Acta Scientiarum

http://periodicos.uem.br/ojs/acta
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v40i1.38403

TECHNOLOGICAL INFORMATION

The influence of oil well on the water generation from the potiguar basin / Brazil

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ABSTRACT. The geometry of oil wells can be decisive for the generation of undesirable residues in the oil and gas production. One of these residues is the produced water, which has increased its volume in the oil fields, becoming a great environmental challenge for the fields managers. Therefore, the objective of this research is to analyze the influence of oil wells types in the generation of produced water. The research was developed in 80 onshore oilfields, in production phase, at the Potiguar basin, considering the years 2014, 2015 and 2016. A conceptual model was formulated with three hypotheses, using multivariate regressions. The results indicated an increasing average of 0.5% (2014 and 2015) in the produced water volume, when 1 vertical well was added to the project; and 1.91% (2016) for each directional well introduced in the project. The age of the field was the most influential variable in the research, reaching, in the year 2015, an effect of 13.7% on the produced water generation.

Keywords: oilfields; production water; multivariate regression; geometry; onshore.

A influência dos poços de petróleo na geração de água na bacia potiguar/Brasil

RESUMO. A geometria dos poços de petróleo pode ser decisiva quanto à geração de resíduos indesejáveis na produção de petróleo e gás. Um desses resíduos é a água produzida que tem aumentando seu volume nos campos petrolíferos e se tornado um grande desafio ambiental para os gestores desses campos. O objetivo desta pesquisa é analisar a influência dos tipos de poços petrolíferos na geração de água produzida. Esta pesquisa foi desenvolvida em 80 campos de petróleo *onshore,* em fase de produção, na bacia potiguar, considerando os anos de 2014, 2015 e 2016. Formulou-se um modelo conceitual composto por três hipóteses, utilizando-se das regressões multivariadas. Os resultados apontam para um aumento de 0,5% (2014 e 2015) no volume de água produzida, em média, quando acrescido um poço vertical no projeto e de 1,91% (2016) para cada poço direcional incrementado no projeto. A idade do campo revelou-se a variável de maior influência na pesquisa, alcançando, no ano de 2015, o efeito de 13,7% sobre a geração de água produzida.

Palavras-chave: campos de petróleo; água produzida; regressão multivariada; geometria; onshore.

Introduction

The demand for oil and its by-products has raised world production over the last decade (2006 to 2015) to a production level of more than 92 million barrels per day (Agência Nacional de Petróleo [ANP], 2016). With the increase in oil production, there is consequently an increase in the quantities of produced water (Clark & Veil, 2009; Nasiri, Jafari, & Parniankhoy, 2017), which requires a severe intervention with sustainable practices in order to avoid environmental damage.

This environmental problem, originated from the generation of water produced in the oil fields, promotes damages to the sustainability of the oil industry, ratifying the search for technologies that causes less impact to the environment (Figueredo et al., 2014).

The produced water origin is related to the environmental conditions that existed during the formation of the oil. A geological environment that had an intense deposition of organic matter, associated with a burial and specific physicochemical conditions tends to gather the necessary conditions to generation of oil in the matrix rocks (Stephenson, 1992).

When this oil is extracted through the wells, whether onshore or *offshore*, it produces aqueous waste effluents called wastewater from oil fields or produced water (PW), responsible for the largest amount of residues from the production and exploration of crude oil (Stephenson, 1992; Mondal & Wickramasinghe, 2008), especially in mature fields, when there is an excessive production of water (Figueredo et al., 2014).

The produced water is an inseparable part of the hydrocarbon recovery process. As the fields become mature, they tend to increase the amounts of water (Khatib & Verbeek, 2003), reaching values close to 100% in the end of the well productive life, therefore the well type can be determinant for a good yield of the oilfield.

In addition to the age factor, oil wells types can interfere in the amount of produced water generated by the field. The oil wells have multiple objectives, among them the promotion of geological formations information and geophysical data (Kaiser, 2007) that contribute to the oil and/or gas deposits discovery and, consequently, to initiate the production or to abandon the well.

To construct a well, it is necessary to have a project whose initial stage is the study of the area in which the well will be drilled, based on analysis of the geological scenario and in wells that were already drilled in the region (Rocha & Azevedo, 2009).

From the information collected, especially the one regarding the marine geology, the depth of the target point and the expected reservoir geometry (Rocha & Azevedo, 2009), it is possible to define the trajectory that the well reaches the greatest potential of producer zone. As far as geometry is concerned, the wells are classified as vertical, horizontal and directional.

The vertical ones are wells whose point of the reservoir to be reached (objective) is in the same vertical line of the drilling rig (Gabbay, Dutra Júnior, Mata, Rodrigues, & Lira, 2014), the main characteristics of this well are: zero degree or only few degrees of the true vertical line, the most usual geometry in oil fields, since it simplifies the process of completion and evaluation of the reservoir. Therefore, considering that in the onshore fields there is a greater efficiency using the vertical wells, the first research hypothesis is insinuated - H_1 - There is negative influence from vertical wells in the generation of produced water in onshore fields.

Although it is widely requested in the oil fields, vertical wells have important limitations: higher pressure drop in regions near the well when compared to horizontal wells; reduced drainage area, especially in tight formations (low permeability); many wells may be required to develop a field (Elyasi, 2016).

Meanwhile, directional wells, unlike vertical wells, are drilled at angles of 45 to 60 degrees or more, from the real vertical line, whose target point is dislocated from the vertical line of the wellhead. This distance, in plan, defines the distance of the directional well, that allows to classify them in conventional, of great separation and of severe separation (Laik, 2018).

Directional wells are often used in *offshore* rigs in order to 'reach' great distances from the platform and they can travel across different trajectory styles to achieve their targets (Laik, 2018). Due to its multiple operational targets, intrinsic costs aggregated to the operation are raised, the second research hypothesis is proposed: H_2 - There is a positive influence of directional wells in the generation of produced water in *onshore* fields.

A particular type of directional well is the horizontal well, whose goal is to increase the productivity and to ultimate the recovery of hydrocarbons. There are two categories of horizontal wells applications: to solve problems from fluids flow characteristics and problems regarding the reservoir heterogeneities. Both applications can be present on the same system (Adesina et al, 2016).

Horizontal wells have a straight section that is drilled horizontally inside the pay zone, enlarging the drainage area in the reservoir. That is, these are extended reach wells where the target is horizontally far away from drilling rig (> 10 km)(Dehua, Guowei, Jing, & Wenying, 2011).

These wells, according to Mukherjee and Economides (1991) can produce up to three times more than vertical wells, however they are riskier in operation and have higher costs than vertical wells. Given the efficiency of this type of well, but permeated by its several risks inherent to the operation, the third research hypothesis can be presented: H_3 - There is a positive influence of the horizontal wells in the generation of produced water in *onshore* fields.

Aimed to horizontal wells, Babu and Odeh (1989) presented an equation to calculate the flow from the pseudo-structural state for a horizontal well, similar to the already known productivity equation for a vertical well. The proposed equation was aimed to study the productivity effects regarding the well length, location and degree of penetration; vertical and horizontal Permeability; and the horizontal dimensions of the drainage volume.

Mukherjee and Economides (1991) presented screening criteria for vertical and horizontal wells with or without induced fractures, as well as a procedure to calculate the optimal number of orthogonal transverse fractures in horizontal wells.

Xu, Li, Liao, and Xu (2014) developed a hydraulic fracturing model for vertical wells with low permeability and tight oil formations (when the reservoir permeability is under than 0.1mD). The productivity analysis concluded that the higher the pressure gradient threshold, the oil well productivity is lower and that the higher the stress sensitivity, the productivity decreases. In addition, the initial productivity of the oil well increases when the fracture length increases, but the rate tends to be smaller.

In light of this, the objective of the present work is to analyze the influence of oil wells types in the produced water generation in *onshore* fields.

This study will establish a significant contribution to specialized petroleum literature, since it deals with variables not yet used in the direct relationship with the production of water associated with petroleum. The result of the research will foster strategic decisions in the area of environmental sustainability of the oil fields by regulatory agencies, field explorers, and the government itself, through public policies.

Material and methods

In the first phase of this research, it was tried to map the number of Brazilian fields, in order to classify later their *offshore* and *onshore* dimensions. Brazil has 472 oil fields, 135 are *offshore* and 337 are *onshore*. The southeastern region of Brazil stands out in *offshore* production, accounting more than 90% of all oil produced *offshore* in the country, while the Brazilian northeast is responsible for more than 70% of the national *onshore* production.

Among the main northeastern basins, the Potiguar basin is predominantly located in the Rio Grande do Norte state and extended to the state of Ceará. The petroleum fields of this basin are in the eastern portion of the northeastern region of Brazil, with a sedimentary area in the emerging portion of approximately 26,700 km^2, while the submerged portion represents an area around 195,400 km^2.

The Potiguar basin holds 22.5% of the Brazilian oil fields and has approximately 6,000 wells in production, based on t reports from 2016. From its 106 oil fields (10 *offshore* and 96 *onshore*), just 80 of them were producing in 2014, 2015 and 2016.

All the fields that only produced gas were eliminated from the analysis, as well as the fields that presented themselves as outliers of the research, resulting in a final sample of 70 fields. The data collected, of secondary origin, are available on the ANP website (2016, 2017) in two databases: fields area and fields production. The two databases were merged, so all variables study were located on a single basis, based on years 2014, 2015 and 2016.

In the modeling, the chosen variables were classified into two classes: the control variables and the independent ones, as presented in Table 1.

Table 1. Study variables.

Variables	Variable type	Description
Produced Water	Dependent	Quantity in m^3 of produced water from oil production.
Vertical Well	Independent	Zero degree or just a few degrees of the actual vertical line, most used geometry in the oil fields.
Horizontal Well	Independent	Extended reach wells where the target is horizontally far from their surface location (> 10 km).
Directional Well	Independent	They are wells drilled at angles of 45 to 60 degrees or more, from the true vertical line, whose target is away from the vertical line passing through the wellhead.
API Gravity	Control	Scale used to measure the density of oil and its by-products.
Field age	Control	Field operation time from the start of production.
Ratio	Control	Relationship between the volume of produced water and oil produced per year.

The independent variables (Vertical wells, Horizontal wells, Directional wells) are used to determine the explanation degree in relation to the dependent variable, i.e., they will serve to measure their influence on the variable (produced water), while the other variables (API Gravity, Field Age and Ratio) will serve as control variables.

To measure the influence of the independent variables on the generation of produced water, multiple regression was used as a multivariate statistical technique. The "X" is an array of explanatory variables that seek a causal relationship with the variable Y and compose the independent variables of the model: Vertical wells, Horizontal wells, Directional wells. The "W" corresponds to an array of control variables (API Gravity, Field Age, and Ratio). These relationships are represented in Equation 1.

$$lny\ (produced\ water) = \beta_0 + \beta_1 * X + \beta_2 * W + \varepsilon \qquad (1)$$

The β_0 represents the model constant; the ε, the residues, while β is the explanation parameter vector for the X and W matrices. If the vectors of the explanation vectors were not consider, a model such as that proposed in Equation 2 is expected.

$$\begin{aligned} lny\ (produced\ water) &= \beta_0 + \beta_1 * Vertical\ wells + \\ &+ \beta_2 * Horizontal\ wells + \\ &+ \beta_3 * Directional\ wells + \beta_4 * Field\ age + \\ &+ \beta_5 * API\ Gravity + \beta_6 * Ratio + \varepsilon \end{aligned} \qquad (2)$$

The multivariable model can consider the relationship of the variable produced water with all the independent variables, with the purpose of answering the hypotheses of this research, as well as with the control variables for each year.

To validate the regressions regarding the assumptions VIF, Tolerance (Multicollinearity), Durbin-Watson (Autocorrelation), Pesaran-Pesaran (Homoscedasticity) and Normality (Kolmogorov Smirnov) tests were performed according to Wooldridge (2010); Hair, Black, Babin, Anderson, and Tatham (2009).

The hypotheses will be considered for the analyzed years and it will be validated if they confirm the causality hypothesis of the variable produced water with the independent variables (vertical wells, horizontal wells, directional wells) for each of the years of this study (2014, 2015, 2016).

The results will be presented in three steps: step I - a multiple regression will be applied in order to measure the causality of the independent and control variables, with the variable produced water (dependent), using, for this, the data of the three years; step II - after applying the assumptions, the model will be delineated from a multiple regression for each year studied (2014, 2015, 2016); step III - the research hypotheses will be analyzed in order to validate or refute them. Hypothesis tests will be performed using the T test and the software used to achieve this research was the SPSS (Statistical Package for Social Sciences) package, version 22.

Results and discussion

The analyzed results were subdivided into two sections to structure the analyzes: multivariate regression and hypothesis test evaluation. A level of 95% of significance was used for definition and consequent exclusion of outliers, the variability of 6 σ, which upper limit is defined by $\mu + 3\sigma$ and the lower limit $\mu - 3\sigma$, where μ = sample average and σ = standard deviation of the sample.

Multivariable regression

Considering the search for the homoscedasticity of the residues, the Napierian logarithm(ln) for the three years analyzed (2014, 2015 and 2016) was applied to the water produced variable to linearize the data. The analyzes will be conducted by applying the Factor = 100 [exp (β) - 1] relationship established by Wooldridge (2010).

Analysis of the assumptions

After three iterations, following the assumptions of multiple regression, three variables were excluded from the model due to their low statistical significance ($p_{valor} > 0.05$), such as: API Gravity, horizontal wells and directional wells for the years 2014 and 2015 and the variables API Gravity, Horizontal wells and Vertical wells, for the year 2016.

As for multicollinearity, tested with FIV and Tolerance, the obtained result was the absence of multicollinearity, that is, the parameters appear within normality. The main test results are described in Table 2.

Table 2. Analysis of the assumptions.

Analysis	2014	2015	2016
Normality *(Kolmogorov Smirnov)*	$P_{valor}>0,1$	$P_{valor}>0,1$	$P_{valor}>0,1$
Autocorrelation *(Durbin-Watson)*	1,927	1,851	1,889
Homocedasticity (Pesaran-Pesaran)	$P_{valor}>0,1$	$P_{valor}>0,1$	$P_{valor}>0,1$
Outliers	10	9	12

Using the KS-Sample (Kolmogorov Smirnov – Sample) normality test, the obtained data was normal, once the null hypothesis was accepted. The autocorrelation was tested by Durbin-Watson, obtaining results close to 2, a value comprised in the interval that attests the absence of autocorrelation. Finally, the homoscedasticity was verified by the Pesaran-weigh test. The residues are homocured, implying the acceptance of the null hypothesis

Therefore, the regressions of the three years analyzed meet the assumptions of multivariate regression, which brings parsimony to the results of this research.

Regression coefficients

The adjusted R^2, presented in Table 3, with values ranging from 0.528 (2016) to 0.605 (2014), have an explanatory factor of the independent variables relative to the dependent variable ranging from approximately 52.8% to 60.5%. Analyzing the F test, it is noticed that since p-value (0.000) is below than 0.05, for all the years studied (2014, 2015, 2016), the hypothesis of R^2 equal to zero is declined, the independent variables have influence on the dependent ones and the models are significant.

Table 3. Multivariable regression to oil fields evaluation.

	Coefficient (2014)	Coefficient (2015)	Coefficient (2016)
Constant	6,527 (p_{valor}*= 0,000)	6,205 (p_{valor}*= 0,000)	7,205 (p_{valor}**= 0,029)
Vertical well	0,005 (p_{valor}*= 0,000)	0,005 (p_{valor}*= 0,003)	-
Water/oil ratio	0,096 (p_{valor}*= 0,001)	0,085 (p_{valor}*= 0,003)	0,060 (p_{valor}*= 0,002)
Field age	0,124 (p_{valor}*= 0,003)	0,137 (p_{valor}*= 0,000)	0,114 (p_{valor}*= 0,000)
Directional well	-	-	0,019 (p_{valor}*= 0,002)
R^2	0,605	0,589	0,528
F	36,25	34,39	24,88
Significance	(p_{valor}*= 0,000)	(p_{valor}*= 0,000)	(p_{valor}*= 0,000)

**Significance level 95% (p_{valor} <0,05) e *Significance level 99% (p_{valor} <0,01)

Equation (1) and Equations (3), (4) and (5) were estimated using the following regression models:

$$\ln(\text{produced water 2014}) = 6{,}527 + 0{,}124 * age + + 0{,}005 * vertical\ wells + 0{,}016 * Ratio + \varepsilon \quad (3)$$

$$\ln(\text{produced water 2015}) = 6{,}205 + 0{,}137 * age + + 0{,}005 * vertical\ wells + 0{,}085 * Ratio + \varepsilon \quad (4)$$

$$\ln(\text{produced water 2016}) = 7{,}205 + 0{,}114 * age + + 0{,}019 * directional\ wells + 0{,}06 * Ratio + \varepsilon \quad (5)$$

From the Equations (3), (4) and (5), the choice of the vertical well in an oil project represents a positive effect on the generation of produced water from oil, that is, for each vertical well incremented in the project, there is an increase, on average, of 0.5% of produced water, considering 2014 and 2015.

For 2016, the variable "vertical wells" did not reach statistical significance ($p = 0.373$), however, the "directional wells" variable had a positive effect on the dependent variable with an average increase of approximately 1,91% in amount of produced water for each directional well in production. This is due to a substantial increase in the number of directional wells (25%) in the Potiguar basin fields, so that there was a reduction in the variability of the data.

From Equation (3), it can be inferred that there is a positive effect of the field age on the dependent variable, 12.4 %, on average, for each year of the oil field in 2014 in consonance with the results of Nasiri, Jafari, and Parniankhoy (2017).

The following years (2015 and 2016) were not different for this variable, regarding this positive impact, on the dependent variable. The positive effects for years 2015 and 2016 were an increase of, on average, 13.7% and 11.4%, respectively, in the amount of produced water for an one-year variation of oil field, considering the *onshore* fields of the Potiguar basin. The variable age was fundamental in the generation of produced water in the *onshore* fields of the Potiguar basin, being also in consonance with the Khatib and Verbeek (2003), Clark and Veil (2009) studies, which considers the increase of age of the oil fields a key factor for the increase of produced water.

On the other hand, the variable "water/oil ratio (WOR)" obtained statistical significance, presenting positive causality for the three years of this analysis (2014, 2015 and 2016), contributing in the increase of the amount of produced water for each variation of a unit in the water/oil ratio, on average, 1.6, 8.87 and 6.18%, respectively for 2014, 2015 and 2016. The result for this variable allows to consider that the growth of the water variable is slightly higher than the increase of the oil volume for the studied years, according to Clark and Veil (2009), Nasiri, Jafari, and Parniankhoy (2017).

It should be noticed that the "horizontal wells" variable was not significant for any of the analyzed years. Once that only five oil fields in the Potiguar basin presented horizontal wells, making them *outliers* of the research for this variable, and also because horizontal wells were considered a type of directional well, which led to a multicollinearity between these two variables.

It should be noted that the API Gravity variable did not present statistical significance for any of the analyzed years. Therefore, for this dataset, there are no effects between the API Gravity and the volume of water produced.

Hypothesis tests

'T' type hypothesis tests were performed with a significance level of 95% and 99%, which the results are described in Table 4. The first hypothesis to be tested (H_1) deals with the influence of vertical wells in relation to produced water. The hypothesis H_0 was rejected for 2014 and 2015, accepting the alternative hypothesis H_1. In relation to 2016, the hypothesis H_0 was accepted.

Therefore, hypothesis 1 (H_1) of the research can be confirmed when regarding the years 2014 and 2015, with 99% of statistical significance. It can be seen that there is a positive causality between the use of vertical wells and the amount of produced water for the oil fields in the Potiguar basin, that is, the volume of produced water increases as the oil field adopts the use of vertical wells as a strategic technological resource for oil production. However for 2016, hypothesis 1 was rejected, since there was no statistical significance for this variable in that year ($p=0{,}402$).

The hypothesis 2 (H_2) deals with the influence of directional wells on the volume of produced water. The hypothesis H_0 was rejected accepting the alternative hypothesis H_1 for 2016, with 99% of significance, which allows to affirm that there is positive causality between the variable directional wells and produced water, that is, the larger the number of wells in 2016, the greater will be the water production. For the years 2014 and 2015 the null hypothesis H_0 was accepted. This means that hypothesis 2 can be validated considering only 2016, since it presented a positive causality, however, the variable directional wells did not obtain, in previous years (2014 and 2015), statistical significance.

Table 4. Tests T results for the research hypothesis.

		2014	2015	2016
Hypothesis 1 (**H_1**)				
Vertical wells	Test t	3,09	0,227	0,843
	P_{valor}	0,003*	0,002*	0,402
Hypothesis 2 (**H_2**)				
Directional wells	Test t	0,639	0,489	3,288
	P_{valor}	0,525	0,626	0,002
Hypothesis 3 (**H_3**)				
Horizontal wells	Test t	-0,792	-0,893	-0,892
	P_{valor}	0,432	0,375	0,376

**Significance level 95% (p_{valor} <0,05) e *Significance level 99% (p_{valor} <0,01).

The hypothesis 3 (H_3) deals with the influence of horizontal oil wells in relation to water production. Differently from the hypotheses H_1 and H_2, in the third hypothesis, H_0 was accepted for all analyzed years, since there was no statistical significance for this variable in any of the years studied. Therefore, the variable H_3 is refuted. It is important to notice that horizontal wells are not very common in oil fields of the Potiguar basin, which contributed to an inconclusive response to this variable.

Conclusion

The results indicate that the effects of the use of vertical wells corresponds to a 3.82 times less impact than the directional wells. The horizontal wells did not present statistical significance for the research data, as well as the API Gravity Variable. Regarding the control variables, the age of the oilfield denotes a fundamental factor for water production having a positive effect.

Therefore, the results allow to affirm that the independent variables Vertical wells and Directional wells interfere in the volume of produced water, being the determinant factors for an efficient management of produced water in oilfields of the Potiguar basin.

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Received on July 28, 2017.
Accepted on November 8, 2017.