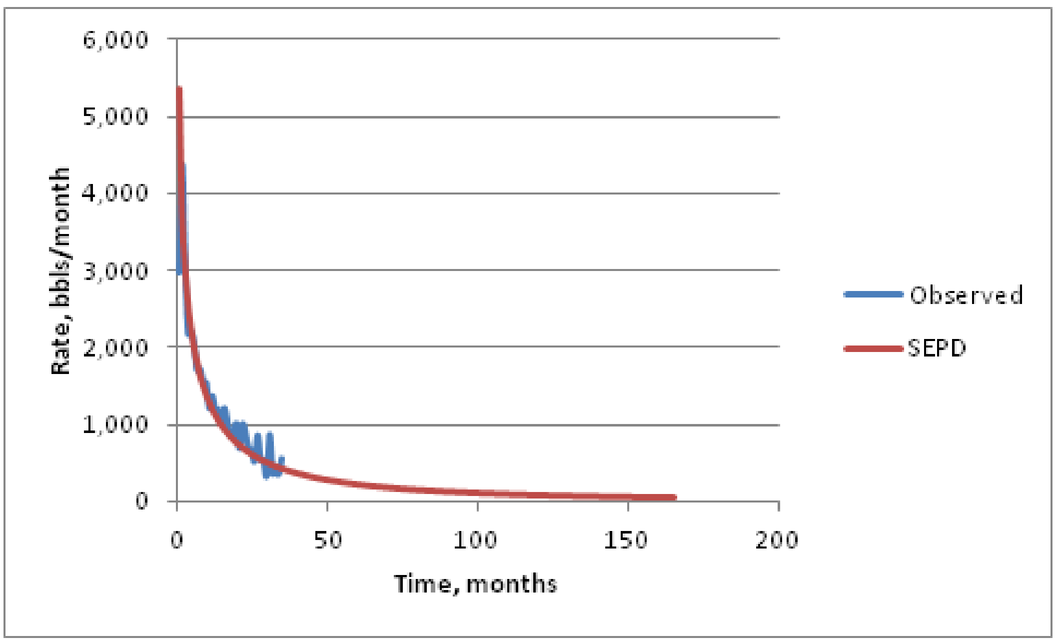

Figure 8.15. Rate vs time for field example 2.

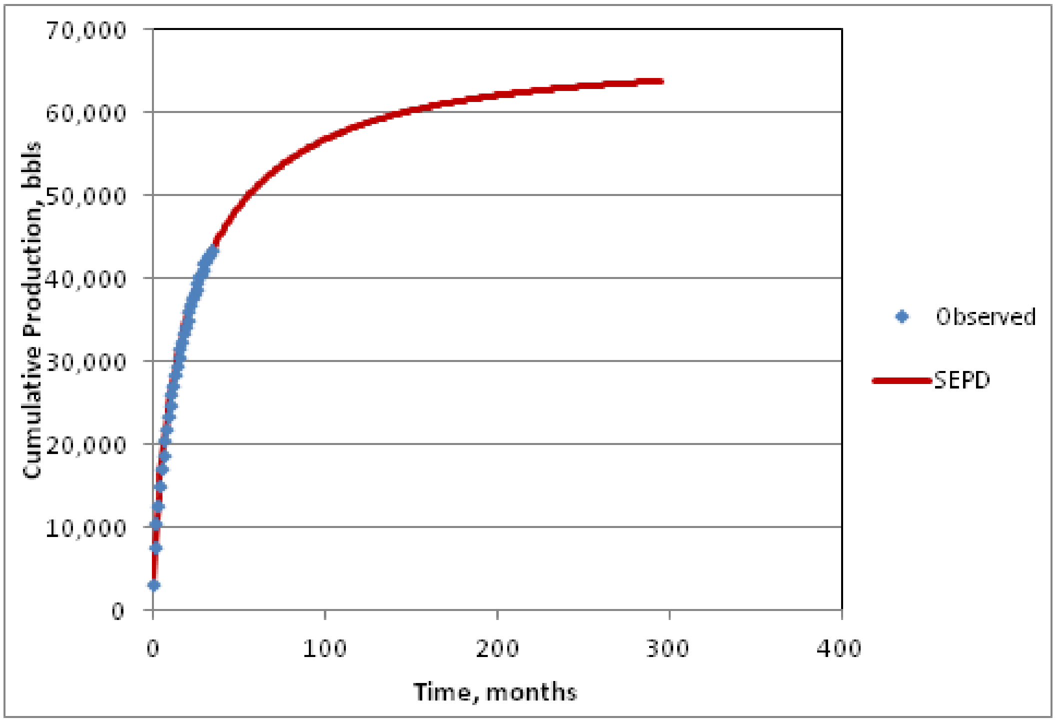

Figure 8.16. Cumulative production vs time for field example 2.

8.2.3 Duong Model

For the Duong model, the first step is to plot the ratio of production rate, q, and cumulative production, Q, vs. production time, to estimate the intercept, a, and the slope, m Fig. 8.17. The resulting best fit parameters are a =1.7 1/d and m = -1.34. Then we plot the dimensionless time, t_D, and the production rate as shown in Fig. 8.18. The intercept Q_{inf} is forced to zero. The resulting best fit parameter, based on Fig. 8.18, is q_1 = 2,200 bbls/month. Using these parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 97,100 bbls.

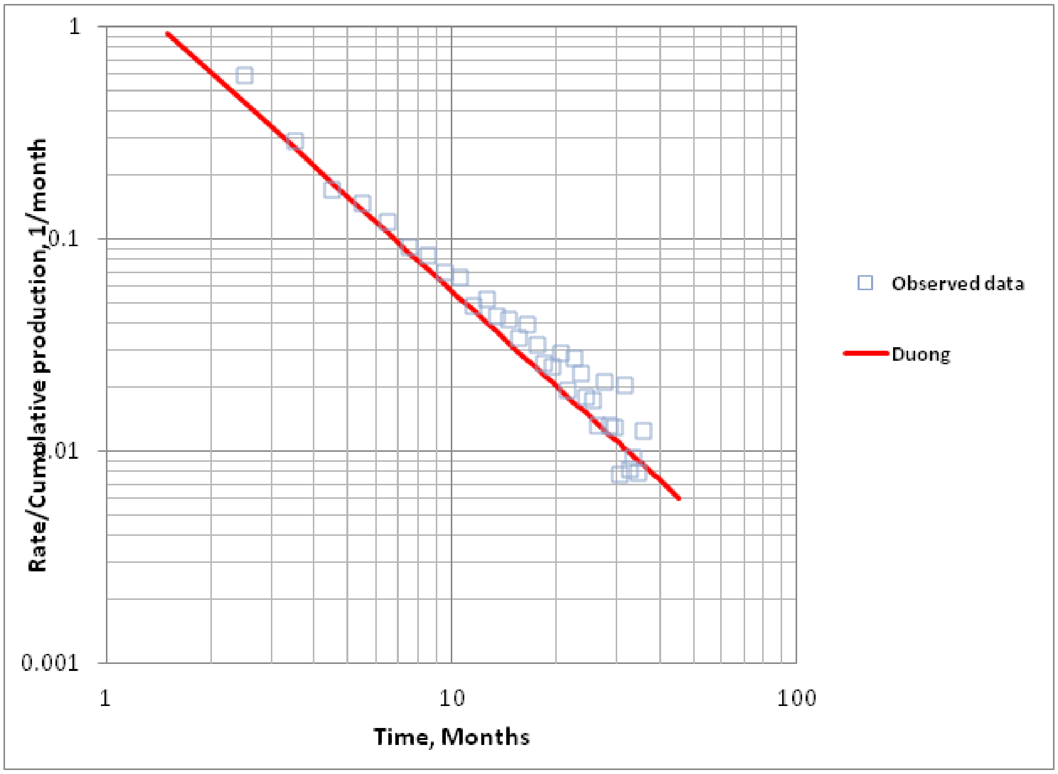

Figure 8.17. Ratio of rate to cumulative production vs time for field example 2.

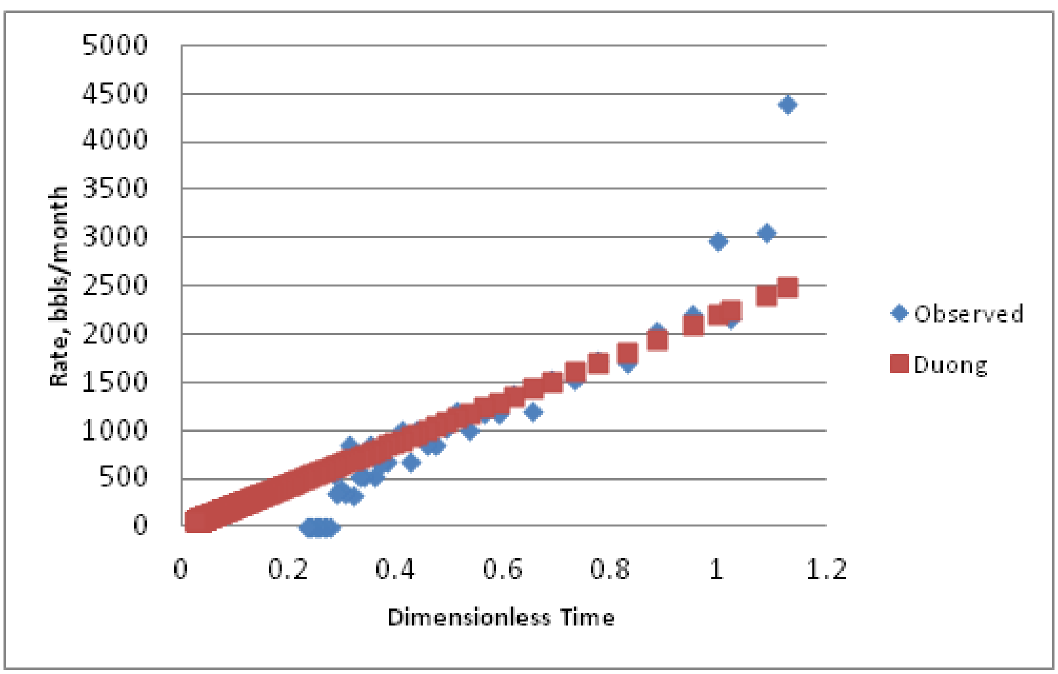

Figure 8.18. Rate vs dimensionless time for field example 2.

8.2.4 Arps+Arps

This is a new method in which Arps super hyperbolic is combined with hyperbolic decline (b<1). At 25.5 months (or when the slope of MBT vs rate becomes 1), we change from the decline exponent b=1.11 to b=0.3. Because insufficient BDF data is available, b= 0.3 has been selected (typically for solution gas drive oil reservoirs). Arps hyperbolic initial decline is 0.032 d^{-1} and initial rate or the rate of switch from Arps super hyperbolic to hyperbolic is 658.4 bbl/month. Using these parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 66,000 bbls.

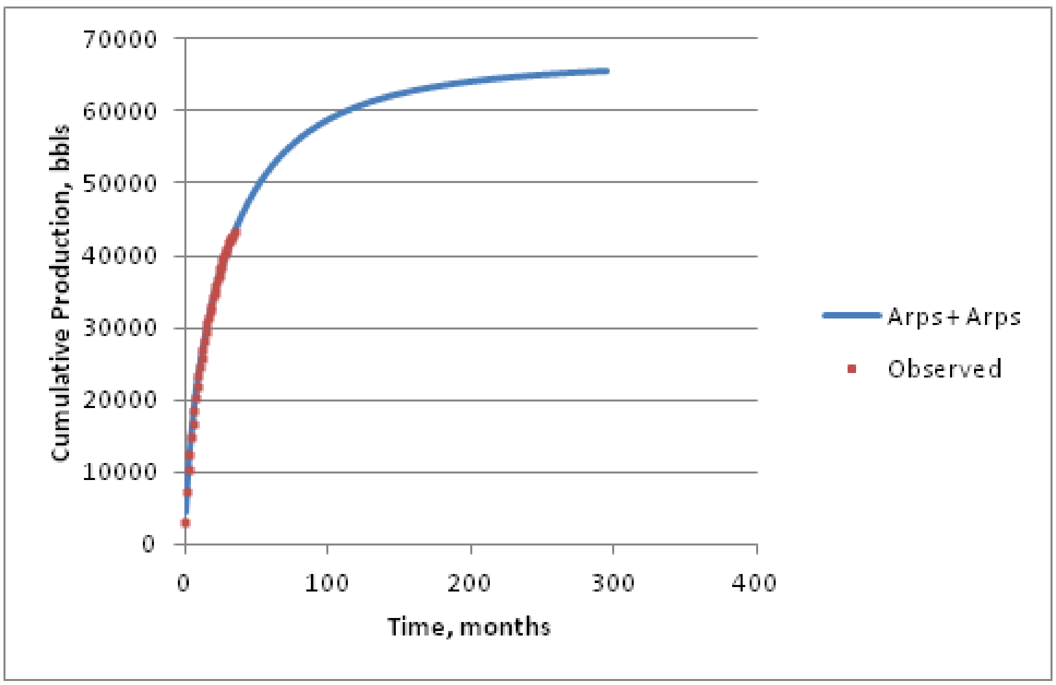

Figure 8.19. Cumulative production vs time for field example 2.

8.2.5 SEPD+Arps

This is a new method in whichStretched Exponential Production decline is combined with hyperbolic decline (b<1). At 25.5 months (or when the slope of MBT vs rate becomes 1), we change from from SEPD to Arps hyperbolic decline.

Because insufficient BDF data is available, b= 0.3 has been selected (typically for solution gas drive oil reservoirs). Arps hyperbolic initial decline is 0.04 d^{-1} and initial rate or the rate of switch from SEPD to hyperbolic is 582 bbl/month. Using these parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 58,700 bbls.

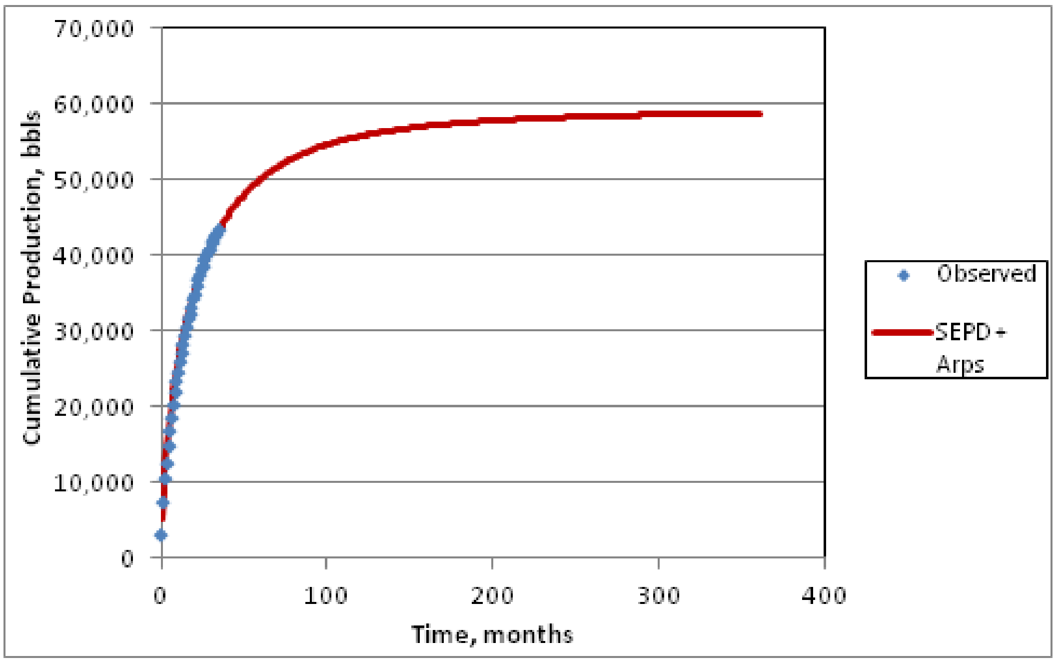

Figure 8.20. Cumulative production vs time for field example 2.

8.2.6 Duong +Arps

This is a new method in which Duong is combined with hyperbolic decline (b<1). At 25.5 months (or when the slope of MBT vs rate becomes 1), we change from from Duong to Arps hyperbolic decline. Because insufficient BDF data is available, b= 0.3 has been selected (typically for solution gas drive oil reservoirs). Arps hyperbolic initial decline is 0.03 d^{-1} and initial rate or the rate of switch from Duong to hyperbolic is 794 bbl/month. Using these parameters, 30-year cumulative production (30-year EUR), Q30, is estimated to be 72,400 bbls.

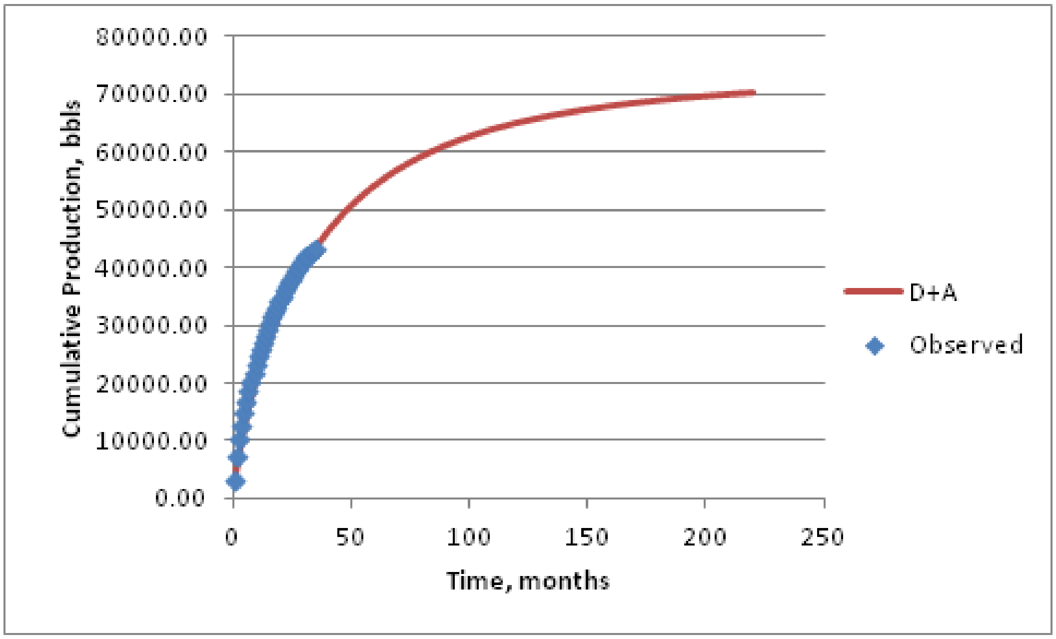

Figure 8.21. Cumulative production vs time for field example 2.

8.2.7 Summary of methods

Fig. 8.22 below shows the aggregation of 30 year forecasts from all the six models discussed above. Arps hyperbolic model gives the most optimistic projection, while the new developed method SEPD + Arps gives the most conservative projection.Table 8.2 shows the summary of the EUR projection for all the six models.

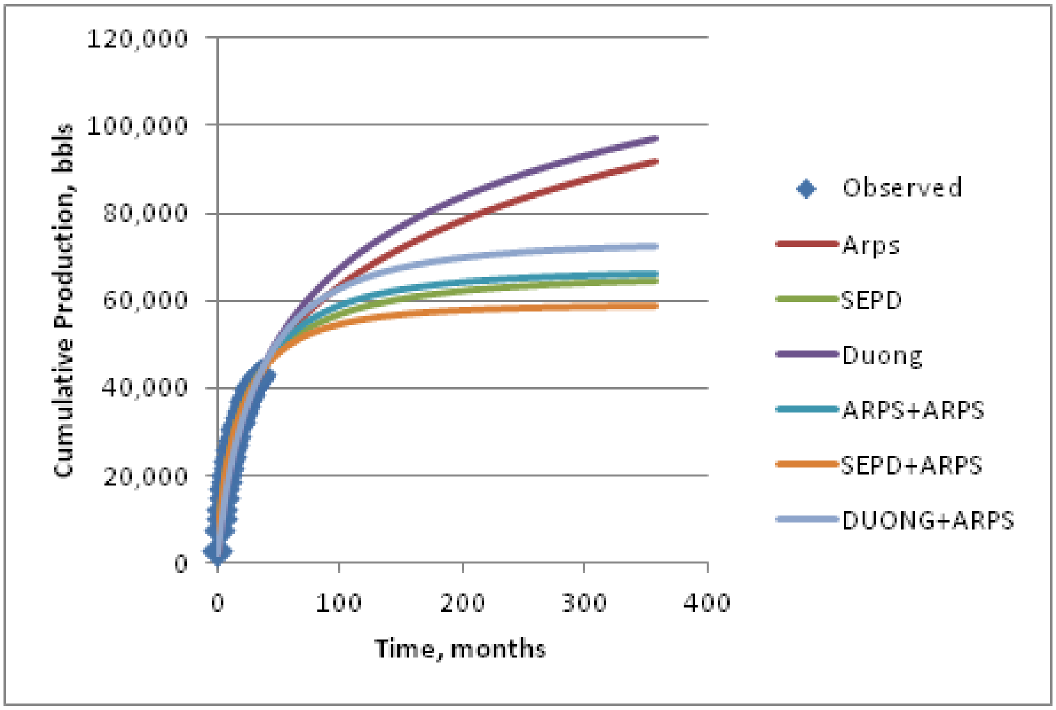

Figure 8.22. Cumulative production vs time, all methods for field example 2.

Table 8.2. Comparision for all methods, example 2

Methods	EUR (Mbbls)
Arps	91.9
SEPD	68.3
Duong	97.
Arps + Arps	66
SEPD + Arps	58.7
Duong + arps	72.4

Chapter 9 Simulated Examples

Simulated rates were obtained using numerical simulation and multiphase flow in Fekete Harmony software. Numerical models solve the nonlinear partial-differential equations (PDE′s) describing fluid flow through porous media with numerical methods. Numerical methods are the process of discretizing the PDE′s into algebraic equations and solving those algebraic equations to obtain the solutions. These solutions that represent the reservoir behavior are the values of pressure and phase saturation at discrete points in the reservoir and at discrete times. The initial gas saturation was assumed to be 0. The simulation was accessed three times at 20, 50 and 100 months to provide a comparative assessment of various decline curve analysis models, and to quantify the uncertainty associated with 25 year EUR estimates. These examples were analyzed using the six decline curve analysis models described earlier, viz., Arps Hyperbolic model, Stretched Exponential Production Decline Model (SEPD), Duong model and the combination of above mentioned models namely, Arps + Arps, SEPD + Arps and Duong + Arps.

9.1 Simulated data of 20 months

From the simulation, rates for the first 20 months were selected to perform the decline curve analysis. As seen in the Fig. 9.1, of production rate, q, vs Material Balance Time, MBT, we can see that Boundary Dominated Flow hasn′t been reached.

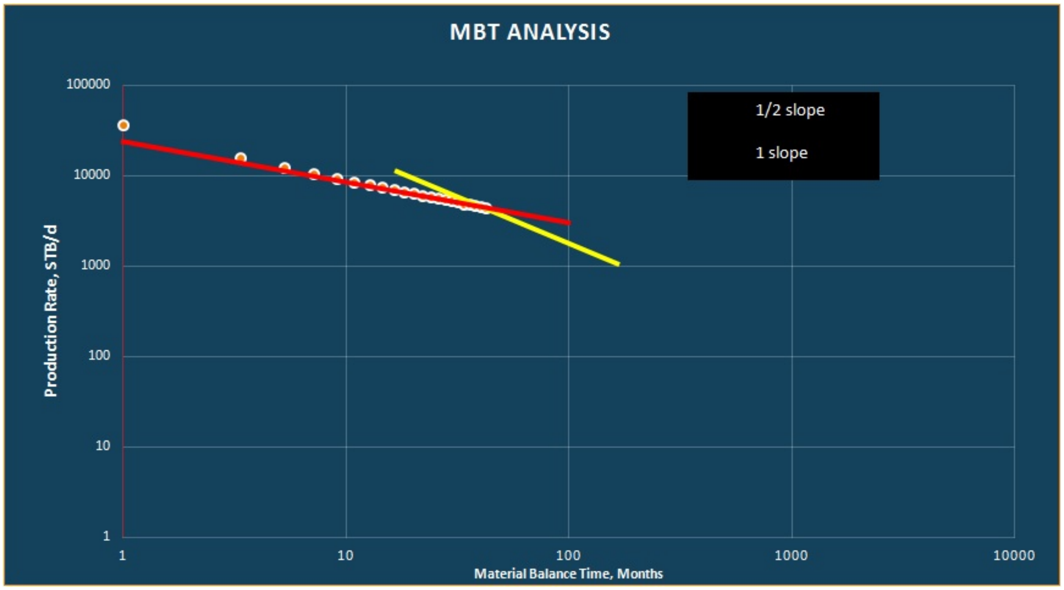

Figure 9.1. Rate vs material balance time for 20 months data.

9.1.1 Arps Hyperbolic Model

For the Arps model, first we plot the ratio of observed production rate, q, and cumulative production, Q, to estimate the decline exponent, b, and the initial decline rate, D_i. The resulting fit is shown in Fig. 9.2. The resulting best fit parameters are b =1.8 and D_i = 3 1/d. Then we plot the production time, t, and cumulative production, Q, as shown in Fig. 9.3. The best fit gives an estimate of the third parameter, q_i, the initial production rate. The resulting best fit parameter is q_i = 60000 bbls/month. Using these fitted parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 639,000 bbls.

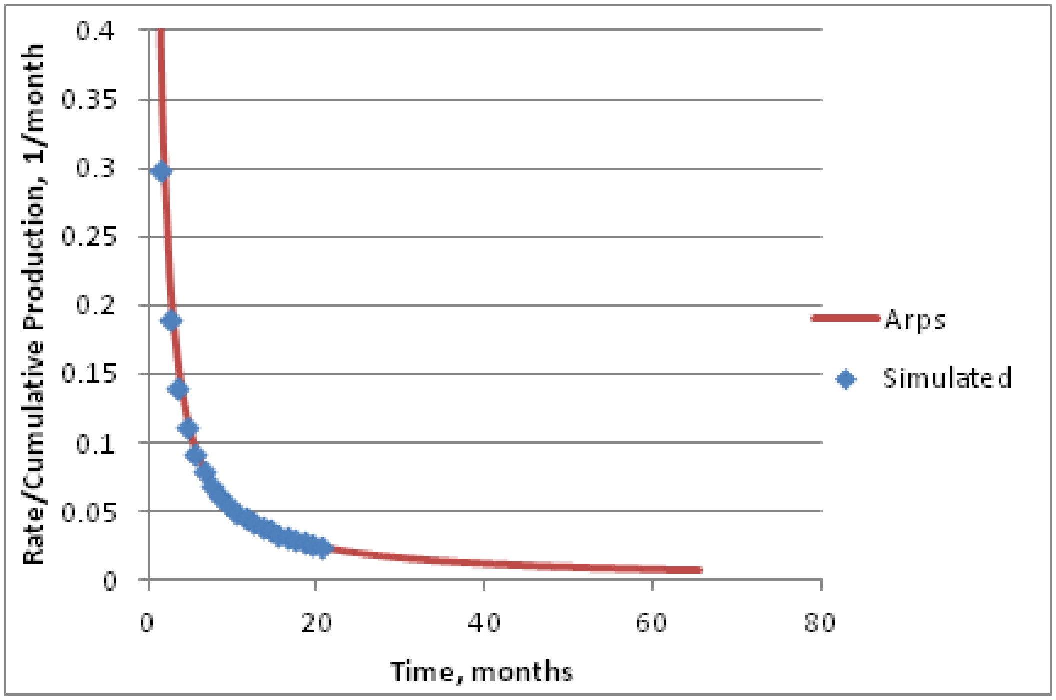

Figure 9.2. Ratio of rate to cumulative production vs time for 20 months data.

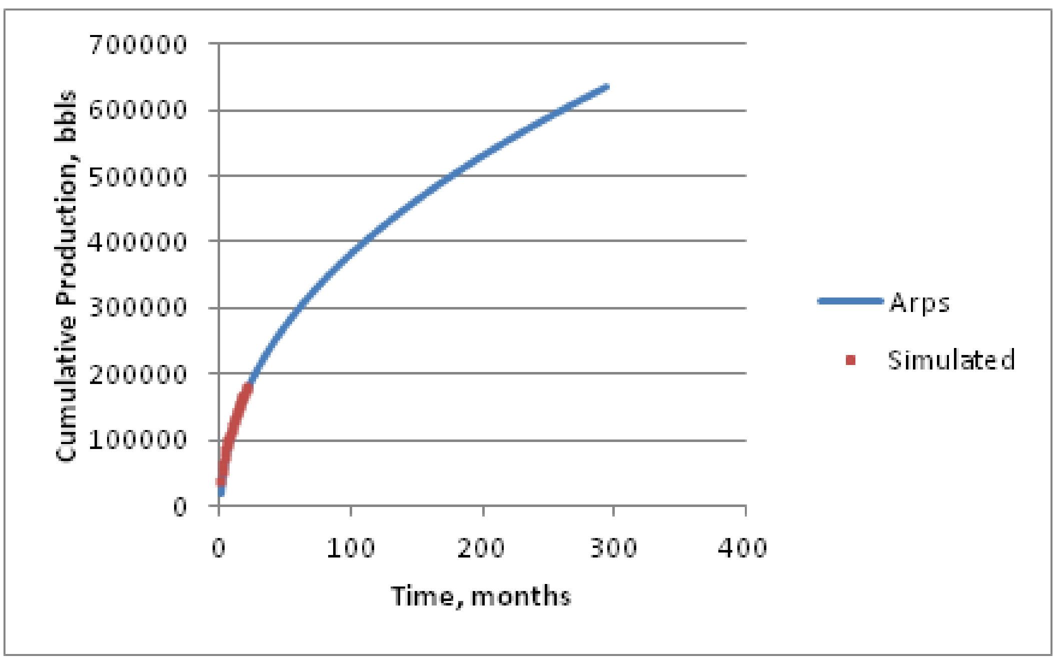

Figure 9.3. Cumulative production vs time for 20 months data.

9.1.2 SEPD

For the Stretched Exponential Decline model, the equations for r_{21} and r_{31}, i.e., the ratio of two year production to one year production and the ratio of three year production to one year production respectively, are used to estimate the characteristic time parameter, τ, and the parameter, n. As the available data was not enough instead of 1, 2 and 3 years; 0.5, 1 and 1.5 years were used. The equations were solved using the VB code in excel. The resulting best fit parameters are τ = 0.12 months and n = 0.218. Then we plot the production time, t, and cumulative production, Q, as shown in Fig. 9.5. The best fit gives an estimate of the third parameter, q_i, the initial production rate. The resulting best fit parameter is q_i = 95000 bbls/month. Using these fitted parameters the 30-year cumulative production (30-year EUR), Q30, is estimated to be 487,000 bbls.

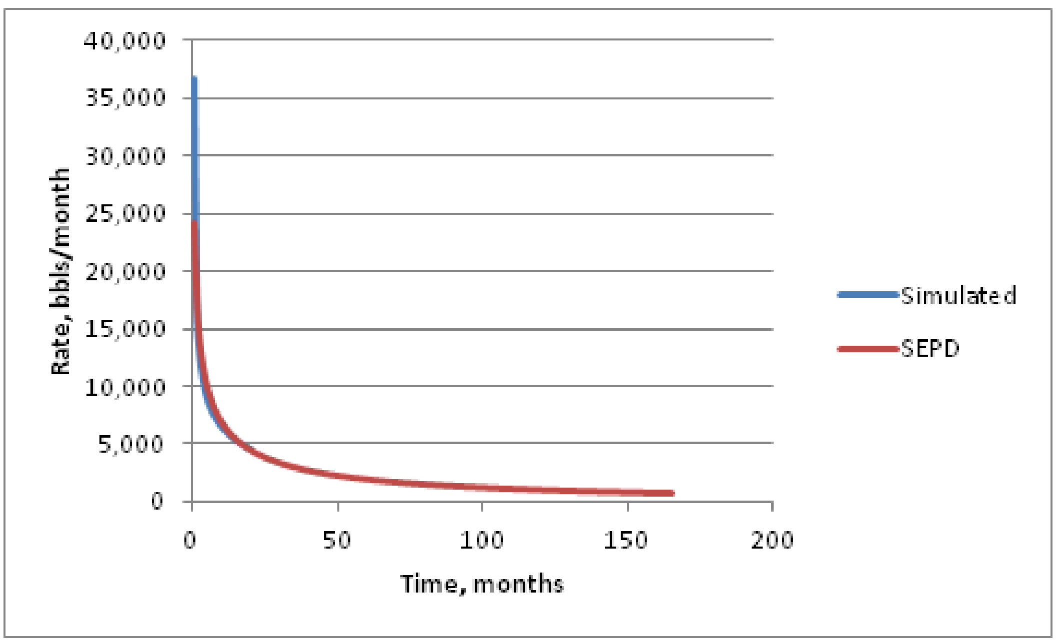

Figure 9.4. Rate vs time for 20 months data.

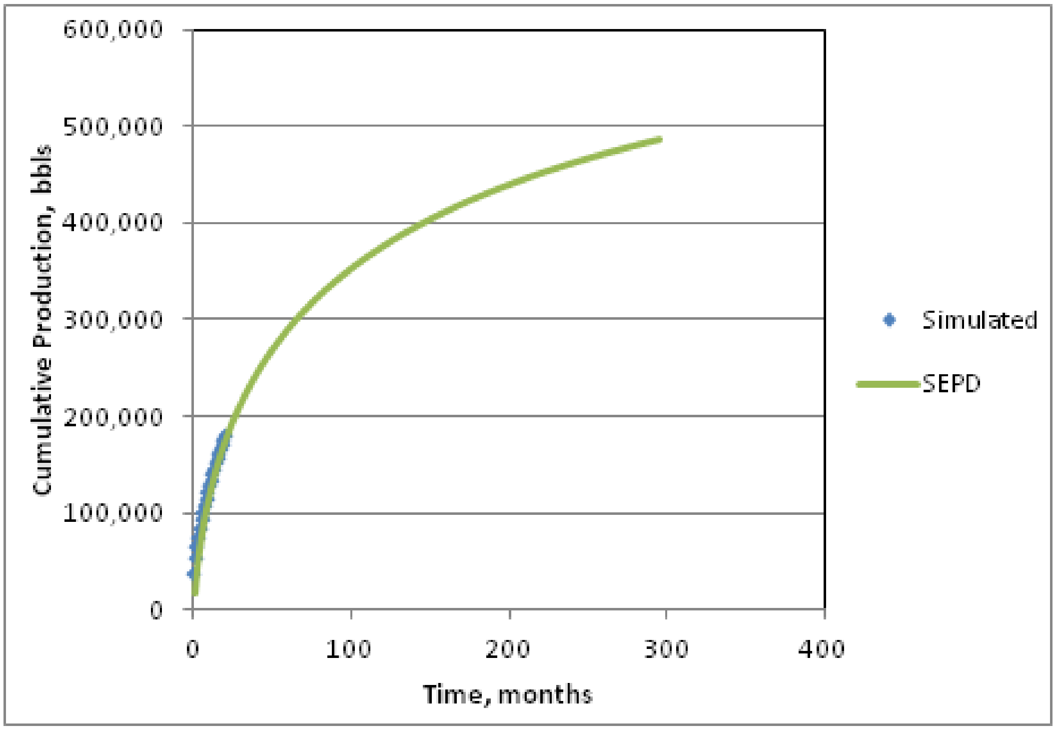

Figure 9.5. Cumulative production vs time for 20 months data.

9.1.3 Duong Model

For the Duong model, the first step is to plot the ratio of production rate, q, and cumulative production, Q, to the production time, to estimate the intercept constant, a, and the slope parameter, m Fig. 9.6. The resulting best fit parameters are a = 0.735 1/d and m = -1.124. Then we plot the dimensionless time, t_D, and the production rate as shown in Fig. 9.7. The intercept Q_{inf} is forced to zero. The resulting best fit parameter, based on Fig. 9.7, is q_i = 22,000 bbls/month. Using these fitted parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 582,000 bbls.

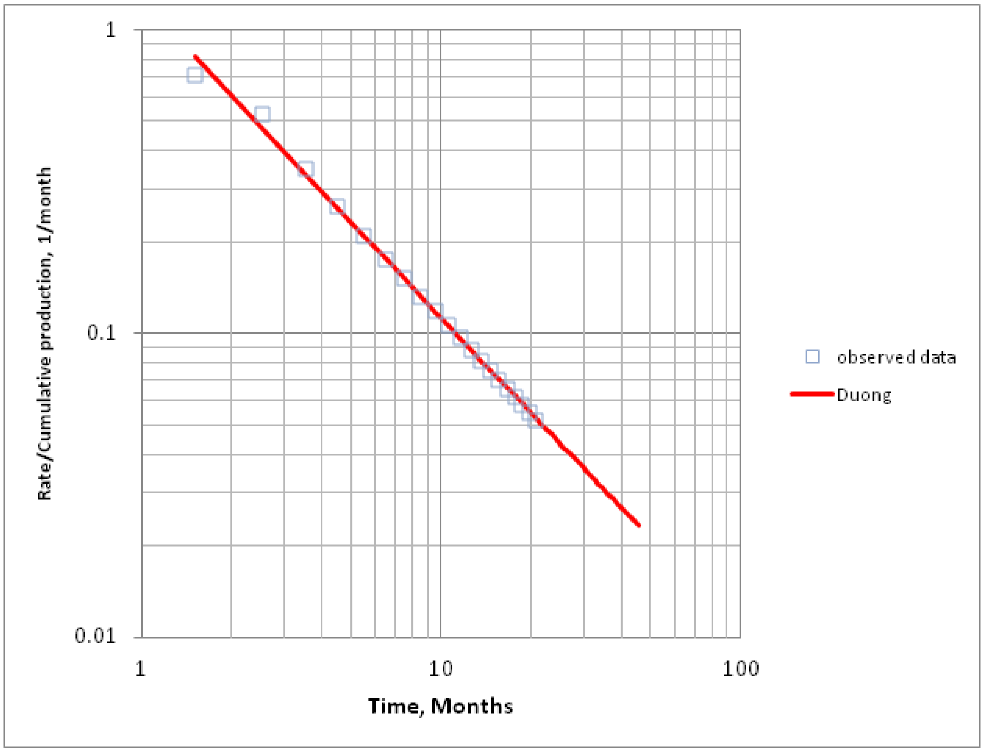

Figure 9.6. Ratio of rate to cumulative production vs time for 20 months data.

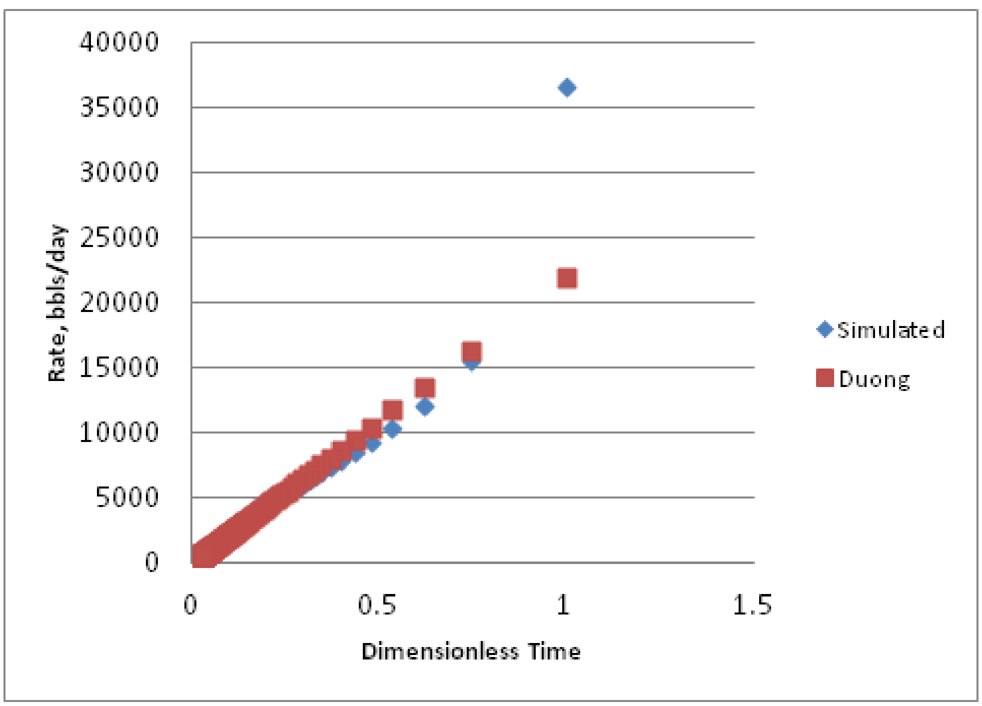

Figure 9.7. Rate vs dimensionless time for 20 months data.

9.1.4 Arps+Arps

As the BDF is not seen (or the slope of MBT vs rate has not yet become 1), we select time to BDF when the terminal decline is 5 % per annum. At the time of switch, b= 0.3 has been selected (typically for solution gas drive oil reservoirs). Arps hyperbolic initial decline at the time of switch is 0.0084 d^{-1} and initial rate or the rate of switch from Arps super hyperbolic to hyperbolic is 2,280 bbl/month. Using these parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 581,000 bbls.

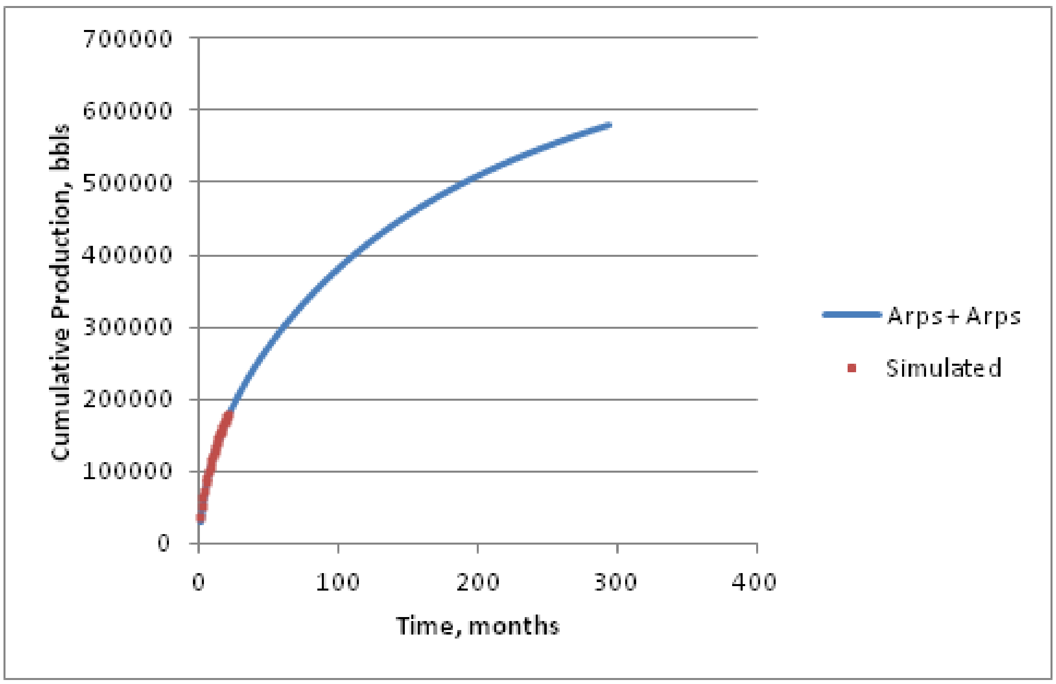

Figure 9.8. Cumulative production vs time for 20 months data.

9.1.5 SEPD+Arps

As the BDF is not seen (or the slope of MBT vs rate has not yet become 1), we select time to BDF when the terminal decline is 5 % per annum. At the time of switch, b= 0.3 has been selected (typically for solution gas drive oil reservoirs). Arps hyperbolic initial decline at the time of switch is 0.013 d^{-1} and initial rate or the rate of switch from SEPD to hyperbolic is 1,800 bbl/month. Using these parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 454,000 bbls.

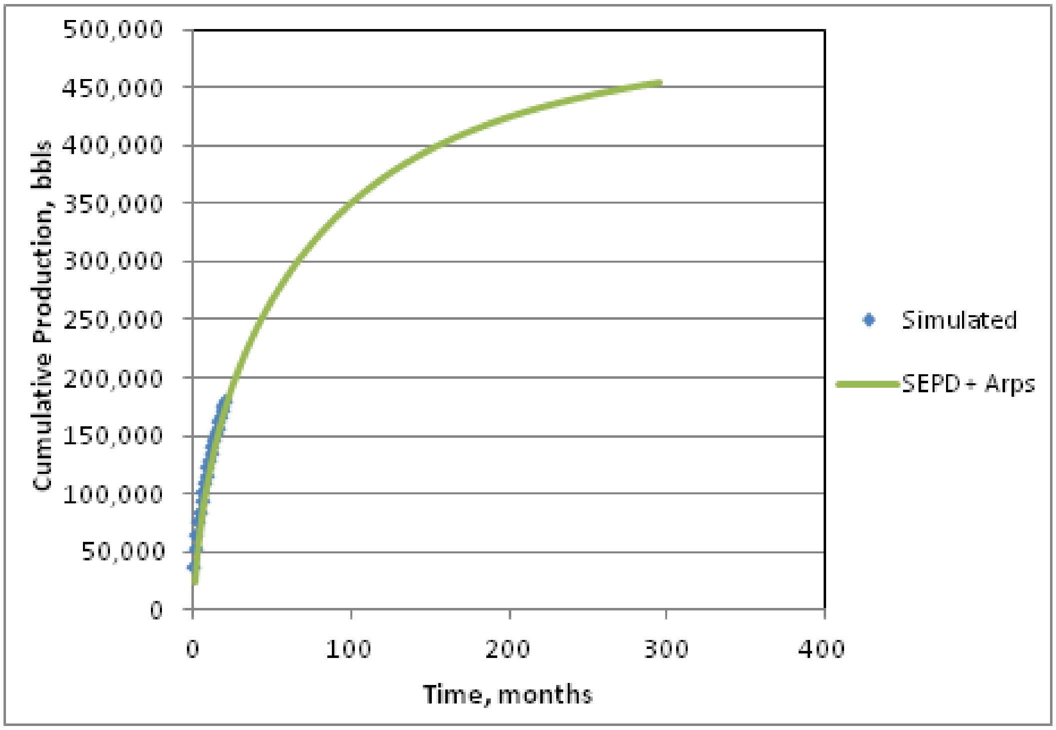

Figure 9.9. Cumulative production vs time for 20 months data.

9.1.6 Duong +Arps

As the BDF is not seen (or the slope of MBT vs rate has not yet become 1), we select time to BDF when the terminal decline is 5 % per annum. At the time of switch, b= 0.3 has been selected (typically for solution gas drive oil reservoirs). Arps hyperbolic initial decline at the time of switch is 0.01 d^{-1} and initial rate or the rate of switch from Duong to hyperbolic is 2,160 bbl/month. Using these parameters, 30-year cumulative production (30-year EUR), Q30, is estimated to be 527,000 bbls.

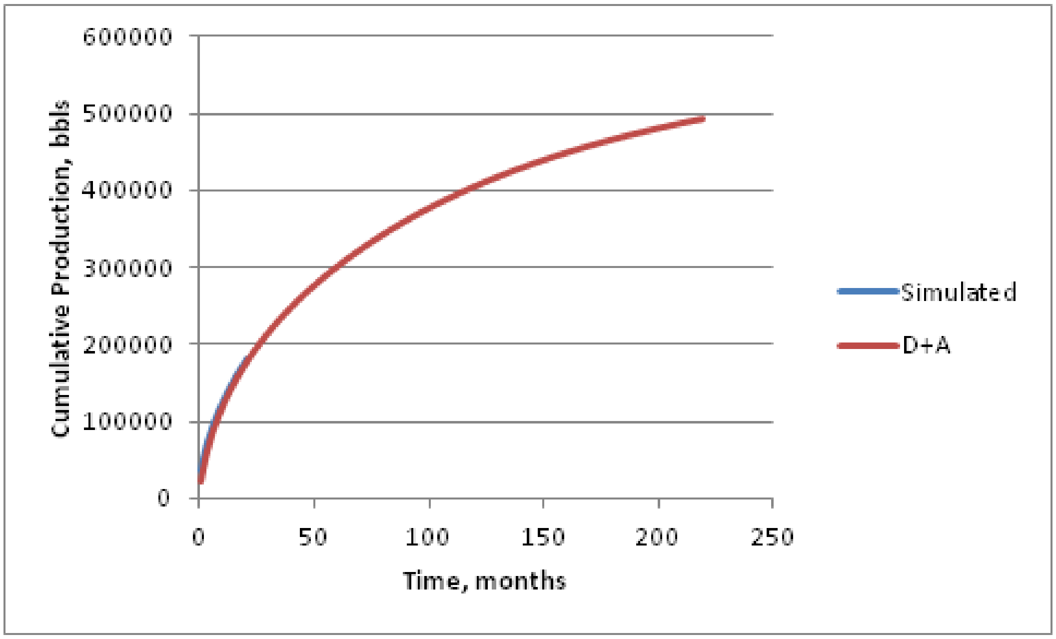

Figure 9.10. Cumulative production vs time for 20 months data.

9.1.7 Summary of results to simulated example

Fig. 9.11 below shows the aggregation of 30 year forecast of all the six models discussed above. Arps hyperbolic model gives the most optimistic projection, while the new developed method SEPD + Arps gives the most conservative projection. Table 9.1 shows the summary of the EUR projection for all the six models.

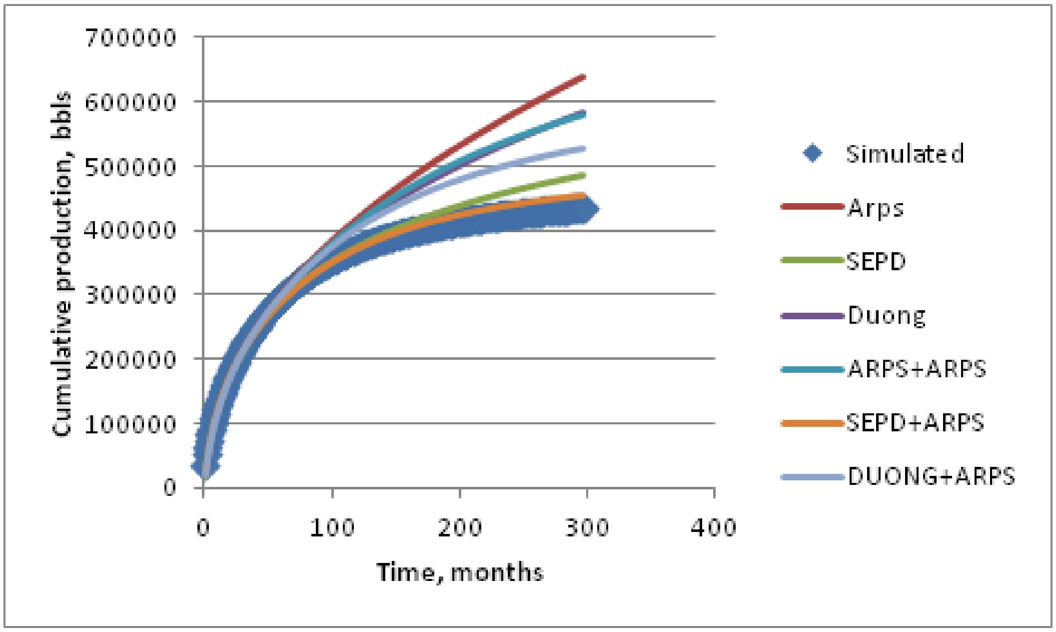

Figure 9.11. Cumulative Production vs time, all methods for 20 months data.

Table 9.1. Comparision for all methods, 20 months of simulated data

Methods	EUR (Mbbls)	percentage error
Arps	639	+47
SEPD	487	+12
Duong	582	+33.6
Arps + Arps	581	+33.3
SEPD + Arps	454	+4.2
Duong + arps	527	+21
Simulated	436	0

9.2 Simulated rates of 50 months

From the simulated data the data of first 50 months was selected to perform the decline curve analysis. As seen in the Fig. 9.12, of production rate, q, vs Material Balance Time, MBT, we can see that Boundary Dominated Flow hasn't been reached.

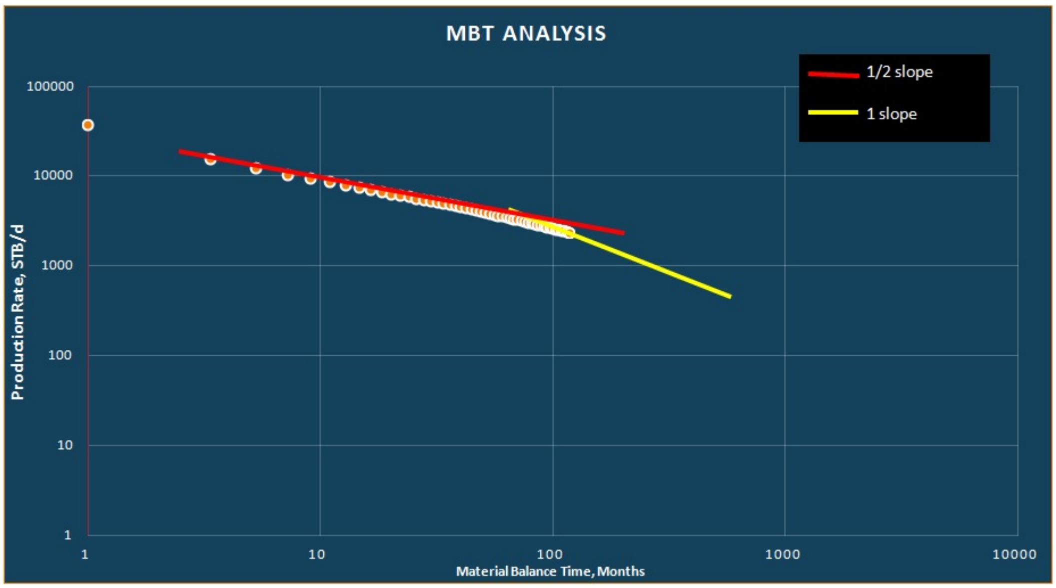

Figure 9.12. Rate vs material balance time for 50 months data.

9.2.1 Arps Hyperbolic Model

Arps Hyperbolic Model: For the Arps model, first we plot the ratio of observed production rate, q, and cumulative production, Q, to estimate the decline exponent, b, and the initial decline rate, D_i. The resulting fit is shown in Fig. 9.13.The resulting best fit parameters are b = 1.5 and D_i = 2 1/d. Then we plot the production time, t, and cumulative production, Q, as shown in Fig. 9.14. The best fit gives an estimate of the third parameter, q_i, the initial production rate. The resulting best fit parameter is q_i = 63,000 bbls/month. Using these fitted parameters, the 30-year cumulative production (30-year EUR), Q, 30, is estimated to be 603.000 bbls.

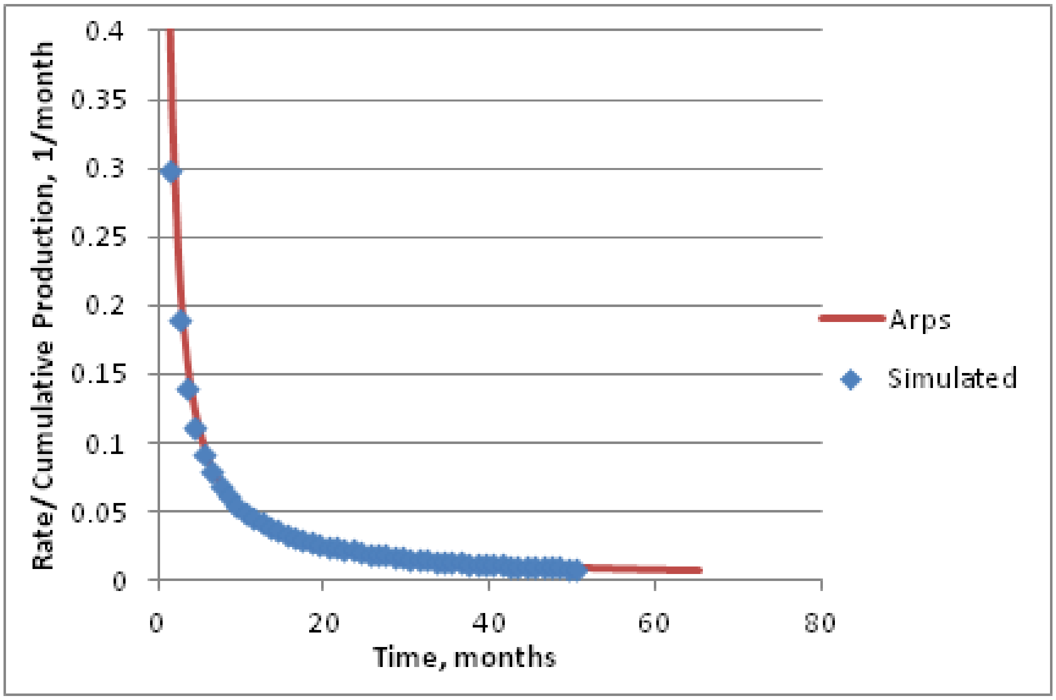

Figure 9.13. Ratio of rate to cumulative production vs time for 50 months data.

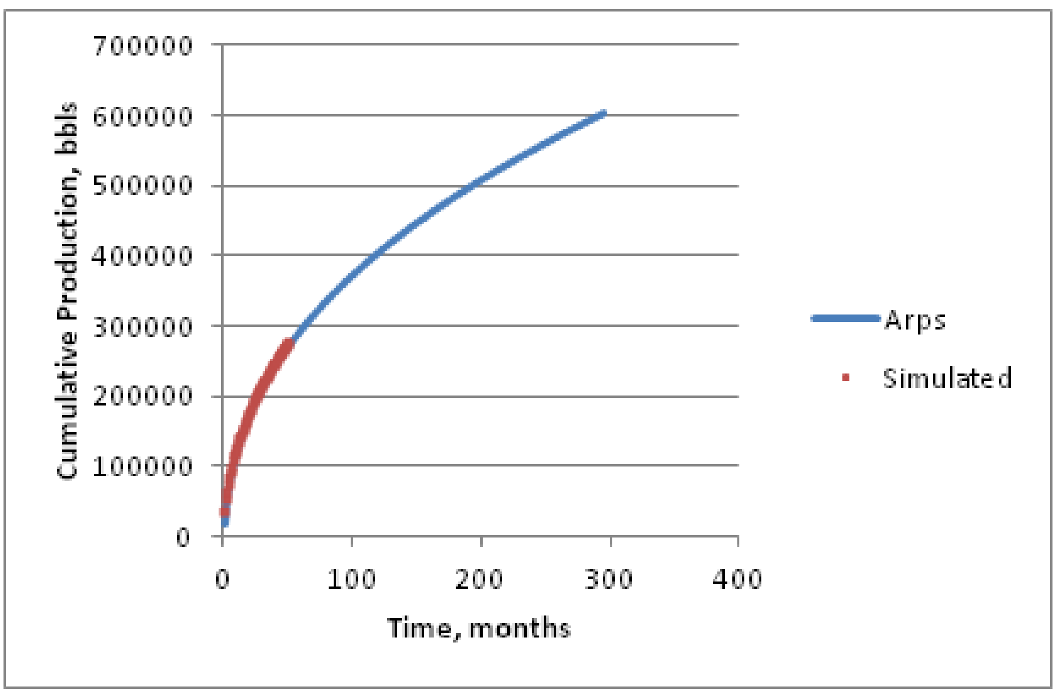

Figure 9.14. Cumulative production vs time for 50 months data.

9.2.2 SEPD

For the Stretched Exponential Decline model, the equations for r_{21} and r_{31}, i.e., the ratio of two year production to one year production and the ratio of three year production to one year production respectively, are used to estimate the characteristic time parameter, τ, and the parameter, n. The equations were solved using the VB code in excel. The resulting best fit parameters are τ = 1 months and n = 0.293. Then we plot the production time, t, and cumulative production, Q, as shown in Fig. 9.16. The best fit gives an estimate of the third parameter, q_i, the initial production rate. The resulting best fit parameter is q_i = 51,500 bbls/month. Using these fitted parameters the 30-year cumulative production (30-year EUR), Q30, is estimated to be 454,000 bbls.

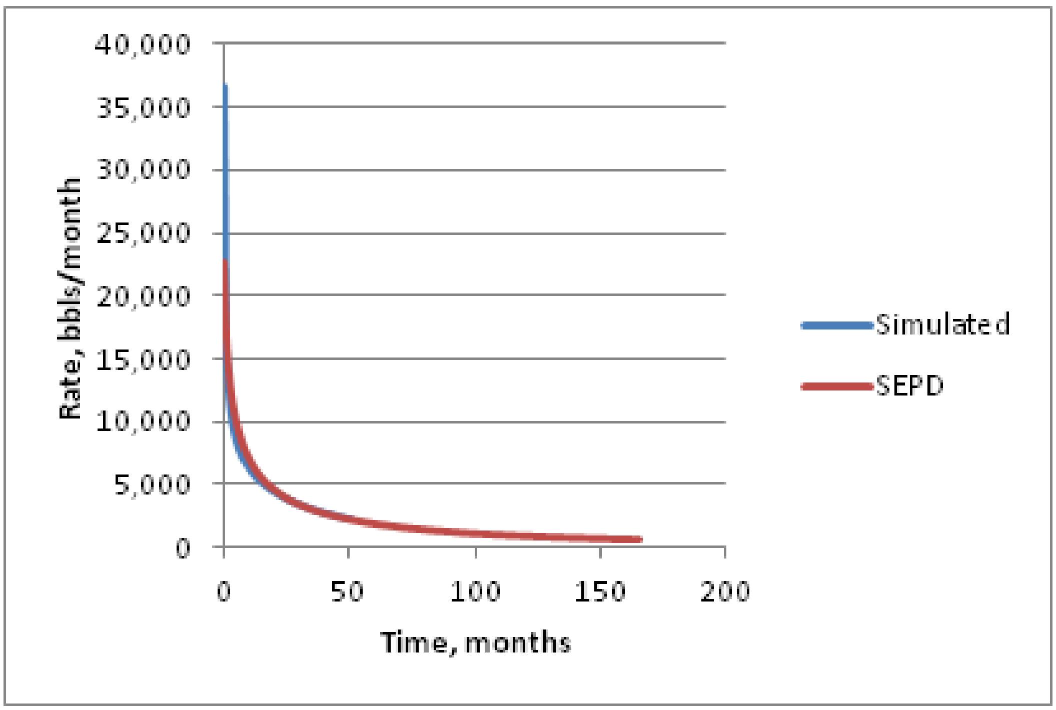

Figure 9.15. Rate vs time for 50 months data.

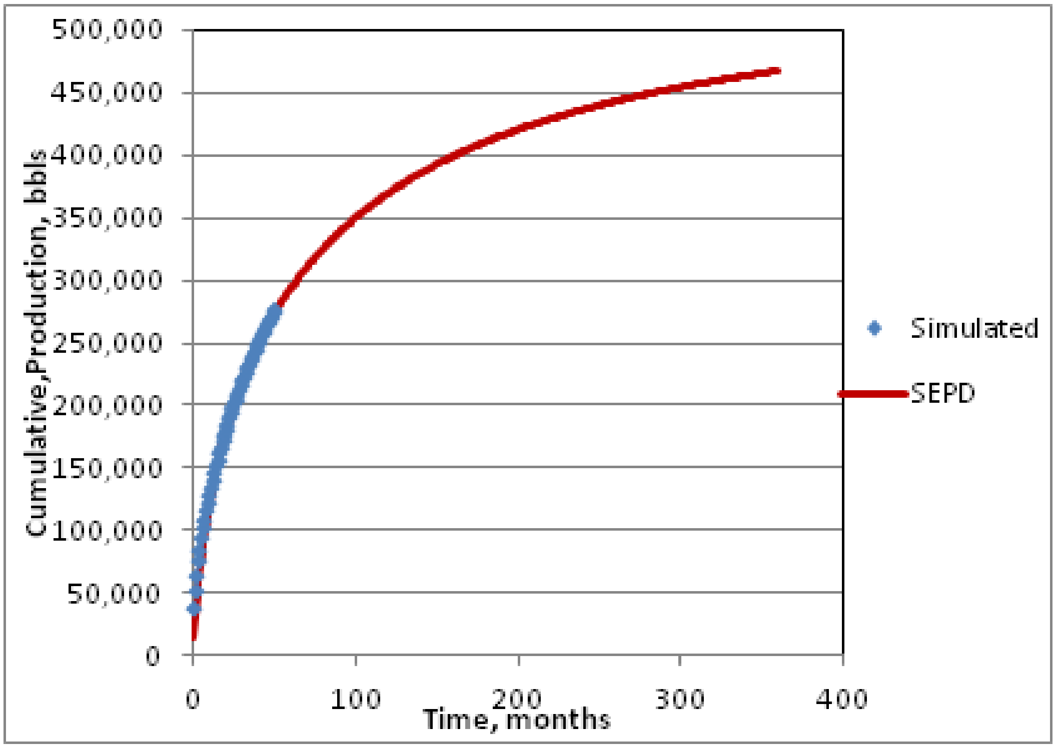

Figure 9.16. Cumulative production vs time for 50 months data.

9.2.3 Duong Model

For the Duong model, the first step is to plot the ratio of production rate, q, and cumulative production, Q, to the production time, to estimate the intercept constant, a, and the slope parameter, m Fig. 9.17. The resulting best fit parameters are a =0.731 1/d and m = -1.119. Then we plot the dimensionless time, t_D, and the production rate as shown in Fig. 9.18. The intercept Q_{inf} is forced to zero. The resulting best fit parameter, based on Fig. 9.18, is q_i = 21,500 bbls/month. Using these fitted parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 545,000 bbls.

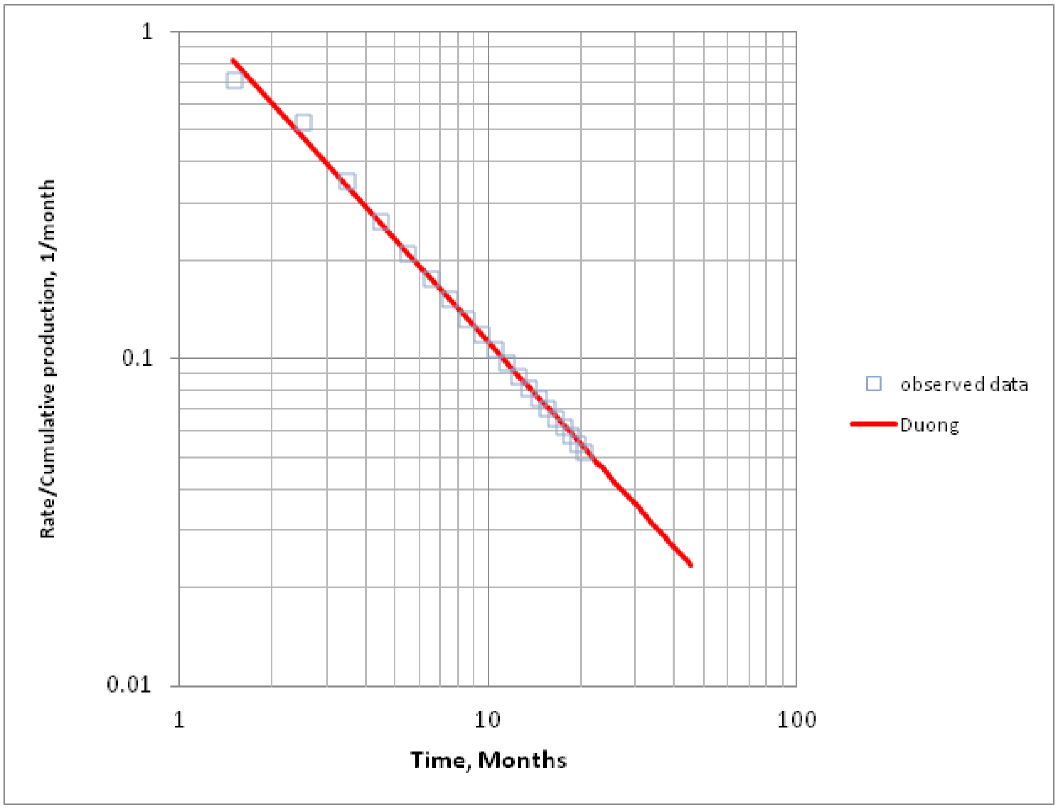

Figure 9.17. Ratio of rate to cumulative production vs time for 50 months data.

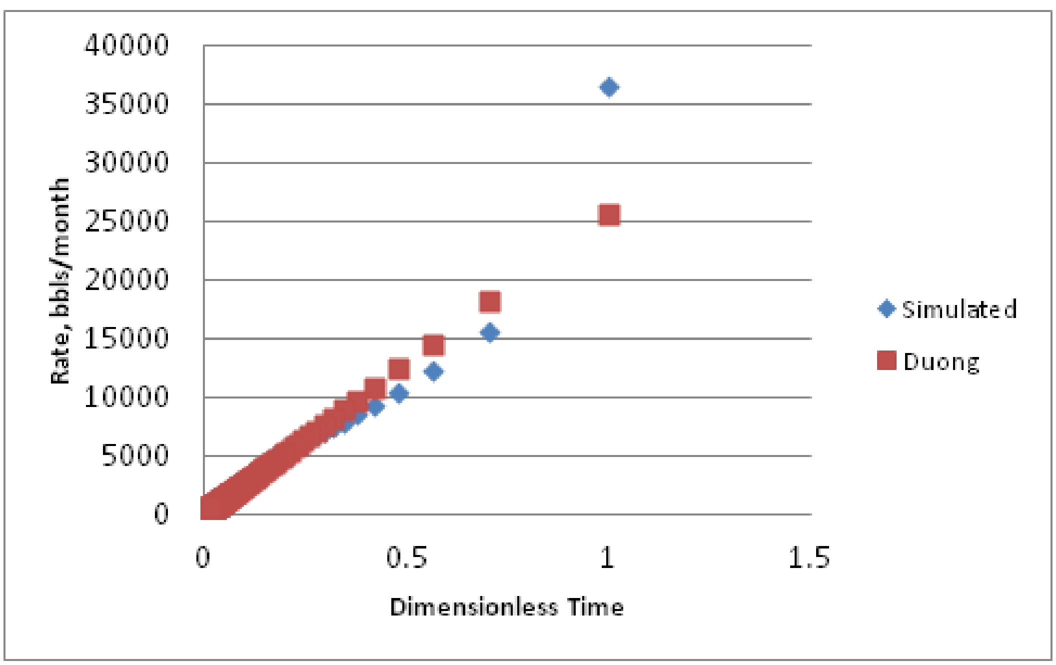

Figure 9.18. Rate vs dimensionless time for 50 months data.

9.2.4 Arps+Arps

As the BDF is not seen (or the slope of MBT vs rate has not yet become 1), we select time to BDF when the terminal decline is 5 % per annum. At the time of switch, b = 0.3 has been selected (typically for solution gas drive oil reservoirs). Arps hyperbolic initial decline at the time of switch is 0.0084 d^{-1} and initial rate or the rate of switch from Arps super hyperbolic to hyperbolic is 1,634 bbl/month. Using these parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 528,000 bbls.

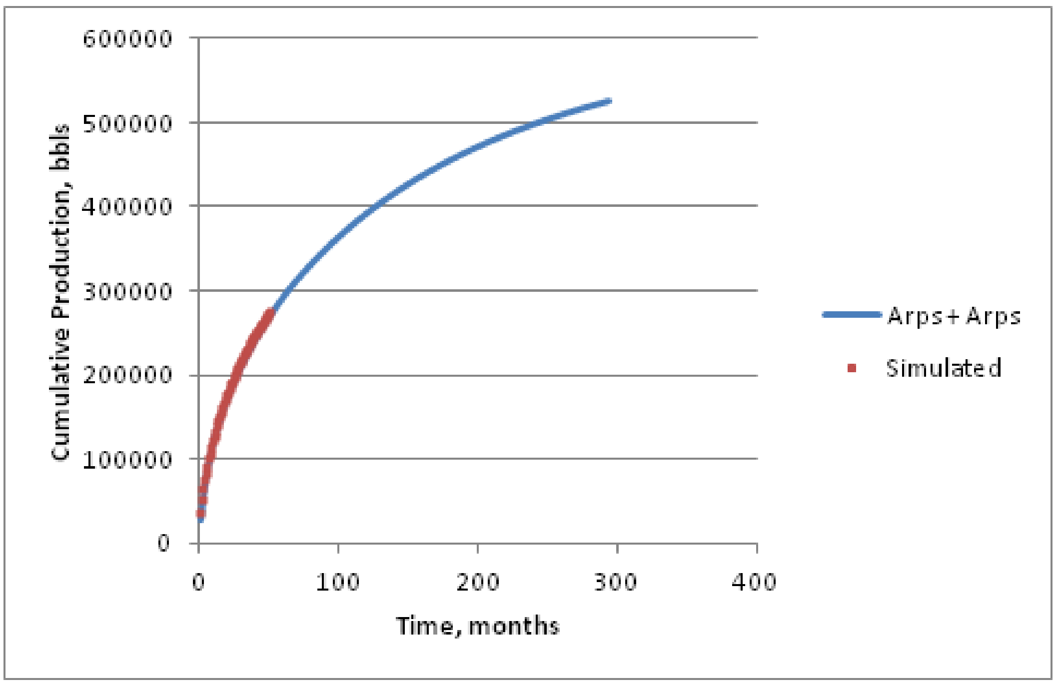

Figure 9.19. Cumulative production vs time for 50 months data.

9.2.5 SEPD+Arps

As the BDF is not seen (or the slope of MBT vs rate has not yet become 1), we select time to BDF when the terminal decline is 5 % per annum. At the time of switch, b= 0.3 has been selected (typically for solution gas drive oil reservoirs). Arps hyperbolic initial decline at the time of switch is 0.013 d^{-1} and initial rate or the rate of switch from SEPD to hyperbolic is 1,400 bbl/month. Using these parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 438,000 bbls.

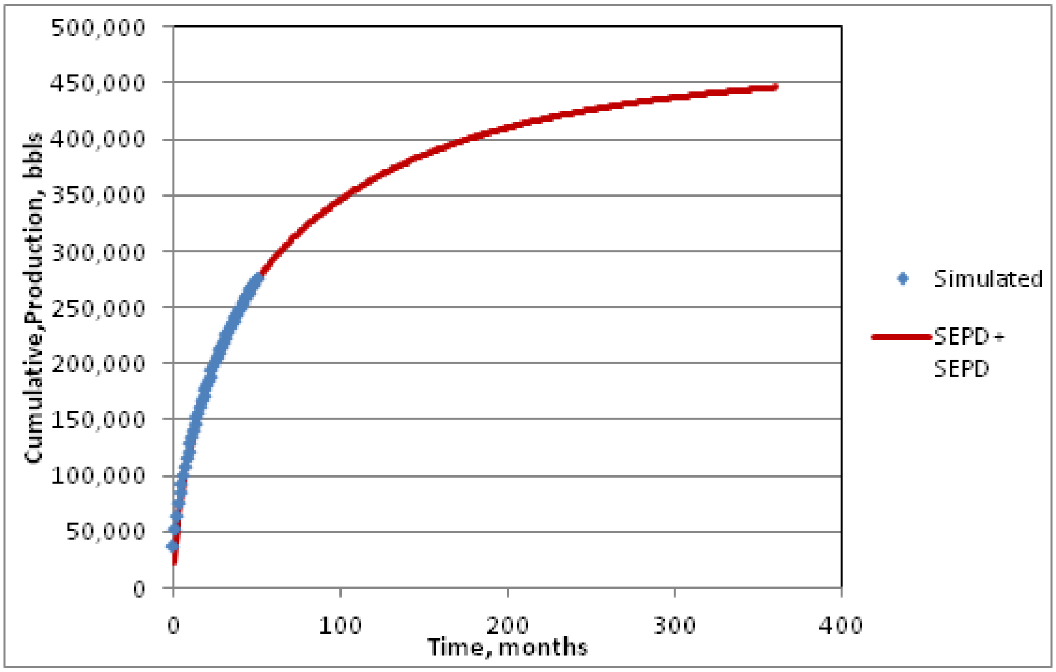

Figure 9.20. Cumulative production vs time for 50 months data.

9.2.6 Duong +Arps

As the BDF is not seen (or the slope of MBT vs rate has not yet become 1), we select time to BDF when the terminal decline is 5 % per annum. At the time of switch, b = 0.3 has been selected (typically for solution gas drive oil reservoirs). Arps hyperbolic initial decline at the time of switch is 0.0086 d^{-1} and initial rate or the rate of switch from Duong to hyperbolic is 1,930 bbl/month. Using these parameters, 30-year cumulative production (30-year EUR), Q30, is estimated to be 505,000 bbls.

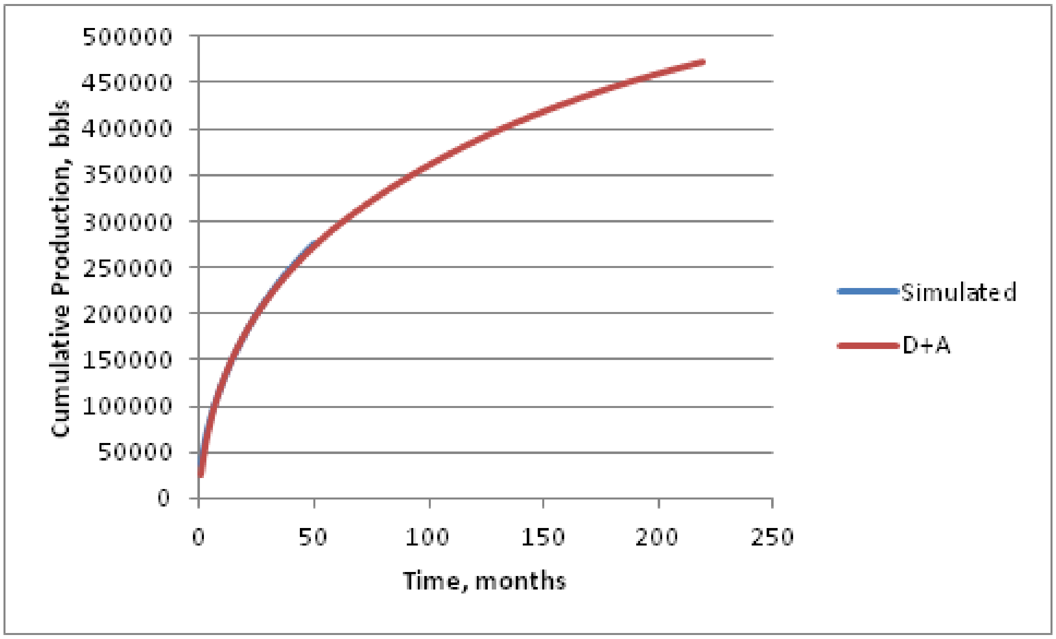

Figure 9.21. Cumulative production vs time for 50 months data.

9.2.7 Summary of methods

Fig. 9.22 below shows the aggregation of 30 year forecast of all the six models discussed above. Arps hyperbolic model gives the most optimistic projection, while the new developed method SEPD + Arps gives the most conservative projection. Table 9.2 shows the summary of the EUR projection for all the six models.

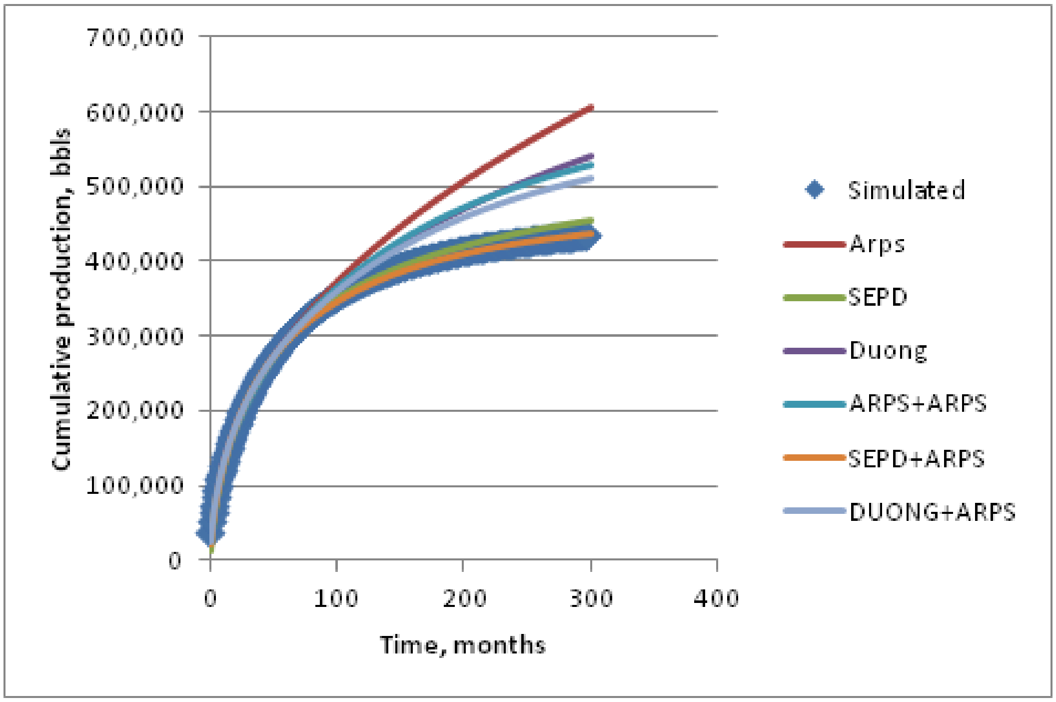

Figure 9.22. Cumulative production vs time, all methods for 50 months data.

Table 9.2. Comparision for all methods, 50 months of simulated data

Methods	EUR (Mbbls)	percentage error
Arps	603	+38.5
SEPD	454	+4.2
Duong	545	+25.1
Arps + Arps	528	+21.1
SEPD + Arps	438	+0.5
Duong + arps	505	+15.9
Simulated	436	0

9.3 Simulated rates of 100 months

From the simulated data, the data of first 100 months was selected to perform the decline curve analysis. As seen in the Fig. 9.23, of production rate, q, vs Material Balance Time, MBT, we can see that Boundary Dominated Flow starts after 60.5 months or can say 200 MBT.

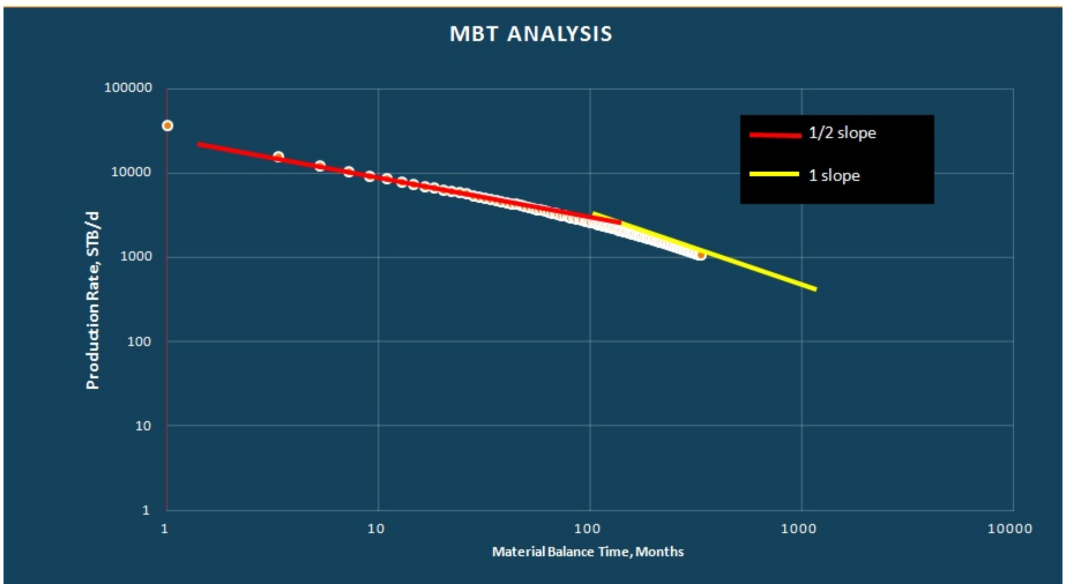

Figure 9.23. Rate vs material balance time for 100 months data.

9.3.1 Arps Hyperbolic Model

For the Arps model, first we plot the ratio of observed production rate, q, and cumulative production, Q, to estimate the decline exponent, b, and the initial decline rate, D_i. The resulting fit is shown in Fig. 9.24. The resulting best fit parameters are b =1.7 and D_i = 2 1/d. Then we plot the production time, t, and cumulative production, Q, as shown in Fig. 9.25. The best fit gives an estimate of the third parameter, q_i, the initial production rate. The resulting best fit parameter is q_i = 50,000 bbls/month. Using these fitted parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 580,000 bbls.

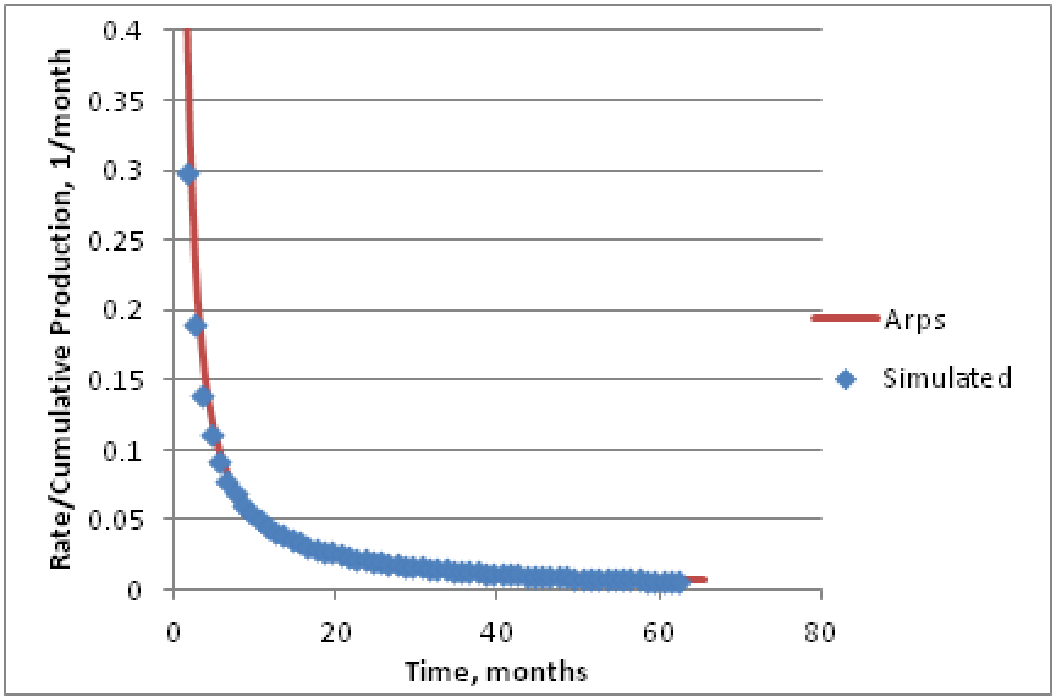

Figure 9.24. Ratio of rate to cumulative production vs time for 100 months data.

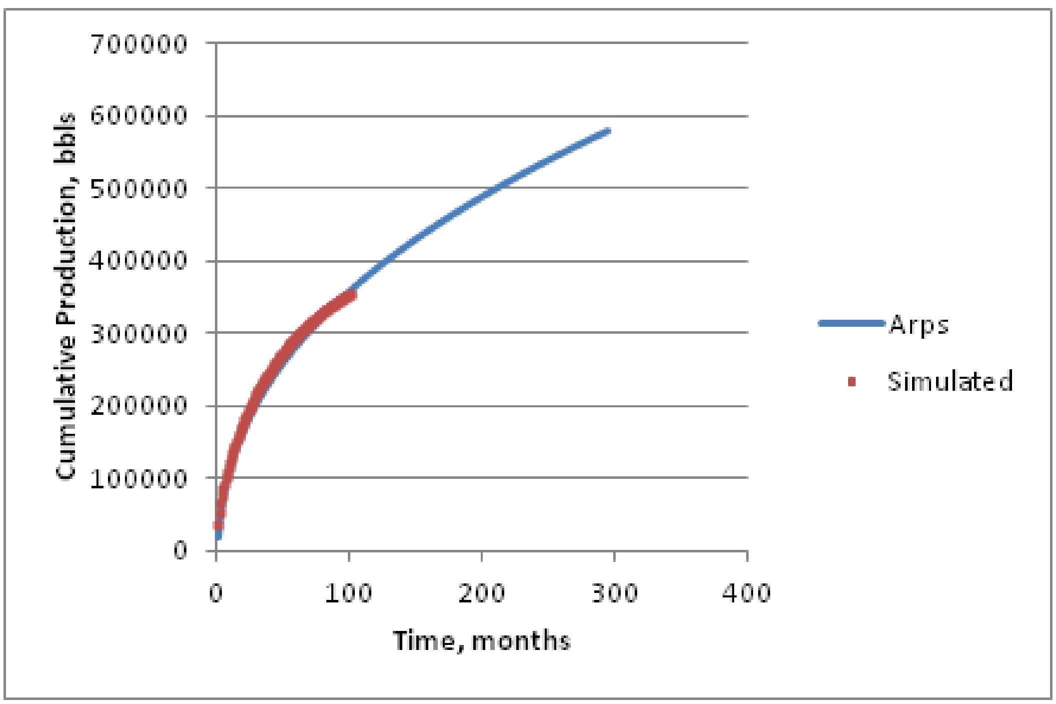

Figure 9.25. Cumulative production vs time for 100 months data.

9.3.2 SEPD

For the Stretched Exponential Decline model, the equations for r_{21} and r_{31}, i.e., the ratio of two year production to one year production and the ratio of three year production to one year production respectively, are used to estimate the characteristic time parameter, τ, and the parameter, n. The equations were solved using the VB code in excel. The resulting best fit parameters are τ = 0.7 months and n = 0.28. Then we plot the production time, t, and cumulative production, Q, as shown in Fig. 9.27. The best fit gives an estimate of the third parameter, q_i, the initial production rate. The resulting best fit parameter is q_i = 60,000 bbls/month. Using these fitted parameters the 30-year cumulative production (30-year EUR), Q30, is estimated to be 454,000 bbls.

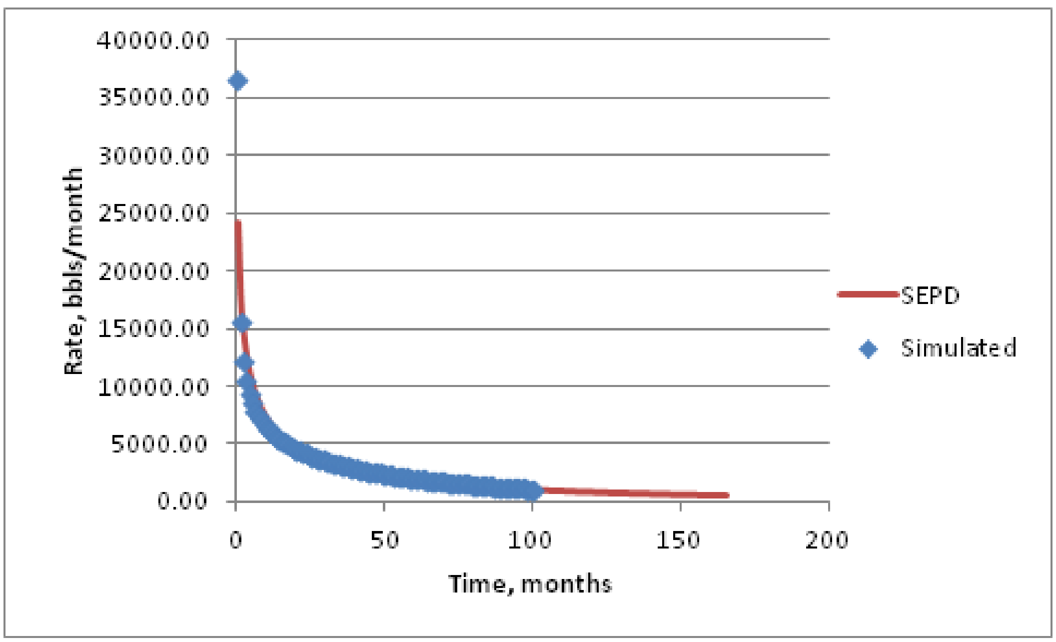

Figure 9.26. Rate vs Time for 100 months data.

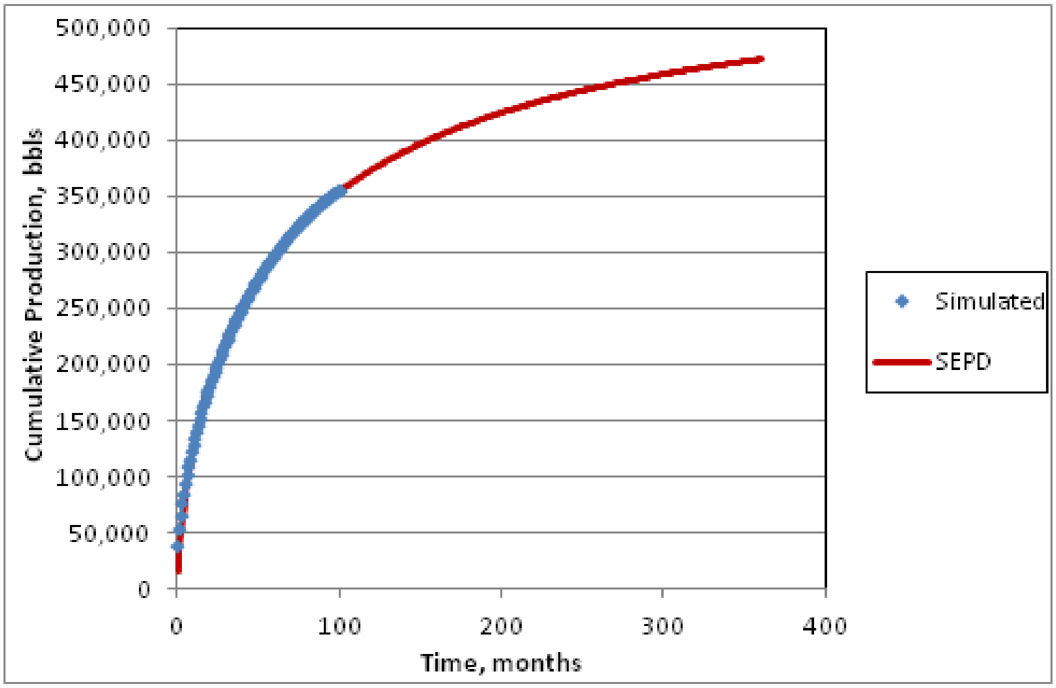

Figure 9.27. Cumulative production vs time for 100 months data.

9.3.3 Duong Model

For the Duong model, the first step is to plot the ratio of production rate, q, and cumulative production, Q, to the production time, to estimate the intercept constant, a, and the slope parameter, m Fig. 9.28. The resulting best fit parameters are a = 0.874 1/d and m = -1.194. Then we plot the dimensionless time, t_D, and the production rate as shown in Fig. 9.29. The intercept Q_{inf} is forced to zero. The resulting best fit parameter, based on Fig. 9.29, is q_1 = 22,500 bbls/month. Using these fitted parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 509,000 bbls.

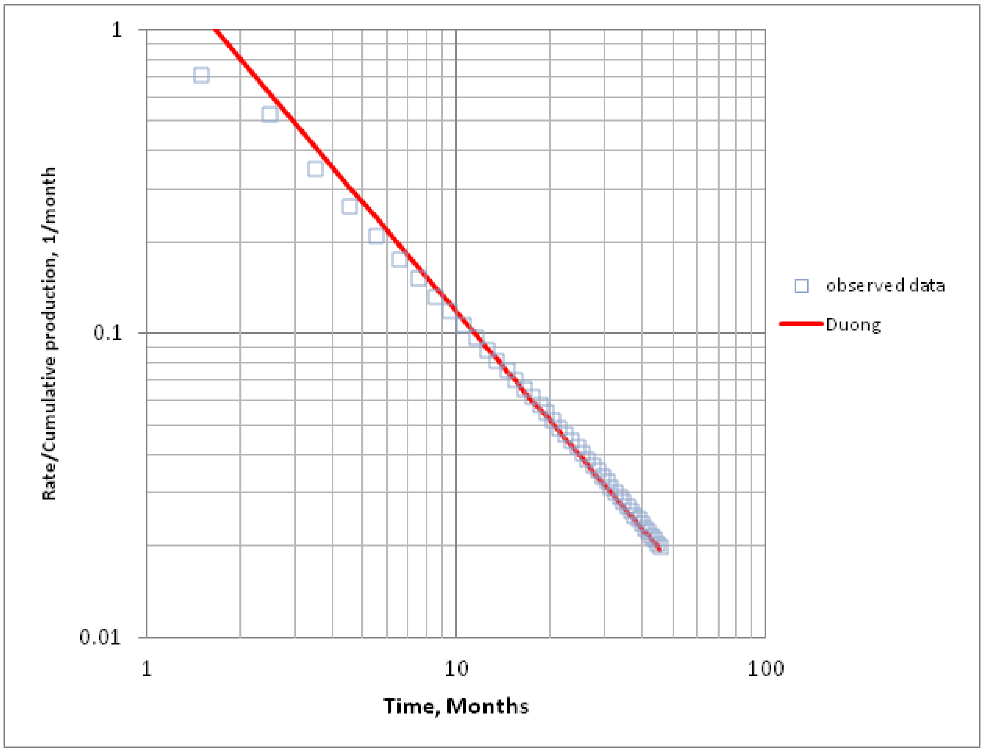

Figure 9.28. Ratio of rate to cumulative production vs time for 100 months data.

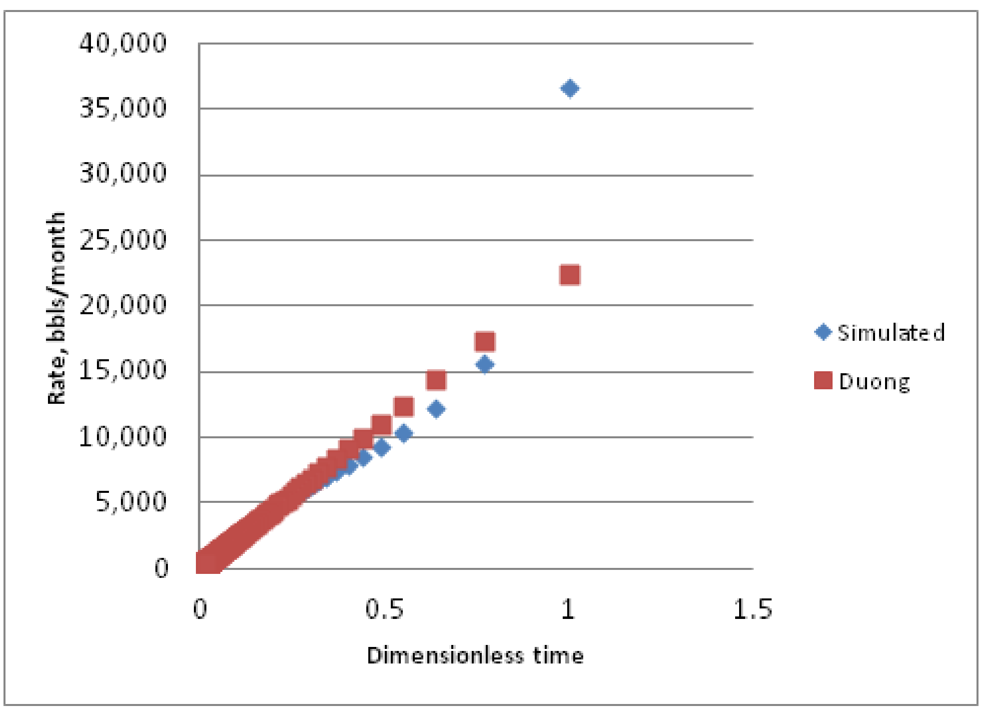

Figure 9.29. Rate vs dimensionless time for 100 months data.

9.3.4 Arps+Arps

At 60.5 months (or when the slope of MBT vs rate becomes 1), we change from the decline exponent b=1.11 to b=0.36, the best fit to the BDF data. Arps hyperbolic initial decline at the time of switch is 0.032 d^{-1} and initial rate or the rate of switch from Arps super hyperbolic to hyperbolic is 658.4 bbl/month. Using these parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 507,000 bbls.

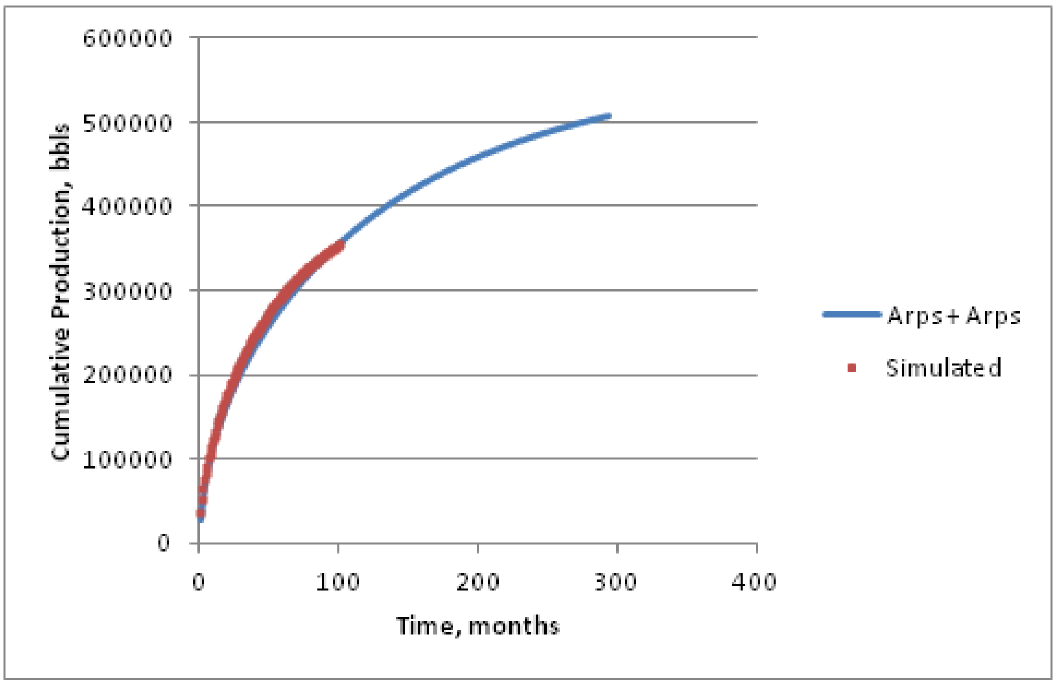

Figure 9.30. Cumulative production vs time for 100 months data.

9.3.5 SEPD+Arps

At 60.5 months (or when the slope of MBT vs rate becomes 1), we change from the decline exponent b=1.11 to b=0.36, the best fit to the BDF data. Arps hyperbolic initial decline at the time of switch is 0.04 d^{-1} and initial rate or the rate of switch from SEPD to hyperbolic is 582 bbl/month. Using these parameters, the 30-year cumulative production (30-year EUR), Q30, is estimated to be 435,000 bbls.

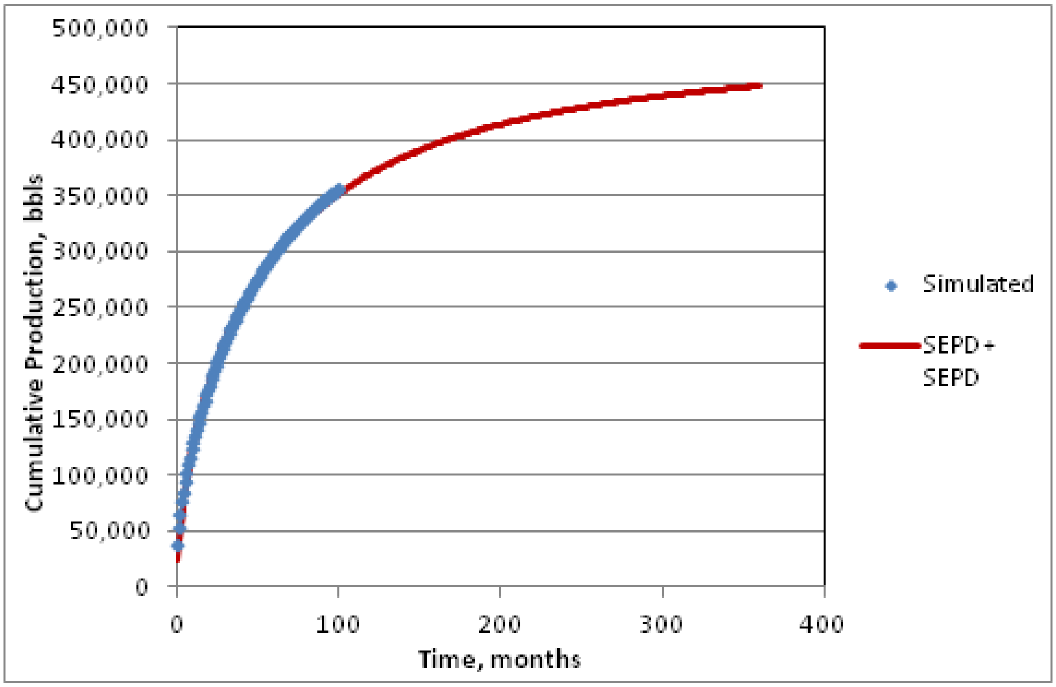

Figure 9.31. Cumulative production vs time for 100 months data.

9.3.6 Duong +Arps

At 60.5 months (or when the slope of MBT vs rate becomes 1), we change from the decline exponent b=1.11 to b=0.36, the best fit to the BDF data. Arps hyperbolic initial decline at the time of switch is 0.03 d^{-1} and initial rate or the rate of switch from Duong to hyperbolic is 794 bbl/month. Using these parameters, 30-year cumulative production (30-year EUR), Q30, is estimated to be 460,000 bbls.

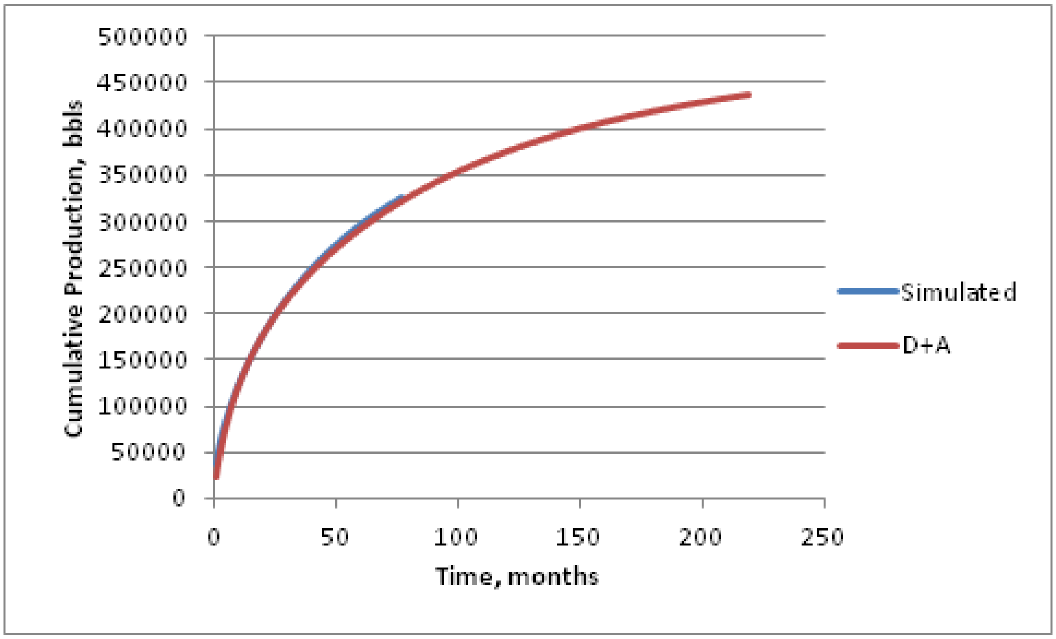

Figure 9.32. Cumulative production vs time for 100 months data.

9.3.7 Summary of methods

Fig. 9.33 below shows the aggregation of 30 year forecast of all the six models discussed above. Arps hyperbolic model gives the most optimistic projection, while the new developed method SEPD + Arps gives the most conservative projection. Table 9.3 shows the summary of the EUR projection for all the six models.

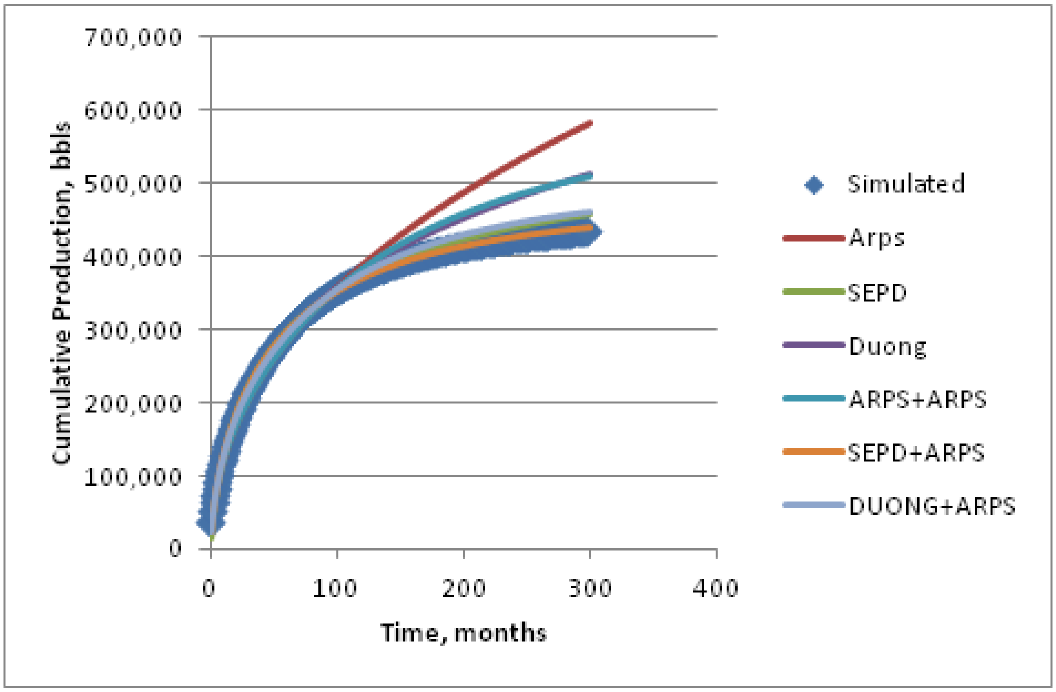

Figure 9.33. Cumulative production vs time, all methods for 100 months data.

Table 9.3. Comparision for all methods,100 months of simulated data

Methods	EUR (Mbbls)	percentage error
Arps	580	+33.2
SEPD	454	+4.1
Duong	509	+16.84
Arps + Arps	507	+16.43
SEPD + Arps	435	-0.26
Duong + arps	460	+5.45
Simulated	436	0

9.3.8 Comparision of Sepd + Arps

Table 9.4 shows the comparision of the Sepd + Arps with the simulated data when different months of data were used. Even if the data of 20 months was used, Sepd + Arps gives us the error of just 5 percent and as the number of months of data used are increaded to 100 than the error is reduced to mere 0.25 percent. So by far Sepd + Arps gives the most reliable answer.

Table 9.4. Comparision of SEPD + Arps method

Time	EUR (Mbbls)	percentage error
20 months	454.048	-4.18
50 months	437.972	-0.49
100 months	434.702	0.26
simulated	435.841	0

Chapter 10 Conclusions

From the analysis made from the field examples and the simulation, we can conclude that:

1) SEPD + Arps gives the most conservative results of all the methods.

2) If enough data is not available then also SEPD + Arps gives the most reliable and accurate results.

3) SEPD + Arps can work without enough Boundary Dominated Flow data available.

4) If we switch to Boundary Dominated flow equal to when the decline rate reaches 5 % per annum, we are close to the exact results.

References

Arps, J.J.: Analysis of Decline Curves, Published in Petroleum Transactions, AIME, 160(1945):228-247.

Can, B. and Kabir, C.S., Probabilistic Performance for Unconventional Reservois with Stretched Exponential model, SPE 143666 presented at the SPE North American Unconventional Gas Conference and Exhibition, The Woodlands, Texas,14-16 June 2011.

Duong, A.N. An Unconventional rate Decline Approach for Tight and Fracture-Dominated Gas Wells, CSUG/SPE 137748 presented at the Canadian Unconventional Resources and International Petroleum Conference, Calgary, Canada, 19-21 October 2010.

Fetkovich, M.J., 1980. Decline Curve Analysis Using Type Curves. SPE Journal of Petroleum Technology 32(6):1065-1077.

Fetkovich, M.J. , Fetkovich, E.J., and Fetkovich, M.D., Useful Concepts for Declin-Curve Forecasting, Reserve Estimation, and Analysis, SPEFE (February 1996) 13-22.

Freeborn, R. and Russell, B., 2012. How To Apply Stretched Exponential Equations to Reserve Evaluation. Paper SPE-162631-MS presented at the SPE Hydrocarbon Economics and Evaluation Symposium. Calgary, Alberta, Canada, 24-25 September 2012.

Ilk, D., Rushing, J.A., and Blasingame, T.A., Exponential vs Hyperbolic Decline in Tight Gas Sands-Understanding the Origin and Implications for Reserve Estimates Using Arps Decline curves, SPE 116731 presented at SPE Annual Technical Conference and Exhibition, Denverm Colorado, USA, 21-24 September, 2008.

Kanfar, M.S. , Wattenbarger, R.A. , Comparison of Empirical Decline Curve Methods for Shale Wells, SPE 162648 presented at SPE Canadian Unconventional Resources Conference held in Calgary, Alberta, Canada, 30 October-1 November, 2012.

Kurtoglu, B., Cox, S.A., and Kazemi, H., 2011. Evaluation of Long-Term Performance of Oil Wells in Elm Coulee Field. Paper SPE-149273-MS presented at the Canadian Unconventional Resources Conference. Alberta, Canada, 15-17 November 2011.

Lee, W.J. and Sidle, R.E., 2010. Gas Reserves Estimation in Resource Plays. Paper SPE 130102 presented at the 2010 SPE Unconventional Reservoir Conference, Pittsburgh, PA, USA, 23-25 February.

Lee, W.J., 2012, Estimating Reserves in unconventionalResources, Unpublished SPE Webinar Notes, 23 February.

Mishra, S., A New Approach to Reserves Estimation in Shale Gas Reservoirs Using Multiple Decline Curve Analysis Models. SPE 1611092 presented at SPE Easten Regional Meeting held in Lexington, Kentucky, USA, 3-5 October, 2012.

Pwc.2013. Shale Oil: The next energy revolution. $http://www.pwc.com/en_GX/gx/oil-gas-energy/publications/pdfs/pwc-shale-oil.pdf$ (downloaded 5 May, 2013).

Valko, P.P., Assigning Value to stimulation in the barnett Shale: A simultaneous Analysis of 7000 Plus Productio Histories and Well Completion records, SPE 119369 presented at 2009 SPE Hydraulic Fracturing Technology Conference, The Woodlands, Texas, 19-21 January 2009.

Valko, P.P. and Lee, W.J., 2010. A Better Way To Forecast Production From Unconventional Gas Wells. Paper SPE-134231-MS presented at the SPE Annual Technical Conference and Exhibition. Florence, Italy, 19-22 September 2010.