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Review Paper: Low Salinity Water Injection for Enhanced Oil Recovery

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Cover Page Footnote

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Review Paper: Low Salinity Water Injection for Enhanced Oil Recovery.

Mahmoud Ali, Moamen Talaat, and Abdelrahman Arafa[1]

Abstract

Low salinity water injection (LSWI) is one of the leading techniques in terms of enhancing oil recovery in sandstone and carbonate formations. Many studies and lab experiments were performed on the LSWI applications. Some studies have pointed out multiple negative observations, while other studies have shown the positive potential of using LSWI in enhancing oil recovery. However, the technology used in LSWI applications is still considered new and more studies need to be performed to figure out new technologies that are low-cost and more efficient. This review paper examines LSWI by analyzing the benefits and drawbacks of employing LSWI in various formations. Primarily, the paper analyzes previous work on LSWI in order to objectively assess the possibility of improved oil recovery and its mechanism. Following that, the study investigates numerous different implementations of the LSWI approach and the leap that has occurred in the oil business. To study the applicability of LSWI, this critical review discusses the experimental and fieldwork that led to the development of low salinity water (LSW) flooding techniques. Upon completion, the article would represent the applicability of LSW flooding in various reservoir conditions, as mentioned in various research studies.

Keywords: Low SAL; LSWI; Fine-migration; Wettability-alteration; EOR; IOR

In the oil and gas industry, a reservoir is depleted through different recovery stages, including primary, secondary and tertiary recoveries. Each recovery stage has its own driving mechanisms. At the start of production, the well is produced using the natural energy of the reservoir. This recovery stage is the primary recovery stage which contains different mechanisms such as solution gas, water influx, gas cap drives, and gravity drainage. The primary recovery stage usually yields from 3 % to 15% from the original oil in place (OOIP). As the reservoir is depleted and the reservoir pressure starts to reach the critical pressure, the secondary recovery processes start to be essential. Usually, it is recommended to start the secondary recovery at the early stage of the well life so that we can ensure the minimum amount of gas to be kicked during flooding operation. Unfortunately, our knowledge of the reservoir at the early stage is usually not sufficient for designing secondary recovery processes. Consequently, the secondary recovery operation is preferred to start before gas is introduced in the reservoir. The main goal of secondary recovery is to maintain the reservoir pressure using fluid injection. It is worth mentioning that secondary recovery processes are displacement processes that do not change any of the fluid or the reservoir properties. On average, secondary recovery drives almost 50% of OOIP. 50% is considered an excellent recovery factor, but it is still unsatisfactory in today's world of energy hunger [1,2].

Although the depletion of the reservoir pressure in both primary and secondary recovery stages is significant, a huge amount of hydrocarbon is left in the reservoir, waiting for technology

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development and cost-efficient solutions. At that stage of well life, the tertiary recovery phase (EOR) is introduced. Tertiary recovery methods concern increasing the oil recovery mainly by changing the fluid and rock properties in an economical way. The EOR process increases the oil recovery by injecting a fluid that is different from the reservoir fluid rather than water or immiscible gas. EOR is done using different techniques such as miscible gas injection, chemical injection, thermal processes, and other EOR methods such as microbial and low salinity water injection (LSWI). Different gasses may be injected, such as HC-gasses, nitrogen, and carbon dioxide. On the other hand, the most common chemical flooding processes are polymer, surfactant, or alkaline injection. In addition, thermal EOR includes combustion and steam flooding. Some technicians use Improved oil recovery (IOR) and EOR interchangeably. However, IOR is a more generic term. IOR refers to any process that leads to an increase in the recovery factor. Both secondary recovery and EOR are subdivisions of IOR. An illustration of the different recovery processes is shown in Figure 1.

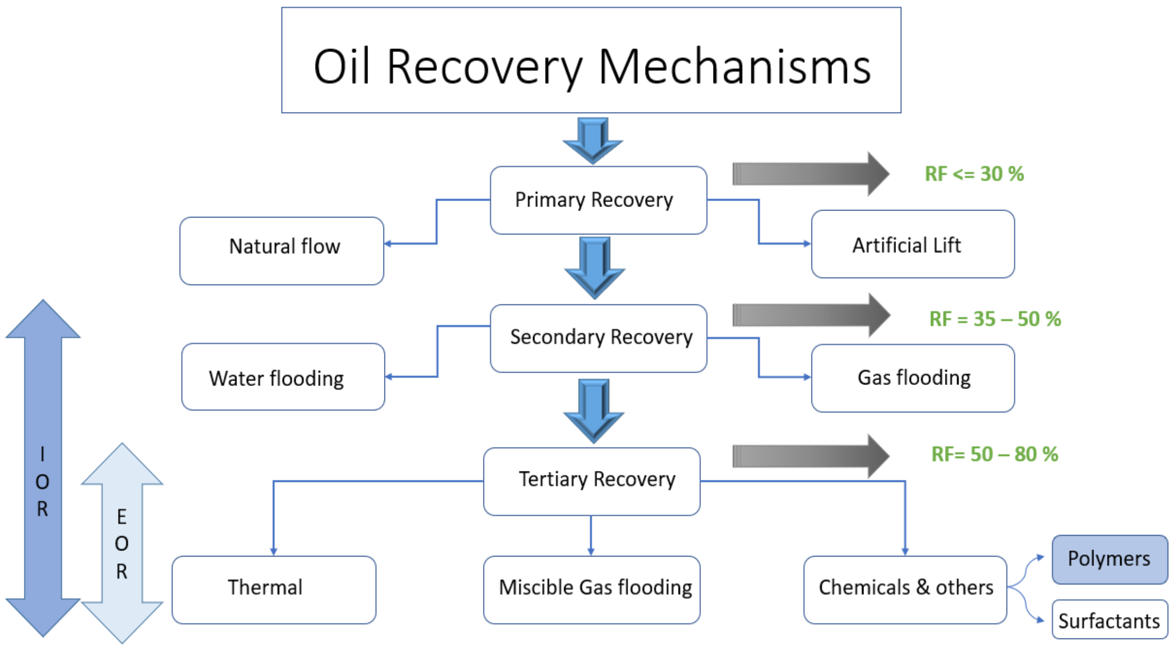


Figure 1. Illustration of the different Oil recovery processes

Amongst the IOR technique, water flooding has been the most commonly used method to enhance the recovery factor since the 19th century. Recently, the industry started to move toward EOR in order to meet the high energy demand due to the Industrial Revolution. LSWI targets wettability alteration of both sandstone and carbonate reservoirs, which is a very efficient technique as observed in both fragmental and carbonate reservoirs. This efficiency is noticed by the increase in the recovery factor of light to medium oil. LSWI also has the advantage of water availability and low capital and operating cost, leading to favorable economic feasibility compared to IOR and EOR. Many experiments on both lab and field-scale found encouraging results of using LSWI to increase oil recovery. However, wettability alteration is believed to be the main driver of increasing oil recovery in LSWI; researchers also found that fine migration and dissolution processes significantly affect the increasing recovery factor (RF). In fact, several researches are in progress to better understand the chemical interactions resulting from using LSWI. Many experiments were conducted on sandstone. Researchers found that clay presence in sandstone is the main reason for wettability alteration. On the other hand, modeling studies are still needed for carbonate reservoirs in order to study the chemical interaction of LSW with carbonate. There are some reasons for the relatively low number of experiments conducted on carbonates. The main reason is the heterogeneity of carbonates which makes it not easy to predict the LSW interaction with carbonates. The main challenge of LSWI is water sourcing and disposal. One way to get LSW is by using multistage distillation of seawater. Here, the concept is to apply heat into high saline water and collect the condensate, low salinity water from the distillation apparatus. The other technique to get LSW is to use pressure to force high saline water into a certain filtration setup through a membrane in order to separate salt from water. In general, the membrane technique is preferred due to space limitations for the distillation apparatus, especially in offshore operations [3,4]. This review paper presents previous laboratory and field work done on sandstones and carbonates to study the effect of LSWI on both formations taking into consideration the LSWI applicability under different reservoir environments.

Experimental Work of LSW on Sandstone

Since the fourteenth century, several experimental researches on sandstone have been done. When scientists opted to substitute freshwater with saline water in their experimental work on Kansas field cores in the fourteenth century, they advocated the use of saline water instead of freshwater. The use of salt water resulted in a 15% increase in recovery factor from the freshwater injection, according to the researchers. In later studies, scientists related the low RF of freshwater to the volume of clay content as freshwater caused the clay to swell. As a result, scientists have started to study water's physical and chemical properties to decrease the probability of clay swelling. In the sixteenth century, scientists began to investigate the salt influence on RF. In some studies, results showed that low salinity water increased the RF by 21% over high saline water due to the clay hydration phenomenon. As salinity concentration was decreasing, both pressure drop and recovery through the core were increasing. On the other hand, some studies in the nineteenth century reported an increase in RF due to an increase in salinity up to a specific limit as shown in Figure 2. In 2007, Zhang [4] conducted many experiments to investigate the effect of salinity on RF. He found out that high saline water of 8000 ppm NaCl has no effect on RF; however, when he used a concentration of 1500 ppm NaCl, the RF was increased significantly. After many years, Patel [5] came to confirm Zhang's outcomes. Patel's research group figured out that LSW caused a reduction in residual oil from 50% to 38% when salinity was decreased from 22000 ppm to 5500 ppm. Besides, the recovery factor increased from 40% to 68% when salinity decreased from 22000 ppm to 50-60 ppm. To sum up the outcomes of the previous studies, there is a salinity level under which the effect of LSW on recovery is significant [2,4,5].

Decreasing the salinity of injected water or the formation water helps decrease residual oil volume significantly. Temperature also plays a role in process efficiency. As the reservoir temperature increases, the water wetness is improved, and the RF is increased. However, the temperature role is still minor relative to the salinity of the water. Further research was conducted to investigate the LSW effect on the wettability alteration of sandstone using spontaneous imbibition. Researchers found that Ca^{+2} concentration in LSWI plays a major role in wettability alteration. As Ca+2 concentration increases, the wettability becomes more oil-wet. Change of wettability into oil wet is not preferred since it leads to a reduction of oil recovery [6]. Consequently, control of Ca+2 in the formation is essential for successful LSWI. In later experimental work on Russian cores, spontaneous imbibition tests showed that LSWI helps to increase RF by altering the sandstone into water-wet by changing relative permeabilities [7].

To sum up the major outcomes of the experimental work done on sandstone, LSWI significantly reduces the residual oil in the reservoir by wettability alteration of the rock into water wet. However, the salinity level should be within the accepted level of salinity as well as the concentration of Ca+2. The reservoir temperature is an advantage to the injection process of low salinity water since it increases the wettability alteration process.

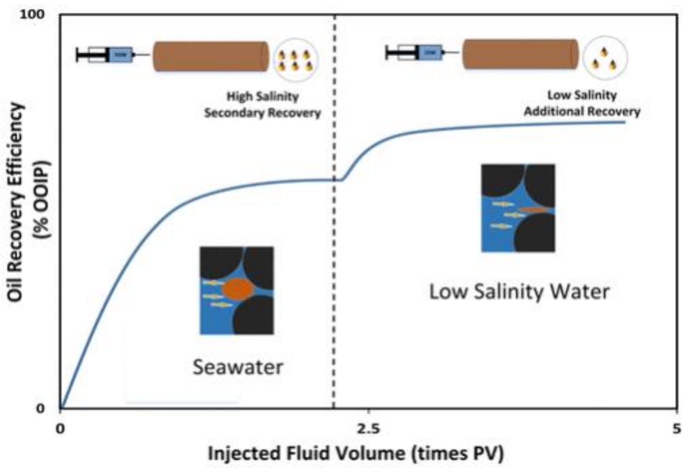


Figure 2. The output of a typical LSWI on sandstone [5]

Experimental Work of LSW of Carbonates

The effect of LSW on carbonates is not well covered due to the heterogeneity of carbonates. Nevertheless, laboratory-scale experiments were conducted to investigate the effect of LSWI on RF of carbonates using core flooding and spontaneous imbibition studies. Studies on limestone cores have found that the high concentration of sulfate ions in LSW helps to increase RF at high temperatures for spontaneous imbibition experiments. The sulfate ion works as a wettability agent that helps to alter the carbonate wettability to water wettability. Spontaneous imbibition of limestone cores resulted in a 40% increase in RF. Using forced injection, the recovery increased to 60% recovery. Many other studies investigated the effect of calcium and magnesium ions on the reduction of residual oil. As illustrated in Figure 3, these studies concluded that wettability alteration occurs in carbonates if the injected water contains either calcium or magnesium ions [2,8].

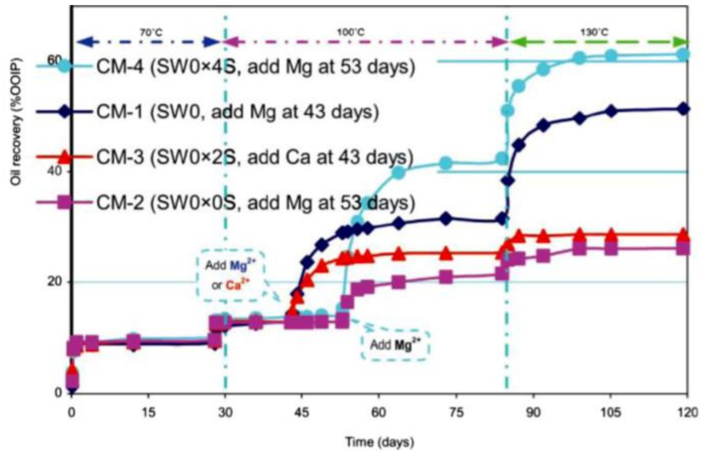


Figure 3. Effect of Mg^{2+} and Ca^{2+} on wettability alteration of carbonates [8]

Many experimental-scale tests investigated core flooding on limestone, dolomite, and chalk. A 36% recovery factor was obtained from limestone cores when using two wt% KCL as a result of the exchange of ions with clays associated with the rock. Also, the effect of incremental diluted seawater on incremental oil recovery was investigated. Figure 4 shows the increments of recovery due to the stepwise reduction in the salinity of injected water. The figure shows that an 18% oil recovery increment is due to LSWI.

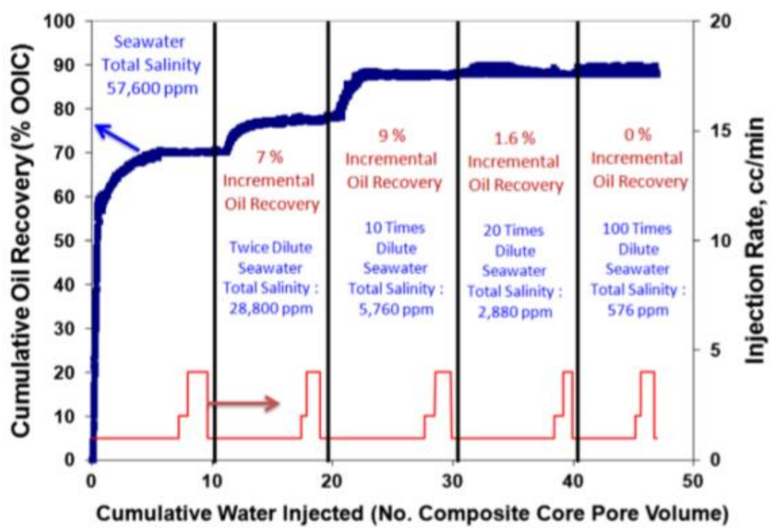


Figure 4. Incremental dilution effect on recovery [8]

To investigate the effect of low-salinity water on dolomite, further studies were conducted. Researchers noticed an increase in the recovery of dolomite due to the use of LSWI. They related the increase of recovery of 20% to the existence of borate (BO_3^{3-}) and phosphate (PO_4^{3-}) [2]. Many other studies were conducted to investigate the hardening and softening of water's effect on wettability alteration. In fact, both the hardening and softening of water have a desired effect on wettability. Softening of LSW helps dissolution. Besides, hardening leads to a change in the surface charge. Both phenomena are needed for wettability alteration. The effect of LSWI on chalk was investigated by injecting seawater followed by LSWI in succession. The outcome of this process did not lead to any further recovery. Nevertheless, at high temperatures, the recovery factor started to increase. Researchers related the recovery increase to fine migration. They noticed that, at high temperatures, a higher-pressure drop is obtained, leading to an increase in capillary number (Nc). The increase of Nc caused fine migration, which led to an increase in pressure drop. [8]

$$Nc = u\mu w/\sigma k rw = k\Delta P / \sigma L \qquad \text{EQN.1}$$

Where u is Darcy's injection velocity, μw is water viscosity, σ is oil-water interfacial tension, k_{rw} is water relative permeability, k is absolute permeability, ΔP/L is the applied pressure gradient.
To sum up the Experimental-scale outcomes on carbonates, LSWI improves oil recovery up to 85% of OOIP. However, the IFT and pH cannot explain the effect of LSWI on carbonates as shown in Figure 5; the leading cause of that recovery increase is the change in carbonate wettability into intermediate-wet. Besides, the increase of calcium, magnesium, and sulfate ions up to a certain level affects oil recovery positively [9].

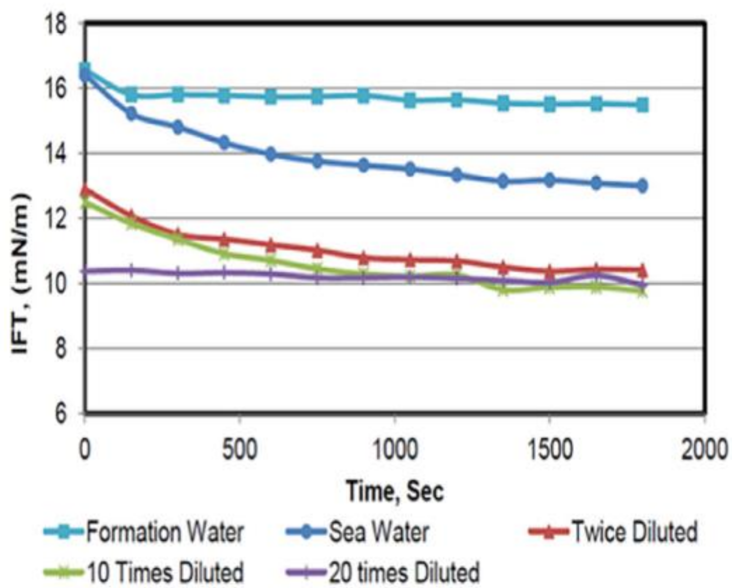


Figure 5. IFT measurements for different brines [9]

Field Work of LSW on Sandstones and Carbonates

Field studies on sandstone rocks confirmed the experimental-scale studies conducted on sandstone plugs. Using the modified log-inject-log technique, residual oil saturation was measured after using different salinity-injected water. Laboratory studies showed that high saline and medium saline water have no significant effect on residual oil saturation. On the other hand, LSWI resulted in a high recovery factor. The fieldwork results are consistent with the lab outcomes. Figure 6 shows a typical difference between high and low-saline water[2,10].

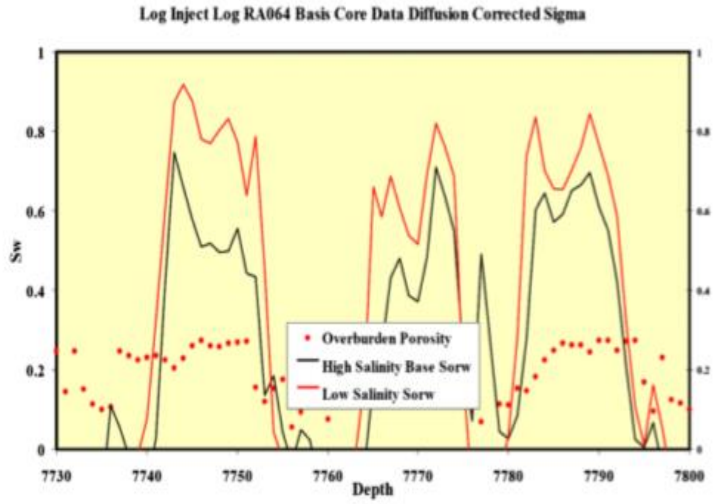


Figure 6. LSW effect on Sw [10]

Single-well chemical tracer tests (SWCTT) were conducted to measure the effect of LSWI on residual oil. The producer and injector were 1040 feet apart. Results show that LSWI of a maximum of 2600 ppm causes a reduction in residual oil by 10%. In general, if water salinity goes down to 5000 ppm, the recovery factor increases from 8% to 19%. These field results are in agreement with the experimental-scale outcomes. The spontaneous imbibition laboratory results and log-inject-log outcomes were confirmed by fieldwork In Syria. The main function of LSWI confirmed by this fieldwork is wettability alteration. Buckley Leverett's theory illustrated in Figure 7 was used to explain the alteration phenomenon [10].

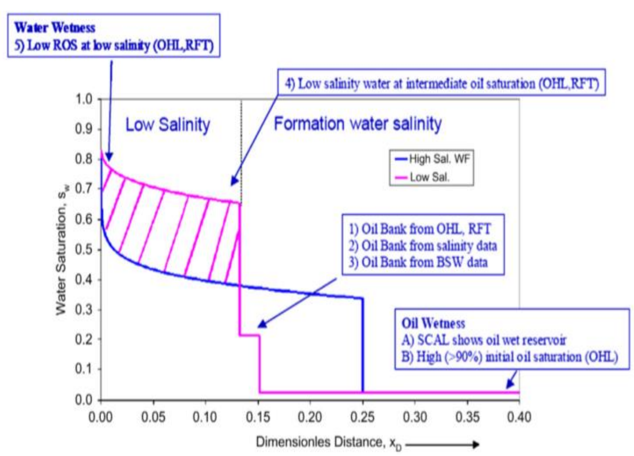


Figure 7. Saturation profile for both high and low salinity water flooding based on Buckley-Leverett [11]

Figure 7 shows that oil banking is in front of LSW shock. That is due to desorbed oil accumulation. While The field is an oil-wet reservoir rock, a recovery factor of 10% to 15% was obtained, confirming spontaneous imbibition results. Further research confirmed that LSWI works well for sandstone with high or low content. In low clay-content sandstone, wettability alteration works very well, which leads to lower residual oil saturation. In the other scenario of high clay content, clay migration causes formation damage which leads to reduced water relative permeability and increased oil recovery factor. Not all fieldworks get to confirm laboratory results.

Many fieldworks on the North Sea and west African fields concluded that LSWI is not that promising compared to laboratory-scale tests due to the complex mineralogy structure when it comes to field application [11,12].

A minimal number of field works were conducted on carbonates. The very first work was conducted in 2012 in a Jurassic carbonate reservoir. The test was conducted to compare the effect of seawater injection versus LSWI (2-10 times more diluted than seawater). The test used different low-salinity water injected in stages, and residual saturation was obtained for every stage. The test resulted in decreasing residual saturation of 7%, which is aligned with the laboratory outcomes. This agreement between lab and field outcomes is encouraging to conduct more research to better understand the RF increase mechanism in carbonates [13].

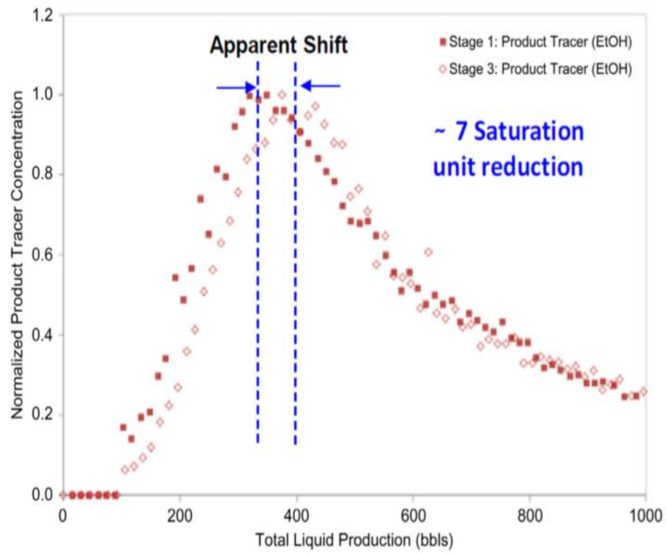


Figure 8. Comparing seawater and LSWI on carbonates. [13]

Mechanism for Low Salinity Water Injection in Sandstone Rocks

Several mechanisms may explain the reasons behind increased recovery factors using low salinity water flooding methods. The suggested mechanisms include fines migration, wettability alteration, PH increase, multi-ion exchange, and salting-in. However, there is no consensus between the scientists on which method is the primary underlying mechanism for incremental oil recovery. This happens due to the complexity of the low salinity water projects and the interactions of the displacing fluid with external factors like crude oil, formation water, and the rock type; moreover, the experiments may give conflicting observations from one mechanism to the other.

Fines Migration

This phenomenon happens initially from the clay particles when the flowing fluid has an insufficient concentration of divalent cations Ca+2 and Mg+2. In the reservoir, fine migration occurs when the low-salinity water bypasses the clay zone; consequently, Low saline water produces clay fines, especially kaolinite fragments. The main advantage of this phenomenon is that the released clay particles will block some of the pore throats, which will divert the water flow into non-swept zones [4,14]. Thus, an increase in the clay content will increase the recovery factor [15]. This makes this method favorable for reservoirs with clay problems. However, fines migration is viewed as an auxiliary, not as the main one, because there has been a number of experiments where fines migration was not observed [16].

pH Increase

If there is a reservoir with low pH values (5 – 6), at such conditions, it becomes easier for both the acidic and the basic components to be adsorbed onto the clay surface. As LSW is injected into the reservoir, the chemical equilibrium is disturbed due to the interaction between the brine and the formation minerals resulting in a loss of cations, especially Ca+2.

Clay minerals on the surface of the rock are negatively charged. Hence, they are constantly seeking positive cations to achieve chemical equilibrium. Ca^{+2} cations get attracted, consequently, to the negatively charged clay minerals resulting in the exchange of H^{+} from the clay minerals. This causes the positive hydrogen ions to get attracted to the clay surface to compensate for the loss of the divalent Calcium ions. As a result of the injection of the low saline water, an increase in the pH close to the clay surface would take place. However, this phenomenon can also occur using high-salinity water. In addition to that, some of the criticism for this mechanism points to the fact that the increase caused by low salinity water injection is not more than one pH in many cases, which makes the medium slightly basic. However, it does not justify the increase in oil recovery using this mechanism [16].

Multi-Ion Exchange

Many scientists claimed that the primary mechanism behind the increase of water wetness due to low salinity water injection is mainly controlled by the exchange of ions present in the crude oil and the clay minerals. The cations in the brine act as a bridge between the negatively charged surface and the carboxylic minerals in the hydrocarbons. This organic material is removed by the ion exchange at the surface [16].

Salting-In

Salting-in means decreasing the salinity of a system by removing the salt from the water. This mechanism has an impact on increasing the solubility of the hydrocarbon in water. Organic materials are solvated in water by the creation using hydrogen bonds around the hydrophobic part. However, the concentration of the divalent ions has a significant impact on the solubility of the organic materials, as the presence of Ca+2, Mg+2, or Na may lead to the breakage of the formed water structure [16,17].

This mechanism has been verified by an experiment that showed that by decreasing the salinity of the used brine, there is an increase in the desorption of 4-tert-butyl benzoic acid in an aqueous suspension of kaolinite [17].

Wettability Alternation in Sandstones

Wettability alteration using LSWI is viewed to be the main mechanism for improving oil recovery. The previously mentioned mechanisms act as auxiliary methods in increasing the recovery. The presence of clay minerals is required for the wettability alteration mechanism to work. Divalent cations such as Ca+2, Mg+2 should be present in the injected water. This technique worked for salinities up to 5000 ppm.

The Wettability alteration mechanism could be explained through double-layer expansion. The clay surface is negatively charged, which attracts positively charged particles on its surface to neutralize it. The attracted cations form 2 layers. The first layer is the “stern” layer which contains only cations as shown in Figure 9. The second layer is the diffusive layer, where the attraction force is lowered between the positive ions (formation) and the negative ions (clay). Thus, cations and anions could coexist in the diffusive layer. The negative components in the oil could be attracted to the cations present in the stern layer making the surface oil wet. However, it was found that in low-salinity water injection projects, the thickness of the diffusive layer increases. Hence, the chance of the negative components of the oil getting closer to the stern layer decreases, creating more water-wet conditions [10,18].

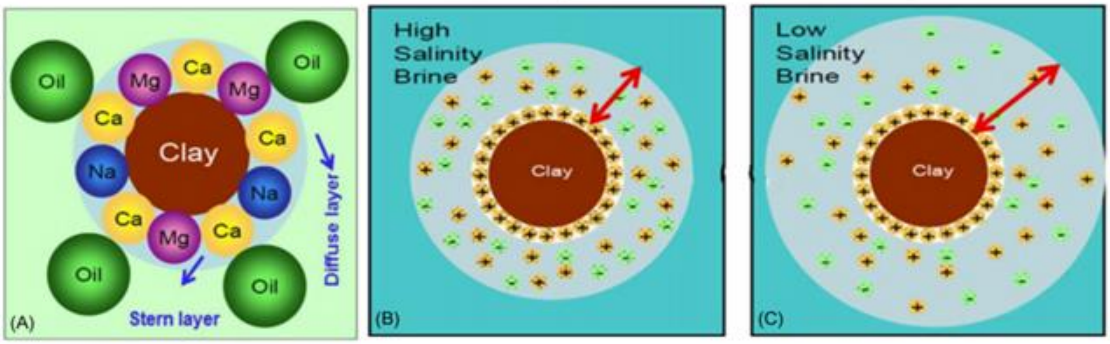


Figure 9. Schematic diagram of electric double layer [18]

Several pieces of research have shown that the cations type had an impact on the efficiency of the oil recovery. This research showed that the contact angle increases with the increase of pressure and temperature. However, if the water salinity decreases, the contact angle also decreases. Nasralla and Nasr-El-Din [19] were trying to increase the double-layer mechanism to increase oil recovery. Their findings concluded that the use of low salinity water injection projects as a secondary recovery method rather than an enhanced recovery method showed increased oil recovery. [19]

The Mechanism for Low Salinity Water Injection in Carbonate Rock

The mechanism by which low salinity water injection projects enhance the oil recovery for carbonate rocks is considered to be less complicated than sandstones as the primary mechanism will depend on the wettability alteration mainly. This phenomenon occurs due to the modification of the surface charge either by dissolution or the desorption of the organic matter.

Several studies were performed to examine the ability to change the charge of the rock surface. Strand et al. [20] tried to investigate the impact of sulfate ions on the wettability alteration of the carbonate rocks and the results are shown in Figure 10.

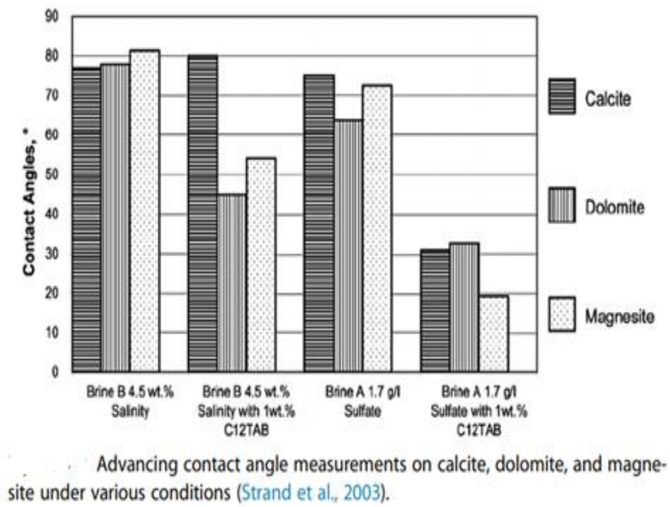


Figure 10. Advancing contact angle measurements on calcite, dolomite, and magnesite. [20]

Experiments have shown that sulfates act as a catalyst by improving the imbibition rates due to their ability to adhere to the rock surface, making it partially negatively charged. This property of sulfates is more efficient below a specific concentration of 1 g/l and at high temperatures. The experiments also showed that depending on the rock types (Calcite, Dolomite, or Magnesite.), the cations and the salinity of the brine along with sulfate could alter the wettability of the carbonate rocks towards a more water-wet rock [20].

Other experiments were performed to confirm the findings by Strand et al. [20]. The experiments done by Hognesen et al. [21] were trying to investigate the impact sulfates had on the imbibition rates and oil recovery. Hognesen et al. [21] conducted the experiment under harsher conditions by increasing the temperature of the experiment to (90 – 130 C). Additionally, Strand et al. [20] showed that sulfates work very well under very high temperatures; this indicates an agreement between both experiments. However, Hognesen et al. [21] decided to increase the sulfate concentration to 2.31 gm/L, which resulted in an incremental increase in oil recovery [21,22].

By increasing the system's temperature, the affinity of the surface to sulfate increases. The adsorption of the sulfates to the rock surface changes it into a partially negatively charged surface. The high temperatures also help in decomposing the negative carboxylic group in the hydrocarbons. Thus, there is a repulsion between the surface of the rock and the hydrocarbons, resulting in increased oil recovery. Although Hognesen et al. [21] used a higher concentration of sulfates, it should be clear that the concentration of the Ca+2 in the brine should be well known to avoid the precipitation of CaSO4, which is unfavorable and may result in unwanted consequences. Overall, the key behind the increased oil recovery is the minerals found in the injected seawater (SO4 -2, Ca+2, and Mg +2). However, it was also found that by reducing the salinity of the injected water, the oil recovery was improved significantly. This could be explained through the reduction in the interfacial tension or wettability alteration [21].

Yousef et al. [22] tried to investigate this dilemma. He wanted to figure out which method is the primary reason for increased oil recovery using low-salinity water injection projects in carbonate reservoirs.

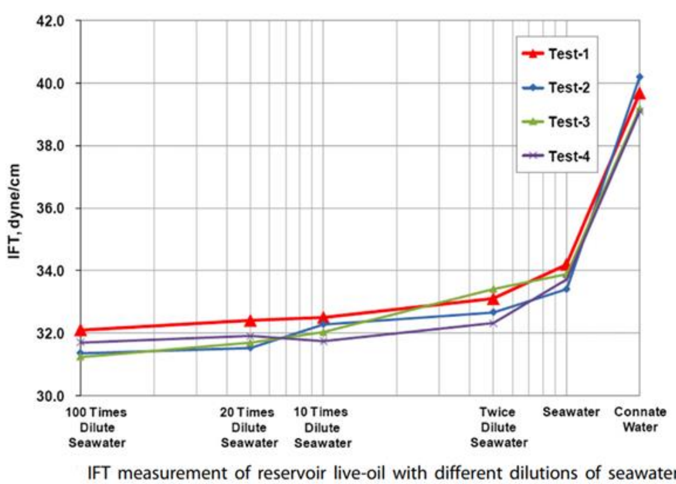
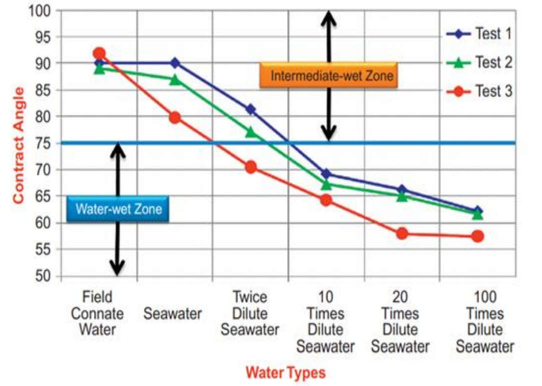
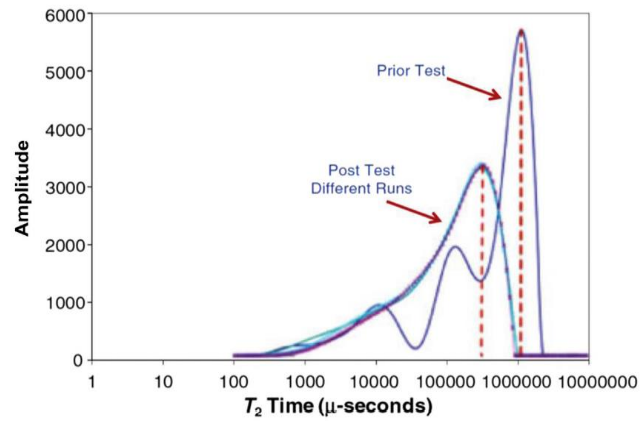


Figure 11. IFT measurements for various salinity levels. [21]



Contact angle measurement of reservoir live-oil with different dilutions of seawater (Yousef et al., 2011).

Figure 12.Contact angle measurements of various dilutions [21]



NMR T_2 distribution for a rock sample before and after the coreflood experiment (Yousef et al., 2011).

Figure 13. NMR T2 distribution [22]

According to the results, Interfacial Tension IFT has no significant impact on incremental oil recovery as shown in Figure 11, and wettability alteration, that is a function in contact angle as shown in Figure 12, is the key mechanism behind this additional oil rise. Yousef et al. [22] tried to examine the mechanism behind the wettability alteration using the Nuclear Magnetic Resonance NMR tool. His findings, as shown in Figure 13, indicate that the amplitudes obtained for the post-test case shifted left, with low and high amplitudes overlapping. This shift is an indication of a faster rate of relaxation as a result of the pore improvement due to dissolution and changes in the carbonate rock surface charge [22].

Heavy Oil Application

There are various methods for injecting low-salinity water that can be employed in compliance control. This takes place when an adequate amount of Ca 2+ to dilute the salinity of the water injected. The reason for using Ca 2+ is because it increases the clay minerals' mobility and reduces the porosity which would lead to a reduction in permeability. The injected water effects are classified into secondary, IOR and EOR according to its chemistry. The IOR is related to SWF- sandstone and carbonates, but the EOR is related to polymer flooding, surfactant flooding, ASP flooding, dilute surfactant, carbonated water, Co2 WAG, steam flooding, and microbial/nanotechnology. The secondary impacts are related to offshore waterflooding. After conducting trials and completing some numerical analysis, it was discovered that the secondary recovery for heavy oil recovered 70% of the original oil in place (OOIP) [23].

LSWI/EWI Polymer Flooding Applications

Researchers and chemists have found several advantages for the low salinity water injection which compensates the polymer flooding [24]. They have addressed that the LSWI hardly needs any additional chemicals which could be economically targeted; however, the seawater would need adding some chemicals in order to acquire the viscous state needed. In addition to this positive economical side, the LSWI would increase the oil recovery as it improves the sweep efficiency; thus, it achieves a faster oil recovery process. Kozaki [25] conducted experiments employing tertiary Berea Sandstone cores and the two different salinity solutions. As he observed, the low-salinity polymer solution, as compared to the high-salinity polymer solution, reduces the saturation of the residual oil by 5 to 10% [26]. Furthermore, a report performed by Vermolen, has stated some other advantages of using the low salinity polymer flooding such as: [27]

1. Lower sensitivity for the mechanical shear
2. Higher stability for high salinity/high temperature formations
3. Higher usage for high salinity/high temperature formations
4. Reduction of the production potential chemistry issues (such as souring, scaling and water/oil separation)
5. Increasing the visco-elasticity of the LSWI.
6. Reduction in the residual oil.

On the other hand, the report has issued several risks for using the low salinity polymer solution such as:

1. Clay swelling
2. Polymer adsorption.
3. Mixing the high salinity with the low salinity.
4. Cation exchange
5. The presence of a polymer factor of retardation resulting from using low salinity water, could lead to oil recovery delay, which would dramatically impact negatively on the project economics.

After investigations, Spildo [28] has observed that adding surfactant injections to the low salinity water is considered as a better choice than surfactant flooding. Surfactant injection with low salinity water increments its performance effectiveness. The surfactant is quite beneficial for eliminating the capillary high pressure and alleviating the mobilized oil trapping [29,30].

LSWI / EWI CO2 Flooding Application

Researchers have used a sequence of geochemical reactions in order to examine the impacts of low salinity water injection and carbon dioxide gas on carbonate oil reservoirs [31,32,33]. Carbonic acid is responsible for rock weathering as it is the most abundant acid in the natural water system. The carbonic acid results from the dissolution of CO2 in water thus its state changes from the gaseous state to an aqueous solution and then forms H2CO3 as in the following reactions [34,35,36].

$$CO_{2(g)} \rightleftharpoons CO_{2(aq)}$$

$$CO_{2(aq)} + H_2O \rightleftharpoons H_2CO_3$$

(Reaction 1)

Consequently, ionization reactions took place as follows:

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$

(Reaction 2)

$$HCO_3^- \leftrightarrow H^+ + CO_3^{-2}$$

(Reaction 3)

Furthermore, the dissolution for Calcite is performed as follows:

$$CaCO_3 \leftrightarrow Ca^{2+} + CO_3^{2-}$$

(Reaction 4)

Then, they add the mixture of carbon dioxide gas and water to the calcium carbonate as in the following reaction:

$$CO_{2(g)} + H_2O + CaCO_3 \leftrightarrow Ca^{2+} + 2\ HCO_3^-$$

(Reaction 5)

Dolomite dissolution is prepared:

$$2CO_{2(g)} + 2H_2O + CaMg(CO3)_2 \leftrightarrow Ca^{2+} + Mg^{2+} + 4HCO_3^-$$

(Reaction 6)

In addition, the anhydrite is ionized in the presence of carbon dioxide gas giving positive and negative ions:

$$CaSO_4 \leftrightarrow Ca^{2+} + SO_4^{2-}$$

(Reaction 7)

The geochemical analysis was made by Al-Shalabi [37] using the PHREEQC equipment (simulator). There were three various modes of injection that were compared which are the CO2 injection, LSWI and the combined injection (LSWI and CO_2 injection). The analysis depicts that the value of the pH-induced wettability alteration pronounced using low salinity water injection only is more than the effect of the combination of the LSWI and CO_2 injection. The pH trend in LSWI only is much higher when compared to the decrease in the same trend but when using CO2 injection and when using the combination of LSWI and CO2 injection[37,38,39]. They have observed carbonic acid formation which gives an explanation of the latter decrease in the pH value. Figure 14 shows this gap in the pH values of LSWI, CO2 injection and the combined injection [40].

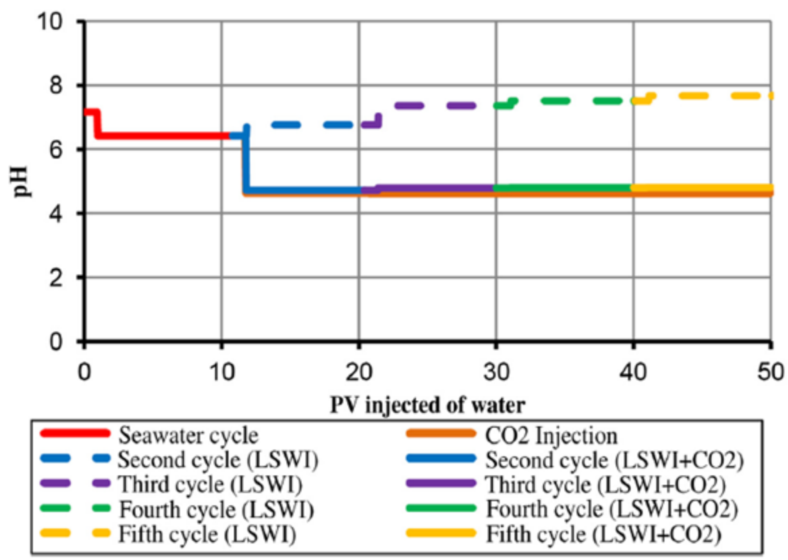


Figure 14. pH plot of LSWI only, CO2 injection only and the combined LSWI and CO2 injection [40].

Conclusion

This work is to investigate Low salinity water injection process, its mechanisms and its applicability under different reservoir conditions. The paper reviews a huge spectrum of field and lab work conducted on both fragmental and carbonate rocks. Both lab and field works conducted by different scientists agree on some facts that the main mechanism of enhancing oil recovery using low-salinity water injection projects is the wettability alteration, especially in carbonate reservoirs[41,42]. However, this is not true for every formation under every condition. The mechanism that works for carbonates does not necessarily work for sandstones due to the change in the chemical competitions and the different depositional environments. As a result, thorough laboratory investigations on representative rocks and fluid samples should be done before any field-scale application to examine the possibility of LSW boosting oil recovery.

Moreover, the study reached a conclusion that the oil's effective permeability becomes a little sensitive to water injection projects compared to low saline injection. It is also found that mixing the low salinity water with EOR mechanisms like polymer, surfactant, and CO_2 flooding projects would result in improved oil recovery [43,44]. However, there is no agreement on which EOR mechanism works well in different reservoirs and under what conditions. CO_2 flooding seems to be one of the most effective alternating methods due to the high solubility of CO2 in low-salinity water, especially in hydrophilic conditions. Still, the water salinity, reservoir pressure and reservoir temperature would be a big determinant of the injection effectiveness. Overall, to maximize the benefits of low-saline water injection projects, it is advisable to perform lab tests before implementing the projects in field scale considering the alternating techniques since every reservoir is unique in terms of composition, heterogeneity, conditions, and geometry.

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