POLITECNICO DI TORINO

MASTER OF SCIENCE IN PETROLEUM AND MINING ENGINEERING

MASTER's DEGREE THESIS

Title

Identification of Water production causes in oil reservoir; A comparative analysis using Chan´s Diagnostic Plot Technique

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ABSTRACT

Excessive water production is one of the most common challenges associated with hydrocarbon production in the oil industry. It affects the performance of the producing well and causes early abandonment of the reservoir. Identification of excessive water production problems should be performed before attempting any water-treating operation. Conventional plots have been used to recognize such issues.

Chan's diagnostic plot is a precise and quick technique to identify the causes of water production effectively. Production data are used to plot the Water-Oil Ratio (WOR) and its derivatives (WOR′) versus time. The specific trend of WOR and WOR' plots are then associated with water coning or channeling according to Chan's interpretation.

The Chan's technique was successfully applied on numerous case studies from technical literatures, which focus on both water coning and channeling phenomena. In the analyzed cases, water channeling was identified as the most common cause of water production.

According to the results of the present work, Chan's technique turns out to be and useful tool to diagnose water production mechanisms, identify the sources of water production, and quantify the production rate of fluids. Thus, it can be used for proper planning water management programs, to control and mitigate water production problems. However, the results obtained by the diagnostic plot technique need to be verified by close monitoring using well logging and well testing techniques to ensure breakthrough time.

Keywords: Water production, Chan's diagnostic plots, water channeling, water conning.

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LIST OF ABBREVIATIONS

WOR	Water-Oil Ratio
WOR´	Derivatives of Water-Oil- Ratio
WC	Water Cut
EPA	Environmental Protection Agency
IOR	Improve Oil Recovery
WOC	Water-Oil Contact
GOC	Gas-Oil Contact
GOR	Gas-Oil Ratio
ICV	Inflow Control Valve
DOWS	Downhole Oil-Water Separation
DWS	Downhole Water Sink
DWL	Downhole Water Loop
WDI	Water Drainage Interval
WRI	Water Re-injection Interval
PAM	Polyacrylamide
HPAM	Hydrolysed Polyacrylamide
PVT	Pressure Volume Temperature

NOMENCLATURE

Pc	Capillary Pressure (psi)
Qc	Critical Rate (STB/Day)
re	External Radius (m)
Ke	Effective Permeability (mD or m^2)
q	Flow rate (bbl/day)
Kh	Horizontal Permeability (mD or m^2)
λ	Mobility
M	Mobility Ratio
Bo	Oil Formation Volume Factor (bbl/STB)
γo	Oil Specific Gravity
ρo	Oil Density (g/cm3)
K	Permeability (mD or m^2)
ΔP	Pressure Drop (psi or Pa)
Krw	Relative permeability to Water (mD)
Kro	Relative Permeability to Oil (mD)
h	Formation Thickness (m)
μ	Viscosity (cP or Pa. S)
Kv	Vertical Permeability (mD or m^2)
Sw	Water Saturation
γw	Water Specific Gravity
rw	Wellbore Radius (m)
Pwf	Well Flowing Pressure (psi)

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Chapter 1 INTRODUCTION

Problem Statement:

One of the major problems in hydrocarbon depletion is the associated water production. Water production, especially in a deep aquifer-driven reservoir, is a complex and challenging operation to control. This problem may rise in the form of tongue, cone, cusp, or a combination of all depending on the location, geological structure, magnitude, and direction of water movement. Some of the drawbacks include a decrease in oil flow rate, increase in water production rate to be handled thereby increasing the cost of surface facilities installations, increase water disposal cost, reduce the efficiency in depletion mechanism, and ultimately early abandonment of affected well with the loss of field total overall recovery.

This study is related to water production in the oil reservoir and focuses on the sources and causes related to the water production. The emphasis is on identifying the sources causing water production and effectively mitigate them with the best possible solution technique. For this purpose, the Diagnostic plots have been used successfully to identify the mechanism of water production.

Study Objectives:

This study would aim to describe a quicker and cheaper way to analyze the performance of each well by the application of K.S. Chan´s Diagnostic plots. This work presents:

- Developing a workflow for the evaluation of water production mechanisms.
- Demonstrate the different sources and causes of water production with the application of remediation techniques accordingly.
- To demonstrate various case studies with the application of Chan´s Diagnostic plot technique in order to identify water production problems.
- Formulating various interpretations by analyzing field production data with standard Chan´s diagnostic plot and providing guidelines for mitigating water production.

Thesis Outline:

The study is divided into six chapters. The outline and organization of this dissertation are as follows:

Chapter 1 presents an overview of the problems associated with water production in an oil reservoir. A brief description of the research approach, objectives, and various sources are studied in this chapter.

Chapter 2 addresses the main challenging problems such as water coning and multi-layer channeling. These problems are tackled with the different techniques recommended by several review papers that are included in this chapter.

Chapter 3 provides an overview of Chan´s Diagnostic plot technique to distinguish the water production mechanisms with some field production examples.

Chapter 4 guides the application of Chan´s Diagnostic plot technique on several case studies that are used to identify the real cause of the water production.

Chapter 05 develops a qualitative and quantitative analysis of these case studies and are correlated with Chans plots for validations.

Chapter 06 provides a conclusion of this project and recommendations for future research work.

1.1 Background:

Excessive water production is undoubtedly one of the most common challenges associated with hydrocarbon production in the oil industry. This problem causes numerous economic and environmental issues for community and oil production companies. Excessive water production affects the performance of production well and causes early depletion. The management and handling of the higher volume of water produced cost very high as the presence of water in the wellbore increase the weighting of the fluid column that leads to an increase in the lifting requirements. Consequently, the operating costs increases and leads to lower drawdown. Water production also enhances corrosion, the presence of scales, and degradation in the field's facilities from the wellbore to the surface facilities. Another problem associated with water production is the cost of separating of treating and disposing of the produced water. Therefore, diagnosing the water production, identifying the causes, and recommending the remedial solutions or shut-offs operations are necessary to tackle the issue. (Abdullah Taha and Mahmood Amani, 2019).

It is certainly logical that identification of excessive water production problems should be performed before attempting any water treating operation. Diagnosis of the cause of water production is necessary to be aware of the whole scenario of the reservoir and production history of the well in the field. (Hamzeh Ali Mohammadi, 2018)

Produced water presents in reservoir rocks and after all, it produces to the surface with crude oil or natural gas as they are commingled with one another. This water could either come from an aquifer or injection wells in the waterflooding process. It is expected that water production would increase with a life of a reservoir. However, an early increase in water production in any reservoir is an undesirable condition. The problem arises when the water production rate exceeding the economic water-oil ratio (WOR) limit or a sudden outburst of water into the oil well and requires immediate attention. The consequences ensure a reduction in the oil recovery factory as oil remains behind the displacement front, as a result reducing the performance of the reservoir. All these along with a decrease in the oil's quantity involve reduced profitability. Water production increases the produced fluid head in the wellbore and creates extra back pressure on the formation. This reduces the well's flow capability; reduces the oil flow rate, often increasing the operating costs and early abandonment of the affected oil well. The environmental issues in connection with water production are another major concern for the oil industry. They must follow the rules and regulations set by Environmental Protection

Agency (EPA) regarding water treatment and disposal facilities. The water production mechanism must be properly investigated and accurately diagnosed in order to design an appropriate and effective treatment method. Incorrect, inadequate, or lack of proper diagnosis usually leads to ineffective water control treatments that cost a lot of time and money. (Minou Rabiei, 2011)

Water production may come in the form of tongue, cone, cusp, or combination of all these depending on the location, magnitude, and direction of water movement. Water is produced into the well due to many different causes. It can be related to mechanical problems, poor completion procedures, or reservoir conditions. The main obstacle in the management of water production studies is the correct diagnosis of nature and the origin of the problems. Each problem type requires a different approach to control and treat the problem effectively. In reality, an oil well can experience a combination of different problem types. However, reservoir-related problems of coning and channeling through high permeability layers are more challenging to diagnose and treat (R.S. Seright et al. 2003).

The mechanism and the volume of the water produced into a wellbore mainly depend on petrophysical properties, type of reservoir fluids, type of lithology, pressure and temperature conditions of the reservoir, geometry, and conditions of the aquifers, trajectory, and location of the drilled wells within reservoir structure, type of completion and stimulation methods, and recovery methods. Depending on the characteristics of the reservoir and type of the diagnosed problem and objectives of the water production treatment, a variety of mechanical, chemical, and well construction techniques can be applied to control and remediate the flow of water into the wellbore.

1.2 The reservoir features characterizing the sources of excessive water production:

Reservoir features that characterize the most susceptible causes to excessive associated water production in oil wells are:

1.2.1 Formation lithology:

The formation lithology is the major source to identify the types of the rock and layer's structure potential to the higher water production. Among the types of rock that are igneous, sedimentary, and metamorphic, the various types of sedimentary rocks are the ones that we as petroleum engineers are more interested in and are capable to produce water along hydrocarbons. Sandstone, shales, limestone, and dolomite are the main types of sedimentary rocks.

The water production in different types of the matrix is caused by different reasons. The clastic type of sedimentary formation that is made of pre-existing rocks characterize different fluid flow around the wellbore while producing the well than fractured reservoirs. The diagnosis of excessive water production problem is decided whether the fluid flow around the wellbore is radial or linear. The fluid flow behind pipe or casing, fracture, and fracture-like features are associated with a linear flow, whereas radial flow normally occurs in matrix reservoir rock when these features are absent. (R.S. Seright, et al. 2003)

There are different methods to judge whether the floe around the wellbore is linear i.e., fracture type, or radial i.e., matrix rock or sand. One simple method is the use of the Darcy equation:

$$q/\Delta P = \sum Kh/[(141.2\ \mu In(re/rw)$$

$$For\ Radial\ flow \qquad q/\Delta P \leq \sum Kh/[(141.2\ \mu In(re/rw)$$

$$For\ Linear\ flow \qquad q/\Delta P >> \sum Kh/[(141.2\ \mu In(re/rw)$$

If $q/\Delta P$ is less or equal to the term on the right side of the equation, the flow will be radial. But if it is much greater (about 5 times or more) it will be linear flow. As the fractures have high permeability streaks, they are more conducive to easily and early flow of the water. (R.S. Seright, et al. 2003).

1.2.2 Petrophysical and reservoir fluid properties:

The petrophysical properties of rocks along with fluid properties play a major role in water production. Based on the petrophysical properties and rock fluid interaction, carbonate rocks are recognized as more permeable and conductive to the fluid flow. Porosity and permeability of reservoir rocks actually depict the ability to store and transmit the fluid in the pores of rocks. High streaks permeable zones are more critical to early water breakthrough into the wellbore. Therefore, fractured reservoirs and highly permeable formations such as carbonate rocks face water coning and channeling phenomena. Besides this, fluid properties such as density viscosity, and rock fluid interaction properties such as relative permeabilities and wettability are the key factors to the sources of higher water production. Heavy oil having higher density and viscosity will produce a higher water-oil ratio (WOR) depending upon several other reservoir rock and fluid properties. Similarly, the higher the relative permeability to water, the higher will be the water-oil ratio. Mobility ratio (M) is the ratio of displacing fluid (water) behind the front to the displaced fluid (oil) in the oil-water reservoir. If this ratio becomes greater than one (1) i.e. (M>1), it is considered unfavorable as water is more mobile than oil in the porous medium and the injected fluid tends to bypass oil and early breakthrough is expected to occur in the producer wells. (Abdus Satter, Ghulam M. Iqbal, in Reservoir Engineering, 2016). This phenomenon where mobility ratio is greater than one can cause water to bypass recoverable oil is called viscous fingering and poor sweep efficiency is experienced. If this ratio is less than one, water will be less mobile than oil and better oil displacement will occur in the producers. Additionally, it is known that mobility ratio as a function of relative permeability has a strong impact on the Water-oil ratio, depending upon different properties of the rock and fluid variation in different zones at different depths. (Djebbar Tiab, Erle C. Donaldson, et al.2016).

1.2.3 Types of drilled wells:

Drilled wells also influence the water production of the reservoir system. Horizontal wells and vertical wells both can produce a large volume of associated water depending on the aquifer strength, production rate, and structure of reservoirs whether it is faulted, fractured, or layered reservoirs. The horizontal and deviated wells drilled in reservoirs having fractures and fault-like features are more prone to produce a higher volume of water than vertical wells. R.S. Seright, 2000). In horizontal wells, the phenomenon called fluid crusting is due to pressure drop near the well completion. On the other hand, in the vertical wells the term coning used to describe the production of usually unwanted second phase concurrently with desired hydrocarbon phase. This term is referred to as coning because the shape of the interface resembles an upright (water coning) or inverted cone (gas coning) when the well produces the undesired fluids in an oil reservoir system. According to Reynolds (2003), coning is due to pressure drop near the wellbore. This causes water inflow from an adjacent connected zone toward the completion. Eventually, water can breakthrough into the perforated or open hole section and higher cuts of the unwanted fluid are produced. Coning is determined by the interactions of two major forces i.e., viscous and gravity in the reservoir. Viscous forces due to pressure gradients caused by the production from a well lead to coning phenomenon whereas the gravity forces due to fluid density difference tend to retard water movement. When the viscous force is greater than the gravity force, the cone will advance further and ultimately breaks into the well. At water breakthrough, higher water cuts of the unwanted fluids are produced. Because of the lower drawdown, horizontal wells may be less prone to water coning than vertical wells.

1.2.4 Location and position of well:

The position and location of wells are a matter of fact that also influences the production rate of reservoir fluids. Well drilled in a fractured or highly conductive reservoir will ease water to breakthrough easily and rapidly. The deviated and horizontal wells have a much greater chance of intersecting vertical or steeply dipping natural fractures compared to conventional wells. Heterogeneity increases with depth, so the wells drilled in highly heterogeneous reservoirs like in limestone might have conductive fractures. Fracture has the potential to flow the fluid, so if a well is drilled in the vicinity of a fracture, then certainly the volume of water production will be very high.

1.2.5 Geometry and Dimension:

The length of the aquifer has a strong effect and produces higher water cut if the reservoir is supported by a large aquifer. Similarly, the thickness of the formation has the same adverse effect. The effect of vertical distance on water-oil contact is also one of the sources to display the water production in an oil reservoir. As the vertical distance increases, the slope of the WOR plot decreases. Increasing the vertical distance, lowers the early water breakthrough and will ultimately enhance the recovery factor. (Kolawole Babajide Ayeni, 2008)

1.2.6 Loss of mechanical integrity and completion problems:

One of the most critical features to produce excessive water in the oil industry is the loss of mechanical integrity and completion problems. This type of production typically occurs as a result if there are leaks in the casing, tubing, and packers or poor cement jobs behind the casing and completion into or close to the water zone. Leaks are due to corrosion or wear and splits caused by flaws, excessive pressure, or formation deformation that can lead to a higher volume of water entry to the wellbore. The most common completion-related problems are flow behind casing, completion into or close to the water zone, and fracturing out of the zone. These problems are usually caused due to poor bonding between cement-casing or cement-formation that eventually provide a large flow conduit to the excessive water production. Channels behind casing can develop throughout the life of a well but are most likely to occur immediately after the well is completed or stimulated. Unexpected water production at these times and points strongly indicates a channel may exist. An improperly designed or poorly performed stimulation treatment can allow the hydraulic fracture to enter a water zone. If the stimulation treatment is performed on a producing well, a fracturing out of zone can allow early water breakthrough. Stimulation techniques cause the natural barriers between hydrocarbon-bearing layers and water-saturated zones to heave and fracture near the wellbore, allowing the water to migrate into the wellbore. Moreover, oil/water contact moving up into perforated zone in a well during normal water-driven production mechanism with time. This problem can be considered a subset of coning and typically is associated with low vertical permeability. This can also be recognized if the well produces below the critical flow rate. (Abdallah Abdelhafeez abakor, et al. 2014).

1.2.7 Water production classification:

Excessive water production is one of the most critical concerns in oil reservoirs which is classified as:

- Water Coning
- Water Channeling

1.2.7.1 Water coning:

Coning occurs in a well on production when the water zone moves up towards the wellbore in the form of a cone. According to Reynold (2003), fluid coning in vertical wells and cresting in horizontal wells are due to pressure drops near the well completion. The major factors affecting water coning tendency are density difference between oil and water, the viscosity of water, formation permeability, pressure drawdown, flow rate, etc. More specifically, the tendency of water to cone is directly proportional to the density difference between water and oil but is inversely proportional to the water viscosity and reservoir permeability. The well is produced so rapidly that viscous forces overcome the gravity forces and draw the water from the lower connected zone toward the wellbore. Eventually, the water can breakthrough into the perforated or open hole section, replacing all or a part of hydrocarbon production. Once the water breakthrough occurs, higher water cuts of the unwanted fluid are produced, and production tends to get worse.

1.2.7.2 Water channeling:

In water channeling the reservoir, heterogeneities cause the presence of high permeability streaks. Fractures and fracture-like features are the most common causes of channeling. Water production could emit via natural fractures from the underlying aquifer. In an unfractured reservoir, having stratification and associated permeability variation among various layers can result in a channeling phenomenon between an injector and producer or from an edge water aquifer to the producer. (Abdallah Abdelhafeez abakor, et al. 2014). High permeability streaks can allow fluid flow that is driving hydrocarbon production to breakthrough prematurely, bypassing potential production by leaving lower permeability unswept. This is very common in active water drive reservoirs. (Echufu-Agbo Ogbene Alexis, 2010). Horizontal and deviated wells are prone to intersect faults or fractures.

1.2.8 Water flooding for enhanced oil recovery:

One more factor that influences the production rate of water in an oil well is the water flooding for enhanced oil recovery. When the production of oil from primary recovery i.e., natural drives, is not sufficient to push the oil from its zone then IOR is adopted to operate the production efficiently: reservoir pressure is maintained by water flooding that also pushes the oil in front that was not recovered with primary production mechanism. In this type of recovery, the mobility of displacing fluid plays a vital role that displaces the oil. The ratio of displacing fluid (water) to the mobility of displaced fluid (oil) should be considered to avoid the alarming situation. Higher mobility ratio greater than one (maybe up to 10) causes serious problems such as the fingering phenomenon, in which water as displacing fluid sweeps through oil and is produced at the producer without displacing oil. Conversely, if this ratio is lower than one, the oil recovery will be enhanced. Since the water flood pushes the oil front toward the producing well so recovery will be economical.

Chapter 2 WATER CONING AND ITS REMEDIAL TECHNIQUES

2.1 Introduction:

Water influx can occur via several mechanisms such as flow-through fractures, channeling, or coning.

2.1.1 Water Coning:

Oscar Dela Gabada (2004) has defined water coning as oil reservoirs that are often enveloped in a gas cap and or an aquifer. Reservoirs with bottom water drive depict high oil recovery due to supplemental energy provided by the natural source called an aquifer. Before the start of production, these reservoirs have defined fluid contacts, which may be, Water-Oil Contacts (WOC) and or Gas -Oil Contacts (GOC). (Fig 2.1)

Once production operation starts, the previously defined contacts OWC or GOC will become deformed from their original plane shape to form a cone or crest depend on the type of fluid that exists. A continuous large oil production rate may cause water to be produced by upward flow mixed with oil as a result of a rapid outburst of water and gas movement towards the well as a sharp pressure drop in the direction of the well occur. This drop in pressure lowers the gas-oil contact and rises the oil-water contact in the immediate vicinity of the wellbore. The counter balancing forces tend to deform the gas-oil and oil-water contacts into the bell or cone shape as shown in fig 2.2 (Ahmed Tarek, 2010). The deformation is referred to as a “cone” if a field is developed by vertical wells whereas this deformation is called crest for horizontal wells.

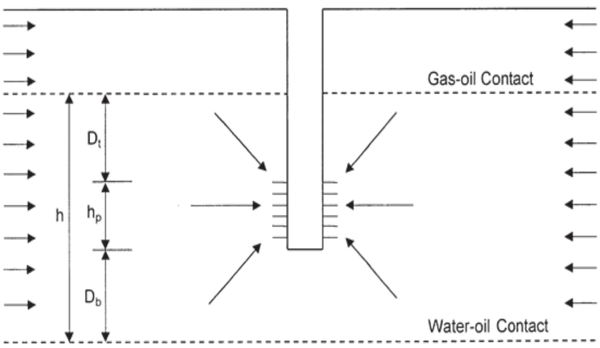


Figure 2-1 Original reservoir at static condition (Ahmed Tarek, 2010)

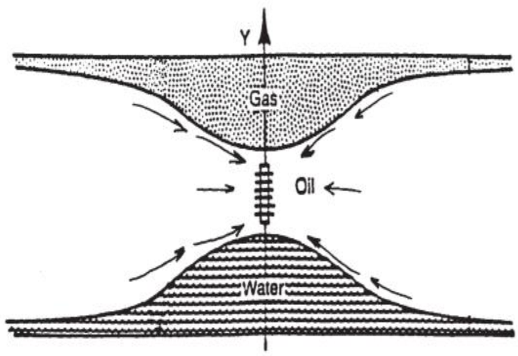


Figure 2-2 A producing well with Coning. (Ahmed Tarek, 2010)

The production of water from oil-producing wells is a common occurrence in oil fields that results from one or more sources and reasons such as the normal rise of oil-water contact (OWC), water coning, and water fingering. In general coning and cusping are the term used to describe the mechanism underlying the upward movement of water and/or downward movement of gas into the perforation of producing well.

The Oil production from wells existing in reservoirs supported with a strong aquifer leads to changing of pressure drawdown around the wellbore and causing the movement of oil/water interface toward the producing interval. This phenomenon is the result of fluids segregation according to their densities when gravitational forces are exceeded by the flowing pressure - viscous force. If the wellbore pressure is higher than the gravitational forces resulting from the density difference between gas and water, then water coning occurs. (Miguel Armenta, 2003). The equation shows the basic correlation between the pressure in the wellbore and at the well vicinity for coning.

$$P - P_{wf} = 0.433(\gamma_w - \gamma_o)\, h_{o\text{-}w} \quad \ldots\ldots\ldots\ldots \quad (2.1)$$

Where P is average reservoir pressure (psi), P_{wf} is the flowing bottom hole pressure (psi), γ_w is water specific gravity, γ_o is oil specific gravity, and $h_{o\text{-}w}$ is the vertical distance from the bottom of the well's completion to the oil/water contact (ft)

In most oil and gas fields over the world, produced water due to coning is normally present in the reservoir even before production starts; as in bottom water aquifer and/or in artificially improved recovery scheme, and as in water injection called as pressure maintenance. Therefore, the production of excessive water has been a continuing problem for operators since the beginning of the petroleum industry. Water coning is characterized by the gradual growth of deformed shape cone of water in the vertical and radial directions. This extent of cone growth depends upon some factors such as total production rate, mobility ratio, anisotropy ratio, oil zone thickness, the extent of the well penetration. water coning depends on the properties of the porous media, oil-water viscosity ratio, distance from oil-water interface to the well, production rate, densities of the fluids, and capillary pressure effects. (Y. Ould-ame et al, 2004). This phenomenon becomes more complicated and challenging in fractured reservoirs due to intrinsic differences in them along with other factors such as heterogeneity and high permeability streaks of the fractures. It is therefore concluded that the study of water coning behavior requires deep, thorough, and conspicuous studies and understanding of reservoir geology, water production, reservoir pressure profile, Gas-oil ratio (GOR), and the entire history profile.

2.1.2 Multilayer Channelling:

Multilayer channeling is one of the reservoir related problems that typically occurs through high permeability layers or fractures and faults. This phenomenon is observed due to the contrast in the permeabilities between multiple layers. There are other possibilities like poor cementing behind casing and loss of mechanical integrity that will cause the channeling phenomenon. Water may channel into the producing well through induced(artificial) or naturally occurring fractures from aquifers or injection wells. Water may breakthrough through high permeability streaks without sweeping the oil from lower permeability zones. (Minou Rabiei,2011). In fig. 2.3, different possibilities can occur to cause the channeling phenomenon.

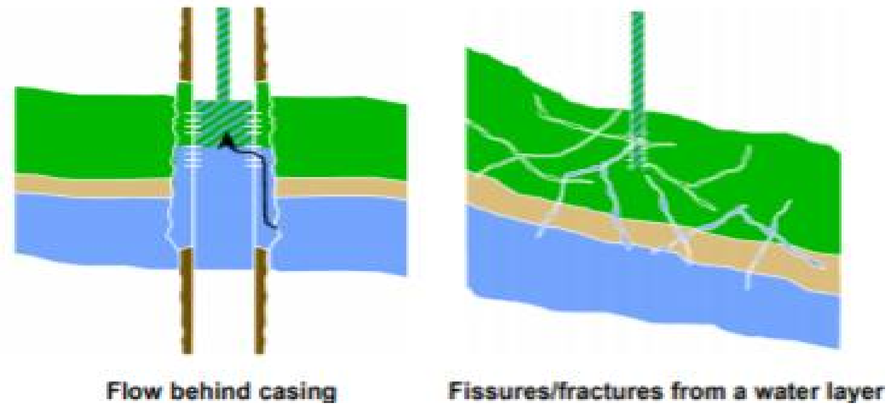


Figure 2-3 showing the examples causing water channeling (Minou Rabiei,2011)

Water coning should not be mistaken for water channeling. The latter is the vertical movement of water through faulty primary cement jobs. The difference between these two situations can be identified by increasing the production rate. This will usually increase water production if it is a water coning problem.

In an oil-water system when a strong water drive or aquifer exists, the wells in the field will likely experience water coning when producing for a long period. Besides this there are more reasons such as producing at a higher production rate, water coning occurs in a more severe manner that leads to rapidly accelerated water production and cannot be controlled further.

In the literature, several studies have been performed to predict and mitigate and have suggested different remedial techniques for water production phenomena in oil production.

While some other authors have developed correlations to predict water production problems in terms of critical production rate, water breakthrough time, and water-oil ratio (WOR).

2.2 Remedial techniques for water production:

There are several approaches or techniques invented to develop water drive reservoirs efficiently and economically. Numerous practical approaches have been developed to prolong the delay of water breakthrough time and minimize the severity of the water production phenomenon in vertical wells. These techniques include:

1. Mechanical and completion methods
    i. Plugs and Packers
    ii. Intelligent well completions
    iii. Downhole oil-water separation technology
    iv. Downhole water sink (DWS) method and Downhole water loop (DWL) method
    v. Drilling horizontal wells
    vi. Total penetration method
2. Chemical Methods
    Polymer flooding and Gel Injection
3. Squeeze Cementing
4. Reservoir rock characteristics and modifying Reservoir fluid properties
    i. Critical Oil production rate
    ii. Effect of Mobility ratio (viscosity and relative permeability)
    iii. Effect of heterogeneity/ Anisotropy Ratio
    iv. Effect of Capillary Pressure

These techniques are applied depending on the type of problem, the extent of the problem, the geology of the subsurface, type of fluid in the reservoir, reservoir behavior, etc.

2.2.1 Mechanical and completion methods:

There are several available technologies that can successfully shut-off the unwanted water production within the wellbore. The impact can be observed in hours in contrast to the chemical solutions. Controlling unwanted water production using a mechanical approach is usually a rig-less job and is relatively cheaper than chemical methods. There are some challenging factors that may affect the success ratio of mechanical solutions for water shut-off. Among these challenges, the setting depth of the plugs and packers can be wrong due to inaccurate reading from the coiled tubing meter. The reservoir condition also plays a vital role in affecting the operation, as the crossflow between the layers can happen and leads to intervention to failure. Additionally, the wellbore condition is also one of the serious challenges that need more attention. Scale presences in the tubing can cause the failure of the operations, as it can create a barrier while running the plug and packer downhole. In the case of highly deviated well it is very challenging to run coiled tubing since they may get stuck in the hole. (Abdullah Taha, et al. 2019).

2.2.1.1 Plugs and Packers:

The installation of plugs and packers is one of the most well-known mechanical solutions for water shutoff and isolation operations inside the wellbore. They are considered successful in eliminating the production from unwanted water zone. (Abdullah Taha, et al. 2019). They are commonly used by oil operators to assist the well's performance and shut-off the excessive water production. This completion tool is known for being economical and reliable in achieving isolation as it can be installed without pulling the production tubing and without the drilling rig. These tools can be installed using coiled tubing that can run them through the wellbore. The results are achieved relatively fast i.e., in hours to days compared to chemical solutions. The concept of plugs and packers is a small diameter element, mainly rubber that can expand downhole the wellbore into the larger diameter creating a seal and isolate the well from undesired zones. There are different types of plugs and packers with different properties and setting techniques. They are designed depending on the properties like temperature, pressure, and salinity of the formation fluids. These might face some challenges while setting at depth and lead to the failure of the operation.

A bridge plug is installed to isolate the bottom section and shut down the additional water production to help the production performance from the upper oil zone (fig. 2.4). The extension of the problem increases if the water source happens to be in the middle or at the top part of the production interval of the tubing in the reservoir section. In such a situation, a blank pipe with upper and lower packers with pre-designed length can be installed to isolate the water production area without compromising the lower and upper oil production zones (fig. 2.5). (Abdullah Taha, et al. 2019).

Besides these, inflatable packers are also used in chemical injection for water shut-off operations.

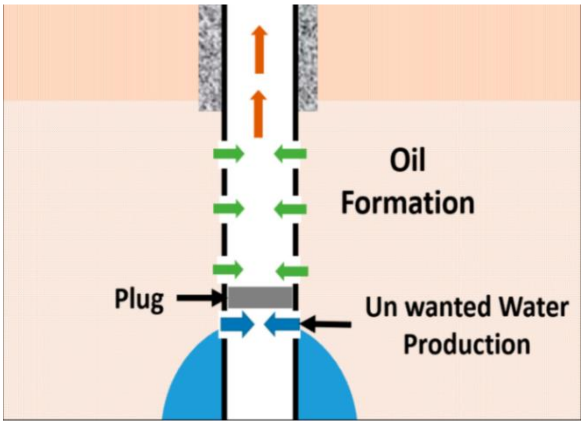


Figure 2-4 Using plug to shut off the production of water from the bottom (Abdullah Taha, et al. 2019)

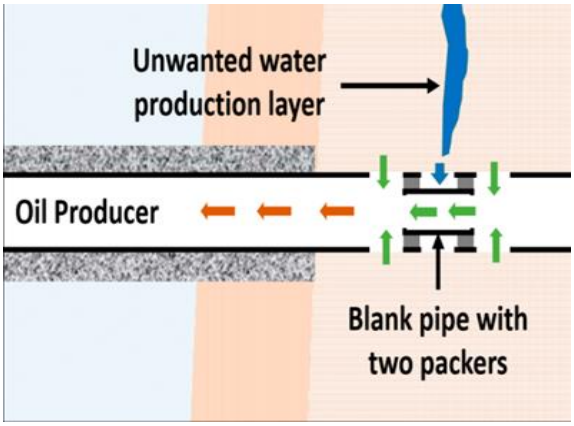


Figure 2-5 Two packers above and below a blank pipe to shut-off water production from middle and upper part (Abdullah Taha, et al. 2019)

2.2.1.2 Intelligent well completions:

One of the most revolutionary interventions in production technologies is intelligent well completion. This technique involves a completion system that has the capability to collect, transmit and analyze wellbore production, reservoir, and completion integrity data followed by having a potential of remote action to enhance reservoir control and well production performance. Therefore, it is well-known for the ability to collect the data and analyze it from the wellbore and allows the direct supervising and monitoring and so controlling the reservoir, wells, and production operations using special tools and equipment that are installed within well completion. The installed components in a typical intelligent well completion include packers, pressure and temperature sensors, downhole Inflow Control Valves (ICV) on the production tubing (fig 2.6). The application of this technology in the oil field is to control water breakthrough, to select the desired zones that can be brought to the production, and to manage water injection for pressure maintenance. (Anietie N. Okon et al, 2018). However, this technology is very expensive due to the high cost of ICV installation.

The design of this completion tool depends on the well characteristics, reservoir conditions, water-oil contact, and reservoir zones. By the application of this completion technology having an on/off interval control valve (ICV) in each interval, the well segments can be shut-off when water breakthrough occurs through the production interval. To sum up, the intelligent well completion does not prevent the occurrence of the coning phenomenon, rather, it controls the severity of the phenomenon.

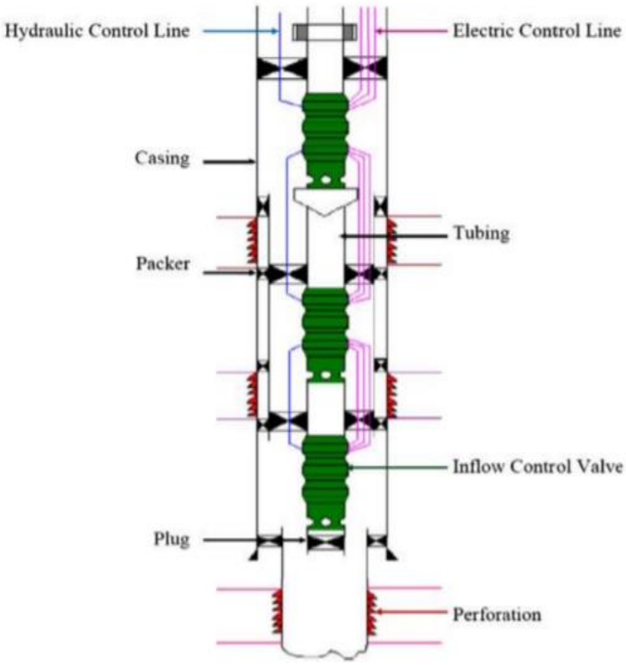


Figure 2-6 Intelligent Well Completion Schematic, showing all components (Anietie N. Okon et al, 2018).

2.2.1.3 Water separation (DOWS) technology:

A Downhole oil-water separation is a relatively new technology that separates hydrocarbons from produced water at the bottom of the well. Then it re-injects most of the produced water into another form that is usually deeper than the producing formation and the hydrocarbons are pumped to the surface. (Awab Osman Abdullah et al, 2015)

This system is typically installed at the bottom of an oil well and separates oil and water. The oil-rich stream is brought to the surface while the water-rich stream is pumped into the injection formation without bringing it to the surface. A DOWS system has many components but the two are prominent components i.e., oil/water separation system and pumping/injection system. These are used to lift oil to the surface and inject water into deeper formations.

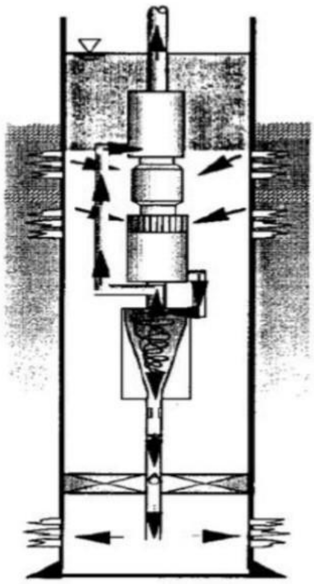


Figure 2-7 A typical design of DOWS (Awab Osman Abdullah et al, 2015)

The two basic types of DOWS systems have been used. One type uses hydro cyclones to mechanically separate oil and water and the other type rely on gravity separation that takes place in the wellbore. The DOWS technology typically uses three basic types of pumping/injection systems. These types are electrical submersible pumps, progressive cavity pumps, and sucker rod pumps.

2.2.1.4 Downhole water sink (DWS) method and Downhole water loop (DWL) method:

Downhole water sink (DWS) is a production technique for producing water-free hydrocarbons from reservoirs with a bottom-water drive and a strong tendency to water coning. (Andrew K. Wojtanowicz, 2006). This method provides an innovative solution for controlling water production and reduces water cut significantly as well as delays the breakthrough time in the water coning phenomenon. DWS involves a dual-completion well with one completed at the oil zone for oil production and the other completed at the water zone for water drainage near oil-water-contact. The drainage completion provides the extra pressure drop below oil-water contact which can balance the rising force at the oil interval, thus suppressing the water coning. (Anietie N. Okon, et al 2017).

Figures 2.8 and 2.9 show principles of two basic variants of the DWS systems, drainage injection, and drainage production. In the system, a well is dual - completed in the oil and water zones, and with the help of a packer, set inside the well at depth of the oil-water contact, the two completions are separated. The water sink (bottom) completion consists of a submersible pump and the water drainage perforations.

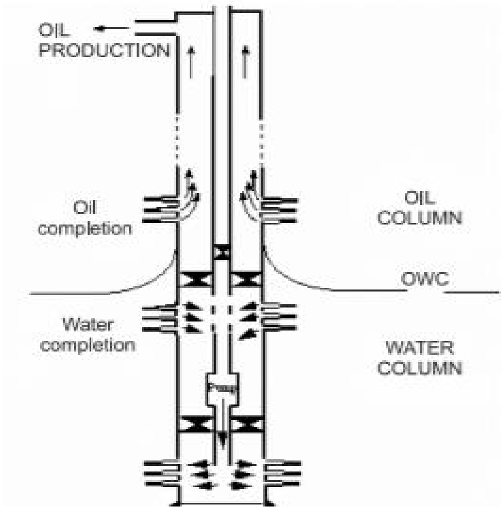


Figure 2-8 DWS water drainage-injection (Andrew K. Wojtanowicz, 2006)

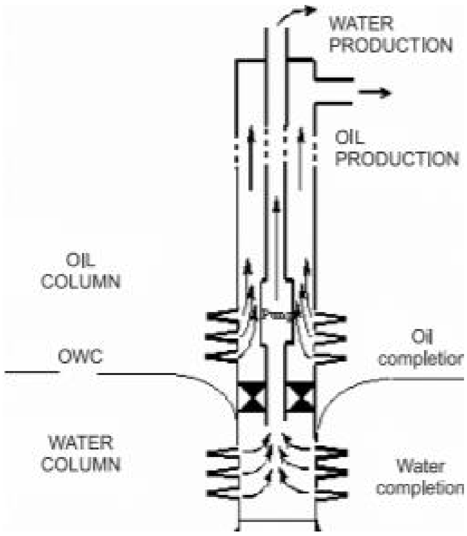


Figure 2-9 DWS water drainage-production (Andrew K. Wojtanowicz, 2006)

Downhole water loop (DWL) technology is developed based on downhole water sink (DWS) well in such a way as to cushion the setback i.e., handling of a very huge volume of water at the surface, experienced with the DWS technology. (Anietie N. Okon, et al 2017). It consists of a triple-completed well where one perforation located at the oil zone and the other two completions are located at the water zone. In this technology, the three completions are separated by two packers, unlike the DWS completion where only one packer is used. The uppermost completion at the oil zone is used for oil production while the second completion - water drainage interval (WDI), is used to produce water simultaneously near the oil-water contact to stabilize the interface. The produced water at the WDI is again re-injected into the same aquifer through the lowest completion - water re-injection interval (WRI) using a submersible pump.

A typical configuration is shown in (fig. 2.10).

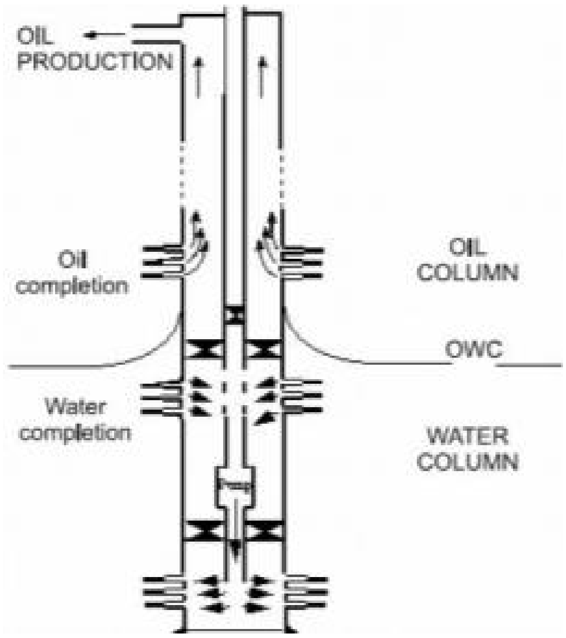


Figure 2-10 Downhole water loop schematic (Anietie N. Okon et al, 2017).

2.2.1.5 Drilling horizontal wells:

Horizontal wells are high-angle wells with an inclination of generally greater than 85° drilled to improve the reservoir performance by placing a long wellbore section within the reservoir. Several researchers have recommended horizontal well technology as a solution for the development of reservoirs problems caused by water production problems especially water coning. (Anietie N. Okon et al, 2017). The vertical wells act like point sources concentrating all the pressure drawdown around the bottom of the wellbore whereas, horizontal wells act as a sink and distribute the pressure drawdown over the long entire section of the wellbore. So, the pressure drawdown is reduced around the wellbore. (Solomon Ovueferaye Inikori, 2002).

Fig. 2.11 shows the schematic of horizontal well configuration in the oil zone of a reservoir. The reason for selecting horizontal over vertical wells according to (Chaperson, 1986) is the actually the horizontal wells can lower drawdown pressure for the same production rate to vertical wells and so as to delay the onset of coning and cresting mechanism and ultimately control water production.

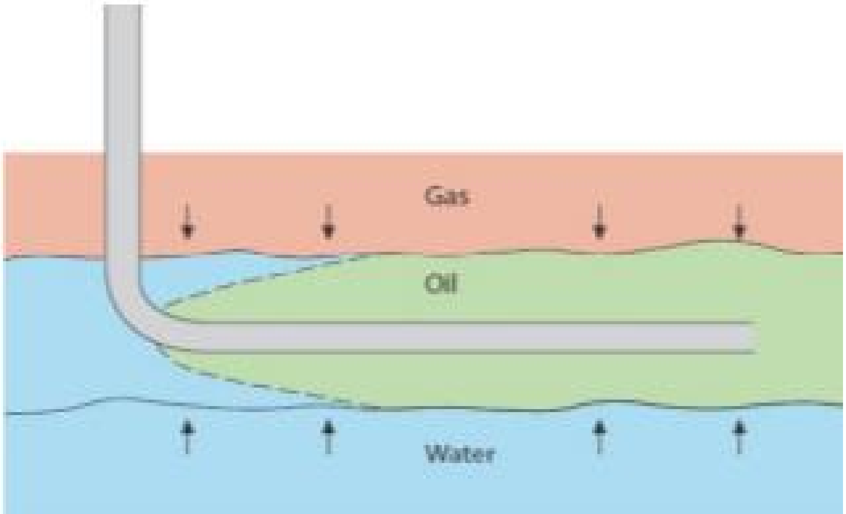


Figure 2-11 Horizontal well schematic (Anietie N. Okon et al, 2017).

2.2.1.6 Total penetration method:

This method typically involves the extension of perforation interval to cross the entire pay zone i.e., oil zone, and into the bottom water zone to maintain the radial flow of fluids. This technique aims to avoid the development of cone and resultant oil bypass. This will result in water production immediately as oil production starts. So, water handling facilities are put in place to accommodate the excessive produced water at the surface. This technology significantly delays the breakthrough time and reduces water cuts. However, over time as production continues the tendency for cone development is unavoidable. (Anietie N. Okon et al, 2017).

2.2.2 Chemical Methods:

Near the wellbore or far from the wellbore in the reservoir, the shut-off operations are performed by several chemical treatments. These treatments achieve better performance in the reservoir as well as blocking the undesired water production zones. Chemical treatment aims to block the open features and high permeability channels to force water to go toward the more resistant path so as to sweep oil from the matrix rock. This will ultimately enhance the overall economical returns. (Abdullah Taha, et al. 2019). The results of chemical solutions can be achieved in months to years, depending on the nature of the reservoir and the properties of the injected chemicals. There are several chemicals used in treating the water shut-off operations, that are as follows:

2.2.2.1 Polymer flooding:

A water shut-off operation, in which polymer flooding is used to increase the viscosity of driving fluid i.e., water to mobilize and displace the oil in the reservoir matrix. This technique is usually applied in the reservoir far from production wells through water injection wells to achieve better sweep efficiency. Eventually, this leads to preventing excessive water production. The application of polymer is very common among oil operators and can be prepared by dissolving the polymer into the injected water and inject it through the injection wells. Polymers used for this purpose are usually of two types: biopolymers and synthetic polymers. Biopolymers are more useful than synthetics because they are not affected by the salinity of the water, and they are insensitive to mechanical degradations. The disadvantage is that they are more expensive than synthetic polymers. Xanthan and scleroglucan are two famous kinds of biopolymers. On the other hand, synthetic polymers are more common since they are cheaper, more available, and perform well with low-salinity water. Polyacrylamide (PAM) and hydrolyzed polyacrylamide (HPAM) are two types of synthetic polymers. There are other chemical techniques for water shutoff operation such as resins, solid particles, and foams that are also effective in obtaining better conformance and enhance the sweep efficiency. Polymers can also play a role in reducing permeability if the molecular weight is increased. (Abdullah Taha, et al. 2019).

Besides this, a polymer is a proven technology for shutting-off the more permeable zone in order to control water production. The caves and loss circulation area are also plugged with the help of polymer flooding. These are used as viscosifiers to increase viscosities and thus improve hole cleaning and solid suspension capabilities of drilling fluids. (Dr. Bicerano, 2018). There are some cases where the volume of water production was very huge e.g., in Kuwait Saudi Arabia, polymers were used to reduce the unwanted water influx. (E. Bedaiwi et al, 2009).

2.2.2.2 Gel Injection:

Gel injection is one of the most well-known chemical treatments for water shutoff operations and is used to reduce the water to oil ratio (WOR) and increase the conformance of the pattern. This process is done by the ability of the gel to reduce the permeability and block the open features, fractures, and high permeability water zones. (Abdullah Taha, et al. 2019). The injected gel is mainly made of water, small volumes of polymers, and crosslinking chemical agents. Gel treatments can entirely seal off layers; therefore, they are considered aggressive and risky conformance control operations. In contrast, polymer gel injection is considered relatively cheaper than other improved oil recovery operations. Gel injection operations are classified into three main stages: modeling, designing, and executing, and are used accordingly.

2.2.3 Squeeze Cementing:

Workover is an activity that is performed to remedy a well and achieve better production. Squeeze cementing, a workover job is one of the remedial operations performed to repair the damage caused due to over-production of water. This process is performed when the cement slurry is pressed under some pressure to a certain point inside the well for repairing purposes. One of the well-known reasons for using squeeze cementing is to isolate water under the wellbore. (Aldo Fadhillah Abraham et al, 2015). The reasons for choosing this treatment are as under:

- Repair primary cement job
- Shut-off water production
- Channels voids due to losses
- Selective shut-off water injection
- Seal lost circulation

Below the Squeeze cementing schematic is shown. (fig.2.12)

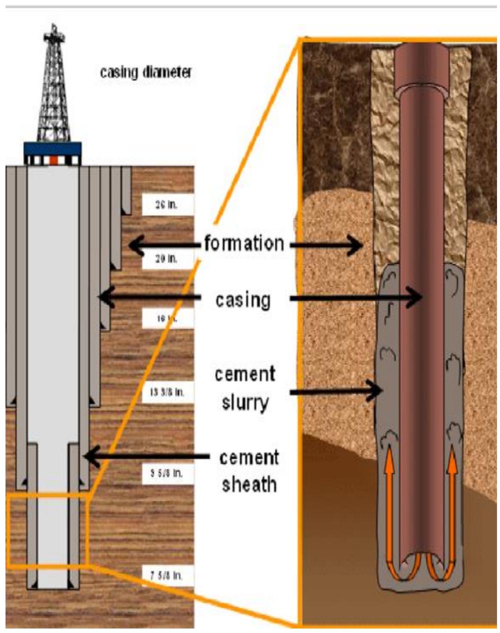


Figure 2-12 oil well squeeze cementing schematic (Drillingcourse.com, 2015)

There are two main controlling variables during squeeze cementing that affect the rate of filtration, these are the fluid loss of the cement slurry and the permeability of the formation.

(Lenin Diaz, 2020). Before the squeeze cementing operation an injectivity test is always performed, this injectivity is directly proportional to effective permeability using Darcy's Law.

$$\text{Injection Rate is a function of} = \frac{\text{Permeability} \times \text{Flow area} \times \text{Pressure Differential}}{\text{Fluid's Resistance to flow} \times \text{Penetration}} \quad \ldots\ldots\ldots \quad (2.2)$$

2.2.4 Reservoir rock characteristics and modifying Reservoir fluid properties:

There are some petrophysical and fluid properties that affect the phenomenon of excessive water production i.e., coning and multilayer channeling. Some of these are alterable while the others are not. The modification of one parameter can directly or indirectly change the other parameter that leads to a change in the amount of water cut. These parameters are modified in such a way that we can achieve our goal of controlling the water coning phenomenon as well as not to disturb the reservoir behavior as we may face other challenges by controlling one. Some of the parameters that affect the water coning phenomenon are:

2.2.4.1 Critical Oil production rate:

Critical rate is defined as the maximum rate at which oil is produced without the production of water (Joshi, 1991). The critical rate for the oil-water system is discussed by several authors using different correlations to calculate the critical rate. When the oil production rate becomes higher than the critical rate, water-oil contact (WOC) rises, and the cone becomes unstable reaching the bottom of the well. The water cone is considered to be stable if the pressure at every point on WOC is the same as the reservoir pressure. (Firdavs A. Aliev et al 2015). All the effective factors in water coning e.g., mobility ratio, vertical and horizontal permeability ratio, viscous forces are considered in critical production rate. There are different approaches to calculate the critical production rate for producing oil. According to Meyer and Garder correlation (1954):

$$Qc = \frac{0.001535(\rho w - \rho o)k(h2 - D2)}{\mu o Bo \ln\left(\frac{re}{rw}\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.3)$$

Where: QC is critical oil rate (STB/D), ρw is water density (gm/cc), ρo is oil density (gm/cc), k is formation permeability (mD), h is oil zone thickness (ft), D is completion interval thickness (ft), µo is oil viscosity (cp), Bo is oil formation volume factor (bbl/STB), re is external drainage radius (ft), and rw is wellbore radius (ft). (Miguel Armenta, 2003)

There are some sensitivity analyses investigated on a fractured reservoir using different reservoir parameters. Reda Abdel Azim, 2016 explained these parameters as oil production rate, mobility ratio, anisotropic ratio, and capillary pressure are used to plot the data against time to check the water cut contents. These parameters are the basis for the modification of fluid flow in order to observe the relationship with the water cut. Graph 2.13 shows the effect of changing oil production rate on the producing water cut. As can be seen from this graph, a decrease in oil production rate delays the water breakthrough time significantly.

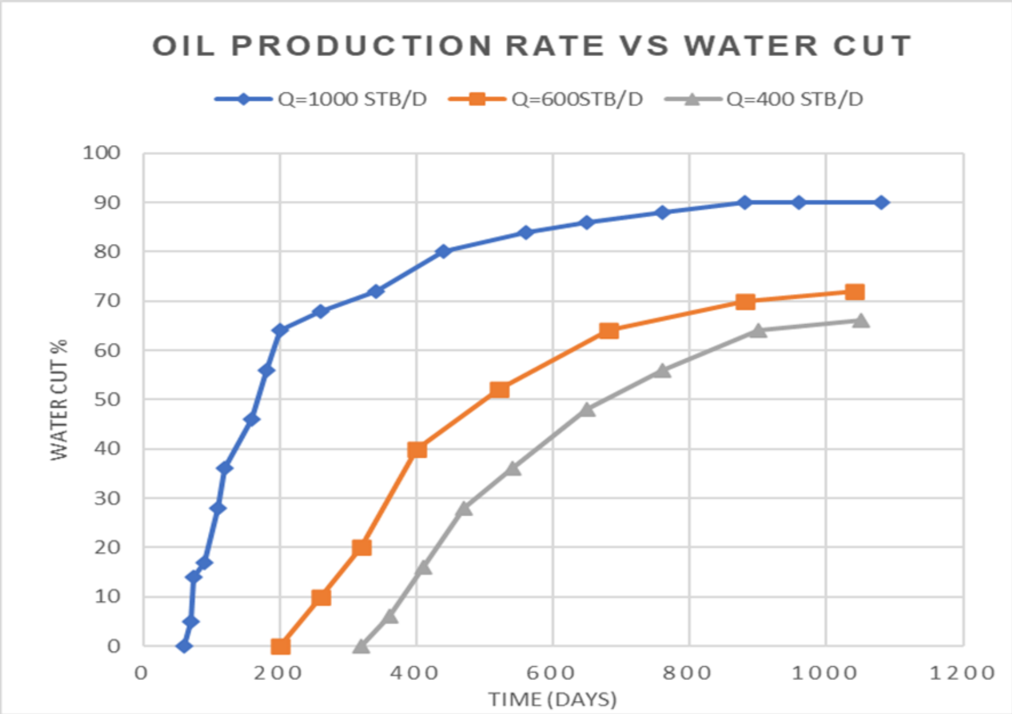


Figure 2-13 illustrating the effect of oil production rate vs water cut and its breakthrough time (Reda Abdel Azim, 2016)

Here the proper size of the choke plays a vital role to adjust the oil production rate.

2.2.4.2 Effect of Mobility ratio (viscosity and relative permeability):

Mobility is the ability of fluid which is the ratio of effective permeability (Ke) to the phase viscosity (μ) and mobility ratio is the ratio of displacing fluid i.e., water (λw) behind the front to the displaced fluid i.e., oil (λo) ahead of the front (in oil-water system). (John R. Fanchi, 2010).

$$\lambda = \frac{Ke}{\mu} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.4)$$

$$M = \frac{\lambda w}{\lambda o} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.5)$$

This property has a strong effect on the water coning phenomenon. As if the mobility ratio is higher than one (1), maybe up to 10, there will be an early breakthrough. The reason is the relative permeability to water will bypass oil and quickly flow towards the producing well. (Abdus Satter et al, 2016).

Graph 2.14 illustrates sensitivity analysis for three mobility ratio values with water cut and time. It is seen that at a high mobility ratio (M = 10), the breakthrough time occurs very fast (5.5 days). On the other hand, when the mobility ratio becomes very small (M= 0.5), the breakthrough time occurs after 200 days of oil production. (Reda Abdel Azim, 2016)

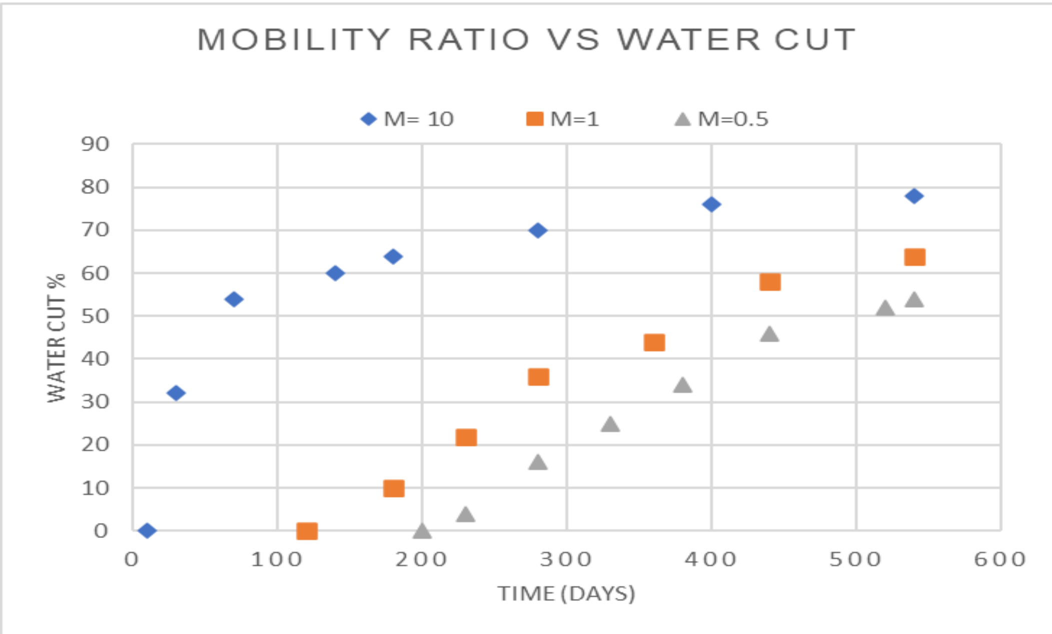


Figure 2-14 showing the relationship between Mobility ratio and water cut with breakthrough time ((Reda Abdel Azim, 2016)

To control the mobility ratio, we need to either decrease relative permeability to water (Krw) or increase water viscosity (by polymer flooding). Also changing the wettability from oil-wet to water-wet, Krw/Kro reduces to half that significantly reduces Mobility ratio. Surfactants are also used to change interfacial tension that changes Sor will ultimately improve oil recovery.

2.2.4.3 Effect of heterogeneity/ Anisotropy Ratio:

Reservoir heterogeneity is measured by the dispersion or scattering of permeability values. A homogenous reservoir is uniform and has permeability variation that approaches zero, whereas an extremely heterogeneous reservoir has permeability variation t approaches to one. Dongmei

Wang, 2013). Tarek Ahmed (2010) has defined reservoir heterogeneity as variation in the reservoir properties as a function of space.

It has been said that most reservoirs are laid down in a body of water by a long-term process, spanning a variety of depositional environments, in both time and space. As a result of subsequent physical, chemical, and biological reorganization, such as compaction, solution, dolomitization, and cementation, palaeontological, the reservoir characteristics are further changed. Thus, the heterogeneity of reservoirs is, for the most part, dependent upon the depositional environments and subsequent events. The reservoir heterogeneity is then defined as a variation in reservoir properties as a function of space. (Tarek Ahmed,2010)

Anisotropy ratio is the ratio of vertical permeability to horizontal permeability (Kv /Kh). The result in figure 2.15 indicates that the water cut increases as a result of increasing the anisotropy ratio value. The physical explanation for this is the increase of vertical permeability will increase the coning into the fractured network because high vertical permeability would reduce the time needed for a water cone to stabilize due to the pressure drawdown around the wellbore. (Reda Abdel Azim, 2016).

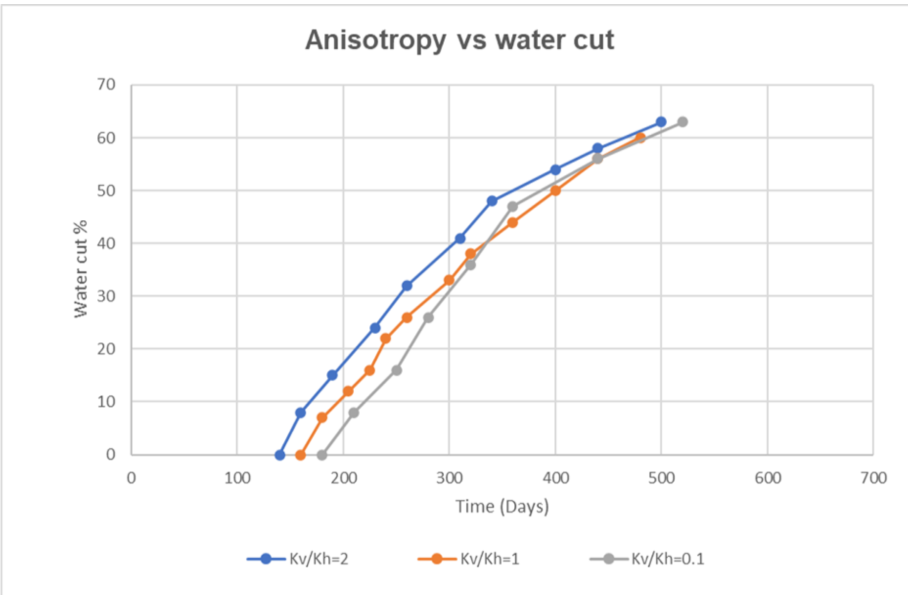


Figure 2-15 showing the effect of anisotropic ratio with water cut along the breakthrough time (Reda Abdel Azim, 2016).

The best control technique to limit this ratio is to produce oil at a lower rate (not lower than the critical rate as it will not be economical).

2.2.4.4 Effect of Capillary Pressure:

Capillary Pressure is the pressure difference across the interface between two immiscible fluids, e.g., oil and water, in the reservoir. (John R. Fanchi, 2002) Or it is the pressure difference generated by curvature at the interface between a wetting and non-wetting phase.

$$P_c = P_{nw} - P_w \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2.5)$$

Where Pc is capillary pressure, Pnw is the pressure of non-wetting and Pw is the pressure is of wetting phase. In the case of a water-oil system, water is the wetting phase and oil is a non-wetting phase.

Capillary pressure plays a crucial role in the water coning mechanism as it is a function of water saturation that has a major role in fluids' relative permeabilities.

In graph 2.16 the results show that as water saturation increases, the relative permeability to water increases but the relative permeability to oil decreases as the rock becomes more water-saturated. (J. Foroozesh, et al 2008). Similarly, in fig. 2.17 it is clear that an increase in relative permeability to water, showing higher water saturation will decrease the capillary pressure. The higher the capillary pressure, the higher will be water cut, which will strongly lower the oil in place.

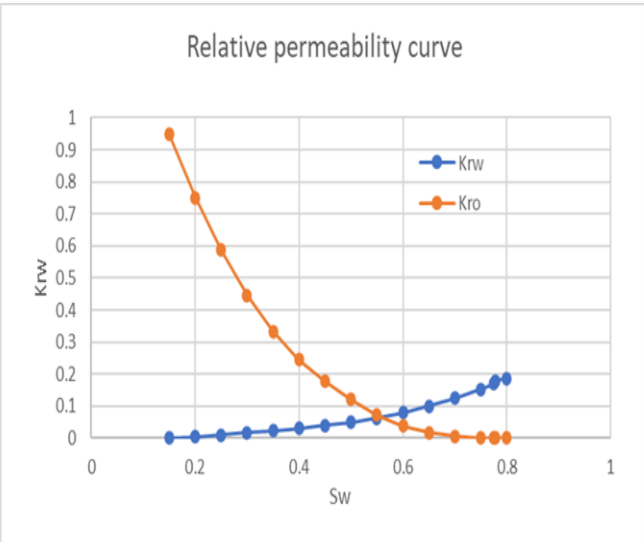


Figure 2-16 relative permeability curves vs water saturation (J. Foroozesh, et al 2008)

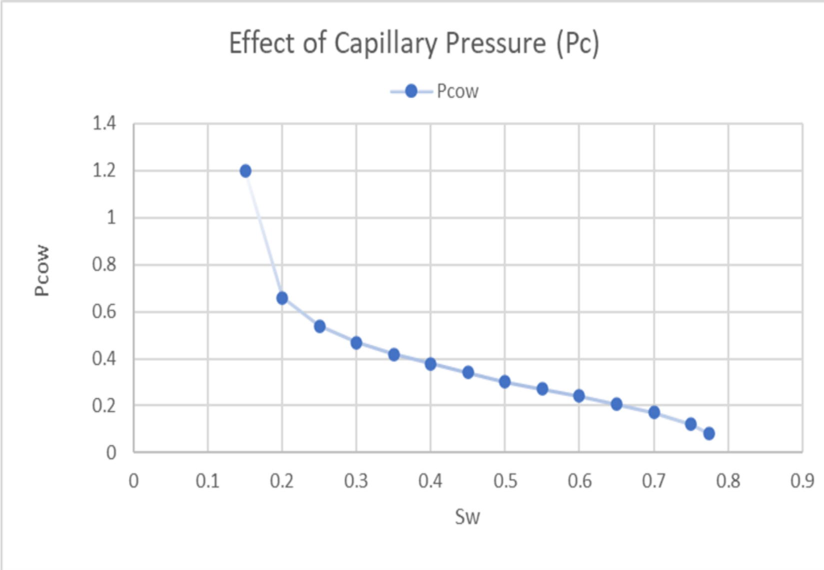


Figure 2-17 Relative permeability curves vs water saturation (J. Foroozesh, et al 2008).

Surfactants can reduce capillary pressure in the matrix by reducing surface tension and/or by changing the wettability of the rock surface when they adsorb on a surfactant. (Rick David Gdanski, 2007).

Chapter 3 Water control Diagnostic plots

3.1 Introduction:

Historically various techniques were used to predict and so mitigate water production problems. Among these techniques, the Decline curve analysis developed by Chan in 1995 has been adopted by oil and gas industries. Chan classified the excessive water production problem into three major types: water coning, multilayer channeling, and near-wellbore problems.

3.1.1 Chan's diagnostic plot

K.S Chan introduced a log-log plot of water to oil ratio (WOR) and derivative of WOR versus time to distinguish between the coning and channeling phenomenon. The value of the Water to oil ratio using actual water and oil production data is calculated by the following equation:

$$\text{WOR} = \frac{Qw}{Qo} \quad (3.1)$$

This equation shows the ratio of the rate of water produced (Qw) to the rate of oil produced (Qo) by a particular well. Similarly, the derivative value for the WOR with respect to time is calculated by the following equation:

$$\text{WOR}' = \frac{d(WOR)}{dt} = \frac{(WOR2 - WOR1)}{(t2 - t1)} \quad (3.2)$$

Equation 3.2 shows the derivatives of the water rate to oil rate that is equal to the WOR calculated at the time period of t2 subtract the WOR calculated at the production time t1 divided by the difference of the time periods (t2-t1).

This method can be used to quickly diagnose and evaluate the mechanisms. This method actually uses plots generated from available production history data. These plots include.

i. Production history for the entire period or water injection period for water and oil
ii. WOR and derivatives of WOR
iii. Cumulative oil produced
iv. Oil and gas rate decline

These plots provide a complete profile of the past and present production behavior and the remaining production potential of well. (K.S. Chan 1995).

3.1.2 Conventional Plots:

In these types of plots, water cut vs time was used to show the progress and severity of excessive water production problems. The correlation between water cut or fractional flow of water and average reservoir water saturation for the two-phase flow is well-known. But it is impractical as saturation distributions change with time throughout the reservoir. The information provided by these plots is very limited in the case of sudden failure completion or rapid breakthrough. The shapes of the water cut plots are very similar so sometimes it is difficult to recognize the problem. Linear and semi-log WOR plots are used to evaluate recovery efficiency, but these plots do not show any detail on reservoir flow behavior. Moreover, this approach has a drawback and is unable to show any detail of the breakthrough time of the layer in multilayer flow. (K.S. Chan, 1995).

3.1.3 Chan's Diagnostic plot Technique:

According to Chan, a set of diagnostic plots have been generated by conducting a series of systematic water control numerical simulation studies using a black oil simulator. The three-dimensional, three-phase simulator has the ability to model the performance of reservoir flow under different drive mechanisms and water injection operations. The log-log plots of water to oil ratio (WOR) vs time were observed more effective in identifying the production trends and the most important problem mechanism. Moreover, the derivatives of the WOR vs time plots were used for differentiating whether the excessive water production is due to water coning or multilayer channeling mechanism.

In the fig. 3.1, there is a clear distinction between a water coning and a multilayer channeling development using the same set of PVT and saturation distribution data, petrophysical data, and the same initial conditions, except for the difference in the model setup is flow geometry.

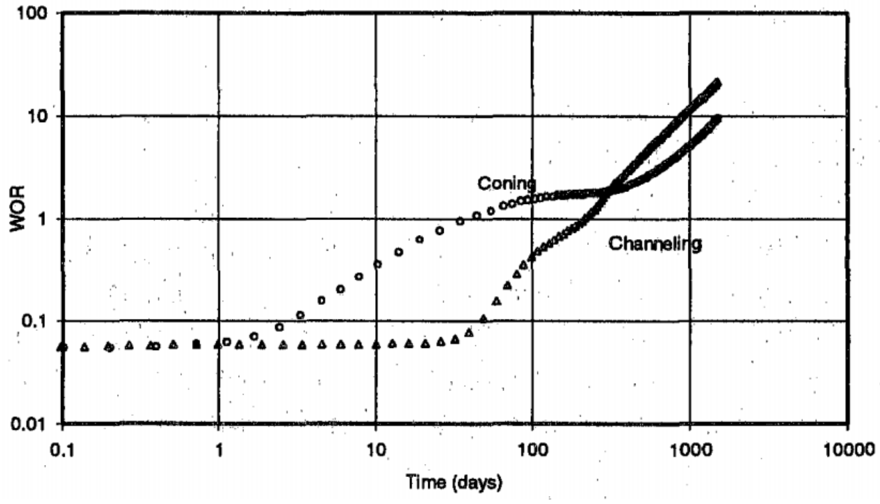


Figure 3-1 Water coning and channeling WOR comparison (K.S. Chan, 1995)

From fig 3.1, it is clear that there are three periods of WOR development. In the early period, the WOR curves remain flat showing almost the initial condition. The value of initial WOR depends on initial water saturation and its distribution among all layers and relative permeability functions. The time duration of this period depends on the water drive mechanism.

It can be observed from fig 3.1 that departure time is very short for coning, depending on different parameters such as the distance between water-oil contact (WOC) and bottom of the nearest perforated interval, anisotropic ratio, production pressure drawdown, and relative permeability functions. The water coning departure time is the time when the bottom water cone has reached the bottom of the perforation interval. Whereas for channeling, the figure depicts a longer departure time but is steeper, the departure time depends on well spacing, injection rate, production pressure drawdown initial water saturation, and relative permeability functions. The water channeling departure time of the WOR curve is water breakthrough at a layer in a multilayer formation.

The second time period illustrated in the figure shows WOR increases with time and the rate of increase is different for different problems. The rate of WOR increase for coning is relatively slow and gradually reaches a constant value at the end of this period. During this period, the bottom water cone grows vertically upward (to cover most of the perforation interval) as well as expands radially and oil saturation decreases to residual oil saturation. Conversely, in the case of channeling the water production from the breakthrough layer increases very rapidly and so the WOR increases relatively fast. The slope of the water channeling WOR depends on initial water saturation and relative permeability functions. The transition period starts when WOR increase becomes slowdown at the end of the second period. This transition period can be very short depending on permeability contrast and corresponds to the production depletion of the first breakthrough layer.

In the third period, in the case of water coning a pseudo-steady-state cone is developed and the well mainly produces bottom water. The water cone becomes a high-water conductive channel where WOR increase becomes very fast resembling that of the channeling case. While in Channelling, the WOR increase resumes the same rate after passing through the transition phase. All the channeling WOR slopes, including the one in the coning case, will be very close because they are mainly controlled by the relative permeability functions, considering the same aquifer characteristics.

Further studies reveal that the time derivative of the WOR (WOR′) can be used to differentiate coning and channeling. Fig. 3.2 and 3.3 show the WOR and WOR′ for coning and channeling, respectively. The WOR′ shows a nearly constant positive slope for channeling but it is completely different as there is changing negative slope for coning.

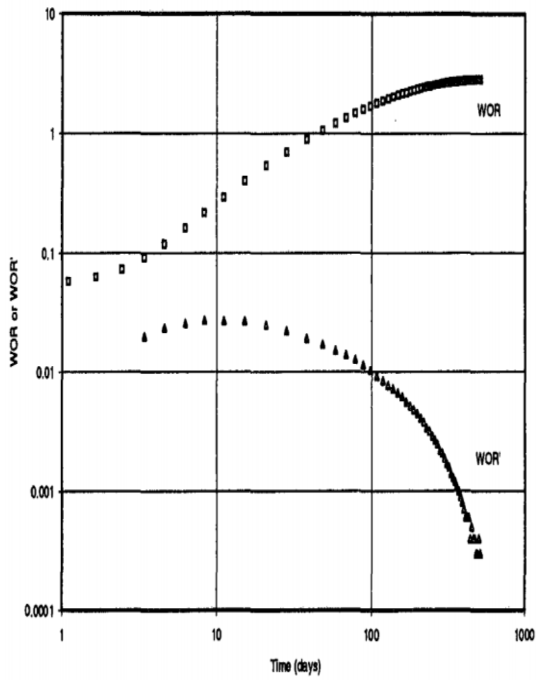


Figure 3-2 Bottom water coning WOR and WOR' derivative (Chan, 1995)

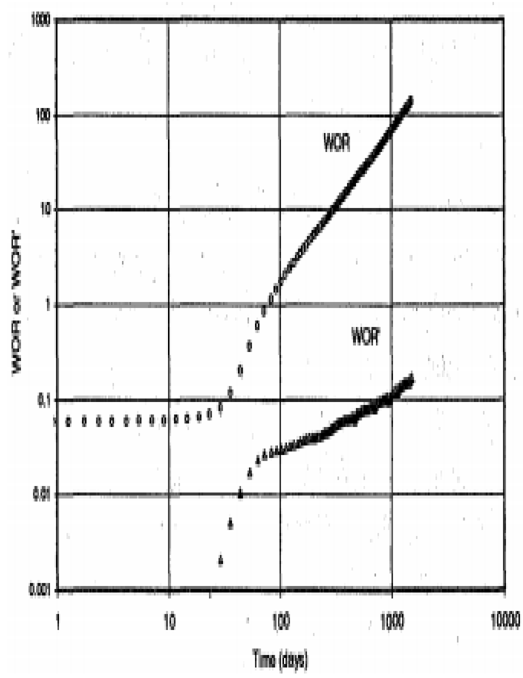


Figure 3-3 Multilayer channeling WOR and WOR' (Chan, 1995)

The slope of WOR′ for channeling is increasing at a constant and very gradual pace compared to the very quick and abrupt increase in the WOR curve for channeling. This WOR′ is very useful as the corresponding curve in coning clearly distinguishes these mechanisms. This WOR′ plot is very useful in order to determine the excessive water production mechanism when the production data is very limited.

There are some examples that reveal the parameters affecting the WOR and its derivative showing different curves for different mechanisms at different time periods.

For a strong water bottom-water drive, the well spacing becomes a crucial factor for the occurrence of the second departure from coning to bottom-water channeling. Fig. 3.4 shows series of simulation plots as a function of well spacing (10-150 acres) and at an anisotropic ratio of 0.1.

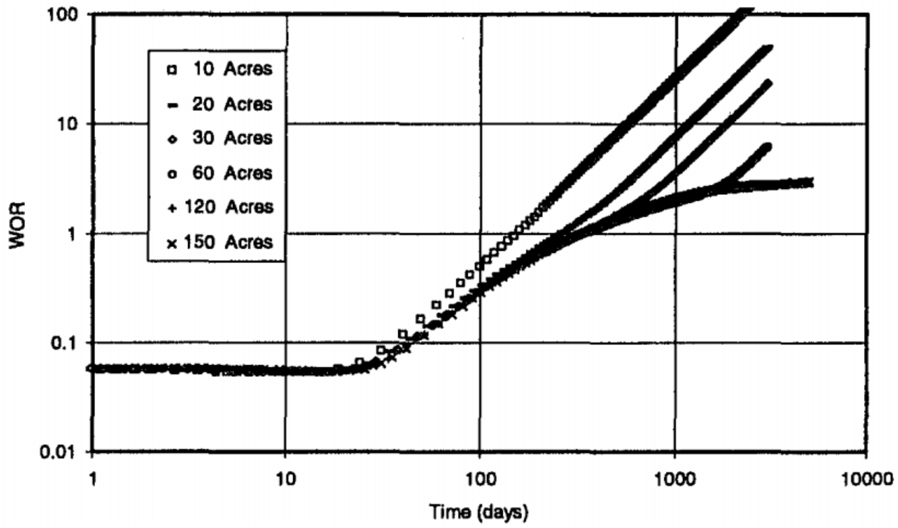


Figure 3-4 Bottom water coning WOR vs well spacing (K.S. Chan, 1995)

For the short well spacing, the second departure time is indistinguishable. The larger the well spacing, the further the delay of this departure time. This phenomenon relies upon several factors such as drawdown, rate and pressure, water influx rate, and the relativity permeability curves.

Another example of Chan's diagnostic plot is the injection of water. Immediately after the beginning waterflooding phenomenon, injected water can very quickly breakthrough in highly conductive channels called thief zones/layers. Fig.3.5 shows such a character where WOR rapidly increases after the injection water breakthrough at the producing well. With a high anisotropic ratio, the water cone up at the wellbore and may rapidly expand to cover the entire zone.

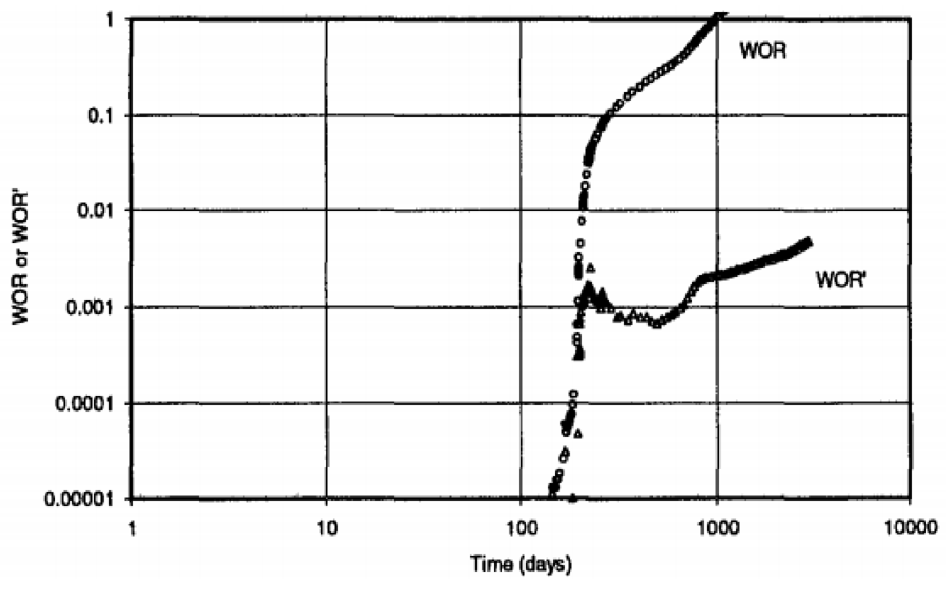


Figure 3-5 WOR and WOR' derivatives for thief layer water recycling (K.S. Chan 1995)

In the figure, the WOR′ curve shows a very steep positive slope within a very short period of time after water breakthrough which is followed by a negative slope that indicates the build-up of a cone. Afterward in the late period of gradual positive slope indicates the completion of water recycling conductive vertical channel construction.

There are some more examples explained by K.S. Chan (1995) highlights the different curves for the WOR and WOR′ against cumulative time based on field production data.

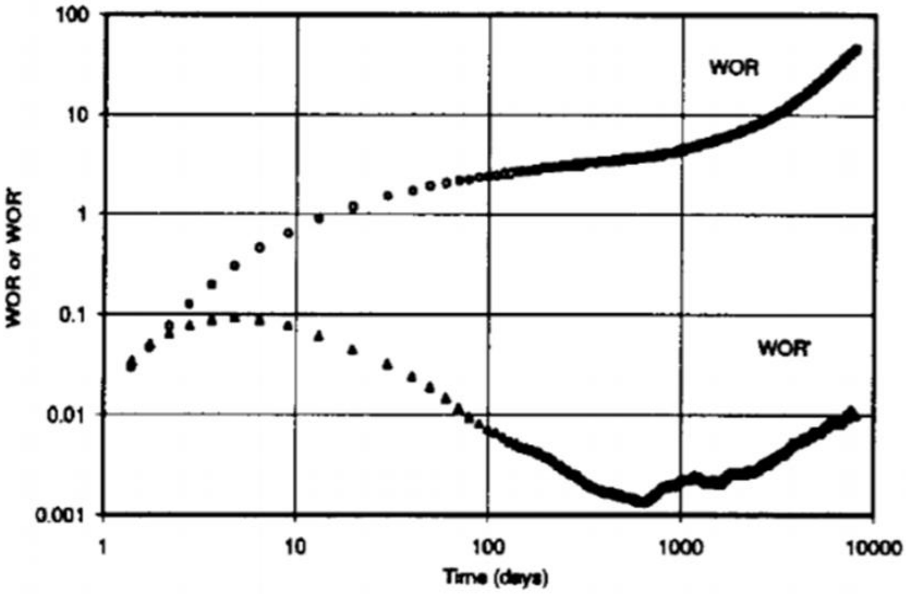


Figure 3-6 Bottom water coning with late time channeling. Chan (1995)

In figure 3.6, Chan's plot shows a negative slope initially for the WOR′. This is called a water coning situation. The graph representing some more characteristics in the later stage of production history since the third period of this trend shows the Channeling phenomenon as the slope becomes positive. (Chan, 1995).

There are some other cases where the formation can have high permeability streaks or fissured layers associated with the well in the water injection displacement pattern. These will consequently cause rapid water breakthrough.

Figure 3.7 shows a drastic WOR increase and so as WOR′. These are the symptoms of rapid water breakthrough or Channeling. (Chan, 1995).

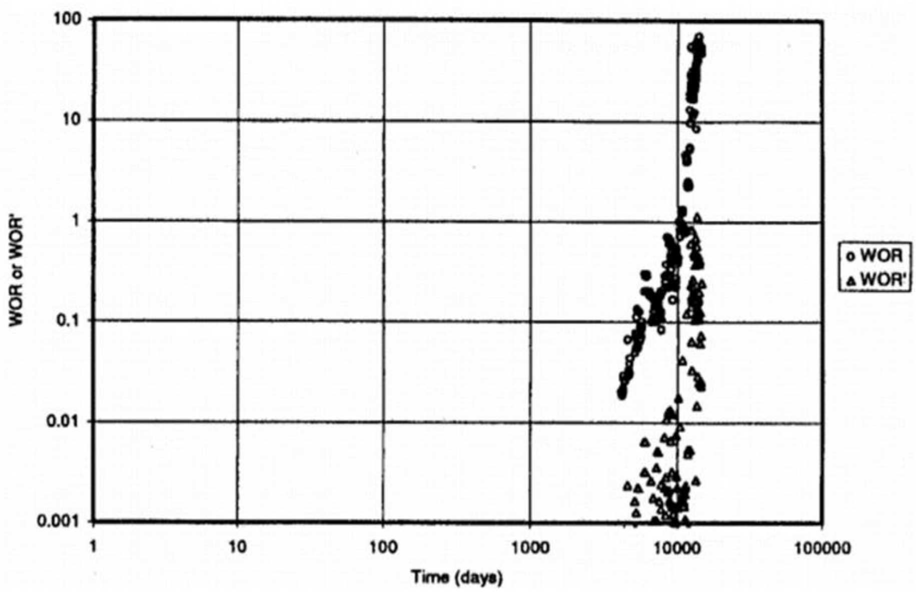


Figure 3-7 Field Example Rapid Channeling. (K.S. Chan,1995).

According to Chan, for some reservoirs, the initial WOR could be very high, such as limestone or dolomite formations, shown in fig. 3.8. the reason can be higher initial water saturation.

Water flooded started in this field at about 2000 days, and the overall WOR trend shows a linear slope that indicates normal displacement behavior as WOR slope is about 0.5 for this well.

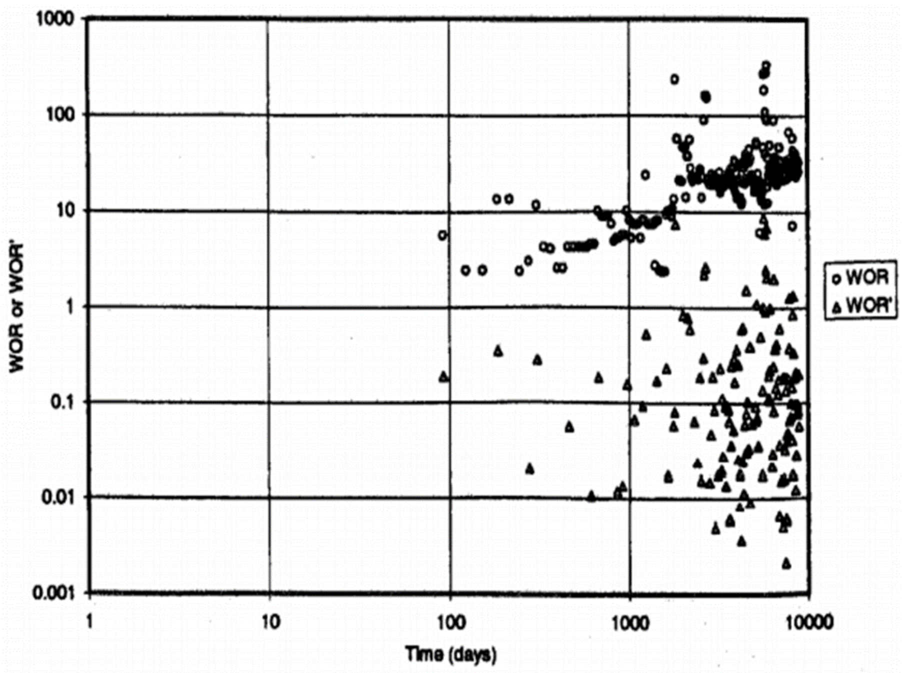


Figure 3-8 Field Example 3: Normal Displacement with High WOR. (K.S. Chan,1995).

Chapter 4 RESEARCH METHODOLOGY

4.1 Background:

The diagnostic plots are the most commonly used technique for the investigation of the overall performance of the reservoir as well as individual wells. These are based on production data that provides the information on the rate of produced oil and water, collected at regular intervals of time. In these plots, the rates of produced oil and water along with the ratio of produced water rate to produced oil rate (WOR) is used for the interpretation and production analysis. After the analysis of these data, the derivative value of the water/oil ratio (WOR′) is calculated that is used for the identification of sources of excess produced water such as water coning and channeling phenomenon. Proper diagnostic techniques significantly enhance the success ratio of traditional treatments both technically and economically. (Abdallah Abdelhafeez abakor Mohamed. et al, 2014).

Identifying the source of excessive produced water is very important because water coning and channeling can badly impact oil productivity due to relative permeability effects. There is also the lifting and managing costs rise with the introduction of heavier wellbore fluids and artificial lift method. Moreover, the increasing produced water will result in additional costs for expanding water handling capacity, its treatment, and disposal along with corrosion control.

4.2 Diagnostic Plots Technique:

In 1995, Chan proposed a new technique to analyze the log-log plot of WOR and derivative of WOR against time in order to differentiate between two common and more complicated water problems i.e., water coning and channeling. Based on Chan's plots, using black oil simulator where the set of PVT data, saturation function data, permeability, and porosity distribution, and the initial conditions are kept constant. The only difference is the flow geometry. In the case of coning, the water-oil contact (WOC) is defined, and bottom water influx is simulated by constant bottom pressure. In this case, only the top portion of the layer is perforated. While in channeling, the bottom layer is eliminated, and water is injected with constant pressure into all layers at the edge and all the layers are perforated. (Chan,1995).

Using the Microsoft excel format in order to calculate and plot the derivative response of each WOR vs time data. In order to do so, firstly the value of water/oil ratio (WOR) is calculated by using the actual water and oil production data, and we use the following equation:

$$WOR = \frac{Qw}{Qo} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.1)$$

The equation for water cut (WC) is as follows:

$$WC = \frac{Qw}{Qw+Qo} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4.2)$$

And the derivative value for the WOR is calculated by the following equation:

$$WOR' = \frac{d(WOR)}{dt} = \frac{WOR2-WOR1}{t2-t1} \ldots\ldots\ldots.. \quad (4.3)$$

The water problem is diagnosed and identified finally with the help of table 4.1.

Table 4-1 Different patterns of sources of water production in the oil-water system (Abdallah Abdelhafeez abakor Mohamed. et al, 2014).

WOR Slope	WOR' Slope	Reason for Water production
Positive	Positive	Channeling
Positive	Negative	Coning
Positive Linear Slope	Horizontal Line	Other near-wellbore problems e.g., Water-Oil Contact Rising

The verification is made by comparing the results of my work with the standard diagnostic plots of Chan.

It is very common practice in the oil industry to use well diagnostics in order to determine the existence of excessive water production, locating the water entry points in the well, and choosing the candidate wells for the treatment. These all steps can be performed after the proper and correct identification of diagnosis of the source of a water production problem. (Abdallah Abdelhafeez abakor Mohamed. et al, 2014).

4.2 Case Studies:

4.2.1 Case study 01:

Field Description:

The wells for this study are from the southwest field of Sudan. The fault-bounded Fula sub-basin is located in the northeast of the Muglad Basin. (Fig. 4.1). The NW-SE-oriented Muglad rift basin is up to 200 km wide and over 800 km long. Major reservoir targets in the Muglad basin are the sandstones in the Bentiu formation. The Fula sub-basin is fault-bounded is up to 41km wide and 120km long. There is a formation called Abu Gabra that has a strong potential to store and transmit hydrocarbons with porosity ranges from 12-20% and permeability from 20-6000 mD. The main formations in this study are Bentiu and Abu Gabra. (Dou Lirong. et al, 2013).

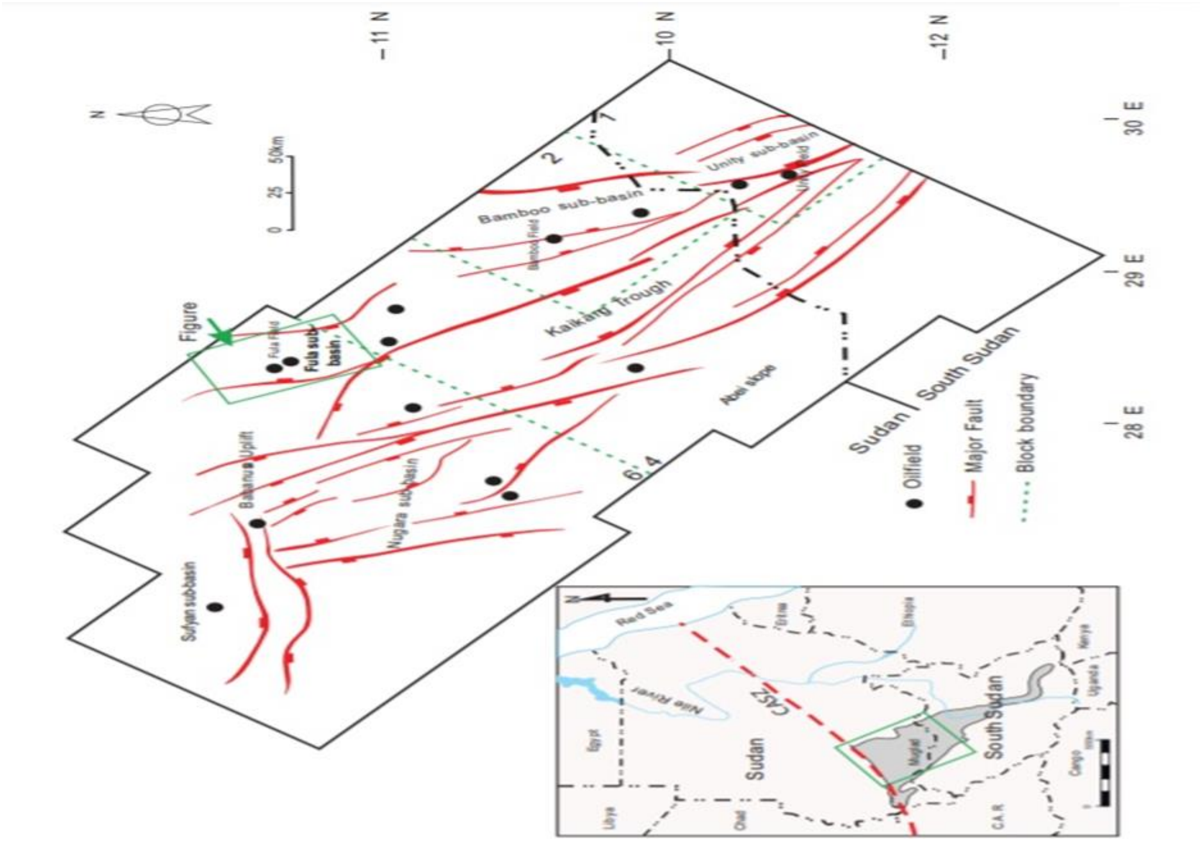


Figure 4-1 shows structural units in the Muglad Basin, which extends from the Republic of Sudan to the Republic of South Sudan, with the location of the Fula sub-basin and the main oilfields so far discovered. (Dou Lirong. et al, 2013).

The field data has been collected from one of the fields in the southeast region of Sudan to investigate the sources of water production. Considering the production data for different wells show different behavior by using Chan's plots.

According to Abdallah Abdelhafeez abakor Mohamed (2014), the wells selected for investigation of the water production need to have the following characteristics:

- High production rate with good cumulative production history
- High thickness and good location on the sand contour map
- Recoverable reserves with optimum water cut

Concerning the application of diagnostic plots Chan´s method, there are four wells targeted in this field of the southwest of Sudan. These wells behave differently from others as the data in the form of the production history of each well illustrate its characteristics and performance.

Using the Microsoft Excel format, the production data and simplified computation of WOR and its derivatives against time along water cut are presented in the different graphs. These graphs are then interpreted with standard Chan´s diagnostic plots.

The production history of well 01 that has performed in that period. The water rate and oil rate are measured in STB/Day and time is taken in Days. The equations used for the calculation of WOR and WOR' are expressed above as 4.1 and 4.3, respectively.

The water cut is the ratio of water rate to the total liquid rate, in this case, oil and water. This ratio is expressed in fractions or percentages. The equation to calculate water cut is expressed in equation 4.2 defined above.

4.2.2 Case Study 02:

Field Description:

The production data for this case study is taken from the 31S reservoir, Elk Hills, California. The geological study of this 31S reservoir is described as the largest of the three anticlines in the Elk Hills. (Abdallah Abdelhafeez abakor Mohamed. et al, 2014). This 31S structure is 9 miles long and 1.5 miles wide. This structure is a sandstone reservoir containing feldspathic, clay-rich deposits. This reservoir is occupied by the Main Body "B" (MBB) and Western 31S reservoir.

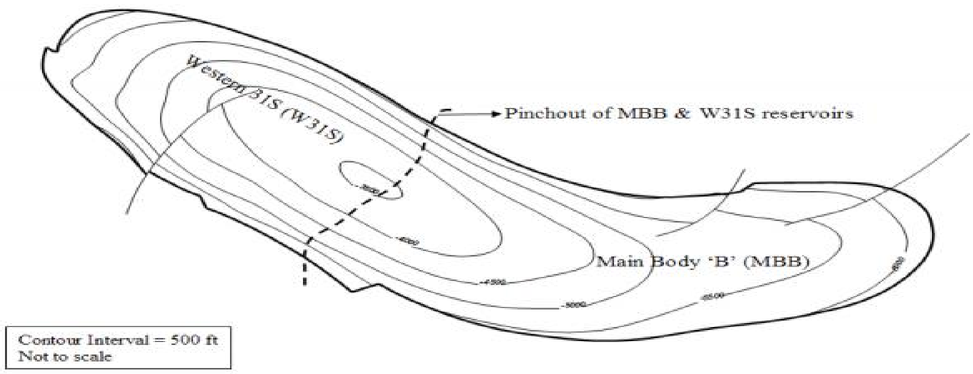


Fig. 4.10 The MBB/W31S Structure (Echufu-Agbo Ogbene Alexis, 2010).

The list of fluid and reservoir rock properties is given in table 4.2.

Table 4-2 Summary of the Reservoir rock and fluid properties for the Case Study (Echufu-Agbo Ogbene Alexis, 2010).

Porosity range	11-26%
Air permeability range	10-250 md
Initial water saturation range	30-45%
Initial average reservoir pressure	3150 psia
Initial bubble point pressure	2965 psia
Reservoir temperature	210º F
Reservoir oil viscosity	0.40 cp
Oil gravity	36º API
Mobility ratio	0.6
Residual oil saturation to water	25%
Rock compressibility	5x10^{-6} per psi
Estimated original oil-in-place	610 MMBO
WOC	6730 ft or 2051 m

The WOR and WOR derivative (WOR′) plots are used in combination to diagnose the reservoir-related water production mechanisms.

In this case study, two wells are targeted for the evaluation and diagnosis of the identification of associated problems.

The WOR and WOR trends are drawn against time based on the production history of the well. It is t basically the rate of water production to the rate of oil rate measured at different periods. This gives an idea according to Chan (1995), the well is experiencing the water coning or Channeling or Multilayer Channeling phenomenon.

4.2.3 Case Study 03:

Field Description:

This case study describes the production history and evaluation of the associated problems encountered in different wells. This study is related to the Jake oilfield which is located in the North-eastern part of Muglad Basin, the largest known rift basin in Sudan (Fig.4.15). The structure is already defined in case study 01. The main formation of this field is Bentiu with oil

API gravity range from 24.63º to 32. 6º, and Abu Gabra with 35.66 to 38.76 API gravity range. (Mohanned Mahgoup. et al, 2015).

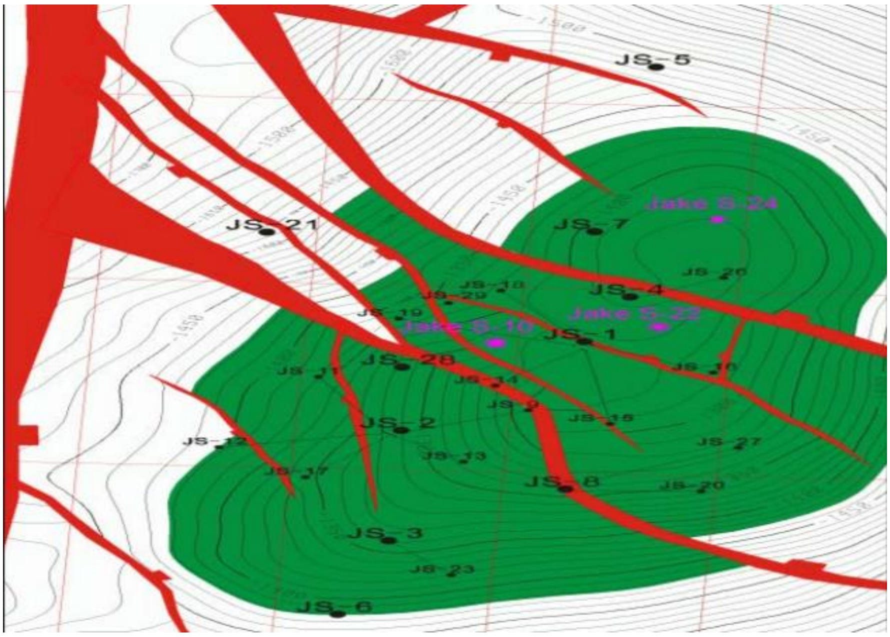


Figure 4-2 Abu Gabra layer structural Map Jake Field (Mohanned Mahgoup. et al, 2015).

There are two wells that are targeted for the investigation to identify the possible reasons for the unwanted water production.

The data is acquired from JS-1 well called in my work as well 01 and JS-4 called here well 02. These wells are the dominant producers. Chan's plots will give a guideline for the wells to identify the possible reasons for the unwanted water production and also apply the suitable water shut-off technique or other decisions. (Mohanned Mahgoup. et al, 2015).

4.2.4 Case Study 04:

Field Description:

In this case, the production history is taken from an article, water control, composed by (Bill Bailey. Et al, 2000). Different oil fields are reviewed in this study and many problems are highlighted in this article as oilfield review.

This study reveals various field production data to examine the source of water production. Various possible mechanisms of water production are discussed and distinguished from each other. The production history plot from the article is read and data is taken in order to identify the related problem. The sudden Simultaneous changes in both oil and water rate are observed against cumulative time.

These plots will be interpreted and are analyzed based on the production data and correlated with Chan's diagnostic plots. These log-log plots are one of the identifying sources of water production problems.

In this study, two cases are diagnosed for interpretation.

Chapter 5 RESULTS AND DISCUSSION

The results and interpretation for different wells located in different fields across the globe are discussed in this chapter. These results are compared with the standard K.S. Chan's diagnostic plots technique and analysis are being made observing the trends of WOR and WOR´ against time.

The trends of WOR and WOR′ against time are the parameters to show whether the well is experiencing water Coning or multilayer Channeling or other near-wellbore problems.

5.1 Case study 01:

5.1.1 Well 01:

For well 01, the profile of production data is used to compute WOR, WOR' and Water cut against time.

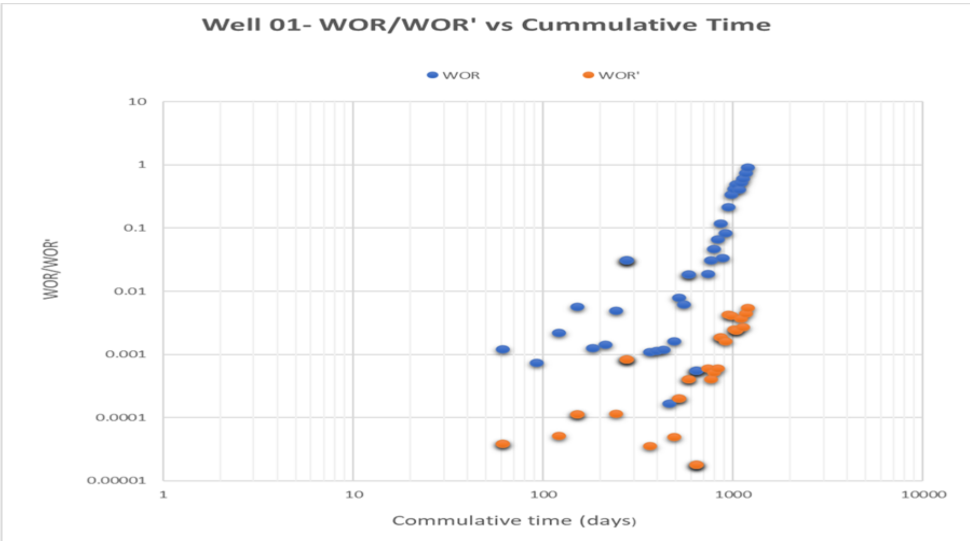


Figure 5-1 WOR and WOR' derivatives plot vs Cumulative Time (Abdallah Abdelhafeez abakor Mohamed. et al, 2014).

In the fig. 5.1, the WOR initially shows a slow increase against time showing the first period of Chan´s plots. Then the graph showing a constant phase called transition period till 700 days. This is exactly what Chan (1995) has revealed in the description of the water production mechanism.

WOR′ against time trend shows an upward curve illustrating a positive slope. After 700 days, the rate of increase of WOR is relatively fast and after almost 900 days, there is a sudden increase in the WOR and WOR´ curve. Similarly, during this time, the WOR′ curve shows a higher positive slope in the late period. This is characteristic of the Water Channeling phenomenon, described by Abdallah, (2014).

The WOR′ trend showing a positive slope that infers the well is experiencing high horizontal permeability. (Abdallah Abdelhafeez abakor Mohamed. et al, 2014).

For the same well, the graph of water cut against time will be calculated using equation 5.2.

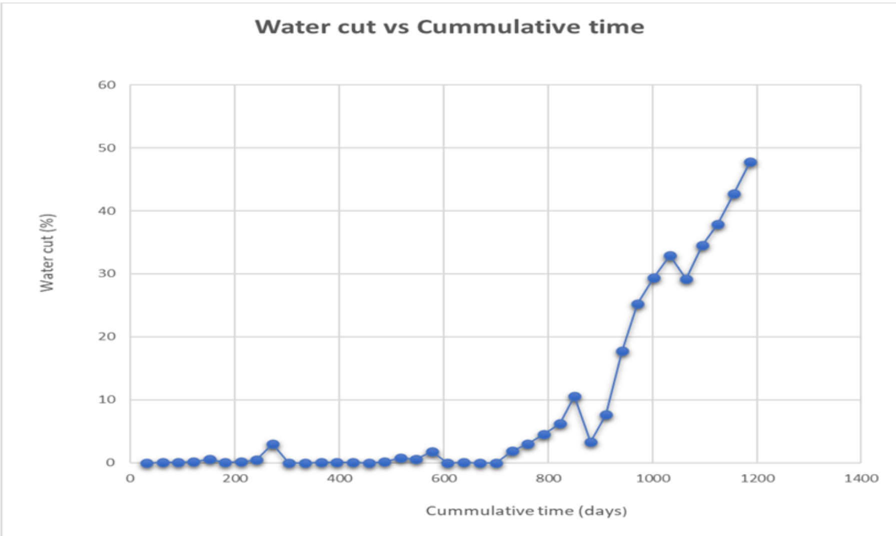


Figure 5-2 Water cut (%) vs time graph (Abdallah Abdelhafeez abakor Mohamed. et al, 2014).

The Water cut is expressed as WC or fw and is measured in fraction or percentage.

From Fig. 5.2 it is inferred that water cut is started to produce after 700 days. There is a sudden outburst of this undesired situation after 900 days again when it goes from 5% to 48% in a year afterward.

5.1.2 Well 02:

For well 02, the production history profile gives the following trends for oil and water production.

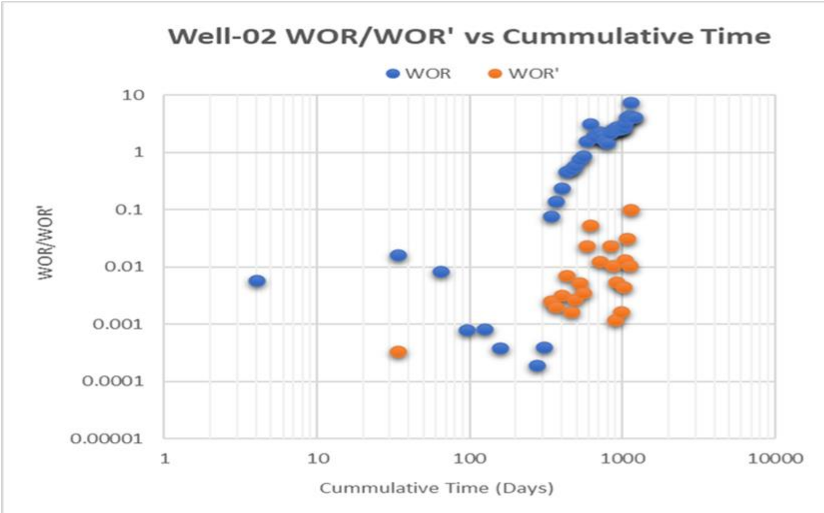


Figure 5-3 WOR and WOR' derivatives plot against Cumulative Time (Abdallah A.A Mohamed, et al, 2014).

In the fig. 5.3, the WOR trend against time indicates very low production of water, and most of the oil percentage is produced.

Then after 350 days there is a sudden and much increase in WOR and reach to approximately 10, while during this time WOR´ curve showing a positive slope against time-variant.

The WOR′ trend showing a positive slope that infers the well is experiencing high horizontal permeability. (Abdallah Abdelhafeez abakor Mohamed. et al, 2014). The data reveals that there is a constant slope showing the transition period, while the late period indicates an abrupt increase in the curve and so is the slope. Keeping the characteristics of Chan´s diagnostic plots, this well shows the Water Channeling phenomenon.

Similarly, the water cut graph against cumulative time for well 02 is shown in figure 5.4.

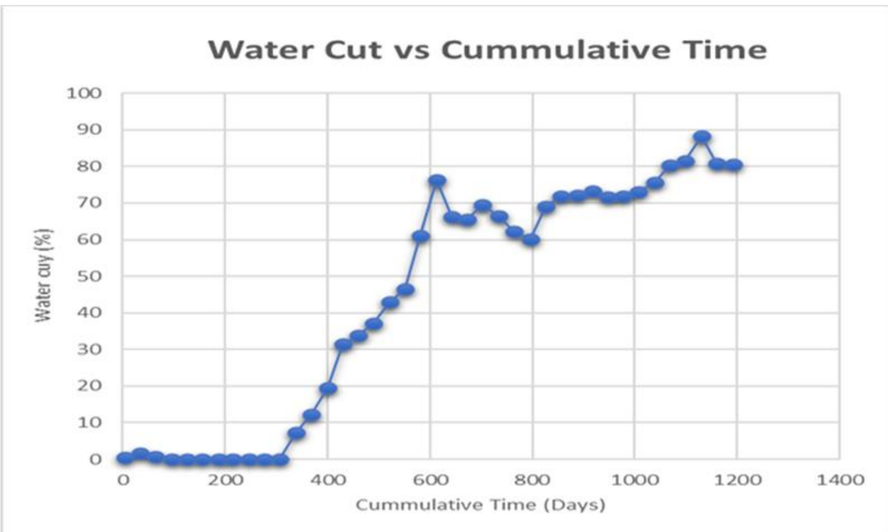


Figure 5-4 Water cut (%) vs Time graph (Abdallah A.A Mohamed, et al, 2104).

In fig 5.4, water cut production starts at 350 days and continuously increasing and reaches almost 90%. This needs to be remediated and controlled.

5.1.3 Well 03:

For well 03, the WOR and WOR ´are showing different behavior against time shown in figure 5.5.

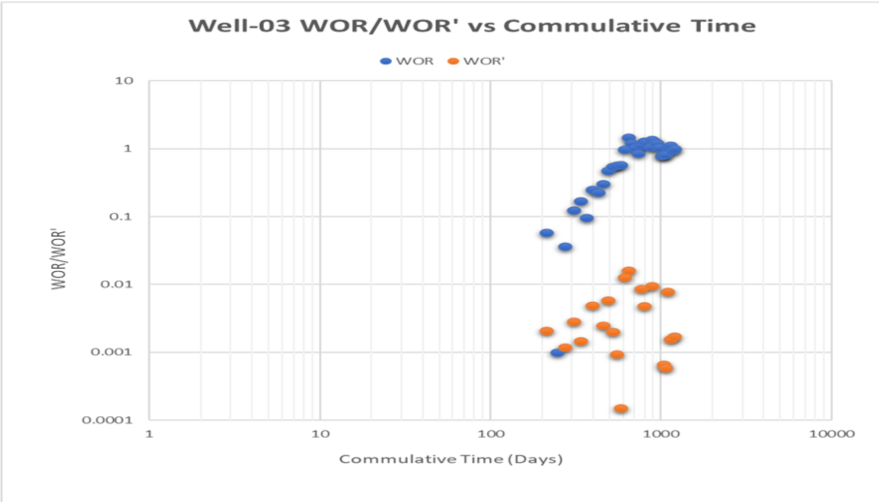


Figure 5-5 WOR and WOR' derivatives plot vs cumulative Time (Abdallah Abdelhafeez abakor Mohamed. et al, 2014).

From fig. 5.5, it can be inferred that the initial WOR is very high. The reason for this initial higher value of WOR could be high initial water saturation. (Abdallah A. A Mohamed, et al, 2014). The water injection in this well is started at about 700 days, said Abdallah A. A Mohamed. et al, 2014).

The WOR´ shows a constant and linear slope with time. The slope of WOR for this well is about 0.5 representing the normal displacement with high water cut, as defined by K.S. Chan fig. 3.8. This characteristic of the curves having normal displacement with higher water cut is validated with Chan´s plot.

The water cut for the same well against time is shown in figure 5.6.

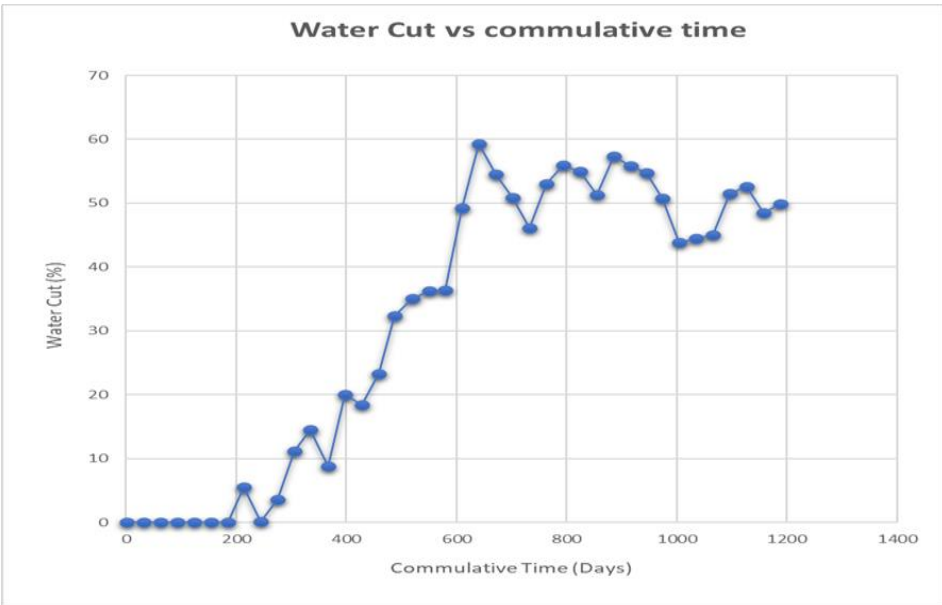


Figure 5-6 Water cut (%) vs Time graph (Abdallah A.A Mohamed, et al, 2104).

In the fig. 5.6, the water cut progressively increases and breakthrough seems to occur at 240 days and then it continues. Due to the higher water cut, it may deplete the reservoir sooner.

5.1.4 Well 04:

The production history of well 04 is shown in the following figure representing the WOR and WOR' curves against cumulative time.

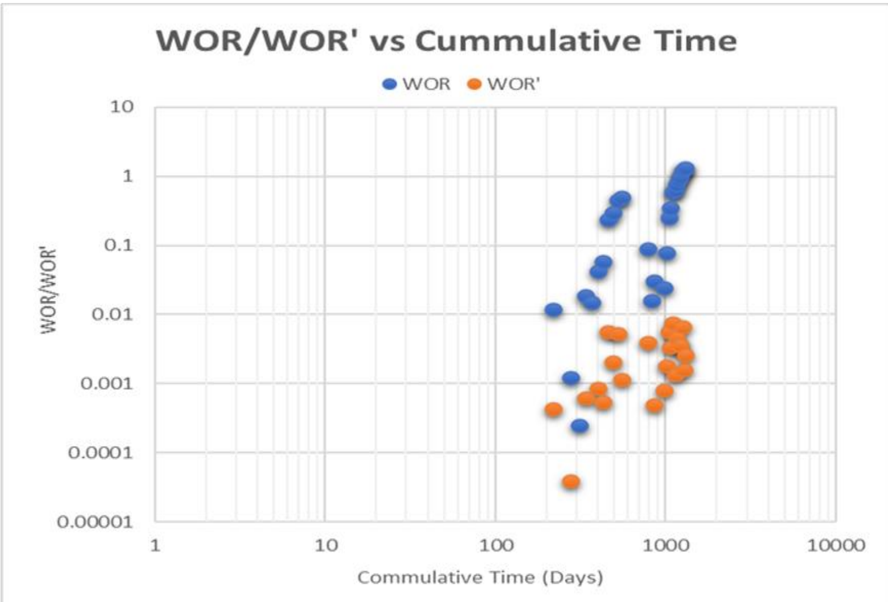


Figure 5-7 WOR and WOR' derivatives plot vs Cumulative Time (Abdallah Abdelhafeez abakor Mohamed. et al, 2014).

In fig 5.7, the WOR and its derivates with time slope indicate a normal linear positive curve. Based on Chan´s plot technique, it can be perceived that the WOR has a higher initial value. It could be due to higher initial water saturation.

This gives an idea of linear slope indicating normal displacement with higher water cut validated by well data with Chan′ s plot shown in figure 3.8.

Similarly, the trend for water cut vs time shows its character in figure 5.8.

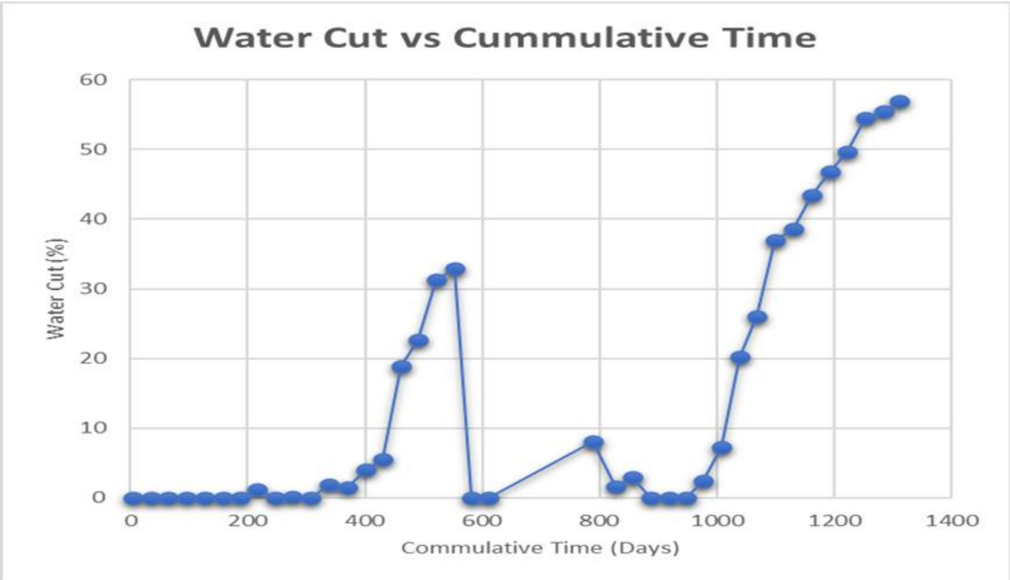


Figure 5-8 Water cut (%) vs Time graph (Abdallah Abdelhafeez abakor Mohamed. et al, 2014).

In fig 5.8, the water cut starts to produce at around 400 days and continues to increase. Then the well might be shut down due to some workover operation or due to this sudden increase of water cut.

Again after 600 days, the well is used to start production, and a water cut was not found for about a year. Eventually, beyond that period the graph shows an abrupt shoot and the water cut reaches around 60%.

Well 03 and well 04 could be shut down or they could be converted into injection wells that may be economically beneficial. (Abdallah Abdelhafeez abakor Mohamed. et al, 2014).

5.2 Case Study 02:

5.2.1 Well 01:

The WOR and WOR' trends are drawn against time based on the production history of the well.

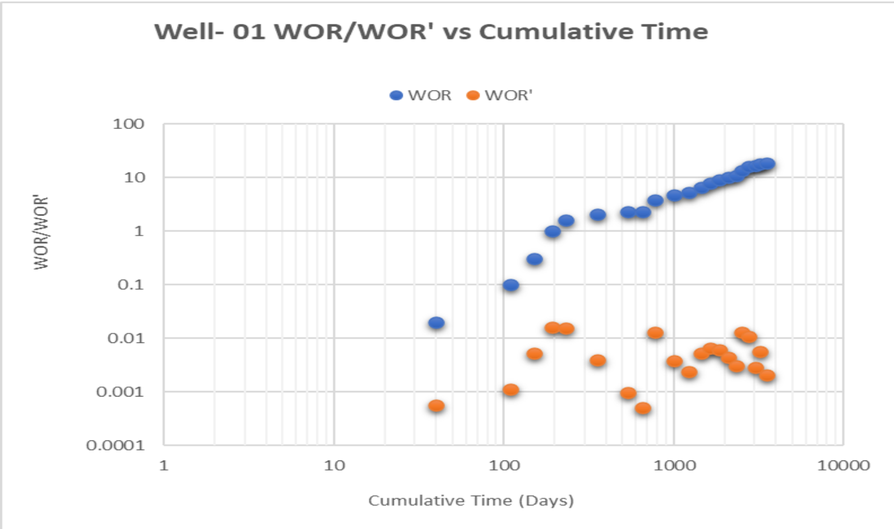


Figure 5-9 Well Diagnostic Plot showing WOR and WOR´ vs Cumulative Time (Echufu-Agbo Ogbene Alexis, 2010).

This graph shows an increase in the WOR trend but with changing slopes.

The WOR trend shows three types of slopes depending on the variation of permeability among layers. The higher permeability corresponds to the fault streaks or fracture, or fissure-like features said by Echufu-Agbo Ogbene Alexis, 2010.

Initially, WOR increases at a higher rate showing a higher positive slope. The middle slope is almost constant showing layer is changed with different permeability. The last period starting after 900 days shows a gradual and constant increase in the WOR curve showing different permeability with changing positive slope. These variations in the slopes are the description of Chan´s diagnostic plot for the Multi-layer Channeling phenomenon.

In the figure, the WOR´ curve shows varying slopes that depict variation in permeability in different layers. (Echufu-Agbo Ogbene Alexis, 2010). The data representing the trend with variable slopes depicting permeability variation in different layers correspond to the multi-layer Channeling phenomenon is validated by Chan, 1995).

The well production data representing these curves are validated by Chan´s plot called the multi-layer Water Channeling phenomenon.

And the graph for the water cut against Cumulative oil production and cumulative time for this case is shown in fig. 5.10 (a) and 5.10 (b) respectively.

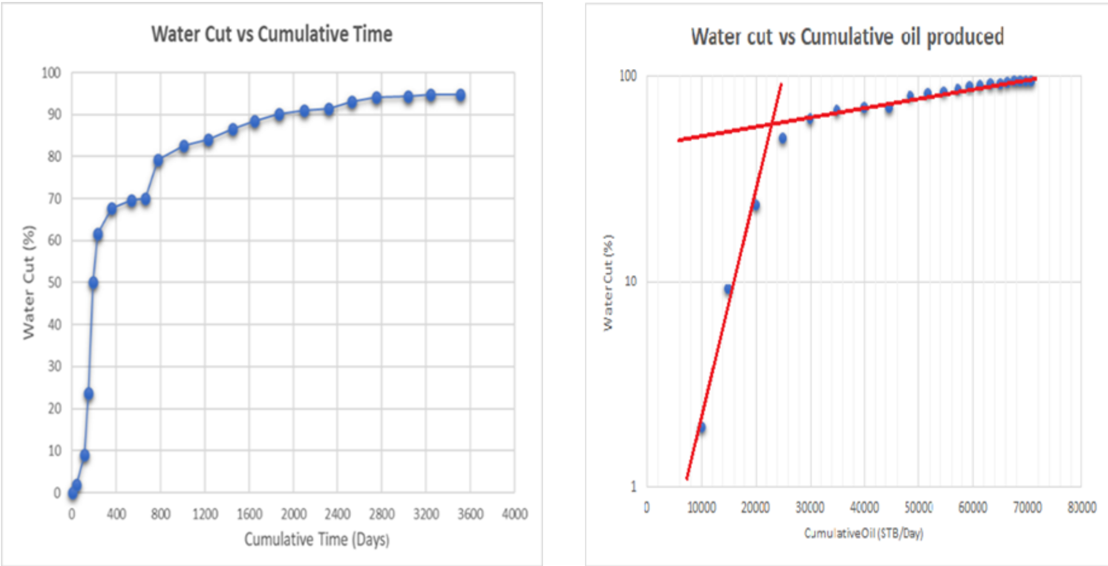


Figure 5-10 (a) Water cut (%) vs Time (Days) graph and (b) Water cut vs Cumulative oil produced STB/D (Echfu-Agbo Ogbene Alexis, 2010).

In fig 5.10 (a), the water cut starts at the very beginning of production and there is a very high percentage of water cut even it goes over 50% in its first year of production.

From fig. 5.10 (b), the log scale of water cut against cumulative oil produced does not show a linear fit from the beginning of oil production and the data is observed scattered a little. however, the plot shows linear extrapolation at higher water cut.

5.2.2 Well 02:

The data of each well shows each point of water and oil production rate with time. This clearly shows the well history and its behavior with time. The shutdown or work over periods is clearly seen in these cases unlike for the overall field production history profile.

The WOR and WOR´ against time are shown in figure 5.11.

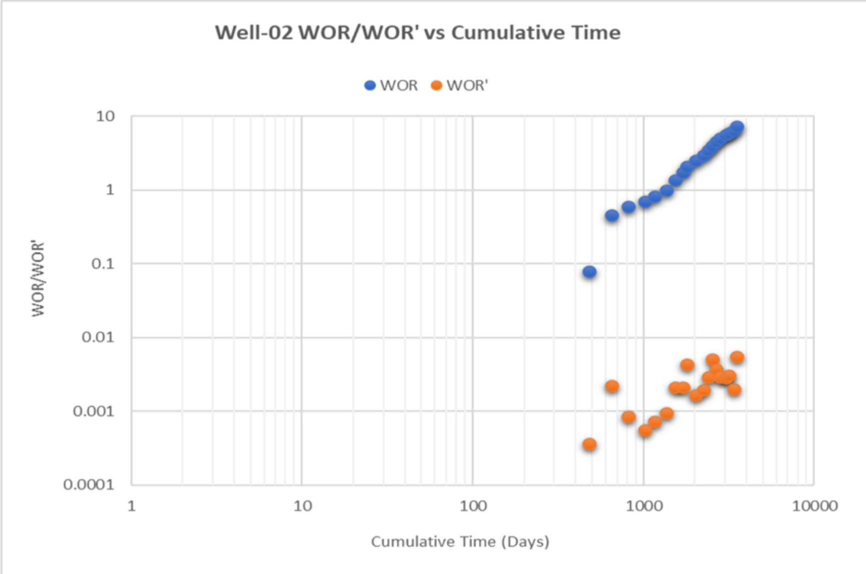


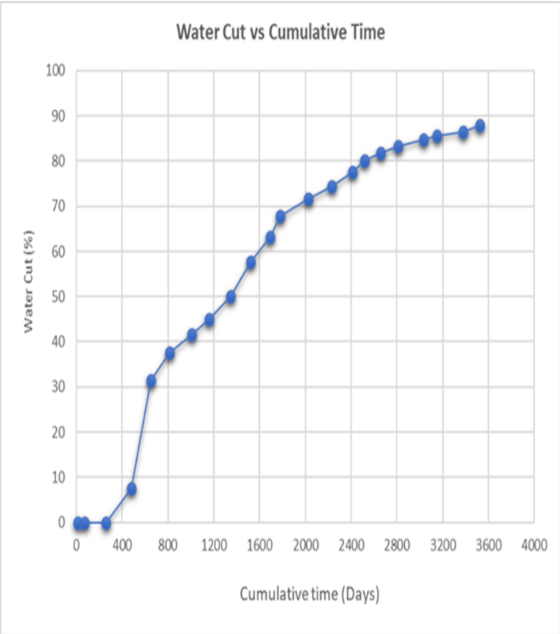
Figure 5-11 Well Diagnostic Plot showing WOR and WOR´ vs Cumulative Time (Echufu-Agbo Ogbene Alexis, 2010).

The figure illustrates the log-log plots for WOR and WOR´ with time. The trends increase very slowly. The gradual increase of WOR with a constant slope shows the transition period of Chan´s method. Afterward, there is a slight increase in the WOR curve suggesting changing from transition to the third and final period.

This type of changing slopes observed in WOR and WOR plots indicating different layers observed Echufu (2010). This multi-layered reservoir shows the water Channeling phenomenon validated by the standard Chan´s plots.

It is inferred that the well exhibits water Channeling phenomenon, but it is different from well 01 as data illustrating 50% of each fluid produced meets at after four (4) years, compared to the well 01 that shows the same figure in 192 days (almost 6 months).

The water cut graph against time and cumulative oil produced is shown in fig. 5.12 (a) and 5.12 (b) respectively.



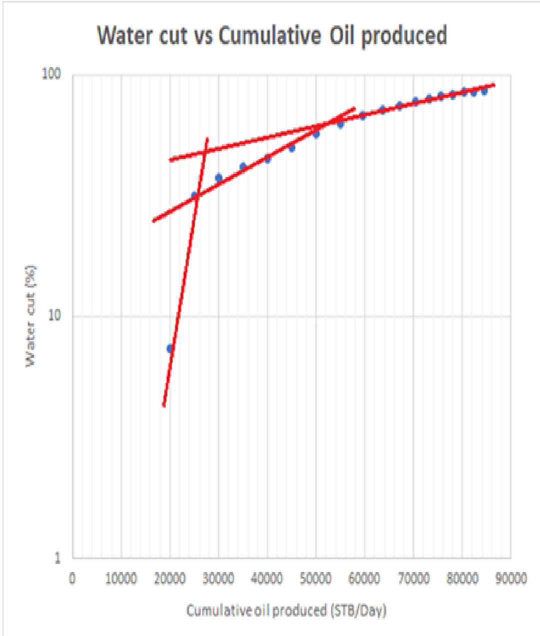


Figure 5-12 Fig. 5.12 (a) Water cut (%) vs Time graph and (b) Water Cut vs Cumulative oil produced STB/D (Echfu-Agbo Ogbene Alexis, 2010).

Fig. 5.12 (a) shows breakthrough occurs approximately after one year from the start of production and then continues. The difference that can be observed between these two wells is the 50% water cut produced in 1300 to 1350 days in well 02 compared to well 01, where the same amount is produced in just 200 days which is huge and must be remediated immediately.

From fig. 5.12 (b), the log scale of water cut against cumulative oil produced does not show a linear fit from the beginning of oil production. However, the plot shows linear extrapolation at higher water cut.

5.3 Case Study 03:

There are two wells that are targeted for the investigation to identify the possible reasons for the unwanted water production.

5.3.1 Well 01:

The WOR and its derivatives (WOR´) trends are drawn against cumulative time to analyze them and identify the source of the production problem.

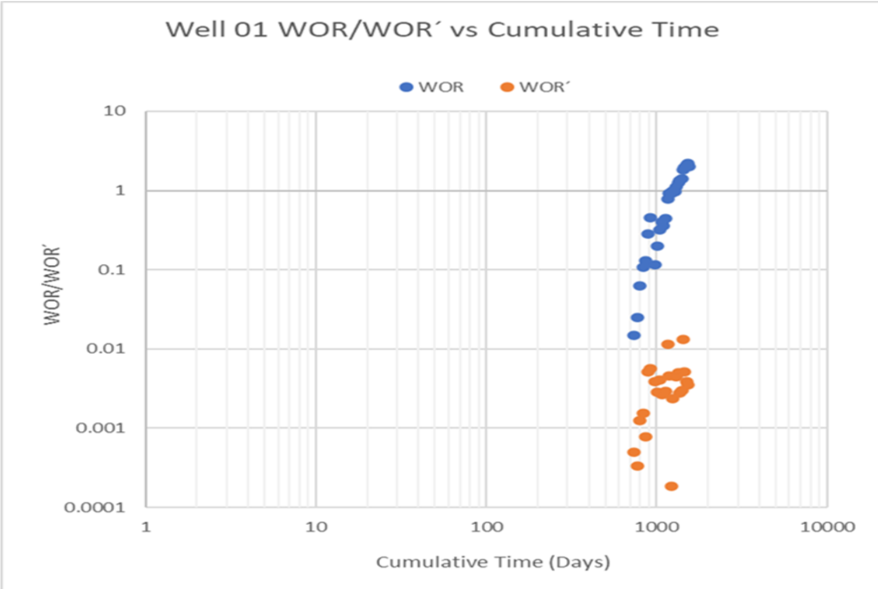


Figure 5-13 Well Diagnostic Plot showing WOR and WOR´ vs Cumulative Time (Mohanned Mahgoup et al, 2015).

Fig 5.13 illustrates that the first period which is constant and not producing water is very long. Then there is an abrupt increase in both WOR and WOR´ against time but the breakthrough occurs quite late and sharp afterward.

This well showing a higher WOR trend with a positive slope characterize high water Channeling phenomenon (Mohanned Mahgoup et al, 2015). This sudden increase with a positive slope for WOR´ curve with other characteristics shows rapid Channeling phenomenon that is in line with Chan (1995) plots shown in figure 3.7. The well must be immediately remediated as it shows good potential for oil recovery.

Similarly, the water cut graph is shown in figure 5.14 representing the breakthrough time and amount of water cut with time to correlate with oil production.

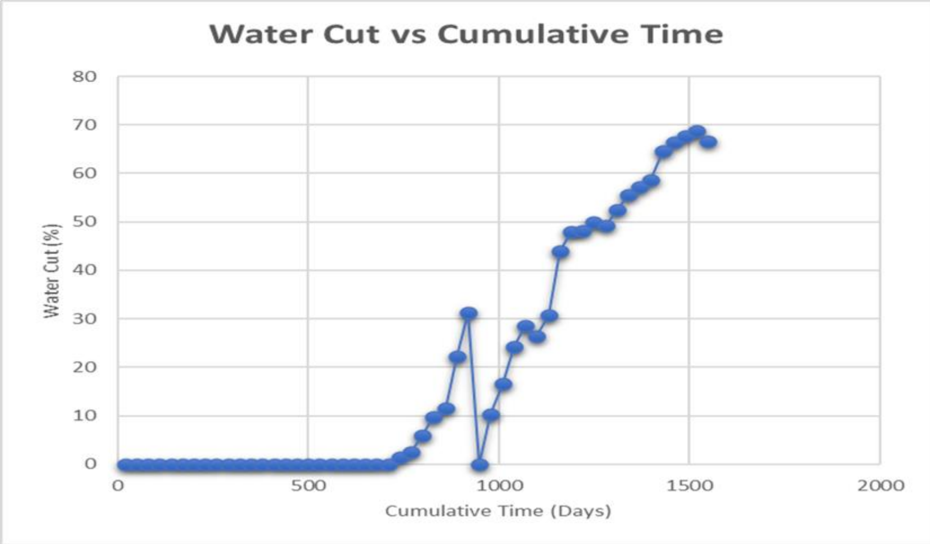


Figure 5-14 Water cut (%) vs Time graph (Mohanned Mahgoup et al, 2015).

In fig 5.14, the water cut curve starts after two years and continues to increase. Then the well is closed for the work over the operation or due to this consistent increase in water cut.

Again, the well is put on production and water cut starts to increase and with higher pace to reach up to the level of 70%. This needs proper management as the well oil recovery is very high even after a 50% water cut.

5.3.2 Well 02:

For well 02, the same procedure is adopted, and using the equation of WOR and WOR′ against time, the trends are drawn shown in the figure below:

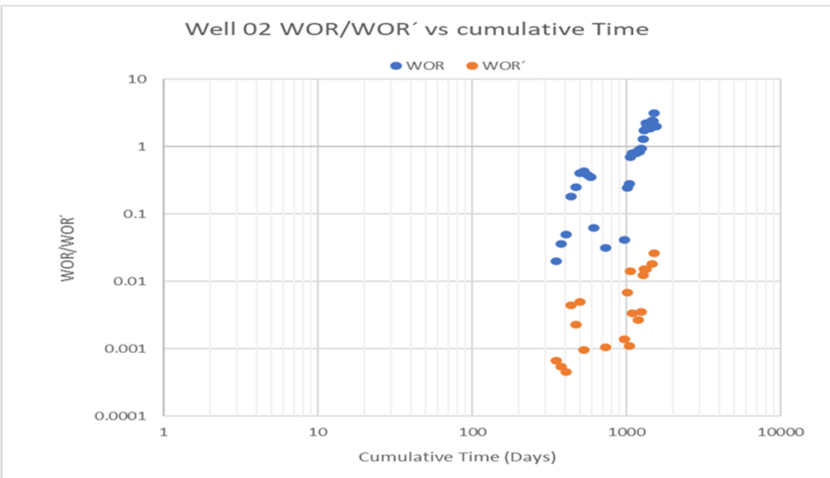


Figure 5-15 Well Diagnostic Plot showing WOR and WOR´ vs Cumulative Time (Mohanned Mahgoup et al, 2015).

This well clearly shows variation in the slopes in both WOR and WOR´ trends. The well behaves as caused by the water Channeling phenomenon because the trend goes up for both trends. (Mohanned Mahgoup et al, 2015).

It is also considered that the well might have been affected by coning problem as there is a higher water cut produced caused by higher drawdown. It can be declared that the well is affected by the multi-layer Channeling phenomenon, indicating some variation in the slopes for WOR data after verifying with Chan´s plots.

Similarly, the water cut equation is used to formulate the graph against time-variant. This can give us an idea of when breakthrough occurs.

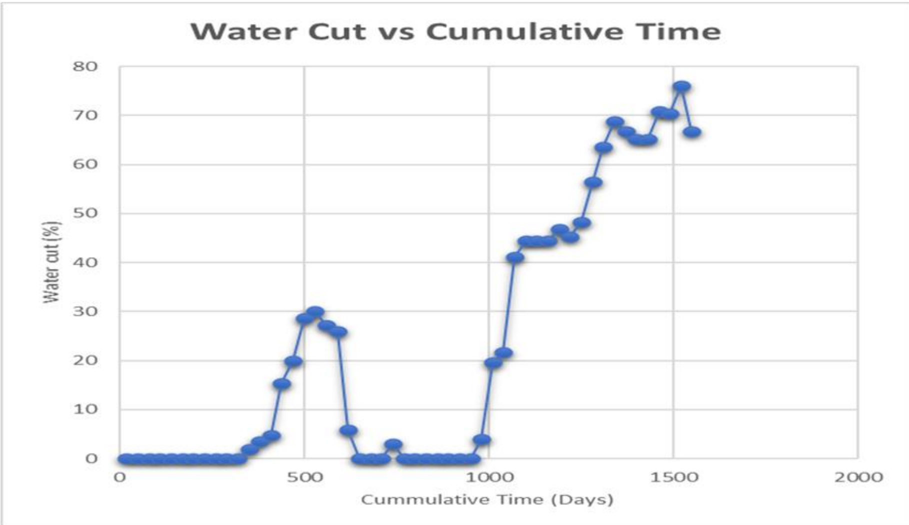


Figure 5-16 Water cut (%) vs Time graph (Mohanned Mahgoup et al, 2015).

Even after closing the production for few months, opening the well for production again starts to produce the water cut and this time with a higher percentage.

The fig. 5.16 illustrates water cut started after one year of production and reach 30%. Then the production was closed for some time, it started again an increase but this time with very high shoot reaches to over 70% and increases continuously.

It is suggested that isolating the lower zone with plugs or packers is the controlling procedure to be conducted for these wells. (Mohanned Mahgoup et al, 2015).

5.4 Case Study 04:

The well is diagnosed after the application of WOR and WOR′ equations using the production data. This case is showing quite different trends from other cases as Bill Bailey with other colleagues have composed this data in their article, oil field review.

5.4.1 Well 01:

The graph shows the WOR and WOR´ plots for this well against cumulative time.

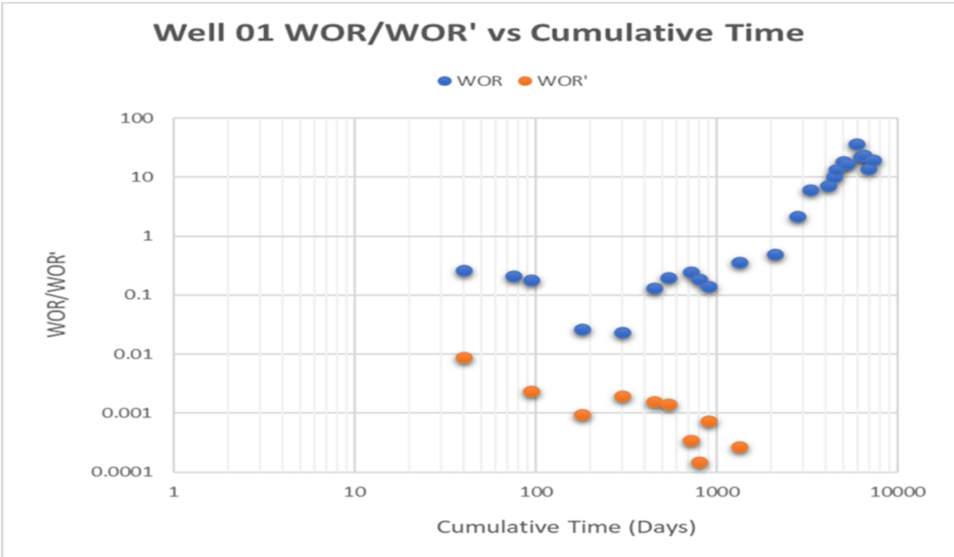


Figure 5-17 Well Diagnostic Plot showing WOR and WOR´vs Cumulative Time (Bill Bailey et al, 2000).

Fig. 5.17 reflects a gradual increase in WOR trend indicating a build-up of water cone early in the well´s life.

The WOR´ against time shows a decline curve and the slope is negative. This negative slope WOR´ is indicated as water Coning occurs in the well, which is in accordance with Chan´s plots. The curve of WOR´ after some constant slope period goes down showing a negative slope in the late period of well´s life. This is called Bottom Water Coning, verified by figure 3.2.

And the water cut graph is shown in figure 5.18 representing the breakthrough time and amount of water cut with time to correlate with oil production.

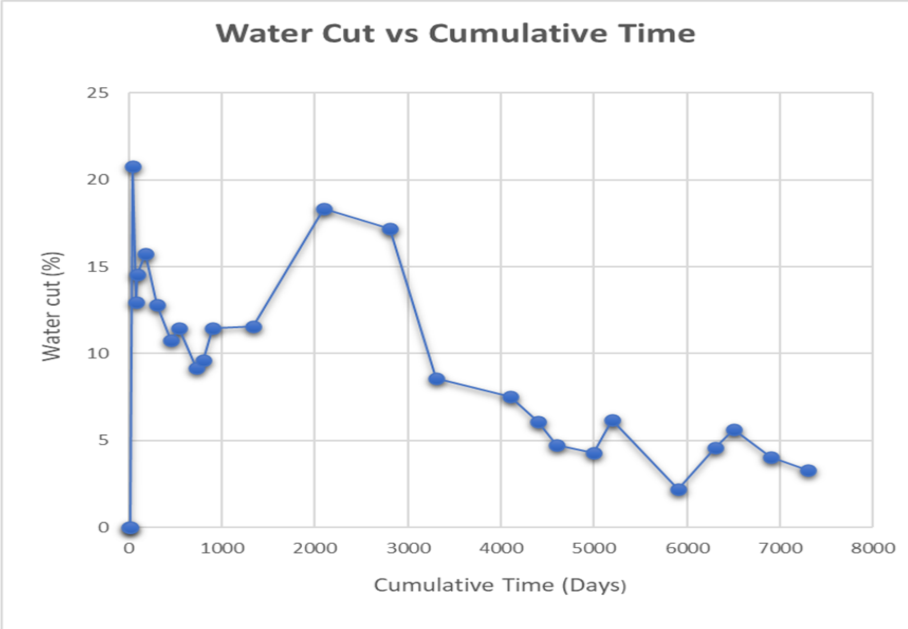


Figure 5-18 Fig. 5.18 Water cut (%) vs Time graph (Bill Bailey et al, 2000).

After only forty days of production, a breakthrough occurs. This is also an indication of the water coning phenomenon as the first period is quite short for coning according to Chan. After an early breakthrough, the water cut trend goes down with time.

5.4.2 Well 02:

In the same way, the WOR and WOR′ plots against Cumulative time are shown in the figure below:

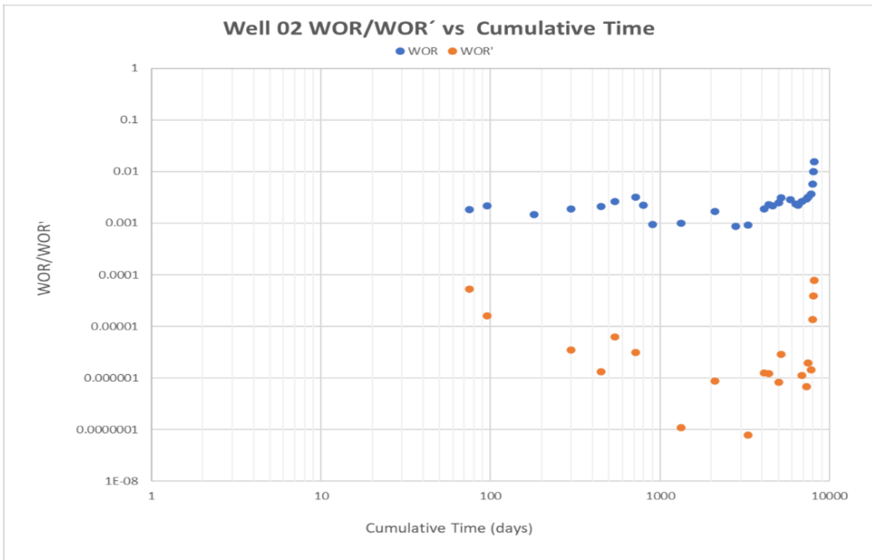


Figure 5-19 Well Diagnostic Plot showing WOR and WOR´vs Cumulative Time (Bill Bailey et al, 2000).

The WOR curve in this study is almost constant showing, not any significant change but at the very least it shows a high spike and trend goes up.

In the WOR´ curve, the trend shows initially a negative slope indicating an early breakthrough. This negative slope according to Chan (1995), shows the water coning phenomenon. With the passage of time, it decreases, but finally, it can be observed there is an increase in the slope at the last period. Chan called this a late-time Channeling phenomenon.

This whole figure after plotting well data infers representing Chan plot shown in figure 3.6 called "Bottom water coning with late time Channeling."

Like in other cases, the water cut plot against time is shown in the figure below:

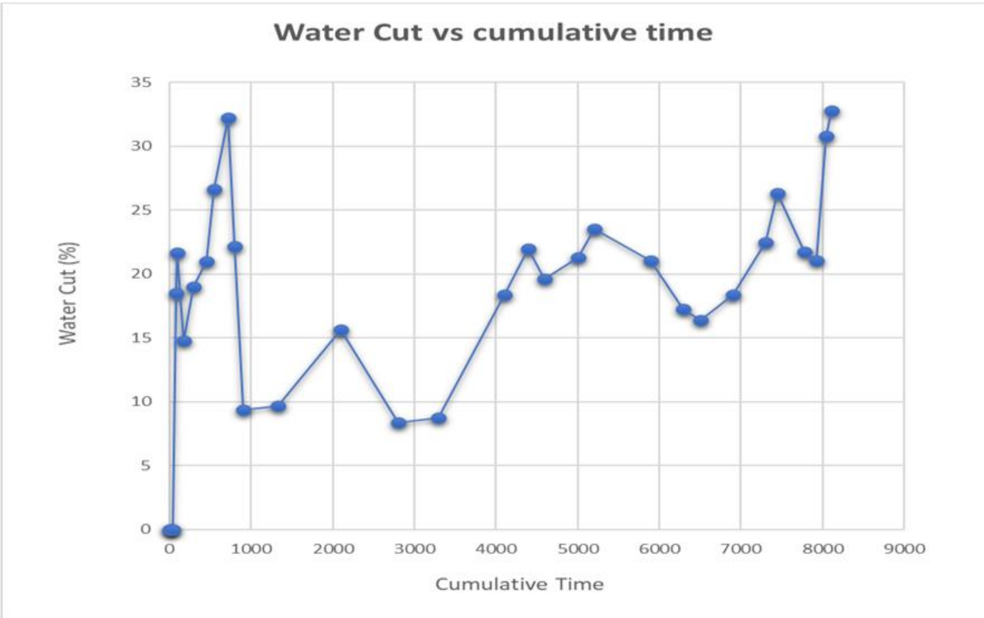


Figure 5-20 Water cut (%) vs Time graph (Bill Bailey et al, 2000).

In figure 5.20, the water cut is produced very early showing early breakthrough. But then it goes down and remains almost constant except at the last stage where it shows higher water cut again.

Thus, the results obtained from various wells in different parts of the world are showing their performances. This would conclude the most dominant cause that produces water production. The results illustrate water channeling is identified as the most common cause of water production in the majority of the wells under this study. The other causes of water-producing mechanisms are bottom water coning, bottom water coning with late channeling, and normal displacement with high water cuts.

Each problem type usually requires a different approach to control and remediate the related problem. These different approaches or techniques are applied depending on the type of problem, the extent of the problem, the geological structure of the subsurface, type of fluid, and reservoir behavior.

The solution to the problems created due to the water coning and channeling are discussed in chapter 02.

Chapter 6 CONCLUSION AND RECOMMENDATIONS

6.1 Summary of the work:

The objective of this work is to understand the application of various diagnostic plots to analyze wellbore or near wellbore problems related to water production problems. These plots are used to guide us in the identification of the cause of water production mechanisms. The research is aimed at developing a detailed diagnosis of various case studies taken from different fields are analyzed and validated with Chan´s diagnostic plots. The interpretations are being made based on the field production data with Chan´s plots. These analyses and interpretations would enable us to understand the performance of actual field case studies along with associated problems.

Using the Microsoft Excel format program by calculating and plotting the production history of all studies with the derivative methods proposed by Chan is an easy, quick, and simple way to diagnose wells. The change in the slopes of WOR and WOR´ against time plots are good indicators for the differentiation of normal displacement and production behavior and more specifically distinguishing the water production mechanisms.

In the first three case studies, it has been observed that most of the wells have experienced the Water Channeling or multi-layer Channeling or rapid Channeling phenomenon. In the first case, there are some wells that are encountered by normal displacement with a high water cut problem. Whereas, in the last case the wells have experienced the Bottom water coning or Bottom water coning with late Channeling phenomenon.

6.2 Recommendations:

The following recommendations are presented for future research work in order to improve the proposed methodology and results obtained in this study.

- All the wells in different cases under this work are studied and diagnosed cause water production problems. The results obtained by the diagnostic plot technique need to be verified by close monitoring using well logging and well testing techniques to ensure breakthrough time and entry points of the particular problem where it started.

- There is an uncertainty in few wells having scattered data or inconclusive evidence of the concerned problems. This uncertainty can be dealt with further work and is a proposed topic for future work.
- Choosing the optimum solution and mitigation technique for the specified problem to control excessive water production is always a key idea to achieve the desired goal.
- There is a need to quantify the uncertainty and risk associated with the use of diagnostic plots, e.g., in case study 03, where the wells are dominated producers in the field production but due to water Channeling problems are considered high-risk wells. This is a proposed research topic for future work to evaluate risk factors associated with excessive water production wells.

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