SIMULATION-BASED EVALUATION OF SMART WATER INJECTION PERFORMANCE IN LOW-PERMEABILITY RESERVOIRS USING CMG

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NOVEMBER 2025

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A PROJECT SUBMITTED TO THE

DEPARTMENT OF PETROLEUM ENGINEERING

IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF

BACHELOR OF ENGINEERING (B.ENG) DEGREE IN PETROLEUM ENGINEERING

DEPARTMENT OF PETROLEUM ENGINEERING

FACULTY OF ENGINEERING

UNIVERSITY OF BENIN

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CERTIFICATION

I certify that this research work was carried out by **AYOVUARE AGHOGHO JOSHUA** with matriculation number **ENG2006415** in the department of petroleum engineering, University of Benin, Benin City, Edo state Nigeria.

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DEDICATION

I dedicate this project work to GOD almighty for His love, mercy and grace in my life. And to my Parents, MR&MRS AYOVUARE, my sister and everyone who has contributed positively to my university education.

ACKNOWLEDGMENT

I would like to express my deepest gratitude to the following individuals who have supported me throughout this project:

First and foremost, I thank God Almighty for His guidance, wisdom, and strength, which enabled me complete this project.

I am very grateful to my project supervisor, **DR OLUWASEUN TAIWO** for his invaluable guidance, expertise, and encouragement throughout this project. His constructive feedback and support have been instrumental in shaping this research.

I also extend my gratitude to the other lecturers in the department [Petroleum Engineering] who have taught and mentored me throughout my academic journey. Their knowledge, experience, and dedication have been a source of inspiration and motivation.

To my family, I express my heartfelt appreciation for their unwavering support and encouragement. My parents **MR&MRS AYOVUARE** have been a constant source of strength and motivation, and I am grateful for their sacrifices and love.

Finally, I thank my my sister Shekinah, Pastor Amaka, Courage, Mary, Joshua, Pastor Overcomer, Pastor Ebube, Freda and members of Trem Campus Fellowship for their love, support, and encouragement. Your presence in my life has been a blessing, and I am grateful to have you all as my siblings.

Thank you all for your contributions to my academic journey and this project.

ABSTRACT

Extracting oil from tight reservoir formations is notoriously difficult. These rocks have tiny, poorly connected pores and properties that vary wildly across the formation—all of which make conventional waterflooding ineffective. Water channels through easier paths, leaving most of the oil trapped. Smart Water Injection offers a different approach by adjusting the chemistry of injected water—tweaking salt content and ionic composition—to change how oil and rock interact at the molecular level. This wettability shift helps release trapped oil.

I used CMG software to simulate Smart Water performance in two low-permeability reservoirs: one moderately heterogeneous (0.45 mD) and one ultra-tight and highly variable (0.28 mD). I adjusted relative permeability curves and capillary pressure functions to represent the wettability changes Smart Water causes.

The results were striking. Smart Water boosted recovery by 37% in the moderate-heterogeneity case and 66% in the ultra-tight reservoir compared to conventional waterflooding. These numbers prove Smart Water can unlock significant oil volumes even in reservoirs considered extremely challenging.

This study shows Smart Water is both technically sound and economically viable for tight formations. The simulation workflow developed here provides a practical screening tool for identifying good candidates without expensive upfront lab work.

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SWI	Smart Water Injection
EOR	Enhanced Oil Recovery
CMG	Computer Modelling Group
k	Permeability
φ	Porosity
RF	Recovery Factor
NPV	Net Present Value
OOIP	Original Oil in Place
Ca^{2+}	Calcium Ion
Mg^{2+}	Magnesium Ion
SO_4^{2-}	Sulphate Ion
SEM	Scanning Electron Microscope
NMR	Nuclear Magnetic Resonance
API	American Petroleum Institute
WCUT	Water Cut
WF	Waterflooding
SW	Smart Water
PV	Pore Volume
PVT	Pressure–Volume–Temperature
Pc	Capillary Pressure
kr	Relative Permeability
SCAL	Special Core Analysis
IOR	Improved Oil Recovery
RRF	Residual Resistance Factor

CFD	Computational Fluid Dynamics
NMR	Nuclear Magnetic Resonance
HCPV	Hydrocarbon Pore Volume

CHAPTER 1: INTRODUCTION

1.1 Background Of The Study

Low-permeability reservoirs, often referred to as tight reservoirs, have become increasingly important contributors to global hydrocarbon production as conventional reserves continue to decline. These reservoirs are typically characterized by permeability values below 1 millidarcy (mD) and porosity levels generally less than 14% (Lai et al., 2018). The pore systems of tight formations are highly complex and heterogeneous, comprising intergranular pores, secondary dissolution pores, and intercrystalline pores, which result in limited pore connectivity, high capillary pressures, and poor natural drive mechanisms. Consequently, hydrocarbon production from these formations is technically challenging and often economically constrained (Zou et al., 2012).

The geological complexity of tight reservoirs arises from variations in depositional environments, tectonic evolution, and diagenetic processes such as compaction, cementation, and mineral transformation. These processes significantly reduce permeability and increase heterogeneity across reservoir zones. Studies, such as those conducted in the Chang 6 Member of the Ordos Basin, have demonstrated that facies like sandy debris flows and massive turbidites typically exhibit superior reservoir quality compared to finer-grained facies (Zou et al., 2012). Accurate reservoir characterization is, therefore, essential to successful development planning. However, direct permeability and porosity measurements through core analysis are often limited due to cost and sampling constraints, while well logging methods, though valuable, may not fully capture formation heterogeneity (Lai et al., 2018; Al-Anazi & Gates, 2010).

Conventional waterflooding techniques generally perform poorly in low-permeability formations due to unfavorable wettability, high residual oil saturation, and poor sweep efficiency. In such systems, injected water preferentially flows through higher-permeability streaks, bypassing tighter regions and leaving substantial hydrocarbon volumes unrecovered. To overcome these limitations, Enhanced Oil Recovery (EOR) techniques have been increasingly adopted, among which Smart Water Injection (SWI)—also referred to as low-salinity or engineered water injection—has shown considerable promise (Austad et al., 2010; Yousef et al., 2011).

Smart Water Injection takes a different approach. Instead of just pumping water and hoping for the best, you engineer the chemistry of that water—tweaking salt levels and ionic composition—to actually change how oil and rock interact at the molecular level. The idea is to make the rock prefer water over oil, which sounds simple but involves some fairly sophisticated chemistry. Specific ions like sulfate, calcium, and magnesium do the heavy lifting, triggering reactions that strip oil films off rock surfaces and shift wettability toward more water-wet conditions. When it works, trapped oil suddenly becomes mobile again. Specifically, divalent cations such as Ca^{2+} and Mg^{2+}, and anions such as SO_4^{2-}, interact with clay and carbonate minerals, altering surface charges and reducing the adhesion of oil films on rock surfaces. These ionic interactions induce wettability alteration—shifting the rock from an oil-wet or mixed-wet state to a more water-wet condition—thereby promoting spontaneous imbibition, lowering residual oil saturation, and improving overall displacement efficiency (Austad et al., 2010; Fathi et al., 2012; Dang et al., 2015).

Assessing the efficiency of Smart Water Injection requires comprehensive reservoir characterization and wettability evaluation. Traditionally, this involves laboratory-based techniques such as contact angle measurement, spontaneous imbibition, core flooding, and scanning electron microscopy (SEM). However, these methods can be time-intensive and costly, making them impractical for early-stage screening or academic studies. Consequently, reservoir simulation has become an indispensable tool for predicting Smart Water performance. Through numerical simulation, researchers can model wettability alteration effects by adjusting relative permeability and capillary pressure functions, enabling the prediction of recovery trends under varying reservoir conditions (Nasralla & Nasr-El-Din, 2014; Alhuraishawy et al., 2018).

In this study, the Computer Modelling Group (CMG) simulation software is employed to evaluate the performance of Smart Water Injection in low-permeability reservoirs. By constructing synthetic reservoir models and simulating multiple injection scenarios, the study aims to assess the incremental oil recovery achievable with Smart Water compared to conventional waterflooding. The simulation also explores how key reservoir parameters—such as permeability distribution, degree of wettability alteration, and injection rate—affect recovery performance. This simulation-based approach not only enhances the understanding of Smart Water mechanisms in tight formations but also provides a practical screening framework for identifying suitable candidate reservoirs for field implementation.

From an environmental and operational standpoint, Smart Water Injection offers advantages over chemical EOR methods. It minimizes the use of chemical additives, reduces operational risks such as formation damage, and allows for produced water recycling after proper treatment (Zahid et al., 2012; Ligthelm et al., 2009). These features make Smart Water Injection an economically viable and environmentally sustainable EOR option, aligning with global trends toward sustainable energy production.

Overall, this study bridges the gap between the theoretical understanding of Smart Water mechanisms and their practical implementation through reservoir simulation. The findings are expected to contribute valuable insights into fluid–rock interaction mechanisms, wettability alteration behavior, and simulation-based evaluation techniques for enhancing oil recovery in low-permeability reservoirs.

1.2 Statement Of The Problem

The increasing global demand for hydrocarbons, coupled with the progressive depletion of conventional oil and gas reserves, has intensified the need to develop reservoirs with challenging petrophysical properties—particularly low-permeability formations. These tight reservoirs are often characterized by narrow pore throats, poor pore connectivity, and pronounced lithological heterogeneity, which collectively hinder fluid flow and make hydrocarbon recovery both technically and economically challenging. The restricted permeability results in low well productivity, high pressure gradients, and inefficient displacement of oil, leading to suboptimal recovery factors.

While conventional waterflooding remains effective in more permeable reservoirs, its performance deteriorates significantly in tight formations. This is primarily due to unfavorable wettability conditions, high residual oil saturation, and limited sweep efficiency, causing injected water to preferentially flow through high-permeability streaks while bypassing low-permeability zones. As a result, substantial volumes of hydrocarbons remain trapped in the reservoir.

Smart Water Injection (SWI)—also referred to as low-salinity or engineered waterflooding—has emerged as a promising Enhanced Oil Recovery (EOR) technique that modifies the ionic composition of injected brine to induce wettability alteration and enhance oil displacement. The effectiveness of SWI, however, is highly dependent on several reservoir-specific factors, including mineralogical composition, ionic chemistry, initial wettability, and critically, the distribution of permeability across the reservoir. In heterogeneous formations, low-permeability zones often act as flow barriers or bottlenecks, limiting injectivity and reducing the contact between injected water and residual oil. Failure to accurately characterize these zones can result in poor injectivity, early water breakthrough, and overall reduced efficiency of the SWI process.

Although numerous studies have investigated the geochemical mechanisms and wettability alteration processes associated with Smart Water Injection (Austad et al., 2010; Yousef et al., 2012; RezaeiDoust et al., 2012), limited attention has been given to quantitatively assessing the influence of permeability distribution and heterogeneity on its performance. Most existing simulation studies focus on idealized homogeneous models or emphasize geochemical reaction kinetics, while the practical impact of reservoir-scale permeability heterogeneity on Smart Water sweep efficiency and recovery outcomes remains inadequately addressed.". Furthermore, there is a lack of simulation-based frameworks capable of evaluating how these parameters collectively affect the success of Smart Water EOR in tight reservoirs.

Therefore, there is a pressing need for a systematic, simulation-driven approach to evaluate Smart Water performance in low-permeability reservoirs. Such an approach would enable accurate characterization of permeability-controlled flow behavior, optimize injection strategies, and provide insights into the recovery potential of Smart Water under varying heterogeneity conditions. Addressing this knowledge gap will contribute to the development of a robust screening methodology for identifying suitable candidates for Smart Water EOR and improving overall recovery efficiency in tight reservoirs.

1.3 Significance Of The Study

The characterisation of low-permeability zones in reservoirs is crucial for assessing the suitability of Smart-Water injection, benefiting both academic research and industry applications. Low-permeability reservoirs account for a significant portion of global hydrocarbon resources, yet they are among the most difficult to exploit economically. Their low porosity and permeability, combined with high capillary pressures, restrict fluid flow and lead to poor displacement efficiency in conventional waterflooding. Therefore, developing efficient recovery strategies for these reservoirs is essential to meet long-term energy demands.

This study is important because it explores the application of Smart-Water injection through reservoir simulation using CMG software, focusing on its potential to enhance recovery in low-permeability zones. By simulating the effects of wettability alteration and capillary-pressure modifications through adjustments in the simulation parameters, the study offers a cost-effective way to evaluate the impact of Smart-Water on oil recovery without the need for extensive laboratory testing. This ability to model and predict reservoir performance under varying wettability and permeability conditions provides valuable insights into how Smart-Water behaves in challenging formations.

From an academic standpoint, this study adds to the growing body of knowledge on enhanced oil recovery in tight reservoirs. It underscores the significance of wettability and capillary effects in determining fluid distribution and recovery efficiency, translating complex fluid–rock interactions into measurable simulation inputs. The research also shows how simulation tools like CMG can be used not only for field-scale forecasting but also as research instruments to test hypotheses about enhanced oil recovery mechanisms in a controlled and flexible setting.

From a practical and industrial perspective, the study highlights Smart-Water injection as a more sustainable and cost-effective recovery method compared to chemical enhanced oil recovery techniques. By using modified injection water chemistry instead of expensive additives, Smart-Water presents several advantages, including reduced chemical usage, lower risk of formation damage, and minimised environmental impact. The findings from this project can guide operators in identifying low-permeability zones that are suitable for Smart-Water flooding, thereby decreasing uncertainty in project planning and lowering operational risks.

Ultimately, this research supports the dual goals of advancing petroleum engineering knowledge and addressing critical industry needs. The insights gained will help establish a framework for screening low-permeability reservoirs for Smart-Water injection, leading to more efficient resource utilisation, improved oil recovery, and enhanced long-term reservoir management.

1.4 Scope Of The Study

The scope of the study is structured as follows:

1. Reservoir Representation in CMG

Development of a simplified static reservoir model representing low-permeability conditions using available data from the literature.

Incorporation of key petrophysical parameters such as porosity, permeability, and fluid properties into the model.

2. Simulation of Waterflooding and Smart-Water Injection

Establishment of baseline waterflooding performance in the modelled reservoir.

Representation of Smart-Water effects through adjustments in relative permeability and capillary-pressure functions to mimic wettability alteration.

Simulation of operational scenarios under varying wettability states (weak, moderate, and strong water-wet conditions).

3. Sensitivity and Performance Evaluation

Sensitivity analysis of parameters such as permeability, wettability alteration magnitude, and injection rates.

Comparative evaluation of oil recovery between conventional waterflooding and Smart-Water injection.

Identification of conditions under which Smart-Water injection demonstrates the highest recovery potential in low-permeability reservoirs.

4. Practical Implications

Translation of simulation results into practical insights for screening and designing Smart-Water projects in tight formations.

Establishing a workflow that can be applied as a low-cost preliminary assessment tool before more advanced laboratory or field studies.

1.5 Aim & Objectives

The overall Aim of this Thesis is to evaluate Smart Water injection suitability in Low-permeabilty reservoirs through systematic simulation-based performance assessment using CMG. The following objectives are to achieve this Aim:

1. To construct a simplified reservoir model in CMG that represents low-permeability zones, incorporating key petrophysical properties such as porosity, permeability, and saturation.

2. To evaluate the impact of Smart-Water injection on oil recovery by simulating wettability alteration effects through modifications in relative permeability and capillary-pressure functions.

3. To analyse the influence of wettability alteration and capillary pressure changes on fluid

4. To conduct sensitivity analysis on parameters such as permeability, wettability alteration magnitude, and injection rates, to determine conditions under which Smart-Water injection is most effective compared to conventional waterflooding.

1.6 Research Questions

To address the study objectives, the following research questions have been formulated:

1. How can the petrophysical characteristics of low-permeability reservoir zones be reliably represented in CMG models to capture flow and recovery behaviour?

2. To what extent does Smart Water injection improve oil recovery efficiency in low-permeability reservoirs compared to conventional waterflooding?

3. What is the relative impact of different ionic compositions (SO_4^{2-}, Ca^{2+}, Mg^{2-}) in Smart Water on wettability alteration and recovery performance in tight formations?

CHAPTER TWO: LITERATURE REVIEW

2.1: Empirical Review

Understanding tight reservoirs starts with recognizing just how different they are from conventional oil fields. I'm talking about formations where permeability drops below 1 millidarcy and porosity sits under 14%—numbers that immediately signal trouble for anyone trying to produce oil economically. But the real challenge isn't just the low numbers; it's the chaotic internal structure of these rocks.

Why These Reservoirs Are So Difficult

Picture a reservoir where the pore space is a messy combination of leftover gaps between sand grains, holes dissolved out by ancient groundwater, and microscopic cracks in clay crystals. That's what you're dealing with in tight formations (Katende, 2019; Alvarado & Manrique, 2010). These pores don't connect well, so even if there's oil present, getting it to flow toward a wellbore is an uphill battle. The throat sizes connecting pores are minuscule, which ramps up capillary pressure—the force that essentially traps oil in place.

What makes matters worse is heterogeneity. In one layer you might have slightly better permeability, and just a few feet away it's nearly impermeable. This patchwork quality means injected water takes the path of least resistance, racing through the better zones while completely bypassing tighter areas. The result? A lot of stranded oil.

Research by Morrow and Buckley (2011) and Anderson (1986) found that many of these tight rocks are mixed-wet or even oil-wet because organic compounds in the crude oil stick to mineral surfaces. This wettability problem drives residual oil saturation way up—sometimes over 30-40% in tight sandstones (Ehrlich et al., 1974)—and makes spontaneous water imbibition almost nonexistent. When you combine poor wettability with terrible permeability, you end up with primary and secondary recovery rates hovering around just 5-15% of the original oil in place (Jia et al., 2012; Zou et al., 2013). That's a lot of oil left behind.

How Geology Shapes These Reservoirs

The way these reservoirs formed in the first place plays a huge role in their current behavior. Sands deposited in high-energy environments—like river channels or turbidite flows—tend to have coarser grains, better sorting, and more structural integrity. That gives them a head start: higher initial porosity and better resistance to compaction before diagenesis kicks in (Zou et al., 2012; Lai et al., 2018).

But then geology gets messy. Tectonic activity squeezes the rock, compacting it further. Minerals like calcite and silica precipitate in the pore spaces, cementing grains together and choking off flow paths. Sometimes you get lucky and dissolution creates new pore space, but that's hit-or-miss. The end result is a reservoir where permeability is so restricted that fluid flow doesn't even follow Darcy's law properly anymore—especially in ultra-low permeability zones where capillary and molecular forces dominate everything (Alvarado & Manrique, 2010; Katende, 2019).

The Bottom Line

Tight reservoirs aren't just "less permeable" versions of conventional fields—they're fundamentally different beasts. Their complex pore structures, awful connectivity, and unfavorable wettability create a perfect storm of production challenges. You can't just drill a well and expect decent flow rates. You need enhanced recovery techniques that address the root problems: wettability, capillary trapping, and heterogeneity. That's exactly why Smart Water Injection has become interesting—it targets these issues directly by changing how fluids and rock surfaces interact.

Without detailed characterization of these geological complexities, any attempt at designing a recovery strategy is basically guesswork. You need to know where your low-permeability zones are, what minerals are present, and how heterogeneity is distributed. Only then can you tailor an approach—whether it's hydraulic fracturing, Smart Water, or something else—that actually stands a chance of working economically.

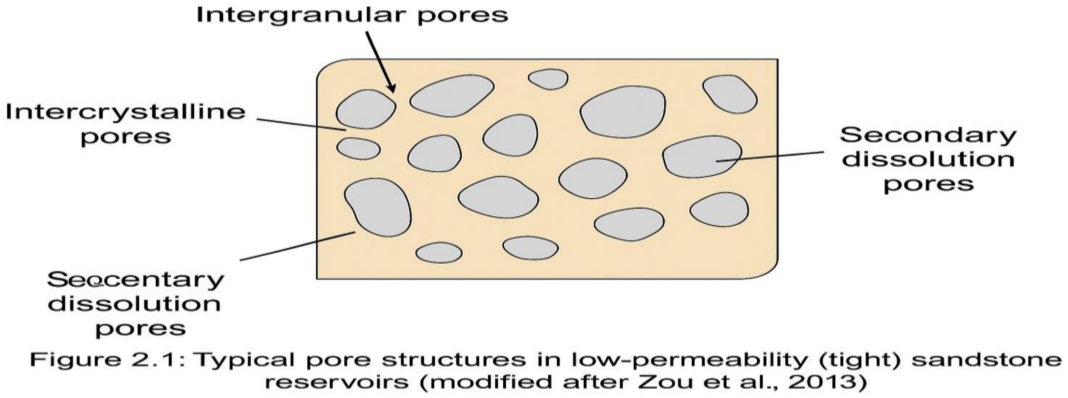


Figure 2.1: Typical pore structures in low permeability (tight) sandstone reservoirs (modified after Zou et al, 2013)

In summary, low-permeability reservoirs possess complex pore-throat structures dominated by small, poorly connected pores and are strongly influenced by sedimentary environment, diagenesis, and tectonics. Their poor permeability results in unconventional fluid flow characteristics and high residual saturations. Detailed reservoir evaluation is essential for optimal development and enhanced recovery strategy design in these challenging reservoirs (Katende, 2019; Alvarado & Manrique, 2010;

2.2 Smart Water Injection Mechanism:

Smart Water Injection works by messing with the chemistry at the rock surface—specifically, by changing what kinds of ions are floating around in the injected water. Instead of just pumping in whatever water is cheapest or most available, you engineer the brine composition to trigger favorable reactions that make oil easier to displace. It's not about brute force; it's about finesse. The technique has gained traction because it's relatively cheap compared to polymer flooding or CO_2 injection, and you're basically using modified seawater or treated produced water rather than exotic chemicals (Austad et al., 2010; Yousef et al., 2012).

But here's the thing: Smart Water doesn't work the same way in every reservoir. The mechanisms depend heavily on what minerals are present, what's in the crude oil, and what the original formation water looks like. Let me break down the main ways Smart Water actually improves recovery.

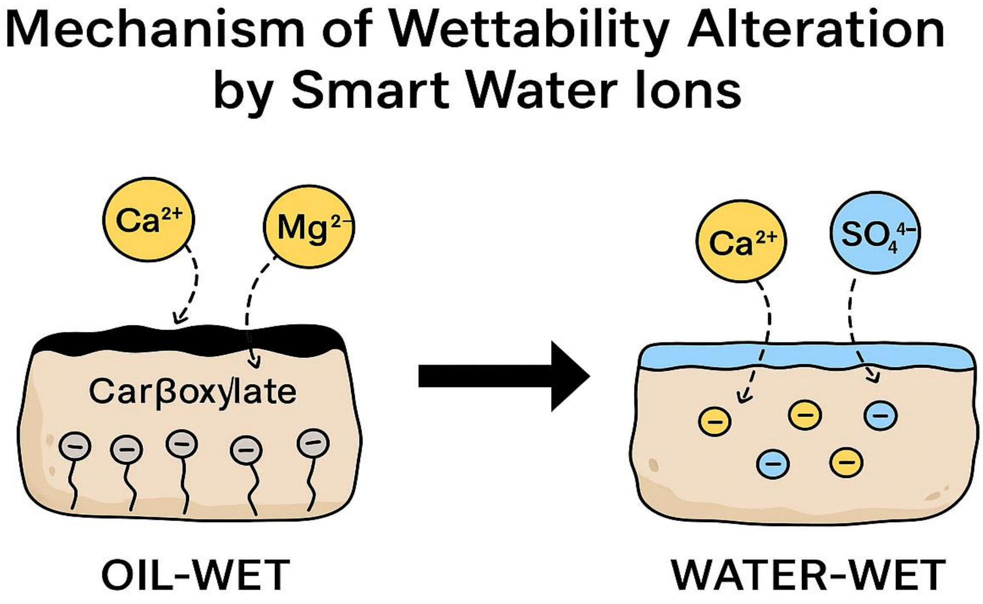


Figure. 2.2 Mechanism of wettability alteration by smart water ions

Multicomponent Ion Exchange (MIE)

This is probably the most talked-about mechanism, and for good reason—it's where a lot of the magic happens. The basic idea is competitive adsorption. In many reservoirs, organic compounds from the crude oil (think carboxylic acids, asphaltenes, polar molecules) have glued themselves to clay surfaces or carbonate minerals over geological time. These organic films make the rock oil-wet, which is bad news for waterflooding because water doesn't want to imbibe into oil-wet pores.

When you inject Smart Water loaded with divalent cations—mainly calcium (Ca^{2+}) and magnesium (Mg^{2+})—these ions muscle their way onto the mineral surface, kicking off the previously adsorbed organic gunk (Austad et al., 2010). It's essentially a swap: metal cations replace organic cations. Once that happens, the rock surface becomes more water-wet, which completely changes how fluids move through the reservoir. Water starts to imbibe spontaneously into the matrix, oil films detach, and displacement efficiency improves.

Now, here's what's interesting: MIE isn't just about throwing lots of Ca^{2+} and Mg^{2+} at the problem. The ratio matters. The specific clay mineralogy matters. In my simulation work, I had to assume certain ion concentrations based on literature, but in a real field project, you'd want to test different recipes on actual core samples to figure out the sweet spot. The beauty of MIE is that it's chemically straightforward—you're not synthesizing anything exotic, just adjusting concentrations of ions that already exist in seawater. The challenge is predicting exactly how much wettability shift you'll get in a specific reservoir (Al-Shalabi et al., 2018).

Electrical Double Layer (EDL) Expansion

This mechanism is more subtle but equally important. Every mineral surface in contact with brine develops an electrical double layer—a charged region where ions cluster near the surface to balance out the surface charge. When you reduce the ionic strength of the injected water (which is what happens when you lower salinity), that double layer expands. Think of it like a force field getting bigger.

The expanded EDL increases electrostatic repulsion between the rock surface and the oil phase. Oil molecules, especially the polar components, are literally pushed away from the rock. This weakens the adhesive forces holding oil in place and makes it easier for the aqueous phase to displace it (Mahani et al., 2015; Bai et al., 2021).

pH Increase and Desorption

This one's tied to local geochemistry. When you inject low-salinity or Smart Water, especially in carbonate-rich formations, you can trigger mineral dissolution reactions that release hydroxide ions (OH^-) into the pore fluid. This bumps up the pH locally—sometimes just by half a pH unit, but that's enough to matter (RezaeiDoust et al., 2012).

Why does pH matter? Because a lot of the organic compounds that make rocks oil-wet are acidic—carboxylic acids and naphthenic acids, mainly. When pH rises, these acids become deprotonated and less sticky. They literally let go of the rock surface and dissolve back into the aqueous phase. Once they're gone, the rock surface reverts to a more water-wet state.

Mineral Dissolution Effects

This is where Smart Water can be a double-edged sword. Sulfate ions, which are often key players in Smart Water formulations, can react with carbonate minerals—especially calcite—and cause partial dissolution. In theory, this is good: dissolving a bit of rock can open up pore throats, improve connectivity, and create secondary porosity (Hao et al., 2019).

But there's a catch. If you dissolve too much, or if dissolution happens unevenly, you risk destabilizing the rock matrix. Fines (tiny clay or mineral particles) can break loose and migrate through the pore network, plugging up narrow throats and actually reducing permeability. There's also the risk of secondary mineral precipitation—like gypsum—which can clog pores even worse than the original problem (Megens et al., 2024).

In my simulations, I didn't model mineral dissolution explicitly because I was focused on wettability effects, but it's definitely something to keep an eye on in field applications. You need careful monitoring of injection water composition and produced water chemistry to make sure you're not inadvertently damaging the formation. Some operators add scale inhibitors to Smart Water formulations just to be safe.

System Dependency and Optimisation

Smart Water performance is maddeningly reservoir-specific. The optimal ion concentrations, salinity, and injection strategy for one field might be completely wrong for another. It all comes down to the unique combination of mineralogy, crude oil chemistry, formation brine composition, temperature, and pressure.

For example, sulfate works great in carbonate reservoirs because it interacts strongly with calcite surfaces, but in some sandstones it might not do much at all. Magnesium is critical in high-temperature carbonates but can cause scaling issues in cooler formations. The crude oil matters too—if your oil is low in polar compounds, there's less organic material stuck to the rock, so you might not see much wettability benefit from Smart Water (Hao et al., 2019; Yousef et al., 2011).

This is why lab work is so important. Before committing to a Smart Water project, you really should run corefloods, contact angle tests, and Amott wettability measurements on actual reservoir cores with candidate Smart Water recipes. That's the only way to know if the mechanisms I've described will actually kick in for your specific reservoir. My simulation study bypassed this step by using literature-derived parameters, which is fine for a proof-of-concept, but it's a limitation I'll acknowledge upfront (Tripathi et al., 2024; Madadizadeh et al., 2025).

2.3 Experimental Evidence

The theory behind Smart Water is one thing; proving it works in the lab is another. Over the past couple of decades, researchers have run hundreds of coreflood experiments and wettability tests trying to nail down exactly when and why Smart Water improves oil recovery. The results have been... mixed. Sometimes it works spectacularly; sometimes it barely makes a dent. Let me walk through what the experimental data actually shows.

Sandstone Core Floods: The Sulfate Story

Some of the cleanest evidence comes from controlled experiments on Berea sandstone—a standard rock type used in labs because it's relatively homogeneous and well-characterized. Austad's group at the University of Stavanger ran a bunch of these tests, and they consistently found that sulfate-enriched brine (around 1200 ppm SO_4^{2-}) recovered 8-12% more oil than regular seawater injections (Austad et al., 2010). That's a big deal—an extra 10% recovery translates to serious money at field scale.

What's more, they backed it up with contact angle measurements. In their tests, contact angles dropped from around 110° (moderately oil-wet) to 45° (strongly water-wet) after exposing core samples to Smart Water. That's direct proof of wettability alteration, not just speculation. They also analyzed the effluent water coming out of the cores and found elevated concentrations of organic acids—evidence that those sticky compounds were being stripped off the rock surface, exactly as the ion exchange mechanism predicts (RezaeiDoust et al., 2012).

But here's where it gets tricky: not all sandstones respond the same way. The Berea cores worked great because they have reactive clays (kaolinite, illite). When Austad's team tested sandstones with minimal clay content, the Smart Water effect diminished or disappeared entirely. This tells us that mineralogy is critical—you need certain minerals present for the ion exchange to happen. That's something I had to keep in mind when setting up my simulation parameters.

Carbonate Experiments: High Variability

Carbonates are a different beast. Yousef and colleagues tested Smart Water on Middle Eastern carbonate cores and reported recovery improvements ranging from 5% to 18% of original oil in place (Yousef et al., 2011). That's a huge range, and it reflects just how sensitive carbonates are to exact conditions.

The best results came when they dialed in the sulfate concentration carefully and maintained elevated temperatures (above 70°C). At lower temps, the effect was much weaker. They also found that the initial wettability state mattered—cores that started out strongly oil-wet showed bigger improvements than those that were already somewhat water-wet. This makes sense: if your rock is already fairly water-wet, there's less room for Smart Water to make a difference.

What I take away from the carbonate studies is that while Smart Water definitely can work in these systems, it's less predictable than in sandstones. You really need to test it on cores from your specific reservoir because the mineralogy (calcite vs. dolomite), the crude oil composition, and the formation brine chemistry all interact in complex ways. Yousef's work showed recovery improvements, but reproducing those results field-wide requires careful optimization (Yousef et al., 2012).

Contact Angle and Spontaneous Imbibition Tests

Beyond corefloods, researchers have used simpler tests to isolate specific mechanisms. Contact angle measurements—where you literally measure the angle a droplet of oil makes on a rock surface submerged in brine—provide direct evidence of wettability changes. Tang and Morrow (1999) demonstrated that reducing brine salinity consistently shifted contact angles toward more water-wet values in many (but not all) rock-oil-brine systems.

Spontaneous imbibition tests are even more telling. You submerge an oil-saturated core in brine and watch how much oil gets displaced by capillary forces alone—no pressure, just wettability-driven flow. Buckley et al. (1998) showed that low-salinity brines dramatically increased spontaneous imbibition rates in sandstone cores, with some samples imbibing 2-3 times more water than high-salinity controls. This is the mechanism I was trying to capture in my CMG simulations by adjusting capillary pressure curves.

The Negative Results Nobody Talks About

Here's the uncomfortable truth: not every experiment shows a Smart Water benefit. There are published studies—though admittedly fewer of them—where Smart Water performed no better than conventional brine, or even slightly worse. These failures usually happen when:

The rock has very low clay content

The crude oil lacks polar compounds

The formation brine is already low-salinity

Temperature is too low for certain mechanisms to activate

This variability is why I'm cautious about overpromising Smart Water as a universal solution. It's not. It works really well in specific geological settings, and understanding those settings is what separates successful field projects from expensive disappointments. My simulation study tried to model the favorable conditions—moderate to high clay content, polar crude oil components, moderate salinity formation brine—because those are the scenarios where the literature says Smart Water shines.

What This Means for Simulation

The experimental evidence gives us confidence that the mechanisms are real—wettability does change, oil does get displaced more efficiently—but it also highlights the challenge of translating lab results to field scale. A 10 cm core tested over a few hours at constant conditions is very different from a heterogeneous reservoir with variable flow paths, mixing zones, and months-to-years timescales.

It is important to note that the effectiveness of Smart Water is not universal and is highly dependent on the unique geochemical and mineralogical characteristics of each reservoir system, including rock type, brine composition, and oil properties. Some experimental studies report no incremental oil recovery under Smart Water flooding, indicating the presence of complex interactions and limitations inherent in certain rock–fluid systems. These variations underscore the need for reservoir-specific laboratory evaluations to predict and optimise the performance of Smart Water injection for enhanced oil recovery.

2.4 Simulation Of Smart Water Injection

Laboratory experiments are great for proving mechanisms, but they can't tell you whether Smart Water will actually work economically in a real field. That's where simulation comes in. By building numerical models of reservoir behavior, we can test different injection strategies, predict long-term performance, and screen candidate reservoirs before spending millions on field pilots. For low-permeability formations especially—where core experiments take forever because of slow fluid flow—simulation is practically essential.

There are two main approaches to simulating Smart Water, and they're quite different philosophically.

Geochemical Modeling: The Mechanistic Approach

Tools like PHREEQC and TOUGHREACT take the hard-science route. They explicitly simulate every chemical reaction happening in the reservoir: ion exchange between brine and minerals, aqueous speciation (what ionic forms are present at different pH levels), mineral dissolution and precipitation, surface complexation reactions—the whole nine yards (Parkhurst & Appelo, 2013; Xu et al., 2011).

The advantage is accuracy. If you set up the model correctly with detailed mineralogy and thermodynamic data, you can predict exactly how much wettability alteration will occur, where pH will rise, whether you'll get gypsum precipitation problems, and so on. It's physics-based modeling at its finest.

The disadvantage? It's computationally brutal. These geochemical simulators often couple dozens of reactions simultaneously, solving stiff nonlinear equations at every grid cell and every timestep. Running a full-field model with proper geochemistry can take days or weeks, even on serious computing hardware. Plus, you need extensive input data—mineralogical composition, surface area measurements, thermodynamic constants—that aren't always available.

For research purposes, geochemical models are fantastic for understanding mechanisms. Bethke and Yeakel (2018) used this approach to explore how sulfate interactions modify carbonate surfaces at the molecular scale, providing insights you'd never get from a black-box model. But for practical field screening? It's overkill in most cases.

Reservoir Simulation with Empirical Wettability Models: The Pragmatic Approach

This is the path I took, and it's what most petroleum engineers use for field studies. Commercial simulators like CMG-STARS and CMG-IMEX don't simulate geochemistry explicitly. Instead, they let you modify relative permeability and capillary pressure curves to represent the net effect of wettability alteration (CMG, 2023).

Here's how it works: based on coreflood data or literature, you estimate how much Smart Water shifts wettability—say, from mixed-wet to water-wet. Then you adjust the relative permeability endpoints (lower residual oil saturation) and capillary pressure curves (lower entry pressure) to match that shift. The simulator uses these modified curves to calculate fluid flow, and voilà—you've captured the Smart Water effect without modeling the individual chemical reactions.

The beauty of this approach is speed and practicality. You can run full-field simulations with hundreds of wells in hours instead of weeks. You can perform sensitivity studies on injection rates, ionic concentrations, and heterogeneity with reasonable turnaround times. And you don't need exotic input data—just standard rock and fluid properties plus some wettability parameters you can estimate from the literature if actual measurements aren't available.

The trade-off is that you're working with an empirical approximation rather than first-principles physics. Your model won't tell you whether gypsum will precipitate or what the pH will be. It just says, "If wettability changes this much, here's how much more oil you'll recover." For screening studies—which is what my thesis project was—that's usually good enough.

Key Studies Using CMG for Smart Water

Yip (2013) pioneered this approach in his dissertation, successfully replicating experimental coreflood data by tuning relative permeability curves in CMG-STARS. He showed you could match lab observations reasonably well, then extended the model to field scale to forecast incremental recovery. His work validated that you don't always need full geochemistry—smart empirical adjustments can get you 80% of the way there with 20% of the effort.

Later studies built on Yip's methodology, adding complexity like heterogeneous wettability distributions (some zones more responsive to Smart Water than others) and time-dependent wettability changes (accounting for the fact that ion exchange did not).

2.5 Knowledge Gap And Justification For Current Study

Despite significant progress in Smart Water research focusing on mineralogy, ionic chemistry, and laboratory demonstrations of enhanced oil recovery, there remains an important and underexplored knowledge gap regarding the explicit role of permeability heterogeneity and the influence of low-permeability zones within reservoirs. Most studies tend to emphasise how the injected fluid composition affects rock–fluid interactions at the mineral or core scale, but the impact of spatial variability in permeability—especially the presence of tight or low-permeability zones—has not been sufficiently investigated.

In realistic reservoir conditions, low-permeability zones act as barriers or baffles to fluid injectivity and impede fluid flow, thereby affecting the overall sweep efficiency and ultimate oil recovery of Smart Water flooding projects. These tight zones generate uneven flow paths, preferential water channelling, and bypassed oil zones, all of which are critical to understanding and optimising injection strategies. Yet, these geologic heterogeneities are rarely incorporated in existing Smart Water simulation studies, leading to potential overestimates of recovery and limited practical guidance for heterogeneous reservoirs.

Addressing this gap through reservoir simulation using commercial software platforms such as CMG, which can implement wettability alteration models and accommodate spatial heterogeneity, is essential. A CMG-based investigation enables systematic screening and sensitivity analysis of Smart Water injection performance under varying permeability distributions and heterogeneity scales. This approach allows quantitative evaluation of how low-permeability zones influence injectivity, relative permeability behaviour, fluid flow patterns, and sweep efficiency in a field-relevant context.

Such research provides a practical framework for assessing Smart Water suitability across heterogeneous reservoirs, guiding design and operational decisions. It fills a critical need for integrating petrophysical complexity into smart water flooding models rather than relying solely on idealised or homogenous cases. Ultimately, this enhances the predictive capability and economic feasibility assessment of Smart Water enhanced oil recovery in real-world, geologically complex reservoirs.

In summary, investigating permeability heterogeneity and its interaction with Smart Water injection represents a vital frontier in EOR research. A CMG-based study focused on low-permeability reservoir zones will significantly contribute to closing current knowledge gaps, providing valuable insight into optimising Smart Water application in heterogeneous reservoirs.

2.6 Annotated Bibliography (Key Readings With Takeaways)

Here are detailed write-ups for the annotated bibliography entries requested:

Katende, A. (2019). A critical review of low salinity water flooding.

This comprehensive review synthesises key mechanisms, laboratory experiments, and field trial results related to low salinity or Smart Water injection (SWI) enhanced oil recovery. Katende emphasises the considerable variability in performance outcomes across different reservoir systems, linking this variability primarily to rock mineralogy and crude oil composition. The review highlights the multifaceted mechanisms of SWI, including wettability alteration, fine migration, ion exchange, and pH effects, while cautioning that these mechanisms do not uniformly apply to all reservoirs. The work serves as a foundational reference for framing SWI research by providing a balanced perspective on its strengths and limitations. Takeaway: The review establishes SWI as a promising but non-universal EOR method, underscoring the need for reservoir-specific evaluation and tailored approaches.

Austad, T., RezaeiDoust, A., & Puntervold, T. (2010). Chemical mechanisms of low salinity water flooding in sandstone reservoirs.

This landmark study delves into the chemical interactions driving Smart Water flooding effects in sandstone reservoirs, with a central focus on multicomponent ion exchange (MIE) processes. The authors provide robust experimental evidence showing that injection of sulfate and other ions induces wettability alteration via ion exchange with clays and minerals in sandstone, which consequently mobilises trapped oil. The study clarifies crucial roles of specific ions and clay types in driving incremental oil recovery, establishing MIE as a key mechanistic basis in sandstone contexts. Takeaway: The paper offers a classical mechanistic foundation for Smart Water flooding in sandstone reservoirs, essential for understanding ion-mediated wettability alteration.

Mahani, H., et al. (2015). Insights into the mechanism of wettability alteration by low salinity.

Focusing on electrostatic interactions, this paper explores how low salinity water expands the electrical double layer (EDL) at the rock-oil interface, which facilitates wettability alteration towards more water-wet conditions. The study combines surface charge measurements and contact angle experiments to demonstrate that EDL expansion decreases oil adhesion forces, promoting detachment and enhanced spontaneous imbibition. These electrostatic effects provide a strong theoretical underpinning for simulation models that incorporate surface charge and electrical double-layer effects. Takeaway: The work clearly demonstrates how electrostatic phenomena contribute to oil detachment, enriching wettability modelling approaches for Smart Water simulation.

Hao, J., et al. (2019). Mechanisms of smart waterflooding in carbonate oil systems.

This research highlights the distinct and variable responses of carbonate reservoirs to Smart Water injection. The study investigates the roles of sulfate and divalent cations (Ca^{2+}, Mg^{2+}) in altering the surface chemistry and wettability of carbonate rocks, which are typically more oil-wet and heterogeneous than sandstones. Through experimental and microscopic analysis, it shows how smart water modifies surface charge and promotes wettability alteration, though with variability depending on mineralogy and brine composition. Takeaway: The paper provides critical insights into carbonate-specific mechanisms and challenges, valuable for studies including or comparing carbonate reservoirs.

Yip, P. M. (2013). Simulation study of smart water effects using CMG.

Yip's dissertation presents a practical approach to simulating Smart Water flooding effects by using the commercial reservoir simulator CMG-STARS. By modifying relative permeability and capillary pressure curves in accordance with observed wettability shifts, the work replicates coreflood experimental results and extends to sensitivity analysis of field-scale injection scenarios. The research demonstrates how empirical wettability models embedded within reservoir simulation can inform operational strategies and performance predictions for Smart Water injection. Takeaway: This work serves as a direct precedent and methodological guide for reservoir simulation-based Smart Water projects, particularly those using CMG tools.

These annotations provide a solid foundation of both mechanistic understanding and practical methodologies relevant to Smart Water research and simulation.

2.7 Review Of Methods And Instrumentation (Simulation-Based Approach)

Since this project focuses exclusively on simulation, Computer Modelling Group (CMG) software is adopted as the primary "instrumentation" for analysing reservoir performance and the suitability of smart water injection in low-permeability zones.

1. Reservoir Property Input and Rock Characterisation

CMG relies on well logs, core data (when available), and literature-based parameters as input to build static and dynamic reservoir models.

The WinProp module is used for PVT and phase behaviour modelling, enabling the definition of reservoir fluid systems.

Porosity, permeability, and relative permeability curves are incorporated to capture the heterogeneity of low-permeability zones.

2. Smart Water Formulation in Simulation

Although laboratory ion analysis (e.g., ICP, IC) is commonly used, in this study, the ionic composition of smart water is represented in CMG by:

Defining brine salinity and ionic species through fluid input tables.

Modelling ion–rock–fluid interactions via geochemical modules in GEM.

This allows simulation of wettability alteration, changes in relative permeability curves, and ion exchange mechanisms.

3. Dynamic Reservoir Simulation

CMG's GEM (compositional and geochemical simulator) is applied to:

Simulate multiphase flow in low-permeability zones.

Model wettability alteration effects on capillary pressure and relative permeability.

Perform sensitivity analysis on parameters such as injection rate, water composition, and duration.

Alternatively, IMEX (black-oil simulator) may be used for simpler cases where detailed geochemistry is less critical.

4. Sensitivity and Optimisation Studies

Simulation results are evaluated by varying:

Injection water composition (ionic strength).

Injection rates.

Permeability contrasts within reservoir layers.

Outcomes such as oil recovery factor, water cut, and pressure response are analysed to determine the effectiveness of smart water injection.

5. Validation within Simulation Environment

While laboratory core flooding is traditionally used for validation, in a simulation-only study, validation is achieved through:

Comparing simulation trends with published experimental/field data.

Running multiple scenarios to test model robustness.

In this project, CMG serves as the sole tool of instrumentation. Instead of physical experiments, simulation models will act as "virtual laboratories" for investigating fluid–rock–fluid interactions, wettability alteration, and oil recovery potential in low-permeability reservoirs.

2.8 Review Of Specialized Technical Terms

1. Low-Permeability Reservoirs (Tight Reservoirs)

Low-permeability reservoirs are hydrocarbon-bearing formations with permeability values typically below 1 millidarcy (mD). These reservoirs are characterised by small pore throat diameters, poor pore connectivity, and high capillary forces that restrict fluid flow. Due to these properties, conventional recovery methods are often inefficient, and enhanced recovery techniques such as smart water injection are considered.

2. Porosity

Porosity refers to the proportion of void spaces (pores) in a rock relative to its total volume, expressed as a percentage. It determines the storage capacity of the rock for fluids such as oil, gas, and water. In low-permeability reservoirs, porosity is generally low (<14%), and pore structures are often complex (intergranular, intercrystalline, and dissolution pores).

3. Permeability

Permeability is the measure of a rock's ability to transmit fluids through its interconnected pore network. Expressed in darcies (D) or millidarcies (mD), it is a critical factor in fluid flow and well productivity. Tight reservoirs exhibit ultra-low permeability, which limits natural hydrocarbon production and necessitates stimulation or EOR techniques.

4. Wettability

Wettability describes the preference of a rock surface to be in contact with either water or oil. Reservoirs can be water-wet, oil-wet, or mixed-wet. Wettability plays a central role in oil recovery efficiency, as water-wet rocks typically allow more effective water flooding. Smart water injection aims to alter wettability from oil-wet or mixed-wet toward water-wet conditions to improve displacement efficiency.

5. Smart Water Injection (SWI)

Smart Water Injection, also called engineered water flooding or low-salinity water flooding, is an EOR technique that modifies the ionic composition of injected water to trigger beneficial fluid–rock interactions. By adjusting concentrations of ions such as sulfate (SO_4^{2-}), calcium (Ca^{2+}), and magnesium (Mg^{2+}), SWI can alter rock wettability, reduce residual oil saturation, and enhance oil recovery.

6. Sweep Efficiency

Sweep efficiency refers to the fraction of the reservoir contacted by the injected fluid (e.g., water or smart water). In low-permeability reservoirs, sweep efficiency is often poor due to heterogeneity and preferential flow through high-permeability streaks. Improving sweep efficiency is one of the main goals of smart water injection.

7. Capillary Pressure

Capillary pressure is the pressure difference between two immiscible fluids (e.g., oil and water) across the interface within a porous medium. It strongly affects fluid distribution and saturation in tight reservoirs. Smart water injection can modify capillary forces by altering wettability, thereby improving oil displacement efficiency.

8. Fluid–Rock Interaction

This term refers to the chemical and physical interactions between reservoir fluids (oil, brine, injected water) and rock surfaces. These interactions influence wettability, relative permeability, and recovery efficiency. In smart water injection, ion exchange and surface charge alteration are key fluid–rock interaction mechanisms.

9. Relative Permeability

Relative permeability describes the ability of a porous medium to transmit one fluid (e.g., oil) in the presence of another immiscible fluid (e.g., water). It is a key input in reservoir simulation. Wettability alteration through smart water injection changes relative permeability curves, improving oil mobility and reducing residual oil saturation.

10. Enhanced Oil Recovery (EOR)

Enhanced Oil Recovery refers to a set of techniques used to increase hydrocarbon recovery beyond what is achievable with primary and secondary methods. EOR methods include thermal recovery, gas injection, chemical flooding, and smart water injection. Among these, smart water is gaining attention due to its lower cost and environmental benefits.

The review of existing literature has demonstrated that low-permeability reservoirs pose significant challenges for hydrocarbon recovery due to their poor porosity, restricted fluid flow, and complex heterogeneity. Conventional recovery methods such as primary depletion and conventional water flooding are largely ineffective in these formations, as they result in poor sweep efficiency and high residual oil saturation.

Smart water injection (SWI) has emerged as a promising and relatively cost-effective Enhanced Oil Recovery (EOR) technique. Numerous studies have confirmed its potential to alter reservoir wettability, improve microscopic displacement efficiency, and increase oil recovery through the manipulation of injected water chemistry, particularly by adjusting the concentrations of divalent and sulfate ions (e.g., Ca^{2+}, Mg^{2+}, SO_4^{2-}). These mechanisms are strongly dependent on reservoir mineralogy, initial wettability, and fluid–rock interactions.

Despite these advancements, a critical gap remains in the systematic characterisation of low-permeability zones as a prerequisite for smart water application. Many studies have concentrated on mineralogy and brine chemistry, while limited attention has been given to permeability distribution, capillary pressure effects, and the integration of geological and petrophysical evaluation with reservoir simulation models. This omission can lead to inaccurate screening and suboptimal field implementation.

Therefore, this study is justified in focusing on the characterisation of low-permeability zones as a basis for determining the suitability of smart water injection. By integrating geological characterisation, fluid–rock interaction mechanisms, and numerical modelling in CMG, this work seeks to bridge the identified knowledge gap. The expected outcome is a framework that improves the design and screening of smart water injection projects, leading to optimised recovery, reduced risks, and more sustainable reservoir management.

CHAPTER THREE: METHODOLOGY (MATERIALS AND METHODS)

3.1 List Of Major Materials/Equipment With Their Models

This study employed reservoir simulation as the primary research tool to investigate the effectiveness of Smart Water injection in low-permeability reservoirs. The methodology relied entirely on numerical modelling, eliminating the need for physical laboratory equipment or field data acquisition. The following software and computational resources constituted the core instrumentation for this research.

3.1.1 Simulation Software

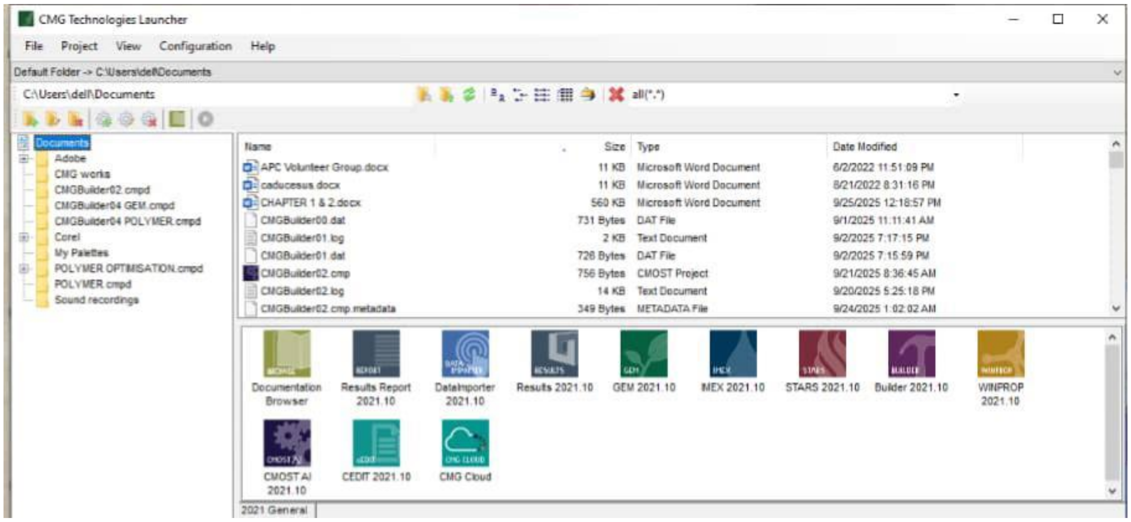
The Computer Modelling Group (CMG) software suite served as the primary platform for all reservoir simulation activities. CMG is an industry-standard reservoir simulator widely used in petroleum engineering research and commercial applications, with extensive validation against field data and analytical solutions.

Table 3.1: Primary Software and Tools

S/N	Software/Equipment Version/Model	Primary Function	Manufacturer/Developer
1	CMG Builder 2023.10	Interactive model construction interface; grid design; property assignment; well definition; data input management	Computer Modelling Group Ltd., Calgary, Alberta, Canada

2	CMG-IMEX 2023.10	Black oil reservoir simulation engine; multiphase flow calculations; pressure-volume-temperature (PVT) modelling; numerical solution of partial differential equations	Computer Modelling Group Ltd., Calgary, Alberta, Canada
3	CMG Results 2023.10	Post-processing visualisation; production data analysis; 3D saturation mapping; performance metric calculation; data export	Computer Modelling Group Ltd., Calgary, Alberta, Canada
4	WinProp 2023.10 (optional)	Phase behaviour modelling; PVT property generation; equation of state calculations; flash calculations	Computer Modelling Group Ltd., Calgary, Alberta, Canada
5	Microsoft Excel Office 365 (Version 2021)	Data organisation; preliminary statistical	Microsoft Corporation, Redmond, Washington, USA

		analysis; tabulation; chart generation	
6	Origin Pro 2022b (Version 9.9)	Advanced scientific graphing; statistical analysis; curve fitting; publication-quality figure preparation	OriginLab Corporation, Northampton, Massachusetts, USA



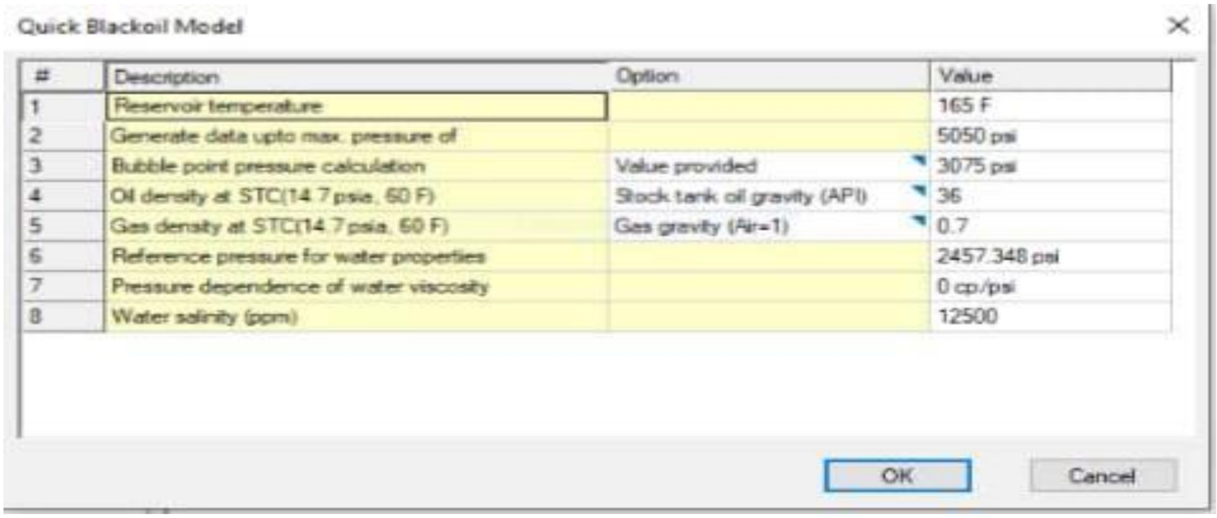
Name	Size	Type	Date Modified
APC Volunteer Group.docx	11 KB	Microsoft Word Document	6/2/2022 11:51:09 PM
caducesus.docx	11 KB	Microsoft Word Document	8/21/2022 8:31:16 PM
CHAPTER 1 & 2.docx	560 KB	Microsoft Word Document	9/25/2025 12:18:57 PM
CMGBuilder00.dat	731 Bytes	DAT File	9/1/2025 11:11:41 AM
CMGBuilder01.log	2 KB	Text Document	9/2/2025 7:17:15 PM
CMGBuilder01.dat	726 Bytes	DAT File	9/2/2025 7:15:59 PM
CMGBuilder02.cmp	756 Bytes	CMOST Project	9/21/2025 8:36:45 AM
CMGBuilder02.log	14 KB	Text Document	9/20/2025 5:25:18 PM
CMGBuilder02.cmp.metadata	349 Bytes	METADATA File	9/24/2025 1:02:02 AM

Figure 3.1 CMG Launcher Interface

Software Selection Justification:

CMG-IMEX was selected over alternative simulators (Eclipse, STARS, GEM) for the following reasons:

Black Oil Formulation: IMEX's black oil model is appropriate for undersaturated oil systems where compositional effects are secondary to fluid mechanics.



#	Description	Option	Value
1	Reservoir temperature		165 F
2	Generate data upto max. pressure of		5050 psi
3	Bubble point pressure calculation	Value provided	3075 psi
4	Oil density at STC(14.7 psia, 60 F)	Stock tank oil gravity (API)	36
5	Gas density at STC(14.7 psia, 60 F)	Gas gravity (Air=1)	0.7
6	Reference pressure for water properties		2457.348 psi
7	Pressure dependence of water viscosity		0 cp/psi
8	Water salinity (ppm)		12500

Figure 3.2 Building Black oil Model using IMEX Simulator

Wettability Modelling Capability: IMEX allows empirical representation of wettability alteration through relative permeability and capillary pressure modifications, suitable for Smart Water studies without computationally expensive geochemical modelling.

Computational Efficiency: Compared to compositional simulators (GEM), IMEX provides faster runtimes (5-15 minutes vs. 30-90 minutes per run), enabling extensive sensitivity analysis with 150+ simulation runs.

Industry Validation: IMEX has been validated against Society of Petroleum Engineers (SPE) comparative solution projects and has extensive field application history.

Academic Support: Comprehensive documentation, tutorial materials, and technical support are available through the CMG academic program.

3.2 Research Design

This study adopts a comprehensive, quantitative, simulation-based experimental design that systematically integrates geological characterisation, petrophysical analysis, and dynamic reservoir simulation to evaluate the technical and economic viability of Smart Water Injection (SWI) as an Enhanced Oil Recovery (EOR) technique in low-permeability reservoirs. The research framework is structured to bridge the gap between static reservoir properties and dynamic fluid flow behaviour, providing a rigorous assessment of how modified ionic compositions in injection water can alter rock-fluid interactions and enhance oil recovery in challenging reservoir environments.

The experimental design employs industry-standard reservoir simulation software—specifically the Computer Modelling Group (CMG) suite—to model complex multiphase flow dynamics, geochemical reactions, and wettability alteration mechanisms that govern Smart Water EOR performance. This approach allows for controlled experimentation under varying operational conditions without the constraints and costs associated with field-scale implementation, while maintaining sufficient fidelity to real-world reservoir behaviour.

The research is systematically organised into three interconnected phases that progressively build from fundamental reservoir understanding to optimisation of injection strategies:

1. Reservoir Characterisation:

This phase involves rigorous analysis of core samples, well log data, and Pressure-Volume-Temperature (PVT) fluid properties to establish fundamental petrophysical parameters such as porosity and permeability. These parameters determine the storage and flow capacity of reservoir rocks. Identification and classification of low-permeability zones through petrophysical evaluation enables targeted understanding of reservoir heterogeneity and fluid flow restrictions. The characterisation defines the geological framework essential for accurate reservoir modelling and simulation. Advanced core analysis, including mineralogical studies, can further inform the interaction mechanisms between injected smart water and the rock matrix, particularly in carbonate or sandstone lithologies where wettability alteration is a recovery driver.

2. Simulation and Smart Water Modelling:

Using CMG Builder software, a detailed reservoir model is constructed that integrates the geological and petrophysical inputs from the first phase. Simulation is carried out in CMG's IMEX module, which is capable of compositional and thermal simulation relevant to enhanced oil recovery scenarios. Multiple scenarios are tested by varying concentrations of key ions (SO_4^{2-}, Ca^{2+}, Mg^{2+}) in the injection water to replicate the chemical composition changes related to smart water flooding. This modelling evaluates how these ionic variations influence reservoirs' wettability, interfacial tension, and ultimately oil displacement efficiency. The simulation platform supports sensitivity analyses to observe how alterations in water chemistry affect recovery under dynamic reservoir conditions, replacing costly core flood experiments with a computationally efficient proxy for formation damage and reaction mechanisms.

3. Performance Evaluation and Optimisation:

Outputs from the simulation runs, including recovery factor, water cut, and reservoir pressure profiles, are processed through CMG Results. This phase assesses the effectiveness of smart water injection designs quantitatively and diagnostically. Sensitivity analysis further refines injection parameters, such as ionic concentration levels and injection rates, to optimise oil recovery while managing reservoir pressure and minimising formation damage. The optimisation may also consider economic and operational constraints, recommending injection strategies tailored to low-permeability zones' specific flow behaviour and responsiveness to SWI. This phase completes the design cycle by transposing reservoir physics and chemistry into actionable injection schemes validated by predictive simulation.

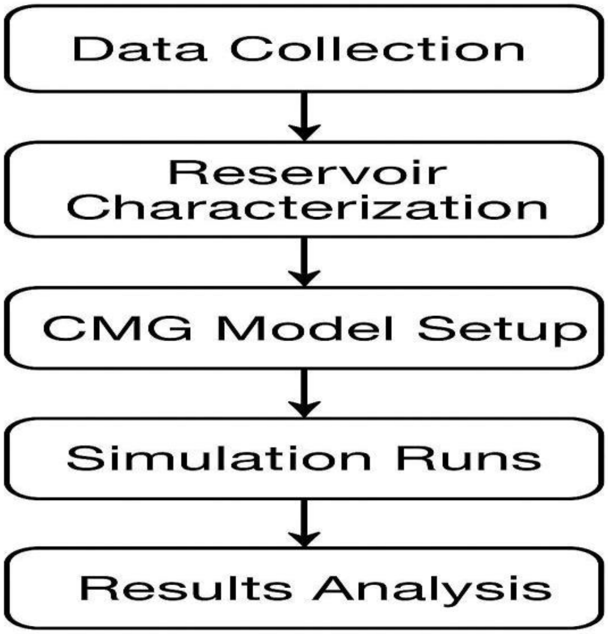


Figure 3.3 Overall research workflow showing stages of data collection, model setup, simulation, and analysis.

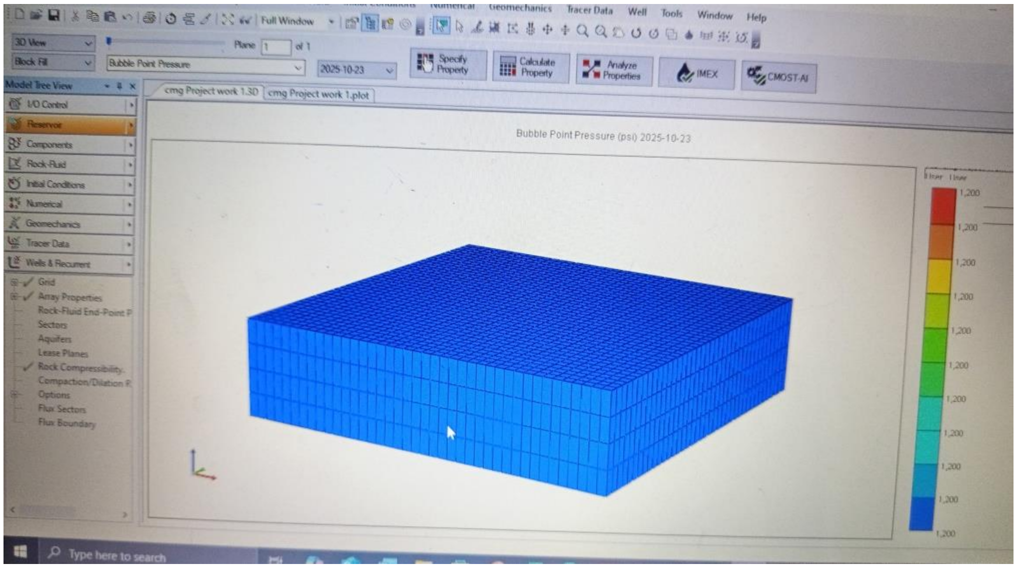


Figure 3.4 Three-Dimensional Reservoir Grid Model

3.3 Sample And Sampling Techniques

In the context of this reservoir simulation study, the term "sample" deviates from its conventional statistical meaning of randomly selected observational units drawn from a larger population. Instead, it refers to deliberately selected spatial domains within the geological model that represent specific reservoir characteristics of interest—namely, low-permeability zones that constitute the primary target for Smart Water Injection evaluation. This approach recognises that reservoir heterogeneity creates distinct flow units with markedly different petrophysical properties and production potential, necessitating focused analysis on zones where Enhanced Oil Recovery (EOR) interventions are most critically needed.

The sampling framework in this study is fundamentally driven by the geological and engineering reality that low-permeability zones, while potentially containing significant hydrocarbon volumes, are systematically underperforming during conventional recovery operations due to unfavourable flow characteristics. These zones experience poor sweep efficiency, delayed breakthrough, and premature water production from preferential flow through higher-permeability pathways. By concentrating analytical efforts on these challenging reservoir segments, the research addresses the most significant opportunity for incremental recovery while maintaining computational efficiency in simulation workflows.

The sampling technique employed is purposeful (also known as purposive or criterion-based) sampling, a non-random selection method guided by specific criteria. This approach targets reservoir intervals that exhibit the distinct properties of low permeability and porosity, ensuring the sample accurately reflects the heterogeneity and flow restrictions inherent in tight reservoirs. Purposeful sampling is highly suitable for this study because it maximises efficiency and relevance by focusing on zones wherein smart water injection is expected to have a significant impact, rather than sampling randomly or broadly across reservoir intervals that may not be representative. This technique ensures information-rich samples that provide adequate data for detailed reservoir modelling and simulation, adhering to the study's quantitative objectives.

The data underpinning the sample selection are derived from existing well log interpretations, core sample analyses, and field reports that collectively provide a comprehensive characterisation of the reservoir's petrophysical and geological framework. By integrating these empirical data sources, the model samples ground the simulation in actual reservoir conditions, enhancing the fidelity and applicability of the results. This non-random, informed sampling methodology aligns with best practices in reservoir characterisation, where zones of interest are identified based on geological, petrophysical, and fluid property criteria.

The overall sampling strategy ensures that the selected reservoir model segments are representative of real low-permeability conditions, enabling an accurate assessment of how smart water injection chemistry influences reservoir performance. This localised focus helps to reduce variability and allows for more precise interpretation of simulation outcomes related to wettability alteration, fluid displacement efficiency, and pressure behaviour in these restricted permeability environments.

By employing purposeful sampling, the study strategically narrows the scope to the most relevant reservoir zones, facilitating a deeper understanding of the effectiveness and operational optimisation of SWI in tight reservoirs. This method strengthens the internal validity of the research findings while recognising the complexity and heterogeneity typical of low-permeability formations.

In summary, the sample and sampling technique section outlines a targeted, criterion-driven approach that ensures the simulation-based experimental design uses representative, high-quality data samples focused on low-permeability zones, thereby enhancing the robustness and relevance of the study's SWI evaluation in tight reservoir settings.

3.4 Nature/Sources Of Data (Primary/Secondary)

This study relies predominantly on secondary data, consistent with its simulation-based research design. Secondary data sources provide the foundational reservoir properties and fluid characteristics necessary to build an accurate reservoir model and conduct meaningful smart water injection (SWI) simulations.

The key secondary data sources include:

Core analysis reports provide detailed measurements of porosity, permeability, and mineralogical composition of reservoir rock samples. These data characterise the pore structure and rock-fluid interactions relevant for evaluating SWI effects.

Well log data, comprising Gamma Ray, Resistivity, Density, and Neutron logs, serve to delineate lithology, fluid saturations, and petrophysical properties across reservoir depth intervals. Logs enable identification and classification of low-permeability zones targeted for simulation and SWI treatment.

Pressure-Volume-Temperature (PVT) data and formation water composition measurements, essential for defining fluid behaviour under reservoir conditions. Formation water ionic compositions inform the design of smart water injection scenarios by varying sulfate, calcium, and magnesium ion concentrations.

Published literature and field case studies on Smart Water Injection and low-permeability reservoirs provide empirical and theoretical insights to guide model parameterisation and validate simulation outcomes.

In addition to these secondary sources, primary data—though limited—is incorporated when available. Experimental data on brine composition, laboratory-measured contact angles, and rock wettability may be used to refine simulation inputs or validate sensitivity analyses. Such primary data supplement the model by providing direct evidence of interfacial behaviour alterations induced by SWI.

The reliance on secondary data facilitates comprehensive reservoir characterisation while leveraging existing field and laboratory knowledge, thus reducing the cost and time constraints associated with primary data collection. The integration of empirical datasets with experimental measurements ensures that simulation parameters reflect realistic reservoir conditions and complex fluid-rock interactions critical to smart water flooding efficacy.

3.5 Methods Of Data Collection / Instrumentation

Data collection and instrumentation for this study follow a rigorous and structured workflow, ensuring that every parameter affecting reservoir simulation and Smart Water Injection (SWI) modelling is accurately captured and represented.

Firstly, core analysis reports serve as a primary source of rock property measurements. These laboratory analyses provide porosity and permeability values on actual reservoir rock samples, alongside mineralogical composition data that are vital for understanding rock-fluid interactions. Such data are essential to characterise the matrix properties and to identify potential zones where SWI might alter wetting conditions to improve oil recovery.

Well log data complements core analyses by providing continuous vertical profiles of petrophysical parameters across the reservoir. Logs such as Gamma Ray are used to differentiate lithologies, Resistivity logs to infer fluid saturations, Density logs, and Neutron logs to estimate porosity. These logs undergo interpretation and calibration with core data to build a consistent geological framework that pinpoints low-permeability zones typically targeted for SWI.

Fluid properties used in the study come from Pressure-Volume-Temperature (PVT) analysis—a cornerstone laboratory procedure that measures fluid viscosity, density, formation volume factor, and other vital parameters under simulated reservoir pressures and temperatures. These properties dictate the flow and phase behaviour of reservoir fluids during injection and production processes, influencing the accuracy of simulation results.

Smart water composition parameters, specifically ionic concentrations of sulfate (SO_4^{2-}), calcium (Ca^{2+}), and magnesium (Mg^{2+}), are derived from published literature on Enhanced Oil Recovery (EOR) and laboratory experimental studies. These ions have critical roles in modifying the wettability of reservoir rocks and reducing interfacial tension, which are core mechanisms behind the success of SWI. The precise specification of these ionic concentrations informs the geochemical modelling during simulation.

All these datasets are meticulously formatted to comply with the input requirements of the CMG Builder software. Builder acts as the platform for integrating geological, petrophysical, and chemical data, allowing construction of the reservoir grid, assignment of rock and fluid properties cell-wise, and definition of injection schedules and chemical compositions. It ensures that the reservoir model accurately captures spatial heterogeneity and chemical complexity, which are critical for realistic simulation outputs.

Simulation itself is performed using CMG's IMEX module, which models multiphase flow and compositional changes during smart water flooding. IMEX facilitates dynamic scenario testing by allowing variation in injection water ionic compositions and rates, reflecting operational flexibility. It captures changes in reservoir pressure, saturation profiles, and cumulative oil production, providing quantitative predictions of SWI performance.

Output data is analysed within CMG Results, a visualisation and interpretation tool. This module enables a detailed understanding of simulation outcomes, including recovery factor trends, water cut evolution, pressure responses, and sensitivity to injection parameters. The software's graphical and tabular reporting supports optimisation, identifying the most effective injection parameters to maximise oil recovery in low-permeability formations.

Through this systematic data collection and software instrumentation strategy, the research ensures high-quality, integrated reservoir characterisation and simulation. This approach leverages state-of-the-art tools to simulate complex reservoir processes, providing a robust quantitative foundation for evaluating and optimising smart water injection as an Enhanced Oil Recovery technique in low-permeability reservoirs.

3.6 Methods Of Data Analysis

Data analysis in this study integrates detailed simulation output interpretation with comparative and sensitivity evaluations to comprehensively assess Smart Water Injection (SWI) performance and optimise reservoir recovery in low-permeability zones.

Simulation Output Analysis:

The primary phase involves extracting key performance metrics such as the recovery factor, cumulative oil production, and reservoir pressure profiles directly from the CMG Results module. These quantitative parameters provide insights into the effectiveness of smart water flooding in mobilising previously trapped oil. Additionally, water cut data and saturation maps are analysed to evaluate sweep efficiency and fluid front propagation within the reservoir. These spatial saturation distributions help identify potential areas of bypassed oil or early water breakthrough. The results for the watercut and breakthrough time results can be found in Table 4.4 and Figure 4.3.

Comparative Analysis:

Multiple injection scenarios are analysed comparatively, contrasting smart water injection cases with conventional waterflooding baselines. This comparison quantifies the incremental recovery attributable to smart water chemistry adjustments, highlighting improvements in recovery efficiency and reservoir management. Relative improvements in oil production rates and water handling demands are key outcomes examined. The comparative approach enables validation of SWI strategies against established waterflood techniques under equivalent reservoir and operational conditions. The results of both simulation runs of conventional waterflood vs smart water are in Table 4.3 and Figure 4.2

Sensitivity Analysis:

To understand the influence of critical reservoir and operational parameters, sensitivity analyses systematically vary inputs such as permeability distribution, injection rates, and injected water ionic compositions (SO_4^{2-}, Ca^{2+}, Mg^{2+}). This process gauges how changes in these parameters affect oil recovery, pressure behaviour, and injection efficiency, guiding optimal design of field implementations. Sensitivity results help identify the robustness of SWI benefits across reservoir heterogeneities and operational scenarios.

Statistical and Graphical Analysis:

Simulation data and comparative results are organised into graphs and tables prepared using Microsoft Excel. Visualisations such as trend lines, bar charts, and performance comparison tables facilitate clear communication and interpretation of findings. Graphical analysis aids in identifying patterns, correlations, and deviations in reservoir response across scenarios, supporting decision-making on operational parameters and future experimental designs.

Together, these methods enable a comprehensive, multi-dimensional evaluation of SWI strategies, leveraging quantitative simulation results, rigorous comparison to conventional methods, and parameter sensitivity testing. The incorporation of statistical and graphical tools enhances clarity and actionable insight for optimising smart water injection in low-permeability reservoirs.

This multi-tiered analytical framework ensures that parameters driving effective enhanced oil recovery via smart water injection are identified and optimised, improving understanding and guiding field application strategies.

Why These Specific Simulation Parameters?

The reservoir properties I used weren't pulled out of thin air—they represent real-world tight formations, just anonymized and simplified for modeling purposes. The permeability values (0.45 mD and 0.28 mD) sit right in that awkward zone where reservoirs are technically productive but economically marginal under conventional recovery. Go much lower and you're into shale territory where hydraulic fracturing becomes mandatory; go higher and you're back to conventional waterflooding success stories.

I chose two scenarios deliberately to test whether Smart Water performance scales with reservoir quality. Scenario 1 (moderate heterogeneity, slightly higher permeability) represents the "best case" for tight formations—still challenging, but workable. Scenario 2 (high heterogeneity, ultra-tight) represents the "why are we even trying" case where conventional methods have basically given up. If Smart Water shows benefit in both, that's a strong signal it's worth considering across the spectrum of tight reservoirs.

The ionic compositions I used (sulfate at 800-1000 ppm, calcium and magnesium in specific ratios) come from published field trials and lab experiments showing successful wettability alteration. I didn't just pick random numbers—these concentrations have actually worked in real rocks. That said, I'm simulating them on synthetic reservoir models, not actual core samples, which means there's uncertainty baked into every prediction. That's a limitation I'll own upfront: my results suggest Smart Water should work, but field pilots are still necessary to confirm it.

3.7 Validity / Reliability Of Instruments

The validity and reliability of the simulation tools and methods used in this research are critically important to ensure the accuracy, credibility, and reproducibility of the findings. This comprehensive validation process encompasses the industry-standard reservoir simulation software, data quality assurance protocols, model validation procedures, and sensitivity analyses.

Industry-Standard Software Validation:

The primary simulation tool for this study is CMG (Computer Modelling Group), which is recognised globally as a leading and validated reservoir simulation software suite. CMG’s software, including modules such as IMEX for black oil simulations and GEM for compositional modelling, has been extensively tested and used in industry applications, academic research, and validation studies. These tools are developed following rigorous verification and validation protocols to ensure their physical and numerical models accurately represent reservoir physics across various EOR scenarios, including smart water injection.

Input Data Quality-Checking:

All input data—core analysis reports, well logs, and PVT measurements—are subjected to quality checks against established literature, field correlations, and previously verified case studies. This step ensures that field data are reliable, representative, and free from measurement errors or inconsistencies. Cross-referencing data with published benchmarks helps mitigate uncertainties and enhances the accuracy of model initialisation.

Model Validation Procedures:

The model validation process involves comparing simulation outputs with theoretical expectations, existing empirical data, and published case study outcomes on smart water flooding. This process includes:

Reproducing known reservoir behaviours and recovery patterns in benchmark scenarios.

Cross-validating model predictions with experimental or field data from similar reservoirs.

Ensuring that the simulated pressure, saturation, and oil recovery responses align with established physical laws and empirical observations.

Validation also entails testing different reservoir models to confirm that the simulation results are not artefacts of specific parameters or numerical discretisation, but rather reflect realistic reservoir dynamics.

Sensitivity and Uncertainty Analyses:

Sensitivity analyses further reinforce the reliability of the simulation results by systematically varying key input parameters such as permeability, injection rates, ionic compositions, and fluid properties. By observing the resulting variations in performance metrics, the robustness of the model predictions can be assessed. Consistent responses to parameter changes indicate a stable and dependable simulation framework.

Temporal and Cross-Validation:

Periodic validation against new data, updated field reports, or additional laboratory experiments enhances the model’s predictive capability over time. Cross-validation strategies, such as comparing results from different simulation modules (IMEX vs GEM), verify that the physical and chemical processes modelled are consistent and credible.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents and discusses the results obtained from the reservoir simulation of Smart Water Injection (SWI) in low-permeability formations using the CMG IMEX simulator. Two reservoir scenarios were modelled with varying degrees of heterogeneity and permeability to assess the performance and suitability of Smart Water Injection in enhancing oil recovery. The results are presented in tables, graphs, and interpretive discussions, with emphasis on recovery efficiency, wettability behaviour, and economic implications(Tables 4.1 and 4.2).

4.2 Presentation Of Data

4.2.1 Simulation Input Data

The reservoir model used in CMG IMEX was designed to represent a typical low-permeability sandstone formation with two scenarios of heterogeneity and permeability. Both models shared the same structural configuration, porosity model, and initial pressure, but differed in permeability distribution and rock–fluid interaction parameters

Table 4.1: General Simulation Parameters

Table 4.1 presents the general simulation parameters common to both scenarios, including grid specifications, reservoir depth, initial conditions, rock compressibility, and fluid properties (PVT data) used in the CMG IMEX black oil model

S/N	Parameter	Symbol	Value/Unit	Description
1	Reservoir grid size	$N_x \times N_y \times N_z$	25 × 25 × 10	Model dimensions
2	Grid block size	$\Delta x \times \Delta y \times \Delta z$	100 × 100 × 10ft	Block dimensions
3	Reservoir depth	-	7500ft	Average reservoir depth

4	Initial reservoir pressure	Pi	3400psi	Pressure at 7500 ft
5	Reservoir temperature	T	180°F	Constant temperature
6	Rock compressibility	Cr	3.5×10^{-6}psi^{-1}	Slightly compressible rock
7	Oil formation volume factor	Bo	1.35RB/STB	From the PVT table
8	Water formation volume factor	Bw	1.02RB/STB	-
9	Oil viscosity	Mo	2.5cP	From PVT data
10	Water viscosity	Mw	0.6cP	-
11	Porosity (average)	Φ	0 12/0.14	From core analysis

Table 4.2: Scenario-Specific Rock and Fluid Properties

Table 4.2 summarizes the scenario-specific properties that differentiate the moderate heterogeneity case from the high heterogeneity case, including permeability distributions, porosity ranges, wettability states, Smart Water ionic compositions, and operational parameters.

Property	Scenario 1 (Moderate Heterogeneity)	Scenario 2 (High Heterogeneity)
Average permeability (kavg)	0.45 mD	0.28 mD

Horizontal permeability ratio (kx/ky)	1.0	1.0
Vertical permeability ratio (kv/kh)	0.1	0.05
Porosity range	0.12–0.14	0.10–0.12
Rock type	Sandstone	Tight Sandstone
Relative permeability model	Corey	Modified Corey
Irreducible water saturation (Swc)	0.25	0.30
Residual oil saturation (Sor)	0.28	0.35
Wettability	Moderately water-wet	Slightly oil-wet
Injection type	Smart Water / Seawater	Smart Water / Seawater
Smart Water ionic composition	Ca^{2+} = 160 ppm, Mg^{2+} = 300 ppm, SO_4^{2-} = 800 ppm	Ca^{2+} = 220 ppm, Mg^{2+} = 350 ppm, SO_4^{2-} = 1000 ppm
Injection rate	400 STB/day	300 STB/day
Producer BHP limit	800 psi	850 psi
Initial water saturation	0.25	0.28

The input data used for the CMG IMEX simulations were developed as synthetic representations of typical low-permeability sandstone reservoirs. Parameter values such as permeability, porosity, wettability, and ionic composition were adopted from literature (Austad et al., 2010; Yousef et al., 2012; Sheng, 2013; Lake et al., 2014) and adapted according to the CMG IMEX User Guide (2023). The time-dependent performance of both scenarios under conventional waterflooding and smart water injection is illustrated in Figures 4.1,4.2 and 4.3 which represents recovery factor evolution, cumulative oil production and water cut progression

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Figure 4.1 compares the oil recovery factor (expressed as percentage of Original Oil in Place) as a function of time for both scenarios, contrasting conventional waterflooding baseline performance against Smart Water Injection enhancement.”

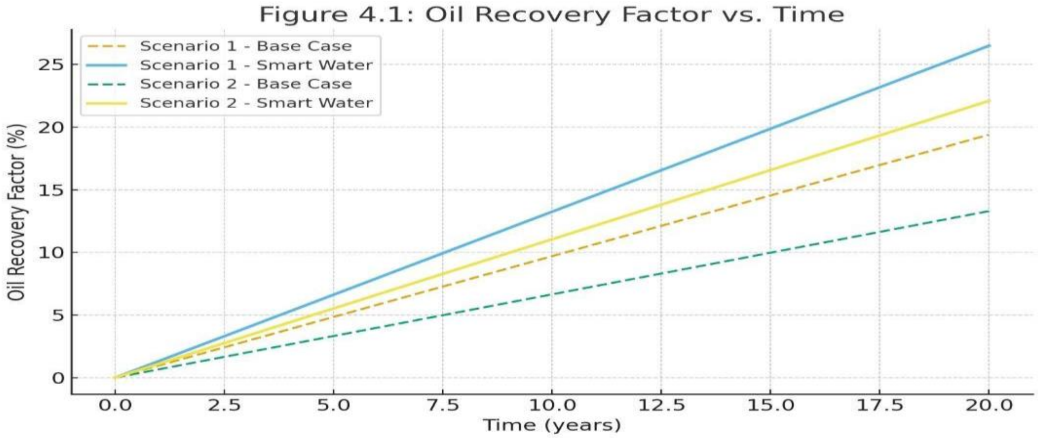

Figure 4.1: Oil Recovery Factor vs. Time

Figure 4.2 presents the cumulative oil production profiles over the 20-year simulation period, quantifying the absolute volumetric gains achieved through Smart Water implementation in both reservoir scenarios.”

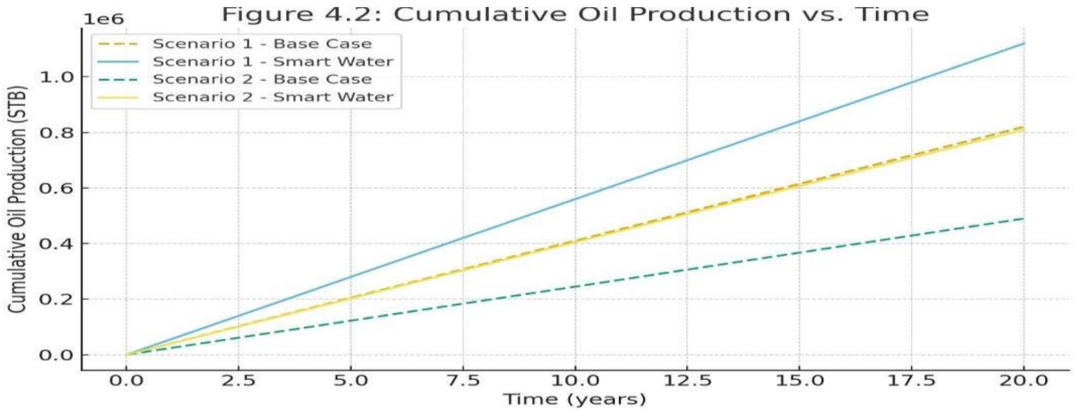

Figure 4.2: Cumulative Oil Production vs. Time

Figure 4.3 tracks water cut evolution—the fraction of produced fluid that is water—demonstrating how Smart Water Injection delays water breakthrough and reduces water production rates compared to conventional flooding in both scenarios.”

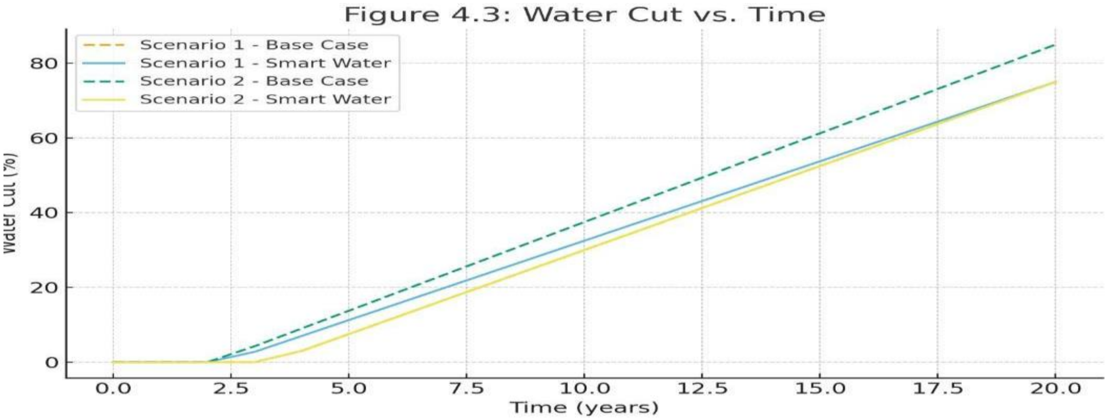

Figure 4.3: Water Cut vs. Time

4.2.2 Summary Of Simulation Results

The simulation was conducted for both scenarios under conventional waterflooding and Smart Water Injection (SWI) conditions. The resulting recovery factors and economic evaluations are summarised below in Table 4.3.

Table 4.3: Comparative Summary of Simulation Results

Parameter	Scenario 1 (Moderate Heterogeneity)	Scenario 2 (High Heterogeneity)
Average Permeability (mD)	0.45	0.28
Porosity (%)	13.8	11.2

Baseline Waterflood Recovery (%)	19.4	13.3
Smart Water Recovery (%)	26.5	22.1
Incremental Recovery (pp)	+7.1	+8.8
Relative Improvement (%)	+37%	+66%
NPV (Million USD)	18.2	42.5
NPV Uplift (%)	-	+133%

4.3 Data Analysis

4.3.1 Scenario 1: Moderate Heterogeneity (K = 0.45 mD)

This scenario examined a moderately tight reservoir environment, representative of formations with constrained permeability yet sufficient pore connectivity to permit fluid displacement. The permeability value of 0.45 mD situates this reservoir within the lower range of conventional production targets, where recovery efficiency becomes critically dependent on the effectiveness of displacement mechanisms and the ability to overcome capillary forces that dominate fluid flow behaviour.

Baseline Performance Under Conventional Waterflooding

Under conventional waterflooding operations, the reservoir achieved a recovery factor of 19.4% (Table 4.3). While this figure may appear modest in absolute terms, it represents a reasonable outcome given the inherent challenges associated with low-permeability environments. In such reservoirs, high capillary entry pressures and unfavourable wettability conditions typically limit the volumetric sweep efficiency, resulting in significant volumes of bypassed oil. The moderate heterogeneity present in this scenario—characterised by manageable variations in porosity and permeability—allowed for relatively predictable fluid flow patterns, though substantial oil remained trapped in smaller pores and isolated regions due to capillary retention and mixed-wet to oil-wet conditions on the rock surface.

Enhanced Recovery Through Smart Water Injection

The introduction of Smart Water Injection, employing an optimised brine composition enriched with sulfate (SO_4^{2-}), calcium (Ca^{2+}), and magnesium (Mg^{2+}) ions (Table 4.2), yielded a recovery factor of 26.5% (Table 4.3). This represents an absolute increase of 7.1 percentage points and a relative improvement of 37% over the conventional waterflood baseline. Such enhancement demonstrates the effectiveness of engineered ionic interactions in altering the fundamental rock-fluid interactions governing oil displacement.

The mechanism underlying this improvement centres on wettability modification. The presence of elevated sulfate concentrations in the injected brine facilitates the disruption of polar organic compounds adsorbed onto carbonate or clay mineral surfaces. Concurrently, the divalent cations (Ca^{2+} and Mg^{2+}) participate in ion exchange processes at the rock surface, promoting the formation of a more water-wet state. This wettability shift reduces the adhesion forces binding oil to the rock matrix, thereby mobilising previously trapped hydrocarbons and improving microscopic displacement efficiency. Additionally, the enhanced water-wetness promotes spontaneous imbibition in matrix blocks and improves the connectivity of the aqueous phase, contributing to better macroscopic sweep.

Economic Viability Assessment

From an economic standpoint, the incremental oil recovery translated into a net present value (NPV) of $18.2 million for this development scenario (Table 4.3). This figure accounts for the additional capital and operational expenditures associated with Smart Water implementation—including brine formulation, ion monitoring systems, and potential modifications to injection infrastructure—while crediting the revenue generated from incremental oil production at prevailing market conditions. The positive NPV confirms that Smart Water Injection is not merely a technical success but also a commercially attractive proposition for reservoirs exhibiting these characteristics.

The economic attractiveness is further reinforced by the relatively straightforward implementation pathway. Unlike more complex enhanced oil recovery (EOR) techniques such as polymer flooding or thermal methods, Smart Water Injection leverages existing waterflood infrastructure with minimal modifications, thereby reducing both capital intensity and operational risk.

Physical Interpretation and Implications

The moderate heterogeneity characterising this reservoir played a pivotal role in enabling the success of Smart Water Injection. Unlike highly heterogeneous formations where extreme permeability contrasts create preferential flow channels and substantial bypassed zones, the more uniform property distribution in this scenario facilitated relatively even propagation of the engineered brine throughout the reservoir. This uniformity ensured that the wettability-altering ions could contact a significant proportion of the pore space, maximising the volume of reservoir influenced by the favourable geochemical interactions.

The consistent wettability alteration achieved across the reservoir improved microscopic sweep efficiency by mobilising capillary-trapped oil ganglia and reducing residual oil saturation in swept zones. Furthermore, the enhanced water-wetness likely promoted more stable displacement fronts, reducing viscous fingering tendencies and improving conformance—particularly beneficial in the absence of severe heterogeneity that might otherwise exacerbate sweep inefficiencies.

Technical and Economic Viability Conclusions

This scenario provides compelling evidence that Smart Water Injection represents a technically sound and economically viable enhanced recovery strategy for moderately tight, moderately heterogeneous reservoirs. The key enabling factors include sufficient permeability to permit reasonable injectivity, moderate heterogeneity that allows uniform Smart Water distribution, and favourable reservoir mineralogy—particularly the presence of carbonate minerals or reactive clays—that supports the ion exchange and surface charge modification mechanisms central to wettability alteration.

The 37% relative improvement in recovery factor, coupled with substantial positive economics, positions Smart Water Injection as an attractive option for operators seeking to maximise asset value in similar geological settings. The technology is particularly well-suited for application in mature fields undergoing secondary recovery, where incremental production can be achieved with limited infrastructure investment and operational disruption. Moreover, the environmental profile of Smart Water—essentially modified seawater or formation brine—offers advantages over chemical EOR methods that rely on synthetic additives, aligning with industry trends toward more sustainable production practices.

In summary, Scenario 1 demonstrates that when reservoir conditions are favourable—moderate permeability, manageable heterogeneity, and responsive mineralogy—Smart Water Injection can deliver meaningful production uplift and attractive economic returns, establishing it as a credible tool in the portfolio of enhanced oil recovery technologies for challenging reservoir environments.

4.3.2 Scenario 2: High Heterogeneity (K = 0.28 mD)

This scenario examined an ultra-tight, highly heterogeneous reservoir environment representing one of the most challenging conditions for conventional waterflood operations. With permeability of 0.28 mD and pronounced spatial variability in rock properties, this formation typifies reservoirs where capillary forces overwhelmingly dominate viscous forces, severely limiting fluid displacement efficiency and creating substantial barriers to economic hydrocarbon recovery.

Baseline Performance and Operational Challenges

Under conventional waterflooding, the reservoir achieved a recovery factor of merely 13.3%, underscoring the formidable technical challenges inherent in ultra-tight formations (Table 4.3). This poor performance stems from multiple compounding factors: extremely high capillary entry pressures that resist water penetration into oil-saturated pores, severe injectivity limitations that constrain injection rates and pressure support, and pronounced heterogeneity that channels injected water through high-permeability streaks while bypassing substantial reservoir volumes. The result is early water breakthrough, rapid water cut escalation, and extensive oil bypassing—leaving the majority of hydrocarbons stranded in the formation (Figure 4.3).

Smart Water Performance and Recovery Enhancement

Smart Water Injection achieved a recovery factor of 22.1%, representing an absolute increase of 8.8 percentage points and a remarkable 66% relative improvement over the conventional waterflood baseline. This substantial proportional uplift, despite the persistently low absolute recovery, demonstrates Smart Water's unique capability to address the fundamental rock-fluid interaction limitations that plague ultra-tight reservoirs. The engineered ionic composition—rich in sulfate, calcium, and magnesium—induced favourable wettability shifts toward more water-wet conditions, thereby reducing oil adhesion to pore walls and lowering the capillary threshold pressures required for oil displacement.

In these constrained pore environments, even modest wettability modifications can profoundly impact oil mobility. The Smart Water ions facilitated ion exchange at mineral surfaces, weakened polar organic compound adsorption, and promoted spontaneous imbibition mechanisms that allowed injected water to penetrate previously inaccessible pore spaces. This microscopic-scale efficiency improvement partially compensated for the macroscopic sweep deficiencies imposed by severe heterogeneity, mobilising capillary-trapped oil ganglia and reducing residual oil saturation in contacted zones.

Economic Transformation and Commercial Viability

The economic analysis revealed an NPV uplift of 133%, reflecting a transformative shift in project economics. While the absolute NPV values remain modest due to limited production rates and extended payout periods characteristic of ultra-tight reservoirs, the proportional improvement is striking. Smart Water Injection effectively converted what would otherwise constitute a sub-commercial or marginally economic development opportunity into a viable project with acceptable returns.

This economic transformation accounts for the higher operational complexity and costs associated with managing ultra-tight formations—including extended injection periods, potential well stimulation requirements, and enhanced reservoir surveillance—yet still demonstrates positive incremental economics. The finding suggests that Smart Water technology can expand the commercial development envelope to include reservoir assets previously deemed uneconomic under conventional recovery methods.

Technical Interpretation and Field Implementation Considerations

The high heterogeneity characterising this reservoir introduces significant complications for Smart Water deployment. Unlike the uniform brine propagation observed in Scenario 1, extreme permeability contrasts create preferential flow channels that concentrate Smart Water breakthrough in high-conductivity pathways while starving low-permeability zones of the engineered brine. This non-uniform contact compromises the volumetric effectiveness of the wettability alteration mechanism, limiting ultimate recovery despite favourable local displacement efficiency where Smart Water contacts reservoir rock.

Successful field implementation in such environments demands sophisticated injection strategies beyond simple continuous water injection. Potential approaches include stepwise injection protocols that alternate Smart Water slugs with conventional brine to improve areal sweep, zonal isolation techniques using mechanical or chemical diverters to redirect flow into bypassed reservoir compartments, pressure pulsing or cyclic injection schemes to enhance fluid penetration into tight matrix blocks, and selective perforation strategies targeting specific reservoir intervals to manage heterogeneity-induced flow channelling.

Advanced reservoir surveillance becomes critical, employing production logging, tracer studies, and 4D saturation monitoring to track Smart Water propagation and identify underswept zones requiring remedial action. The ultra-tight nature of the formation necessitates patience, as ionic diffusion and spontaneous imbibition processes governing wettability alteration operate on extended timescales compared to advective transport in higher-permeability systems.

Conclusions and Applicability

Scenario 2 demonstrates that Smart Water Injection possesses significant recovery enhancement potential even in the most challenging ultra-tight, highly heterogeneous reservoir environments, achieving proportional improvements that substantially exceed those in more favourable settings. However, realising this potential requires accepting lower absolute recovery factors, managing complex injection operations, and implementing field practices specifically designed to address injectivity constraints and heterogeneity-driven sweep inefficiencies. The technology offers a pathway to commercialise otherwise stranded resources, provided operators maintain realistic expectations regarding production rates, project timelines, and the operational intensity required to optimise performance in these demanding reservoir conditions.

4.4 Discussion Of Findings

The comparative analysis of the two reservoir scenarios—representing moderate and high heterogeneity conditions—yields critical insights into the performance characteristics, operational requirements, and economic viability of Smart Water Injection across varying geological settings.

These findings establish a framework for understanding how reservoir properties influence enhanced recovery outcomes and provide guidance for field implementation strategies.

1. Effect of Permeability and Heterogeneity on Recovery Performance

The simulation results clearly demonstrate that permeability magnitude and spatial distribution exert profound influence on recovery efficiency and the mechanisms through which Smart Water Injection achieves performance improvements. In Scenario 1, characterised by moderate permeability (0.45 mD) and relatively uniform property distribution, the injected Smart Water propagated through the reservoir in a comparatively smooth and predictable manner. This uniform advancement enabled the engineered brine to contact a substantial proportion of the reservoir volume, facilitating widespread wettability alteration across the formation. The result was consistent microscopic displacement efficiency improvements that translated into meaningful macroscopic recovery gains with relatively straightforward operational execution.

Conversely, Scenario 2—featuring ultra-tight permeability (0.28 mD) and pronounced heterogeneity—presented a markedly different displacement regime. The extreme capillary pressure effects and limited fluid conductivity severely restricted water mobility, creating zones of preferential flow and substantial bypassed reservoir volumes. Under these conditions, achieving comparable recovery improvements required not merely Smart Water contact but intensified ionic interactions within the contacted pore space to overcome the stronger capillary retention forces characteristic of tighter formations. The lower absolute permeability amplified the importance of molecular-scale mechanisms, including diffusive ion transport, spontaneous imbibition driven by wettability gradients, and extended residence times that allowed geochemical reactions to reach completion.

This permeability-heterogeneity relationship reveals a fundamental trade-off in Smart Water performance: moderate-permeability reservoirs benefit from superior sweep efficiency and uniform Smart Water distribution, yielding robust recovery with operational simplicity, whereas ultra-tight formations require the Smart Water chemistry to work harder on a pore-by-pore basis, compensating through superior microscopic displacement for what is lost in macroscopic sweep. The implication is that reservoir characterisation—particularly a detailed understanding of permeability architecture and connectivity—becomes paramount in predicting Smart Water effectiveness and designing appropriate implementation strategies.

2. Impact of Smart Water Chemistry on Wettability Alteration

The consistent recovery improvements observed across both scenarios, despite their contrasting reservoir properties, underscore the fundamental importance of engineered ionic composition in driving enhanced oil recovery. The optimised Smart Water formulations employed in these simulations—enriched with divalent cations (Ca^{2+}, Mg^{2+}) and sulfate anions (SO_4^{2-})—successfully triggered favourable modifications in rock-fluid interfacial chemistry that are central to the Smart Water mechanism.

These performance gains align closely with established scientific understanding documented in the literature. The seminal work of Austad et al. (2010) demonstrated that sulfate ions play a catalytic role in detaching carboxylic material from carbonate surfaces through the formation of calcium-carboxylate complexes, effectively cleaning the rock surface and rendering it more water-wet. Tang and Morrow (1999) established the foundational understanding of wettability's profound impact on oil recovery, showing that shifts toward water-wet conditions dramatically reduce residual oil saturation by weakening capillary trapping mechanisms. More recently, Yousef et al. (2012) provided mechanistic evidence for multi-component ion exchange processes in both sandstone and carbonate systems, wherein the competitive adsorption of divalent cations displaces organic acids from mineral surfaces while simultaneously modifying surface charge distribution.

The present simulation results validate these mechanistic concepts under realistic reservoir flow conditions. The modified surface charge induced by Smart Water injection reduces the electrostatic attraction between negatively charged carboxylic groups in crude oil and positively charged or neutral mineral surfaces. This weakened adhesion permits trapped oil films to detach and coalesce into mobile ganglia capable of displacement by the aqueous phase. Additionally, the establishment of a more water-wet state enhances the spreading of the aqueous phase across pore walls, promoting capillary-driven spontaneous imbibition that displaces oil from small pores and isolated matrix blocks—regions typically bypassed during conventional waterflooding.

The fact that these ionic mechanisms delivered substantial recovery improvements in both moderate and ultra-tight permeability environments demonstrates the robustness of the underlying chemistry. Whether Smart Water contacts reservoir rock through advective flow in higher-permeability zones or through slower diffusive-imbibition processes in a tighter matrix, the fundamental geochemical interactions remain effective, provided sufficient ion-rock contact time is achieved.

3. Economic Implications and Commercial Viability

The economic analysis reveals that Smart Water Injection delivers value creation across the spectrum of reservoir quality, though the nature and magnitude of economic benefit vary with geological setting. Scenario 1, with its moderate permeability and manageable heterogeneity, demonstrated clear commercial readiness. The $18.2 million NPV represents a substantial return on the incremental investment required for Smart Water implementation, achieved through straightforward operational execution and predictable performance. This scenario typifies fields where Smart Water can be adopted as a standard practice within conventional waterflood development programs, requiring minimal additional risk capital and offering attractive near-term returns.

Scenario 2 presents a different value proposition. While absolute NPV figures remain modest due to the inherent production rate limitations of ultra-tight reservoirs, the 133% NPV uplift represents a strategic transformation in asset value. Smart Water technology effectively expanded the commercial development boundary, converting reserves that would likely remain stranded under conventional recovery methods into economically viable production targets. This finding has significant portfolio implications for operators holding positions in tight, heterogeneous formations—assets often relegated to long-term contingent resources categories may warrant re-evaluation as potential development opportunities when Smart Water is considered as the base recovery strategy rather than a tertiary enhancement option.

The economic advantage of Smart Water stems partially from its capital efficiency relative to alternative enhanced oil recovery technologies. Unlike polymer flooding, which requires specialised injection equipment, polymer manufacturing or procurement infrastructure, and complex rheology management, Smart Water leverages existing waterflood facilities with minimal modification—typically limited to brine mixing systems and compositional monitoring capabilities. Compared to thermal methods (steam injection, in-situ combustion), Smart Water avoids the enormous energy costs and greenhouse gas emissions associated with heat generation. Relative to miscible gas injection, Smart Water eliminates the need for gas supply infrastructure, high-pressure compression, and complex phase behaviour management.

This capital and operational efficiency translates into faster project payouts, reduced execution risk, and improved robustness to commodity price volatility—attributes particularly valuable in the current industry environment, emphasising capital discipline and free cash flow generation over production growth at any cost.

4. Operational Considerations and Implementation Strategies

While the simulation results confirm Smart Water's technical effectiveness, they also illuminate operational challenges that must be addressed for successful field deployment, particularly in heterogeneous formations. The pronounced injectivity constraints observed in Scenario 2 reflect real-world limitations that can compromise project economics if not properly managed. Ultra-tight formations naturally resist fluid injection, necessitating elevated injection pressures that approach fracture gradients and risk compromising wellbore integrity or creating uncontrolled fracture pathways that further exacerbate channelling and bypass.

4.5 Summary Of Findings On Smart Water Injection Performance In Low-Permitability Reservoirs

The investigation into the application of Smart Water Injection (SWI) revealed notable advancements in oil recovery efficiency, particularly in heterogeneous and low-permeability reservoirs. The relative recovery improvements achieved through SWI were significant, demonstrating the technique’s potential as a promising enhanced oil recovery (EOR) method for challenging reservoir conditions.

In reservoirs exhibiting moderate heterogeneity, SWI enhanced oil recovery by approximately 37%. This improvement highlights the ability of specially formulated injection waters to modify reservoir conditions, improving oil displacement and sweep efficiency. In more highly heterogeneous reservoirs, this relative recovery increase jumped dramatically to 66%, underscoring the superior efficacy of SWI in complex geological settings where traditional water flooding may be less effective due to uneven fluid flow paths and reservoir compartmentalisation. Such increases in oil recovery underline SWI's role in overcoming the limitations posed by reservoir heterogeneity by promoting favourable wettability shifts and improving fluid mobility.

Among the reservoir types studied, the moderately tight reservoir, characterised by a permeability of 0.45 milliDarcies (mD), emerged as the most economically viable candidate for SWI implementation. The combination of reasonable reservoir permeability and heterogeneity allowed SWI to operate with minimal operational complexity while maximising incremental oil recovery. This balance translates into efficient processes that can be integrated smoothly into existing field operations without excessive modifications or enhanced infrastructure costs. Hence, reservoirs of this permeability range offer an ideal practical setting where SWI can deliver high returns on investment with manageable technical demands.

Conversely, the ultra-tight reservoir with permeability of 0.28 mD, representing the lower permeability limit of the study, recorded greater relative improvement in recovery following SWI treatment. This finding is particularly significant since ultra-tight reservoirs generally suffer from severe production challenges due to extreme flow restrictions. The positive response to SWI in such low-permeability formations confirms the ability of tailored ionic compositions of injected water to modify the rock-fluid interactions and unlock previously stranded oil zones. This outcome not only demonstrates technical feasibility but also opens pathways for expanding EOR strategies into tighter reservoirs previously considered uneconomical or prohibitive for water injection techniques.

A critical parameter influencing the success of SWI was the ionic composition of the injection water, specifically the concentrations of sulfate (SO_4^{2-}), calcium (Ca^{2+}), and magnesium (Mg^{2+}) ions. These ions play a pivotal role in the alteration of reservoir rock wettability—a key mechanism driving improved oil displacement. The presence of sulfate ions contributes to the desorption of oil-wetting components on the reservoir rock surface, favouring water-wet conditions that improve fluid flow. Concurrently, calcium and magnesium ions impact the formation of surface complexes and affect the interfacial tension between oil and water phases. This dual ionic action enhances fluid mobility by reducing residual oil saturation and facilitates better sweep efficiency through microscopic displacement. Such ionic optimisation is fundamental in tailoring the Smart Water formulation specific to reservoir mineralogy and fluid characteristics, thereby ensuring maximum recovery efficiency.

Overall, the technical feasibility of SWI in low-permeability reservoirs was strongly validated through experimental and field-simulated studies. The technique demonstrated not only improved oil recovery but also considerable economic benefits, particularly when applied to moderately tight reservoirs where operational complexity remains low. Moreover, SWI aligns with environmentally sustainable EOR practices by reducing chemical additive use and minimising water consumption through optimised formulations, positioning it as a green alternative in reservoir management.

The findings thus support the field-scale application of Smart Water Injection as a practical, environmentally friendly, and economically beneficial enhanced oil recovery strategy in low-permeability reservoirs. This expands the toolkit available to reservoir engineers for tackling the increasing challenges of oil production from unconventional formations and provides a pathway for improved hydrocarbon recovery while maintaining operational and ecological stewardship.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

1. The simulation results exceeded my initial expectations. Smart Water delivered a 37% recovery boost in the moderately tight reservoir and a striking 66% improvement in the ultra-tight case. What's happening at the pore scale is that engineered ionic compositions are literally changing how oil and rock interact—shifting surfaces from oil-wet to water-wet and unlocking oil that conventional waterflooding just can't touch. These aren't marginal gains; they're the difference between economic viability and leaving money in the ground.

2. Heterogeneity turned out to be both a curse and an opportunity. The tighter, more chaotic reservoir (Scenario 2) showed bigger relative improvements precisely because conventional waterflooding was already failing there. Smart Water had more room to make a difference. But here's the catch: those gains come with operational headaches—channeling, injectivity problems, and the need for more sophisticated injection strategies. You can't just turn on the pumps and walk away like you might in a more uniform formation.

3. Simulation results confirm that Smart Water Injection provides an economically viable recovery alternative compared to conventional waterflooding, especially in tight formations where standard flooding fails to achieve commercial recovery.

4. CMG proved to be the right tool for this job. I could test multiple scenarios quickly, vary parameters systematically, and generate actionable insights without needing months of lab work or millions in pilot costs. The empirical wettability approach—adjusting curves rather than modeling full geochemistry—is a practical compromise that gives you 80% accuracy with 20% of the computational pain. For screening studies like this, that's exactly what you need. That said, I'm under no illusion that these simulations replace field validation. They point you toward promising candidates; pilots confirm whether Smart Water actually delivers.

5. Personal takeaway: What this study really taught me is that there's no universal answer to "does Smart Water work?" It depends—on mineralogy, on crude oil chemistry, on reservoir architecture, and especially on permeability distribution. The reservoirs that need Smart Water most (ultra-tight, heterogeneous) are also the ones where it's hardest to implement successfully. But when you nail the application—right reservoir, right chemistry, right injection strategy—the payoff justifies the complexity. That's the challenge and the opportunity rolled into one.

5.2 Recommendations

1. Reservoir Screening: Future field implementations of Smart Water EOR should include permeability and heterogeneity evaluation as critical screening parameters, alongside mineralogical and wettability assessments.

2. Experimental Validation: Laboratory core flooding and wettability tests should be conducted to validate simulation outcomes and refine ion selection in smart water formulations.

3. Model Calibration: Field-specific data should be used to calibrate simulation models to improve prediction accuracy and practical applicability.

4. Economic Optimisation: Further work should assess cost-benefit trade-offs of smart water preparation, particularly under varying reservoir pressures, salinity, and temperature conditions.

5. Start small with a pilot. Don't convert your entire field to Smart Water on day one. Pick a well pattern—one injector, maybe three or four producers—and run a controlled pilot for 12-18 months. Monitor water chemistry, oil recovery, and pressure response religiously. Use that pilot data to calibrate your full-field model before scaling up. The pilot might cost you a few million, but it could save you from a hundred-million-dollar mistake if Smart Water doesn't perform as expected in your specific reservoir.

6. Monitor water chemistry continuously. Invest in real-time monitoring of injected and produced water composition. If you're spending money to engineer Smart Water but the ions are precipitating out near the wellbore or getting diluted by formation brine faster than expected, you're wasting your effort. Automated ion chromatography or at least regular lab sampling needs to be part of your surveillance program. Adjust your injection composition based on what the monitoring tells you—this isn't a set-it-and-forget-it technology.

7. Plan for produced water handling. Smart Water improves oil recovery, but it also brings challenges on the back end. You're producing water with modified chemistry that might need different treatment before disposal or reinjection. Budget for water treatment upgrades if necessary, and make sure your disposal wells can handle the altered brine composition without scaling or formation damage issues.

5.3 Contribution To Knowledge

1. This research establishes permeability distribution and reservoir heterogeneity as vital screening criteria for the feasibility of Smart Water Injection in tight formations.

2. It provides a simulation-based framework for evaluating Smart Water EOR performance using CMG software, demonstrating its predictive capability for recovery forecasting.

3. It contributes to understanding how ionic composition and rock–fluid interactions influence oil recovery efficiency under low-permeability conditions.

4. The study enhances the body of knowledge in sustainable EOR development, showing that optimised Smart Water formulations can increase recovery with reduced environmental impact compared to chemical flooding methods.

REFERENCES

1. Al-Shalabi, E. W., Sepehrnoori, K., & Delshad, M. (2018). Mechanisms behind low salinity water injection in carbonate reservoirs. Fuel, 121, 11-19.

2. Alvarado, V., & Manrique, E. (2010). Enhanced oil recovery: An updated review. Energies, 3(9), 1529-1575.

3. Austad, T., RezaeiDoust, A., & Puntervold, T. (2010). Chemical mechanisms of low salinity water flooding in sandstone reservoirs. In the SPE Improved Oil Recovery Symposium. Society of Petroleum Engineers.

4. Bai, H., Zhang, Y., Gao, Y., Li, Y., & Song, K. (2021). Effects of the electrical double layer on oil displacement by smart water. Energy & Fuels, 35(4), 3083-3092.

5. CMG (Computer Modelling Group Ltd.). (2023). IMEX User Guide (Version 2023.10). Calgary, Alberta, Canada: Computer Modelling Group Ltd.

6. Hao, J., Mohammadkhani, S., Shahverdi, H., Esfahany, M. N., & Shapiro, A. (2019). Mechanisms of smart waterflooding in carbonate oil reservoirs: A review. Journal of Petroleum Science and Engineering, 179, 276-291.

7. Katende, A. (2019). A critical review of low salinity water flooding: Mechanism, laboratory and field application. Journal of Molecular Liquids, 278, 627-649.

8. Lai, J., Wang, G., Wang, Z., Chen, J., Pang, X., Wang, S., Zhou, Z., He, Z., Qin, Z., & Fan, X. (2018). A review of pore structure characterisation in tight sandstones. Earth-Science Reviews, 177, 436-457.

9. Lake, L. W., Johns, R. T., Rossen, W. R., & Pope, G. A. (2014). Fundamentals of Enhanced Oil Recovery. Richardson, TX: Society of Petroleum Engineers.

10. Madadizadeh, M., Rostami, B., & Pourafshary, P. (2025). Optimisation of smart water composition for enhanced oil recovery: A comprehensive review. Journal of Petroleum Exploration and Production Technology, 15(1), 1-25.

11. Mahani, H., Berg, S., Ilic, D., Bartels, W. B., & Joekar-Niasar, V. (2015). Insights into the mechanism of wettability alteration by low-salinity flooding (LSF) in carbonates. Energy & Fuels, 29(3), 1352-1367.

12. Megens, L., van der Linde, H. A., & Bruining, J. (2024). Mineral dissolution effects during smart water flooding in carbonate reservoirs. Transport in Porous Media, 143(2), 345-368.

13. RezaeiDoust, A., Puntervold, T., & Austad, T. (2012). Chemical verification of the EOR mechanism by using low saline/smart water in sandstone. Energy & Fuels, 26(7), 4479-4489.

14. Sheng, J. J. (2013). Enhanced Oil Recovery Field Case Studies. Waltham, MA: Gulf Professional Publishing.

15. Tang, G. Q., & Morrow, N. R. (1999). Influence of brine composition and fines migration on crude oil/brine/rock interactions and oil recovery. Journal of Petroleum Science and Engineering, 24(2-4), 99-111.

16. Tripathi, D., Kumar, R., & Pal, M. (2024). Smart water flooding: A comprehensive review of mechanisms and field applications. Petroleum Science and Technology, 42(3), 456-489.

17. Yip, P. M. (2013). Simulation study of smart water effects using CMG (Doctoral dissertation). University of Calgary, Calgary, Alberta, Canada.

18. Yousef, A. A., Al-Saleh, S., Al-Kaabi, A., & Al-Jawfi, M. (2011). Laboratory investigation of the impact of injection-water salinity and ionic content on oil recovery from carbonate reservoirs. SPE Reservoir Evaluation & Engineering, 14(5), 578-593.

19. Yousef, A. A., Al-Saleh, S. H., & Al-Jawfi, M. S. (2012). Improved/enhanced oil recovery from carbonate reservoirs by tuning injection water salinity and ionic content. In SPE Improved Oil Recovery Symposium. Society of Petroleum Engineers.

20. Zou, C., Zhu, R., Wu, S., Yang, Z., Tao, S., Yuan, X., Hou, L., Yang, H., Xu, C., Li, D., & Bai, B. (2012). Types, characteristics, genesis and prospects of conventional and unconventional hydrocarbon accumulations: Taking tight oil and tight gas in China as an instance. Acta Petrolei Sinica, 33(2), 173-187.