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A dry gas material balance with an infinite aquifer influence: A comparative study between the unsteady state model of van Everdingen-Hurst and analytical model

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Aquifer water influx is an important natural mechanism for primary recovery. It affects the performance of all types of reservoirs, also natural gas reservoirs. Water influx provides pressure support during reservoir depletion, resulting in slower pressure decline. Consequently, gas reservoirs associated with large aquifers show a flattening, cubic behavior of the p/z vs. G_p curve, which allowed the development of the present analytical model. For modelling of water influx into a reservoir, classical models have been developed by many authors. Among the classical models, the unsteady state method of van Everdingen-Hurst was selected to be used in this work, as this is the best suited in terms of solving the diffusivity equation. In order to use the analytical model for comparative purposes, there was a need of calibrating the two unknown parameters, α and β, appearing in the water influx equation. In this work, two workflows were presented for computing water influx in a comparative manner between the unsteady state model of van Everdingen-Hurst and the analytical model. The results showed that the correlation between both models depends on the two unknown parameters, α and β.

Key words: Infinite aquifer, dry gas material balance, cubic cumulative model, water influx.

INTRODUCTION

Most hydrocarbon reservoirs are surrounded by aquifers. Aquifers may in some cases be significantly greater than the gas reservoir, ranging from infinite in size to less than insignificant, with corresponding large to negligible effect on the reservoir performance (Ahmed, 2005).

In reservoirs adjoined by water aquifers, water drive may be the primary production mechanism. In these reservoirs, the production of hydrocarbons causes a pressure drop in the hydrocarbon/water interface. Due to this pressure drop, a pressure differential develops from the surrounding aquifer into the reservoir. Thus, the aquifer reacts by encroaching across the original hydrocarbon-water contact, filling the reservoir pore spaces (Feng et al., 2015).

The invasion of reservoir rock by aquifer water may have a significant impact on reservoir performance.

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Therefore, water influx into hydrocarbon reservoir must be accurately predicted (Shimada, 2009).

In order to calculate the amount of encroaching water influx, mathematical models (Ahmed, 2005) have been developed by different authors, where the following four models stand out: Schilthuis steady state, van Everdingen and Hurst unsteady state, Carter-Tracy unsteady state and Fetkovich pseudosteady state.

Over the years, water influx models have been improved, Agarwal (1967) presented an analytical simplified model for the material balance of gas reservoir experiencing water influx, further improved and presented by Zonoozi and Blansigame (Blansigame and Zonoozi, 2005).

To use Agarwal's model for computing water influx is a challenging task. There is a need of calibrating the unknown parameters α and β for a specific data set. The Agarwal water influx model was further developed in this work, to match the reservoir's historical production and pressure data when incorporated in the material balance for dry gas reservoirs.

The correct identification of reservoir drive mechanism is crucial in arriving at an accurate estimate of in-place volumes (Alattar, 2009). Ignoring the possibility of water influx can lead to a significant over-estimation of gas initially in place (Istiak et al., 2016). For that reason, correct estimation of gas initialy in place (GIIP) is very crucial for reservoir management and decision-making for field development (Istiak et al., 2016).

The general objective of this work is to analyse the correlation between the van Everdingen and Hurst model and cubic cumulative production model hereafter considered as analytical model.

LITERATURE REVIEW

All classical aquifer models are the solutions for diffusivity equation. Accurate estimations of cumulative water influx into gas reservoirs are very crucial for material balance computations in water drive gas reservoirs. In literature, there are several classical aquifer models. Based on that the unsteady state method of van Everdingen-Hurst was selected, among the classical models, to be used in this work, as this is the best suited in terms of solving the diffusivity equation [11],[12].

The analytical model, developed by Agarwal (1967) allows a direct computation of the cumulative water influx.

van Everdingen and Hurst unsteady-state model

The model presented by van Everdingen and Hurst (1949) deals with two types of aquifers: radial and linear. Applying the Laplace transformation, van Everdingen and Hurst solved the diffusivity equation of the reservoir-aquifer system considering as boundary condition a constant terminal pressure (CTP) in the boundary (Alattar, 2009). The final form of the CTP solution is written as:

$$W_e = U \Delta P W_D \left(t_D \right) \quad (1)$$

where U is the influx constant of water into the aquifer, in bbl/psia, represented by Equation 2:

$$U = 1.119 f \phi h c_t r_g^2 \quad (2)$$

W_e is the cumulative water influx due to a pressure drop ΔP (psia) imposed at the reservoir radius r_g, at time t = 0, in bbls, $W_D(t_D)$ is a dimensionless water influx function, *f* is the relative encroachment angle ($^o/360^o$), ϕ is the aquifer porosity fraction, c_t is the total aquifer compressibility in psia^{-1}, and t_D is the dimensionless time (Marques and Trevisan, 2007).

$$t_D = \frac{2.309 kt}{\phi \mu c_t r_g^2} \quad (3)$$

The dimensionless water influx $W_D(t_D)$ is presented in tabular form or as a set of polynomial expressions giving W_D as a function of t_D for a range of ratios of the aquifer to reservoir radius. In this work, the polynomial approach proposed by Edwardson et al. (1962) is used and found much easier to deal with than the look up tables or charts that may sometimes require interpolations. The proposed polynomial equations proposed by Edwardson essentially approximate the W_D data in three dimensionless time regions (Ahmed, 2005).

(a) For $t_D < 0.01$:

$$W_{eD} = \sqrt{\frac{t_D}{\pi}} \quad (4)$$

(b) For 0.01 < tD < 200:

$$W_{eD} = \frac{\left(1.2838\sqrt{t_D} + 1.19328 t_D + 0.269872 (t_D)^{3/2} + 0.00855294 (t_D)^2\right)}{\left(1 + 0.616599\sqrt{t_D} + 0.0413008 t_D\right)} \quad (5)$$

(c) For tD > 200

$$W_{eD} = \frac{-4.29881 + 2.02566 t_D}{\ln\left(t_D\right)} \quad (6)$$

New p/Z-G_p^3 cubic cumulative production model for the water influx

The cubic cumulative model proposed by Agarwal (1967) is a simplified model for the material balance of gas reservoirs experiencing water influx.

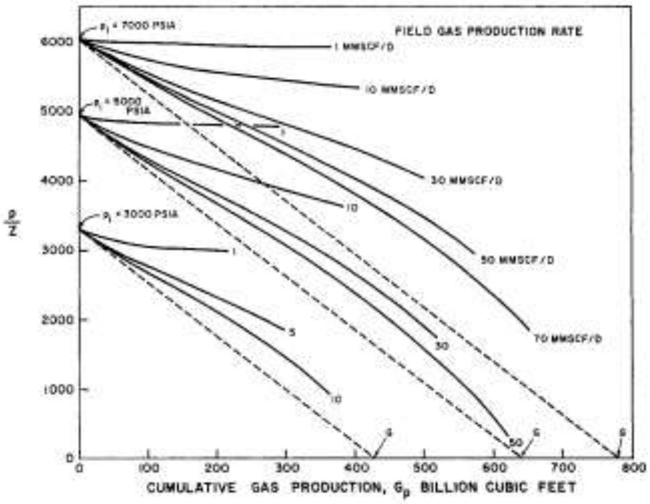

Figure 1. p/z vs Gp Cubic behavior, Agarwal (1967)

This analytical model is based on cubic behavior of the relationship between p/z vs G_p curve as indicated in Figure 1.

Eliminating the abnormal pressure, water production/ injection, and gas injection terms in the general material balance of a dry gas reservoir system and after some mathematical adjustments, it gave the following definition (Blansigame and Zonoozi, 2005):

$$\frac{p}{Z} = \frac{p_i}{Z_i} \frac{1}{\left[1 - \frac{W_e B_w}{G B_{gi}}\right]} \left[1 - \frac{G_p}{G}\right] \tag{8}$$

To validate the cubic behavior of p/Z vs. G_p performance, we consider the behavior of the “water influx” term:

$$\frac{1}{\left[1 - \frac{W_e B_w}{G B_{gi}}\right]} \text{ Versus } \frac{G_p}{G}$$

Thus, the “water influx” term can be written in the form:

$$\frac{1}{\left[1 - \frac{W_e B_w}{G B_{gi}}\right]} = \left[1 + \alpha\left(\frac{G_p}{G}\right) + \beta\left(\frac{G_p}{G}\right)^2\right] \tag{9}$$

Substituting the water influx term from Equation 9 into the gas material balance in Equation 8, we obtain:

$$\frac{p}{Z} \approx \frac{p_i}{Z_i}\left[1 - (1-\alpha)\left(\frac{G_p}{G}\right) + (\beta - \alpha)\left(\frac{G_p}{G}\right)^2 - \beta\left(\frac{G_p}{G}\right)^3\right] \tag{10}$$

One possible benefit of the cubic material balance formulation is the algebraic manipulation of the p/Z – G_p^3 model to yield a direct calculation of the water influx function (W_e) (Blansigame and Zonoozi, 2005):

$$W_e = \frac{G B_{gi}}{B_w}\left[1 - \frac{1}{\left[1 - (1-\alpha)\left(\frac{G_p}{G}\right) + (\beta - \alpha)\left(\frac{G_p}{G}\right)^2 - \beta\left(\frac{G_p}{G}\right)^3\right]}\right]\left[1 - \frac{G_p}{G}\right] \tag{11}$$

Applying this calculation requires that the p/Z-G_p^3 expression be calibrated to get α and β to a specific data set. The calibration will be done using a subroutine for solver function and also using a tool for data analysis called type curve solution.

Havlena and Odeh interpretation

Neglecting water expansion and pore compaction, the material balance equation for gas reservoirs subjected to water influx can be expressed as Alattar (2009):

$$\frac{F}{E_g} = G + \frac{W_e B_w}{E_g} \tag{12}$$

where the terms F and E_g is defined by:

(1) Underground Fluid withdrawal F:

$$F = G_p B_g + W_p B_w \tag{13}$$

(2) Gas expansion E_g:

$$E_g = B_g - B_{gi} \tag{14}$$

Using the production, pressure and PVT data, the left side of expression (Equation 12) should be plotted as a function of cumulative gas production, G_p. This is simply for display purposes to inspect its variation during depletion. If the reservoir is affected by natural water influx, the plot of F/E_g will usually produce concave downward shaped arc whose exact from is dependent upon the aquifer size and strength (Alattar, 2009).

Equation 12 can be interpreted as a linear function. Once a straight line has been achieved, based on matching observed production and pressure data, it shows that a suitable mathematical model to describe the performance of the reservoir has been found (Dake, 2001) and the interception in ordinate axis gives us the value of GIIP.

MATERIALS AND METHODS

In this work, we will consider an edge infinite acting aquifer with

Table 1. Superposition matrix for water influx calculation (time vs. pressure steps).

Time step	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Δp_1	W_{D1}	W_{D2}	W_{D3}	W_{D4}	W_{D5}	W_{D6}	W_{D7}	W_{D8}	W_{D9}	W_{D10}	W_{D11}	W_{D12}	W_{D13}	W_{D14}	W_{D15}	W_{D16}	$W_{D..}$
Δp_2		W_{D1}	W_{D2}	W_{D3}	W_{D4}	W_{D5}	W_{D6}	W_{D7}	W_{D8}	W_{D9}	W_{D10}	W_{D11}	W_{D12}	W_{D13}	W_{D14}	W_{D15}	$W_{D..}$
Δp_3			W_{D1}	W_{D2}	W_{D3}	W_{D4}	W_{D5}	W_{D6}	W_{D7}	W_{D8}	W_{D9}	W_{D10}	W_{D11}	W_{D12}	W_{D13}	W_{D14}	$W_{D..}$
Δp_4				W_{D1}	W_{D2}	W_{D3}	W_{D4}	W_{D5}	W_{D6}	W_{D7}	W_{D8}	W_{D9}	W_{D10}	W_{D11}	W_{D12}	W_{D13}	$W_{D..}$
Δp_5					W_{D1}	W_{D2}	W_{D3}	W_{D4}	W_{D5}	W_{D6}	W_{D7}	W_{D8}	W_{D9}	W_{D10}	W_{D11}	W_{D12}	$W_{D..}$
Δp_6						W_{D1}	W_{D2}	W_{D3}	W_{D4}	W_{D5}	W_{D6}	W_{D7}	W_{D8}	W_{D9}	W_{D10}	W_{D11}	$W_{D..}$
Δp_7							W_{D1}	W_{D2}	W_{D3}	W_{D4}	W_{D5}	W_{D6}	W_{D7}	W_{D8}	W_{D9}	W_{D10}	$W_{D..}$
Δp_8								W_{D1}	W_{D2}	W_{D3}	W_{D4}	W_{D5}	W_{D6}	W_{D7}	W_{D8}	W_{D9}	$W_{D..}$
Δp_9									W_{D1}	W_{D2}	W_{D3}	W_{D4}	W_{D5}	W_{D6}	W_{D7}	W_{D8}	$W_{D..}$
Δp_{10}										W_{D1}	W_{D2}	W_{D3}	W_{D4}	W_{D5}	W_{D6}	W_{D7}	$W_{D..}$
Δp_{11}											W_{D1}	W_{D2}	W_{D3}	W_{D4}	W_{D5}	W_{D6}	$W_{D..}$
Δp_{12}												W_{D1}	W_{D2}	W_{D3}	W_{D4}	W_{D5}	$W_{D..}$
Δp_{13}													W_{D1}	W_{D2}	W_{D3}	W_{D4}	$W_{D..}$
Δp_{14}														W_{D1}	W_{D2}	W_{D3}	$W_{D..}$
Δp_{15}															W_{D1}	W_{D2}	$W_{D..}$
Δp_{16}																W_{D1}	$W_{D..}$
$\Delta p_{..}$																	$W_{D..}$

radial flow. The data used is from an unknown field, and adopted from Dake (2001) to be used for the two comparative models.

van Everdingen-Hurst model

The unsteady state model of van Everdingen-Hurst is the most accurate method for predicting water influx. It gives results near to what can be obtained by having real field data (Ahmed, 2005).

Computing water influx using van Everdingen and Hurst, is obtained through the following steps (Agarwal, 1967; Ahmed, 2005; Alattar, 2009):

Step 1: Determine the water influx constant U or B [bbl/psi], using Equation 2.
Step 2: Calculate the corresponding dimensionless time, for each time period, using Equation 3.
Step 3: Determine the dimensionless water influx W_{eD} or W_D, using Edwardson expression, Equations 4, 5 and 6.
Step 4: Calculate the cumulative water influx [bbl], using Equation 1.

In calculating the cumulative water influx into a reservoir at successive intervals, it is necessary to calculate the total water influx from the beginning.

The pressure drop Δp, for each time step is calculated using Timmerman and McMahon approximation (Dake, 2001).

The van Everdingen and Hurst model uses the superposition principle for computing water influx.

Therefore, to calculate the cumulative water influx W_e at some arbitrary time t, which corresponds to the end of the n^{th} time step, requires superposition of the solutions of, Equation 1, to give:

$$W_e(t) = B\big[\Delta P_o W_D(t_D) + \Delta P_1 W_D(t_D - t_{D1}) + \cdots + \Delta P_j W_D\big(t_D - t_{Dj}\big) + \cdots + \Delta P_{n-1} W_D(t_D - t_{Dn-1})\big]$$

This means that the complex expression for Equation 1, can simply be evaluated as the scaler or dot product, presented in Table 1.

Finally, the cumulative water influx for each time step using matrix form is calculated by:

$$W_e = B\sum \Delta p W_D \tag{15}$$

New p/Z-G_p^3 cubic cumulative production model for the water influx

Computing water influx using the cubic cumulative model of Agarwal, is obtained through the following steps (Agarwal, 1967; Ahmed, 2005; Alattar, 2009; Blansigame and Zonoozi, 2005):

Step 1: Verification of quadratic behavior of p/Z vs. G_p, presented in Equation 9.
Step 2: Calibrate the two unknown parameters, α and β, using type curve or solver solution.

Type curve solution

The type curve [5] solution will be used to help in calibration to get α and β.

(a) Observed data is plotted using an appropriate format: Using the observed data, we plot a graph P_D vs G_p/G using the Equations 17 and 18. The calibration is done using the type curve solution and also by a subroutine developed for solver function.
(b) A "match" is found between observed data and a dimensionless solution by sliding the data plot over the type curve plot. In this step, different combination for α and β is done. The best values is considered as the good match between observed data a dimensionless solution acquired using Equation 19.
(c) The "match" is used to determine model parameters for the observed data.

For that, the p/Z-G_p^3 in Equation 10 can be rearranged to yield:

$$\left[1-\frac{p}{Z}\frac{Z_i}{p_i}\right] \approx \left[(1-\alpha)\left(\frac{G_p}{G}\right) - (\beta-\alpha)\left(\frac{G_p}{G}\right)^2 + \beta\left(\frac{G_p}{G}\right)^3\right] \tag{16}$$

Table 2. Superposition matrix, for water influx calculation.

Pressure drop/Time step		0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.25	3.50	3.75	4.00	4.25	4.50	…
Δp_1	61.99	160.89	252.90	332.83	406.30	475.53	541.67	605.42	667.25	727.47	786.33	844.01	900.65	956.38	1011.27	1065.42	1118.89	1171.73	1224.00	…
Δp_2	120.59		312.99	491.98	647.49	790.42	925.09	1053.76	1177.78	1298.05	1415.21	1529.72	1641.93	1752.12	1860.53	1967.32	2072.66	2176.68	2279.48	…
Δp_3	110.65			287.19	451.43	594.11	725.26	848.83	966.89	1080.69	1191.04	1298.54	1403.61	1506.57	1607.68	1707.15	1805.14	1901.80	1997.24	…
Δp_4	111.57				289.56	455.15	599.02	731.25	855.84	974.87	1089.61	1200.88	1309.27	1415.20	1519.01	1620.96	1721.25	1820.05	1917.50	…
Δp_5	116.10					301.32	473.65	623.36	760.96	890.62	1014.49	1133.89	1249.68	1362.47	1472.71	1580.74	1686.83	1791.20	1894.01	…
Δp_6	108.38						281.29	442.15	581.91	710.36	831.39	947.03	1058.49	1166.58	1271.87	1374.78	1475.62	1574.66	1672.08	…
Δp_7	103.72							269.18	423.12	556.86	679.79	795.61	906.27	1012.94	1116.38	1217.14	1315.62	1412.12	1506.89	…
Δp_8	103.67								269.05	422.92	556.60	679.47	795.24	905.84	1012.46	1115.85	1216.56	1314.99	1411.45	…
Δp_9	98.63									255.98	402.38	529.56	646.46	756.61	861.84	963.28	1061.65	1157.46	1251.12	…
Δp_{10}	90.20										234.11	368.00	484.32	591.23	691.96	788.21	880.97	970.94	1058.57	…
Δp_{11}	85.03											220.68	346.89	456.53	557.31	652.26	742.99	830.43	915.23	…
Δp_{12}	83.21												215.95	339.45	446.75	545.36	638.28	727.06	812.63	…
Δp_{13}	81.35													211.13	331.87	436.76	533.18	624.02	710.81	…
Δp_{14}	77.71														201.68	317.01	417.21	509.31	596.09	…
Δp_{15}	74.68															193.82	304.66	400.96	489.47	…
Δp_{16}	72.48																188.10	295.68	389.13	…
Δp_{17}	70.56																	183.13	287.86	…
Δp_{18}	74.72																		193.92	…
…	…																			…

Defining: Dimensionless pressure and dimensionless cumulative gas produced as:

$$p_D \approx \left[1 - \frac{p}{Z}\frac{Z_i}{p_i}\right] \quad (17)$$

$$G_{pD} \approx \left[\frac{G_p}{G}\right] \quad (18)$$

Which yields the final dimensionless form:

$$p_D \approx (1-\alpha)G_{pD} - (\beta-\alpha)G^3{}_{pD} + \beta G^3{}_{pD} \quad (19)$$

Step 3: Calculate the cumulative water influx [bbl], using Equation 11.

RESULTS AND DISCUSSION

Water influx using the van Everdingen and Hurst model

The pressure drop Δp, for each time step is calculated using van Everdingen, Timmerman and McMahon (Ahmed, 2005) approximation.

For dimensionless water influx W_D, we used the Edwardson et al. (1962) polynomial expressions, presented in Equations 4, 5 and 6.

Thus, we get the dimensionless time t_D, pressure drop Δp and dimensionless water influx W_D. Then, we elaborate the superposition matrix presented in Table 2.

The water influx for each time step is given by Equation 1. The results of computation of water influx are presented in Table 3.

Water influx using the cubic cumulative model

First, we prove the quadratic behavior presented in Equation 9. This is as shown in Figure 2. This gives us Equation 9 in the following form:

$$\frac{1}{\left[1 - \frac{W_e B_w}{G B_{gi}}\right]} = 0.1753\left(\frac{G_p}{G}\right)^2 + 0.0128\left(\frac{G_p}{G}\right) + 1.0012 \quad (20)$$

This relation proves the quadratic behavior of Equation 9. The values of α and β needs to be calibrated in order to compute the water influx by using Equation 11.

In order to use Equation 11 to computer water influx, there is a need of calibrating the cubic cumulative model ($p/z - G_p^3$).

Table 3. Water influx for each time step.

Time t (Years)	Dimensionless Time, t_D	Reservoir Pressure Pr (Psia)	Pressure Decrement Δp (psia)	Dimensionless Water Influx W_D	Water Influx We (MMrb)
	-	4,090.00			0.00
0.25	2.05	3,966.02	61.99	2.595	1.95
0.5	4.09	3,848.81	120.59	4.080	5.44
0.75	6.14	3,744.71	110.65	5.369	9.18
1	8.18	3,625.68	111.57	6.554	14.58
1.25	10.23	3,512.51	116.10	7.671	22.24
1.5	12.28	3,408.92	108.38	8.738	30.38
1.75	14.32	3,305.08	103.72	9.766	39.35
2	16.37	3,201.58	103.67	10.764	49.16
2.25	18.42	3,107.82	98.63	11.735	61.10
2.5	20.46	3,021.17	90.20	12.685	74.10
2.75	22.51	2,937.76	85.03	13.615	84.90
3	24.55	2,854.76	83.21	14.529	99.41
3.25	26.60	2,775.06	81.35	15.428	116.15
3.5	28.65	2,699.35	77.71	16.313	134.41
3.75	30.69	2,625.71	74.68	17.187	149.84
4	32.74	2,554.39	72.48	18.050	166.31
4.25	34.79	2,484.58	70.56	18.902	182.71
4.5	36.83	2,404.96	74.72	19.745	201.16
4.75	38.88	2,323.46	80.56	20.580	219.17
5	40.92	2,241.88	81.54	21.406	236.22
5.25	42.97	2,165.70	78.88	22.225	256.40
5.5	45.02	2,093.18	74.35	23.037	277.42
5.75	47.06	2,026.30	69.70	23.843	295.71
6	49.11	1,966.36	63.41	24.642	315.84
6.25	51.16	1,904.20	61.05	25.435	337.84
6.5	53.20	1,838.56	63.90	26.223	358.58
6.75	55.25	1,772.97	65.62	27.006	375.14
7	57.29	1,700.85	68.86	27.783	393.69
7.25	59.34	1,644.98	64.00	28.556	412.61
7.5	61.39	1,596.83	52.01	29.324	429.67
7.75	63.43	1,548.80	48.09	30.088	443.54

The calibration is done using type curve solution and also by a subroutine developed for solver function.

Type curve solution

The type curve solution, presented in Figure 3, gives a better match for combination of α and β, as illustrated in Table 4.

Solver function

A subroutine using VBA-Visual Basic for Applications-2013 was developed for a solver function, in order to get the best approximation values for α and β as illustrated in Table 5.

The 2 (two) presented workflows allows the computation of water influx using the van Everdingen-Hurst and the cubic cumulative production model of Agarwal. The comparison of results is illustrated in Figure 4.

The results demonstrate clearly that the correlation between both methods depends on the calibration of the two unknown parameters α and β, appearing in the cubic cumulative model (Blansigame and Zonoozi, 2005).

Under this assumption the cubic cumulative production model with an approximation values of α =0.020573 and β =0.173889, results in a perfect match between the van Everdingen-Hurst model. Using this approximation for the unknown parameters α and β, the Havlena-Odeh (Dake, 2001) plot method in history matching, was perfomed and reservoir-aquifer performance is as shown in Figure 5.

The full Havlena and Odeh, from Equation 12, illustrated

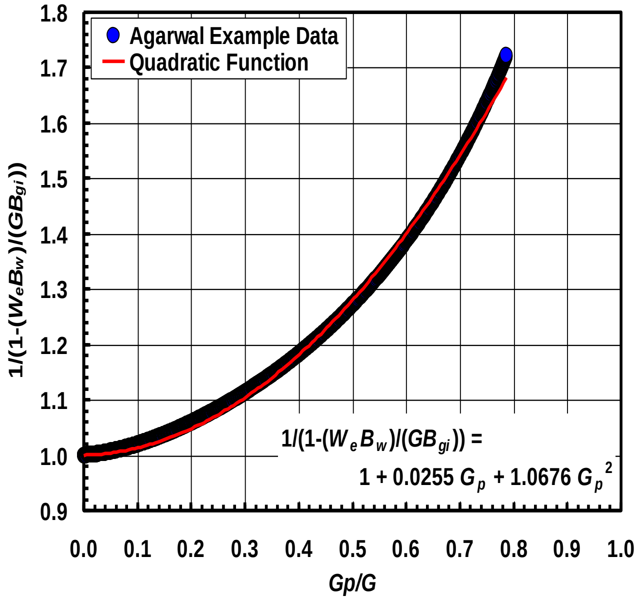

Figure 2. Quadratic behavior of "Water Influx" vs. G_p/G. Blansigame and Zonoozi (2005)

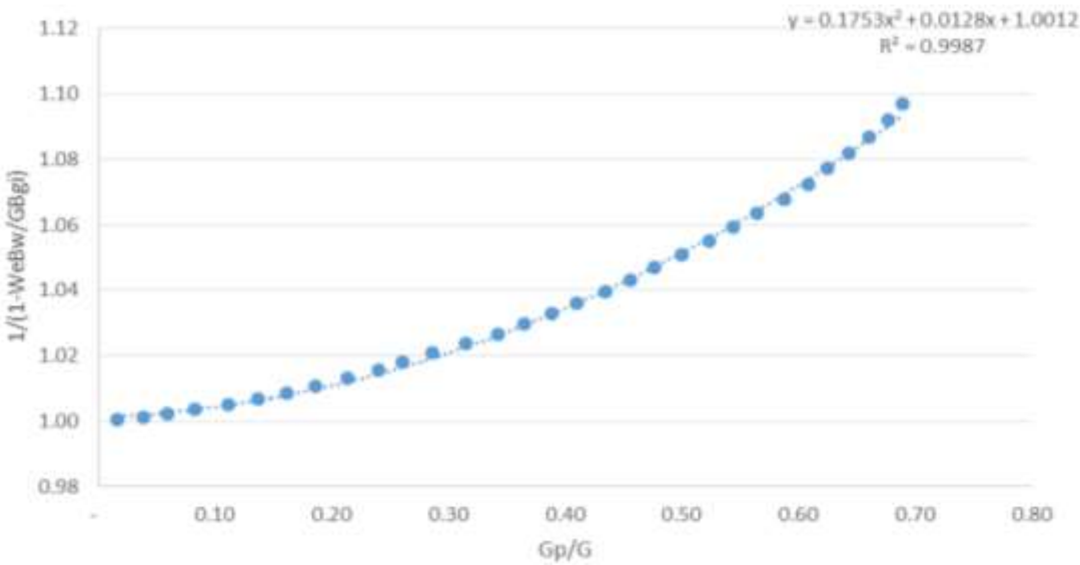

Figure 3. Approximation proof (Quadratic Behavior).

Table 4. Values of α and β using type curve solution.

Approximation	α	β
I	0.055447	0
II	0.00069	0.201177
III	0.10636	0.22986
IV	0.25	0
V	0.01008	0.166654

Table 5. Values of α and β using solver function. (by the Author: using VBA Code-2013 in Esxel spreadsheet).

Approximation	α	β
I	0.010086	0.166654
II	0	0.203711
III	0.015164	0.147997
IV	0.00069	0.201177
V	0.020573	0.173889

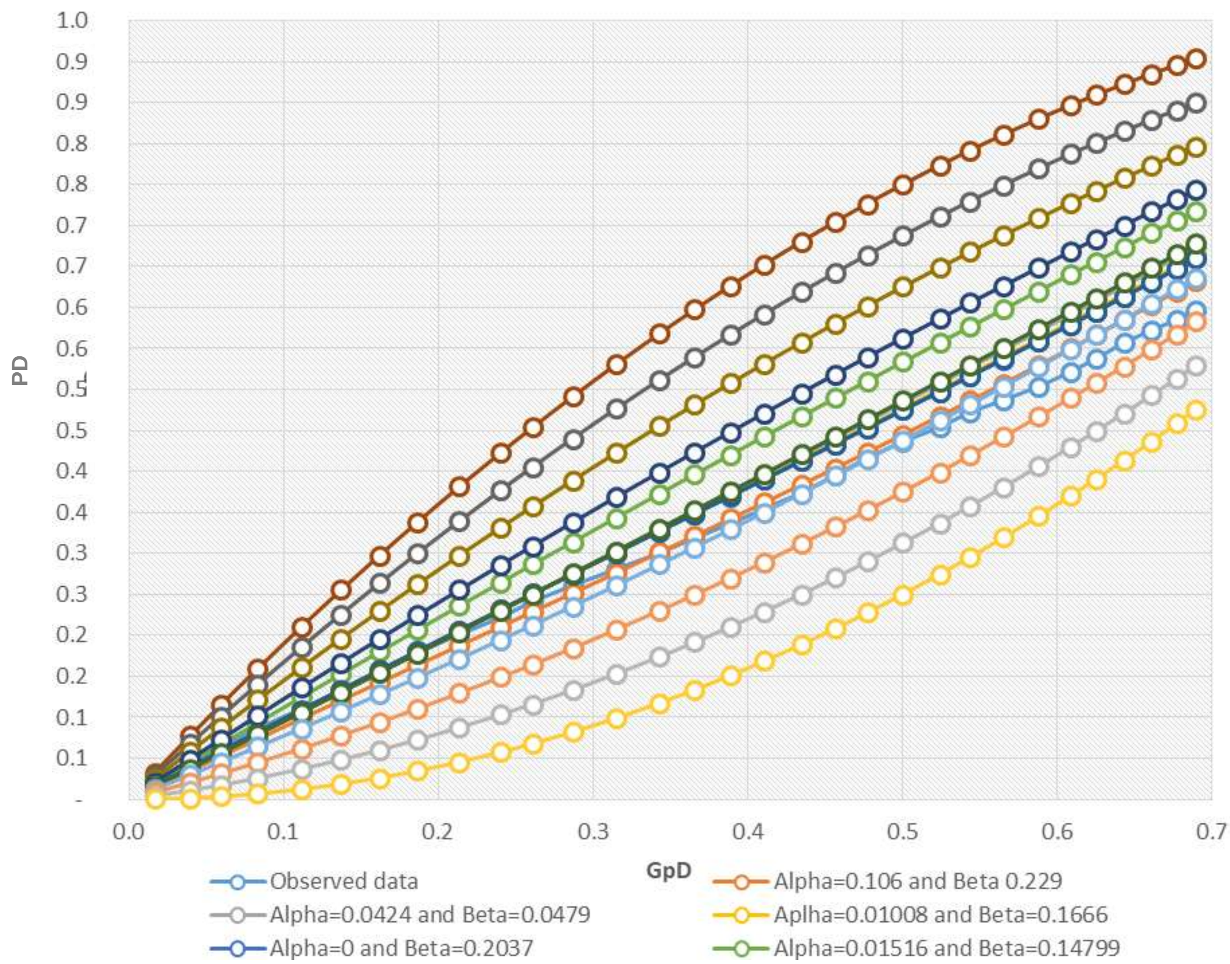

Figure 4. Type curve match for different values of α and β.

in Figure 6 shows that a correct water influx model was found, and the interception in ordinate axis gives us an approximate value of Gas Initially In Place (GIIP) of 1117 Bscf, which is identical with the correct value 1116 Bscf. This finding is aligned with the results obtained by Dake (2001). The improved material balance method demonstrated the hazards of not taking into account the influence of water influx in P/Z plots, as it can leads in overestimation of GIIP and this can have serious economic consequences for the project.

Conclusions

In this work, two workflows for computing water influx was presented.

The first workflow was for the van Everdingen-Hurst method which requires the use of the superposition

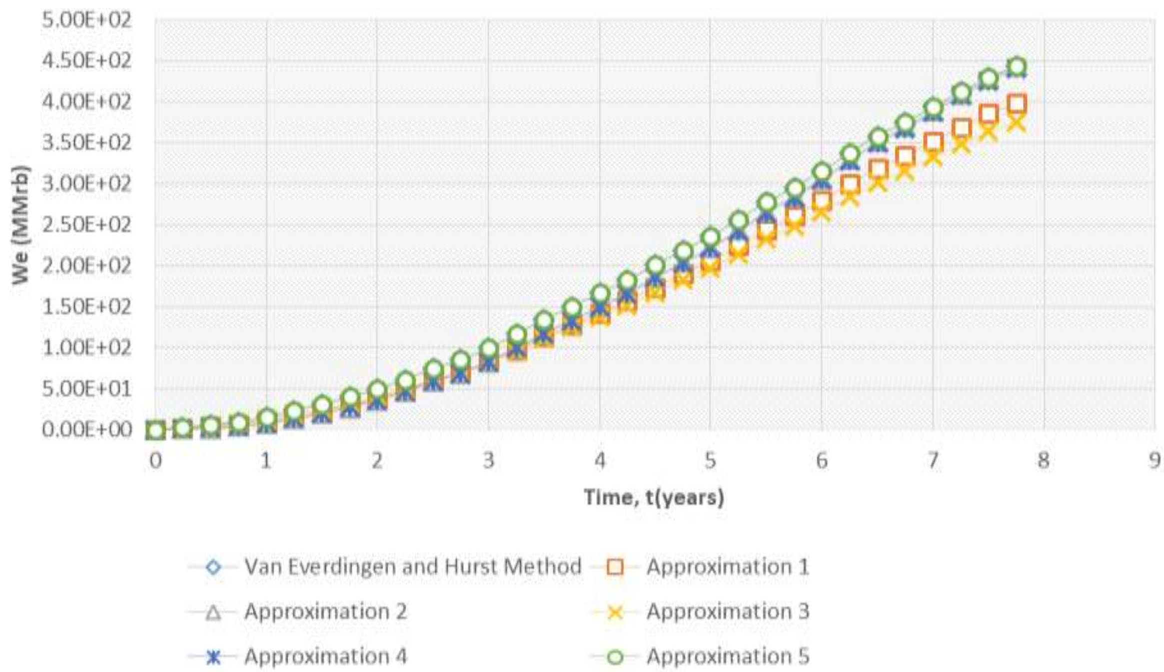

Figure 5. Comparison between van Everdingen-Hurst and cubic cumulative production model for different values of α and β.

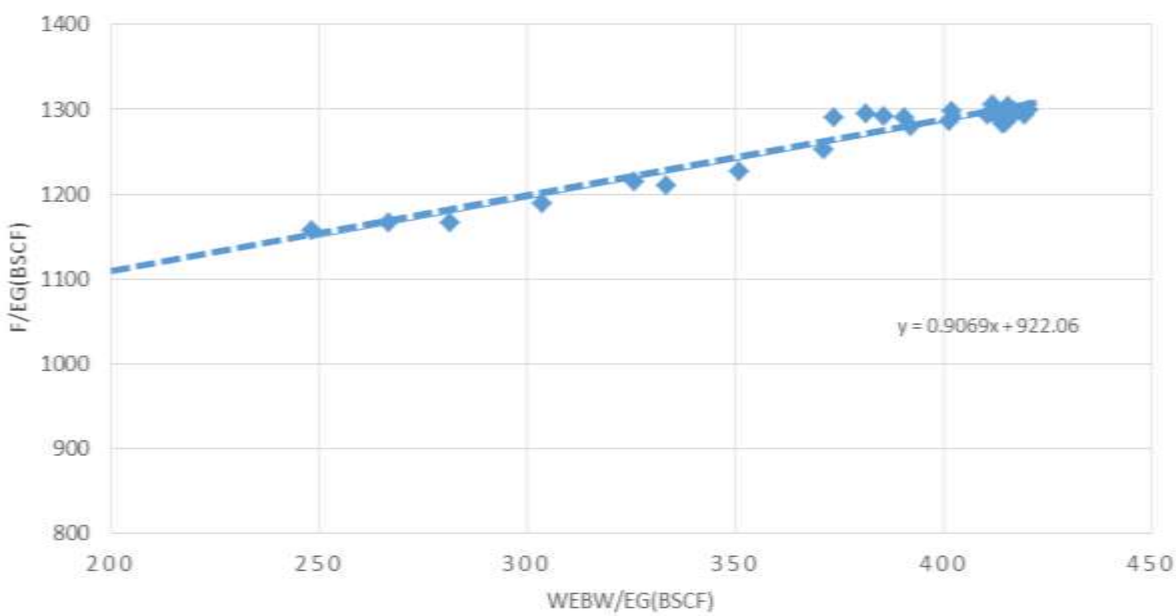

Figure 6. Application of the Havlena-Odeh plot in history matching reservoir-aquifer performance.

principle in order to find the cumulative water influx for each time step. For that reason a superposition matrix was created and the values of dimensionless water influx W_D was calculated using the Edwardson polynomials expressions.

The second workflow was for the cubic cumulative production model of Agarwal, in which there was a need of correct calibration of the unknown parameters α and β. In order to determine those parameters, two solutions were proposed. One is the type curve solution and the other one was the solver function. The most accurate solution was found for an approximation values of α

=0.020573 and β =0.173889. This solution was introduced in the derived equation for computation of water influx, presented by Blansigamen and Zonoozi (2005).

The results of cumulative water influx using cumulative production model of Agarwal was included in the generalized material balance for gas reservoirs using the Havlena and Odeh technique and a well matched solution was obtained.

The successful comparison between both methods demonstrated that it depends on the values of the unknown parameters α and β, appearing in Agarwal's model.

The results obtained in this work could be useful for industrial applications of the material balance for dry gas under influence of an infinite active aquifer. It will improve the computation of cumulative water influx using production data obtained in a reservoir, resulting in a more accurate estimation of GIIP.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests

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