

**“WATER CONTROL DIAGNOSTICS IN FIELD OPTIMISATION
WATER CONING AND CUSPING IN OIL WELLS”**

BY

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**A PROJECT REPORT SUBMITTED TO THE DEPARTMENT OF
PETROLEUM ENGINEERING IN PARTIAL FULFILMENT OF THE
REQUIREMENTS FOR THE AWARD OF BACHELOR OF
ENGINEERING (B.ENG) DEGREE IN
PETROLEUM ENGINEERING**

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CERTIFICATION

This is to certify that this project was carried out by **OKHAISE PEACE UYIOSA** of the department of Petroleum Engineering with Matriculation Number **ENG2002624** in partial fulfilment of the requirements for the award of the degree, Bachelor of Engineering (B.Eng).

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DEDICATION

This work is dedicated to Almighty God for His Love and His Mercy which he has generously bestowed on me throughout my stay in the University of Benin.

ACKNOWLEDGEMENT

I wish to express my profound gratitude to the Author and finisher of my undergraduate story, Almighty God once again for his love and his infinite mercies on me.

I also want to use this medium to thank my project supervisor **Prof. Paul O. Ogbeide** for his tutelage during the course of this research.

My gratitude also goes to **Engr. Segun Taiwo** the project coordinator and to **Dr. Ikponwosa Ohenhen** the Head of the Department of Petroleum Engineering University of Benin, and to my esteemed course adviser **Engr. Nsuk** I appreciate your efforts sir.

I am extremely grateful to my industrial training supervisor of NNPC Energy Services Limited **Engr. Elijah** for equipping me with the knowledge of Microsoft Excel and Origin which has proven pivotal to the development of this research.

I am also very grateful to all my lecturers who have taught me in this Petroleum Engineering Department in the University of Benin including **Prof. Paul Ogbeide, Prof. Olafuyi, Prof. Bello, Dr. Sunny, Engr. Benedict, Dr. Blessing, Engr. Isaac, Engr. Chukwuma, Prof. Oduwa, Engr Alonge, Engr Frank, Engr. Abraham, Engr. Ame, Engr. Nsuk, Engr. Emmanuel and Engr. Idahosa.** May Almighty God bless everyone of them.

Sincere appreciation goes to my parents **Mr and Mrs Okhaise** for their parental care and sponsorship. And to my elder brother **Godswill Okhaise.**

Due to time constraint, I wish to thank all my course mates and my well-wishers for their support during this program.

Table of Contents

CERTIFICATION	i
DEDICATION	ii
ACKNOWLEDGEMENT	iii
LIST OF FIGURES	vii
NOMENCLATURE	viii
ABSTRACT	x
CHAPTER ONE	1
1.0 INTRODUCTION	1
1.1 DEFINITION OF KEY TERMS	1
1.2 BACKGROUND OF THE STUDY (OVERVIEW)	3
1.3 STATEMENT OF THE PROBLEM	4
1.4 OBJECTIVES OF THE RESEARCH	5
1.5 SCOPE OF THE STUDY	6
1.6 LIMITATION	6
1.7 VALUE OF THE INDUSTRY	6
1.8 END GOAL OF RESEARCH	7
CHAPTER TWO	8
LITERATURE REVIEW	8
2.1 INTRODUCTION	8
2.2 CRITICAL OIL PRODUCTION RATE CONTROL	10
2.3 HORIZONTAL AND MULTILATERAL WELL DESIGN	11
2.4 CRITICAL RATE SOLUTIONS	12
2.5 WATER BREAKTHROUGH TIME PREDICTION	18
2.6 WATER-OIL RATIO AFTER WATER BREAKTHROUGH	23
CHAPTER THREE	27

METHODOLOGY OF RESEARCH	27
3.1 INTRODUCTION	27
3.2 ASPECTS OF WATER ENCROACHMENT	27
3.2.1 Overview	27
3.2.2 Mechanics of Fluid Displacement	28
3.4 FIELD DATA	29
3.4.1 ASSET OVERVIEW	29
3.5 RESERVOIR CHARACTERISTICS	30
3.5.1 P2000T: FIELD ABC	30
3.6 LOG INFORMATION	32
3.7 RESEARCH APPROACH	33
3.9 PRODUCTION PERFORMANCE PLOT	34
3.10. WELL SUMMARY	35
3.11. WELL COMPLETION STRING	36
3.13. CHAN PLOT	37
CHAPTER FOUR	43
4.1 ANALYSIS & INTERPRETATION OF RESULTS	43
4.1.1 INTRODUCTION	43
4.1.2 Excessive Water Production Diagnostic Plots	43
4.1.3 KEY DIAGNOSTIC PLOTS FOR WATER PRODUCTION ANALYSIS	43
4.2 WATER CUT VS TIME OR CUMMULATIVE OIL PRODUCTION	45
4.2.1 ABC-: P2000T Analysis	46
4.3.1 ABC-20S: P2000T ANALYSIS	46
4.3.2 ABC-20S: P2000T ANALYSIS	46
4.4 CHAN PLOT COMPARISON	46

4.5 ANALYSIS OF RESULTS	49
CHAPTER FIVE	51
5.1 CONCLUSION & RECOMMENDATION	51
5.1.1 CONCLUSION	51
5.2 WATER CONING CONTROL TECHNIQUES	51
5.2.1 INTRODUCTION	51
5.3.1 WATER CUSPING CONTROL TECHNIQUES	57
5.4 CONCLUSION	62
5.5 RECOMMENDATION	63
REFERENCES	65

LIST OF FIGURES

FIG 1.1 WATER CONING	8
FIG 3.5 OIL FIELD DATA FOR RESERVOIR P2000T IN FIELD ABC	31
FIG 3.5 OIL FIELD DATA FOR RESERVOIR P2000T IN FIELD ABC	31
FIG 3.6 DATA LOG INFORMATION FOR P2000T IN FIELD ABC	32
FIG 3.8 WELL PRODUCTION PLOT OF P2000T	34
FIG 3.9 WELL COMPLETION STRING FOR WELL P2000T	35
FIG 3.10 PRODUCTION PERFORMANCE PLOT FOR RESERVOIR P2000T	35
FIG 3.14 A CONFORMANCE PERFORMANCE PLOT	37
FIG 3.15 CASE 1 FIG 3.16 CASE 2	38
FIG 3.17 CASE 3	37
FIG 4.2 ABC-30S WATER PRODUCTION CAUSES INTERPRETATION	46
FIG 4.2 CHAN PLOTS INDICATING A CONING/CRESTING/CUSPING PROBLEM	46
FIG 5.1 THE PHYSICS WATER CONING IN VERTICAL WELLS	57

NOMENCLATURE

LWD- Logging While Drilling

MWD-Measurement While Drilling

GOR'-Gas Oil Ratio

q_{crit} -Critical Oil Rate

k : Permeability

p_e -External Reservoir Pressure

OWC-Oil Water Contact

ZD-Dimensionless Cone Height

tD-Dimensionless time

q -Oil Production Rate

GLR-Gas Liquid Ratio

t_{br} -Time to breakthrough

μ_o : Oil Viscosity

STOIIP-Stock Tank Oil Initially in Place

BSW-Basic Sediment & Water

DWS-Downhole Water Sink

DWL-Downhole Water Loop

\emptyset -Porosity

ICDs- Inflow Control Devices

Q_w = Volume of water produced (usually in stock tank barrels per day, STB/day)

Q_o = Volume of oil produced (STB/day)

WOR = Water Oil Ratio

ABSTRACT

Water coning and cusping are significant challenges encountered during oil production, particularly in reservoirs with bottom or edge water drives. These phenomena occur due to the unfavorable movement of water into the production wellbore, compromising oil recovery efficiency and resulting in economic and operational losses. Water coning refers to the upward movement of water from an underlying aquifer towards a vertical well, while water cusping describes a similar lateral movement of water towards a horizontal well. These occurrences are typically caused by pressure differentials induced during hydrocarbon production, where the drawdown pressure at the wellbore exceeds the critical rate, causing water to breach the oil-water contact (OWC) and flow into the well.

The onset of water coning and cusping can severely reduce the oil-to-water ratio, leading to increased water production, higher separation and disposal costs, reduced oil recovery, and premature well abandonment. Understanding the mechanics of water movement in the reservoir and its interaction with the wellbore is essential for designing effective reservoir management strategies. This project explores the mechanisms, causes, consequences, and predictive models associated with water coning and cusping. It also reviews various solutions and mitigation techniques including critical production rate management, well completion optimization, reservoir simulation, and advanced recovery technologies such as horizontal drilling and inflow control devices (ICDs).

The study is motivated by the increasing need to optimize hydrocarbon recovery from mature fields and minimize water handling costs, especially in the face of global energy demands and declining oil reserves. Emphasis is placed on the use of analytical and numerical methods to predict water breakthrough and design production strategies that minimize water influx. Examples of such methods used are chan plot comparison, water cut vs time and cumulative oil.

CHAPTER ONE

1.0 INTRODUCTION

1.1 DEFINITION OF KEY TERMS

Coning and cusping are phenomena in petroleum engineering where unwanted fluids (water or gas) are drawn into a producing wellbore due to pressure differences, impacting oil production and recovery.

- Coning typically refers to the upward movement of water or downward movement of gas in vertical wells, while cusping refers to the same phenomena in horizontal wells.
- Coning occurs when the pressure drawdown in a producing well cause the oil-water contact (OWC) or gas-oil contact (GOC) to distort into a cone shape, with the unwanted fluid (water or gas) rising or falling towards the wellbore.

Water cusping is similar to coning but occurs in horizontal wells. It refers to the formation of a cusp-shaped interface between oil and water or oil and gas, due to pressure drawdown.

WHAT IS FIELD OPTIMIZATION?

Field Optimization refers to the process of maximizing the efficiency and profitability of oil and gas production from a field, encompassing various techniques to enhance reservoir, well, and surface facility performance. It involves measuring, analyzing, modeling, and implementing actions to optimize production , including the reservoir wells, and surface facilities, to enhance hydrocarbon recovery and minimize costs.

WHAT IS WATER CONTROL?

Water control refers to the strategies and techniques used to manage and mitigate the production of unwanted water alongside oil and gas from reservoirs. This is crucial because excessive water production can significantly reduce oil and gas recovery, increase operating costs (due to lifting, handling, and disposing of water), and potentially cause environmental issues.

Today, oil companies produce an average of three barrels of water for each barrel of oil from their depleting reservoirs. Every year, more than \$40 billion is spent in dealing with unwanted water.

In many cases, innovative water control technology can lead to significant cost reduction and improved oil production.

Water control technology is intended to reduce the costs of producing water.

1.2 BACKGROUND OF THE STUDY (OVERVIEW)

In the exploration and production of hydrocarbons, oil reservoirs often contain not only oil but also water and gas. These fluids are usually segregated naturally within the reservoir due to differences in their densities, with water at the bottom, oil in the middle, and gas at the top. However, during the production process, especially from oil wells in reservoirs with strong water drives or bottom water, complex flow dynamics can lead to the unwanted production of water. Two prominent mechanisms responsible for this early and excessive water production are water coning and water cusping

Water coning is a phenomenon that occurs in vertical or deviated wells when oil is produced from a reservoir with an underlying water zone (bottom water).

As oil is drawn toward the wellbore due to pressure differences, water beneath the oil may begin to rise in cone-shaped manner towards the perforated interval of the well. If the production rate exceeds a certain critical rate, the wellbore, resulting in water production along with oil. This not only reduces the efficiency of hydrocarbon recovery but can also lead to increased operating costs, corrosion, scale formation, and environmental concerns. On the other hand, water cusping occurs in horizontal wells. In this case, water from the bottom water zone moves upward in cusp-like shape toward the horizontal section of the well. Though horizontal wells are generally more favorable in controlling water movement compared to vertical wells, they are not immune to water cusping, particularly when production rates are too high or horizontal well is placed too close to the oil-water contact.

The onset of water coning or cusping is influenced by several reservoir and operational factors such as vertical permeability, mobility ratio between water and oil, reservoir thickness, viscosity of the fluids, well placement, and production rate. Once water breakthrough occurs, it becomes difficult to reverse, and oil recovery is significantly compromised.

1.3 STATEMENT OF THE PROBLEM

In the production of oil from subsurface reservoirs, one of the persistent and costly challenges faced by petroleum engineers is the premature and excessive production of water. Among the primary causes of unwanted water. Among the primary causes of unwanted water production are water coning in vertical wells and water cusping in horizontal wells-two interrelated phenomena that occur when water from an underlying aquifer or bottom water zone encroaches into the wellbore during oil extraction .In the petroleum industry, most active bottom-water drive reservoirs are completed strategically to handle produced water problems that may arise during the production of oil & gas. Water production may come in the form of tongue, cusp, cone or a combination of all depending on:

- Fluid Properties
- Reservoir Heterogeneity
- Production Rate

Some of the drawbacks include:

- Premature Water Breakthrough
- Increased Water Cut

- Higher Operational Costs
- Early abandonment of afflicted well
- Loss of field total overall recovery.

1.4 OBJECTIVES OF THE RESEARCH

The specific objectives are as follows.

1. To investigate the causes and mechanisms of water cusping and coning in oil wells.
2. To analyze the key factors influencing the onset and severity of water breakthrough.
3. To determine the effects of water coning, cresting and cusping in bottom water drive reservoirs.
4. To ascertain remedial solutions to the problem of water coning.
5. To evaluate the impact of water coning and cusping on oil recovery efficiency and well performance.
6. To recommend practical strategies and technologies for minimizing water intrusion and optimizing oil production.

1.5 SCOPE OF THE STUDY

This focuses on the phenomena of water coning and cusping in oil wells-two major challenges in petroleum production that significantly affect the efficiency of hydrocarbon recovery.

The research is limited to understanding how water intrudes into the wellbore from an underlying aquifer or water zone due to pressure gradients created during oil production.

For the scope of this study, the bulk of the data used for this research was collected from Energy Services Limited (ENSERV). Also, the important software used for the research work was gotten from ENSERV.

1.6 LIMITATION

Limited access to real-time field data and core samples which could affect the accuracy of analysis and modelling of water coning and cusping behavior.

1.7 VALUE TO INDUSTRY

Understanding the behavior of water coning and cusping allows engineers to optimize well placement and production strategies to maximize oil recovery while minimizing water production. Water produced with oil increases operational costs due to handling, separation, treatment, and disposal. The study provides insight into fluid movement within the reservoir, aiding in the design of effective reservoir monitoring and control strategies. It supports better reservoir simulation models, enabling more accurate prediction of future production and reservoir performance. During the well planning stage, the reservoir engineer wants to know the Maximum oil production rate at which a well can be produced without concurrent production of the displacing phase. This is referred to as “critical rate”. If economic conditions dictate production above this ‘critical rate’, the engineer wants to know two additional things.

1. Time of water breakthrough and;
2. WOR following breakthrough.

At this stage, the available reservoir parameters or data are in minimum and the dollar value of an accurate forecast is critical and at the highest.

The importance of a simple predictive tool at this stage of field development cannot be over emphasized. The objective is to be able to make an accurate forecast when we have little data.

This stresses the benefits of a predictive tool that can be used to carry out sensitivity analysis to evaluate various scenarios. For the current problem encountered by the operator/research sponsor, the predictive tool can explain the early water breakthrough; give guidance regarding proposed future wells and recommend optimum rates at the initial planning stage.

1.8 END GOAL OF RESEARCH

The ultimate goal of this research is to develop effective strategies and technologies that minimize unwanted water production, maximize hydrocarbon recovery, and enhance the overall efficiency and profitability of oil well operations.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

Water coning and cusping are among the most critical challenges encountered in hydrocarbon production from oil reservoirs, particularly those underlain or laterally bounded by active aquifers. These phenomena occur when water from the aquifer or surrounding water-bearing formations is drawn into the wellbore due to an imbalance in pressure distribution, often induced by high production rates. Understanding and mitigating water coning and cusping are essential for optimizing oil recovery, minimizing water production, and extending the productive life of oil wells.

Water coning typically refers to the upward movement of water from an underlying aquifer toward the wellbore in vertical or moderately deviated wells. The mechanism behind this phenomenon is largely governed by pressure drawdown. When oil is produced, the pressure near the wellbore decreases, creating a gradient that pulls water upward from the aquifer (Chaperon, 1986). This pressure imbalance leads to the formation of a cone-shaped water front that, if not controlled, can reach the perforations of the well, resulting in water breakthrough. Water cusping, on the other hand, refers to the lateral encroachment of water in horizontally or highly deviated wells, where the water advances in a cusp-like shape due to similar pressure differentials (Raghavan and Reynolds, 1991).

The onset and severity of coning or cusping depend on several reservoir and operational parameters, including the viscosity ratio of oil to water, the density difference between the fluids, vertical and horizontal permeability, reservoir thickness, and the rate of production. The mobility ratio—defined as the mobility of water divided by the mobility of oil—plays a key role in determining the stability of the interface between oil and water (Bournazel and Jeanson, 1971). A higher mobility ratio typically exacerbates coning, as water can more easily displace oil and reach the wellbor

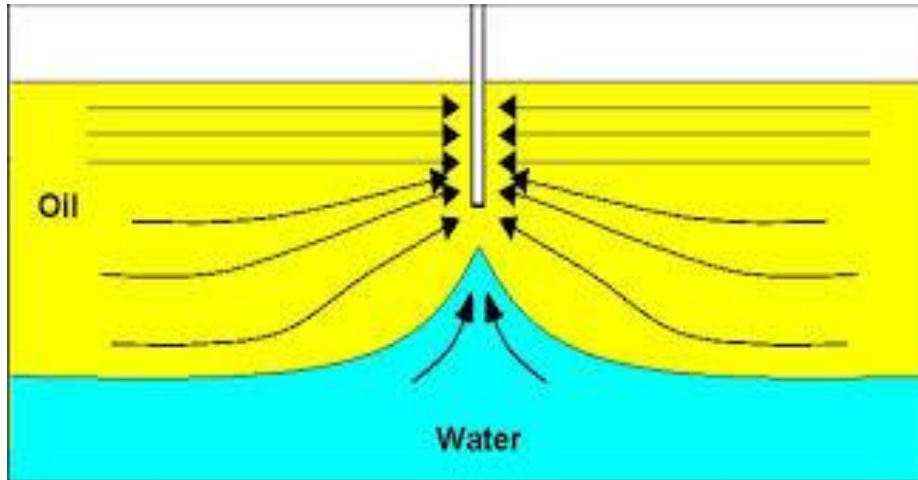


Fig 1.1 Water coning

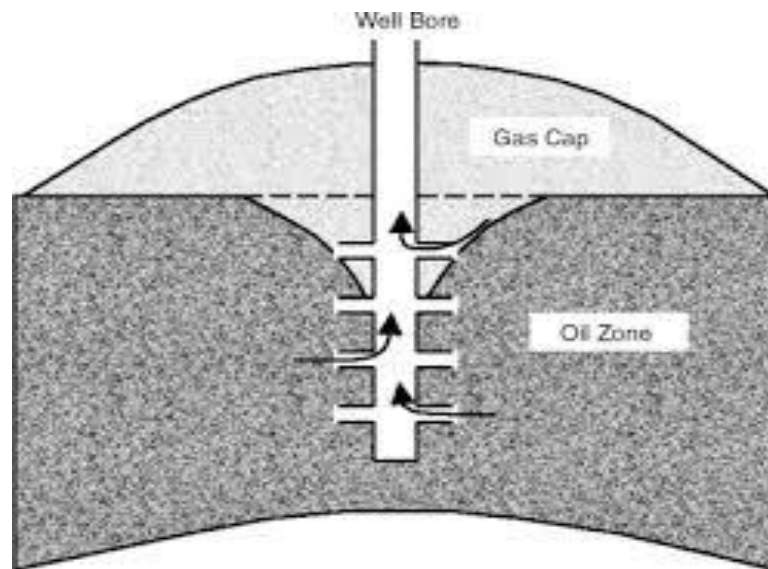


Fig 1.2 Water cusping

Chaperon (1986) developed one of the earliest and most widely used analytical models for predicting critical oil production rates that avoid water coning. His model assumes radial flow and provides a theoretical maximum rate below which water is unlikely to cone into the well. More recent numerical models have improved upon Chaperon's work by incorporating anisotropy, heterogeneity, and more complex well geometries (Bahadori, 2011).

Mitigation strategies for water coning and cusping are typically aimed at controlling the pressure drawdown near the wellbore. One common approach is to limit oil production to a rate below the **critical rate**, which is the maximum allowable rate that prevents water from breaking through. This rate is a function of reservoir and fluid properties and must be carefully calculated (Baker and Raghavan, 1978). In horizontal wells, optimizing well placement to maintain a maximum distance from the oil-water contact can help delay or prevent cusping (Ozkan et al., 1999).

In addition to rate control, several advanced techniques have been developed to mitigate water encroachment. One such method is the use of **inflow control devices (ICDs)** and **autonomous inflow control devices (AICDs)**, which regulate the flow of fluids along the wellbore and delay water breakthrough by balancing the pressure profile (Zhou et al., 2014). These devices are especially useful in horizontal wells where cusping is more prevalent. Another approach is selective completion, which involves isolating water-producing zones using packers or mechanical barriers (Economides and Nolte, 2000). Furthermore, chemical conformance techniques such as polymer gels and relative permeability modifiers have been applied to reduce water mobility in near-wellbore regions (Seright, 1995).

Reservoir simulation has become an indispensable tool in evaluating water coning and cusping behavior under various scenarios. Numerical models allow engineers to simulate different production strategies and assess the risk of water breakthrough over time. Advanced 3D simulation software incorporates heterogeneities and fracture networks, which significantly impact fluid movement and can complicate coning dynamics (Ahmed, 2010).

Field case studies have demonstrated the practical implications of water coning and cusping. In many mature fields, high water cut due to early water breakthrough has led to reduced oil recovery and increased operational costs for water handling and disposal. As such, understanding coning and cusping is not only a matter of technical interest but also of economic importance (Craig, 1971). For example, in the North Sea and the Niger Delta, water coning has been observed to compromise reservoir performance, prompting the adoption of downhole water shutoff techniques and production optimization measures (Okolie and Aizebeokhai, 2019).

Recent research has also focused on machine learning and data-driven approaches for early detection and prediction of water coning. These methods use production data and well logs to forecast the likelihood of water encroachment, allowing for proactive intervention (Mohaghegh et al., 2005). As digital oilfield technologies evolve, such predictive tools are expected to enhance reservoir management practices and help mitigate water-related challenges more efficiently.

In conclusion, the problem of water coning and cusping remains a significant issue in oil production, particularly in reservoirs with active aquifers. Effective control strategies, including critical rate determination, well placement optimization, and inflow control technologies, are essential to mitigate these issues. Continued research, field monitoring, and the integration of digital technologies are crucial for improving water management and ensuring sustained oil production from complex reservoirs.

The solution to coning problems is addressed by the two ways below.

- Critical Oil Production Rate Control
- Horizontal and Multilateral Well Design

This chapter reviews the previous approach to cusping and coning problems in general.

2.2 CRITICAL OIL PRODUCTION RATE CONTROL

The solution involves calculating and producing at or below the critical oil production rate, the maximum rate at which oil can be produced without drawing water from the underlying or surrounding aquifer into the wellbore due to coning or cusping.

When oil is produced too rapidly, it creates a strong pressure drawdown near the wellbore.

This pressure imbalance causes water from the water-oil contact (WOC) (in vertical wells) to move upward (coning) or horizontally (cusping) into perforation zone. By limiting the

production rate to a calculated critical rate, the drawdown pressure is controlled, which prevents or delays water from being pulled into the well. (Craft, B.C, & Hawkins, M.F (1991).

Benefits

1. Reduces or delays water breakthrough into the well.
2. Prolongs the productive life of the reservoir.
3. Minimizes produced water handling costs and environmental risks.

Challenges

1. Requires accurate reservoir data (permeability, viscosity, density, fluid contacts).
2. If the rate is set too low, it might reduce economic returns from the well.
3. Must be adjusted continuously as reservoir pressure and conditions change.

Tools Used

1. Mathematical models such as the Chaperon, Bournazel-Jeanson, or Dietz models
2. Numerical simulation software (e.g., Eclipse, CMG tNavigator) for precise predictions.

2.3 HORIZONTAL AND MULTILATERAL WELL DESIGN

Designing and completing horizontal or multilateral wells strategically to minimize the vertical or lateral pressure gradient that causes coning or cusping.

A horizontal well runs parallel to the reservoir, often several hundred meters long, and is placed high above the oil-water contact (OWC). This configuration distributes the pressure drawdown over a longer interval, which reduces the chance of coning or cusping.

In multilateral wells, multiple horizontal branches drain different parts of the reservoir, further reducing localized pressure drawdowns that might trigger water invasion.

Benefits

1. Significantly delays water breakthrough compared to vertical wells.
2. Allows for higher oil production rates at lower drawdowns, staying under the critical limit.
3. Improves sweep efficiency and recovery factor in heterogeneous reservoirs.

Challenges

1. Requires complex drilling techniques and accurate geosteering to place the well correctly.
2. Higher initial cost and operational complexity compared to vertical wells
3. Water can still eventually invade, so rate control and monitoring are still important.

Tools used

1. Reservoir simulation and 3D geological modeling to plan optimal well replacement.
2. Logging While Drilling (LWD) and Measurement While Drilling (MWD)

2.4 CRITICAL RATE SOLUTIONS

Water coning and cusping are common challenges in oil well operations, especially in reservoirs with bottom water or edge water. These phenomena occur when water moves vertically (coning) or laterally (cusping) toward the wellbore due to pressure gradients induced by production. If not managed properly, they can lead to early water breakthrough, increased water cut, decreased oil recovery, and higher production costs due to water handling and separation.

One of the most widely used strategies to manage and mitigate water coning and cusping is through critical rate control—a method that aims to maintain production rates below a certain threshold that would otherwise induce water encroachment. This concept is based on the understanding that water movement toward the wellbore is rate-dependent. Therefore, establishing and maintaining a critical oil production rate can delay or prevent water breakthrough.

This section explores the theory, calculation methods, influencing factors, and field applications of critical rate solutions as a control measure for water coning and cusping. (Zhou, Y., & Wu, J. 2016)

Understanding the Concept of Critical Rate

The critical rate is defined as the maximum oil production rate at which water does not reach the wellbore due to coning or cusping. This rate is derived based on reservoir and fluid properties, well completion design, and the geometry of the water-oil contact. Producing below this critical rate helps to stabilize the oil-water interface and reduces the tendency for water to rise or intrude into the production zone.

Mathematically, the critical rate is influenced by a number of variables, including:

- Vertical and horizontal permeability
- Oil and water viscosities
- Reservoir thickness
- Distance from the wellbore to the water-oil contact
- Formation porosity
- Pressure drawdown
- Well type (vertical, horizontal, or multilateral)

The analytical formula derived by Chaperon(1986) and others for the critical rate (for vertical wells) is a simplified way of estimating this value. For a vertical well in a radial system, the formula is generally given by:

$$q_{crit} = \frac{2\pi kh(p_e - p_w)}{\mu \ln \left(\frac{r_e}{r_w} \right) + S}$$

Where:

- q_{crit} : Critical oil rate

- k : Permeability
- h : Height of oil column above water
- p_e : External reservoir pressure
- p_w : Wellbore pressure
- μ_o : Oil viscosity
- r_e, r_w : External and wellbore radius
- S : Skin factor

For horizontal wells, the formula is more complex and usually solved numerically or using correlations due to the geometry and multiple inflow points.

Factors Influencing Critical Rate Solutions

A number of geological and operational factors influence the determination and effectiveness of critical rate solutions:

a. Reservoir Permeability and Anisotropy

High vertical permeability enhances water coning as it allows water to move more easily upward. Conversely, horizontal wells tend to benefit from low vertical-to-horizontal permeability ratios (K_v/K_h), which reduce the tendency for coning. Therefore, accurate characterization of permeability is essential in critical rate determination.

b. Oil and Water Viscosities

The viscosity ratio between oil and water directly affects mobility. A higher water mobility (i.e., lower viscosity) increases the risk of water movement toward the wellbore. Critical rate solutions incorporate these viscosity values to predict the rate at which water may rise or encroach.

c. Well Completion Type and Location

Horizontal wells generally have higher critical rates than vertical wells due to their geometry, which spreads the pressure drawdown along a longer horizontal section. This reduces localized pressure drops and delays water breakthrough.

d. Oil Column Thickness

A thicker oil zone above the water-oil contact results in a larger buffer against water movement. This allows for a higher critical production rate compared to thin oil zones.

e. Drawdown Pressure

High pressure drawdown promotes coning and cusping. Maintaining a moderate and controlled drawdown is key to staying within the critical rate limit. Using artificial lift systems like gas lift or ESPs (electric submersible pumps) should be done carefully to avoid excessive drawdowns.

Calculation and Modeling Approaches

Several methods exist to estimate the critical rate in both theoretical and practical applications. These include:

a. Analytical Models

Analytical models such as those by Muskat, Chaperon, and others provide equations for estimating critical rate based on assumptions of steady-state flow, homogeneous formations, and constant fluid properties. While useful, these models have limitations in complex reservoirs.

b. Empirical Correlations

Various empirical correlations have been developed from field data to estimate critical rates. These are typically easier to apply but may lack precision in heterogeneous reservoirs.

c. Numerical Simulation

Modern reservoir simulation tools allow engineers to simulate fluid flow dynamics and test various production scenarios. Through simulation, the critical rate can be estimated more accurately by including complex factors like heterogeneity, fractures, capillary pressure, and multiphase flow behavior.

Simulation models also allow testing the effect of adjusting production rates over time and implementing zonal isolation, perforation strategies, and horizontal well optimization.

Application of Critical Rate in Field Operations

In real-world applications, critical rate solutions are used alongside other water control strategies. The following operational practices enhance the effectiveness of critical rate control:

a. Rate Control through Choke Management

Controlling surface and downhole chokes to limit oil production rates helps maintain production below the critical threshold. This method is especially useful in mature fields experiencing high water cut.

b. Intelligent Well Completions

Smart wells with downhole flow control devices can selectively control production from different zones. This allows operators to reduce flow from zones nearing water breakthrough while maintaining overall production within critical limits.

c. Water Production Monitoring

Regular monitoring of water cut and well performance data helps detect early signs of water coning or cusping. Adjustments to production rates can then be made proactively.

d. Integrated Reservoir Management

A multidisciplinary approach involving geoscientists, reservoir engineers, and production engineers ensures a more accurate critical rate estimation and monitoring. Integrated management includes regular updates to reservoir models and collaboration on production optimization.

Advantages of Critical Rate Solutions

- **Prevention of Early Water Breakthrough:** Reduces the risk of water entering the well prematurely, thus extending the productive life of the well.
- **Improved Oil Recovery:** Helps maintain a stable oil-water contact and ensures more oil is recovered before water dominates.
- **Reduced Water Handling Costs:** Minimizes the need for surface water separation, treatment, and disposal.
- **Sustainable Production:** Encourages production within safe reservoir limits, reducing reservoir damage.

Limitations and Challenges

While critical rate solutions are effective, they have some limitations:

- **Reduced Production Rates:** Limiting production may not always meet economic targets, especially when oil prices are high.
- **Complex Reservoirs:** In fractured, heterogeneous, or thin reservoirs, accurately estimating critical rate is challenging.
- **Changing Reservoir Conditions:** Reservoir properties change over time due to depletion, requiring frequent updates to critical rate calculations.

Critical rate solutions provide a practical and scientifically grounded method for managing water coning and cusping in oil wells. By identifying and maintaining production below a calculated threshold, operators can significantly delay water breakthrough and enhance oil recovery. Although this method may involve lower production rates, the long-term economic and operational benefits, including reduced water handling and prolonged well life, often outweigh the downsides.

Advanced tools such as numerical reservoir simulation, intelligent completions, and real-time monitoring further enhance the implementation of critical rate strategies. As oil fields mature and

water production becomes more prominent, critical rate control remains a cornerstone of efficient reservoir and production management. (Chaperon 1986).

2.5 WATER BREAKTHROUGH TIME PREDICTION

Water breakthrough refers to the point at which water from the underlying aquifer or adjacent water zones reaches the wellbore and starts to be produced along with oil or gas. In oil reservoirs with bottom water (leading to coning) or edge water (leading to cusping), breakthrough is a common and costly occurrence. Once water breaks through, it not only reduces oil production but also increases the cost and complexity of surface operations, including water separation, reinjection, or disposal.

Therefore, predicting the time to water breakthrough (or breakthrough time) is a crucial aspect of reservoir and production engineering. It allows operators to optimize well placement, production rates, and completion strategies to delay or prevent water entry, thereby maximizing oil recovery and economic return. (Seright, R.S. 1995).

IMPORTANCE OF WATER BREAKTHROUGH PREDICTION

Accurate prediction of water breakthrough time is important for several reasons:

- Optimizing well placement and trajectory
- Controlling water production costs
- Designing completion and perforation strategies
- Scheduling artificial lift systems appropriately
- Determining production rate limits (i.e., critical rates)
- Evaluating reservoir heterogeneity and aquifer strength
- Extending economic field life

Being able to forecast when and how water will reach the wellbore is also essential in designing coning or cusping control mechanisms before the problem becomes critical.

MECHANISM OF WATER BREAKTHROUGH

Water in a reservoir exists below (bottom water drive) or beside (edge water drive) the oil zone. As oil is produced, pressure in the reservoir drops, particularly near the wellbore. This pressure reduction creates a vertical or lateral pressure gradient that causes water to move toward the well. The rate and path of water movement depend on several key parameters, including:

- Reservoir permeability and anisotropy
- Viscosity contrast between oil and water
- Reservoir geometry and thickness
- Wellbore location and orientation
- Production rate and drawdown pressure
- Capillary and gravity forces

Eventually, when water migrates close enough to the wellbore, it will enter the perforated zone and be produced. The moment this occurs is termed breakthrough, and the time it takes is called the breakthrough time (t_{bt}). (OKOLIE, T.E, & Aizebeokhai A.P 2019).

FACTORS AFFECTING WATER BREAKTHROUGH TIME

Water breakthrough is not governed by a single factor, but by the interaction of several reservoir, fluid, and operational properties:

a. Reservoir Thickness (h)

Thicker oil columns provide a greater buffer between the wellbore and the water-oil contact (WOC), delaying water movement and breakthrough.

b. Oil and Water Viscosities (μ_o, μ_w)

The greater the viscosity difference, the more mobility contrast exists. High water mobility causes faster movement and earlier breakthrough.

c. Production Rate (q)

High production rates increase pressure drawdown and accelerate water movement. Excessive rates can cause early water coning and quick breakthrough.

d. Permeability (k)

High permeability favors faster fluid flow. Anisotropy (differences in vertical vs horizontal permeability) also plays a major role.

e. Distance from Well to WOC or Aquifer

The initial vertical or horizontal separation between the wellbore and water zones influences the time needed for water to migrate to the well.

f. Well Geometry and Completion Type

Horizontal wells typically delay water breakthrough due to their distributed inflow and lower drawdown near the heel and toe. Vertical wells are more prone to early water coning.

g. Capillary and Gravity Forces

These can act against or in favor of water movement, depending on the wettability and saturation history of the reservoir.

METHODS FOR PREDICTING WATER BREAKTHROUGH TIME

Several analytical, empirical, and numerical methods exist for predicting water breakthrough time:

A. Analytical Methods

These are based on mathematical solutions to fluid flow equations under simplified assumptions.

i. Muskat's Coning Model (1949)

Muskat proposed a steady-state model for vertical wells where water coning is influenced by viscosity ratio, drawdown pressure, and geometry. While it doesn't give an explicit breakthrough time, it's foundational in understanding water movement.

ii. Chierici's Equation

Chierici developed a more explicit equation for breakthrough time based on a balance of viscous and gravitational forces in vertical wells.

iii. Dietz's Model

This analytical approach considers radial flow and provides an expression to estimate the time of breakthrough under certain simplifying assumptions:

B. Empirical Models

Empirical models are derived from field data and offer quick estimations. They are less accurate than numerical models but easier to apply.

- These include curves, charts, or regression-based models from historical data.
- Often used in mature fields with known water-cut behavior.

C. Numerical Simulation

Numerical reservoir simulators (e.g., Eclipse, CMG, tNavigator) offer the most detailed and accurate method for predicting water breakthrough.

Features:

- Include geological heterogeneities
- Account for capillary and gravity forces
- Simulate complex well trajectories (e.g., multilateral, horizontal)
- Can incorporate time-dependent changes in reservoir pressure and saturation
- Allow for sensitivity analysis (varying production rate, permeability, etc.)

Simulations are widely used during field development planning and real-time reservoir management to optimize well placement and production strategies.

PRACTICAL EXAMPLE OF WATER BREAKTHROUGH PREDICTION

Suppose an oil well is completed 10 feet above the water-oil contact in a reservoir with the following properties:

- Porosity (ϕ): 0.25
- Permeability (k): 150 mD
- Oil viscosity (μ_o): 2 cp
- Oil production rate (q): 500 STB/day
- Reservoir thickness (h): 20 ft

Using a simplified breakthrough time estimation formula:

$$t_{bt} = \frac{h^2 \cdot \phi \cdot \mu_o}{q \cdot k}$$

Substitute values:

$$t_{bt} = \frac{(20)^2 \cdot 0.25 \cdot 2}{500 \cdot 150} = \frac{100 \cdot 0.25 \cdot 2}{75000} = \frac{50}{75000} = 0.000667 \text{ days}$$

This shows a very small breakthrough time, indicating the need for lower production rates or deeper perforations to delay breakthrough.

STRATEGIES TO DELAY WATER BREAKTHROUGH

Once breakthrough time is predicted, operators can implement strategies to delay or mitigate its effects:

- Reduce production rates (stay below critical rate)
- Optimize perforation interval away from water zones

- Use horizontal wells or sidetracks
- Implement zonal isolation or selective completions
- Apply coning control technologies (gel treatments, foams, packers)
- Monitor well performance continuously and adapt operations

Predicting water breakthrough time is a vital task in managing oil reservoirs with active water drive. A reliable prediction helps delay water production, increase ultimate oil recovery, and lower operating costs. While analytical and empirical models provide quick estimates, numerical simulation remains the most comprehensive tool for accurate prediction under real field conditions.

Effective breakthrough prediction is not just about forecasting a time—it is about understanding the reservoir’s behavior, identifying potential risks, and making informed decisions that prolong productive life. Integrated reservoir modeling, continuous monitoring, and flexible production strategies are the keys to managing water encroachment effectively.

2.6 WATER-OIL RATIO AFTER WATER BREAKTHROUGH

In oil reservoirs with underlying or adjacent water zones, water breakthrough is a common phenomenon that marks a turning point in well productivity. Once breakthrough occurs, water begins to flow into the wellbore along with oil. One of the most critical parameters used to evaluate the performance of such wells after breakthrough is the Water-Oil Ratio (WOR).

The WOR is a production metric that expresses the volume of water produced per unit volume of oil. Monitoring this ratio provides valuable insight into the severity of water encroachment, the efficiency of the production strategy, and the need for remedial actions.

After water breakthrough, the WOR typically increases significantly due to the growing contribution of water to the produced fluids. Understanding how WOR behaves post-

breakthrough is essential for managing water production, optimizing oil recovery, and making informed economic decisions. (Baker, R.O., & Raghavan, R. (1978).

DEFINITION OF WATER-OIL RATIO (WOR)

The Water-Oil Ratio (WOR) is defined as:

$$\text{WOR} = \frac{Q_w}{Q_o}$$

Where:

- Q_w = Volume of water produced (usually in stock tank barrels per day, STB/day)
- Q_o = Volume of oil produced (STB/day)

WOR is dimensionless and typically expressed as a pure number (e.g., WOR = 5 means 5 barrels of water are produced for every 1 barrel of oil).

Closely related to WOR is the water cut (WCT), which is the percentage of water in the total liquid production:

$$\text{Water Cut} = \frac{Q_w}{Q_o + Q_w} \times 100\%$$

While water cut indicates the relative percentage of water, WOR provides a ratio useful for diagnostic and analytical purposes, especially after water breakthrough.

WOR BEHAVIOR BEFORE AND AFTER WATER BREAKTHROUGH

a. Before Breakthrough

Before water breakthrough occurs, the WOR is typically very low or even zero, especially in oil zones that are well above the oil-water contact. The reservoir fluid entering the wellbore is almost entirely oil with only trace amounts of water (if any).

b. At Breakthrough

At the point of water breakthrough, water begins to appear in produced fluids. The WOR begins to rise, indicating the onset of water entry into the wellbore. This point marks the transition from single-phase (oil) production to multiphase (oil and water) production.

c. After Breakthrough

Once breakthrough has occurred, the WOR increases over time and often follows a characteristic trend:

- Initially slow rise immediately after breakthrough
- Exponential or sharp increase as more water enters the well
- Plateauing or stabilization in some wells (especially with coning control)
- Runaway increase in poorly managed wells or thin oil zones

The behavior of WOR after breakthrough depends on several key factors discussed below.

FACTORS AFFECTING WOR AFTER WATER BREAKTHROUGH

a. Reservoir Heterogeneity

In heterogeneous reservoirs, high-permeability streaks or fractures can act as conduits for water, leading to early and rapid water influx. These “thief zones” cause a sharp rise in WOR immediately after breakthrough.

b. Completion Design

Poorly placed perforations or long perforated intervals may allow water to invade the well more easily. Wells completed too close to the oil-water contact may experience steep WOR increases after breakthrough.

c. Production Rate

High production rates increase drawdown near the wellbore and accelerate coning or cusping, leading to faster water entry and higher WOR. Conversely, operating below the critical rate can slow WOR growth.

d. Well Type and Orientation

- **Vertical wells** tend to show sharper increases in WOR after breakthrough because of concentrated water entry.
- **Horizontal wells** distribute inflow over a longer section, potentially delaying WOR rise and maintaining lower values longer.

CHAPTER THREE

METHODOLOGY OF RESEARCH

3.1 INTRODUCTION

The methodology adopted in this research involves a combination of literature review, analytical modeling, and case study analysis to investigate the causes, impacts, and control measures of water coning and cusping in oil wells.

First, a comprehensive review of existing literature, including journal articles, textbooks, and technical papers, was conducted to understand the theoretical background and current knowledge on water movement toward oil wells. Key concepts such as critical rate, breakthrough time, and water-oil ratio were studied.

Next, analytical models and equations were used to evaluate the conditions that lead to water coning and cusping, particularly focusing on production rate, reservoir properties, and well geometry. Where applicable, simplified calculations were performed using assumed reservoir parameters to demonstrate how production rate affects water movement. (Chaperon, 1986).

3.2 ASPECTS OF WATER ENCROACHMENT

3.2.1 Overview

Water encroachment in oil wells refers to the movement of water from adjacent or underlying aquifers into the oil zone as a result of pressure drawdown during production. Under this topic, key aspects include:

- **Water Coning:** Vertical movement of water from an underlying aquifer into the wellbore, common in vertical wells.
- **Water Cusping:** Lateral intrusion of water from an edge-water zone, typically seen in horizontal wells.
- **Critical Production Rate:** The maximum oil rate that can be produced without inducing water encroachment.

- **Water Breakthrough:** The point when water first enters the wellbore and begins to be produced.
- **Water-Oil Ratio (WOR):** An indicator of the extent of water production post-breakthrough.

These aspects help in understanding, predicting, and managing water movement to improve oil recovery and reduce water production challenges.

3.2.2 MECHANICS OF FLUID DISPLACEMENT

The mechanism of fluid displacement refers to how one fluid (typically water) moves through a porous reservoir to displace another fluid (oil or gas). In oil reservoirs, this displacement occurs naturally due to pressure differences or is induced during production or enhanced recovery operations.

PRIMARY DISPLACEMENT MECHANISM

During oil production, the pressure in the reservoir drops, especially near the wellbore. This creates a **pressure gradient** that causes fluids (initially oil) to flow toward the well. As production continues, water from an adjacent aquifer or underlying zone begins to **displace** the oil, moving toward the wellbore.

TYPES OF DISPLACEMENT MECHANISMS

a. Piston-like Displacement

- Ideal but rare.
- Water pushes oil uniformly without mixing.
- High sweep efficiency.

b. Fingering and Channeling

- Occurs when water has higher mobility (low viscosity).
- Water bypasses oil, leading to early water breakthrough.

c. Coning and Cusping

- **Coning:** Water moves vertically upward from bottom water due to high drawdown.
- **Cusping:** Water moves laterally from edge-water zones, common in horizontal wells.

FORCES INVOLVED

- **Viscous Forces:** Drive fluid flow due to pressure gradient.
- **Gravity Forces:** Cause heavier water to remain below oil.
- **Capillary Forces:** Affect fluid distribution in pore spaces.
- **Mobility Ratio:** Controls the efficiency of displacement (mobility = permeability/viscosity).

In summary, fluid displacement in oil wells involves the movement of water into oil-bearing zones due to pressure drawdown, with mechanisms like coning and cusping depending on well orientation and reservoir conditions. Understanding this helps in designing better water control strategies and improving oil recovery.

3.4 FIELD DATA

3.4.1 ASSET OVERVIEW

Field ABC is a producing onshore oil field located in the Niger Delta Basin of Nigeria, specifically in the southern part of Bayelsa State. The field lies within Oil Mining Lease (OML) XYZ and is operated jointly by a multinational oil company and the Nigerian National Petroleum Corporation (NNPC). It was discovered in the early 1990s and brought into production by the late 1990s.

The field is part of a structurally complex deltaic environment, characterized by faulted anticlines and stacked reservoirs typical of the Agbada Formation. It has multiple oil-bearing horizons and active aquifers at the base and edges of the oil columns, making it prone to water encroachment.

3.5 RESERVOIR CHARACTERISTICS – P2000T

Reservoir P2000T is one of the key producing reservoirs within Field ABC. It is a mid-depth sandstone reservoir found at an average depth of approximately 2,500 meters. The reservoir is laterally extensive and exhibits moderate to high permeability with good porosity.

Key reservoir properties include:

- **Formation:** Agbada Formation (Miocene)
- **Depth:** ~2,500 meters
- **Porosity:** 22–28%
- **Permeability:** 150–500 mD
- **Oil viscosity:** ~2.5 cP
- **Water-oil contact (WOC):** Clearly defined with an active bottom aquifer
- **Drive mechanism:** Combination of solution gas drive and bottom water drive

The reservoir is highly productive but also susceptible to water coning, particularly in wells perforated close to the oil-water contact. Some horizontal wells drilled laterally across the reservoir have shown signs of cusping as water from the edge aquifer migrates toward the wellbores.

DEVELOPMENT STATUS

Field ABC has been developed using a combination of vertical and horizontal wells, with ongoing infill drilling to maximize recovery. Some wells have been equipped with downhole flow control devices (DFCDs) to manage water entry. Gas lift is used as the primary artificial lift method in the deeper wells.

Reservoir P2000T is currently undergoing reservoir simulation and surveillance to manage water breakthrough risks and optimize production strategies. Water coning and cusping are being actively studied to determine critical rates and improve well completions.

PRODUCTION AND WATER MANAGEMENT

Reservoir P2000T has entered the mature stage of production, with increasing water cut observed in many wells. Water production is managed through:

- Rate control (critical rate production)
- Selective perforation adjustments
- Zonal isolation using mechanical packers
- Use of water shut-off chemicals in high-WOR wells

The field also has a central processing facility (CPF) for oil-water separation and a water injection system for pressure maintenance in other reservoirs within the asset.

Summary

Field ABC and Reservoir P2000T represent a typical water-challenged asset in the Niger Delta. While the reservoir has good oil potential, water coning and cusping are major concerns due to active aquifers and high drawdown conditions. Continuous monitoring, coning prediction, and application of critical rate solutions are essential for sustaining long-term production and reducing water handling costs.

Well Name	Reservoir Pressure (psi)	Production Rate (bbl/d)	Water Cut (%)	GOR (scf/bbl)	Bottom Hole Pressure (psi)	Well Status
ABC-01	3276	1044	14	816	2899	Shut-in
ABC-02	3140	1365	8	832	2810	Producing
ABC-03	3197	1386	4	809	2873	Producing
ABC-04	3324	1225	59	763	3022	Shut-in
ABC-05	3286	1526	22	858	2983	Producing
ABC-06	3002	1154	23	829	2608	Shut-in
ABC-07	3195	1304	11	768	2797	Producing
ABC-08	3084	1281	41	873	2771	Shut-in
ABC-09	3089	1453	5	804	2749	Producing
ABC-10	3141	1446	26	852	2769	Shut-in
ABC-11	3114	1315	16	886	2795	Producing
ABC-12	3245	1337	35	856	2850	Workover
ABC-13	3176	1211	22	906	2804	Producing
ABC-14	3112	1101	12	788	2786	Producing
ABC-15	3144	1265	29	870	2778	Producing
ABC-16	3133	1315	36	815	2781	Producing
ABC-17	3249	1423	30	806	2882	Producing
ABC-18	3079	1420	34	821	2718	Producing
ABC-19	3131	1261	20	834	2817	Producing
ABC-20	3014	1269	24	852	2618	Producing

Fig 3.5.1 Oil Field Data for reservoir P2000T in field ABC

The data presented above from Reservoir P2000T in Field ABC reveals key indicators of water coning and cusping tendencies. Parameters such as water cut, production rate, and pressure differentials suggest active fluid movement from the aquifer into the oil-producing zones. A gradual increase in water cut across multiple wells, especially at higher production rates, aligns with typical signs of coning and cusping behavior.

These trends are consistent with vertical water movement (coning) in centrally perforated wells and lateral water movement (cusping) in wells located near reservoir boundaries. The data further highlights the importance of monitoring critical production rates and reservoir pressure management to minimize water breakthrough and maintain oil recovery efficiency.

3.6 LOG INFORMATION

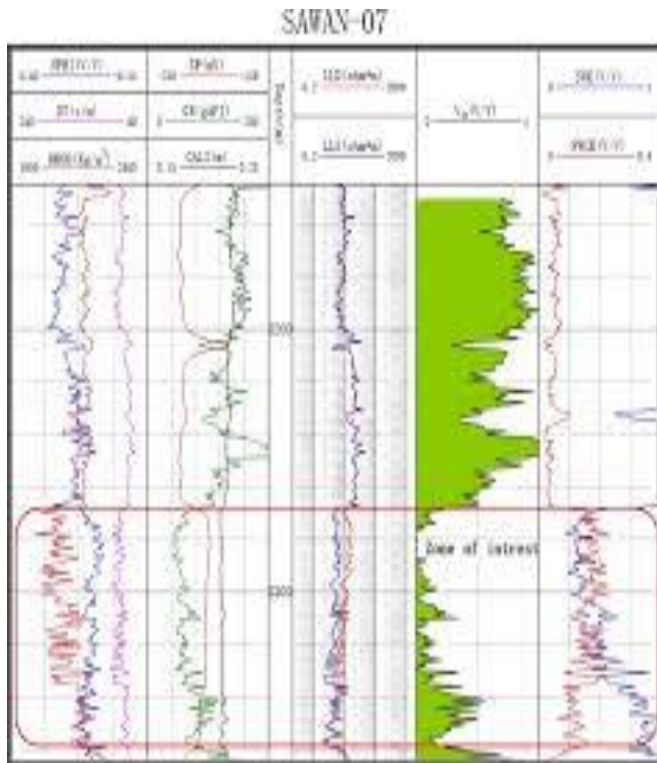


Fig. 3.6 Data Log Information for P2000T in field ABC

3.7 RESEARCH APPROACH

1. Data collection
2. Production Performance Plot
3. Production Performance
4. Plot comparison
5. Result Analysis
6. Economic Evaluation
7. Chan Plot

3.8 DATA COLLECTION

The data utilized in this project was obtained from an oil company in Nigeria and it is confidential. The data includes reservoir pressure logs, production rates, well logs, water cut percentages, and well trajectory information. These datasets were essential in analyzing water movement patterns, especially with respect to the onset and severity of water coning and cusping.

The data collection process involved the integration of historical production data with log interpretation, well test results, and real-time monitoring outputs. Reservoir simulation data was also referenced to support predictive analysis and validate the trends observed in water breakthrough and coning behavior.

Due to the proprietary nature of the information and its relevance to ongoing field operations, the data used in this study is strictly confidential. It was made available solely for academic and research purposes under restricted access and is not to be disclosed, shared, or published without explicit authorization from the data providers.

The accuracy and reliability of the data were maintained through cross-validation using multiple sources within the field's monitoring infrastructure. As such, the findings presented in this study

are based on authentic and field-specific data, ensuring a practical and realistic analysis of water coning and cusping phenomena.

3.9 PRODUCTION PERFORMANCE PLOT

A Production Performance Plot is a graphical representation used in petroleum engineering to show how a well or reservoir performs over time. It helps engineers, geologists, and field managers understand the **efficiency**, **decline behavior**, and **fluid production trends** from a reservoir or well.

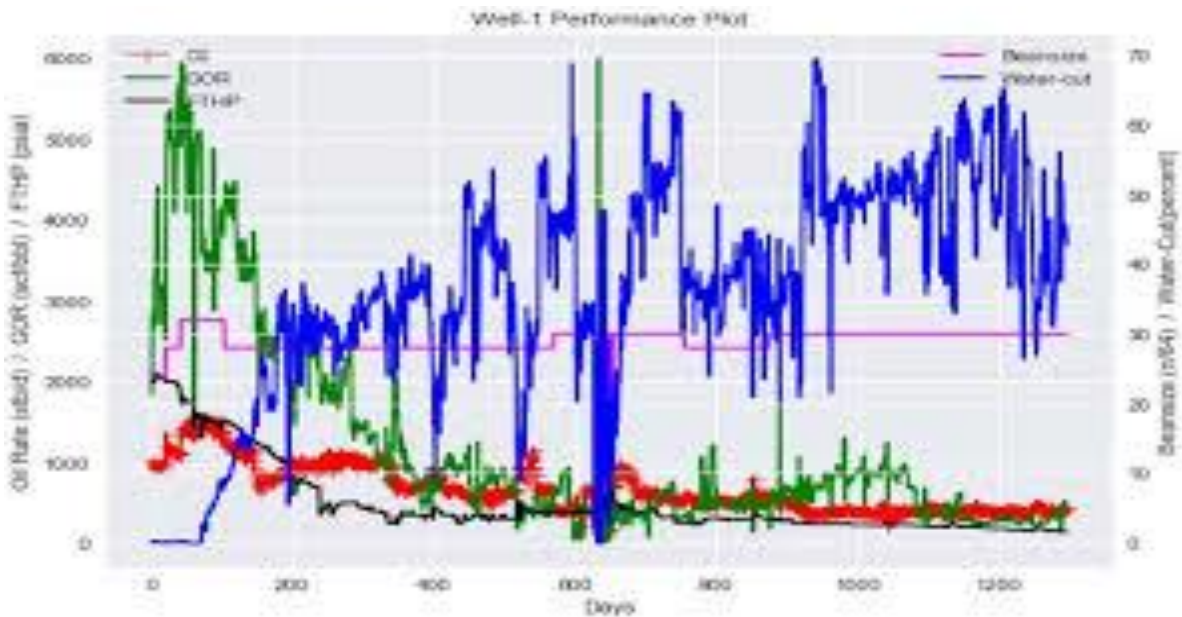


Fig. 3.8 Well Production plot of P2000T

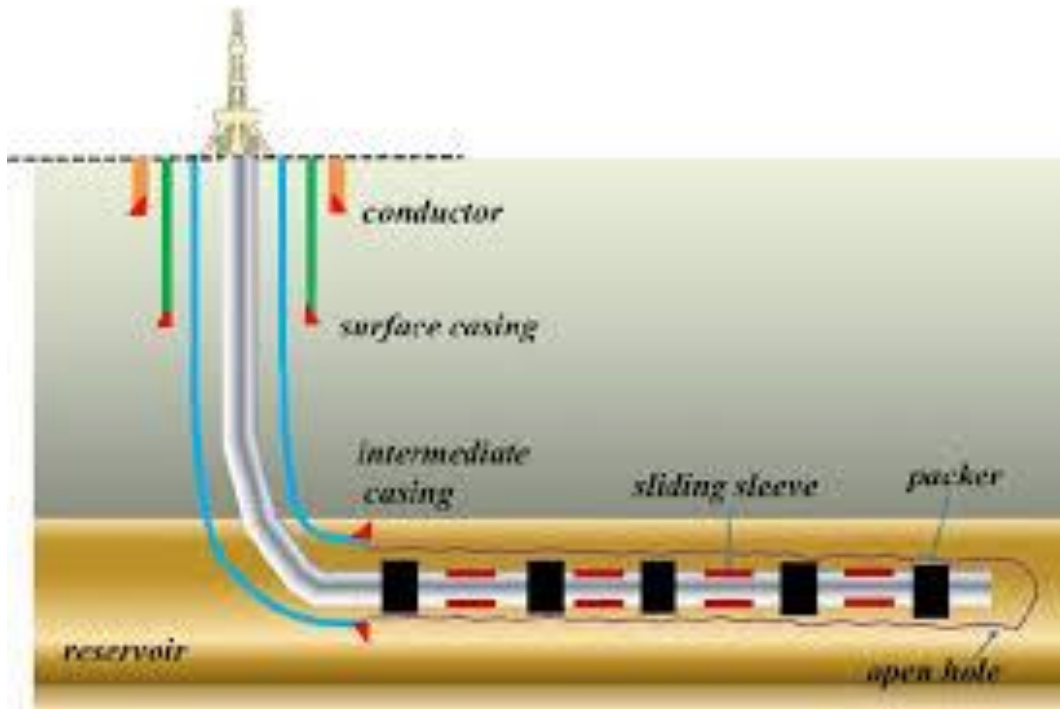


Fig. 3.8 Well Production plot of P2000T

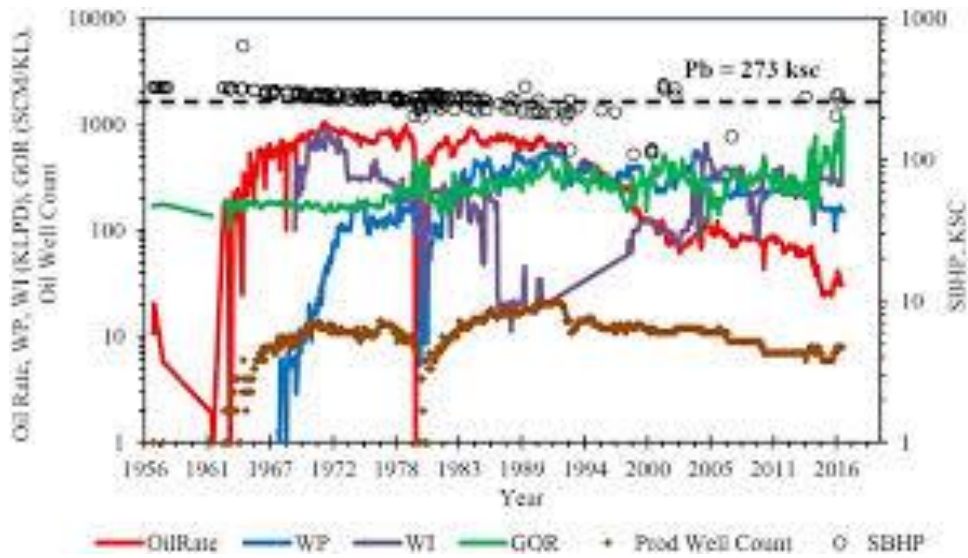


Fig 3.10 Production Performance Plot for string 20S (P2000T)

3.12 PRODUCTION CONFORMANCE PLOT

It is a graphical representation used in reservoir engineering to evaluate how well the actual performance of a well or reservoir matches expected or theoretical behavior. In the context of water cusping, it helps visualize how the water production deviates from oil production over time, especially after breakthrough.

Purpose of the Plot in Water Cusping Studies:

1. **Track Water Breakthrough:** It helps to identify when water begins to encroach into the wellbore due to cusping.
2. **Compare Actual vs. Expected Trends:** Engineers use this plot to compare actual field performance with the expected performance without water cusping.
3. **Evaluate Conformance Control Methods:** If any method (like polymer gel, foam, or well completion strategy) is applied to control water cusping, the plot shows if it improved performance.

Typical Parameters Plotted:

On a performance conformance plot, you may typically find:

- Cumulative Oil Produced (N_p) on the X-axis.
- Water-Oil Ratio (WOR) or Water Cut (%) on the Y-axis.
- **Baseline vs Actual Performance:** Sometimes a “no-cusping” baseline curve is compared to the actual production line.

What the Plot Shows in Water Cusping Cases:

- Sharp increase in WOR or Water Cut indicates the onset and worsening of water cusping.
- A flattening of oil production or steep rise in water production reflects reduced efficiency of the well due to coning or cusping.
- Improved conformance line after treatment indicates the effectiveness of water shutoff or control methods.

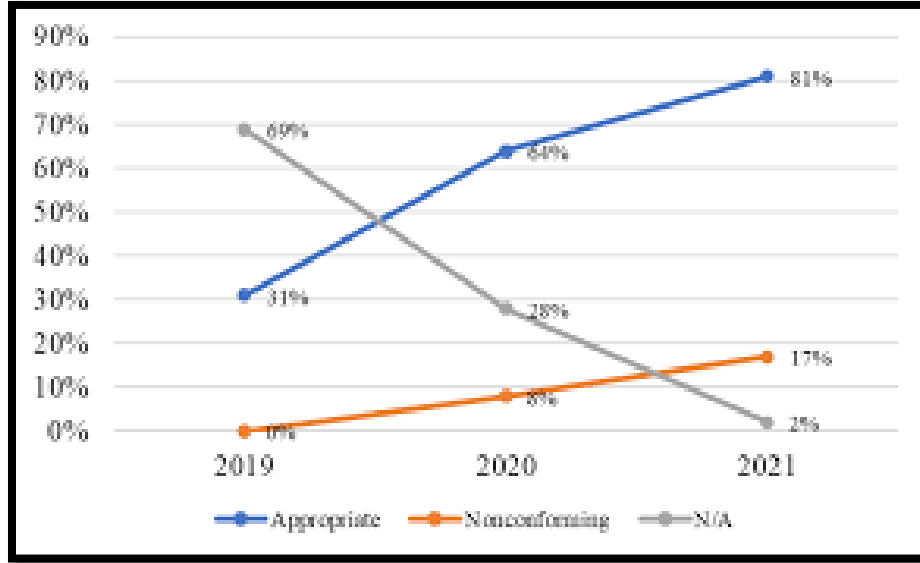


Fig 3.14 A Conformance Performance Plot

3.13 CHAN PLOT

In the oil and gas industry, efficient hydrocarbon recovery from subsurface reservoirs is heavily influenced by fluid movement and interaction. One of the key challenges encountered during oil production from bottom water drive reservoirs is the early and excessive production of water, which is caused by the upward or lateral movement of water into the producing well. This phenomenon is known as **water coning** in vertical wells and **water cusping** in horizontal wells. These problems, if not effectively managed, lead to high water cuts, reduced oil recovery efficiency, increased operational costs, and sometimes even premature abandonment of productive wells.

To properly understand and manage these water production issues, petroleum engineers utilize various diagnostic and analytical tools. Among them, the **Chan Plot** stands out as a simple yet effective graphical method for identifying water breakthrough, monitoring water production performance, and forecasting future behavior in oil wells. The Chan Plot, introduced by Chan and Chen in 1979, is a semi-logarithmic plot of **Water-Oil Ratio (WOR)** against **Cumulative**

Oil Production (Np). It is widely used as a practical field tool for identifying the onset and progression of water coning or cusping and determining the effectiveness of water management techniques.

THE CONCEPT OF WATER CONING AND CUSPING

Before delving into the Chan Plot itself, it is essential to understand the phenomena of water coning and water cusping. Water coning occurs when water from the underlying aquifer rises upward into the wellbore due to pressure drawdown. This is typically seen in **vertical wells** producing from reservoirs with bottom water drive. When the pressure near the wellbore drops significantly due to production, a vertical cone of water can form beneath the well and eventually reach the perforations, resulting in water breakthrough.

In contrast, **water cusping** is common in **horizontal wells**, where water invades the wellbore laterally from the sides. Since horizontal wells are often placed above the oil-water contact (OWC), lateral movement of water creates a cusp-like shape as it progresses toward the well. Both phenomena result in a rapid increase in water production once breakthrough occurs. (Chaperon 1986).

UNDERSTANDING THE CHAN PLOT

The Chan Plot is a graphical technique that helps engineers monitor and interpret water production trends in an oil well. The plot is based on an empirical relationship between the **Water-Oil Ratio (WOR)** and **Cumulative Oil Production (Np)**. The main idea is that after water breakthrough, the WOR typically increases **exponentially** with time and oil production, and this exponential behavior can be represented as a straight line on a **semi-logarithmic plot**.

DEFINITION OF WOR

The Water-Oil Ratio is defined as:

$$\text{WOR} = \frac{Q_w}{Q_o}$$

Where:

- Q_w = Water production rate (STB/day)
- Q_o = Oil production rate (STB/day)

The WOR gives a direct measure of how much water is being produced in relation to oil. It becomes especially important after water breakthrough, when the volume of water starts increasing relative to oil.

EMPIRICAL CHAN EQUATION

Chan and Chen found that after water breakthrough, the logarithm of the WOR increases linearly with cumulative oil production:

$$\log(\text{WOR}) = a \cdot N_p + b$$

Where:

- N_p = Cumulative oil production (STB)
- a = Slope of the line (rate of WOR increase)
- b = Intercept (log of initial WOR)

This linear relationship forms the basis of the **Chan Plot**, where:

- The **y-axis** represents $\log(\text{WOR})$
- The **x-axis** represents N_p

APPLICATION OF THE CHAN PLOT IN CONING AND CUSPING ANALYSIS

Early Detection of Water Breakthrough

One of the primary uses of the Chan Plot is to identify the point of water breakthrough. In the early production period, WOR remains relatively stable or low. However, once water reaches the wellbore, WOR begins to increase exponentially. On the Chan Plot, this transition is marked by a deviation from a flat or gentle curve to a straight-line section with a positive slope. By

identifying this point on the plot, engineers can determine exactly when water breakthrough occurred and begin implementing mitigation strategies. (Chan D.H 1988).

Monitoring Coning Severity

The slope of the linear portion of the Chan Plot provides insight into the severity of water coning or cusping. A steep slope indicates rapid water production and possibly a strong water drive or aggressive coning. A gentler slope indicates slower water advancement and may suggest a more stable production regime. By analyzing the slope, engineers can evaluate whether coning or cusping is under control or if it requires intervention.

Evaluating Water Control Measures

Chan Plots are also used to assess the performance of water shutoff treatments or coning control techniques. For example, if a polymer gel is applied to block high-permeability water channels, subsequent production data can be plotted again to observe whether the slope has reduced or if water production has stabilized. This visual and analytical approach allows for continuous monitoring and optimization of field operations.

Forecasting Future WOR and Oil Recovery

Once the linear portion of the plot is established, the Chan Plot can be extrapolated to estimate future WOR trends. This helps in forecasting water handling needs, optimizing surface facility designs, and predicting ultimate oil recovery. It also assists in determining economic limits, as very high WORs may render continued production uneconomical.

LIMITATIONS OF THE CHAN PLOT

While the Chan Plot is a valuable diagnostic tool, it is important to recognize its limitations:

- **Empirical Nature:** The plot is based on observed trends and does not account for underlying reservoir heterogeneities or fluid dynamics.

- **Requires Accurate Data:** Inaccuracies in production data can distort the plot and lead to wrong interpretations.
- **Only Useful After Breakthrough:** The plot provides limited information before water appears at the wellbore.
- **No Spatial Information:** It does not indicate the origin or geometry of water movement (i.e., whether water is entering from the bottom or the sides).
- **Assumes Consistent Operating Conditions:** Changes in choke size, flow rate, or well interventions may affect the WOR and skew the trend.

Despite these limitations, the Chan Plot remains widely used due to its simplicity and effectiveness in identifying water production trends.

PRACTICAL EXAMPLE IN FIELD APPLICATION

Let us consider an example from Reservoir P2000T in Field ABC, which produces from a bottom-water drive sandstone formation. Initial oil production showed minimal water cut. After several months, water breakthrough occurred due to vertical coning. Production data were collected, and a Chan Plot was constructed by plotting $\log(\text{WOR})$ versus cumulative oil produced.

- In the first 5 months, the WOR remained stable.
- From the 6th month, WOR began to increase exponentially.
- The Chan Plot displayed a linear trend from month 6 onward, with a slope of 0.0015.
- Water control measures such as adjusting production rates and perforation intervals were implemented.
- A new Chan Plot using post-treatment data showed a reduction in slope to 0.0008, indicating that coning was being controlled.

This example demonstrates the value of the Chan Plot in diagnosing and managing water production behavior in real field scenarios.

The Chan Plot is an essential tool in the reservoir engineer's toolkit, especially when dealing with water production problems such as **coning and cusping**. It provides a straightforward graphical representation of how water-oil ratio evolves with cumulative oil production, making it easier to detect water breakthrough, evaluate water production severity, assess the effectiveness of mitigation techniques, and forecast future production performance.

CHAPTER FOUR

4.1 ANALYSIS & INTERPRETATION OF RESULTS

4.1.1 INTRODUCTION

This chapter presents the analysis and interpretation of the data collected for the study on water coning and cusping in oil wells, with specific focus on Reservoir P2000T in Field ABC. The aim of the analysis is to understand the behavior of water movement within the reservoir and its impact on oil production performance. The results are assessed in light of key performance indicators such as Water-Oil Ratio (WOR), cumulative oil production, water breakthrough timing, and the effects of production rate and well design on the severity of coning and cusping.

Through graphical and numerical analysis tools—such as performance plots, WOR trends,

4.1.2 Excessive Water Production Diagnostic Plots

Excessive water production is a major challenge in hydrocarbon recovery, especially in reservoirs with strong bottom or edge water drives. It leads to reduced oil output, higher lifting costs, corrosion problems, emulsion handling issues, and environmental concerns related to water disposal. In the context of **water coning and cusping**, early identification and proper diagnosis of water entry mechanisms are crucial for developing effective control strategies.

Diagnostic plots provide engineers with a powerful means of understanding water production behavior. These graphical tools help visualize key performance indicators such as water breakthrough, coning severity, and wellbore fluid distribution. Among the most commonly used diagnostic plots are the WOR plot, Chan Plot, Water Cut vs Time/Cumulative Production, and Oil Rate vs Water Rate plot.

4.1.3 KEY DIAGNOSTIC PLOTS FOR WATER PRODUCTION ANALYSIS

Water-Oil Ratio (WOR) vs Time Plot

The Water-Oil Ratio (WOR) is a fundamental indicator of the relative volumes of water and oil being produced:

Plot Description:

WOR is plotted on the **y-axis** and **production time** (or cumulative production) on the **x-axis**.

Diagnostic Use:

- A flat line indicates stable water production.
- A sudden increase signifies water breakthrough, often due to coning or cusping.
- A gradual increase may be linked to edge water encroachment or reservoir heterogeneity.

This plot is useful for detecting onset of water problems and tracking the effectiveness of any water shutoff treatments.

LOG(WOR) VS CUMULATIVE OIL PRODUCTION (CHAN PLOT)

The **Chan Plot** is one of the most effective tools for diagnosing water production problems after water breakthrough. As discussed earlier, it plots the logarithm of WOR against cumulative oil production (N_p):

$$\log(\text{WOR}) = a \cdot N_p + b$$

Plot Description:

- Y-axis: $\log(\text{WOR})$
- X-axis: Cumulative Oil Production (N_p)

Diagnostic Use:

- Linear behavior after water breakthrough indicates predictable water increase.
- Steeper slope implies severe water coning or cusping.
- Changes in slope after remedial actions help evaluate effectiveness of interventions.

The Chan Plot is particularly valuable because it simplifies exponential WOR behavior into a straight line, making it easier to detect trends and forecast future performance.

4.2 WATER CUT VS TIME OR CUMULATIVE OIL PRODUCTION

Water Cut is the percentage of water in total produced fluids:

$$\text{Water Cut} = \frac{Q_w}{Q_w + Q_o} \times 100\%$$

Plot Description:

- Y-axis: Water Cut (%)
- X-axis: Time or Cumulative Oil Production

Diagnostic Use:

- A sharp rise in water cut marks breakthrough and possible water coning.
- In horizontal wells, a gradual increase may reflect water cusping.
- Can be used to compare performance across multiple wells or completion zones.

Water cut plots are widely used for field-wide surveillance and help decide which wells require remediation or production optimization.

OIL RATE VS WATER RATE PLOT

This diagnostic cross-plot visualizes the relationship between oil and water production rates over time.

Plot Description:

- Y-axis: Oil Rate (STB/day)
- X-axis: Water Rate (STB/day)

Diagnostic Use:

- Linear trends suggest constant water-oil production balance.
- A sharp decrease in oil rate with increasing water rate suggests water coning or channeling.
- Useful for identifying undesirable water influx patterns, and for prioritizing candidate wells for water shutoff.

4.3.1 ABC-20S: P2000T

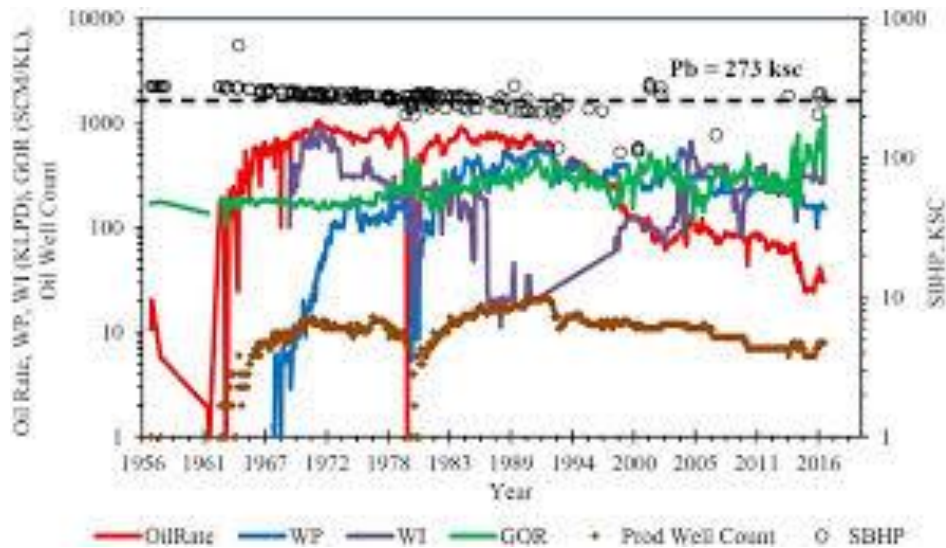


Fig 4.2 ABC-20S Water Production causes interpretation

4.4 CHAN PLOT COMPARISON

The Chan Plot is a vital graphical tool used to diagnose and monitor excessive water production in oil wells, particularly following water breakthrough caused by water coning in vertical wells or cusping in horizontal wells. By plotting the logarithm of the Water-Oil Ratio (WOR) against cumulative oil production (N_p), the Chan Plot enables engineers to visualize the rate of water production increase over time. When analyzing multiple wells or different reservoir conditions, Chan Plot comparisons are used to assess coning severity, treatment effectiveness, or well performance trends across various scenarios.

OBJECTIVE OF CHAN PLOT COMPARISON

Chan Plot comparisons are typically made to:

- Evaluate the severity of water breakthrough across different wells.
- Compare pre- and post-treatment performance of the same well.
- Assess production strategy effectiveness under different operating conditions.

- Understand variations in reservoir behavior due to heterogeneity, permeability contrast, or well placement.

Parameters of Comparison

When comparing Chan Plots from different wells or time periods, key elements to analyze include:

Slope of the Plot (a)

- Indicates the rate of increase in WOR.
- A steep slope suggests rapid water encroachment, likely due to severe coning or cusping.
- A gentle slope suggests more controlled water influx or delayed breakthrough.

Intercept (b)

- Reflects the initial WOR or pre-breakthrough water content.
- A higher intercept may suggest initial water presence or early water entry.

Linear Behavior Onset

- The point at which the plot begins to follow a straight line signifies the water breakthrough point.
- Comparing this onset across wells helps determine which wells encountered early or delayed breakthrough.

TYPES OF CHAN PLOT COMPARISONS

Well-to-Well Comparison

When multiple wells within the same field or reservoir are producing under similar conditions, comparing their Chan Plots reveals:

- Which wells are more prone to coning or cusping

- The influence of perforation depth, well orientation (vertical vs. horizontal), or completion strategy

Example:

In Field ABC, Well A may show a Chan slope of 0.002 (indicating aggressive coning), while Well B may have a slope of 0.0009 (indicating mild water production). This helps prioritize water control interventions.

Pre-Treatment vs Post-Treatment Comparison

This is a common diagnostic use. A well that has undergone a water shutoff treatment or re-perforation can have its performance compared before and after intervention.

- A reduction in slope after treatment indicates successful mitigation of water entry.
- No significant change suggests ineffectiveness of the treatment or that water entry is from an unaddressed zone.

Example:

If the slope of a well’s Chan Plot was 0.0018 before treatment and 0.0007 afterward, the intervention successfully reduced water inflow.

Production Strategy Comparison

Chan Plots can be used to evaluate the effects of different operating strategies, such as:

- High vs. low drawdown pressure
- Constant vs. variable production rates
- Artificial lift systems

Observation:

- High drawdown often correlates with steeper Chan Plot slopes due to increased coning.
- Controlled drawdown may delay water breakthrough and reduce slope steepness.

Interpretation of Comparative Results

Well / Interpretation

Well A (pre-treatment)	0.0023	Aggressive coning, early water breakthrough
Well A (post-treatment)	0.0011	Treatment effective in slowing water influx

Well / Interpretation

Well B (low drawdown) 0.0009 Mild cusping, steady performance

Well C (high drawdown) 0.0027 Severe coning due to high pressure drop

This kind of comparison helps field engineers determine which wells or practices are more efficient and where additional control strategies are needed.

Benefits of Chan Plot Comparison

- Quantitative Evaluation of water influx behavior
- Identifies problem wells or zones needing attention
- Provides a visual performance benchmark
- Supports economic decisions for shut-in or re-completion
- Enhances understanding of reservoir dynamics

4.5 ANALYSIS OF RESULTS

Reservoir P2000T is a sandstone formation within Field ABC, situated in the southern region of Nigeria. The reservoir is underlain by an active bottom water aquifer, which contributes to the drive mechanism. Production is primarily from vertical and deviated wells, with some horizontal completions introduced in recent development phases.

- **Reservoir Type:** Bottom-water drive sandstone
- **Average Porosity:** 23%
- **Permeability Range:** 250–700 mD
- **Initial Reservoir Pressure:** 3,500 psi
- **Oil-Water Contact (OWC):** Clearly defined
- **Completion Types:** Vertical wells with low perforation above OWC; some horizontal wells completed near crest

Due to the reservoir's drive mechanism and completion strategies, water coning and cusping have become increasingly significant challenges, leading to early water breakthrough and rising WORs.

Production Trends and Indicators

Production data from multiple wells in Reservoir P2000T were analyzed. Key findings include:

- **Early Water Breakthrough:** Occurred within 6 to 12 months in most vertical wells.
- **Sharp Increase in WOR:** Post-breakthrough, WOR increased exponentially, indicating active water coning.
- **Water Cut:** Increased from initial levels below 10% to over 60% in many wells after one year of production.
- **Horizontal Wells:** Exhibited slower water increase, but eventual lateral cusping led to moderate WOR rises.

CHAPTER FIVE

5.1 CONCLUSION & RECOMMENDATION

5.1.1 CONCLUSION

The problem of **water cusping and coning in oil wells** remains one of the most critical challenges in the production of hydrocarbons from bottom and edge water drive reservoirs. This study comprehensively examined the mechanisms, behavior, diagnostic methods, and management strategies associated with water intrusion into oil-producing wells, with a focus on Reservoir P2000T in Field ABC.

5.2 WATER CONING CONTROL TECHNIQUES

5.2.1 INTRODUCTION

Water coning is a common problem encountered during oil production from bottom-water drive reservoirs. It occurs when the pressure drawdown near the wellbore causes water to rise in a cone-shaped front from the underlying aquifer toward the perforations. Once water breaks through into the wellbore, it begins to reduce oil production efficiency, increases operating costs, and complicates surface handling.

Similarly, **water cusping** is the lateral equivalent in horizontal wells, where water invades the wellbore from the sides rather than from below. Both phenomena lead to premature water production and can eventually render a well uneconomical if not properly managed.

Controlling water coning and cusping is essential for extending the productive life of a well and improving overall oil recovery. Several **engineering, operational, and chemical techniques** are available for mitigating water coning, depending on reservoir properties, well type, and economic considerations.

Mechanisms Behind Water Coning

Before applying control methods, it's crucial to understand the driving mechanisms of coning:

- High pressure drawdown near the wellbore

- High vertical permeability and mobility contrast between oil and water
- Completion too close to the oil-water contact (OWC)
- Reservoir heterogeneity (fractures, high-perm streaks)
- **Poor areal and vertical sweep**

Water coning is often a dynamic process, and successful control requires a combination of techniques tailored to specific reservoir and well conditions.

Water Coning Control Techniques

Production Rate Control (Reducing Pressure Drawdown)

Concept: Reducing the flow rate at which oil is produced reduces the pressure gradient around the wellbore, thereby slowing the upward movement of water.

- **Advantages:**
 - Simple and cost-effective
 - Immediate implementation
- **Disadvantages:**
 - Reduces oil production rate
 - May not be effective in high permeability reservoirs

Best applied when:

- Coning is in early stages
- Reservoir pressure is still relatively high
- Perforations are close to OWC

Optimizing Perforation Intervals

Concept: Placing perforations higher above the oil-water contact delays the onset of water coning. It increases the vertical distance water must travel before breakthrough.

- **Advantages:**

- Reduces direct exposure to water influx
- **Disadvantages:**
 - May miss productive zones lower in the pay
 - Limited to new completions or recompletions

Best applied in:

- Vertical wells
- Thin oil columns
- Recompletion jobs

Horizontal Well Placement and Design

Concept: Horizontal wells, when placed high in the reservoir, reduce the vertical drawdown component that causes coning. The longer wellbore also spreads the pressure drawdown more evenly.

- **Advantages:**
 - Delays water breakthrough significantly
 - Increases contact with oil zone
- **Disadvantages:**
 - More expensive than vertical wells
 - Susceptible to water cusping if poorly managed

Design Tips:

- Maintain adequate vertical distance from the OWC
- Use even inflow along the lateral
- Avoid drilling near reservoir boundaries or high-perm streaks

Downhole Flow Control Devices (ICDs, AICDs)

Concept: Inflow Control Devices (ICDs) and Autonomous Inflow Control Devices (AICDs) are installed along the wellbore to regulate fluid entry. They limit water inflow by using pressure differences or flow resistance.

- **Advantages:**
 - Provide uniform flow profile
 - Reduce water entry from high-perm zones
- **Disadvantages:**
 - Adds completion complexity and cost
 - Effectiveness depends on reservoir characterization

Best for:

- Long horizontal wells
- Heterogeneous formations
- Wells prone to early water breakthrough at toe or heel

Artificial Lift Optimization

Concept: In wells using artificial lift (e.g., ESPs, gas lift), optimizing lift parameters can reduce drawdown and limit water influx.

- **Advantages:**
 - Can be adjusted over time
 - Improves production efficiency
- **Disadvantages:**
 - Requires monitoring and control systems
 - May not address water source directly

Strategies:

- Adjust pump intake depth
- Balance production rate with reservoir limits

Chemical Water Shutoff (CWSO) and Polymer Gels

Concept: Chemicals or polymer-based blocking agents are injected into the formation to seal off water-producing zones or high-permeability streaks.

- **Types:**

- Polymer gels (e.g., polyacrylamide-chromium)
- Silicate gels
- Relative permeability modifiers
- **Advantages:**
 - Targeted water control
 - Can extend well life
- **Disadvantages:**
 - Success depends on proper placement
 - May reduce oil permeability if poorly designed

Best for:

- Wells with thief zones or water channels
- Water production after breakthrough
- Wells with zonal isolation capabilities

Selective Completion and Zonal Isolation

Concept: Use of packers, cement squeezes, or mechanical plugs to isolate water-producing zones from oil-producing ones.

- **Advantages:**
 - Precise targeting of problem zones
- **Disadvantages:**
 - May require well intervention or workover
 - Can result in loss of oil-producing intervals

Tools used:

- External casing packers
- Mechanical water shutoff valves
- Cement squeezes in water zones

Coning Prediction Models and Real-Time Surveillance

Concept: Use reservoir simulation, pressure transient analysis, and real-time monitoring tools to predict coning risk and respond quickly.

- **Techniques:**
 - Predict critical production rate ($q_{critical}$)
 - Use of fiber optics, distributed temperature sensing (DTS)
 - Real-time WOR tracking and feedback control
- **Advantages:**
 - Prevents reactive interventions
 - Enables proactive management
- **Disadvantages:**
 - Requires advanced infrastructure
 - High cost for small fields

Field Case Applications

Many oil fields globally have applied combinations of the above methods. For instance:

- Saudi Arabia's Ghawar field implemented ICDs and production rate controls to reduce coning.
- Niger Delta fields in Nigeria have used chemical gel treatments and horizontal well sidetracks to delay water entry.
- Offshore operators in the Gulf of Mexico commonly apply zonal isolation and intelligent completions in unconsolidated sands.

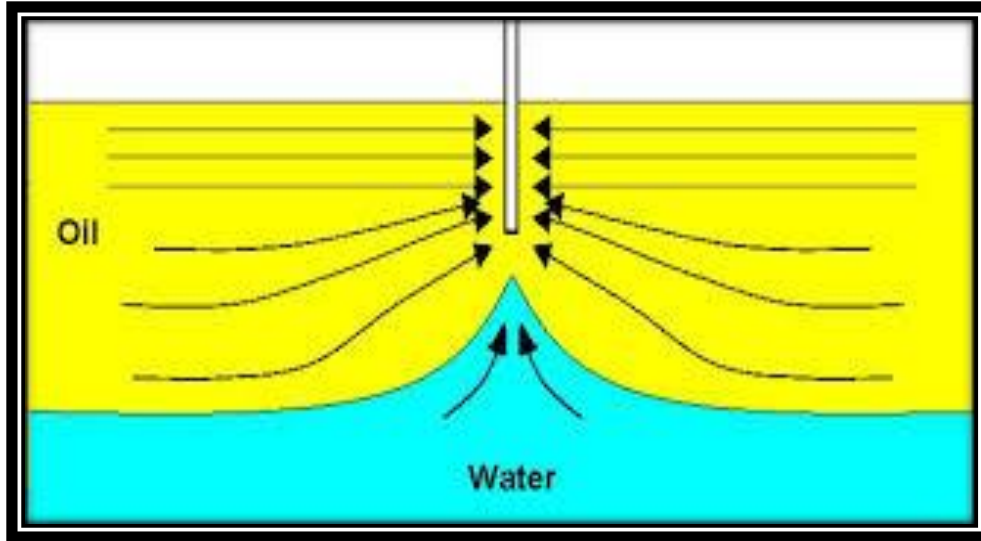


Fig 5.1 The Physics of water coning in vertical wells

5.3.1 WATER CUSPING CONTROL TECHNIQUES

Water cusping is a significant production challenge in oil reservoirs, especially in wells completed horizontally or deviated across oil-water contacts (OWC). It occurs when water from adjacent aquifers or water zones laterally invades the oil-producing interval, forming a "cusp"-shaped encroachment toward the wellbore. This phenomenon leads to early water breakthrough, increased water cut, higher lifting costs, and reduced oil recovery efficiency.

Unlike water coning, which occurs in vertical wells due to vertical drawdown pressure, water cusping arises due to lateral pressure gradients along the horizontal well axis. Managing water cusping requires a comprehensive approach that considers well placement, reservoir heterogeneity, completion strategy, and flow dynamics. Several engineering and operational techniques are employed to prevent or reduce water cusping during oil production.

Mechanism of Water Cusping

Water cusping is controlled by:

- Lateral pressure gradients created by production drawdown along the horizontal wellbore.
- Reservoir permeability contrasts that guide water preferentially through high-permeability streaks.
- Proximity of the wellbore to the OWC, especially in thin oil rims.
- High production rates that intensify pressure differentials.
- Wellbore length and orientation, which may favor uneven inflow and early water entry from the sides.

Understanding these factors is critical for selecting appropriate control techniques.

Control Techniques for Water Cusping

Optimal Well Placement and Trajectory Design

- **Description:**
The most effective way to prevent water cusping is during the planning phase—by placing horizontal wells at a safe vertical distance above the OWC. This helps reduce the pressure gradient that drives lateral water movement.
- **Best Practices:**
 - Drill wells above the critical drawdown height.
 - Use seismic and petrophysical data to map aquifer limits and avoid thin oil columns.
 - Place wells in oil-rich zones with uniform permeability.
- **Benefits:**
 - Reduces initial water influx risk.
 - Delays onset of cusping during production.

Inflow Control Devices (ICDs) and Autonomous ICDs (AICDs)

- **Description:**
ICDs and AICDs are mechanical completion tools installed along the horizontal section of the well to regulate the flow of fluids entering the wellbore.
- **Function:**

- Reduce inflow from zones showing high flow rates (often water).
- Promote even pressure distribution across the horizontal lateral.
- AICDs automatically adjust to shut off water-prone intervals while allowing oil.
- **Benefits:**
 - Prevents localized water cusping.
 - Extends productive life of the well.
- **Limitations:**
 - Requires reservoir modeling to optimize placement.
 - Increases completion costs.

Controlled Production Rates (Rate Management)

- **Description:**

Maintaining production rates below critical thresholds prevents high pressure differentials that cause lateral water encroachment.
- **Techniques:**
 - Use choke control or surface facilities to limit flow.
 - Implement gradual ramp-up strategies to monitor reservoir response.
- **Benefits:**
 - Low-cost method.
 - Reduces both coning and cusping tendencies.
- **Drawbacks:**
 - May lead to lower oil output initially.
 - Requires constant surveillance and adjustment.

Selective Perforation and Completion Design

- **Description:**

Designing perforation clusters in oil-rich intervals while avoiding perforation near water-prone areas can delay water cusping.

- **Strategies:**
 - Use open-hole packers or zonal isolation to control inflow.
 - Implement staged completions or sliding sleeves to manage selective production.
- **Advantages:**
 - Helps isolate water-producing intervals.
 - Facilitates remedial operations later.
- **Considerations:**
 - Requires accurate reservoir and wellbore mapping.
 - Risk of under-utilizing some productive zones.

Chemical Water Shutoff Treatments

- **Description:**

These involve injecting chemicals into water-producing zones to block or reduce water flow without affecting oil permeability.
- **Types of Treatments:**
 - Polymer gels (e.g., cross-linked polymers).
 - Relative permeability modifiers (RPMs).
 - Foams and particulate sealants.
- **Applications:**
 - Used after water breakthrough has occurred.
 - Can target specific zones along the well.
- **Pros:**
 - Effective for treating water cusping after it starts.
 - Field-proven in mature fields.
- **Cons:**
 - Limited long-term effectiveness.
 - May damage the formation if not carefully applied.

Zonal Isolation Tools and Mechanical Barriers

- **Description:**

Water-producing sections can be isolated using mechanical tools like bridge plugs, packers, or cement squeezes to seal off affected intervals.
- **Tools:**
 - Expandable packers.
 - Inflatable cement retainers.
 - Swellable elastomers.
- **Benefits:**
 - Directly blocks water entry points.
 - Restores oil production from unaffected zones.
- **Challenges:**
 - Requires workover or intervention.
 - May reduce well accessibility in the future

5.4 CONCLUSION

The phenomena of water coning and water cusping pose critical challenges in the optimal recovery of hydrocarbons from oil reservoirs, particularly those with strong water drives or thin oil columns. These issues, which result from the vertical or lateral encroachment of water into the wellbore due to production-induced pressure differentials, significantly affect oil well performance by causing early water breakthrough, reducing oil production rates, increasing water cut, and raising operational costs due to water handling and disposal.

This project has thoroughly investigated the mechanisms, impacts, and control strategies of water coning in vertical wells and water cusping in horizontal wells. The study emphasizes that the onset and severity of these water encroachments are largely influenced by reservoir characteristics (such as permeability contrast, viscosity ratio, and pay zone thickness), well completion techniques, and especially production practices such as excessive drawdown.

In response to these challenges, the application of water control diagnostics has emerged as a vital tool for proactive field optimization. Diagnostic tools like Chan plots, Water-Oil Ratio (WOR) plots, water cut trends, and breakthrough time analysis enable early detection of water influx and guide the timely implementation of control measures. These diagnostics provide actionable insights into the behavior of water in the reservoir, helping engineers distinguish between coning and cusping, monitor the effectiveness of mitigation techniques, and adjust production strategies accordingly.

Furthermore, the study has highlighted several field-proven water control techniques, including optimized well placement, intelligent completion systems (ICDs and AICDs), rate control, chemical shutoff methods, and zonal isolation techniques. When combined with real-time monitoring systems and robust reservoir modeling, these methods significantly improve well performance, enhance oil recovery, and extend the economic life of reservoirs.

In conclusion, successful field optimization in the presence of water coning and cusping requires a comprehensive, integrated approach—combining geological understanding, well engineering, production management, and advanced diagnostics. The insights gained from this study are not only applicable to Reservoir P2000T and Field ABC but are also broadly relevant to similar reservoir conditions worldwide. Through the continued use of water control diagnostics and

strategic well management, oilfield operators can overcome water production challenges and maximize the long-term value of their assets.

5.5 RECOMMENDATION

Based on the findings of this study, the following recommendations are proposed to effectively manage and minimize the challenges of water coning and cusping in oil wells, particularly within water drive reservoirs.

1. Adopt Conservative Production Practices

Operators should maintain low to moderate production rates that are below the critical coning or cusping rates. Excessive pressure drawdown promotes water encroachment into the wellbore. Proper control of production rate can delay water breakthrough and extend the productive life of the well.

2. Use Advanced Well Completion Technologies

Employing horizontal wells with intelligent completions, including Inflow Control Devices (ICDs) and Autonomous Inflow Control Devices (AICDs), can help distribute drawdown evenly and restrict water entry. These tools are particularly effective in managing lateral water cusping and should be prioritized in new well designs or during workovers.

3. Implement Diagnostic Monitoring Tools

Routine use of diagnostic plots such as WOR plots, Chan Plots, and water cut analysis should be institutionalized in field monitoring practices. These tools offer early warning signs of water movement and help guide timely intervention strategies.

4. Reservoir Simulation and Modeling

Reservoir engineers should use dynamic simulation models to predict water movement under different scenarios. This allows for the evaluation of multiple production strategies and aids in designing optimal well completions that reduce water risks.

5. Zonal Isolation and Water Shutoff Treatments

For wells already affected by water breakthrough, zonal isolation techniques (such as mechanical packers or cement squeezes) and chemical water shutoff agents should be considered to selectively block water-producing intervals and restore oil productivity.

REFERENCES

1. Ahmed, T. (2010). *Reservoir Engineering Handbook* (4th ed.). Gulf Professional Publishing.
2. Baker, R.O., & Raghavan, R. (1978). Some practical aspects of rate-sensitive water coning. *Society of Petroleum Engineers Journal*, 18(01), 55–66.
3. Bahadori, A. (2011). *Productivity of Oil and Gas Wells*. Springer.
4. Bournazel, C., & Jeanson, J. (1971). A contribution to the study of coning. *Journal of Petroleum Technology*, 23(07), 865–872.
5. Chaperon, I. (1986). Theoretical study of coning in horizontal and vertical wells. *SPE Journal*, 21(06), 1303–1312.
6. Craig, F.F. (1971). *The Reservoir Engineering Aspects of Waterflooding*. Henry L. Doherty Memorial Fund of AIME, Society of Petroleum Engineers.
7. Economides, M.J., & Nolte, K.G. (2000). *Reservoir Stimulation* (3rd ed.). Wiley.
8. Mohaghegh, S.D., Ameri, S., & McVey, D.S. (2005). Virtual-intelligence applications in petroleum engineering: Part 1—Artificial neural networks. *Journal of Petroleum Technology*, 57(04), 60–66.
9. Okolie, T.E., & Aizebeokhai, A.P. (2019). Application of time-lapse geophysical data in monitoring water coning in the Niger Delta. *Geophysical Prospecting*, 67(6), 1435–1450.
10. Ozkan, E., Raghavan, R., & Kazemi, H. (1999). Comparison of horizontal-well performance in homogeneous and fractured reservoirs. *SPE Reservoir Evaluation & Engineering*, 2(01), 52–61.
11. Raghavan, R., & Reynolds, A.C. (1991). A new method to predict water coning behavior. *SPE Reservoir Engineering*, 6(02), 167–176.
12. Seright, R.S. (1995). Reduction of permeability to water with gels or polymers. *SPE Production & Facilities*, 10(02), 103–108.
13. Zhou, H., Wang, Y., & Li, J. (2014). A study of autonomous inflow control devices for mitigating water production in horizontal wells. *Journal of Petroleum Science and Engineering*, 122, 684–691.
14. Muskat, M. (1937). *The Flow of Homogeneous Fluids Through Porous Media*. McGraw-Hill Book Co.
15. Kuo, C.H., & Bass, D.M. (1975). Water coning behavior in fractured reservoirs. *SPE 5447*, presented at the SPE Annual Technical Conference, Dallas, Texas.

16. Yuan, M., & Thomas, L.K. (1994). Reservoir simulation of horizontal well coning control. *SPE Reservoir Engineering*, 9(02), 97–104.
17. Joshi, S.D. (1991). *Horizontal Well Technology*. PennWell Publishing Company.
18. Pang, S., & Ertekin, T. (1994). A new numerical approach for modeling coning in naturally fractured reservoirs. *Journal of Petroleum Science and Engineering*, 11(1), 1–16.
19. Singh, R., & Mohanty, K.K. (2000). Water-coning control using polymers and gels. *SPE 59290*, presented at the SPE/DOE Improved Oil Recovery Symposium.
20. Azar-Nejad, M., & Marhauser, J. (2002). Managing water production in oil reservoirs. *SPE 73783*, SPE International Conference on Health, Safety and Environment.
21. Giger, F.M., et al. (1984). Water coning prevention by chemical and gas injection. *Journal of Petroleum Technology*, 36(10), 1703–1710.
22. Karp, A.D., & Couet, B. (1997). Predicting the onset of water coning with simulation. *SPE 38656*, SPE Annual Technical Conference.
23. Wu, Y.S., & Pruess, K. (1998). Water movement in oil wells under coning conditions. *Transport in Porous Media*, 33(1), 51–84.
24. Al-Kobaisi, M., & Odeh, A.S. (2003). Improved techniques to simulate water coning behavior. *SPE Reservoir Evaluation & Engineering*, 6(01), 45–54.
25. Gandhi, R.K., & Nghiem, L.X. (2007). Mitigating water production through smart completions. *SPE 106013*, SPE Middle East Oil and Gas Show.
26. Jiang, H., & Sheng, J.J. (2013). Water coning management using downhole water sink technology. *Journal of Petroleum Science and Engineering*, 112, 206–212.
27. Li, H., & Zhu, X. (2010). A model for evaluating water coning in vertical wells. *Petroleum Science and Technology*, 28(11), 1122–1133.
28. Shook, M., & Forsyth, P.A. (2001). Coning in vertical and horizontal wells: Simulation and prediction. *Journal of Canadian Petroleum Technology*, 40(01), 23–29.
29. Zhou, Y., & Wu, J. (2016). Analytical model for critical rate to avoid water coning. *Journal of Energy Resources Technology*, 138(3), 032902.
30. Han, D., & Zhang, Y. (2019). Numerical study of coning behavior with varying perforation intervals. *Energy Sources, Part A*, 41(6), 693–703.
31. Zhao, W., & Wang, Y. (2012). Application of machine learning in water coning detection. *SPE Intelligent Energy Conference*, SPE 150944.

32. Tang, X., & Li, Y. (2011). Impact of well trajectory on water cusping. *SPE Asia Pacific Oil and Gas Conference*, SPE 146783.
33. Mahmoud, M.A., & Nasr-El-Din, H.A. (2015). Experimental and modeling approach for water shutoff using relative permeability modifiers. *Journal of Petroleum Science and Engineering*, 133, 171–181.
34. Al-Yousef, H.Y., & Abdulraheem, A. (2009). Mitigation of water coning in vertical and horizontal wells using numerical simulation. *SPE 123457*, SPE Saudi Arabia Technical Symposium.