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Diagnosing and Controlling Excessive Water Production: State-of-the-Art Review

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Abstract

The oil and gas sector faces a complex issue with excessive water production (EWP), having substantial economic and environmental consequences. The reasons that lead to EWP are called water production mechanisms (WPMs). They are classified into mechanical, completion, and reservoir problems. Each water production mechanism (WPM) needs a certain form of treatment that is suited to that situation. However, controlling water production becomes more difficult when it is related to reservoir problems. Therefore, understanding these reasons is essential to properly analyze the current situation and design the best solution for the problem. It is essential to pinpoint the problem's source first as the probability of a successful remedy is limited without a suitable diagnostic method prior to implementing a treatment strategy. Well testing and logging methods, and analytical and empirical approaches are the traditional techniques for WPM diagnosis. This paper investigated the most modern and successful strategies used to diagnose the source of EWP and suggest the proper water shutoff technique. This paper shows that the diagnostic plots derivative technique is the best way to determine the reason for EWP problems. These plots, however, should be used in conjunction with other approaches like production logging and reservoir modeling. Then, chemical, or mechanical treatment techniques can be used to stop EWP depending on the cause of the production. Mechanical techniques should typically be employed when dealing with water production management in the wellbore or adjacent to the wellbore. In contrast, chemical techniques must be utilized for matrix or fracture plugging.

Introduction

One of the most important issues associated with hydrocarbon production is excessive water production. On a worldwide scale, oil firms are expected to generate 210 million barrels of water every day [1]. Water production in the USA was roughly 21 billion barrels per year [2], which is significantly more than the yearly productions of oil and gas, which are 1.9 billion bbls and 23.9 TCF, respectively [3]. Even though this issue is more common in ancient wells, water production problems may likewise happen within recently drilled wells [4]. Excessive water production results in several economic issues for oil corporations. First of all, it reduces the performance and longevity of producing wells. The fluid column's weight is increased by the presence of water in the wellbore, necessitating more lifting [5]. Also, unreasonable water production can accelerate pipe corrosion if the crude oil is sour [6].

Excessive water production may be caused by a well issue (mechanical failure) or by reservoir factors such as water coning, water breakthrough in high permeability zones, or water channeling from the water table to the well through natural cracks [7]. Arentz [8] utilized a conservative estimate of one dollar per cubic meter for the management of produced water, which included lift, treatment, and disposal. Understanding the formation characteristics and the field's particular problems aids in avoiding unnecessary water production from the wellbore planned [9]. Many studies have been developed to diagnose and control the reason for excessive water production. This paper reviewed the most popular and commonly used techniques to diagnose the reason for excessive water production and determine the proper solution.

Water Production Mechanisms

The reasons for excessive water production are called Water Production Mechanisms (WPMs). Previous studies have classified these WPMs according to the authors' interests and the purpose of their work. Seright et al. [10] classified WPMs depending on the degree of treatment complexity into four categories, which are more relevant to the design and implementation of water production management strategies, as shown in Table 1. On the other hand, Arnold et al. [11] stated the 10 main WPMs that could be encountered during water production; these mechanisms range from the simplest to the most complex one, as depicted in Figure 1.

Table 1 Classification of WPMs base on treatment complexity (After Seright et al.[10])

Treatment Class	Water Production Mechanisms (WPMs)
Class A Traditional remedies	• Casing leaks with no movement restrictions. • Flow without limitation behind the pipe. • Nonfractured wells (injectors or producers) with efficient crossflow barriers.
Class B Remedies with gelants	• Casing leaks with movement restrictions. • Movement without limitation behind the pipe. • "2D coning" across an aquifer hydraulic crack. • A natural facture system that leads to an aquifer.
Class C Therapy using pre-made gels	• Fractures or faults that go through a directional or horizontal well. • Channeling among wells caused by a single fracture. • The natural fracture system permits well-to-well channeling.
Class D Gel therapies should not be utilized for difficult issues	• 3D coning. • Cusping. • Crossflow channeling through strata without fractures.

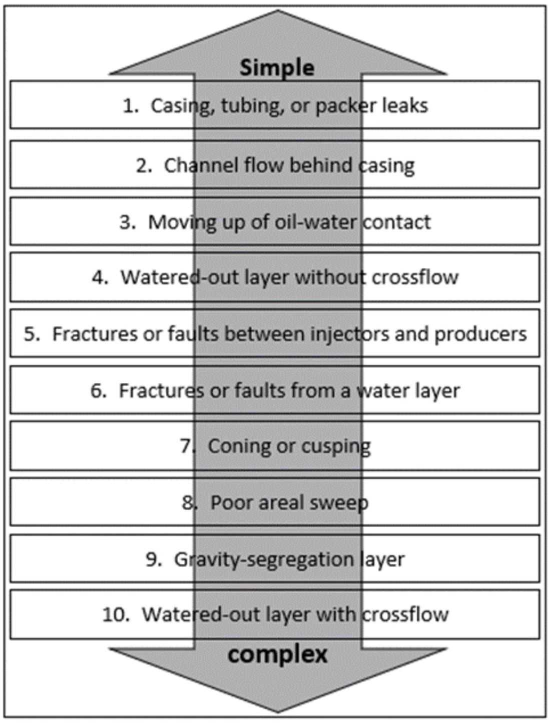

Figure 1 The main ten WPMs, ranging from the simplest to the most complex (After Arnold et al. [11])

Sheremetov et al. [12] categorized the WPMs based on the position of the water intake into the well and utilized this categorization to establish the needed input factors for their research. The WPMs categorization was introduced by Reynolds and Kiker [13] and Del Bufalo Paez [14], depending on the nature and sources of the issue. They categorized the WPMs as mechanical, completion, and reservoir-related issues. Mechanical issues include holes in casing (as seen in Figure 2), tubing, and packers caused by corrosion, wear, and splits due to the flow, high pressure, or formation deformation. Flow behind the casing, shifting oil-water contact, and fractures or cracks in the water layer are completion-related issues as shown in Figure 3. Water channeling across layers of extreme permeability or faults and fissures and water coming from a nearby water region are two examples of reservoir issues depicted in Figure 4 [15]. Water production issues connected to well integrity are often simpler to resolve, but if these problems relate to the reservoir, controlling water production becomes more difficult [16]. The most significant issues that contribute to global excess water production are channeling and coning; other issues are less common [17–19].

Identifying Water Production Mechanisms

The water production mechanism must be identified in order to effectively control the produced water [7,16]. Seright et al. [10] and Baily et al. [20] underlined that the primary cause of ineffective and failed water management remedies in the industry was a lack of comprehension of the water production mechanisms. They explained that some oil exploration and production (E&P) companies checked the application of the water shutoff technique without the process of using diagnostic procedures, which made it not successful. However, Chou et al. [21] showed that there is always communication between injection well and production well in the water shutoff technique, and this technique should involve diagnostic procedures [22]. Precise diagnostics in complicated flow regimes, especially in cracked deposits wherever water production might occur earlier than planned, are sometimes difficult and expensive to achieve [23].

A review of the previous studies reveals that numerous authors believe that a correct diagnosis for the water production mechanism (WPM) is required prior to every therapy process [21,22,24–26]. An adequate and quick diagnosis of the WPM is necessary whenever it is desired to use a controlling technique (mechanical or chemical shutoff). However, incorrect diagnosis results in ineffective treatment or inaccurate control, both of which waste time and money [17]. This paper discussed the most popular and commonly used techniques to diagnose excessive water and what the proper solution is for each problem.

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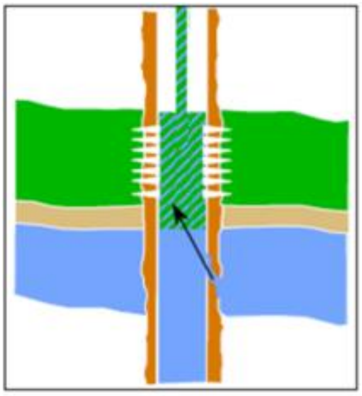
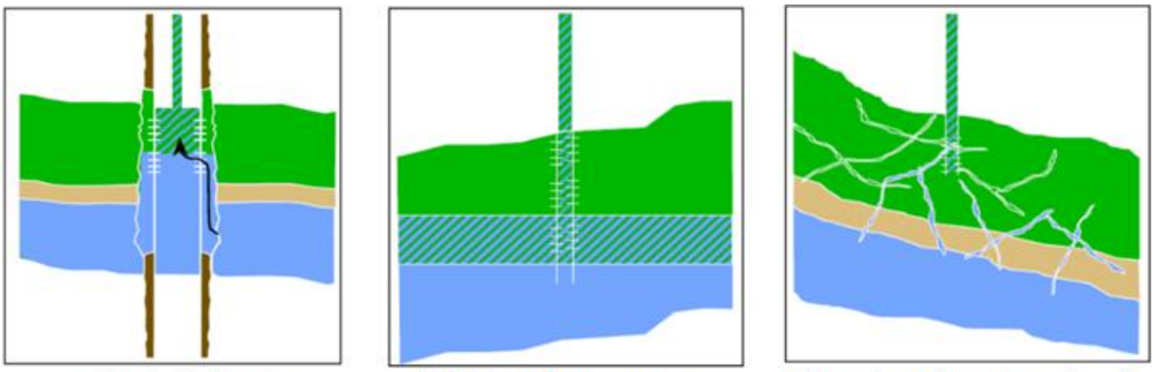


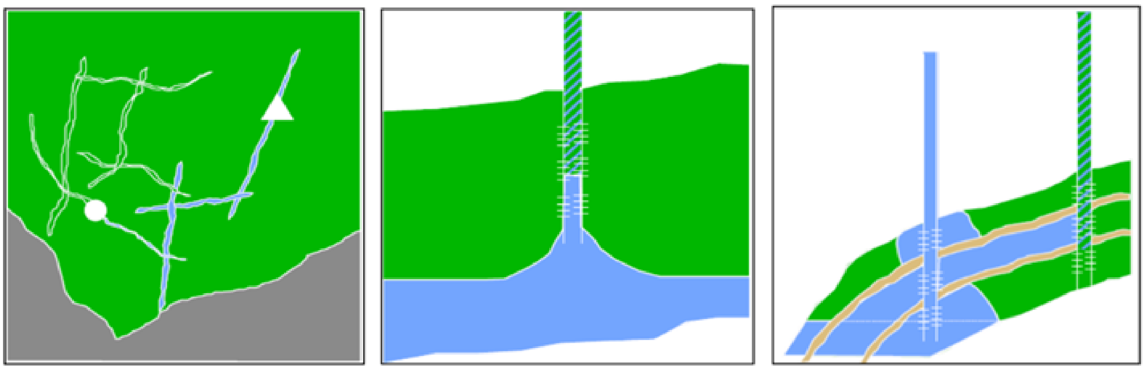
Casing leak

Figure 2 Mechanical issues example (After Elphick and Seright [15])



a. Flow behind casing | **b.** Shifting oil-water contact | **c.** Water layer fractures and cracks

Figure 3 Examples of issues due to completion (After Elphick and Seright [15])



a. Cracks between producer and injector | **b.** Water cusping or coning | **c.** High permeability layer without Crossflow

Figure 4 Examples of issues associated with reservoirs (After Elphick and Seright [15])

Fondyga [27], Reynolds and Kiker [13], and Bailey et al.[20] reviewed known diagnostic methods and approaches for finding WPMs in wellbore. There are two kinds of approaches that exist. The majority of the equipment in the first category is utilized for logging and surveying in order to evaluate and track the well, reservoir, and fluid flows' physical characteristics. Analytical and empirical procedures in view of production information make up the second category. In view of the characteristics of the reservoir and the fluid, other authors have developed less prevalent WPM diagnostic strategies [28–31]. Traditionally, the production logging tool (PLT) is used to identify water inflow zones when the water cut rises excessively at extreme levels. Logging tools and their application might be costly. Sometimes it is necessary to shut down the well while logging, which has an impact on the production rate and income, and the processing of log data, as well as their analysis and interpretation, can be costly and time-consuming [32]. The abundance of information included in log data is likewise difficult for human intelligence to comprehend [33]. Al Hasani et al. [7] highlighted the limitations of production logging tool (PLT) in horizontal wells. The difficulty in detecting downhole fluid holdups and fluid velocities as well as the complex flow dynamics imply that PLT can only be utilized in horizontal wells in limited circumstances. Furthermore, except for a very small number of instances, good logging technologies are unable to diagnose the type of WPM. Well diagnostics are commonly used in the oil industry to locate the well's water entry point, select candidate wells for treatment, and determine whether excessive water production exists.

This paper extensively examines analytical and empirical techniques (second approach for discovery WPMs) for analyzing oil production data, such as a decline curve or plots of the proportion of water to oil (WOR) versus the total amount of oil produced over time or time as mentioned in previous researches [20,34–37]. The following is a brief description of these plots:

Recovery Plot

Figure 5 depicts a recovery plot, a type of semilogarithmic graph based on the proportion of water to oil (WOR) to the total volume of oil produced over time. The entire quantity of the produced oil from a reservoir at any given point in the field's life cycle is referred to as cumulative oil production. The recovery plot may be utilized to extrapolate the final oil recovery and forecast future performance. The quantity of oil produced with no water production remediation is depicted at the intersection of this plot and the economic WOR plot. The rate of WOR at which the expense of managing delivered water is comparable to the cost of produced oil is referred to as the economic WOR limit. The extrapolated production is equal to the anticipated reserves if the well is producing enough water. Otherwise, excess water production necessitates water control treatments if the expected oil reserve for that well is less than the predicted oil production at the WOR economic limit [20].

Plot of History Production

Figure 6 illustrates a logarithmic chart of oil and water production flow rates as a function of time. During the field life cycle, rate changes can be visualized, and any "uncorrelated behaviors" can be evaluated with this plot [38], for instance, changes in rate with no alterations in pressure. According to Bailey et al. [20], wells with water production issues typically exhibit both a decrease in produced oil and an increase in produced water simultaneously.

Analysis of Decline Curve

A basic component of a decline curve analysis is a plot of production rates versus either time or overall production of a field or well [20]. It is frequently used to identify production issues and predict future well performance [39]. The decline curve graphic assumes that previous production trends and conditions may be extrapolated to predict how production will behave in the future. Figure 7 depicts a simple and uncomplicated method of examining an oil well's excessive water production problem by drawing the rate of oil production versus the collective oil production. A steady rate of decline that follows a straight line is what we mean when we talk about the normal depletion; overproduction of water could be the cause of any sudden shifts in the slope of the decline. Any variation from the predicted predictions of future production, however, does not always indicate a problem with water production and may be an indication of other issues like severe pressure depletion or the accumulation of damage [20].

Choke-back and Shut-in evaluation

In addition, Bailey et al. [20] recommend using a diagnostic tool for WPM investigations to analyze WOR behavior during choke-back and well shut-in periods. They emphasize that the decrease in WOR during shut-in or choke-back could be caused by a water coning or water flowing from a fissure crossing a deeper water layer. On the other hand, the WOR value is thought to rise when water from fissures or faults intersects a water layer below.

Nodal Investigation

Nodal investigation is a process that determines how a production system is designed based on the performance of the reservoir and the downhole tubing, or reservoir "plumbing" system. One of Bailey et al.'s [20] suggested strategies is nodal investigation to analyze WPM. The pressure loss via four subsystems from the reservoir bottom to the surface equipment accounts for the overall fluid pressure loss in the production system. The porous medium, well completions, tubing string, and flow line are examples of these subsystems [40]. The total pressure drop in the production system is inversely related to the entire amount of fluid that is produced from the reservoir to the surface. As a result, it is necessary to analyze the entire production system as a single unit. As shown in Figure 8, Clegg and Lake [41] displayed a nodal approaches diagram for the purpose of evaluating the sensitivity of three distinct outflow component combinations, designated A, B, and C. They explained that there is no continuity and no intersection with the inflow performance curve, so the well won't be expected to flow with System A for outflow curve A. Because continuity is satisfied when the outflow performance curves B and C intersect with the inflow performance curve, the well should produce at the rate and pressure indicated by the intersection points. There may be a problem if the rates differ from what is anticipated. Nodal investigation is a helpful technique for examining how a production system behaves, but it necessitates a thorough comprehension of the fluid flow throughout the entire system, which is frequently lacking in practice [41]. In order to locate the excessive flow resistance that causes significant pressure losses in tubing systems, a nodal investigation can be used. Any change to a system component can affect how quickly things are produced [42]. For instance, it's a widely held belief that preventing a well from producing water will lessen the water cut. This is definitely the case of traditional coning. In other situations, it is based on the nature of the issue and the reservoir pressures. For instance, the WOR (measured when the well is put back on the production line) will depend on the water issue and pressures involved if a well is shut in for an extended period of time. Renpu [40], Clegg and Lake [41], Guo et al. [39], Beggs [42], and Bailey et al. [20] provide a more in-depth explanation of the theory and practice of nodal analysis.

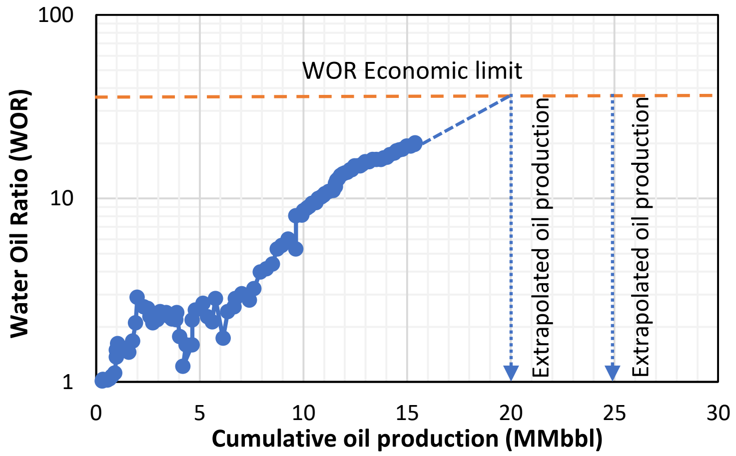


Figure 5 Sample of recovery plot (After Bailey et al. [20])

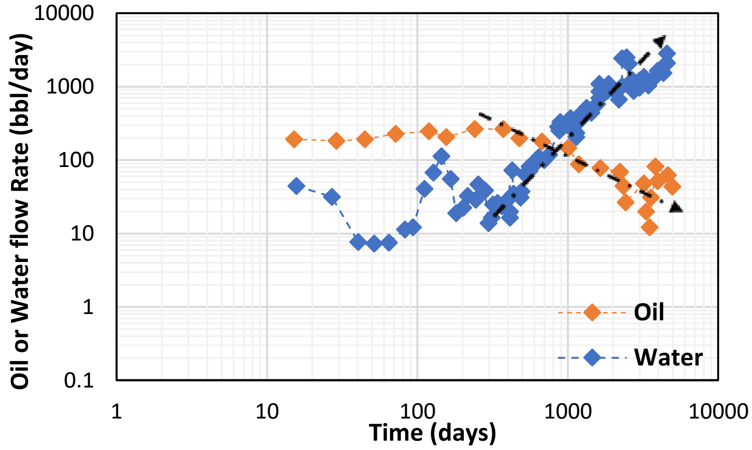


Figure 6 An illustration of a plot in production history (After Bailey et al. [20])

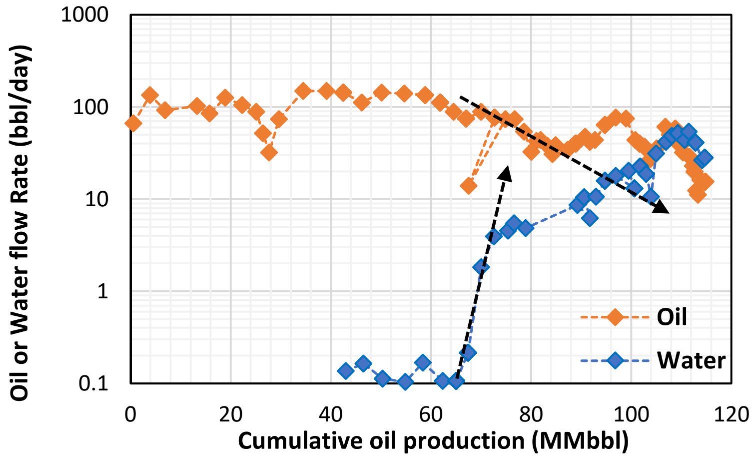


Figure 7 An illustration of a decline curve analysis (After Bailey et al. [20])

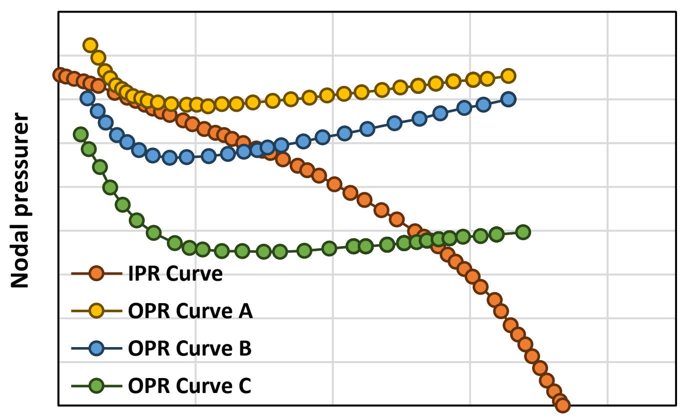


Figure 8 Curves for the inflow and outflow of nodal systems (After Clegg and Lake[41]).

Diagnostic WOR plots

The "X–Plots" that were developed by Ershaghi et al. [43] were applied to clarify and extrapolate the production of oil and water. One-dimensional Buckley Leverett modeling was used to create these plots, which have been successfully utilized in the field to evaluate production efficiency. The fact that the X–plot does not provide any diagnostic information regarding the source of water production is a major flaw.

Using production data and the Darcy flow equation, Novotny [31] established a method for verifying the potential water production source. He derived the magnitude of the shift in the predicted value of the formation's absolute permeability obtained from the reservoir's normal oil/water relative permeability ratio, which he used as the basis for his diagnosis. This kind of identification was entirely dependent on predicted absolute permeability, which didn't think about the detected series of time and was heavily reliant on the obtainability of a "reliable" relation between the reservoir's relative permeabilities.

Utilizing log plots of the water oil ratio and its derivative (WOR/(d(WOR)/dt)) versus time is one of the most well-known strategies for figuring out where water comes from [18]. This strategy has been shown to be the most effective method of determining the source of water production issues [16]. Chan used numerical simulation to create his plots to examine how (WOR/(d(WOR)/dt)) changed over time under various production mechanisms. According to Chan's assessment, the WOR vs Time plot for both coning and channeling shows three behavioral stages, as shown in Figure 9. As a theoretical model for controlling and treating oil and gas wells that produce too much water, the Diagnostic Plots derivative approach was proposed [18]. The mechanisms of channeling and coning were examined in these plots, as can be seen in Figures 10 and 11. The derivative of the water oil ratio (d(WOR)/dt)) has a negative slope that changes for coning while remaining approximately constant for channeling

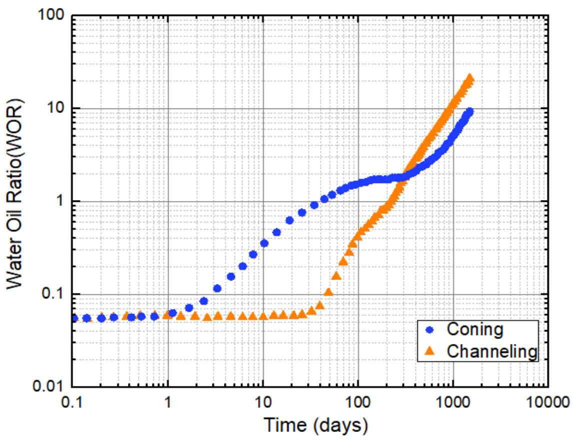


Figure 9 Comparison of channeling and water coning WOR (After Chan K.S. [18])

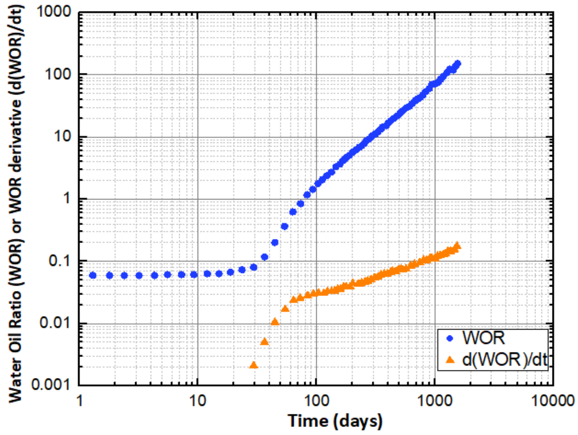


Figure 10 Multilayer channeling WOR and its derivative (d(WOR)/dt) (After Chan K.S. [18])

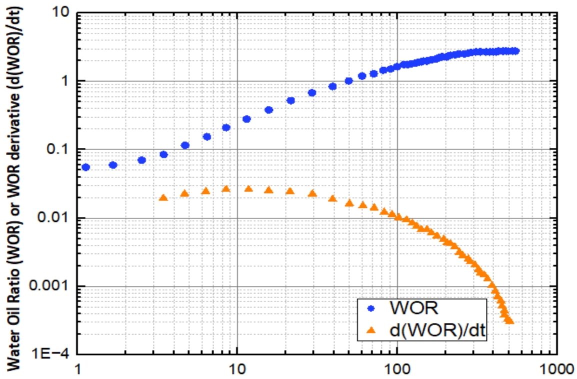


Figure 11 WOR and its derivative (d(WOR)/dt) Bottom water coning (After Chan K.S. [18])

Seright et al. [19] contradicted the utilization of WOR plots as an indicative instrument for WPM recognition. They discovered that the WOR and d(WOR)/dt diagnostics plots are not universal and are susceptible to being interpreted incorrectly; subsequently, they should not be utilized alone to figure out what's causing too much water production. Love et al. [44] and Stanley et al. [45] presented two examples of successful water treatment research design in New Mexico and Indonesia, separately. In any case, it is pivotal to take note of that in the two investigations, the WOR diagnostic plots were utilized as an enhancement to different approaches, for example, production logging and reservoir modeling, rather than as a stand-alone technique.

Yortsos et al. [37] carried out an analytical and numerical study on the water flooding process and showed that the well pattern and the reservoir relative permeability could be related to the late time slope of Chan's diagnostic in a log plot. They successfully demonstrated that the "X–plot" is a unique instance of the 1-D-6 displacement at average time after conducting their research in one, two, and three dimensions. Even though the work done with the Yortsos and Chan groups is one of the best methods for figuring out where produced water might come from, the time-domain analyses still introduce noise into the results.

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The application of WOR Plots for vertical and horizontal wells including, a diagnostic derivative method of water production problem was considered a unique, and inexpensive method of identifying excessive water production [7,46].

By using spectral analysis of production data, Egbe and Appah [30] suggested a procedure aimed at identifying oil well water coning issues. They modified the WOR plots based on utilizing Fourier transformation to change surface WOR from the time space over completely to a range of frequencies. Energy distribution, correlation structure, and spectral bandwidth for both non-coning and coning processes were discovered through the utilization of the autocovariance function and the spectral density function. They concluded that periodic spectra with a narrow spectral breadth were represented by wells with a coning problem.

Gasbarri et al. [28] proposed a method for diagnosis that makes use of multiphase flow meters and transient tests. Three fundamental models of producing water mechanisms involving water channeling, coning, and the stream behind casing were created through reservoir simulations. Distinct ranges of a number of characteristics, including the API gravity, amount of production, permeability proportion, and width of the stream channel behind the casing, were utilized to construct various examples of the aforementioned basic cases.

An empirical approach for modeling and forecasting the edge–water coning problem was established by Ayeni [29]. Using a variety of model variables, he executed many reservoir simulations. As a consequence, practical relationships between reservoir properties and model factors have been discovered. For the purpose of estimating the time of breakthrough, rate of crucial streams, and performance of WOR after a water breakthrough, these empirical correlations were suggested.

Rabiei et al. [47] used WOR data and static reservoir metrics to diagnose the mechanisms of water production using a meta-learning classification approach called logistic model trees (LMT). In order to ape the excess water production brought on by coning, channeling, and gravity-segregated 7 flows, synthetic reservoir models were developed. After that, a few of the input parameters for each model were changed to produce a variety of cases. By segmenting these plots at specific points, several key features are heuristically extracted from WOR against oil recovery factor plots. Then, LMT classifiers are used to combine these features with the parameters of the reservoir to create classification models that can predict the water production mechanism in a variety of pre- and post-water-production scenarios.

Reyes et al. [48] established a relationship between the production of water, reservoir properties, and configuration of a well by utilizing instruments for operational reliability and six-sigma optimizations. The corresponding effects of the water production mechanism can be determined using these relationships. To identify the source of water production, they initial took a gander at the important factors utilized to display commonplace oil wells involving the produced fluids volume, WOR, water cut, mobility ratio, pressure of the reservoir, pressure of wellhead, pressure drop at seepage region, injectivity index, remaining stores, oil costs, cost of water production, reservoir depletion, water invasion, and impact of specific gravity. Then, they modeled the relationships between causes and effects using informal loop graphs.

Al-Ghanim and Al-Nufaili [49] utilized Chan's approach to construct log diagrams of water oil ratio (WOR) and its derivative d(WOR)/dt against time for an oil well producing from sandstone reservoirs in the Middle East. These plots were viewed as successful in deciding if the well is encountering multi-facet directing (positive slope for the time derivative of water oil proportion curve) or water coning (negative slope for the time derivative of water oil proportion curve). To choose wells that are reasonable possibility for water control treatment, the symptomatic schemes utilized in their research give a helpful and quick technique for identifying WPMs.

Tabatabaei et al. [50] presented methods for interpreting temperature profiles to determine a variety of well conditions. The inflow profile of a well is normally the much more basic well feature that might be inferred from the profile of temperature. They demonstrated how typical reversal techniques applied to observe temperature profiles may quantitatively identify the locations and rates of such inflows of gas or water. This approach can be utilized either prior to or after the stimulation therapy to assist design the stimulation or to estimate the stimulation's outcomes.

In their work, Mahgoup and Khair [17] tried to start a plan to manage Jake Oilfield's unnecessary water production in Sudan and identified the causes of the issues. Several diagnostic plots were presented and contrasted with Chan's standard diagnostic plot after the production data were analyzed. They concluded that in wells with a high-permeability sandstone zone, water production is primarily caused by channeling, while conning is only present in two wells.

Talebian and Beglari [51] provided a methodology for selecting water shutoff (WSO) candidates based on production data. The WSO candidates were chosen based on their heterogeneity index, decline curve analysis, water oil ratio, and the impact of excessive water production on well ultimate recovery. Through the presented screening, the mechanism and source of the produced water were identified using the Chan plot and Stiff diagram.

Nmegbu et al. [6] used WOR derivative diagnostic methods and subsequent water shutoff for oil gain opportunities to investigate excessive water production diagnosis and control in Niger Delta oilfields. The findings revealed that channel casting leaks, fractures opened out of zones, completion in or near water, barrier breakdown, channeling through higher permeability zones or fractures, coning and cresting, and inadequate well surveillance and reservoir and facility management are some WPMs in the oil fields.

Shabibi and Sahraei [52] conducted research to detect WPMs in one of Iran's oilfields and address them using gel injection. After confirming the existence of the water production issue with the help of a recovery plot, a created sector model and Chan diagnostic diagrams were used to investigate WPM. According to their study's decline-curve analysis diagrams, recovery plot, Chan derivative diagram, and fluid flow movement schematic shape, the mechanism of water production is an underwater injection channel flow process. Using a simulation of gel injection, they then reduced the rate of production of water and increased the rate of production of oil.

Engineers and operators should, in an ideal scenario, make use of all the data that is available to estimate the issue at hand, locate the precise WPM source, and implement the appropriate solution to decrease or prevent the flow of water. Table 2 summarized the most frequent WPMs, potential conditions; diagnostic methods associated with every WPM, and suggested solutions for each WPM. These details were gleaned from many sources in previous studies of WPM [4,10–13,15,18–22,27,53–57].

Table 2 Mechanisms of water production, diagnostics, and solutions (After Rabiei [57])

WPM	Causes/ Definition	Possible Diagnosis/Likely Condition	Suggested Solutions
Casing, tubing or packer leaks	•The holes from corrosion. •Wear and split due to flaws •Excessive pressure. •formation deformation.	• Devices for flow profiling. • Logging While Drilling, cement bond logs. • Temperature and noise logs. • Tests for leaks and casing integrity. • Televiewers in boreholes. • Electromagnetic tools and electrical potential. • Surveys of radioactive tracer. • TDS/Chloride Tests.	• Pressing shutoff liquids. • Utilizing plugs, patches, cement, and packers (Mechanical shutoff). • Using gels (silicates, water-soluble organic monomers, or organic polymers) for tiny leaks.
Channel flow behind casing	• Poor cement-casing or cement-formation bonds. • Most likely to happen right away after the well has been completed or stimulated.	• Devices for flow profiling. • Logging While Drilling, cement bond logs. • Temperature and noise logs. • Tests for leaks and casing integrity. • Televiewers in boreholes. • Electromagnetic tools and electrical potential. • Surveys of radioactive tracer. • Trend of scaling water.	• Resin-based fluids and high-strength squeeze cement are injected into the annulus for unrestricted flow. • Gel-based fluids of lower strength are placed in the formation to stop the flow into the annulus for narrow or constrained flow paths.
Moving oil/water contact	• During common water-driven production, a consistent oil-water contact rises into a perforated zone in a well. • This issue can be considered as a subset of coning, but the coning tendency is so low that near wellbore shutoff is effective.	• Characterized by a low vertical permeability, typically less than 1md. • A diagnosis can't be founded exclusively on the known entrance of water at the lower part of the well since different issues likewise cause this conduct as well. • Could be identified if the well produces less than the critical flow rate.	• For vertical well: using a mechanical system (cement plug or bridge plug) to abandon the well from the bottom. • For horizontal well: Any near-wellbore solution or wellbore should extend far enough up or down-hole from the interval of producing water to reduce water from flowing horizontally beyond the treatment and put off further water breakthrough. • Otherwise, once the WOR becomes economically impossible a sidetrack can be considered.
Poor areal sweep	• In anisotropic formations with high permeability layers, water begins to flow preferentially through these channels when water flooding is applied.	• Low permeability barriers in their initial and current states. • A lack of integrity in the barriers. • A relative mobility between water and oil. • Injection effectiveness.	• Redirect injected water away from the pore space, which had previously been swept by water. • In this scenario, infill drilling frequently succeeds in increasing recovery. • Requires either a significant treatment volume or a continuous viscous flood, which are usually unprofitable.

Table 2 Mechanisms of water production, diagnostics, and solutions (After Rabiei [57])(continued)

WPM	Causes/ Definition	Possible Diagnosis/Likely Condition	Suggested Solutions
Gravity segregated layer	• The lower portion of the formation is the only part of a thick reservoir layer with good vertical permeability that is swept by water due to gravity-segregated flow. • The issue might become more severe if there is an unfavorable oil/water mobility ratio.	• Occurs in heterogeneous formations that are anisotropic and fractured. • A lack of injections.	• Any treatment in the injector intended to close the lower perforations has only a slight impact on sweeping more oil before gravity segregation once takes control. • Gel injection, foamed viscous-flood fluids, or a combination of the two may likewise enhance vertical sweep.
Coning or cusping	• Vertical pressure gradient is the main cause. • Water from a lower connected zone moves towards the wellbore when viscous forces prevail over gravity forces. • The maximum rate at which oil can be produced without producing water through a cone is called	• WOR curves with negative derivative slopes that are gradually increasing. • Pulsed neutron spectroscopy (PSG) log. • Thermal multigate decay (TMD) log. • Monitoring the field performance. • Well testing and Fluid density variations.	• Placing a lot of gel above the equilibrium OWC (not very suitable, efficient, or cost-effective). • A double channel production procedure including puncturing above or underneath the oil/water contact might be efficient. • When applied to cusping or coning issues in non-fractured matrix reservoir rock, gelants or gel treatments have a very low success rate.
High permeability layer	• Watering out high-permeability layers that are separated by impermeable barriers is a usual issue with multilayer production. • A water-flood injection well or an active aquifer could be the source of the water.	• Low permeability barriers' initial and current conditions. • A relative mobility between water and oil. • A lack of injections. • Reservoir simulation. • Comprehensive well control and mapping. • Well logging and Tracer overviews.	• Mechanical or Rigid shutoff liquids in either the injector or producer. • Sand or cement plugs are utilized to plug water zones found at the bottom of wells, and cement or carbonate gels with gelants injection are utilized if it is above an oil zone.
High permeability layer with crossflow	• High-permeability layers without impermeable barriers between them are susceptible to water crossflow.	• Low permeability barriers' initial and current conditions. • A relative mobility between water and oil. • Determining whether there is crossflow in the reservoir is crucial.	• Crossflow away from the wellbore makes attempts to alter the production or injection profile close to the wellbore ineffective. • If the permeable thief layer is thin and has a high permeability compared to the oil zone, it might occasionally be feasible to economically place deep penetrating gel there.
Fractures or Faults between injector/producer	• Under flood conditions, injection water can rapidly penetrate producing wells in naturally fractured formations. • It frequently occurs whenever a fracture system is extensive or fissured.	• Well testing (Pressure transient test). • Inter-well tracers. • Drilling fluid loss from severe fractures or faults in wells is prevalent.	• The injector is being injected with a flowing gel. • The best treatment right now, except for narrow fractures (fracture width 0.02 in), is gel therapy. • An alternative would be to extrude preformed gels through cracks.
Fractures or faults from a water layer (2D coning)	• Fractures that cross a deeper water zone can likewise result in water production. • When hydraulic fractures pierce a water layer vertically, a similar issue arises.	• Particularly in constrained dolomite zones, the fractures in many carbonate reservoirs are typically steep and tend to form in clusters that are widely spaced from one another. Therefore, it is unlikely that these fractures will cross a vertical well bore. • When water is produced through conductive faults or fractures that cross an aquifer, it is common to see these fractures in horizontal wells.	• Utilizing polymers. • These fractures could be treated by pumping flowing gel. • Large treatment volumes are required to stop the fractures from the well.

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Water Management

The expense of separating, treating, and disposing of excessive water is one of the primary issues associated with excessive water production during oil production in oilfields. Oil exploration and production (E&P) companies' budgets are strained because of these major issues. For instance, disposing of excessive water costs approximately one million US dollars annually in Alberta. According to Thomas et al. [58] and Permana et al. [59], preventing the production of excessive water will decrease operational costs and, conversely, increase business profitability. As a result, McIntyre et al. [9] recommend shutting off water to the oilfields to manage and control the excessive water. The shutoff procedure is only successful if both the water entry in the well and a thorough understanding of the excessive water production mechanism are present [16]. According to Mahgoup and Khair [17], the most effective method for managing and, in some instances, preventing excessive water production in oilfields is water shutoff.

Arnold et al. [11] depicted a comprehensive water management system as shown in Figure 12. An integrated strategy for designing a water management system that takes into account the production optimization plan and analyzes operational parameters like well type, well location, and flow condition was presented by Eduin et al. [60]. The best field performance of the suggested operation parameters was then determined through an economic evaluation. Arthur et al. [61] conducted a comprehensive analysis of various generating water treatment methods established by oil and gas companies, research organizations, water treatment firms, and universities. Avoiding surface water production, injecting produced water, discharging produced water, reusing in oil and gas activities, and consuming for beneficial uses are just a few examples.

Yong-Ge et al. [62] investigated the effect of nitrogen foam solution on the shutoff procedure to determine nitrogen foam's capacity to control excessive water. They simulated foam injection into one horizontal well and three vertical wells using numerical simulation. Their research reveals a significant improvement in water control in a horizontal well, but the shutoff method was unsuccessful in the vertical wells tested.

SUN and BAI [63] conducted a detailed evaluation of water control strategies used in horizontal wells and offered water control approaches for various completion types. Technical efforts for water management have focused over the past three decades on the improvement and application of gels to reduce the production of water and create stream obstacles. In a variety of ways, various gels were used.

Taha and Amani [64] provided a comprehensive review of the procedures for shutting off the water, beginning with defining and then moving on to the various conventional mechanical and chemical solutions to the undesirable problem of water production.

Kassab et al. [65] offered a comprehensive explanation of the numerous options for managing water. The first step was water minimization methods, which included three different applications in three different wells and two methods for recycling and reusing water.

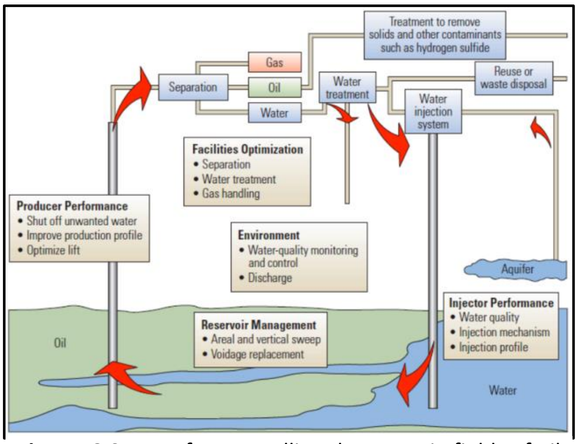


Figure12 System for controlling the water in fields of oil and gas (Arnold et al. [11])

Water Shutoff Materials and Methods

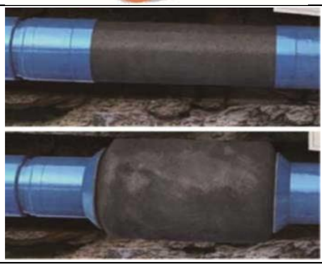
To find the best solution to a problem, a different strategy is needed for each one. Therefore, in order to effectively treat issues with water production, the issue's nature should first be accurately obtained [15]. As shown in Table 3, a wide range of materials and procedures may be employed to treat excessive water production issues [10]. WPMs can be attacked and controlled with a variety of sophisticated methods. Mechanical, chemical, and completion solutions are the most common categories for these methods [20]. According to Reynolds and Kiker [13], each method works for some WPMs but rarely for others. Packers, plugs, and sleeves are examples of mechanical solutions, while cement, gels, resins, foams, emulsions, and polymers are examples of chemical solutions. Alternative completion strategies include sidetracks, dual completions, and multilateral wells. Due to its structure, foamed cement can inhibit the formation of water or gas channels [66].

For mechanical solutions, packers might be utilized to close the surplus water zone. As shown in Table 4, there are expandable and non-expandable types of packers. The expandable tubular, bridge plug, straddle packer, swell packer, and inflatable cement retainer are all examples of expandable packers. In vertical wells, a common non-expandable packer is the cement packer. Because of the gravity impact, uncompleted sealing in the annulus may occur in horizontal wells. It is appropriate for upper zone isolation to prevent undesired fluids from entering[63].

Table 3 Methods and Materials for Water Shutoff (After Seright et al. [10])

Physical and Chemical Plugging Agents	**Well and Mechanical Techniques**
Calcium carbonate, cement, and sand.	Patches, packers, and bridge plugs.
Gels and Resins.	Infill drilling and Well abandonment.
Microorganisms, foams, emulsions, particulates, & precipitates.	Control of pattern flow.
Floods made of polymers or mobility-controlling materials.	Horizontal wells.

Table 3 Characteristics and sealing mechanisms of commonly used packers (After SUN and BAI [63])

Brand	Manifestation	Retrievability	Elongation	Mechanism of Sealing
Cement plug		No	No	The annulus is completely filled by cement by forming a solid block.
Inflatable packer		Yes	Yes	Inflatable packers expand because of the bladder's expansion. For isolation, inflatable components occupy the entire annulus.
Bridge plug		Yes	Yes	Bridge blocks expand as a result of mechanical extension. For separation, inflatable components occupy the entire annulus.
Straddle packer		Yes	Yes	Both the inflatable packer and the straddle packer inflate similarly. For separation, inflatable elements occupy the entire annulus.
Swell packer		Yes	Yes	Contact with well fluids is what causes swell packers to swell. The annulus is completely occupied by inflatable components for separation.
Cement retainer		Yes	Yes	Distension occurs when the rubber bladder expands. The cement is injected after it has expanded.
Expandable tubular		No	Yes	The tubular will expand to provide sealing because of the pressure exerted between the shoe of the clad and the base of the cone.
External casing packer (ECP)		No	Yes	The expansion of the rubber bladder is what results in the inflation. The annulus is completely occupied by inflatable elements for isolation.

According to Xiaofang and Honggang [67], mechanical packers are able to 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 are able to shutoff the excessive water. As a result, many situations necessitate chemical solutions. In-situ gels (Cr(III) and HPAM) as well as additional ingredients that might be included to alter the characteristics of in-situ gels are among these methods [68]), swelling agent and polymers (a polymer like PAM can expand when swelling agent is present [69]), water swelling polymer (WSP, also referred to as premade particle gels [70,71]), micro matrix cement (it can get through holes as small as 0.05 millimeters [72]), HWSO plugging agent (HWSO made from an ethylene methacrylate copolymer, alkyl bromine, and acrylamide [73,74]). All these materials are just a few examples of chemical solutions. Numerous manuscripts 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 [75]. The production of water has been reduced by the application of microgels in 10 gas storage wells [76]. More than 60 wells have been used to redirect in-depth fluid flow using submicrogels (bright water) [77,78].

The majority of horizontal wells constructed as open-hole utilize chemical rather than mechanical techniques to shutoff excessive water due to operational challenges and economic considerations. Using two different gels in the Ratawi Oolite reservoir (Wafra field), Uddin et al. [79], reported performing a water shutoff operation in an open-hole horizontal well [80]. In order to protect the upper heel oil production zone, coiled tubing was utilized to set a non-harmful gel packer made of crosslinked HEC polymer. After the gel plug, the water shutoff gel was pumped into the bottom water zone beneath the gel plug to regulate water production. Right after treatment, the water cut decreased from 82 to 70–80 percent. In a similar vein, Dashash et al. [81] reported a successful water shutoff task in a horizontal producer in the South Ghawar field completed as an open-hole. All water was produced from the well's toe, according to a PLT run [82]. To separate the area where the water is produced, they utilized inflatable packers in their design. In order to improve the sealing strength, the inflatable packer was sealed with a 61-meter cement plug in the annulus, followed by injecting 91.4 m of high-viscosity gel in order to prevent cement slumping issues. The water cut (after treatment) was reduced by 50%, and 159 m3/day more oil was produced from the well.

The most popular mechanical method, next to chemical methods, is the combination of inflatable packers and cement plugs. Successful use of this technique was reported by Al-Umran et al. [83] in a well in the Hawiyah region of the Ghawar field. The toe of the horizontal section served as the water entry point. By installing an inflatable packer and then a cement plug, water is controlled. Without experiencing any operational issues, the water control job successfully increased oil production and decreased water cuts. Similar to this, Al-Zain et al. [84] reported another treatment for an open-hole producer in the same field that successfully reduced water cut from 47.8% to 8.4% and increased oil rate from 492.9 m3/day to 1 049.4 m^3/day.

According to Lane and Seright [85], a well that was constructed as a cased-hole with cemented liners had a successful water control operation. The faulty interval connection with the aquifer was the source of the excessive water. They made the decision to forgo using mechanical water control techniques in favour of chemical ones in order to protect the perforated zone. The polymer gel made of HPAM and Cr (III)-acetate was injected into the reservoir using the bullhead method because of the preferable permeability difference. The production data showed that while oil production rose from 7.4 104 m3/day to 11.6 104 m3/day, the water cut decreased from 90% to 72%.

In Canada, a successful water shutoff operation was documented by Zaitoun et al. [69] and Zaitoun and Pichery [86], respectively, in a well completed with a slotted liner and in four heavy-oil horizontal wells. The bullhead method was used to treat the wells by forcing polyacrylamide (PAM), a swelling agent, and a polymer solution through slotted liners. A decrease in water cut from 85% to 50% was seen in the production statistics, along with an increase in oil production.

According to Zaitoun et al. [87], chemical substances like HPAM with low hydrolysis could also be used to regulate the amount of water produced in gas wells. Similarly, a water shutoff task in a well in the southwest region of Venezuela's Zuata field was published by Foucault et al. [88]. Due to the requirements for sand control, the well was completed with a 177.8 mm slotted liner with a 0.5 mm slot width. Polymer gel, matrix cement, and cement rings were used to manage the water. Two cement rings were first established, and then, utilizing retrieved cement retainers, micromatrix cement was injected into the space between the two cement rings. The internal wellbore and the matrix were sealed with gel and cement. The post-job findings revealed that the water cut decreased from 80% to less than 5% within two weeks and stabilized at 2%–3% at a production rate of 159 m^3/day. Slotted liners or sand screens are frequently employed in conjunction with an external casing packer (ECP). The proposed zonal isolation for well stimulation uses a perforated liner with ECP completion. Utilizing many ECPs will raise the cost of completion. It might not be necessary to use cement or another type of zonal isolation plugging agent if the ECP is constructed. Even though the ECP can only seal the external annulus, fluids may still pass through it and have an impact on the amount of water produced.

Completions may occasionally be altered depending on particular circumstances. Due to the need for sand control and challenges with filter cake cleaning, Jinzhong et al. [89] and Zhang et al. [90] reported a newly designed completion method in Jidong oilfield. The new completion method included swell packers and a flow-regulating water control screen. The new completion method resulted in higher oil production and a lower water cut when compared to the well that only used a conventional sand screen completion. Additionally, Rao et al.'s [91] report on a cutting-edge completion technique for a horizontal well in a bottom water reservoir in the Dagang oilfield to manage excessive water. An unfavorable problem with water production was caused by the early water coupling. Swell packers, plug-in packers, and modified sand screens were all used in the newly developed well completion method.

Selection of the water shutoff technique

The choice of water management technique depends on the type of well completion. Chemical, mechanical, or a combination of technologies can be used to manage water in open-hole horizontal wells. Because most mechanical packers can be retrieved, they can offer a temporary seal for further treatments. In addition to mechanical techniques, some substances, such as gels, can potentially temporarily seal the target zone. There are two techniques to establish gel packers: one is with expandable packers and an inflatable cement retainer, and the other is with straddle packers with perforated nipples. The operation tools will either be removed from the wellbore or left there once the gel stopper has been installed. Through coiled tubing, operating tools are inserted into the wellbore. Bullhead injection is a technique used in some instances to inject chemical plugging agents directly into the reservoir. To ensure that the greatest number of chemicals possible enter the target zone, there must be a significant permeability differential between the target zone and matrix. For all packer positions, depth correction is a prevalent issue. In order to set the packer at the intended depth, a fiber optic is a tool that helps coiled tubing boost the depth control's precision. The wellbore's temperature anomaly could be a sign of a water entry point. According to Burov et al. [92], fiber optic can identify water entrance locations by detecting this temperature change. This method can only be employed, though, when the aquifer temperature and reservoir temperature are clearly different from one another. Otherwise, the fiber optic may not be sensitive enough to pick up the difference. Water shutoff is done using two different techniques in cased-hole wells: chemical and mechanical. Chemical substances are frequently injected using the bullhead approach because the cased-hole completion provides the best wellbore stability. Through perforations, chemicals can penetrate the target zone. To permanently seal the water surplus zone, inflatable packers and cement plugs are used together. Water control can only be carried out through chemical techniques in these kinds of completions because screen liners and pre-drilled liners are easy to collapse. Some chemical treatments involve utilizing inflatable equipment to create zonal separation and then injecting chemicals afterward. Chemicals are pumped into coiled tubing and straddle packers in perforated liner completion wells to create annular chemical packers (ACP), which are placed between open-hole and slotted liners [93,94]. A liner with an ECP-completing method isolates a water production zone or seals it on its own. The benefit of EPC is that it reacts quickly to excessive water. If too much water is found, the ECP will shutoff the annulus. Nonetheless, the increased price and the challenges with depth correction are obstacles. According to Yu Hongjiang and Zhang Fengwu [95], ECP has been utilized by the Daqing oilfield to stop the flow of water from deviated wells.

The implementation of the abovementioned techniques is influenced by reservoir and wellbore conditions. The additional factors that should be considered while constructing a water control project include cost, operational challenges, retrievability, etc. Mechanical packers function better at sealing wellbore features, while chemical packers are capable of entering the matrix to seal features like cracks, channels, and wormholes, depending on the aim of the plugging. In order to prevent the damage caused by plugging agents in non-target zones or locations, retrievable packers are occasionally required to offer temporary plugging. After providing temporary sealing, the majority of mechanical packers, including straddle packers, can be retrieved. The combination of some inflatable packers with cement packers, however, can offer permanent sealing. Additionally, some chemical packers, including transient gel packers, can be eliminated after utilization. Furthermore, mechanical packers, particularly ECPs, are more expensive than chemical packers. Therefore, if the reservoir conditions permit bullhead injection, chemical technique is the best option due to cost concerns in managing excessive water production. Although it is simpler to pump chemical packers, all chemical water control projects could be at risk of formation damage. Chemical compounds can sometimes create irreversible damage. Chemicals must be introduced accurately to avoid formation damage. Chemicals can be injected into target zones using straddle packers with perforated nipples. However, because of their low bearing weight, mechanical packers can’t be utilized in wells that have perforated liners. Typically, when choosing a method for shutting off the water in a horizontal well, a mechanical method is preferred over a chemical one. Combining mechanical and chemical methods is becoming more and more popular when choosing a water shutoff method in the future for open hole and slotted liner completion wells[63].

Conclusions

In several oil fields all over the world, excessive water production has been a main problem. In addition to having a negative influence on the rate of oil production, excessive water production necessitates expensive and time-consuming water management procedures, such as therapeutic activities in the oil wells and the oil fields and wastewater disposal considerations for the environment. It may seem impossible to achieve the objectives of decreasing the costs of excessive water production and releasing more recoverable reserves from mature fields, but certain immediate successes are possible. Today's reservoir engineering places a high priority on understanding water flow issues and finding solutions to them. Water control can be a useful reservoir management strategy when used in conjunction with an appropriate diagnosis and the implementation of proven options for resolution. The diagnosis of the current water issue is the first step in water management. There are three applications for well diagnosis: recognizing wells that would make good candidates for water control; identifying the source of the water issue and choosing the best water-control strategy; and locating the well's water entry point so that a treatment can be properly positioned. Water coning, casing leaks, poor cement behind the casing, and connected open fractures or a high permeability zone are all potential sources of undesirable water production. Numerous different analytical techniques have been developed to distinguish between the various sources of unsuitable water. These approaches rely on information from logging measures, water/oil ratios, and production data. To ensure a successful water shutoff, it is necessary to use a variety of diagnostic methods to locate the water entry point and investigate all the well's information. The most effective technique for identifying the cause of issues with excessive water production is the diagnostic plot derivative approach. But in order to be effective, these plots must be utilized in concert with other strategies like production logging and reservoir modeling. Techniques for shutting off the water can be employed independently or in conjunction. Chemical or mechanical solutions can be used, depending on the situation, to stop the production of unwanted water. Particle gels have been proposed by several researchers as a means of homogenizing reservoirs and preventing the production of unwanted water. When planning a water shutoff project, the type of completion should be taken into account. In cased-hole and open-hole wells, mechanical and chemical solutions can both be applied. Only chemical solutions can be utilized to control excessive water production in wells that have been completed with perforated liners and wells that have been completed with sand screen pipe; mechanical solutions can only temporarily isolate zones. In comparison to chemical solutions, mechanical solutions are slightly more expensive, and depth correction is difficult. If the water entry point is at the toe, either mechanical or chemical solutions can be utilized separately. For wells with a water entry point close to the heel or along the lateral, a combination of packers should be established. This paper presents water control strategies for wells of various completion types and provides an integrated review of excessive water production diagnosis techniques that have been utilized in both horizontal and vertical wells.

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Conflicts of interest

There are no conflicts to declare.

Nomenclature

Abbreviations:

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
LMT = Logistic model trees
WSO = Water shutoff
TDS = Total Dissolved Solids
PSG = Pulsed neutron spectroscopy log
TMD = Thermal multigate decay log
WSP = Water swelling polymer
PPGs = Preformed particle gels
ECP = External casing packer
ACP = Annular chemical packers

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