Diagnosis and Control of Excessive Water Production in a Yemeni Oilfield

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Abstract

The phenomenon of excessive water production (EWP) poses a multifaceted challenge to the oil and gas industry, affecting both economic and environmental dimensions. The identification of this issue is contingent upon the utilization of various methodologies, encompassing well testing, well logging, reservoir modeling, and analytical methodologies. Prominent among these is the Water-Oil Ratio (WOR) diagnostic plot technique, which stands out as the most straightforward and cost-efficient method for identifying the root causes of EWP issues. This research undertakes an examination of the diagnosis and management of EWP across nine wells within a Yemeni oilfield. The outcomes substantiate the presence of water production issues within all the wells under scrutiny. Upon comparing Chan's standard diagnostic plot with various WOR diagnostic plots, it becomes evident that the primary mechanism of EWP in all wells, except for two, is multilayer channeling via fractures or zones of elevated permeability. Considering this, it is advised to employ mechanical solutions for wells exhibiting near-wellbore water channeling, whereas chemical solutions are deemed more appropriate for addressing water production issues in other wells. The utilization of gel treatment methodologies, particularly those involving preformed particle gels, is recommended as a chemical solution approach. Furthermore, the study's outcomes indicate the necessity of a well selection process, ensuring the selection of suitable well candidates and the application of the appropriate water shutoff technique.

Introduction

The production of water is one of the most significant technical, environmental, and economic challenges that oil production faces. Water production decreases the useful lifespan of the oil reservoir and causes major issues such as fine migration, hydrostatic loading, and tube corrosion (Nmegbu et al. 2020). The environmental effects of managing, processing, and discarding produced water can have a significant negative influence on the profitability of oil extraction processes. The biggest waste stream resulting from the oil industry is produced water (Canbolat and Biotech 2016). On a global basis, oil companies are anticipated to produce 210 million barrels of water per day (Khatib and Verbeek 2002). Water production in the USA was roughly 21 billion bbls of water per year (Clark and Veil 2009), which is significantly more than the yearly productions of oil and gas, which are 1.9 billion bbl and 23.9 TCF, respectively (EAI 2006). Although it is more prevalent in outdated wells, problems with water production can also arise in newly drilled wells (Joseph and Ajienka 2010). In gas wells, higher gas injection is needed to lift the gas from the wellbore to the surface when there is an excessive amount of water production (Ahmad et al. 2012). Overproduction of water can be caused by a well issue (mechanical failure) or by other reservoir-related issues such as water coning, water breakthrough in high permeability zones, or water channeling from the water table to the well through faults or natural fractures (Al Hasani et al. 2008). In general, it is simpler to address water production issues related to well integrity, but when reservoirs are involved, managing water

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production becomes more challenging (Alexis 2010). To prevent unnecessary water production from planned wells, it is important to comprehend the formation features and field-specific issues (McIntyre et al. 1999).

Identification of the water production mechanism (WPM) is necessary for effective management of the water that is produced. The diagnosis of the WPM must be made with great precision before treatment (Chou et al. 1994; Kabir 2001; McIntyre et al. 1999; Prado et al. 2005; Sidiq and Amin 2008). Accurate diagnosis in complex flow regimes, especially in fractured deposits where water production may occur earlier than expected, is sometimes difficult and expensive to achieve (Sarkar et al. 2002). Coning and channeling are the main issues that result in the world's excessive water production (EWP), while the other issues are not as prevalent (Mahgoup and Khair 2015; Sarkar et al. 2002; Seright et al. 1998). Evidently, the two main components that contribute to the efficiency of the shut-off operation are comprehending the mechanism of EWP and locating the entrance of water in the wellbore. Finding water production mechanisms (WPMs) within a wellbore can be achieved through the utilization of either of two diagnostic techniques or strategies. A variety of analytical and empirical procedures that utilize production data make up the second category, while the first category mostly comprises survey and logging instruments (Chan 1995; Reynolds and Kiker 2003). For many operators, it has been common practice to utilize production logging tool (PLT) to identify the water inlet, choose the shutting-off strategy, and schedule the task. It's important to emphasize that due to the intricate nature of fluid entry mechanisms and the fluid dynamics involved in multi-phase flow within horizontal wellbores, advanced PLT is still constrained by certain limitations (Al Hasani et al. 2008; Hamdoon et al. 2024).

The water production mechanism has been studied through the development of various methods and techniques. Most of them involve specialized plots, such as time versus the linear water cut (Hwan 1993), graphical representations of linear water oil ratio (WOR) (Higgins and Leighton 1974), semi-log of WOR (Mungan 1975), X-plot technique (Ershaghi and Abdassah 1984), Wilhite's WOR approach (Willhite and Waterflooding 1986), Novotny's technique (Novotny 1995), diagrams of the WOR in log-log format (Chan 1995), the Egbe and Dulu approach (Egbe and Appah 2005), and the technique of Yortsos et al. (Yortsos et al. 1999).

The most widely utilized technique for identifying the water production mechanism is to utilize log-log plots of the WOR and its derivative (d(WOR)/dt) as a function of time (Chan 1995). It has been demonstrated that this approach is the most successful in identifying the source of problems with water production (Alexis 2010; Hamdoon et al. 2024). According to Abass and Merghany (2011) and Al Hasani et al. (2008), employing WOR plots in both vertical and horizontal wells is instrumental in diagnosing issues of excessive water production. Furthermore, the derivative approach is considered a singular and cost-effective method for identifying such problems.

Oil corporations are attempting to decrease water production through the implementation of water shut-off activities to enhance profitability. Water shut-off actions in the oil and gas sector can be carried out mechanically (utilizing a packer to insulate the wet zone and compress cement, and then selectively reperforating the higher part) or chemically (with polymers and other chemical compounds).

Several studies have effectively utilized diagnostic plots to pinpoint the mechanism and dynamics of excessive water production in oilfields. In this study, we focused specifically on WOR diagnostic plots due to their proven efficacy as analytical and empirical tools for analyzing oil production data and identifying water production issues. Since the field under study lacked PLT data, we analyzed production data utilizing Chan's diagnostic plots (the quickest, most dependable, and least expensive diagnostic technique available). By utilizing the WOR diagnostic plot, we successfully diagnosed excessive water production in a Yemeni oilfield. Subsequently, based on the diagnostic results, we recommended the appropriate water shut-off method to provide a practical solution to the water production issues.

Controlling Excessive Water Production. The primary issue with excessive water production during production in oilfields is the cost of separating, processing, and discarding extra water. These significant problems put a burden on the budgets of oil exploration and production corporations. Thomas et al. (2000) and Permana et al.

(2015) stated that reducing the amount of water produced will save operating expenses and, consequently, enhance company profitability.

Water shut-off is the best strategy for controlling and, in certain occurrences, avoiding excessive water production in oilfields (Alexis 2010; Sarkar et al. 2002). In order to ascertain nitrogen foam's capability to manage excessive water, Liu et al. (2012) looked into how the nitrogen foam solution affected the shut-off process. Through numerical modeling, they model the injection of foam into three vertical wells and one horizontal well. Their findings show that water control can be much improved in a horizontal well, but the shut-off technique did not work in the vertical wells that were evaluated. On the other hand, Sun and Bai (2017) carried out a thorough study of water control strategies employed in horizontal wells in order to provide water control options for different types of completions.

The techniques for shutting off the water were thoroughly reviewed by Taha and Amani (2019), who started by describing the problem of water production and then moved on to discuss several traditional mechanical and chemical options. Many choices for controlling water production were thoroughly explained by Kassab et al. (2021). The initial stage was water reduction techniques, which involved two recycling and reusing approaches as well as three distinct applications in three different wells.

To determine the optimal solution, every problem requires a distinct approach. Consequently, it is important to precisely ascertain the nature of the problem before attempting to treat water production issues (Elphick and Seright 1997). There are numerous sophisticated techniques for controlling and attacking WPMs. The most popular classifications for these techniques are mechanical, chemical, and completion solutions (Bailey et al. 2000). Reynolds and Kiker (2003) state that while every approach is effective for certain WPMs, it is rarely effective for others. Mechanical solutions include things like packers, plugs, and sleeves, whereas chemical solutions include things like cement, gels, resins, foams, emulsions, and polymers. Multilateral wells, double completions, and sidetracks are a few instances of alternative completion techniques. In a recent study, Chen et al. (2022) discussed the mechanisms and impacts of water shut-off using blind pipe in high water cut oil wells. Their conclusion suggests that the findings from the research can offer technical guidance for implementing water shut-off strategies and improving oil recovery using blind pipes in the designated oil reservoirs.

Mechanical packers can seal large openings near the wellbore as well as in the well hardware. In some cases, however, by getting into the tiny cracks or matrix that mechanical packers are unable to reach, sealing materials can shut-off the excessive water. Depending on the type of issue with water production, Bin Marta et al. (2024) reviewed the materials and procedures that can be taken into account to control and avoid the water production issue.

In fact, there are a variety of control choices available (mechanical, chemical, and combination solutions), depending on what kind of issue arose at the well. In most cases, a combination of remedies is needed to solve various issues effectively. Cost is a crucial consideration that will increase in combination with the complexity of the issue. The best choice for the candidate will assist in determining the appropriate approach. Combination solutions are frequent when there are several difficulties and shut-off solutions (mechanical or chemical) depend on the complexity of the issue. In cases of flow behind casing, leaks in the casing, and near-wellbore issues, mechanical solutions are the best option. Additionally, it might address water-out zones without creating issues with crossflow or the rise of oil water contact (OWC). Precise fluid placement is essential for chemical treatments. Coiled tubing with inflated packers might be utilized to make sure that the majority of treatment fluids are put in the target zone without posing a hazard to oil zones (Bailey et al. 2000). **Figure 1** illustrates the procedure of coiled tubing dual injection, which involves pumping protection fluid downward from the coiled tubing to the annulus of the casing and transporting treatment fluid through the coiled tubing.

For the past thirty years, the development and usage of gels to decrease water production and create stream barriers has been the focus of technical efforts for water control. Different types of gels were employed in different ways.

Numerous articles have documented the effective usage of preformed particle gels (PPGs), microgels, and submicron-sized particles to reduce water production from established oil fields. For instance, PPGs have been effectively used in over 5,000 wells (Bai et al. 2013). Diagnosis of the reservoir issue, selection of a suitable candidate choice of gel, design of parameters, and placement of gel are all necessary for the successful application of gel therapies. The special benefits that particle gels offer over conventional in-situ gels make them very exciting options.

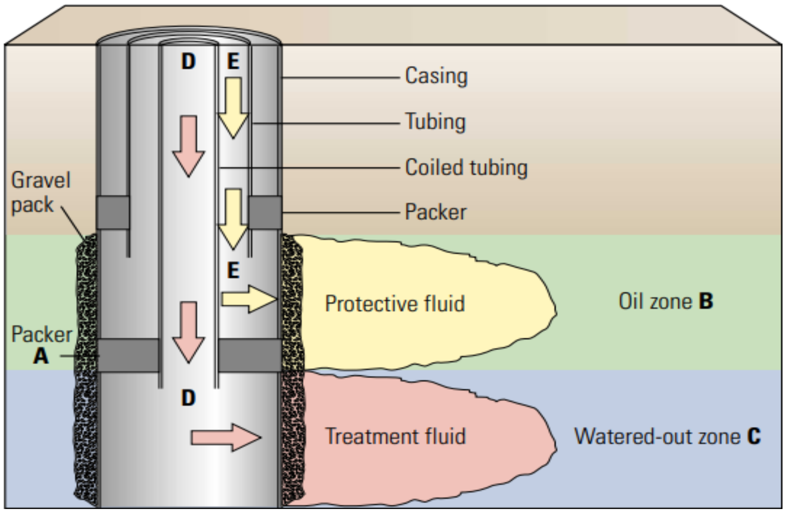


Figure 1—Water shut-off with chemical treatment fluid (Adapted from Bailey et al. 2000).

One of the important things that may affect the success of water shut-off operations is the proper well selection process. Before choosing a good candidate for water shut-off treatments, a great deal of data must be reviewed based on the available previous studies (Kabir et al. 1999). However, not all data and information are available and ready to be reviewed so that wells selection candidate were carried out using the available data as follows:

Production History. Selected wells for water shut-off treatments have a significant amount of water production, i.e. produced water > 4,000 BWPD. WOR and its derivative (d(WOR)/dt) plotted against time in a diagnostic log-log manner as explained by Chan (1995) can be very helpful to determine characteristic trends for different mechanisms whether the well has channeling or coning or combination. Those mechanisms were selected as consideration to select water shut-off treatments candidate.

Completion History. Historical water shut-off treatments which might have ever been completed at selected wells or offset wells were reviewed. Since there were good results of water shut-off treatments. This effort was going to be carried out again.

Wellbore Schematic and Well Log. Both data were reviewed and selected the wells which have perforation interval > 5 ft.

Structural Map and Cross-Sections. Both data were reviewed to avoid selecting the well located at the lowest structure of the field and as reference to comparing selected wells to other wells' location in the same structure.

It is imperative to perform an in-depth evaluation of the intervention technique and to promote the expected outcomes based on production performance data. **Figure 2** depicts the steps of the most proficient method to assess water production issues successfully. This technique is all-inclusive. It might not, nevertheless, be applied to all reservoirs because each one might have unique characteristics.

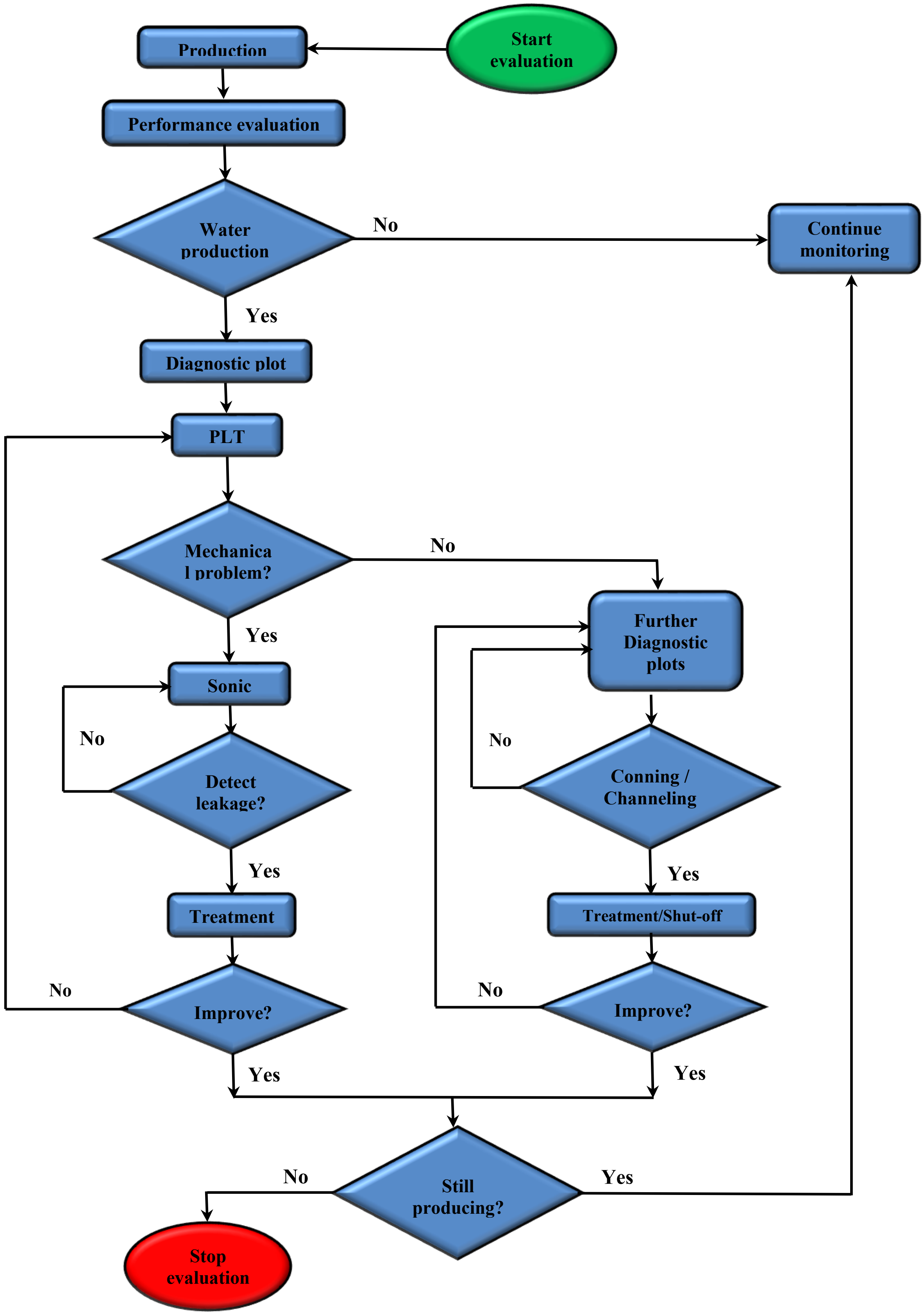


Figure 2—Flow diagram for intervention process and investigation of high-water-production wells.

Methodology

Data pertaining to production were compiled from the field, and subsequent procedures were executed to identify the issues associated with excessive water production. The initial phase in ascertaining the presence of water production issues involved the creation of a flow rate diagram delineating both water and oil production. Subsequently, the water production issues within the wells under examination were preliminarily investigated employing a recovery plot, decline-curve analysis, and production history plot. Per the recovery plot depicted in **Figure 3**, wells experiencing water production issues generally exhibit water production rates that have surpassed the economic WOR threshold.

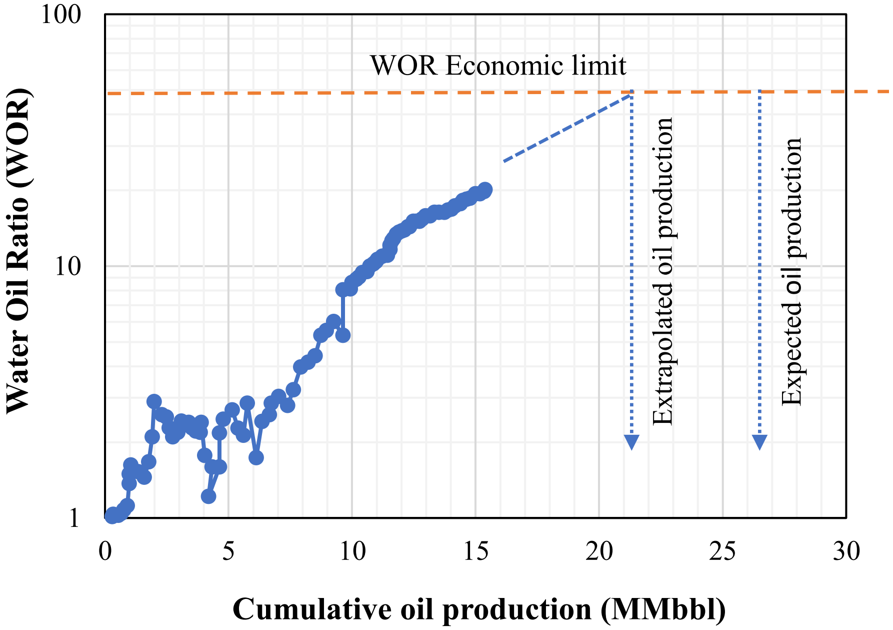


Figure 3—Recovery plot sample (modified after Bailey et al. 2000).

Water production commonly exhibits an immediate increase in tandem with oil production in wells experiencing water production issues (**Figure 4**). **Figure 5** illustrates the analysis of decline curves, indicating that when production is characterized by a linear trend, the reservoir's discharge is normal, and deviations in the graph’s slope denote alterations in water production.

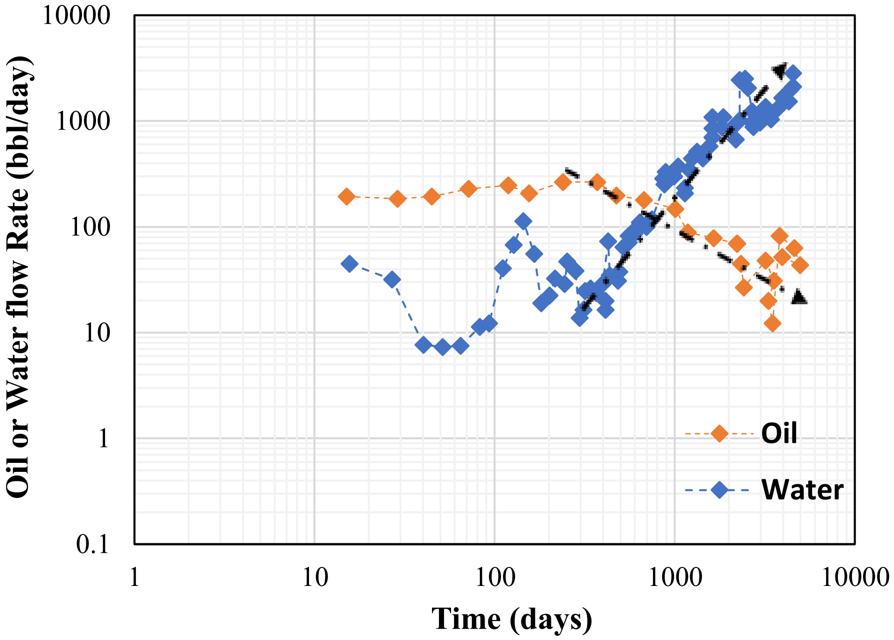


Figure 4—A sample plot of production history (modified after Bailey et al. 2000).

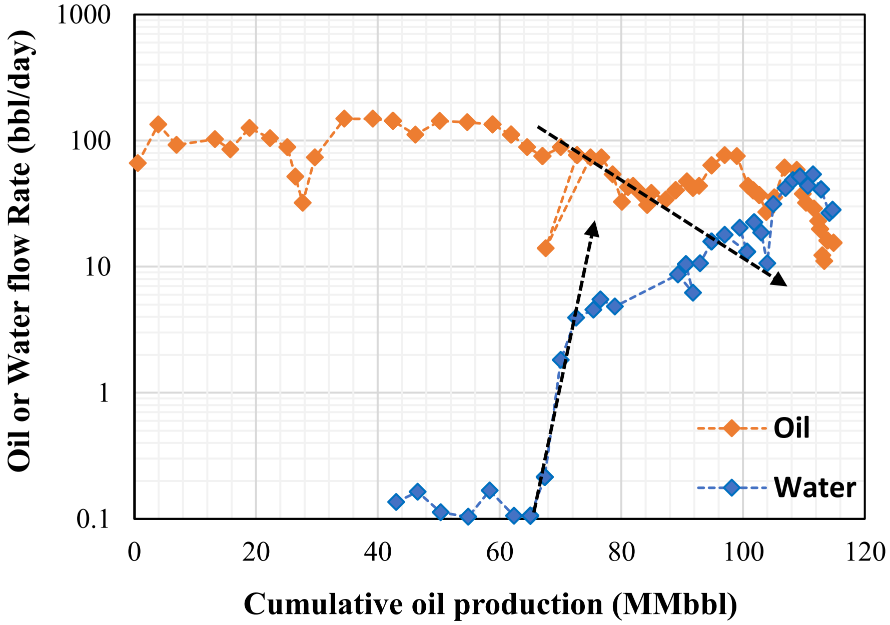


Figure 5—Decline curve analysis sample (modified after Bailey et al. 2000).

After confirming the existence of the water production problem, the Chan diagnostic plot was applied to investigate the water production mechanism. **Figure 6** illustrates how diagnostic plots are supposed to differentiate between the various mechanisms of water production. In a production well, log-log diagrams of the WOR time derivatives versus time are thought to be able to differentiate between water coning, channeling resulting from layers with high permeability, and normal with a high water cut.

For determining the cause of the issues with water production, the derivative method is thought to be the most suitable approach. As a result, this method is regarded as a one-of-a-kind approach and has been proposed as a straightforward, speedy, and cost-effective strategy for identifying mechanisms of excessive water production. The following is an illustration of the method for distinguishing and diagnosing water issues.

First and foremost, we utilize the actual rate of water and oil production to determine the value of the WOR and its derivative (d(WOR)/dt) by applying **Eqs. (1)** and **(2)**:

$$\mathrm{WOR} = \frac{Q_w}{Q_o}, \qquad (1)$$

$$\frac{d(\mathrm{WOR})}{dt} = \frac{(\mathrm{WOR}_2 - \mathrm{WOR}_1)}{(t_2 - t_1)} \qquad (2)$$

Thereafter, we plot the WOR and its derivative (d(WOR)/dt) versus time on a log-log scale. Finally, based on the Chan diagnostic plots as depicted in Figure 6 and with the assistance of **Table 1**, we can verify the mechanism and cause of the water production issue.

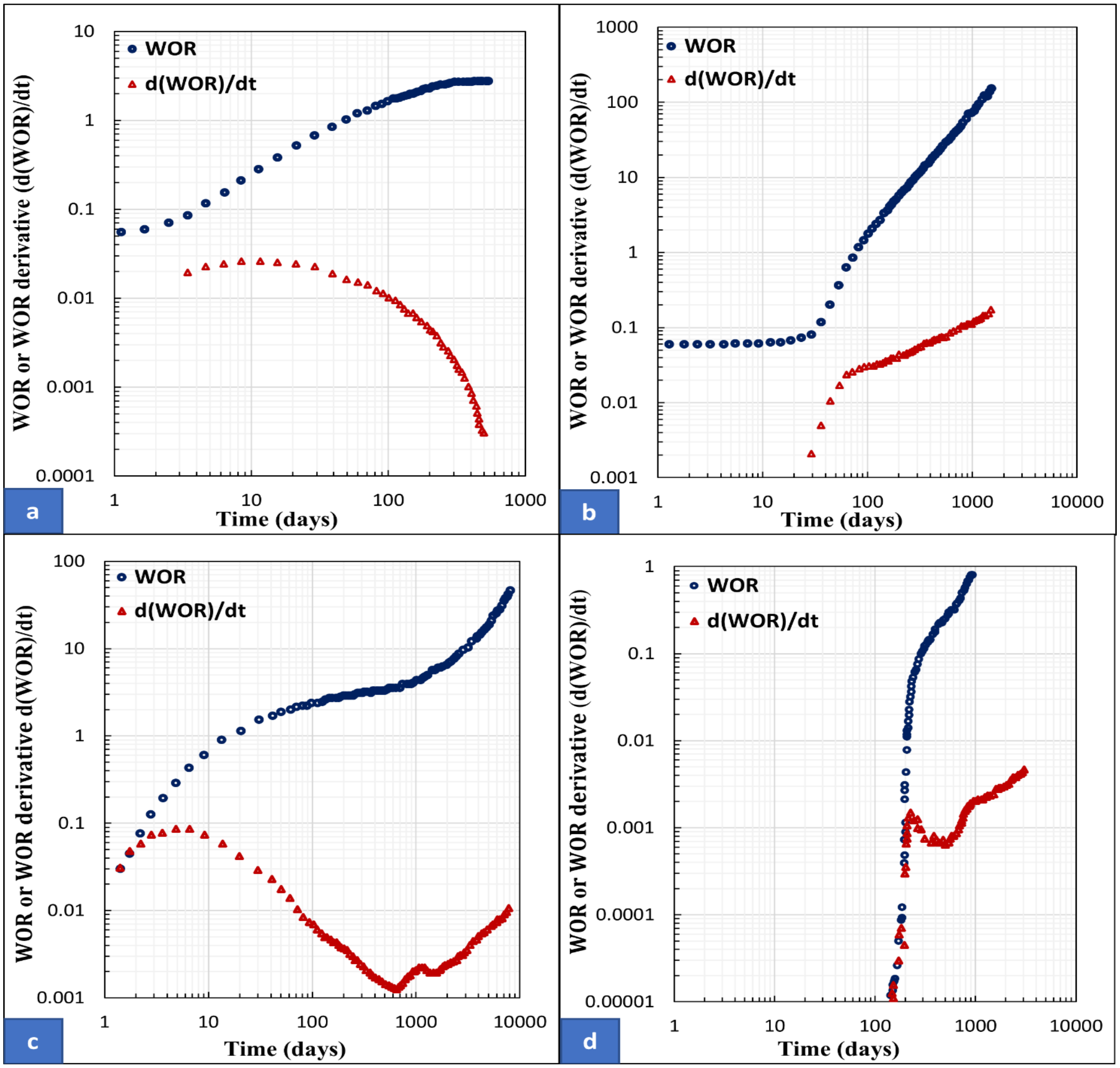


Figure 6—Chan diagnostic plots (modified after Chan 2010): a) Bottom water coning; b) Multilayer channeling; c) Bottom water coning with late time channeling behavior; d) Thief zone.

Table 1—The mechanisms and causes of water production problem (Adapted from Changalvaie 2012).

Slope of the WOR	Slope of the WOR derivative (d(WOR)/dt)	The probable cause of the water problem
Positive slope	Positive slope	Multilayer Channeling
Positive slope	Negative slope	Water Coning (Cusping)
Positive linear slope	Horizontal line	Shifting of the OWC

Case Study

The study area is in a noteworthy hydrocarbon-rich area in the east-central part of the Republic of Yemen. This oilfield was discovered in the year 2000 following the drilling of the second exploration well. It is located approximately 550 kilometers east of Yemen's capital, Sana'a. The field extracts oil from the Lower Cretaceous clastic deposits, commencing oil production in 2001. The study area, characterized by a flat topography, lacks distinct geological features and is situated at an elevation of around 950 meters above sea level. Presently, the field experiences an average water cut of about 98%. Cased-hole completions are predominant in this field, and early production involved a combination of outputs from multiple interval perforations.

The available dataset in this field includes core plug data, petrophysical data, production data, pressure volume temperature (PVT) data, as well as geological and seismic structural data. Core data consists of measurements of porosity and permeability, along with experimental assessments of oil and water relative permeability, water saturation, and capillary pressure. However, PLT data was missing. Hence, only production data is utilized for the analysis of this study.

According to both petrophysical and seismic structural data, the reservoir rocks predominantly consist of clean, porous, and permeable sandstone zones interspersed with claystone interbeds. Through well logging analysis, the clastic reservoir of this field is encountered at depths of approximately 4,817 ft.

Based on the well-logging data analysis, the reservoir has been subdivided into four distinct subunits, each exhibiting varying reservoir characteristics and hydrocarbon potential. Notably, the first and third subunits emerge as the primary hydrocarbon-bearing units. More specifically, the first subunit stands out as the most favorable unit, boasting the highest hydrocarbon saturations (oil saturation up to 65%) and optimal reservoir attributes. Across the first subunit, the average petrophysical parameters fall within the ranges of 4-21% for shale volume, 16-23% for total porosity, 11-19% for effective porosity, and 0-65% for hydrocarbon saturation. Conversely, the second subunit demonstrates inferior reservoir characteristics, with shale volume exceeding 30% and effective porosity falling below 15%. On the other hand, according to pressure and PVT data analysis, the reservoir fluid type is dead oil, exhibiting a notably low gas-liquid ratio (GLR).

Results and Discussion

Determination of the water production issue. The presence of the water production problem is determined by using three different types of plots. The first is known as the recovery plot, which shows the cumulative oil production and the logarithm of the WOR in graphical form, where the wells with excessive water production problems have water production exceeded the WOR economic limit (the rate of WOR at which the expense of managing delivered water is comparable to the cost of produced oil). In this case, water control procedures are required. The second graph is a logarithmic illustration of the flow rates of oil and water produced over time, referred to as the production history plot. It can be utilized to identify any "uncorrelated behaviors" during the field life cycle (Ilk et al. 2007). In wells experiencing issues with water production, there is typically a concurrent decrease in oil production and an increase in water production (Bailey et al. 2000).

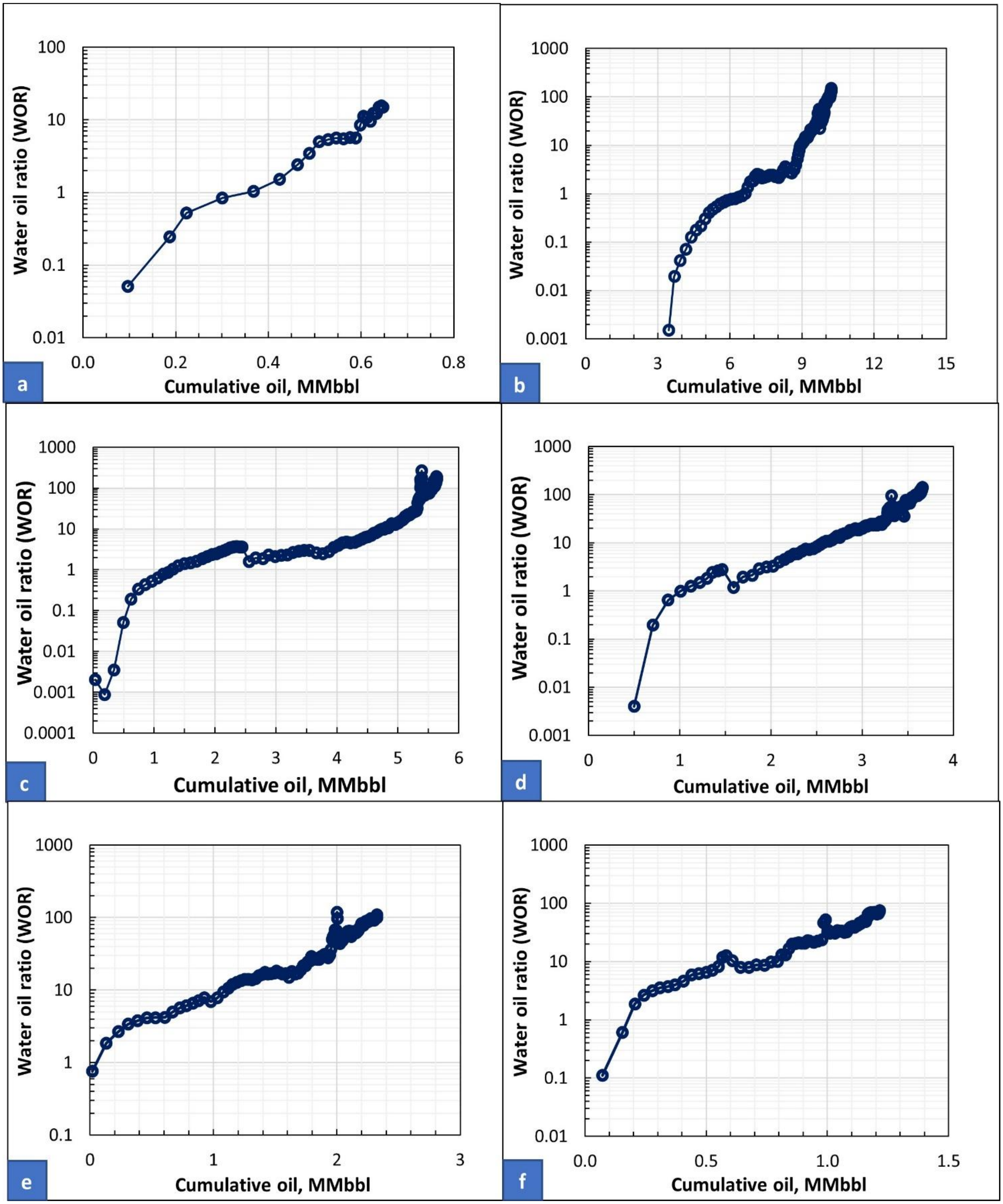


Figure 7—Recovery plots for six selected wells a)W-1, b) W-2, c) W-4, d) W-9, e) W-11, f) W-28.

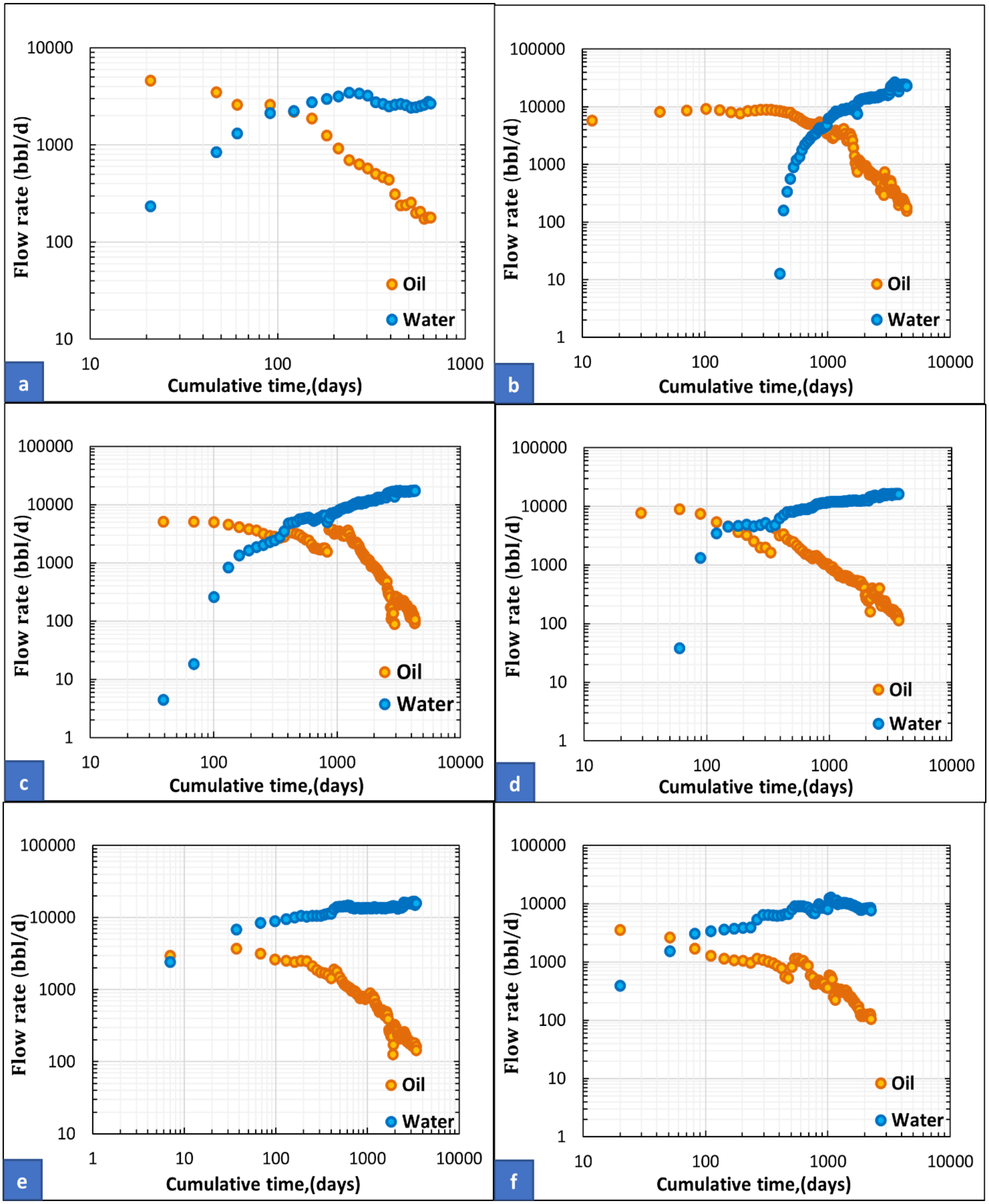


Figure 8—Production history plots for six selected wells: a)W-1, b) W-2, c) W-4, d) W-9, e) W-11, f) W-28.

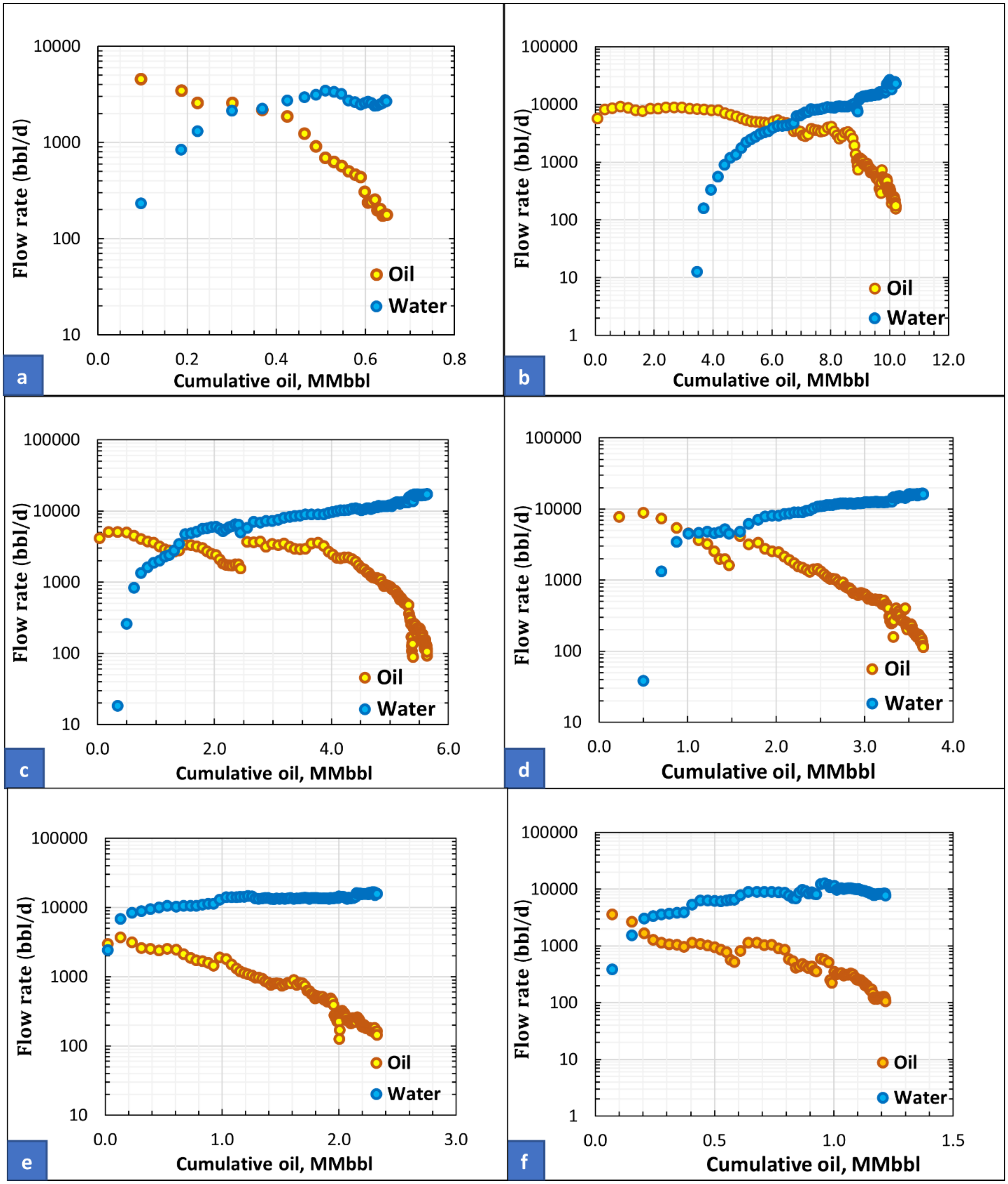


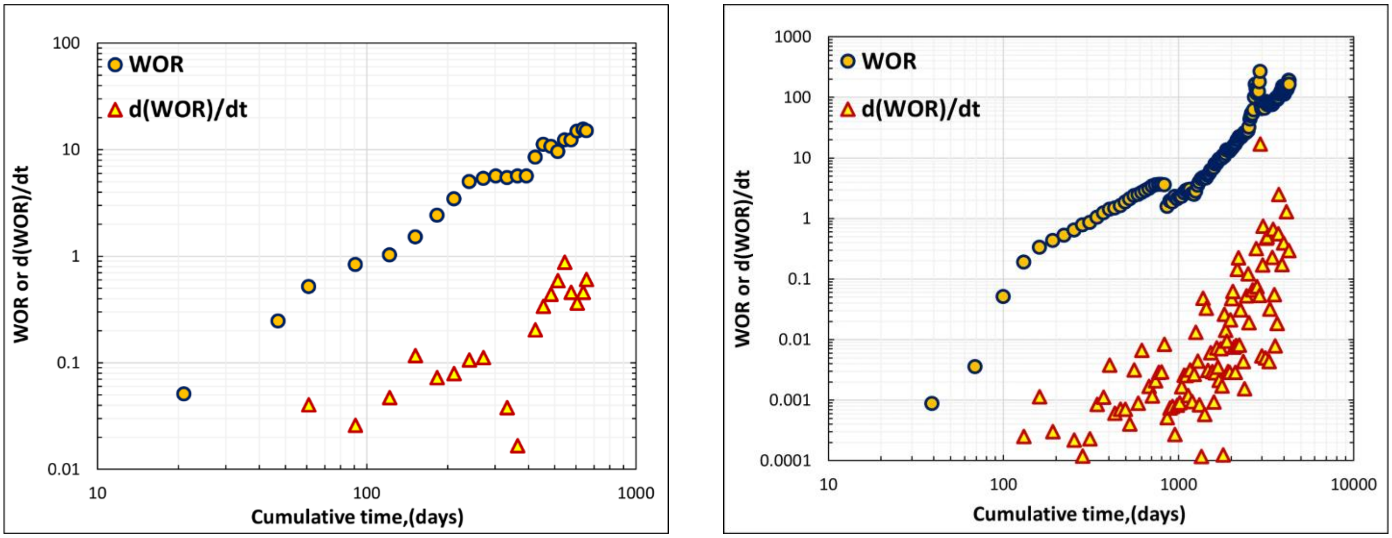
Figure 9—Decline curve analysis for six selected wells: a)W-1, b) W-2, c) W-4, d) W-9, e) W-11, f) W-28.

Plotting production rates versus time or the overall production of a field or well is the third form of plot known as decline-curve analysis (Bailey et al. 2000). It is often applied to forecast future well performance and identify production issues (Guo et al. 2007). Any abrupt changes in the decline's slope could be the result of an excess of water being produced. The accumulation of damage or severe pressure depletion, for example, may be signs of other problems rather than a water production issue; therefore, it is important to take into account any divergence from the anticipated future output predictions (Bailey et al. 2000). As seen in **Figure 7**, recovery plots have been created for six wells that were chosen for the current investigation (W-1, W-2, W-4, W-9, W-11, and W-28 wells). Water is produced approximately eight times more frequently than oil. The field's economic range is defined as the amount of water produced for every barrel of oil produced. That is, the proportion of water to oil is equivalent to one. Most of the graphs show identical results for exceeding the water production WOR economic limit, which indicates the existence of excessive water production problems.

Figure 8 illustrates production history plots for six selected wells under study. Water production has increased, and oil production has simultaneously decreased, which means these wells have a problem with water production.

On the other hand, **Figure 9** displays decline curve analysis diagrams for six wells in the research region that corresponds to the clastic sandstone reservoir. All the plots demonstrate that typical reservoir discharge occurs when production is represented by a straight-line diagram and that water production is indicated by a change in the graph's slope, which confirms the occurrence of excessive water production.

Diagnosing the water production problem. The approach of the WOR diagnostic diagram was utilized on nine wells in the oilfield to identify the origins of issues related to water production. The WOR and d(WOR)/dt log-log diagrams were plotted versus time utilizing the real production data for nine wells that were chosen for the current investigation (W-1, W-2, W-4, W-9, W-10, W-11, W-14, W-15, and W-28 wells), as shown in **Figures 10** to **13**. These graphs provide an image of the production activities of the past and present. It was discovered that these graphs were useful for figuring out the production trends and root causes of water production issues. The derivative of WOR has been discovered: an approach for identifying whether multilayer channeling or water coning is the major cause of a well's excessive water production issue. The diagnostic plot’s appearance may change because of production alterations. The production well's drawdown pressure as well as the corresponding injection wells' injection rates and layer injection distributions could alter because of these alterations. An excellent illustration of the WOR and d(WOR)/dt deviations from the linear slope in the second period could be found in Figure 10.



(a) W-1

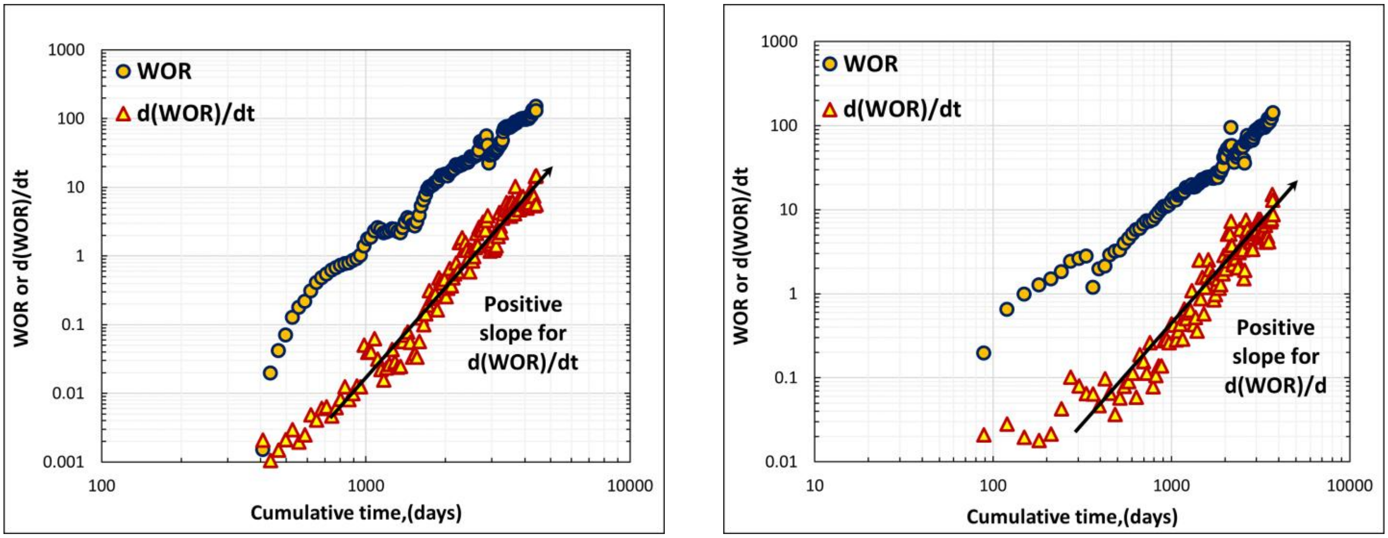
(b)W-4

Figure 10—Multilayer Channeling with production changes.

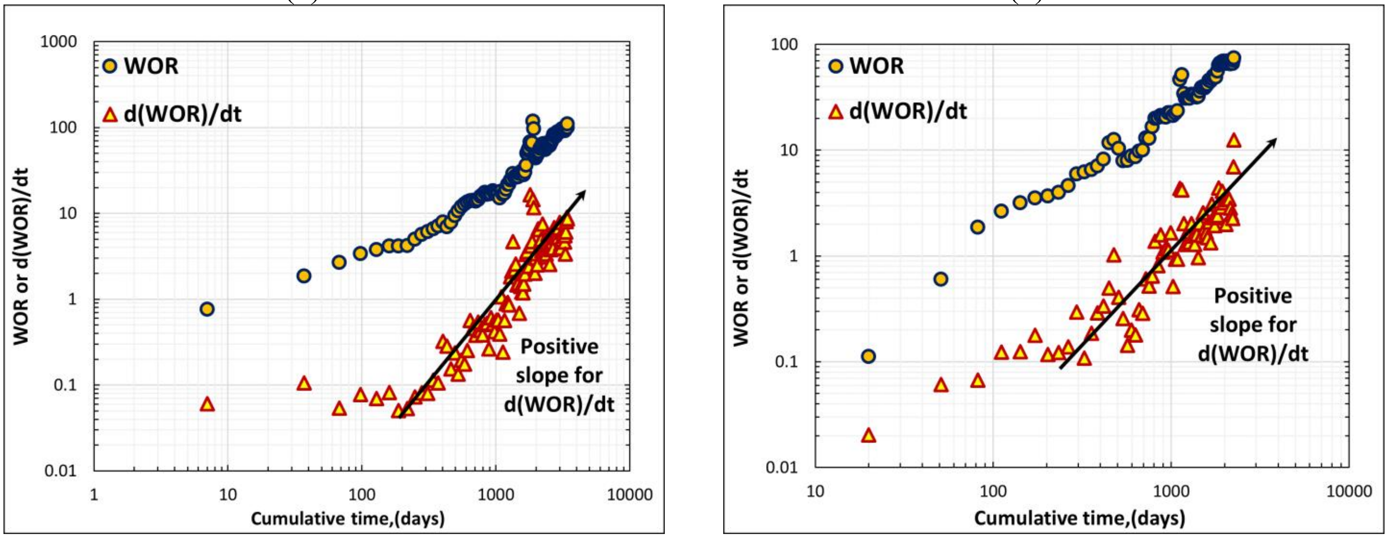
Figure 11 provides a good illustration of a multilayer sandstone formation’s typical production procedure. Observe that both the slope and the initial WOR departure point are identified clearly. During this second period, the d(WOR)/dt diagram clearly shows a linear and positive slope, suggesting a water channeling scenario. The extent of this period ranged between 2,500 and 4,500 production days.

In many cases, a near-wellbore issue might unexpectedly happen during a typical displacement and production process. Figure 12 depicts such a dramatic problem occurring in two sandstone wells under the study (W-10 and W-15). WOR was steady at first, but it was higher than 1. After applying a waterflood, the WOR rose quickly and had a linear slope. As of late, the WOR rise has been accelerating, and the slope has nearly reached infinity. This analysis was supported by the trend and progression of d(WOR)/dt. The crest of d(WOR)/dt was very high (about 500).

The starting WOR for certain reservoirs may be extremely high. Figure 13 provides a nice illustration. It's for a normal well (W-14) in the study area that produces from a sandstone formation. The original WOR was about 7 (80% water cut); this might result from a high initial water saturation. Normal displacement behavior is shown by the linear slope of the overall WOR trend.

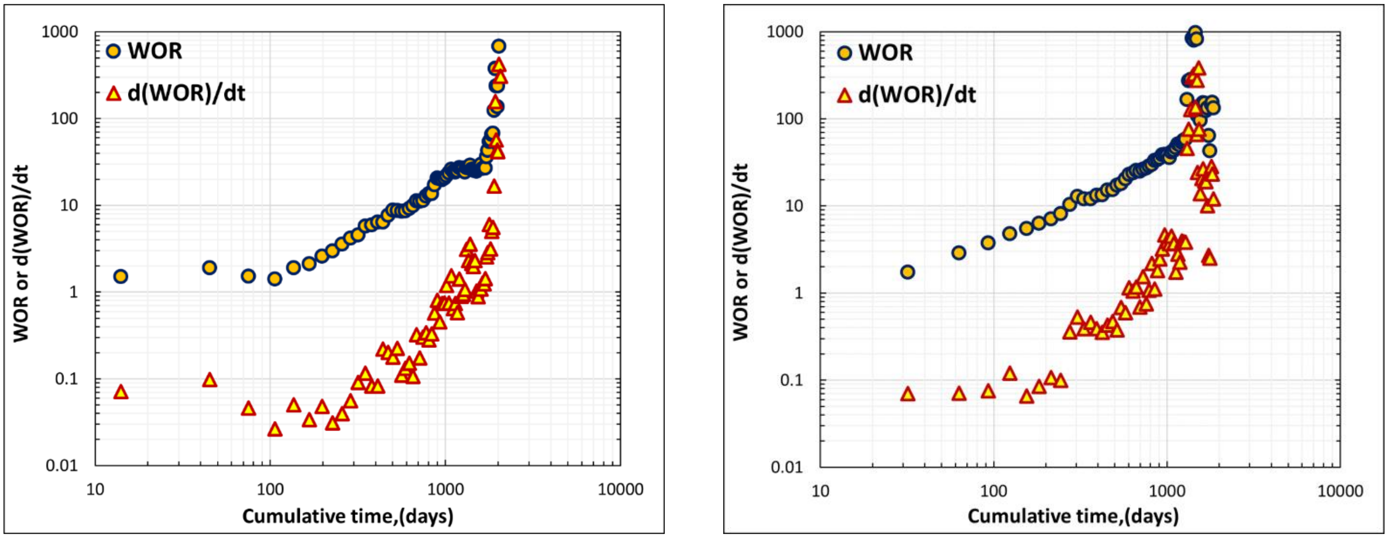


(b) W-2 (b)W-9



(c) W-1 (b)W-28

Figure 11—Multilayer channeling of various wells.



(d) W-10 (b)W-15

Figure 12—Near wellbore water channeling.

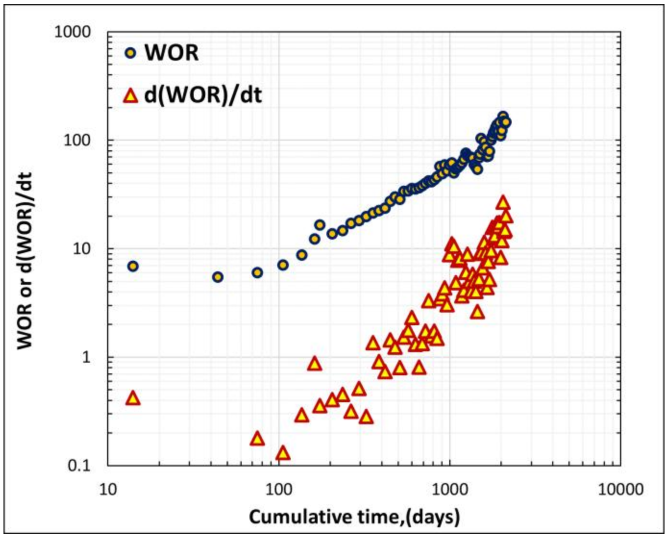


Figure 13—High WOR with normal displacement of W-14.

Conclusions and Recommendations

A diagnosis of excessive water production was established for nine wells in the Yemeni oilfield based on the production history data that was available. The analysis is carried out using a Chan diagnostic plot, a production history plot, a recovery plot, and a decline curve analysis. From this investigation, the most significant conclusions and recommendations are as follows:

1. All wells under study exhibit the existence of excessive water production issues, as confirmed by recovery plots, production history plots, and decline curve diagrams.
2. The findings indicate that multilayer channeling through fractures and/or zones with high permeability, alongside near-wellbore water channeling, are the main factors contributing to excessive water production observed in the field under investigation.

3. It is recommended to implement the well selection process to ensure the selection of the well candidate and apply the proper water shut-off technique to get the best water control before doing any water shut-off activities.
4. Based on the diagnosis results, it is recommended to apply the mechanical solution to the wells of near-well channeling, while the chemical solution is the best option to solve the water production problem in the studied field.
5. The application of gel treatment technology must be implemented carefully to achieve the chemical water shut-off treatment. Preformed particle gels (PPGs) are recommended due to their distinct benefits over conventional in-situ gels.
6. It is recommended that before doing any water shut-off activities, operators in the field advocate the implementation of the carbon/oxygen log to compare whether the perforation intervals have been watered out and whether fluid contacts have been shifted.
7. The diagnosis results indicated that the water cut in the investigation region was so high. As a result, it is advised to convert some of these wells to observation wells for use in the well interference test, which can be used to estimate the permeability direction and aid in the design of a good water flooding activity.

Nomenclature

EWP = Excessive water production
WPMs = Water production mechanisms
WPM = Water production mechanism
PLT = Production logging tool
WOR = Water oil ratio
d(WOR)/dt = Derivative of the water oil ratio
OWC = Oil water contact
WSO = Water shut-off
PPGs = Preformed particle gels
BWPD = Barrel water per day
PVT = Pressure Volume Temperature
t = Cumulative time.

Conflicting Interests

The author(s) declare that they have no conflicting interests.

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