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Production Rate Decline-Based Models for Oil Reservoir Performance Prediction in Niger Delta

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***Abstract* - In the oil and gas industry, reservoir performance analyses are established to facilitate the field development and planning strategies. One of the available tools to perform this analysis is production rate decline analysis. Thus, several models: Arps, Reciprocal and Quadratic model have been developed and fitted to handle this estimation in some oil producing fields in the world. In Niger Delta, no fitted production rate decline models are available in the public domain for the prediction of oil reservoir(s) production performance. In this course, the Arps' model: Exponential, Harmonic, and Hyperbolic, Reciprocal and Quadratic models were fitted using multivariate analysis to predict the production history: production rate (q) and cumulative production (N_p) of an oil field in Niger Delta. The fitted models have decline constants of 0.000353day^{-1}, 0.000434day^{-1}, 0.000332day^{-1}, 0.000403day^{-1} and 0.000189day^{-1} for Exponential, Harmonic, Hyperbolic, Reciprocal and Quadratic, respectively. For the Hyperbolic model, the obtained decline exponent (b) is 0.5957. Also, the statistical validation of these fitted models resulted in absolute error, standard deviation and coefficient of determination of 0.0089, 0.4433 and 0.9991 for Exponential, -0.0011, 0.4455 and 0.9935 for Harmonic and 0.0005, 0.4460 and 0.9939 for Hyperbolic. Additionally, the reciprocal and quadratic models have absolute error, standard deviation and coefficient of determination of -0.0136, 0.4452 and 0.9883, and 0.0001, 0.4460 and 0.9998, respectively. These statistical results indicate that the Quadratic and Exponential models are more prolific models than the other for predicting the production rate decline of the oil field. Therefore, the fitted Quadratic and Exponential models can be used as a quick and robust tool to predict the reservoir performance on the "XYZ" oil field in the Niger Delta.**

Keyword: Production rate decline analysis, Oil reservoir, Arps' models, Reciprocal model, Quadratic model, Niger Delta

1. INTRODUCTION

The early exploration of oil and gas in the Niger Delta region of Nigeria dates back to the early 1950s when the first commercial reserve was discovered at Oloibiri, in the present day Bayelsa State in 1956 (Okon, 2010). Since then, exploration and production of oil and gas activities have been on the increase; as more discoveries are made. In other words, several oil fields have been developed in the Niger Delta. It is worth noting that in oil field development plan, reserves have to be well established before the company's limited available resource is expended on the execution of the given project. This strategic decision is made to avoid engaging in a risky and unprofitable venture (Makinde *et al.*, 2011). Therefore, one of the sole responsibilities of a petroleum engineer; especially reservoir engineer is to estimate the recoverable reserves of a reservoir. Brons (1963) mentioned that choosing the reserves estimation method is critical for accurate forecast that are, in turn, vital for sound managerial planning. Thus, one of the approaches of estimating the reservoir recoverable reserves is the reservoir performance analysis using production rate decline analysis. Hook (2009) added that decline curve analysis (DCA) is the frequently used approach for recoverable reserves estimation as it is a function of rate of decline of petroleum extraction over a period of time. Therefore, this approach is based on the assumptions that the trend of production history of oil and/or gas reservoir(s) and factors causing the historical decline remain unchanged during the forecast period (Okon *et al.*, 2017). Hence, these factors include both reservoir conditions and operating conditions. Ahmed and McKinney (2005) maintained that some of the reservoir factors that affect the decline rate are pressure depletion, number of producing wells, drive mechanism, reservoir characteristics, saturation changes and relative permeability. Also, Ahmed (2006) added that the operating conditions that influence the decline rate include: separator pressure, tubing size, choke setting, workovers, compression, operating hours and artificial lift. Although the production rate decline analysis comes with its limitations, the biggest advantage of this reservoir(s) recoverable reserves estimation method is that, it is virtually independent of the size and shape or the actual drive mechanism of the reservoir (Doublet *et al.*, 1994). Thus, the detailed description of the reservoir or production data is not required to perform this production rate decline analysis. Arps in 1945 put together the earlier works by Arnold and Anderson (1908), Cutler (1924), Roeser (1925) and Miller (1942) to develop an all-inclusive empirical model for production rate decline analysis. This Arps' equation as expanded in Table 1 categorized production rate decline curve into exponential, harmonic and hyperbolic declines. The hyperbolic equation is the universal Arps' equation of which the exponential and harmonic declines are special cases (Makinde *et al.*, 2011). Fetkovitch in 1980 presented type curve approach to analyze production rate decline data. The type curve consists of two segments, that is, transient and boundary dominated production periods. The transient portion comes from constant pressure type curve developed by Van Everdingen in 1949 while the boundary dominated portion is the same as Arps (1945) depletion stems (Okon *et al.*, 2017). Further works by Blasingame and Lee (1988) and

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Agarwal *et al.* (1999) are similar to Fetkovitch's type-curves for analysis of production data. The major difference is the introduction of flowing pressure data in the production rate to solve for hydrocarbon in-place analytically. Recently, Reese et al. (2007) and Johnson et al. (2009) presented reciprocal and quadratic models respectively, for production rate decline analysis. The reciprocal model assumes that flowing well bottom-hole pressure is approximately constant and was used to estimate hydrocarbon reserves using only rate-time production data. This model requires a plot of the reciprocal of production rate (q^{-1}) against the cumulative production to production rate ratio $\left(N_p/q\right)$ as presented in Table 1. Additionally, the quadratic model as developed by Johnson *et al.* (2009) is based on the Semi-analytical formulation by Blasingame and Rushing (2005) and Empirical formulation by Ilk *et al.* (2008). In essence, decline curves of various forms as mentioned can be used to create significant outlooks for hydrocarbon production of a single well or an entire field. However, it should be noted that in many field cases a single curve is not sufficient to obtain a good fit and it may be necessary to use a combination of curves to obtain good agreement (Haavardsson and Huseby, 2007). Though, the mentioned models have been tested and validated to be effective in some regions of the world, they are yet to be used as much as the Arps' approach; especially in the Niger Delta. Then, Okon *et al.* (2017) fitted the production rate decline models for gas field in the Niger Delta and established the quadratic model as the most efficient and robust model for analyzing the reservoir performance of the gas field. Therefore in this paper, the various production rate decline models were fitted and validated for use as quick and robust tools for oil reservoirs performance predictions in the Niger Delta.

Table 1: Production Rate Decline Models

S/N	Author(s)	Models	Production Rate (q_t)
1.	Arps (1945)	Exponential	$q_t = q_i e^{-D_i t}$
2.		Harmonic	$q_t = \dfrac{q_i}{\left[1 + D_i t\right]}$
3.		Hyperbolic	$q_t = \dfrac{q_i}{\left[1 + D_i b t\right]^{1/b}}$
4.	Reese et al. (2007)	Reciprocal	$\dfrac{1}{q_t} = \dfrac{1}{q_i} + \dfrac{D_i}{q_i}\left(\dfrac{N_p}{q_t}\right)$
5.	Johnson et al. (2009)	Quadratic	$q_t = q_i - D_i\left(N_p\right) + \dfrac{D_i^2}{q_i}\left(N_p\right)^2$

where:

q_t = Production Rate at time t, Stb/day
q_i = Initial Production Rate, Stb/day
t = time, Days
D_i = Decline Constant, Day $^{-1}$
b = Decline Exponent
N_p = Cumulative Oil Production, Stb

2. MATERIALS AND METHODS

2.1. Data Acquisition and Models Fitting

The oil production data of the "XYZ" oil field in the Niger Delta for a period of about 12.32 years (i.e., 4500 days) were obtained from 25 wells. These data include: oil production rate (q_t) and cumulative oil production (N_p) of the "XYZ" oil field. The range of these oil production data is presented in Table 2. Multivariate analyses were performed based on the existing oil production rate decline models available in the literature, these include: Arps (i.e., Exponential, Harmonic and Hyperbolic), Reciprocal and Quadratic model to determine the decline constant (D_i) and decline exponent (b) - in terms of Hyperbolic model for the "XYZ" oil field in Niger Delta. Using the Microsoft Excel Solver, the generalized reduced gradient (GRG) iteration protocol was used to perform nonlinear regression to fit the mentioned production rate decline models to the field history production data. The obtained production rate decline constant (D_i) for the various models and decline exponent (b) for Hyperbolic model are presented in Table 3. Also, the fitted production rate decline and cumulative production models are presented in Table 4.

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Table 2: Summary of Production data

Type of data	Range
Production Rate (q_t), Stb/Day	501.30 – 5998.90
Cumulative Production (N_p), Stb	5998.90 – 14724688
Number of Wells	25
Period of Production (t), Day	4500

2.2 Models Validation

The various fitted models' predictions were compared with the obtained field production data from the "XYZ" oil field. The parameters considered for comparison were field oil production rate ($q_{t_{field}}$) and fitted model predicted oil production rate ($q_{t_{model}}$) against time (t), field cumulative oil production ($N_{P_{field}}$) versus fitted model predicted cumulative oil production ($N_{P_{model}}$), and field cumulative oil production ($N_{P_{field}}$) and fitted model predicted cumulative oil production ($N_{P_{model}}$) against time (t). These comparisons are presented in Log-Log plot owing to the extremity of the data range. In addition to these comparisons, statistical analyses were performed to validate the reliability of the fitted oil production rate decline models' predicted values. The statistical methods used are the average error (E_{avg}), absolute error (E_{abs}), root mean square error (E_{rms}), coefficient of determination (r^2), standard deviation (S_D) and normalized standard deviation (NS_D). The respective mathematical equations of these statistical tools are expanded in Appendix A, and the results of the statistical analyses are presented in Table 5.

3. RESULTS AND DISCUSSION

The performed multivariate analysis resulted in different production rate decline constants (D_i); as depicted in Table 3, for the various production rate decline models. This result indicates that the production rate decline constant obtained for the "XYZ" oil field in Niger Delta depends on the production rate decline model. Therefore, establishing the decline constant (D_i) and the rate decline model that will accurately predict the production performance of the "XYZ" field is of essence. Hence, Table 4 present the fitted production rate decline models for evaluating the "XYZ" field performance.

Table 3: Decline Constants for the Fitted Production Rate Decline Models

S/N	Constants	Production Rate Decline Models				
		Exponential	Harmonic	Hyperbolic	Reciprocal	Quadratic
1.	Decline Constant (D_i); Day^{-1}	0.000353	0.000434	0.000332	0.000403	0.000189
2.	Decline Exponent (b)	0	1	0.5967	-	-

Table 4: Production Rate Decline and Cumulative Production Fitted Models

S/N	Models	Flow Rate (Q_t)	Cumulative Production (Np)
1.	Exponential	$q_t = q_i e^{-0.000353t}$	$N_{P(t)} = 2824.85(q_i - q_t)$
2.	Harmonic	$q_t = \frac{q_i}{[1+0.000434t]}$	$N_{P(t)} = 1.5\times10^7 \ln\left(q_i / q_t\right)$
3.	Hyperbolic	$q_t = \frac{q_i}{[1+0.000198t]^{1.676}}$	$N_{P(t)} = 4.6\times10^7 q_i \left[1-\left(\frac{q_t^{0.4034}}{q_i^{0.4034}}\right)\right]$
4.	Reciprocal	$\frac{1}{q_t} = \frac{1}{q_i} + \frac{4.03\times10^{-4}}{q_i}\left(\frac{N_p}{q_t}\right)$	$N_{P(t)} = 2481.38(q_i - q_t)$
5.	Quadratic	$q_t = q_i - 3.07\times10^{-4}(N_p) + 5.97\times10^{-12}(N_p)^2$	$N_{P(t)} = 3257.33(q_i - q_t)$

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Table 5: Statistical Validation Analysis

S/N	Validation Tools	Production Rate Models				
		Exponential	Harmonic	Hyperbolic	Reciprocal	Quadratic
1.	Average Error (E_{avg})	-0.0089	-0.0011	0.0005	-0.0136	0.0001
2.	Absolute Error (E_{abs})	0.0272	0.0287	0.0221	0.0488	0.0001
3.	Root Mean Square Error (E_{rms})	0.0013	0.0011	0.0009	0.0039	0.0000
4.	Coefficient of Determination (r^2)	0.9991	0.9935	0.9939	0.9883	0.9998
5.	Standard Deviation (S_D)	0.4433	0.4455	0.4460	0.4452	0.4460
6.	Normalized Standard Deviation (NS_D)	0.2974	0.2986	0.3005	0.2986	0.2992

3.1. Comparison of Fitted Models' Predictions

As earlier alluded that nonlinear regression using generalized reduced gradient (GRG) iteration protocol was performed with the obtained field production data to determine the decline constants of the various rate decline models. The fitted production rate decline models' predictions were compared with the obtained field production data. The results are presented in Figures 1 through 15 for the various production rate decline models. Additionally, the statistical validations of the fitted models are present in Table 4.

a. Arps Models:

The obtained results based on the Arps' models are presented in Figures 1 through 9. The exponential approach for the decline production rate analysis is presented Figures 1 through 3. The comparison of the fitted model's (as presented in Table 4) prediction with field production data in Figure 1 indicates an alignment of the predicted oil production rate with the actual field oil production rate data. Figure 2 also shows the comparison of the field cumulative oil production data with the model predicted cumulative oil production on cumulative oil production (N_p) versus time (t) plot. The Figure depicts a close prediction of the field "XYZ" cumulative production data with the fitted model. Then, the degree of this close prediction between the field cumulative production and predicted cumulative production is evident in Figure 3 with the coefficient of determination (r^2) of 0.9991. On the other hand, Figures 4 through 6 show the predictions of the harmonic approach rate decline model. The fitted model's prediction based on the mentioned approach resulted in close prediction of the "XYZ" field production data, as the predicted data closely aligned with the field data. These alignments of the predicted data are observed in both the production rate – time plot (Figure 4) and cumulative production – time plot (Figure 5). In addition, the statistical evaluation of predicted cumulative production and field cumulative production resulted in coefficient of determination (r^2) of 0.9935; as depicted in Figure 6.

Also, Figures 7 through 9 present the comparison of the fitted model's predictions based on hyperbolic approach with the field production data. Similarly, the obtained results for the production rate – time and cumulative production – time plots show close alignment of the predicted data and the field production data; with a coefficient of determination (r^2) of 0.9939. In all, the fitted Arps models' prediction of the "XYZ" field production performance is promising, as the different models: exponential, harmonic and hyperbolic model with decline constants of 0.000353/day, 0.000434/day and 0.000332/day respectively resulted in close prediction of the Niger Delta field production data.

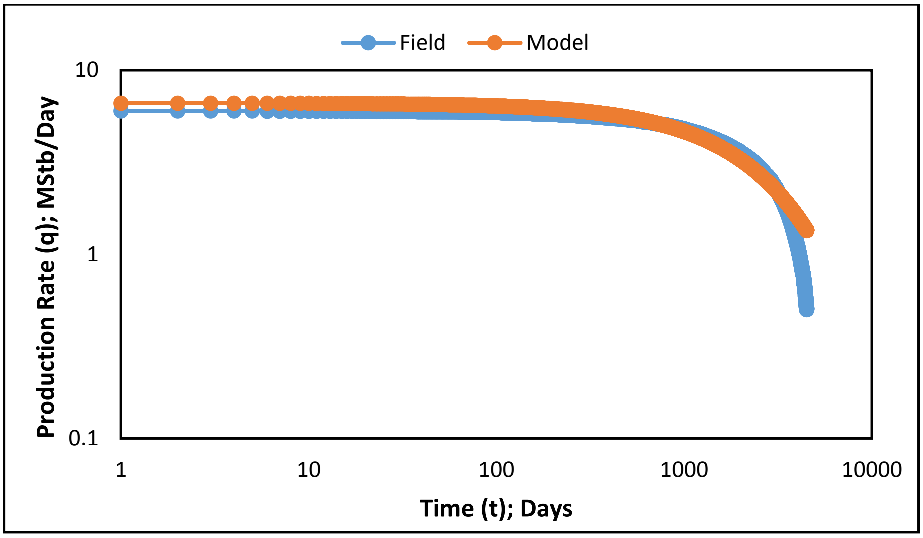

Figure 1: Field and Predicted Oil Production Rate vs. Time Plot (Exponential Model)

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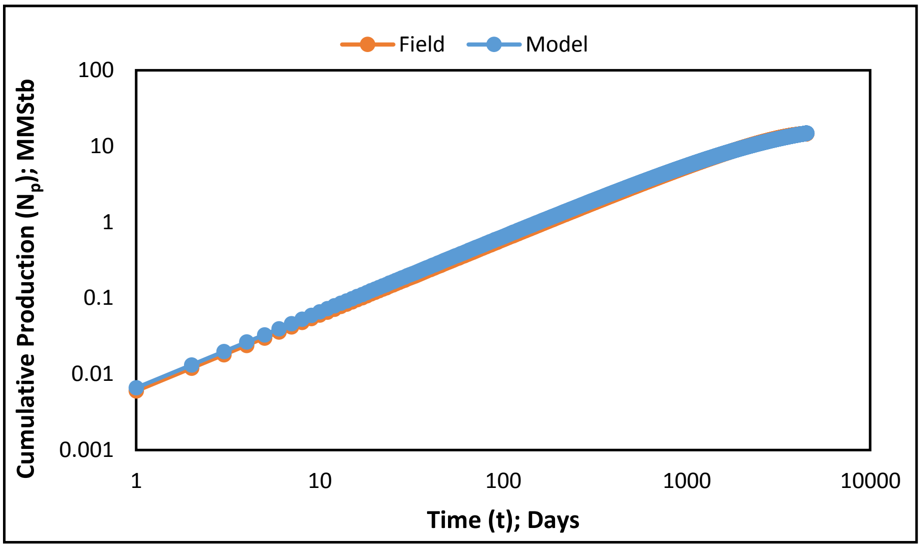

Figure 2: Field and Predicted Cumulative Production vs. Time Plot (Exponential Model)

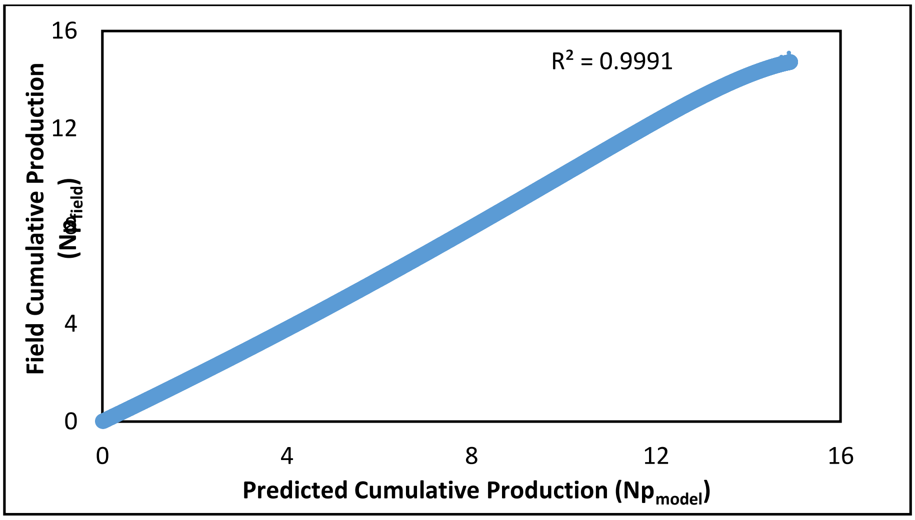

Figure 3: Comparison of Field and Predicted Cumulative Oil Production (Exponential Model)

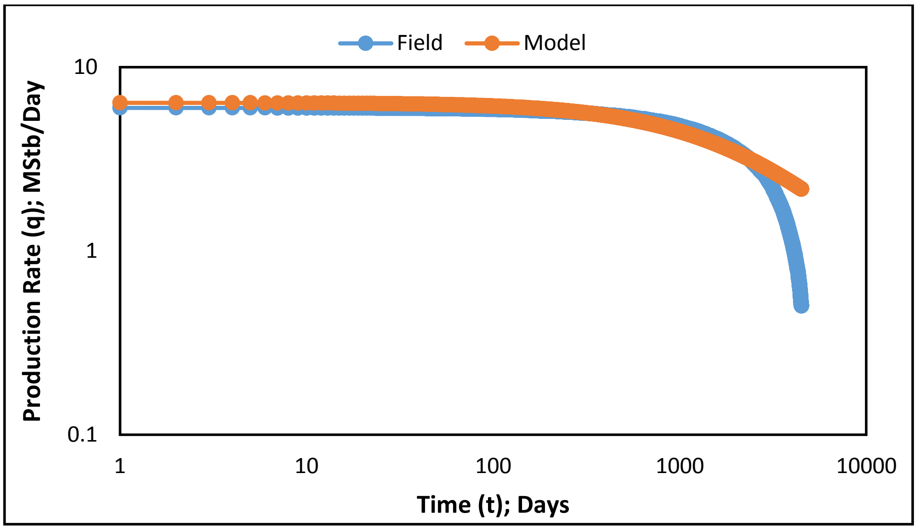

Figure 4: Field and Predicted Oil Production Rate vs. Time Plot (Harmonic Model)

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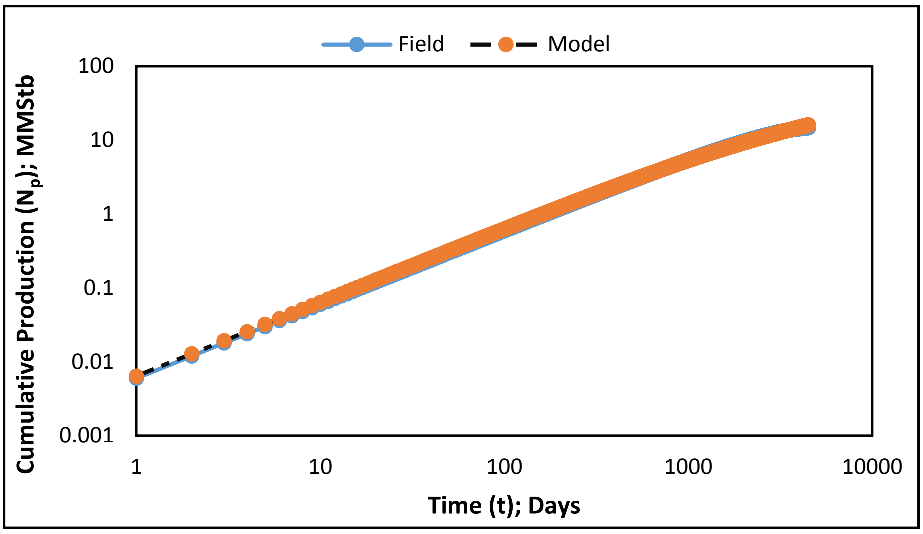

Figure 5: Field and Predicted Cumulative Production vs. Time Plot (Harmonic Model)

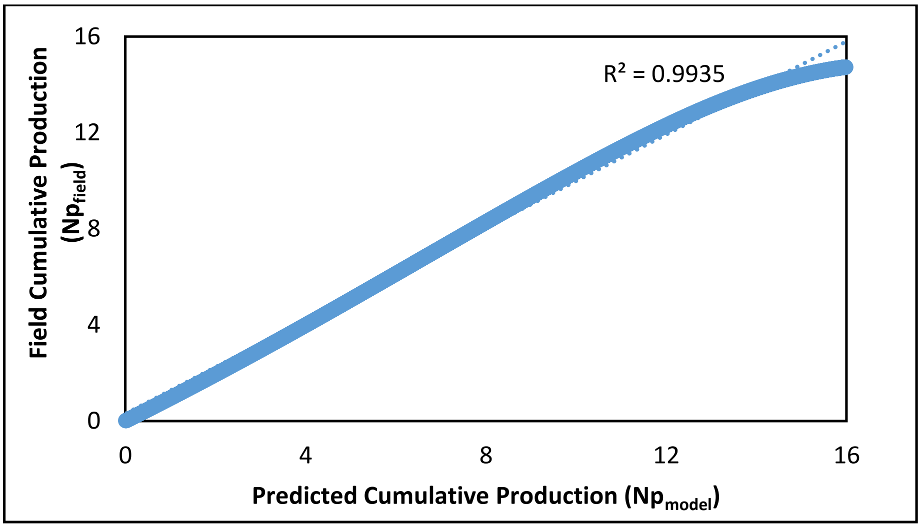

Figure 6: Comparison of Field and Predicted Cumulative Oil Production (Harmonic Model)

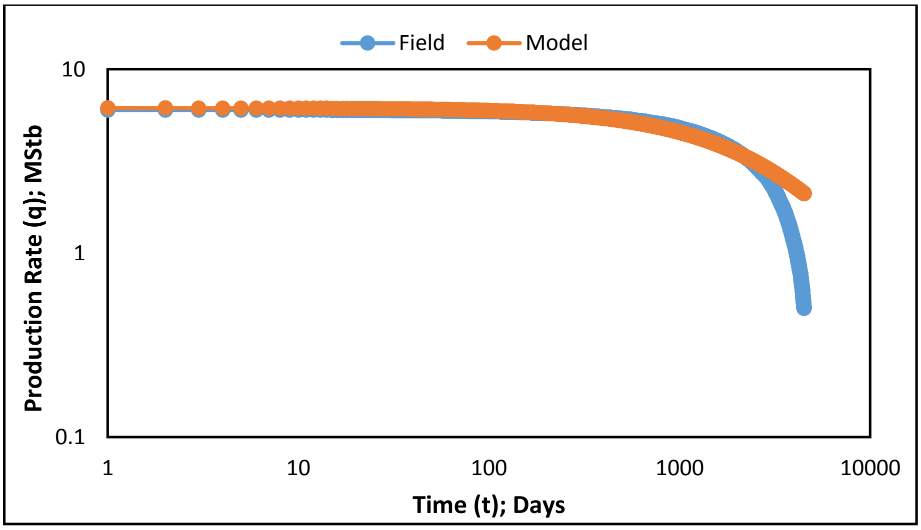

Figure 7: Field and Predicted Oil Production Rate vs. Time Plot (Hyperbolic Model)

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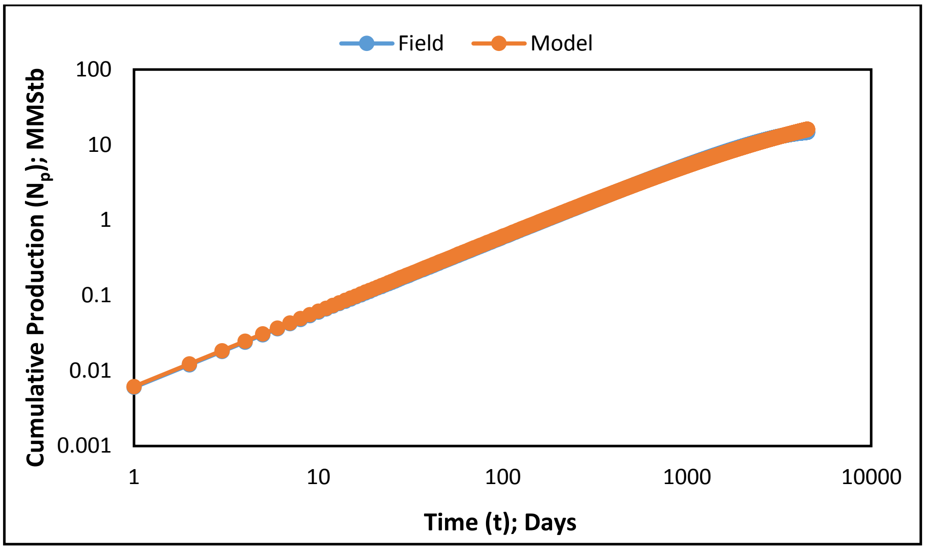

Figure 8: Field and Predicted Cumulative Production vs. Time Plot (Hyperbolic Model)

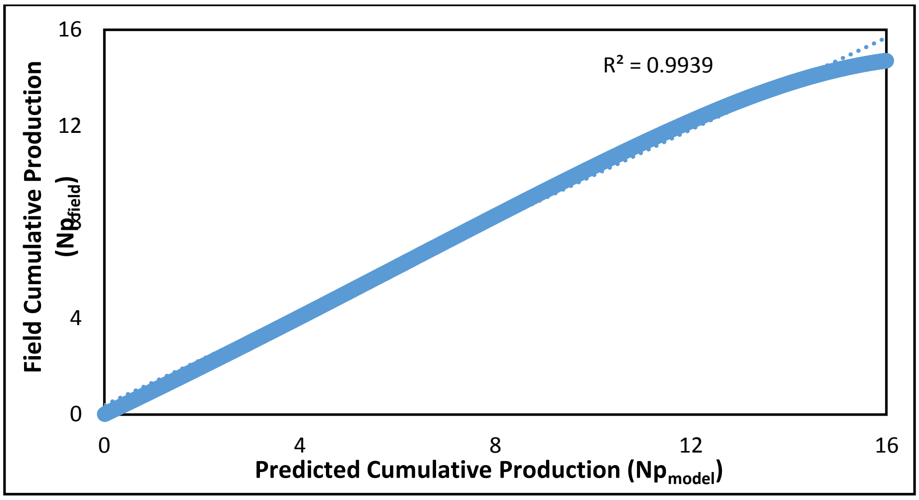

Figure 9: Comparison of Field and Predicted Cumulative Oil Production (Hyperbolic Model)

b. Reciprocal Model

For the fitted production rate decline model based on reciprocal approach, Figures 10 through 12 depicts the obtained results for the comparison of the predicted and field production data. That is, production rate – time relationship and cumulative production – time relationship. The predicted cumulative production of the field "XYZ" from the fitted Reciprocal model resulted in a close alignment with the actual field "XYZ" cumulative production data (Figure 11). However, the predicted production rate in Figure 10 shows slight difference at the early year of production, but later aligns with the actual field production rate data. In this connection, Okon *et al.* (2017) maintained that this is attributed to the reciprocal nature of the modeled production rate data which restrict the flexibility of the model; since the reciprocated production rate data are returned to normal form to compare with the actual field data. This effect is also observed in the comparison of the predicted cumulative production ($N_{P_{model}}$) with the actual field cumulative production ($N_{P_{field}}$) in Figure 12. The disparity at the early predicted production data accounted for the obtained coefficient of determination (r^2) of 0.9883; which is the least among the fitted production rate decline models.

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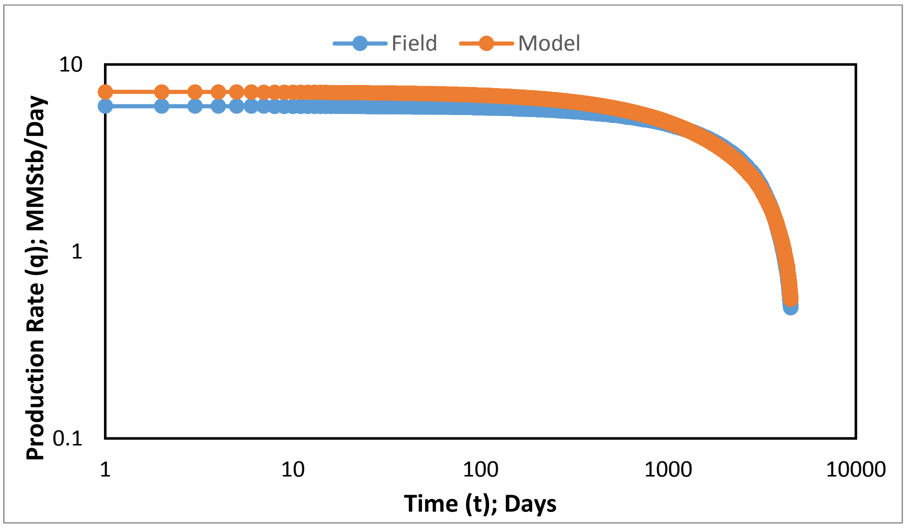

Figure 10: Field and Predicted Oil Production Rate vs. Time Plot (Reciprocal Model)

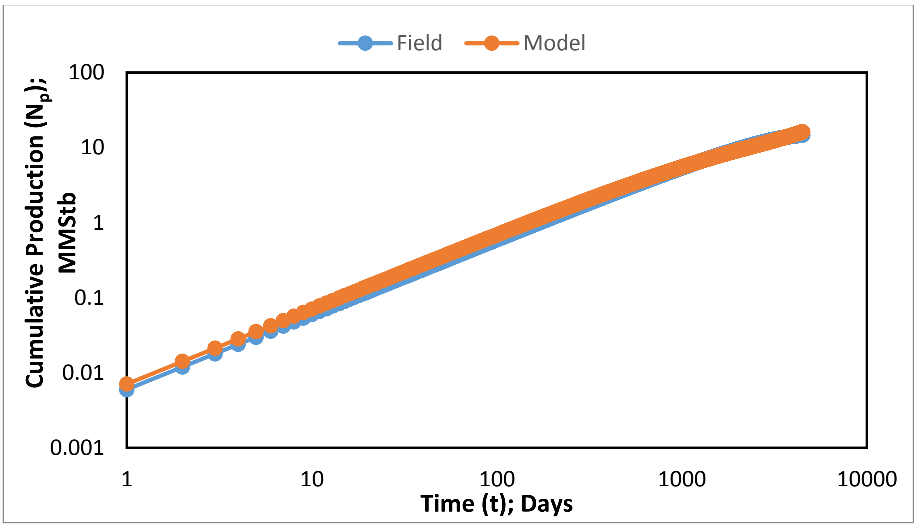

Figure 11: Field and Predicted Cumulative Production vs. Time Plot (Reciprocal Model)

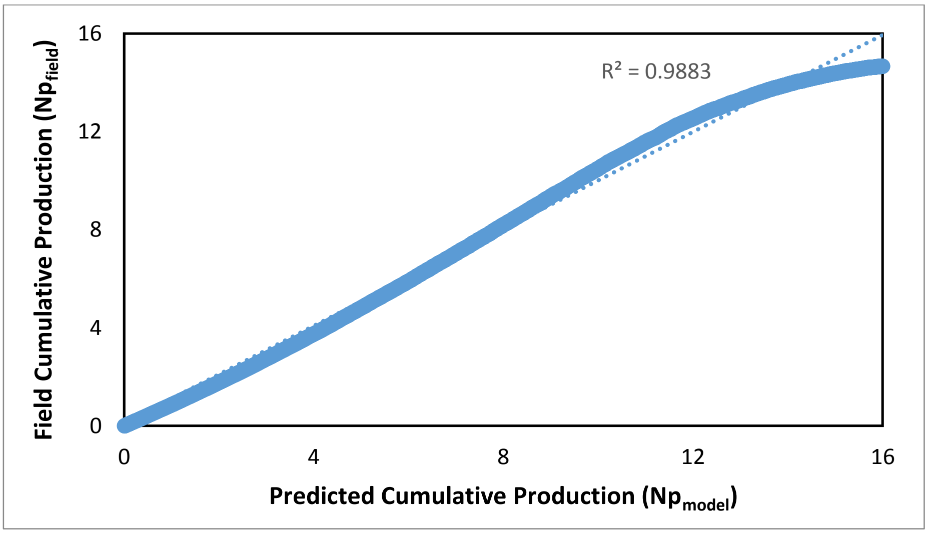

Figure 12: Comparison of Field and Predicted Cumulative Oil Production (Reciprocal Model)

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c. Quadratic Model

Figures 13 through 15 depict the fitted Quadratic model predictions of the "XYZ" field production data. Figure 13 presents the comparison of the predicted production rate ($q_{t_{model}}$) with the actual field production rate ($q_{t_{field}}$). From the Figure, there is a close alignment of the predicted and the actual production data; especially at the early production period of the "XYZ" field. The latter period production prediction shows slight difference between the predicted and actual data; as also noticed with the Arps' models prediction. Interestingly, the fitted model predicted cumulative production aligned closely with the actual field cumulative production; as observed in Figure 14. Thus, the alignment of these data resulted in coefficient of determination (r^2) of about 1.0 (i.e., 0.9998). Additionally, the statistical evaluation of the fitted Quadratic model as presented in Table 5 shows that this model gives a better prediction of the "XYZ" field production performance than the other production rate decline models.

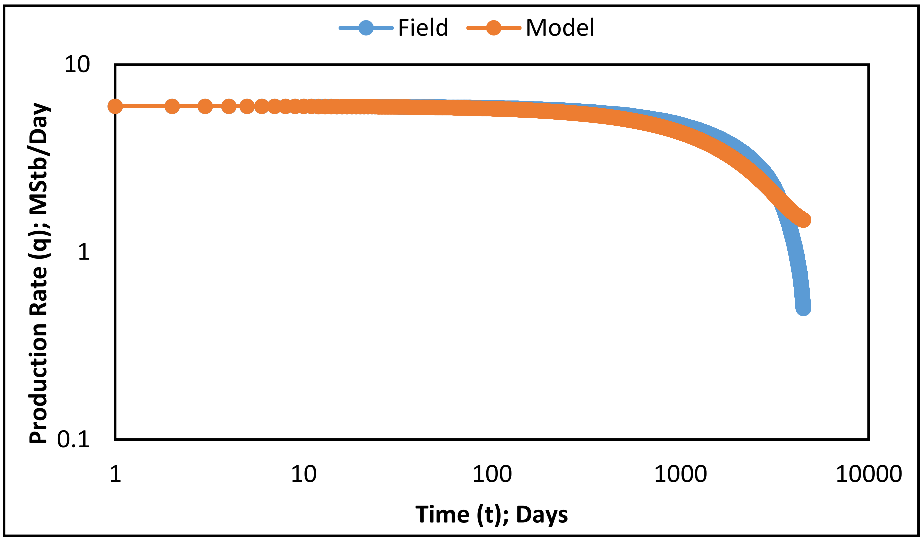

Figure 13: Field and Predicted Oil Production Rate vs. Time Plot (Quadratic Model)

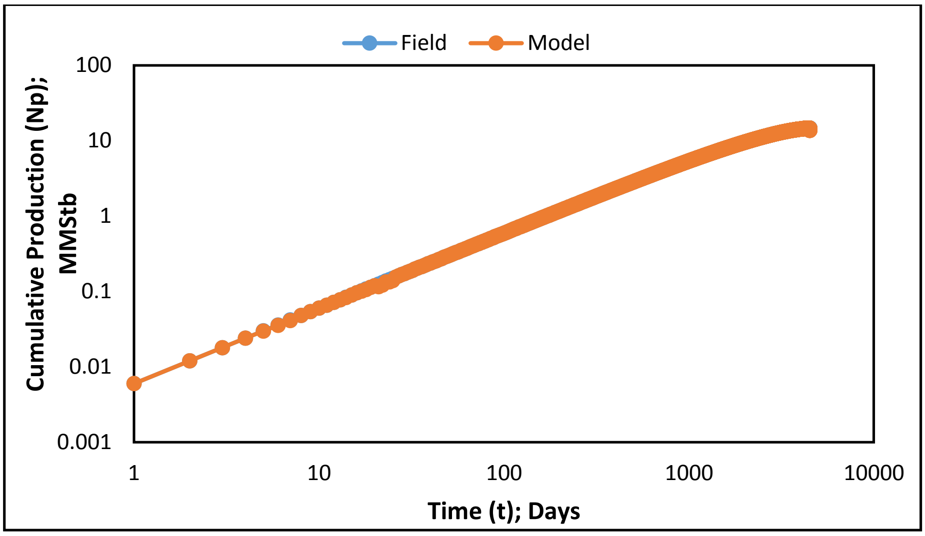

Figure 14: Field and Predicted Cumulative Production vs. Time Plot (Quadratic Model)

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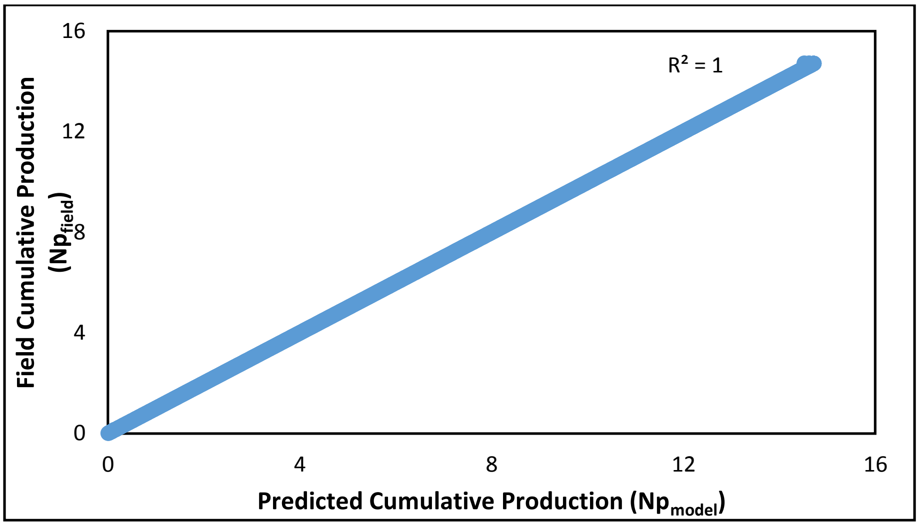

Figure 15: Comparison of Field and Predicted Cumulative Oil Production (Quadratic Model)

Finally, a comparison of all the fitted models' predictions depicted in Figures 1-B and 2-B in Appendix B, indicate that the Arps and Quadratic models have about the same predictions of the field production data for both production rate and cumulative production. The Reciprocal model predictions are very close to the actual field production data at the later year of production than its predictions of the early period of production. Therefore, the fitted Exponential and Quadratic models can be used as a quick tool to predict the production performance of the "XYZ" oil field in the Niger Delta.

4. CONCLUSION

In the petroleum industry, reservoir performance analysis using production rate decline approach has centered on the traditional Arps' models; even the recently propounded reciprocal and quadratic models are not left out. However, no available literature has fitted these models to evaluate their prediction capabilities of oil field(s) in the Niger Delta. Therefore, this paper compares the potential of the fitted production rate decline models based on production data obtained from the 'XYZ' oil field in Niger Delta and the following conclusions were drawn:

i. the established decline constants (D_i) of the various models: Exponential, Harmonic, Hyperbolic, Reciprocal and Quadratic are 0.000353day^{-1}, 0.000434day^{-1}, 0.000332day^{-1}, 0.000403day^{-1} and 0.000189day^{-1} respectively for the 'XYZ' oil field in the Niger Delta;

ii. the Arps' models predicted the 'XYZ' oil field performance with an absolute error, standard deviation and coefficient of determination of -0.0089, 0.4433 and 0.9991 for Exponential, -0.0011, 0.4455 and 0.9935 for Harmonic and 0.0005, 0.4460 and 0.9939 for Hyperbolic;

iii. the fitted Reciprocal model prediction of the oil field production performance with an absolute error, standard deviation and coefficient of determination of -0.0136, 0.4452 and 0.9883 respectively; and

iv. the Quadratic model accurately predicted the field production history with an absolute error, standard deviation and coefficient of determination of 0.0001, 0.4460 and 0.9998, respectively. In lieu of the established coefficient of determination, the quadratic and exponential models can be used as quick and robust tools to predict the 'XYZ' oil field performance in the Niger Delta.

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APPENDIX A

The equations used to perform the statistical analysis of the fitted models' prediction and field cumulative production:

1. Average Error:

$$E_{avg} = \frac{1}{n}\sum_{i=1}^{n}\frac{N_{p_{field}} - N_{p_{model}}}{N_{p_{field}}} \qquad \text{1-A}$$

2. Absolute Error:

$$E_{abs} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{N_{p_{field}} - N_{p_{model}}}{N_{p_{field}}}\right| \qquad \text{2-A}$$

3. Root Mean Square Error:

$$E_{rms} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{N_{p_{field}} - N_{p_{model}}}{N_{p_{field}}}\right)^2 \qquad \text{3-A}$$

4. Coefficient of Determination:

$$r^2 = 1 - \frac{\sum_{i=1}^{n}\left(N_{p_{field}} - N_{p_{model}}\right)^2}{\sum_{i=1}^{n}\left(N_{p_{field}} - \overline{N}_{p_{model}}\right)^2} \qquad \text{4-A}$$

5. Standard Deviation:

$$S_D = \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(\frac{N_{p_{field}} - N_{p_{model}}}{N_{p_{field}}}\right)^2 - \sum_{i=1}^{n}\left(\frac{N_{p_{field}} - \overline{N}_{p_{model}}}{N_{p_{field}}}\right)^2} \qquad \text{5-A}$$

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6. Normalized Standard Deviation

$$NS_D = 100\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{N_{p_{field}} - N_{p_{model}}}{N_{p_{field}}}\right)^2} \qquad \text{6-A}$$

where:

$N_{p_{field}}$ = *Field Cumulative Production*

$N_{p_{model}}$ = *Predicted Cumulative Production*

n = *Total Number Field Production Data*

$\overline{N}p_{model}$ = *Average Predicted Cumulative Production*

APPENDIX B

Comparison of all the fitted models' predictions with the actual field production data of the "XYZ" field in Niger Delta:

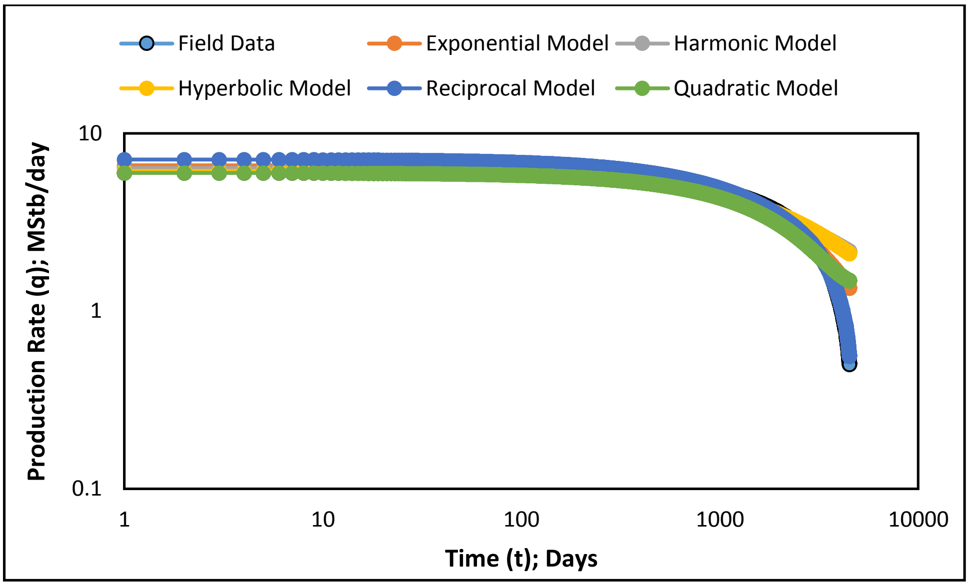

Figure 1-B: Comparison of Field and Predicted Production Rate (All Models)

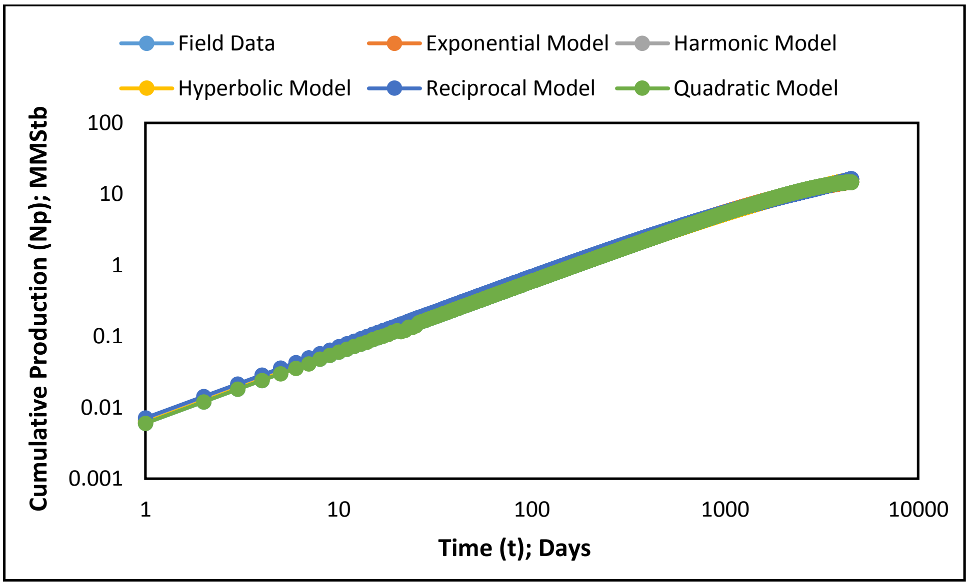

Figure 2-B: Comparison of Field and Predicted Cumulative Production (All Models)

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