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# Water Coning Prediction: An Evaluation of Horizontal Well Correlations

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**Abstract:** Oil production from bottom-water drive reservoirs is characterized by water production related problem - water coning. Most times, horizontal wells are used to attenuate this production challenge. That notwithstanding, overtime, depending on the production rate, water coning is also experienced with horizontal wells. Therefore, several correlations have been developed to predict the critical rate, breakthrough time and water-cut performance after breakthrough in horizontal wells. However, limited studies have evaluated the predictions of these developed water coning correlations. Therefore, an evaluation has been made to predict the various water coning correlations in horizontal wells. The obtained results show that the critical rate directly depends on the stand-off to drainage width and horizontal well length to drainage width ratios. Also, it is shown that the breakthrough time directly depends on the horizontal well length to drainage width ratio. Furthermore, the correlations developed from water-cut data for the prediction of post-water behaviour (i.e., water-cut performance) after breakthrough indicate more proficient water-cut profile than the correlations developed from water-oil ratio. Therefore, to prolong the occurrence of water coning in horizontal wells, the ratios of stand-off to drainage width and horizontal well length to drainage width should be considered to achieve maximum critical oil rate and breakthrough time in bottom-water reservoirs.

**Keywords:** Bottom-Water Reservoir, Water Coning Prediction, Critical Rate, Breakthrough Time, Water-Cut Performance, Horizontal Wells

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## 1. Introduction

In the petroleum industry, the use of horizontal well in the production of oil and gas is not limited to increasing the well deliverability, improved well productivity, reduce the number of producing wells, effectively drain the reservoir, among others. The technology is sometimes used as water coning attenuation approach; especially in thin-oil column reservoirs with strong active bottom-water drive. Generally, in strong bottom-water drive reservoirs, oil production from well (s) in these reservoirs lead to changing pressure drawdown around the wellbore, which causes the movement of oil/water interface toward the producing interval. Most times, vertical wells exhibit a large pressure drawdown in the wellbore vicinity than horizontal wells. Horizontal wells provide an option whereby pressure drawdown is minimized and high production rate sustained

[1]. In addition, at low drawdown, horizontal wells can have a larger capacity to produce oil compared to conventional vertical wells. However, the problem of water coning; termed water cresting in horizontal wells, is still experienced in bottom-water drive reservoirs. Therefore, water coning according to Okwananke and Isehunwa [2] is the upward movement of water into the perforations of a producing well. In both vertical and horizontal wells, water coning occur when there is an imbalance of forces between viscous and gravity forces [3]. Azim [4] added that there are essentially three forces: capillary, gravity and viscous, controlling the mechanism of water coning. Thus, the severity of water coning in oil and gas production cannot be undermined, as it results in production related problems like: excessive water production, water disposal challenges, low oil productivity, etc.

The study of water coning phenomenon in reservoir engineering is fundamental as most petroleum reservoirs are

sandwiched between gas and water zones. The early studies of this phenomenon made reference to the work of Muskat and Wyckoff [5]. This pioneer study led to the development of correlations: critical rate, breakthrough time and post-water behaviour after breakthrough by several authors to predict water coning. Among these correlations, Osisanya *et al.* [6] mentioned that critical rate is probably the most discussed coning parameter. In horizontal wells, water coning is very complex and difficult to solve analytically, as the flow geometry is not as simple as the vertical well. However, several studies have been carried out to understand the mechanism of water coning in horizontal wells and some correlations have been developed. Authors like Efros [7], Kracher *et al.* [8], Giger [9], Chaperon [10], Joshi [11], Yang and Wattenbarger [12], Recham *et al.* [13], and others have provided critical rate correlations for horizontal wells. On the other hand, Papatzacos *et al.* [14], Ozkan and Raghavan [15], Bahadori [16], Makinde *et al.* [17], etc. provide correlations for coning breakthrough time in horizontal wells. For the post-water behaviour (i.e., water-cut performance) after breakthrough Yang and Wattenbarger [12], Souza *et al.* [18] and Permadi and Jayadi [19] presented correlations for horizontal wells. Unfortunately, there are significant variations in the predictions of the numerous water coning correlations. Inikori [20] maintained that these variations arise mainly due to the approximating assumptions used to simplify the complex mathematical solutions of the two- or three-phase flow in porous media. Therefore, this paper evaluates the various water coning correlations for horizontal wells to assess the most reliable correlation (s) for the prediction of this production rate-sensitive phenomenon during oil production in bottom-water drive reservoirs.

## 2. Water Coning Mechanism in Horizontal Wells

In bottom-water drive reservoir, be it vertical or horizontal well, the flow of oil from the reservoir to the well introduces an upward dynamic force upon the fluids [21]. This dynamic (viscous) force, due to wellbore pressure drawdown, causes the bottom water to rise to a certain point at which the dynamic force is balanced by the height of the water beneath that point. Then, as the distance from the wellbore increases the pressure drawdown and the upward dynamic (viscous) force caused by it decreases. This development causes the water-oil contact (WOC) below the oil completion interval to rise toward the perforation. In horizontal wells (as depicted in Figure 1), the mentioned phenomenon is experienced at the heel than the toe of the horizontal well. At low production rate, a stable cone is experienced as the dynamic force offsets the gravity contrast between the oil and water phase [1]. Over time, this contrast between the water and oil cannot offset their mobility differences, then, the water cone becomes unstable and rises towards the well completion.

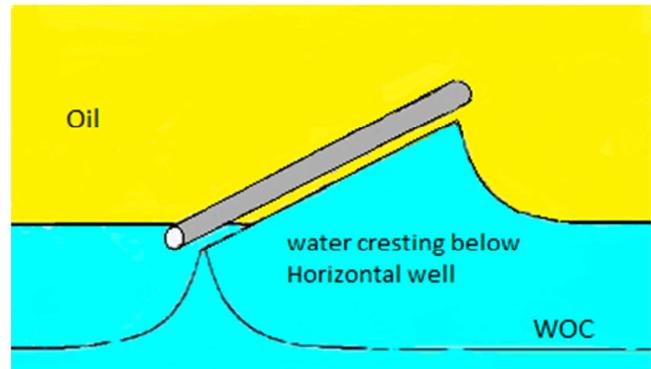


Figure 1. Water Coning in Horizontal Well [22].

According to Karami *et al.* [23] planning to avoid and/or separate the water produced during water coning takes a long time. As earlier alluded, several correlations have been developed to predict water coning in horizontal wells. These correlations: critical rate, breakthrough time and water-cut performance after breakthrough are developed based on two approaches (i.e., analytical and numerical). Also, Okon *et al.* [1] added that the assumptions regarding: reservoir types, reservoir parameters and flow types, and the model used are incorporated in these approaches to develop the correlations. For the critical rate, one of the assumptions is that the water cone has risen to a certain height before its breakthrough into the well. Additionally, the analytical approach establishes the critical rate correlations based on the equilibrium conditions of gravity forces and pressure gradients. Practically, producing oil below the critical rate is not economical. Therefore, operating companies often produce at a rate higher than the critical coning rate. Once the production rate exceeds the critical rate, the water cone moves toward the well and subsequently breaks into the wellbore. At this point, knowing the breakthrough time helps to improve well management and extend well life without water production [24]. So far, available correlations to predict horizontal wells breakthrough time are based on analytical and numerical approaches. Currently, there is no analytical solution to estimate water-cut performance after breakthrough in horizontal wells; or even in vertical wells. The available correlations for post-water (water-cut) breakthrough performance predictions are developed based on numerical simulation data. Thus, some of the available correlations to predict water coning in horizontal wells are presented in Tables A1 through A3.

## 3. Horizontal Well Correlations Evaluation

Even though horizontal well technology is one of the water coning attenuation methods, prediction of water coning (cresting) phenomenon in horizontal wells is a necessity to achieve maximum oil production and/or recovery from the reservoir. To evaluate the potentials of these water coning correlations' predictions in horizontal wells, the basic reservoir and fluid properties data were extracted from the

work of Khalili [22] and Kumar *et al.* [25]. These extracted data as presented in Table 1 were used to evaluate the various

water coning correlations presented in Tables A1 through A3.

**Table 1.** Basic Reservoir and Fluid Properties.

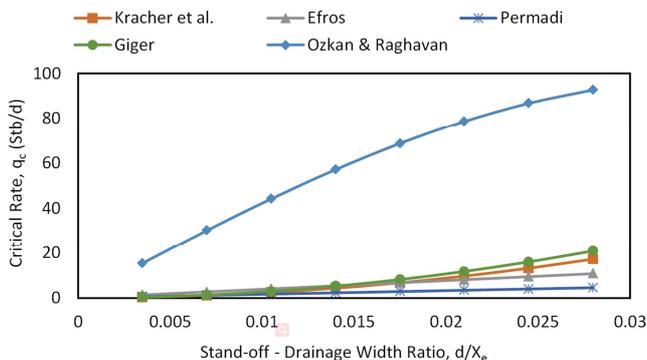
Reservoir data		Fluid data	
Drainage Width ( $X_c$ ), ft	2000	Density of water, $\rho_w$ (lb/ft <sup>3</sup> )	62.40
Horizontal permeability, $k_h$ (md)	100	Density of oil, $\rho_o$ (lb/ft <sup>3</sup> )	43.67
Vertical permeability, $k_v$ (md)	10	Oil viscosity, $\mu_o$ (cp)	0.7
Pay zone thickness, $h$ (ft)	70	Water viscosity, $\mu_w$ (cp)	1.0
Standoff from WOC, $d$ (ft)	56	Oil formation volume factor, $B_o$	1.10
Average reservoir pressure, $P$ (psi)	3769	Water formation volume factor, $B_w$	1.00
Formation porosity, $\phi$	0.32	end-point oil relative permeability ( $k_{ro}$ )	0.72
Wellbore radius, $r_w$ (ft)	0.25	end-point water relative permeability ( $k_{rw}$ )	0.40
Length of horizontal well, $L$ (ft)	1500	Connate water saturation, $S_{wc}$	0.25
Half drainage length, $Y_c$ (ft)	2000	Residual Oil Saturation, $S_{or}$	0.24
Oil production rate, $q$ (stb/day)	1500		

Source: Khalili [22] and Kumar *et al.* [25].

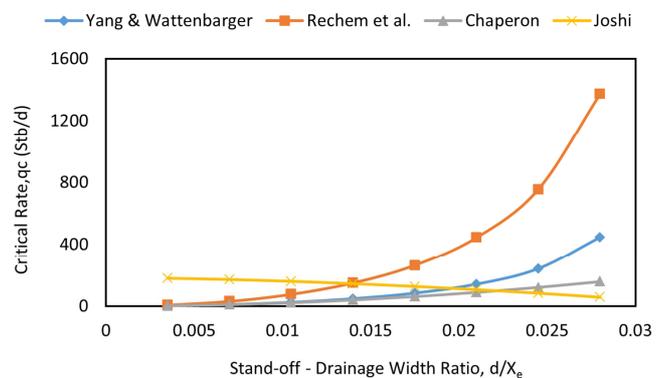
## 4. Results and Discussion

### 4.1. Critical Rate

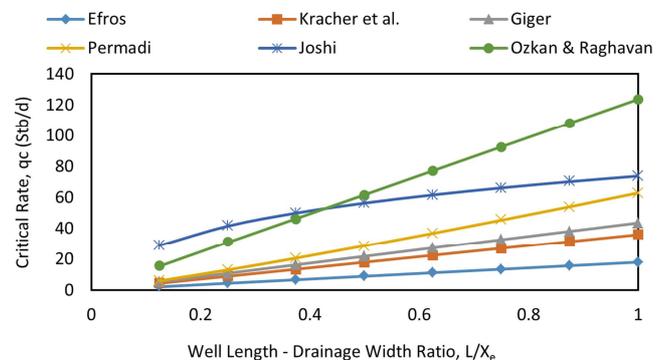
For the evaluation of the various critical rate correlations in horizontal wells, two parameters were used to evaluate the critical rate prediction of the various correlations. These parameters are: stand-off to drainage width ( $d/X_c$ ) and horizontal well length to drainage width ( $L/X_c$ ). The obtained results as depicted in Figure 2 indicate that Kracher *et al.* [8], Efros [7], Permadi [26] and Giger [9] correlations have the same profile and close critical rate predictions. However, these correlations' predicted critical rates which were very low compared to the prediction of Ozkan and Raghavan [15] with about 92.74stb/d at stand-off to drainage width of about 0.028. Figure 3 further presents the critical rate against stand-off to drainage width results. This result indicates that Chaperon [10], Joshi [11], Yang and Wattenbarger [12], and Recham *et al.* [13] correlations predict high critical rate; as Recham *et al.* [13] correlation predicted the highest among these correlations. From the Figures, it is observed that the critical rate increases as the stand-off to drainage width increases for all correlations; except for Joshi [27] correlation which predicts the reverse. This implies that, in horizontal wells, critical rate is stand-off to drainage width dependent. Therefore, it requires consideration during placement of horizontal well to prolong water coning occurrence in bottom-water drive reservoirs.



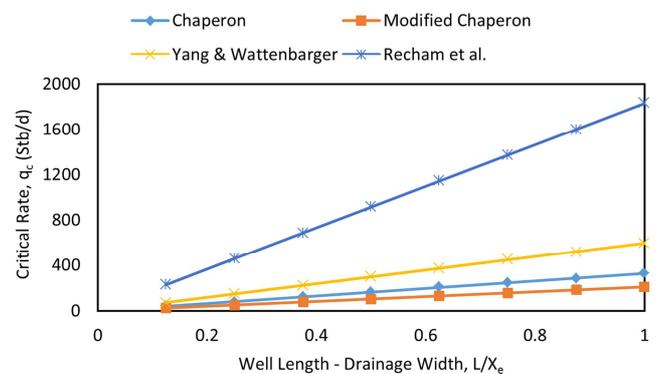
**Figure 2.** Critical Rate vs. Stand-off - Drainage Width Ratio.



**Figure 3.** Critical Rate vs. Stand-off - Drainage Width Ratio.



**Figure 4.** Critical Rate vs. Well Length - Drainage Width Ratio.



**Figure 5.** Critical Rate vs. Well Length - Drainage Width Ratio.

On the other hand, Figures 4 and 5 present the critical rate

against horizontal well length to drainage width ( $L/X_e$ ) prediction of the various correlations. From the results, it is noted that the critical rate is directly dependent on the well length - drainage width ratio. However, the results further indicate that these correlations: Efros [7], Kracher *et al.* [8], Giger [9], Permadi [26], Joshi [11] and Ozkan and Raghavan [15] resulted in low critical rate prediction when compared to the predictions of Chaperon [10], modified Chaperon by Joshi [27], Yang and Wattenbarger [12] as well as Recham *et al.* [13]. Interestingly, almost all the correlations have the same trend of predicting the critical rate against well length to drainage width in horizontal wells. Just like stand-off to drainage width ratio ( $d/X_e$ ), the obtained results indicate that well length to drainage width ( $L/X_e$ ) is another factor to be considered in horizontal well placement to suppress early water cone in bottom-water drive reservoirs.

**4.2. Breakthrough Time**

The breakthrough time was evaluated as a function of horizontal well length to drainage width ratio ( $L/X_e$ ); as presented in Figure 6. From the obtained results, it is observed that all the correlations have the same profile except for Makinde *et al.* [17] correlation. Also, the various correlations predicted different breakthrough time at the same horizontal well length to drainage width ratio ( $L/X_e$ ). This variance in the correlations predictions are attributed to the different approaches and assumptions made in the development of the correlations. Furthermore, the result indicates that water coning (cresting) breakthrough time in horizontal well increase as the horizontal well length to drainage width ratio increases. Meaning, the breakthrough time is directly dependent on the horizontal well length to drainage width ratio ( $L/X_e$ ). Therefore, this observation further supports the use of horizontal well technology to delay water coning tendency in bottom-water drive reservoirs.

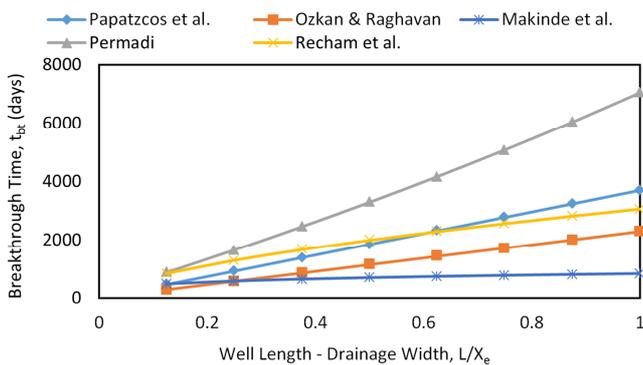


Figure 6. Breakthrough Time vs. Well Length - Drainage Width Ratio.

**4.3. Water-cut After Performance Breakthrough**

Figure 7 presents the different correlations prediction of post-water behaviour (i.e., water-cut performance) after breakthrough in horizontal wells. From the Figure, Yang and Wattenbarger [12] and Souza *et al.* [18] correlations have the same profile but different predictions of the water-cut

performance. That is, Yang and Wattenbarger [12] and Souza *et al.* [18] correlations predicted water-cut of about 33% and 95% respectively after 10.5 years. For Permadi and Jayadi [19] correlation, its prediction was not of a typical water-cut profile; as the obtained water-cut profile was exponential in nature. Meaning, a near steady water-cut profile was not established as the evaluated water-cut performance approaches 1 (100%); as observed in the case of Souza *et al.* [18] correlation prediction profile.

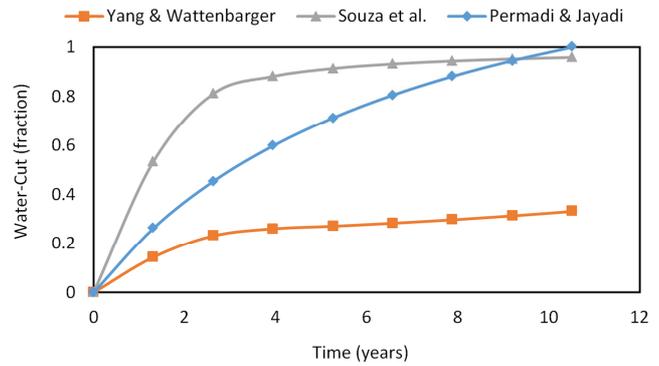


Figure 7. Water-cut Performance after Breakthrough vs. Time.

In summary, this evaluation has put forward the reliability of the various correlations to predict water coning in horizontal wells. The approaches: analytical, empirical, numerical or combined and the assumptions used in the development of the correlation are factors that affect the reliability of its prediction. Thus, most of the various water coning correlations evaluated in this study predicted different values for the water coning parameters: critical rate, breakthrough time and water-cut performance after breakthrough in horizontal wells. Additionally, despite the variance in their predictions, some of the correlations have about the same profile for the water coning parameters in horizontal wells.

**5. Conclusion**

The use of horizontal well technology as water coning (cresting) suppression approach does not completely eliminate this production rate-sensitive phenomenon in bottom-water drive reservoirs. Therefore, the proper prediction of this phenomenon in horizontal wells is of essence. Hence, several authors have developed correlations to predict water coning in horizontal wells based on numerous approaches and assumptions. However, limited works have evaluated the consistency of these correlations to predict coning parameters in horizontal wells. Therefore, this study evaluates the various water coning correlations in horizontal wells, and the following conclusions are drawn:

- i. all the correlations predicted different values for the water coning parameters: critical rate, breakthrough and water-cut performance after breakthrough in horizontal wells;
- ii. in horizontal wells, critical production rate directly depends on stand-off to drainage width and

horizontal well length to drainage width ratios, while breakthrough time directly depends on horizontal well length to drainage width ratio; and

- iii. also, correlations to evaluate post-water behaviour or water-cut performance after breakthrough developed from water-cut data predict more realistic water-cut profile than correlations from water-oil ratio data.

Therefore, in bottom-water reservoirs with active aquifer, placement of horizontal well should consider stand-off to drainage width as well as horizontal well length to drainage width to achieve optimum critical production rate and breakthrough time.

### Nomenclature

- $q_c$  = critical rate, *stb/d*
- $\Delta\rho$  = water-oil density difference, *lb/ft<sup>3</sup>*
- $\mu_o$  = oil viscosity, *cp*
- $\mu_w$  = water viscosity, *cp*
- $r_w$  = wellbore radius, *ft*
- $r_e$  = drainage radius, *ft*
- $r_{we}$  = effective wellbore radius, *ft*
- $r_{eh}$  = horizontal well drainage radius, *ft*
- $h$  = pay-zone thickness, *ft*
- $A$  = reservoir area, *ft<sup>2</sup>*
- $d$  = stand-off from WOC, *ft*
- $k_v$  = vertical permeability, *md*
- $k_h$  = horizontal permeability, *md*
- $k_{ro}$  = oil relative permeability at  $S_{wc}$
- $t_{bt}$  = breakthrough time, *days*

- $B_o$  = oil formation volume factor, *rb/stb*
- $B_w$  = water formation volume factor, *rb/stb*
- $M$  = mobility ratio
- $g$  = gravity constant, *ft/hr<sup>2</sup>*
- $\varphi$  = formation porosity, *fraction*
- $\alpha$  = mobility ratio exponent
- $h_{ap}$  = height above perforation, *ft*
- $h_{bp}$  = height below perforation, *ft*
- $h_{wb}$  = breakthrough height (cone height), *ft*
- $h_w$  = water zone thickness, *ft*
- $q_o$  = oil production rate *stb/d*
- $q_{cD}$  = dimensionless critical rate
- $\lambda_o$  = end-point oil mobility, *Pa/s*
- $X_D$  = dimensionless drainage width
- $Z_D$  = dimensionless cone height
- $(t_D)_{bt}$  = dimensionless breakthrough time
- $S_{wc}$  = connate water saturation
- $S_{or}$  = residual oil saturation
- $X_e$  = drainage width, *ft*
- $Y_e$  = reservoir length parallel to horizontal well, *ft*
- $L$  = horizontal well length, *ft*
- $\Delta P_v$  = pressure drawdown due to viscous effects, *psi*
- $\Delta\gamma$  = difference between hydrostatic gradients of water and oil, *psi/ft*
- $WC$  = water-cut
- $WC_D$  = dimensionless water-cut
- $WOR$  = water-oil ratio

### Appendix

#### Appendix A

Table A1. Correlations for Water Coning Critical Rate in Horizontal Wells.

Author (s)	Approach	Correlations	Assumption (s)
1. Efros [7]	Analytical	$q_c = 4.888 \times 10^{-4} \frac{\Delta\rho k_h h^2 L}{\mu_o B_o \left[ 2y_e + \sqrt{2y_e + \left(\frac{h^2}{3}\right)} \right]}$	Critical rate is nearly independent of drainage radius.
2. Kracher <i>et al.</i> [8]	Analytical	$q_c = 4.888 \times 10^{-4} \frac{\Delta\rho k_h h^2}{\mu_o B_o 2y_e} \left[ 1 - \frac{1}{6} \left( \frac{h}{2y_e} \right)^2 \right]$	Constant cone height at infinite distance and incompressible flow in the oil zone.
3. Giger [9]	Analytical	$q_c = 9.498 \times 10^{-7} \frac{\Delta\rho k_h h^2 L}{\mu_o B_o D \left[ \sqrt{1 + \frac{16H^2}{3D^2}} + 1 \right]}$	Used 2D mathematical model and free surface boundary condition with assumption that the free surface is at a large distance.
4. Chaperon [10]	Empirical & Regression Analysis	$q_c = 4.886 \times 10^{-4} \left[ \frac{\Delta\rho L k h}{\mu_o B_o} \right] \left( \frac{h}{X_A} \right) q_{ic}^* ; X_D = \frac{D}{h} \sqrt{\frac{k_v}{k_h}}$ where: $q_{ic}^* = 3.9624955 + 0.0616438(X_D) - 0.000504(X_D)^2$	The influence of the cone shape on the flow pattern negligible.

Author (s)	Approach	Correlations	Assumption (s)
5. Joshi [11]	Analytical	$q_c = 2.46 \times 10^{-5} \frac{\Delta \rho k_h [h^2 - (h - D_b)^2]}{\mu_o B_o \ln \left( \frac{r_{eh}}{r_{we}} \right)}$ $r_{we} = \frac{r_{eh} (L/2a)}{\left[ 1 + \sqrt{1 - (L/2a)^2} \right] \left( \frac{h}{2r_w} \right)^{h/L}}$ <p>where: <math>a = \frac{L}{2} \left[ 0.5 + \sqrt{0.25 + \left( 2r_{eh}/L \right)^2} \right]^{1/2}</math></p>	Constant pressure at drainage boundary and at the wellbore.
6. Ozkan and Raghavan [15]	Analytical	$q_c = \frac{\Delta \rho k_v h_{bp} L}{651.4 \mu_o B_o \sqrt{k_h}} \left[ 1.0194 - 0.1021 \left( \frac{h_{bp}}{h} \right) - 0.2807 \left( \frac{h_{bp}}{h} \right)^2 \right]$	The bottom water drive reservoir can be represented as a constant pressure boundary (i.e., pressure at the oil and water interface is constant).
7. Joshi [27]	Empirical & Regression Analysis	$q_c = 7.827 \times 10^{-6} \left( \frac{L}{D} \right) \frac{\Delta \rho k_h [h - (h - D_b)]^2}{\mu_o B_o} q_{ic}^*$ <p>where: <math>q_{ic}^* = 3.9624955 + 0.0616438(X_D) - 0.000504(X_D)^2</math></p>	Based on Chaperon (1986) work to handle the expression for dimensionless flow rate ( $q^*$ ) in Chaperon's equation.
8. Permadi [26]	Analytical	$q_c = \frac{7.08 \times 10^{-3} k_h L \Delta \rho h_{woc}}{\mu_o B_o \left[ X_e - Y_e \sqrt{\frac{h}{L}} + h \frac{k_v}{k_h} \left\{ \ln \left( \frac{Y_e}{2r_w} \sqrt{\frac{h}{L}} \right) - \frac{1}{2} \right\} \right]}$	Slightly compressible fluids flow; bottom-water moves horizontally at residual oil saturation and pressure at WOC is constant.
9. Yang and Wattenbarger [12]	Analytical	$q_c = \frac{\Delta \rho h L k_{ro} \sqrt{k_v k_h}}{\mu_o B_o} q_{cD}$ <p>where: <math>q_{cD} = 4.7921 \times 10^{-4} D^{0.32} \left( \frac{1}{X_D} \right)^{0.65} \left[ \frac{1}{1 + M^{0.4}} \right] \left[ \frac{h_{bp}^2}{(h - h_{ap})^2 - h_{bp}^2} \right]</math></p>	Based on the work of Addington (1981) with the assumption that water is displacing oil in a piston-like manner.
10. Recham <i>et al.</i> [13]	Numerical Simulation & Regression Analysis	$q_c = \frac{\Delta \rho h L \sqrt{k_v k_h}}{325.86 \mu_o B_o} q_{cD}$ <p>where:</p> $q_{cD} = 1.17 \times 10^{-3} (X_D)^{0.61} \left[ \frac{1}{1 + M^{4.45}} \right] \left[ \frac{1}{1 - (h_{ap}/h)} \right]^{2.77} \left[ \frac{(h_{bp} - 1)^2}{(h - h_{ap})^2 - (h_{ap} - 1)^2} \right]$	For the modelled reservoir, 3D radial model for water coning vertical well and 3D irregular Cartesian model for water cresting (coning) in horizontal well.

Table A2. Correlations for Water Coning Breakthrough Time in Horizontal Wells.

Author (s)	Approach	Correlations	Assumption (s)
1. Papatzacos <i>et al.</i> [14]	Semi-analytical	$t_{bt} = 1.856 \times 10^{-1} \frac{\phi h^2 L \sqrt{k_v k_h}}{q_o B_o k_v}$	moving boundary approach, for predicting cone evolution in the transient state
2. Ozkan and Raghavan [15]	Analytical	$t_{bt} = 2.226 \times 10^{-1} \frac{k_h h^2 L f \sqrt{k_v}}{q_o B_o k_v \sqrt{k_h}}$ <p>where: <math>f = \phi(1 - S_{wc} - S_{or})</math></p>	The bottom water drive reservoir can be represented as a constant pressure boundary (i.e., pressure at the oil and water interface is constant).
3. Makinde <i>et al.</i> [17]	Numerical Simulation & Regression Analysis	$t_{bt} = 8.98 \times 10^5 \left[ \frac{\phi^{1.092} A^{0.964} L^{0.264} k_v^{0.108} k_h^{0.324}}{q^{1.490} h_{ap}^{2.103}} \right]$ $t_{bt} = \frac{7899(\mu_o + \mu_w) \phi (1 - S_{or}) h_{woc}^2}{k_v (\Delta P_v - \Delta \gamma h_{woc})}$	Initial oil saturation in the aquifer is zero, the region between initial WOC and water invaded zone is at residual oil saturation.
4. Permadi [26]	Analytical	$\mu_o q B_o \left[ X_e - Y_e \sqrt{\frac{h}{L}} + h \sqrt{\frac{k_v}{k_h}} \left\{ \ln \left( \frac{Y_e}{2r_w} \sqrt{\frac{h}{L}} \right) \right\} \right]$ <p>where: <math>\Delta P_v = 141.24 \frac{k_h h L}{k_v h L}</math></p>	Slightly compressible fluids flow; bottom-water moves horizontally at residual oil saturation and pressure at WOC is constant.
5. Recham <i>et al.</i> [13]	Numerical Simulation & Regression Analysis	$t_{bt} = 12657 (1 + M)^{0.37} \left( \frac{1}{X_D} \right)^{0.78} \left( \frac{1}{q_D} \right)^{0.62} \left[ 1 - \left( \frac{h_{bp}}{h} \right)^2 \right]^{-0.54} \left[ 1 - \left( \frac{h_{ap}}{h} \right)^2 \right]^{-5.86}$ <p>where: <math>q_D = \frac{325.86 \mu_o B_o q_o}{\Delta \rho L h \sqrt{k_v k_h}}</math>; <math>X_D = \frac{X_e}{h} \sqrt{\frac{k_v}{k_h}}</math>; <math>M = \frac{\mu_o k_{rw}}{\mu_w k_{ro}}</math></p>	For the modelled reservoir, 3D radial model for water coning vertical well and 3D irregular Cartesian model for water cresting (coning) in horizontal well.

Table A3. Correlations for Water-cut Performance after Breakthrough in Horizontal Wells.

Author (s)	Approach	Correlations	Assumption (s)
1. Yang and Wattenbarger [12]	Numerical Simulation & Regression Analysis	$WOR = 0$ for $h_{bp} > h_{wb}$ $\log(WOR + 0.25) = m(h_{bp} - h_{wb}) + \log(0.25)$ for $h_{bp} \leq h_{wb}$ where; $m = 0.004 \left[ 1 + 2.7496(1 + M^{0.25}) \frac{X_e^{0.18}}{h} \left( \frac{1}{X_D} \right)^{0.4} \left( \frac{1}{q_D} \right)^{0.5} \left( 1 - \frac{h_{ap}}{h} \right)^{0.3} \right]$ $\left[ \frac{h - h_{ap}}{h_{wb}} \right]^2 = 1 + 4.7921 \times 10^{-4} X_e^{0.32} \left( \frac{1}{q_D} \right) \left( \frac{1}{1 + M^{0.4}} \right) \left( \frac{1}{X_D} \right)^{0.65}$ $WC = 1 - \frac{q_{oD}}{q_D}$	Based on the work of Addington (1981) with the assumption that water is displacing oil in a piston-like manner.
2. Souza <i>et al.</i> [18]	Numerical Simulation & Regression Analysis	where; $q_{oD} = q_D \left( \frac{t_{bID}}{2t_D - t_{bID}} \right)^m$ ; $t_D = \frac{\Delta \rho g \lambda_o k_v t}{\phi h_o}$ ; and $t_{bID} = t_{bID}^0 e^{-\alpha \Delta Z_D}$ ; $\Delta Z_D = 0.005$ for $m = 0.50$ ; $\alpha = 2.9727$ and $t_{bID}^0 = 1.6310$	Homogeneous reservoir with constant viscosity with negligible capillary effects and under constant total production rate.
3. Permadi and Jayadi [19]	Numerical Simulation & Regression Analysis	$WC = \frac{1}{\frac{q_o B_w}{q_w B_o} + 1}$ where; $\frac{q_w}{q_o} = 0.025 q_i^{0.23} (M)^{0.45} \left( \frac{X_e Y_e}{dL} \right)^{0.503} \left( \frac{k_v}{k_h} \right)^{0.14} \left( \frac{h_w}{d - h_w} \right)$	Reservoir pressure at the lateral boundary is constant throughout the producing life of the well. Steady-state flow and negligible effects of gravity forces, capillary forces, wellbore friction losses etc.

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