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The New EOR Frontiers - Reduced Salinity Waterflooding

W.N. Aggrey*, Samuel Afari and Kwame Sarkodie

KNUST
Kumasi-Ghana

Corresponding author's email: aggreynkrumah {at} yahoo.com

ABSTRACT--- ***Reduced salinity waterflooding is a new EOR technique in which the salinity of injection water is tuned to improve oil recovery compared to conventional seawater flooding or other higher saline water. Simply injecting enough reduced salinity waterflooding water in sandstone reservoirs has been reported to increase oil recovery under certain conditions. Three main possible mechanisms regarding Reduced salinity waterflooding have been proposed in literature despite the lack of universal justification of how the process works improving oil recovery. A common feature among the suggested mechanisms is the release of divalent cations from the rock surface. Several schools of thought have hypothesised that Reduced salinity waterflooding results in change in wettability of the sandstone rock. As a consequence the previously attached oil mostly to clay minerals (kaolinite) is then released and floated away. Numerical simulation concept was used to model reduced salinity waterflooding water injection on field scale at reservoir conditions. The model was used to examine the effect of slug injection of reduced salinity waterflooding water, barriers preventing vertical flow, connate water banking, grid refinement and variation in the position of high permeability layer on field oil recovery factor and cumulative oil produced. The study indicated that Reduced salinity waterflooding is recovers more oil when the high permeability layer is positioned on top and when the low salt water is injected in the oil leg. The slug injection concept reduces the requirements for reduced salinity waterflooding water flood and recovers nearly the same percentage of oil. The study concluded that reduced salinity waterflooding water injection yields higher recovery and has more economical potential compared to other conventional water flooding systems. Sensitivity analysis on timing illustrated that early start of reduced salinity waterflooding water injection is immensely beneficial to Reduced salinity waterflooding improved oil recovery technique.***

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1. INTRODUCTION

Reduced salinity waterflooding water injection is a lucrative emerging water-based EOR technique because of its potential upsides and simple field practice. It involves adjusting the salinity of the injection water with salt composition of less than 6000ppm of tds.

The injected reduced salinity waterflooding water acts on capillary forces holding oil in reservoir pore spaces. As results the interfacial tension acting between the formation minerals and oil complexes is reduced due to wettability change leading to the improved oil recovery. General literature indicates multi-component ion exchange is the basic mechanism that drives this Reduced salinity waterflooding improved recovery. This fundamental mechanism requires sandstone reservoir (not Aeolian) to release the capillary-bound oil from charged clay minerals. Other required conditions include substantial clay content (>10%, significant kaolinite content uniformly distributed), mixed/intermediate wettability, polar hydrocarbon group (suitable for normal crude oil not volatile oil and gas condensates) and presences of divalent cations (esp. Ca^{2+}ions).

The benefits of reduced salinity waterflooding water injection include high ior potential, cost effectiveness, low-CO_2 foot print, minimal environmental effects, operational simplicity and can be combined with other recovery methods such as polymers, silicate or alkaline.

The leading challenge is defining the fundamental drive mechanism to invent a reliable field scale prediction model. [larger. A, 2006].

The application of Reduced salinity waterflooding is accomplished by obtaining the right salinity well-adjusted for the formation rock and fluids. Various technologies are employed to treat produced water for reduced salinity waterflooding water injection which presents significant cost. Desalination cost is a function the type of technology, geographic location, plant capacity and feed water quality. Frankiewicz, d.(SPE Services, Inc.) estimated a typical produced water treatment costs of US$0.05 to 0.30/bbl and facilities capital costs of 50 to 250 US$ per daily bbl of treating capacity.

Lager, 2008 pointed out that reduced salinity waterflooding water injection can improve oil recovery as high as 2-42% of STOIIP. The exact mechanism that triggers Reduced salinity waterflooding improved oil recovery is still been debated. Among these mechanisms are multi-component ion exchange, pH variation, fines migration and clay dispersion.

2. LITERATURE REVIEW

There is a comprehensive prove of published literature on Reduced salinity waterflooding to increase oil recovery in sandstone formations [SPE 129421, 36680, 102239]. Several research groups have conducted most laboratory experiments (core flooding) to examine Reduced salinity waterflooding improved oil recovery. Webb, McGuire et al conducted extensive laboratory study on reduced salinity waterflooding water injection at both ambient and reservoir conditions. They published that reduced salinity waterflooding water injection results in increased oil recovery [Webb 2005, Agbalaka 2008]. British petroleum conducted many field experiments on pilot scale in endicott and single well test in Prudehoe Bay fields at North Slope Alaska and reported reduced salinity waterflooding improved recovery of 10% and 8-19% OOIP respectively. [SPE93903]. [Vleder 2010] have also reported Reduced salinity waterflooding improved oil recovery at Omar field in Syria of 10-15% STOIIP.

Several schools of thought have invented many postulates to explain this Reduced salinity waterflooding improved recovery. Some ideas have shown that Reduced salinity waterflooding may result in reservoir wettability change. Reservoir wettability is a function of its salinity through the amount of divalent cations. The higher the cation concentration the higher the oil-wetness. It is predicted that reduced salinity waterflooding water improves oil recovery by changing the oil-wet state to a more water-wet state. [Ligthelm 2009].

Tang and Morrow, 1999 postulated that reduced salinity waterflooding water improved recovery requires significant clay fraction, connate water and mixed wettability conditions as basic requirements. However, Reduced salinity waterflooding improved recovery was seen in dolomite cores despite the absence of significant clay content [Pu et al 2008]. Larger and Sharma also observed no Reduced salinity waterflooding effect in secondary core floods when divalent ions were absent connate water. Other schools of thought also predicted that crude oil as defined by its acid and base numbers does not effect Reduced salinity waterflooding improved oil recovery. Boussour et al(2009) conducted coreflood experimednts meeting the above conditions but no appreciable improved recovery was observed.

There have been many successful experiments at both laboratory and field scale on reduced salinity waterflooding water injection. Alotaibi et al (2010) investigated reduced salinity waterflooding water behaviour through contact angle and Zeta potential measurement. They reported that different crude oil/rock//brine system wets differently and that Zeta potential (measure of wetness) tends to decrease as salinity decreases. Zhang and morrow showed Reduced salinity waterflooding improved recovery in both secondary and tertiary modes for two cores with different crude oils. Snorre field off the coast of norway yielded little or no Reduced salinity waterflooding improved recovery when single well chemical tracer test were conducted.[Skrettingland 2010]. They ascribed this to initial water-wet condition of the reservoir with high saline brine.

According to one idea, Reduced salinity waterflooding improved recovery could work with polymer flood despite the sensitive nature of polymers to salinity especially divalent cations. They reported that the polymer concentration could be diluted to about 5-10 times with desalination cost recovered in 1-4 years [Ayirala 2010].

2.1 Reduced salinity waterflooding Improved Oil Recovery Mechanisms

Fines Migration:

An attempt to explain the Reduced salinity waterflooding mechanism was first reported by Tang and Morrow (1996). They noticed production of kaolinite fines along with increase oil recovery during Reduced salinity waterflooding flood on Berea core samples. They ascribed the fine migration to low salinity induced permeability damage. The partial release of clay particles attached to crude oil was then proposed as the mechanism responsible for this improved oil recovery. This mechanism was justified by increased in pressure drop and permeability reduction. Deryaguin-Landau-Verwey-Overbeek(DVLO) theory of colloids also demonstrated this mechanism of fines migration. Dvlo theory indicated that permeability reduction occurs if the ionic strength of the injected brine is equal to or less than the critical flocculation concentration (CFC). CFC strongly depends on the relative concentration of divalent cations.

Zhang and Morrow 2007, contradictorily reported Reduced salinity waterflooding improved recovery without fines production. Other schools of thought reported no Reduced salinity waterflooding improved recovery despite great quantity of clay production (Boussour 2009), and Reduced salinity waterflooding improved recovery without fine production (Lager 2006).

British petroleum also reported Reduced salinity waterflooding improved recovery during its several coreflood experiments on a range of sandstone formations both at reduced and full reservoir conditions. From the above criticisms, it is clear that this mechanism is deficient in explaining the relationship between fine migration and Reduced salinity waterflooding improved oil recovery.

pH Variation:

Different ideas have proposed pH increase as the alternative driving mechanism for Reduced salinity waterflooding. The rise in pH has been attributed to carbonate dissolution and cation exchange reaction. Carbonate dissolution (i.e. calcite and/or dolomite) results in generation of excess hydroxide ions, (OH- ions) and cation exchange occurs between clay minerals and the invading water. The dissolution reactions are relatively slow and dependent on the amount of carbonate material present in the rock. Austard et al 2010 proposed a calcium-mediated desorption mechanism for the ph increase. The injection of reduced salinity waterflooding water displaces the chemical potential equilibrium between the adsorbed divalent cations and the supernatant divalent cations. The difference in chemical potential then acts as the driving force to restore the lost equilibrium by diffusion from the calcium-rich rock surface to the calcium poor supernatant. The loss of Ca^{2+} from the rock surface creates a site for cation exchange. A proton, H^+, from the invading fresh water quickly occupies these sites resulting in generation of hydroxide ions.

$$\text{Clay-}Ca^{2+} + H_2O \rightleftharpoons \text{Clay-}H^+ + Ca^{2+} + OH^- \quad ....(1)$$

The freed oh- ion caused an increase in ph which then triggers the following ph-sensitive acid/base reactions to occur as illustrated below**:**

$$\text{Clay-}NHR_3^+ + OH^- \rightleftharpoons \text{Clay} + R_3N + H2O \quad .... (2)$$

$$\text{Clay-}RCOOH + OH^- \rightleftharpoons \text{Clay} + RCOO^- + H2O \quad ....(3)$$

Austard indicated that the dominant functional groups found in crude oil (acidic carboxylic groups and basic cyclic compounds of pyridine) have similar pKa of 4.7-4.9 and thus would have similar adsorption and desorption behavior. They showed that these acid/base adsorption/desorption follows the ordinary acid/base reaction which is strongly ph sensitive with adsorption of quinolone (basic material) and benzoic acid (acidic material) varying inversely with pH. Austad et al. Proposed that reservoir surface chemistry is much more complex with equilibrium adsorption of divalent cations, acidic and basic materials, and h+ according to the affinity order $Li^+ < Na^+ < K^+ < Mg^{2+} < Ca^{2+} < H^+$. Basic and acidic organic materials have to compete with dissociated cations for active sites. The shortfall of the Austad's mechanism is that acid-base reactions with proton transfers are very fast due to low activation energy. Low salinity behavior is sensitive to temperature.

Another school of thought predicted that if a threshold pH of 9 needed for the in-situ saponification could be obtained in a petroleum reservoir then Reduced salinity waterflooding improved recovery is similar to alkaline waterflood [McGuire et. al. 2005]. They hypothesised that soap is formed when oil is exposed to higher ph low salinity brine as shown in equations 3 and 4.

$$(RCOO)_3C_3H_5 + 3NaOH^- \, 3 \rightleftharpoons (RCOONa) + C_3H_5(OH)_3 \quad ..... (4)$$

Fat alkali soap glycerol

$$2(RCOONa) + Ca(HCO_3)_2 \rightleftharpoons (RCOO)_2Ca + 2(NaHCO_3) \quad ... (5)$$

Soap hardness insoluble soap curd

This soap in equation 4 reduces the interfacial tension, and the rose pH increases the wettability of the reservoir. The low salinity water cannot precipitate out the soap due its softness and low divalent cation concentration. The justification for pH increase during Reduced salinity waterflooding flood was accounted for by the facts reported by Tang and Morrow (2002) .they stated that the effluent pH increased by 2 point from pH of 8 to 10. They reported reduction of interfacial tension along with the increased oil recovery.

Conflicting evidence throws doubt on this mechanism being the cause of Reduced salinity waterflooding improved recovery effect. At the moment the best Reduced salinity waterflooding core floods results (ca. 40% increase in oil recovery) are attributed to north sea reservoir which has crude oil with very low acid number(AN<0.05). From literature [SCA2006-36] alkaline water flooding requires high AN (AN > 0.2) to generate enough surfactant to induce wettability reversal and/or emulsion formation. There has also been no direct correlation between the increased oil recovery due to Reduced salinity waterflooding floods and the acid number of the crude oil. Some ideas have indicated that the high pH required for this alkaline-flood-like Reduced salinity waterflooding mechanism to occur is somewhat impossible. Since most fields are acidic due to the presence of H_2S and CO_2. Heriot-Watt University performed an experiment on a north slope core sample where the pH rose from 5 to 6 with an increase in oil recovery. The institution found that the high pH does not account for the increased oil recovery due to Reduced salinity waterflooding flood.

Multi-Component Ion Exchange Mechanism:

It involves the competition of all the ions in pore water for the mineral matrix exchange sites. Since natural exchangers show different selectivity for different cations, the ratio of sorbed over solute concentration varies for individual cations. This theory was applied to enhanced oil recovery in the 70's [SCA2006-36.]. Valocchi et al.[SCA2006-36] also applied this theory by injecting fresh water in a brackish water aquifer and noticed that the concentration of Ca^{2+} and MG^{2+} in different control wells were lower than the invading water and the connate brine. Similar results were also seen during Reduced salinity waterflooding floods done at British Petroleum and Heriot-Watt University. Lager et al. (2006) formulated multi-component ion exchange as the mechanism responsible for Reduced salinity waterflooding improved recovery. Sposito (1989) suggested a list of mechanisms for organic matter adsorption onto clay material. Among these, four are strongly affected by multi-component ion exchange Reduced salinity waterflooding flood:-cation exchange, ligand bonding, cation and water bridging. Adsorption by cation exchange occurs when molecules containing quaternary nitrogen or heterocyclic ring replace exchangeable metal cations initially bound to clay surface. Ligand bonding refers to the direct bond formation between a multivalent cation and a carboxylate group.these bonds are stronger than cation bridging and cation exchange bonds and lead to the detachment of organo-metallic complexes (RCOO-M; where M represents the multivalent cation) from the mineral surface. Cation bridging is a weak adsorption mechanism between polar functional group and exchangeable cations on the clay surface. It is to note that on some occasion if the exchangeable cation is strongly solvated (i.e Mg^{2+}) water bridging will occur. It involves the complexation between the water molecule solvating the exchangeable cation and the polar functional group of the organic molecule. Larger(2006) adjusted it down to Van der Waals interactions, ligand exchange and cation bridging as the dominant adsorption mechanism. An experiment was devised to test this mechanism. A very small amount of divalent cation concentrations in the effluent was seen during Reduced salinity waterflooding flood. The benefits of divalent cations were then linked to Reduced salinity waterflooding improved recovery. Multivalent cation bridging and exchange was the only mechanism that confirms the presence of calcium. They postulated that cation bridging is the predominant mechanism driving the Reduced salinity waterflooding flood improved recovery.

Again, they predicted that polar components in crude oil form organo-metallic complexes with the presence of calcium in reservoir at the rock surface. This makes the surface oil-wet during Reduced salinity waterflooding flood. The free cation in the injection brine then exchanges with the bound organo-metallic complex and thus freeing the cation-bridge bound oil. As a check they conducted core flood experiment. They pre-flooded a core with high salinity sodium chloride until only traces of Ca and Mg are left. Then they flooded the core with dead crude oil and preserved the core. They continued with a high salinity waterflood and got a 42%OOIP and reduced salinity waterflooding waterflood got 48%OOIP recovery at 25 degree Celsius. At reservoir temperature (102 degree Celsius) the conventional high salinity gave 35%OOIP recovery. Subsequent high salinity flooding containing sodium chloride (no Ca^{2+} or Mg^{2+}) yielded 48%OOIP recovery while the low salinity yielded no additional recovery. This strongly confirms the postulate that Reduced salinity waterflooding improved recovery is predominantly driven by cation-bridging bound oil. Reduced salinity waterflooding improved recovery was not observed for the high temperature scenario when the clay-oil adsorption mechanism was absent. Lager et al. Justified for this theory based on studies of water layer thickness by small angle neutron scattering and X-rays. (Lee et al. 2010). Lager's multi-component ion exchange theory falls short beyond the cation-bridge bound organics.

3. METHOD AND ANALYSIS

3.1 Application of Reduced salinity waterflooding Flood to Mainee Field Data.

Initially, the model was used to history match parameters to give correct water production rate of an under saturated oil reservoir with a small aquifer that started producing oil from a single well on 9 August 2005. Water injection was scheduled to start on 01 May 2006 up to 01 September 2008. The field porosity is about 29% with permeability varying from 23 to 2750mD. Four tables with 96 fluid relative permeabilities were used to model the Reduced salinity waterflooding flood. Salt was modelled as a single lumped component in the aqueous phase. Water saturation was varied from 0.15 to 0.90 among the different relative permeability curves with residual oil saturation of 35 %.(high salinity curves Fig.1 and low salinity curves Fig. 2). The viscosity and density of the aqueous phase, capillary pressure, and relative permeability were a function of salinity. The relative permeability curves show the definitive and fractional flow behaviour, Fig 4. The eclipse software usually interpolates between nodes of the relative permeability curves and switches from the reference high salinity to low salinity. The model was used to forecast the incremental oil recovery potential from reduced salinity waterflooding water injection. The simulation was run where reduced salinity waterflooding water is injected in secondary recovery mode after one and half year depletion.

3.2 Method of Simulating Reduced salinity waterflooding Water Injection

The keyword LOWSALT in the RUNSPEC [Eclipse 100, 2009.] section activates the reduced salinity waterflooding option. It allows the user to modify the saturation and relative permeability end points for water and oil phases as a function of the salt concentration as well as the water-oil capillary pressure. Given two sets of saturation functions, one for reduced salinity waterflooding and one for high salinity, the saturation end points are first modified as:

$S_{wco}=F_1S^L_{wco} + (1-F_1)S^H_{wco}$, $S_{wcr}=F_1S^L_{wcr} + (1-F_1)S^H_{wcr}$, $S_{wmax}=F_1S^L_{wmax} + (1-F_1)S^H_{wmax}$,

$S_{owcr}=F_1S^L_{owcr} + (1-F_1)S^H_{owcr}$, [Chuck Kossack, Schlumberger Adviser]

Where, H stands for high salinity, L stands for low salinity, F1 weighting factor is a function of salt concentration and corresponds to second column of the LSALTFNC keyword.

Swco is the connate water saturation, Swcr is the critical water saturation, S_{wmax} is the maximum water saturation, S_{owcr} is the critical oil saturation in water. Then eclipse now interpolates similarly between high salt tables and low salt tables (ie relative permeabilities for water and oil, and oil-water capillary pressure at the scaled saturations), as ;

$k_{rw}=F_1k^L_{rw} +(1-F_1)k^H_{rw}$, $k_{ro}=F_1k^L_{ro} + (1-F_1)k^H_{ro}$, $p_{cow}=F_2P^L_{cow}+(1-F_2)p^H_{cow}$

Where, f2 is a function of the salt concentration, and corresponds to the third column of the LSALTFNC keyword, k_{rw} is the water relative permeability, kro is the oil relative permeability p_{cow} is the oil-water capillary pressure.

The LSALTFNC is activated in the PROPS section. This keyword is set to input the weighting factors for the reduced salinity waterflooding saturation functions of the salt concentration. These coefficients are used in calculating the saturation end points, the water, oil relative permeabilities and the water-oil capillary pressure when the LOWSALT option is active. The keyword LWSLTNUM in the REGIONS section defines the low salinity table number to be used to calculate relative permeability and capillary pressure in each grid block [Eclipse 100,2009]. The SATNUM keyword defines high salinity saturation functions input. These are computed as a weighted average between the low salinity oil-wet saturation function and the high salinity oil-wet saturation functions. The weighting factors are taken from the LWSLTNUM table in the LSALTFNC keyword. The keyword PVTWSALT supplies water PVT data for runs in which low salinity water injection is active. This keyword replaces PVTW keyword in the PROPS section. This keyword allows the user to specify water PVT functions as a function of salt concentration. The keyword SALTVD was introduced in the solution section to specify table of salt concentration versus depth for each equilibration region. The keyword WSALT in the SCHEDULE section was used to specify the concentration of salt in the injection stream of each well. F_1 is the weighting factor for the low salinity saturation endpoints and the relative permeabilities interpolation. F_2 is also weighting factor for capillary pressures. F_1 and F_2 factors perform in the same nature. The value of 0 means high salinity saturation functions (previously defined by SATNUM) should be used, and that of 1 means low salinity saturation functions (previously defined by LWSLTNUM) will be used. The values are defined as monotonically decreasing, as it would reflect the real case of injection more than the sudden change.

3.2 Sensitivity Analysis

Due to time constraint and for achievement of good results, the main sensitivity variables considered were: continuous slug injection of the various sources of water used for Reduced salinity waterflooding flood(brackishwater, seawater and brine), the presence of barriers preventing vertical flow, banking of connate water, refinement of the grid sizes, shifting the position of the high permeability layer and initialization time for reduced salinity waterflooding water injection.

3.3 Base Case Model

A reference case numerical simulation was constructed on field scale at reservoir conditions to examine the upshot of some operational restrictions on recovery factor, cumulative oil produced, and net present values computed to estimate economic worth of Reduced salinity waterflooding flood injection. The reference case module entail three scenarios; continuous injection of high-salt water (brine), seawater and low-salt (brackishwater) for 3600 days.

3.4 Application of Slug Injection Concept to Reduced salinity waterflooding Water Flooding Technique

This concept involves injection of a volume of salt solution as a slug at one point in the reservoir (injector). Following the injection the salt mixes quickly throughout the depth of the formation and less rapidly across its width as it travels down the entire reservoir with the general flow of water. The injected salt disperses longitudinal resulting in a leading edge with relatively low concentrations of salt solution, a central zone of high concentrations followed by trailing edge of decreasing concentration. [vol.8 number 2 Spring 2005].The slug injection concept was demonstrated by continuously injecting high-salinity water (brine) for 3600 days then tuning to low salinity flood and finally flooding the reservoir with seawater for the same time-scale at each instance. This was permutated for the other two injection techniques (brackishwater & seawater floods).

3.5 Presence of Barriers Preventing Vertical Flow.

The EQUALS keyword in the GRID section was used to set the transmissibility's between the five layers to zero. Between layer 1 and layer 2 definitions MULTZ 0.0 1 50 1 1 5 5 / was inserted ,and between layer 4 and layer 5 definitions MULTZ 0.0 1 50 1 1 10 10 / was inserted. This will prevent any flow between grid layers 1 and 2, and between grid layers 4 and 5.

3.6 Connate Water Banking

The impact of connate water banking was demonstrated by making portions of the connate water inaccessible. This was by carried out by reducing the initial oil-water contact at 4960ft to 4920ft (40ft up layer 2) and increasing it to 4980ft (40ft down layer 5).

3.7 Grid Refinement

The base case model was refined by a factor 5 in the X-Direction and a factor of 5 in the Z-Direction using the AUTOREF keyword in the RUNSPEC section. It automatically refined the model by 5 1 5/.

3.8 Variation in Position of High Permeability Layer.

The high permeability layer was placed in the bottom instead of the middle, i.e. PERMX 23 md, 74 md, 680 md, 2750 mD. The PORO, NTG, and the SATNUM keywords were maintained. Likewise, it was positioned at top of the module. Eclipse was run and the difference in recoveries observed.

3.9 Start Time for Reduced salinity waterflooding Water (Brackish Water) Injection.

Studies indicates that reduced salinity waterflooding water (brackish water) injection is more promising as it gives better recovery and produces more oil comparatively to the other techniques of conventional water flood systems. The difficulty is what time is it desirable to inject reduced salinity waterflooding water? Sensitivity analysis was run on timing by injecting reduced salinity waterflooding water (brackish water) using the DATE keyword in the SUMMARY section.

3.10 Economic Significance.

Spreadsheet cash flow models for each of the modelled scenarios were constructed using oil production data generated by Eclipse 100 and the underlying assumptions below. These were used to calculate NPV's for various oil recovery techniques.

4. DISCUSSION OF RESULTS

Thirty simulation cases have been analyzed. But results of some simulation cases are presented. The oil recovery efficiencies from the base case low salinity water injection techniques analysed tends to increase as the salinity of the injection water decreases. These results point out that the case with continuous injection of brackish water recovers more oil for longer period than that of brine and seawater with the latest water breakthrough time. This observation agrees with general literature. Larger (2006) ascribed this increased in recovery to multivalent cation bridging and exchange as the fundamental mechanism driving this improved oil recovery. The injected reduced salinity waterflooding water (brackishwater) introduces protons (H^+ ions) which cause the cation bridge-bound polar hydrocarbon (oil) to detach from the rock surface. The desorbed mobile oil which was previously adsorbed to kaolinite (clay) can thus float away leading to the increased in recovery. The decreased in recovery is as a result of adsorption of more cations to kaolinite during the high-salinity water injection (seawater and brine). One school of thought attributed this development to clay swelling and fines migration. The brackish water causes the clay in the rock to swell. The clay swelling results in reduction of the pore volume containing oil. Thus, dislodging the oil leading to this observed improved recovery. The brackish water also disperses the clays into very fine particles. This plug up the established channels of flow either entirely or partially. Consequently, new channels of flow are created which when flooded with reduced salinity waterflooding water leads to the observed improved recovery. This additional recovery is however associated with the development of high pressure drop.

4.1 Cumulative Salt Injection and Water Cut Analysis:

From Fig.8 above, it can be learned that after 2079 days (5.28 years) the high-salinity water (brine) at field salt injection rate of 21.23 million barrels/day would arrive at the producer breaking through early at 88.91% water cut. In contrast the reduced salinity waterflooding water would breakthrough latest after 7 years (2559 days) with the lowest cumulative salt injected at 4.25 million barrels/day.

4.2 Application of Slug Injection Concept to Reduced salinity waterflooding Water Flooding Technique

The slug high saline water injects 2.0E+10 stock tank barrels brine and recovers 52%. Similarly, that of slug injection of seawater injects 8.3E+09 stock tank barrels and recovers 55%. While the slug brackishwater injects 6.0E+09 stock tank barrels and recovers 58%. These simulation results show small difference in oil produced relative to the base case continuous injection. The small differences in oil recovery can be attributed to the leading edge water effect and decreasing salinity ratio. It can be concluded that slug injection reduces the requirement for low salinity water and recovers nearly the same percentage of oil.

4.3 Effect of Barriers Preventing Vertical Flow on Cumulative Oil Produced and Recovery Factor.

The simulation results from Table 9 and Fig.10 above indicate no significant difference in both water cut and field oil recovery. Inspecting the saturation profile of the injected water reveals that the pressure gradient stays constant as the water moves away from the wellbore into the formation. This is due to the fact that gravity partially segregated forces tends to dominate similar to the base case continuous injection scenario. The kv/kh ratio is unrealistically high(~1), thus making the effect of the transmissibility barriers negligible.

4.4 Connate Water Banking

From the simulation results it can be observed that reducing the initial oil-water contact from 4960ft to 4920ft in layer 2 results in significant decrease in field oil recovery to 48.51% whereas raising it to 5000ft in layer 5 results in a substantial incremental oil recovery of 61.01% relative to the base case continuous low salinity water injection with field oil recovery efficiency of 58%. According to one idea, connate water in a reservoir is the water that actually displaces oil from the pores of the rock during a waterflood [SPE102239]. Reducing the initial oil-water contact to 4920ft increases the water saturation. The connate water then forms a zone separating the emerging injected low salinity water front from the continuous oil phase. The connate water saturation of the reservoir is thus swept from the pore space ahead of the injection water leading to this decreased in recovery. The increased recovery as a result of the raised initial oil-water contact to 5000ft could be attributed to reduced water saturation and increased residual oil saturation since it is only formation water that remains in the reservoir.

4.5 Grid Refinement.

Fig15 clearly indicates that the simulation results depends on the level of numerical dispersion and relative permeability effects. This is due to mixing of the injected low salinity water with the connate water resulting in an intermediate salinity which has less leading edge effect. As a consequence, the recovery factor of the refined model thus reduces. This behavior is observed in both the brine and brackish water flood. The low salinity water saturation profile shows that the injected water preferentially flow through the bottom layers leaving the top layer saturated with significant high levels oil. A smooth flood front propelling the injected water towards the producer with small difference in water cut relative to the base case coarse model could be noticed. The longest finger in the shape flood front reaches the producer first creating an earlier water breakthrough at 7 years.

4.6 Variation in Position of High Permeability Layer.

It can be seen from fig.16 that altering the position of the high permeability layer to the bottom of the module results in significant reduction in field cumulative oil production and field oil recovery and delay in water breakthrough. The injected brackish water tends to preferentially flow through the high permeability bottom layer due to gravity dominated forces resulting in a poor sweep, hence the reduced recovery. The reverse is observed when the high permeability layer is positioned at the top of the module. The oil is highly saturated at the top layer. Positioning the high permeability layer on the top tends to make viscous and capillary forces overcome gravity dominated forces. The incremental production and recovery efficiency is thus noticed due to improved sweep efficiency.

4.7 Economic Significance

From the studies the Reduced salinity waterflooding water flood (brackishwater flood) improved oil recovery is more beneficial comparatively to the other conventional water flooding techniques with payback period of two years. This result though is a cautious remark taking into effect the numerous latent challenges and cost elements they may carry during actual field studies. However on the whole Reduced salinity waterflooding carries a huge potential compared to certain conventional EOR methods.

5. CONCLUSION

Numerical simulation approach was use to model Reduced salinity waterflooding and analyse its effect at reservoir conditions on field scale. Three sources of water with different salinities were modelled. Brackish water (lowest saline water) was used to demonstrate reduced salinity waterflooding water flood, seawater was modelled as conventional waterflood and brine was modelled as high salinity water flood. In all these cases, the use of brackishwater as reduced salinity waterflooding water flood recovers more oil and yielded the highest NPV with payback period estimated at 2 years. Sensitivity analysis on timing showed that early start of reduced salinity waterflooding water injection is immensely beneficial to Reduced salinity waterflooding improved oil recovery technique. Its does recommended that field with Reduced salinity waterflooding Potential initiates it at the onset of field development.

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APPENDICES

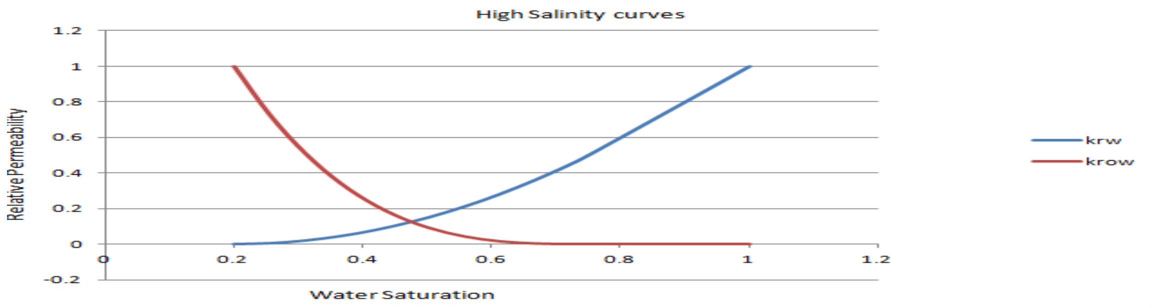

Figure 1. High salinity water saturation against relative permeability.

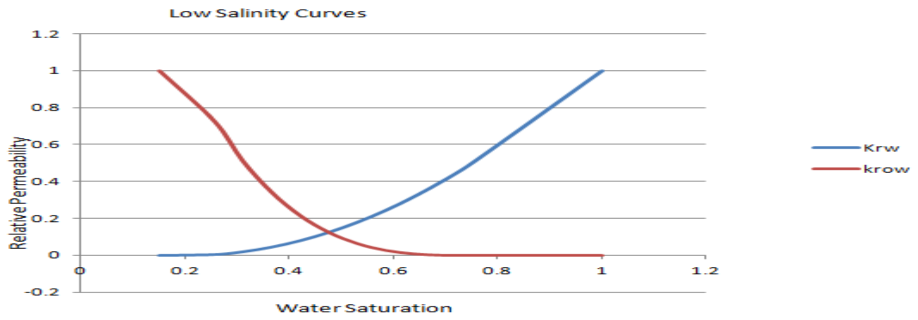

Figure 2.Reduced Salinity relative permeability against water saturation.

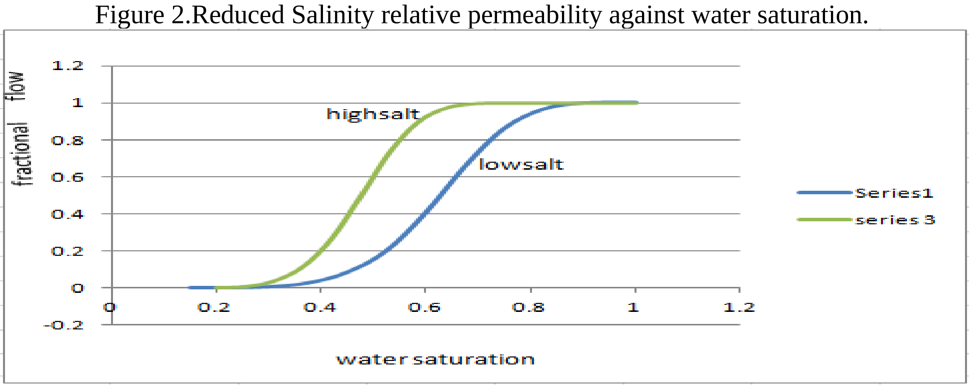

Figure 3. Fractional flow behaviour of reduced salinity waterflooding water and high salinity water.

Table 1. Salinities of the various sources of water used for the simulation.

Source	Salinity, ppm
Reduced salinity (Brackish water)	20000
Seawater	35000
High-salinity water	100000
Reservoir salinity	100000

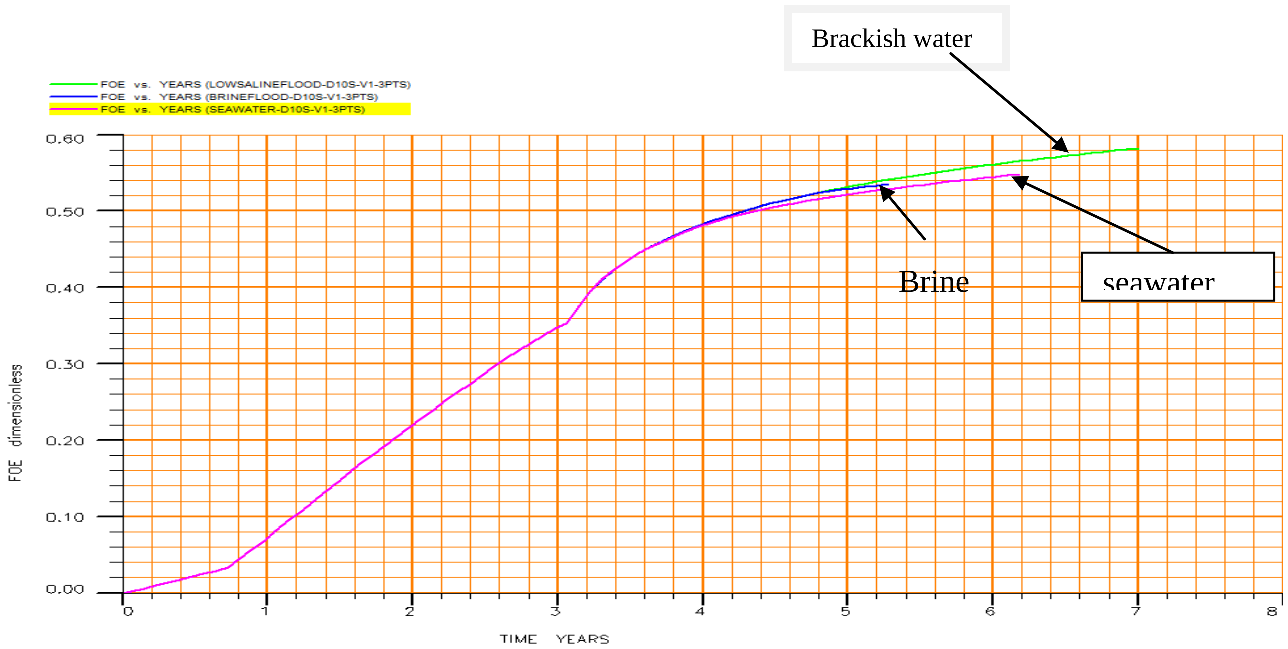

Figure 4. Field oil recovery efficiencies for all three base case scenarios

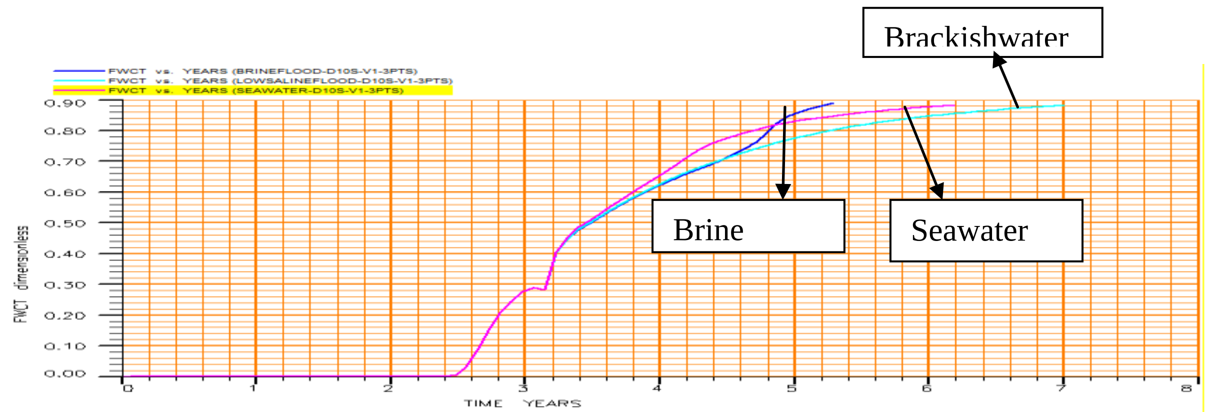

Figure 5. Field Cumulative Salt Injection and Water Cut Analysis

Brackish water

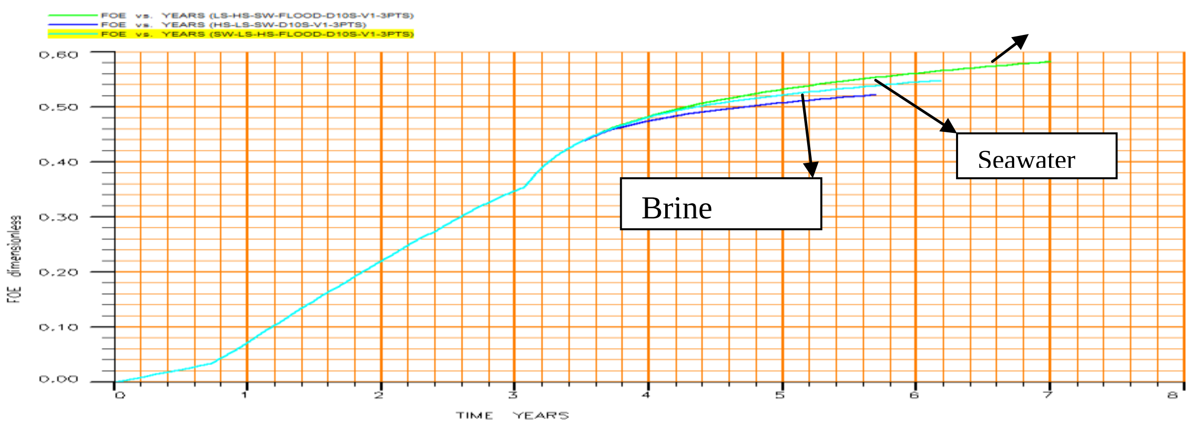

Figure 6. Field oil recovery factors for slug injection of reduced salinity waterflooding water injection.

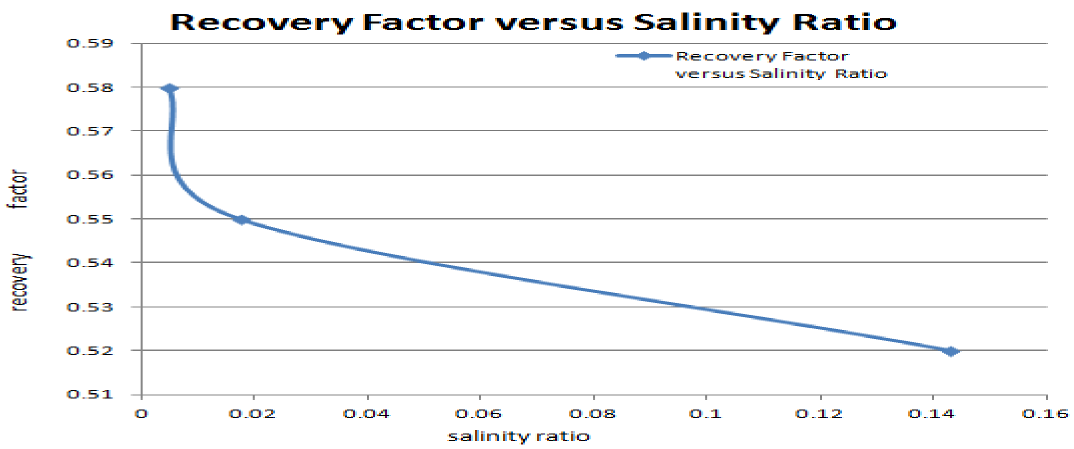

Figure 7. Recovery Factor versus salinity ratio

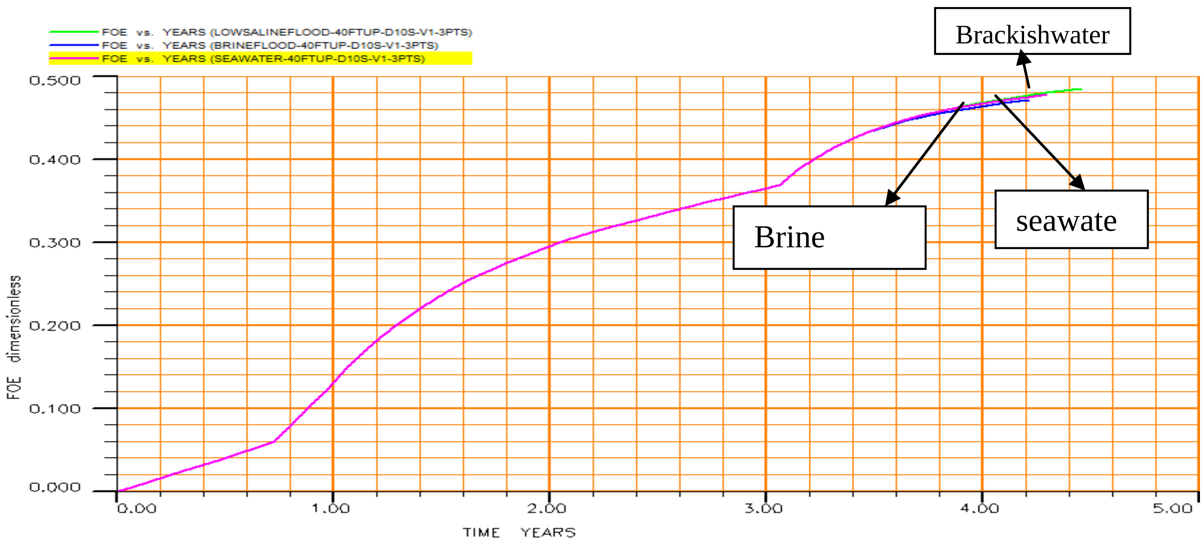

Figure 8. Field oil recovery of connate water bank at OWC of 4920 feet in layer 2.

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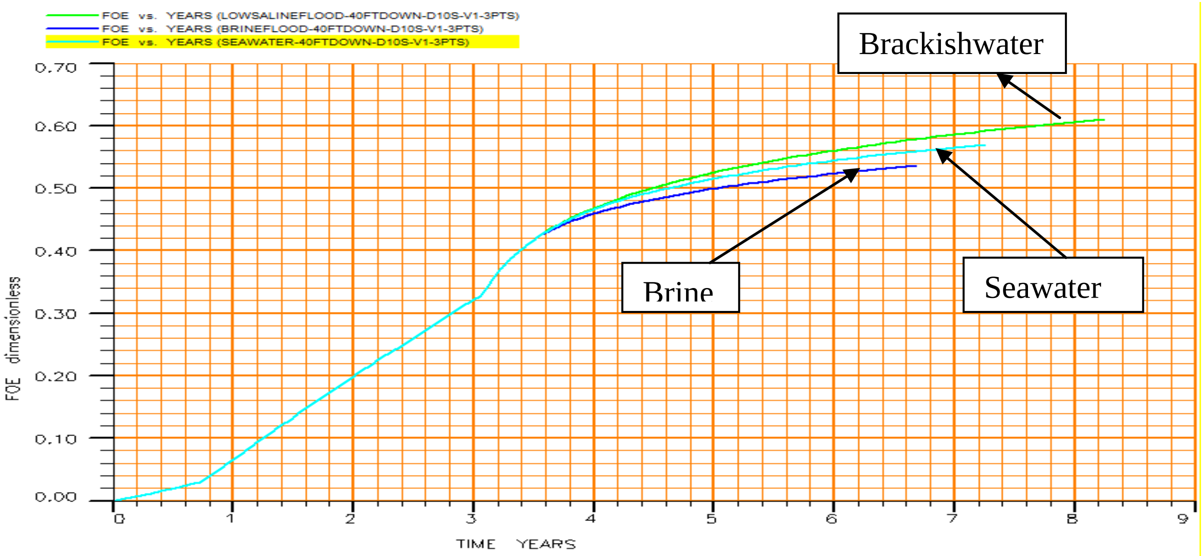


Figure 9. Field oil recovery of connate water bank at 5000 feet in layer 5

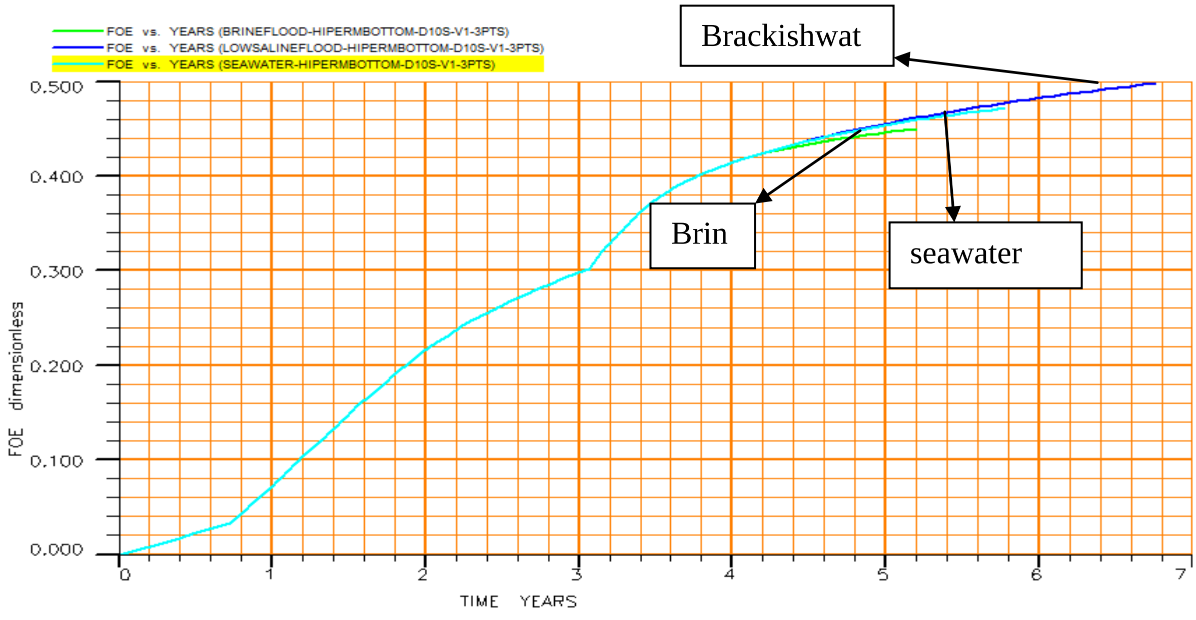


Figure 10. Field oil recovery efficiency of case with high permeability layer placed at bottom layer.

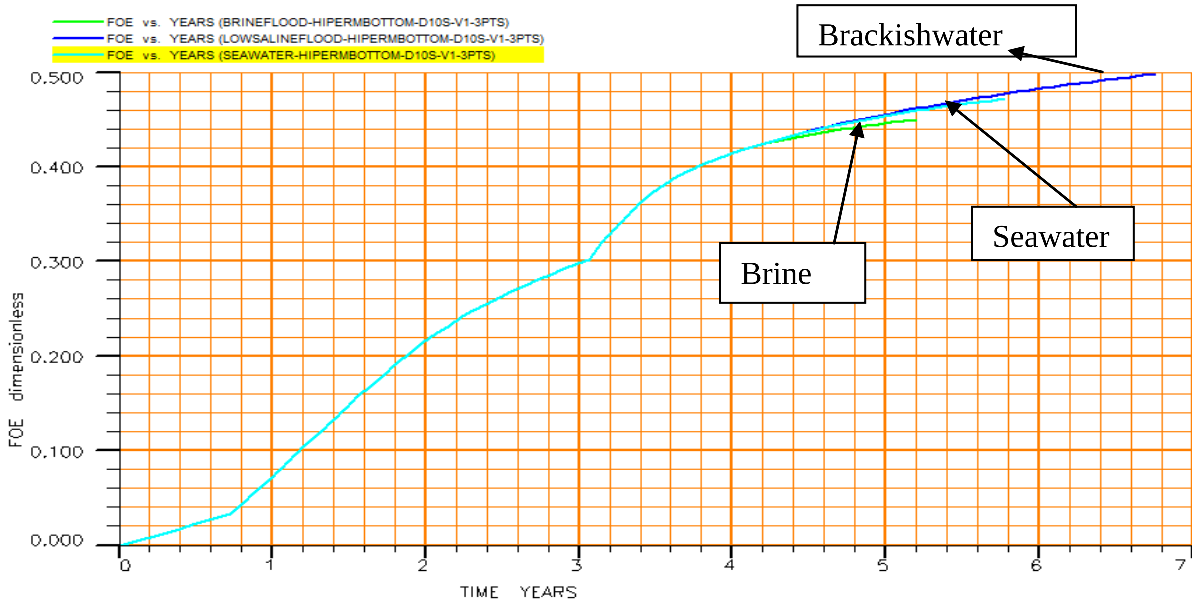


Figure 11. Field oil recovery efficiency of case with high permeability layer placed at top layer

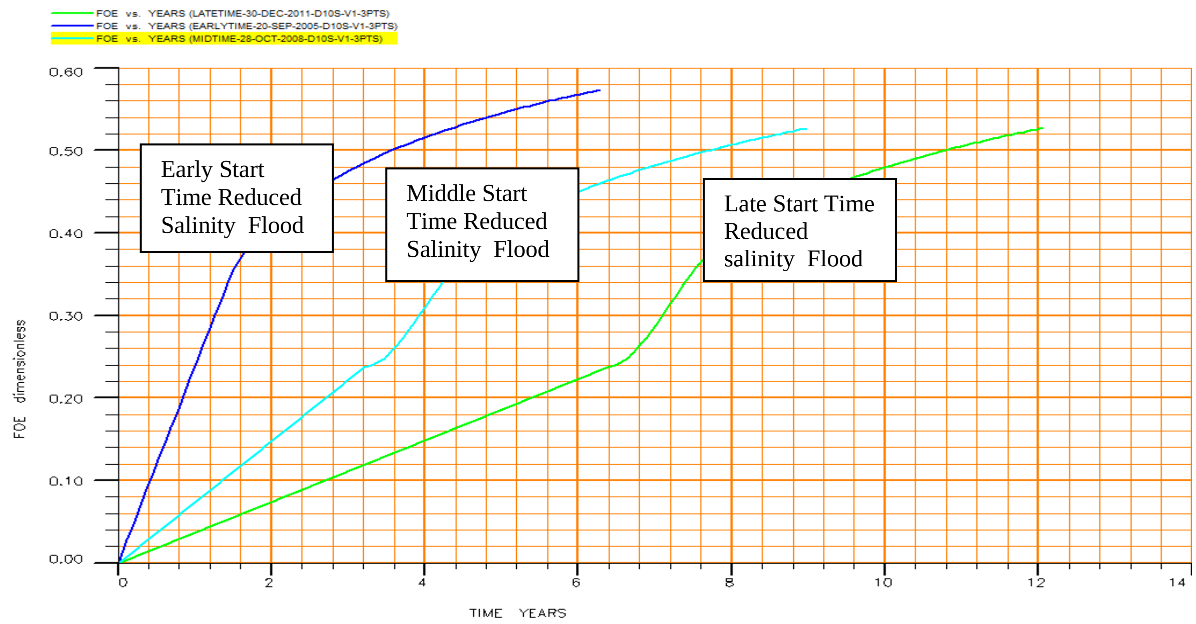


Figure 12. Field oil recovery efficiency of different injection time of reduced salinity waterflooding water.

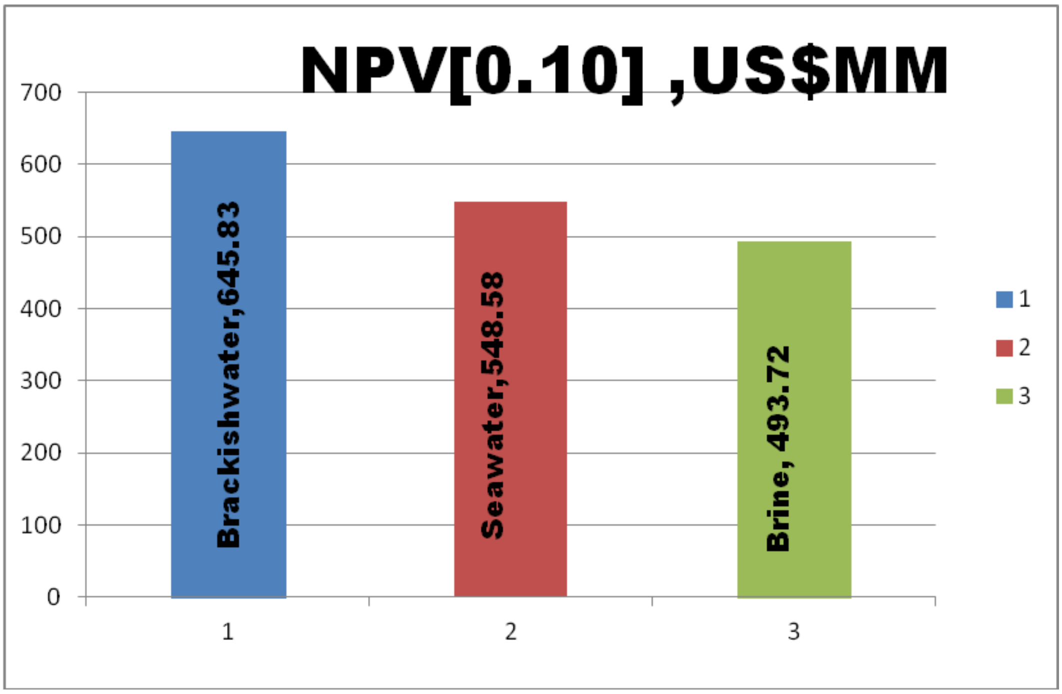
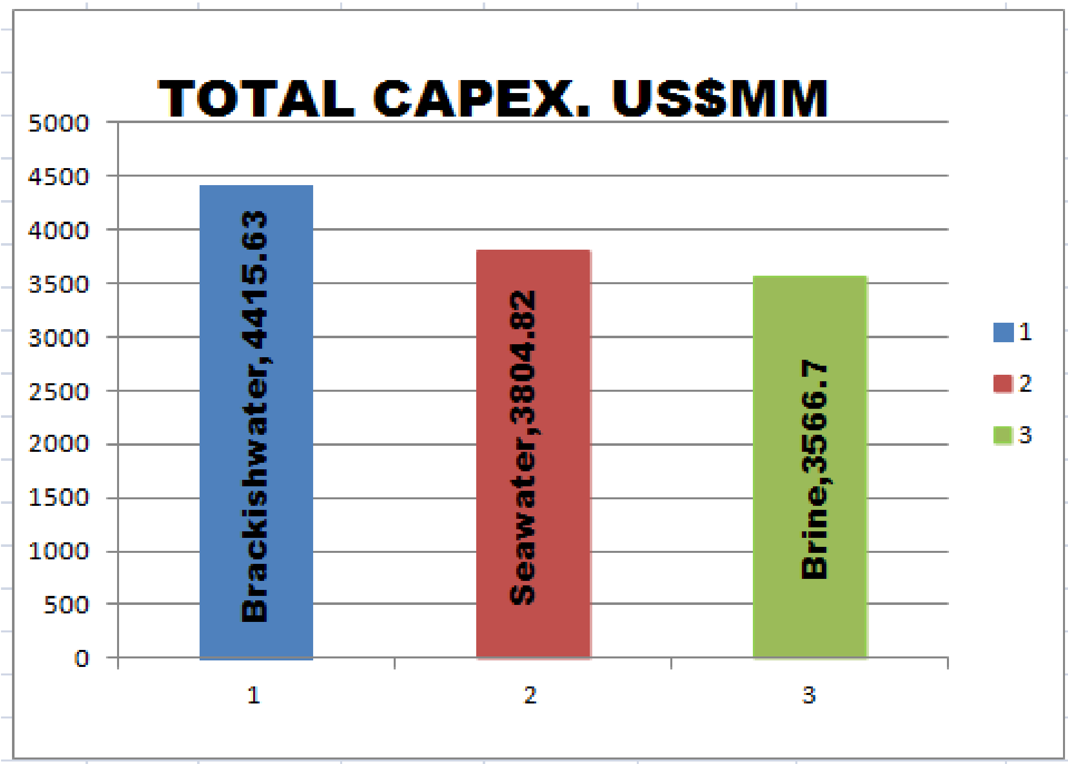
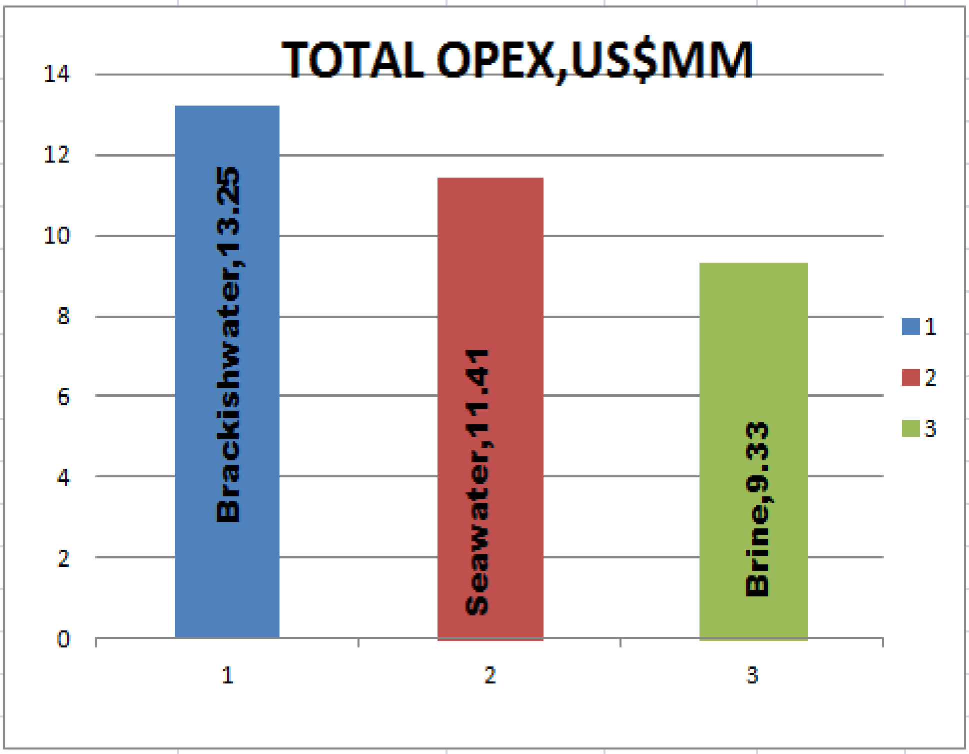


Figure18: Estimated Net Present Values, Total Opex and Capex of Reduced salinity waterflooding Flood.





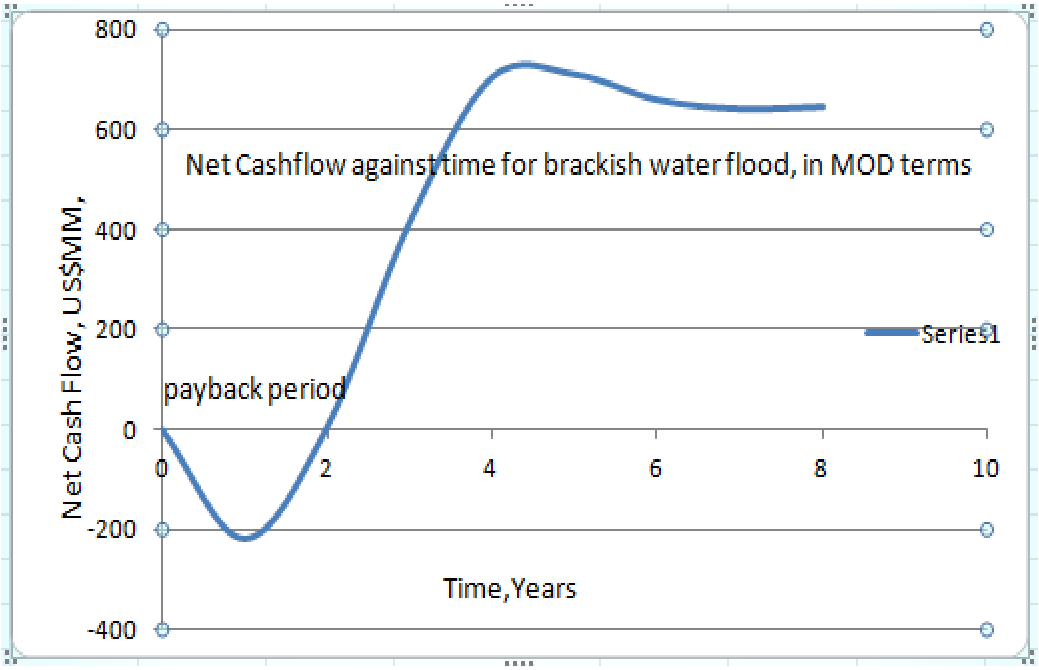


Figure 13. Net Cashflow curve for Reduced salinity Waterflooding (Brackishwaterflood)