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Diagnostic Method and Adaptability Analysis of Multiple Water Breakthroughs in Horizontal Well in Combined Well Pattern

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Abstract

The combined well pattern has been widely used in reservoir development, with a common pattern being a horizontal well in the center for oil production and multiple vertical wells around for water injection. For this type of well pattern, determining the horizontal well is affected by which injection wells, especially when the injecting water breaks through, accurately determining the direction of water inflow will provide an important basis for targeted water well measures. Based on the production performance data of horizontal wells, the semi logarithmic relationship curves of water-oil ratio, derivative water-oil ratio, and cumulative production were used for the first time to determine the breakthrough problem of water injection in the surrounding water injection wells of horizontal wells based on their response characteristics. The adaptability of this method under different influencing factors was analyzed. Introducing the parameter of cumulative production not only preserves the variation trend of the derivative of water-oil ratio with time, but also facilitates the processing of actual production data.

Keywords

Combined Well Pattern, Multiple Water Breakthroughs in Horizontal, Derivative of Water-Oil Ratio

1. Introduction

Horizontal well technology is an important technology to improve the development effect and recovery efficiency of oil and gas fields. However, for the problem of water breakthrough in horizontal wells, due to the complex seepage field, theoretical derivation of water breakthrough time faces many difficulties. Lang

Zhaoxin et al. used the conformal transformation method to derive the water breakthrough time of horizontal wells in a five-point well network (Lang et al., 1993; Qu et al., 1995; Yao et al., 2007), but the solution was too complex. Many scholars have focused their research on the issue of water breakthrough in production wells on actual production data. Yang Jun et al. represented the A-type water drive curve as the ratio of water-oil ratio to accumulated water production, and evaluates the effectiveness of water injection development (Yang et al., 2008). Chen Minfeng et al. used the trend of changes in the water-oil ratio, derivative of water-oil ratio, and production time relationship curve of oil wells to determine the cause of water channeling in oil wells (Chen & Jiang, 2007), but the above method was only limited to the case that the development well was vertical well. Zhang Xiansong et al. applied the diagnostic method of water-oil ratio derivative to the diagnosis of water channeling type in horizontal wells (Zhang & Ding, 2012), but this method could only distinguish the coning of bottom water and hyperpermeability channeling. Yuan Yufeng et al. studied water channeling law of multi-component thermal fluid huff & puff in edge bottom heavy oil reservoir (Yuan et al., 2022), but it was only applicable to the diagnosis of water breakthrough caused by edge and bottom water displacement in once. Therefore, there is a need for a method that can apply actual production data to diagnose multiple occurrences of water breakthroughs in horizontal wells during artificial water injection displacement.

Based on literature research and theoretical analysis and numerical simulation methods, this article proposes a method that can quickly determine the breakthrough time of multiple water injection wells around a horizontal well. This method uses oil well production performance data to obtain the semi logarithmic relationship curve between water-oil ratio, water-oil ratio derivative, and cumulative production. Based on the curve response characteristics, the number and time of breakthrough wells in the surrounding water injection wells can be determined.

2. The Introduction of Derivative Curves

In the research process of diagnostic methods for water breakthrough characteristics in horizontal wells, Chen Minfeng and Zhang Xiansong et al. took the water-oil ratio derivative curve as the research object (Chen & Jiang, 2007; Zhang & Ding, 2012), mainly because the slope of the water-oil ratio curve changes when water breakthrough occurs in the production well, and the derivative curve of the water-oil ratio amplifies this change. In general, water-oil ratio of and water-oil ratio derivative are as follows:

$$WOR = \frac{Q_o(t)}{Q_w(t)} \tag{1}$$

$$WOR' = \frac{WOR(t_1) - WOR(t_2)}{t_1 - t_2} \tag{2}$$

In which, WOR is water-oil ratio, WOR' is water-oil ratio derivative, Q_o is the daily oil production of horizontal wells, m^3/d; Q_w is the daily water production of horizontal wells, m^3/d; t is time, d.

However, in the actual production of oil fields, there is a problem of production time rate, which leads to the formula not being able to reflect the continuous variation of water-oil ratio well. Therefore, the derivative of water-oil ratio with cumulative oil production as the independent variable is introduced, and its expression is as follows:

$$WOR = \frac{Q_o\left(N_p\right)}{Q_w\left(N_p\right)} \tag{3}$$

$$WOR' = \frac{WOR\left(N_{P1}\right) - WOR\left(N_{P2}\right)}{N_{P1} - N_{P2}} \tag{4}$$

In which, N_P is cumulative oil production, 10^4 m^3; N_{P1} and N_{P2} represent cumulative production at different times, 10^4 m^3.

Cumulative oil production is positively correlated with time, which preserves the variation trend of water-oil ratio corresponding to time. At the same time, without considering the influence of time rate, it can better describe the process of continuous change of water-oil ratio.

3. Study on Water Appearance Characteristics of Horizontal Well with Multiple Unequal Points

According to the geological characteristics of S oilfield, a fine mechanism model of 47 × 47 × 10 black oil was established, in which the permeability was 2000 × 10^{-3} μm^2, the porosity was 0.33, the crude oil viscosity was 162 mPa·s and the initial oil saturation was 0.64. The basic well pattern is set as a five-point well pattern, with a horizontal production well H1 in the center with a horizontal section length of 250 m, and four vertical water injection wells I1, I2, I3 and I4 around it with a spacing of 460 m and a row spacing of 230 m. The following four scenarios are designed: Model 1: Only one of the injection wells, I1, injected water at an injection rate of 250 m^3/d, and the other wells were closed. Model 2: Two injection wells, I1 and I2, injected water at the injection rate of 250 m^3/d and 150 m^3/d respectively, while the other wells were closed. Model 3: Three injection wells, I1, I2 and I3, injected water at the injection rates of 250 m^3/d, 150 m^3/d and 100 m^3/d, respectively, while the other wells were closed. Model 4: Injection wells I1, I2, I3, and I4 were injected at 250 m^3/d, 150 m^3/d, 100 m^3/d, and 50 m^3/d, respectively (as shown in **Figure 1**).

Calculate the data from the above model and draw the curve of water-oil ratio and water-oil ratio derivative with respect to cumulative oil production for analysis (as shown in **Figure 2** and **Figure 3**).

As can be seen from **Figure 2** and **Figure 3**, the water-oil ratio curves calculated by each model have no great difference in shape, but the water-oil ratio derivative curves have obvious differences: each addition of a well leads to an additional peak in the derivative curve. The following takes 4 effective injection wells around horizontal wells as an example, and there are obvious peaks a, b, c and d on the derivative curve of water-oil ratio, as shown in **Figure 4**.

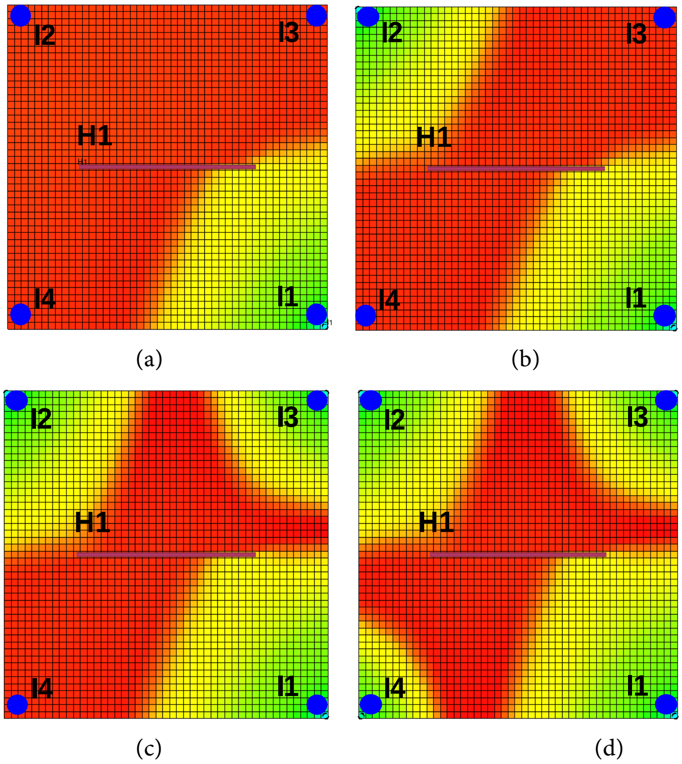

Figure 1. Five-point combined well pattern models with different water injection modes. (a) One injection well for water injection; (b) Two injection wells for water injection; (c) Three injection wells for water injection; (d) Four injection wells for water injection.

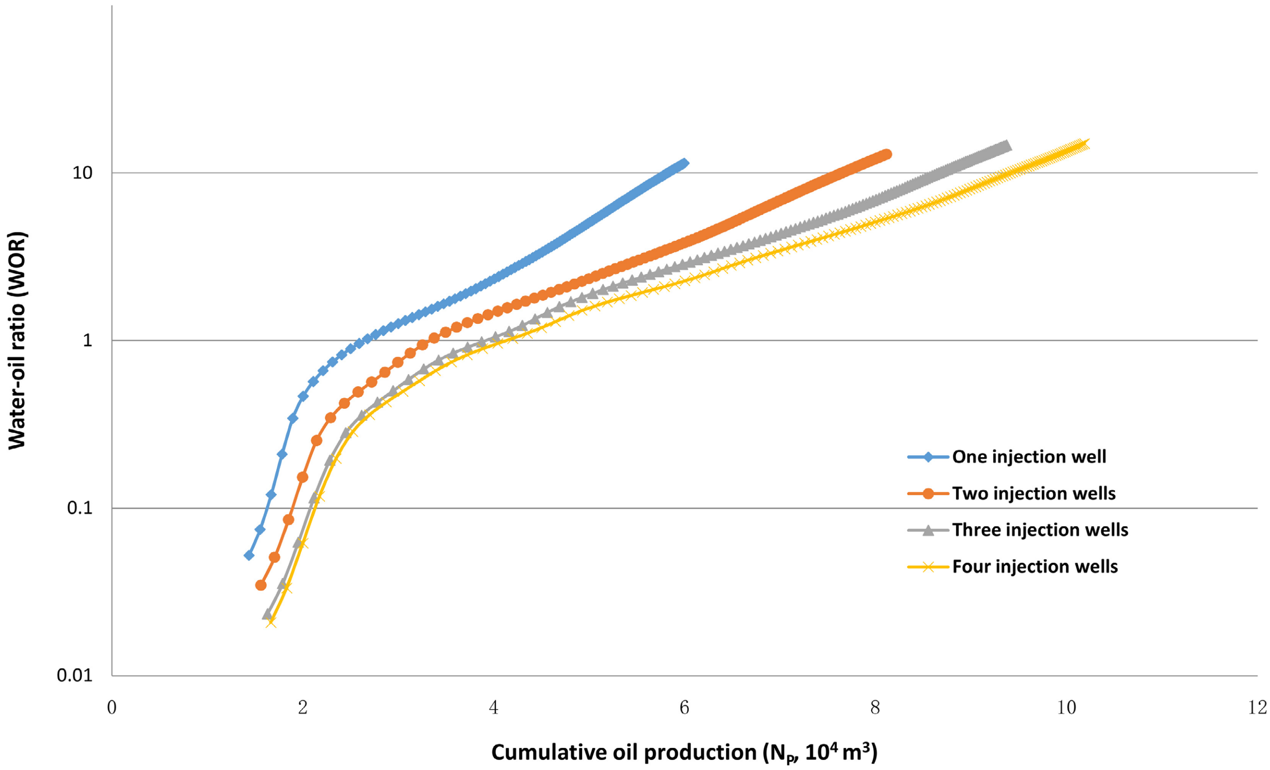

Figure 2. Relation curve between water-oil ratio and cumulative oil production.

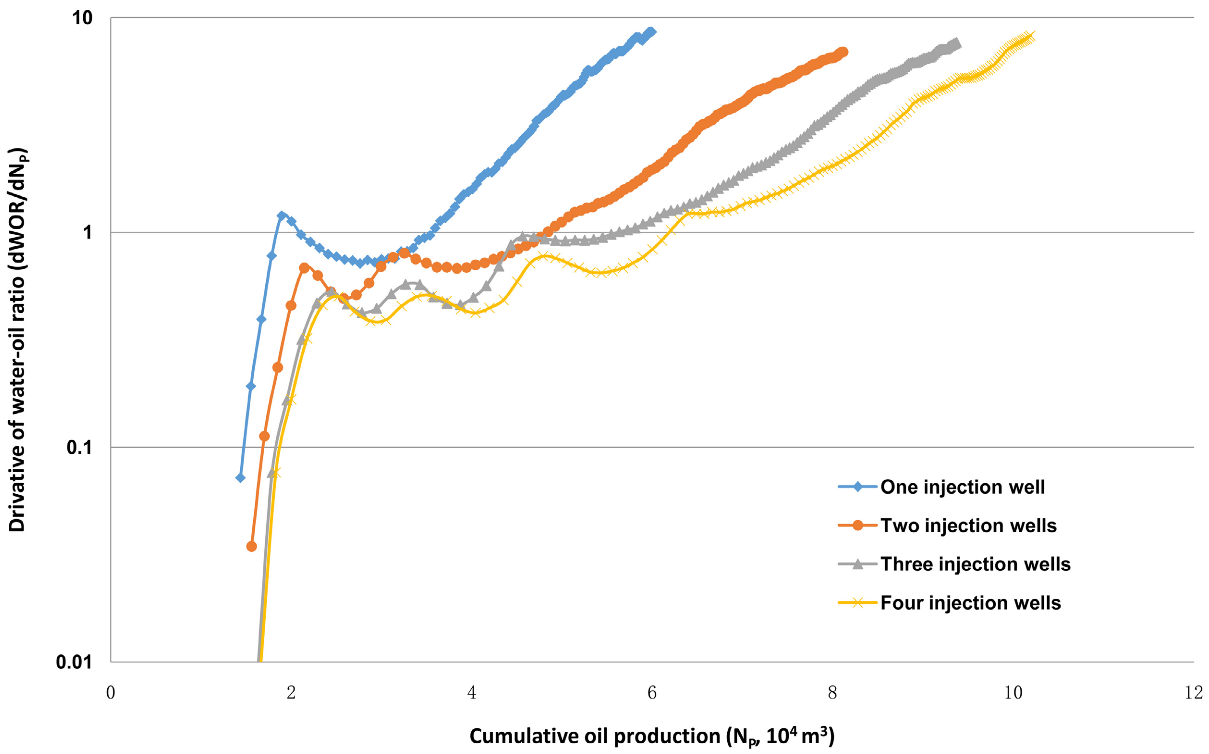

Figure 3. Relation curve between derivative of water-oil ratio and cumulative oil production.

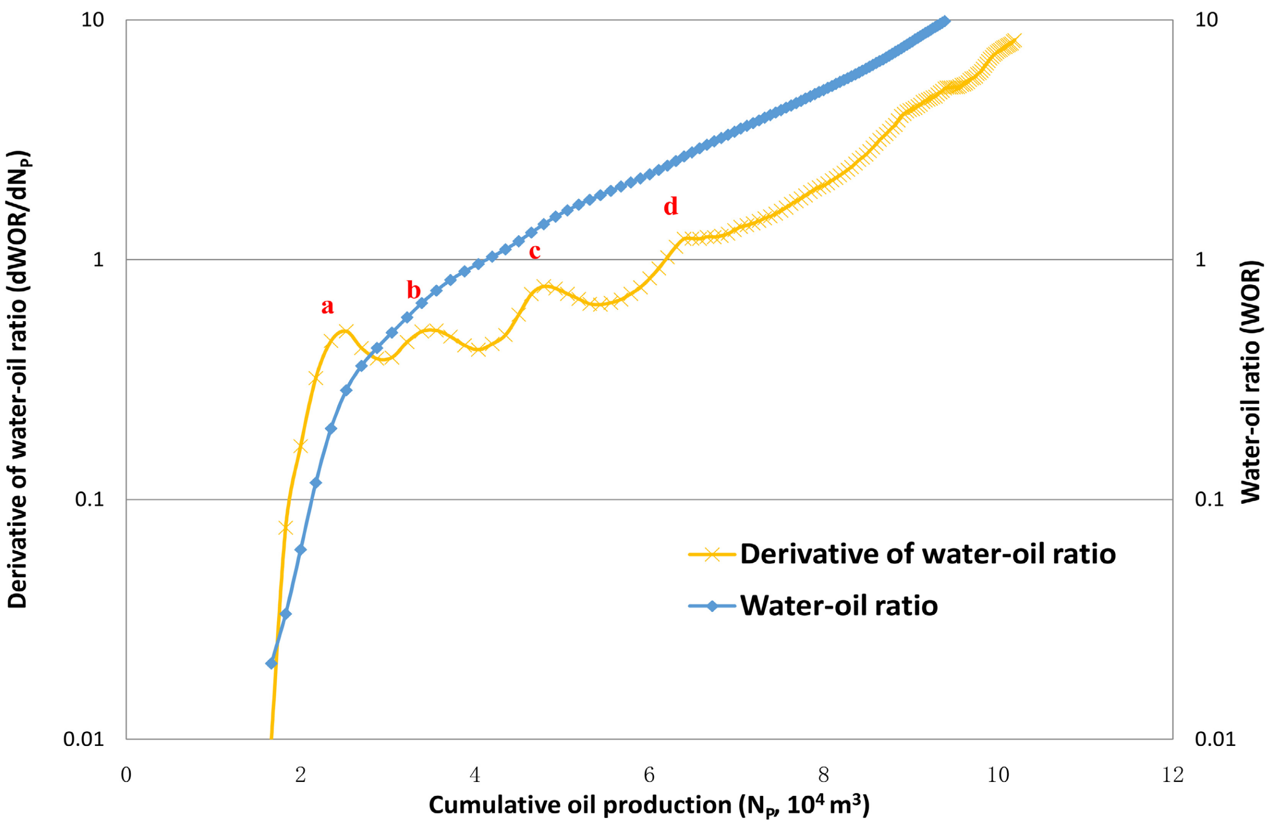

Figure 4. Relationship curves of effective water-oil ratio and derivative of water-oil ratio with cumulative oil production of four injection wells.

When the horizontal well reaches the saturation of the water-front at a certain point, the injected water breaks through, and the rise rate of water-oil ratio gradually speeds up, so the water-oil ratio derivative also shows an upward trend. When the water breakthrough point reaches the average saturation of the formation at the time of water breakthrough, the water breakthrough reaches equilibrium, and the growth rate of the water-oil ratio gradually slows down and tends to stabilize. Therefore, the derivative curve of the water-oil ratio shows a downward trend until the next injection of water breaks through, and the derivative curve of the water-oil ratio rises again.

4. Adaptability Analysis of Water Breakthrough Recognition Methods at Multiple Points and Different Times in Horizontal Wells

In the above analysis process, the reason for water breakthrough at multiple points and different times in horizontal wells is the difference in injection volume between different injection wells. Considering that other factors may also cause water breakthrough at multiple points in a horizontal well at different times, this article separately discusses the water breakthrough at multiple points at different times caused by differences in injection well location and injection timing, to verify the reliability of this method.

4.1. The Difference in the Location of Injection Wells in the Well Network Causes Water Breakthrough at Different Times

Based on the five-point well pattern in the above model, two injection wells I5 and I6 are added on both sides of the horizontal well, and the well pattern is transformed into a row well pattern, with I1, 12, I3, I4, I5 and I6 as the injection wells. The injection volume of 4-hole corner wells I1, 12, I3 and I4 is set at 150 m^3/d. According to the usual injection volume splitting principle, the injection volume of I5 and I6 of the two side wells located on both sides of the horizontal well should be twice that of wells I1, i.e. 300 m^3/d, as shown in Figure 5.

In this model, the water-oil ratio derivative curve of well H1 is shown in Figure 6. There are two obvious peaks a and b on the curve, which are corresponding to the water-oil ratio derivative curve of edge well waterflood breakthrough and corner well waterflood breakthrough.

4.2. Differences in Water Injection Timing in Water Injection Wells Result in Water Breakthrough at Different Times

Based on the five-point well pattern model, adjustments have been made to the timing of water injection in water injection wells, the injection volume of each well was 150 m^3/d, and the starting water injection time of each well I1, I2, I3 and I4 is delayed by 100 days in sequence, as shown in Figure 7.

The water-oil ratio derivative curve of well H1 in this model is shown in Figure 8. The four peaks a, b, c and d in the figure are the response of water injection breakthrough I1, I2, I3 and I4 on the water-oil ratio derivative curve.

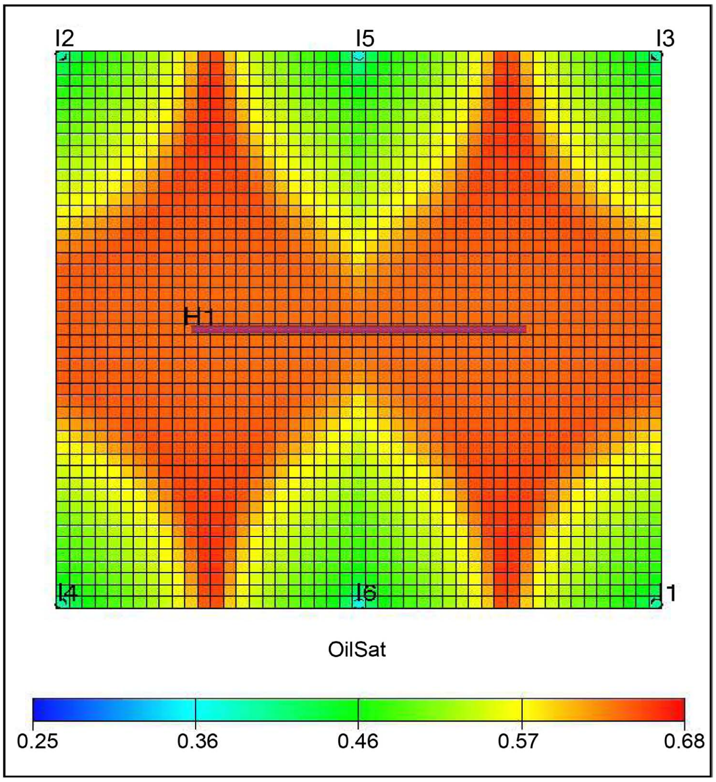

Figure 5. Row well pattern of 6 injection wells around horizontal wells.

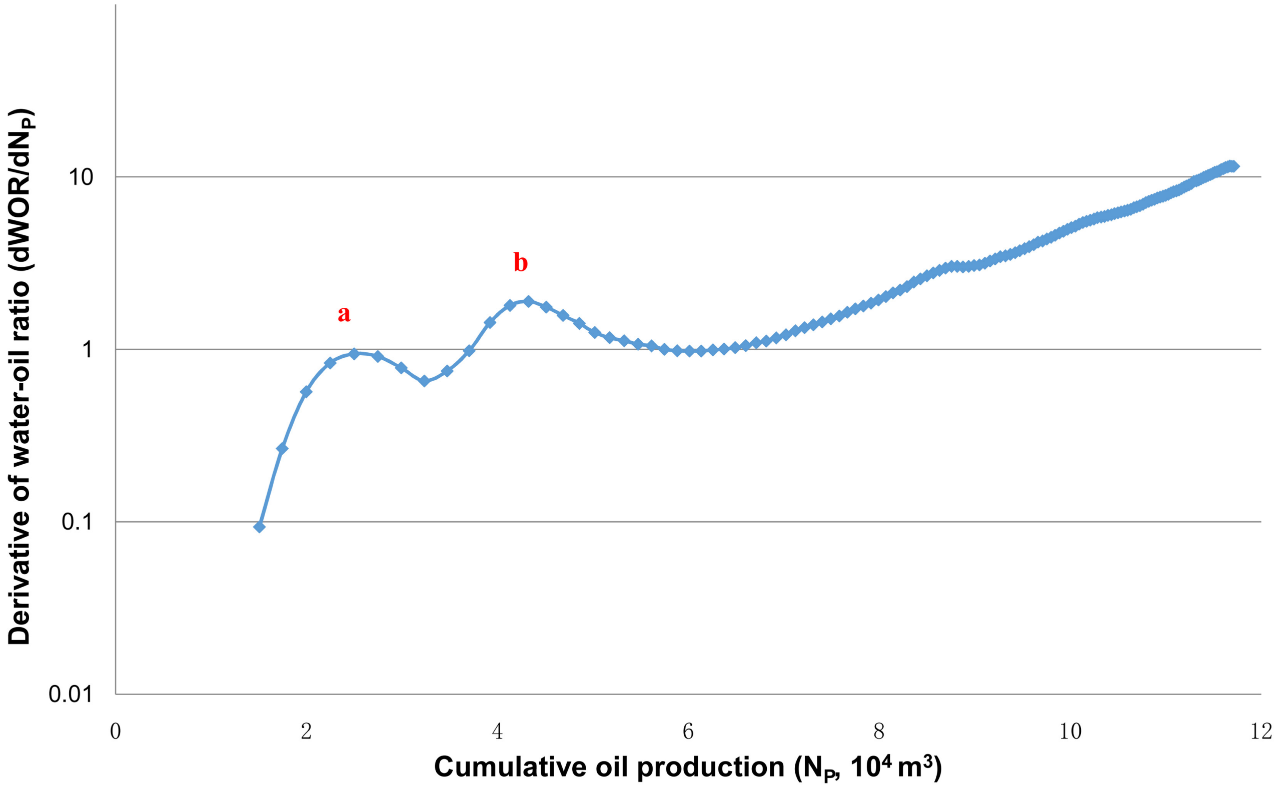

Figure 6. Relation curve between derivative of water-oil ratio and cumulative oil production of the horizontal well in row well pattern.

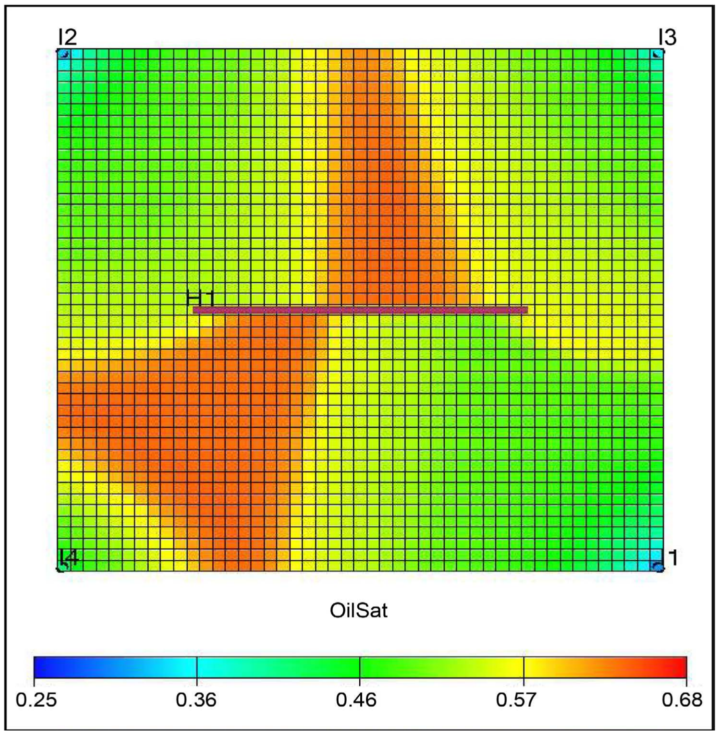

Figure 7. Injection wells inject water at different times in five-point well pattern.

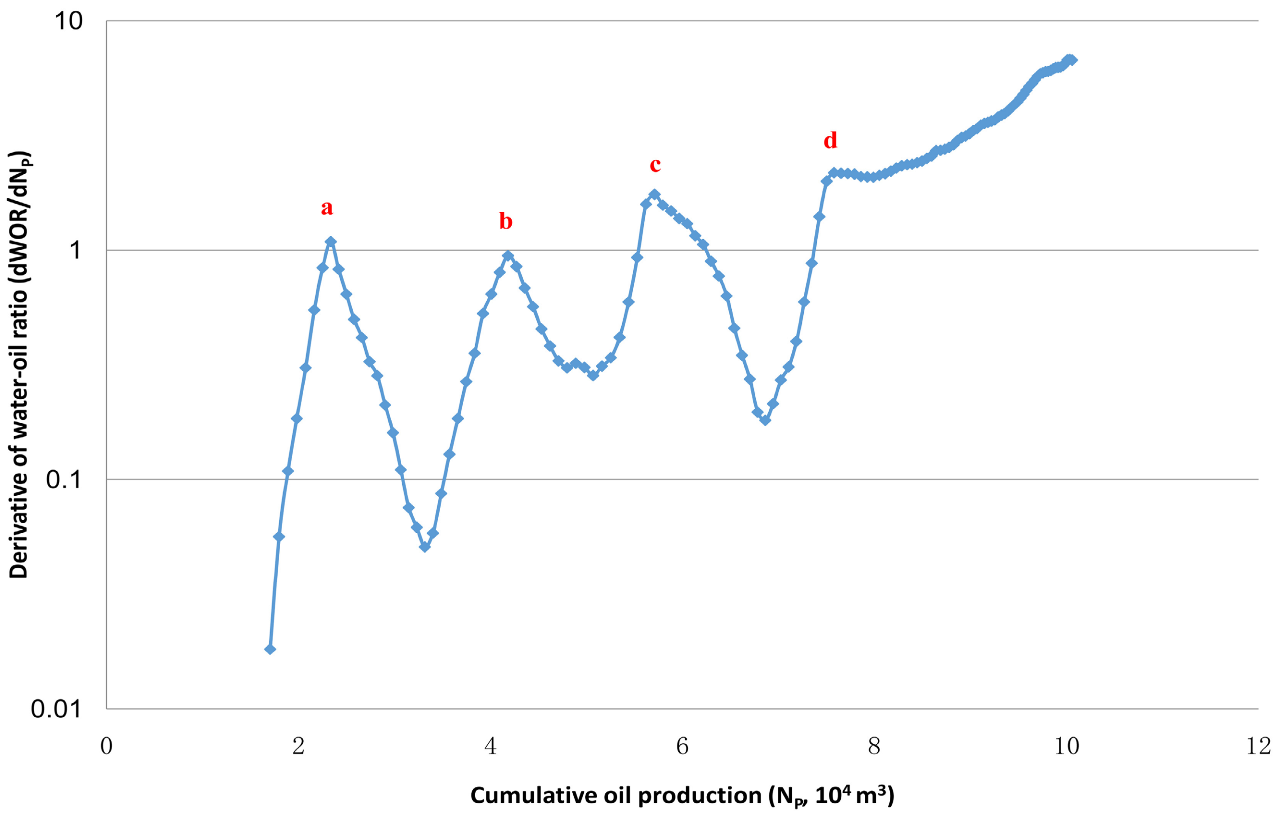

Figure 8. Relation curve between derivative of water-oil ratio and cumulative oil production of the horizontal well in five-point well pattern.

Based on the above analysis, the differences in injection volume, injection production well spacing, and injection timing lead to water breakthrough at multiple points and different times in horizontal wells, which will respond on the water-oil ratio derivative curve. The number of peaks represents the number of times the injection water has broken through.

5. Conclusion

1) By analyzing the characteristics of the water-oil ratio derivative curve of horizontal wells in water injection development oilfields, a method for identifying the time of water breakthrough in horizontal wells is obtained: after the injection water breaks through, the water-oil ratio derivative curve will appear as a wave peak.

2) The differences in injection volume, injection production well spacing, and injection time lead to multiple points and different times of water channeling in horizontal wells, which will have a significant response on the water-oil ratio derivative curve, forming peaks. The number of peaks represents the number of times the injection horizontal plane has broken through.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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