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Review Paper

Low Salinity Water Flooding (LSWF), Can We Move Forward? The Economic Case

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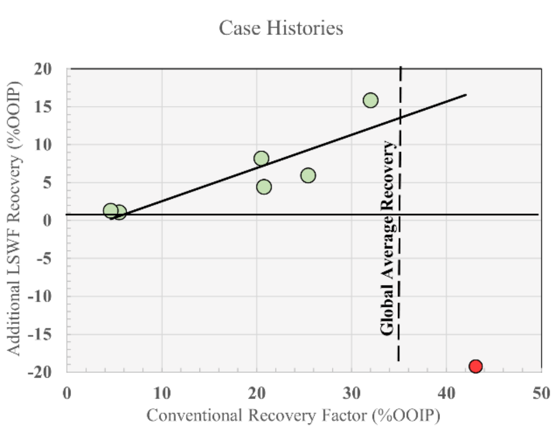
ABSTRACT

Low-salinity water flooding (LSWF) is a technique used in both improved oil recovery (IOR) and enhanced oil recovery (EOR) and may be employed at any stage of hydrocarbon production. The use of LSWF is very desirable because of the low cost of operations, lack of environmental impact, and industry-wide experience with water injection during secondary recovery. Indeed, LSWF has become a favorite topic for both academic and industry researchers with hundreds of scientific papers written. Despite the volume of research into LSWF, standard industrial processes and lab tests that typically go with a standard production technique are still lacking. The first successful field test was in 2004, but nearly two decades later there are still few field projects because the technique is perceived as experimental rather than operational. Here, it is suggested that there is sufficient knowledge to screen and test candidate reservoirs, assess the economics, and use LSWF on a broader scale rather than continuing to conduct iterative cycles of experimental investigations. In addition to providing a thorough economic analysis of a multi-field LSWF project, we provide and discuss the current terminologies, favorable conditions, and screening techniques.

KEYWORDS: Low salinity; Waterflooding; Smart water; Economics; Low Salinity Water Technology.

GRAPHICAL ABSTRACT



HIGHLIGHTS

- Summary of the performance to date of low salinity water flooding for laboratory and field.
- Current industry process of assessing and implementing the technique.
- Basis for formulating a traditional screening tool.
- Economic evaluation of the process on the field scale.

1. Introduction

Low-salinity water flooding (LSWF) is the practice of replacing the saline produced water that is normally recycled during waterflood operations with another water that has reduced salinity and/or modified ionic content to improve recovery (Bartels et al. 2019) There is no specific degree of dilution of the connate water to achieve the effect, but many cases suggest much lower salinity (Sheng, 2014). LSWF has several key advantages including functioning in both sandstone and carbonate reservoirs, low cost of operations, lack of environmental impact, and leverages the industry-wide acceptance and experience with waterflooding. However, even with the wealth of knowledge from academic and industry researchers (360 papers from 2015 to 2019) (Bartels et. al.2019) and 16 review papers, (see Table 1), the technique is still perceived as experimental rather than operational. All LSWF projects require answers to three main questions: (1) how well the target reservoir will (crude oil, brine, rock (CBR) system) respond to LSWF; (2) how much oil will be produced during the LSWF; and (3) what the economics of LSWF for the target reservoir are. Answers to each question are essential in moving the current

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knowledge to standard technology. The review of the literature shows there is sufficient knowledge to screen and test candidate reservoirs, evaluate project economics, and move LSWF into practice on a larger scale. One key missing component in the literature is economic analysis of actual projects which supports the perception that LSWF is economically speculative. In this paper, we present and discuss current terminologies and knowledge, identify favourable conditions for LSWF, discuss current screening techniques and criteria, and then focus on the economic case for LSWF using a full-field example.

Table 1
Recent papers reviewing low salinity waterflooding.

Year	Authors	Number of references in paper
2018	Bartels et al	169
2014	Sheng	59
2016	Bassir et al.	57
2013	Dang et al	44
2016	Jackson et al	134
2016	Strand et al	45
2016	Sohal et al	92
2017	Afekare and Radonjic	131
2017	Kilybay et al	33
2017	Purswany et al	93
2017	Awolayo et al	289
2018	Derkani et al	203
2019	Katende and Sagala	167
2019	Chavan et al	95
2017	Ding and Rahman	218
2015	Al-Shalabi and Sepehrnoori	153

2. Overview of the Current Knowledge

Table 1 is a list of review papers that summarize many of the hundreds of LSWF studies performed over the last five years (Bartels et al. 2019, Sheng 2014, Bassir et al. 2016, Dang et al.2013, Jackson et al. 2016, Strand et al. 2016, Sohal et al. 2016, Afekare and Radonjic 2017, Kilybay et al. 2017, Purswany et al.2017, Awolayo et al.2018, Derkani et al.2018, Katende and Sagala 2019, Chavan et al.2019, Ding and Rahman 2017, Al-Shalabi and Sepehrnoori 2015). These review papers discuss a range of topics including proposed mechanisms of LSWF in sandstones and carbonates based on investigations at three different scales: (1) the core-to-reservoir scale, (2) the pore-network scale; (3) and the sub-pore scale (Bartels et al. 2019). Table 2 lists publications that have proposed mechanisms for LSWF by categories (Webb et al. 2006, Patil et al. 2008, Berg et al. 2009, Vledder et al. 2010, Ashraf et al.2010, Chen et al.2004, Wideroee et al.2010, Emadi et al.2013, Mahani et al .2013, Romero et al. 2013, Al-Shalabi et al. 2014, Aghaeifar et al. 2015, Yang et al. 2015, Lager et al. 2006, Austad et al. 2010, Sorbie et al. 2010, RezaeiDoust et al. 2011, RezaeiDoust et al. 2010, Brady et al. 2012, Fjelde et al. 2013, Brady et al. 2015, Tang et al. 1997, Pu et al. 2018, Kumar et al. 2010, Fogden et al. 2011, Zeinijahromi et al. 2015, Hamouda et al. 2014, McGuire et al. 2005, Alotaibi et al. 2010, Alvarado et al. 2014, Moeini et al. 2014, Ligthelm et al. 2009, Lee et al. 2010, Sorop et al. 2013, Hiorth et al. 2010, Pu et al. 2010, Sohrabi et al. 2016, Pinerez et al. 2017, Fredriksen et al. 2016, Sandgren et al. 2011, Chavez-Miyauchi et al. 2017, Gachuz-Muro et al. 2016). In the past five years, most researchers identify changes in wettability as responsible for increased oil recovery, but the specific details remain unclear. One outcome of reviewing these studies is the recognition that the lack of systematic experimental design and goals significantly hinders full understanding. Experimental protocols and data types are not consistent in LSWF studies (Jackson et al. 2016, Patil et al.2008). For example, many studies do not perform essential measurements for the acid and base content of oil, brine pH, pH change, and effluent chemistry. There is also a wide range of experimental protocols and measurement techniques. Core flooding is widely used in Middle Eastern carbonate studies, but North Sea chalk studies generally use imbibition (Sohal et al. 2016). This lack of standard measurements or laboratory protocols limits the value of the current experimental data. However, one aim of this paper is assessed if there are sufficient consistent observations to implement this technique more broadly despite the lack of agreement on proposed mechanisms. For perspective, we offer the example of CO2 flooding which has been widely used for decades without full knowledge of mechanisms (Jarrell et al.2002, Teklu et al. 2016). Therefore, industry experience shows that complete understanding is not required to implement new processes that increase recovery.

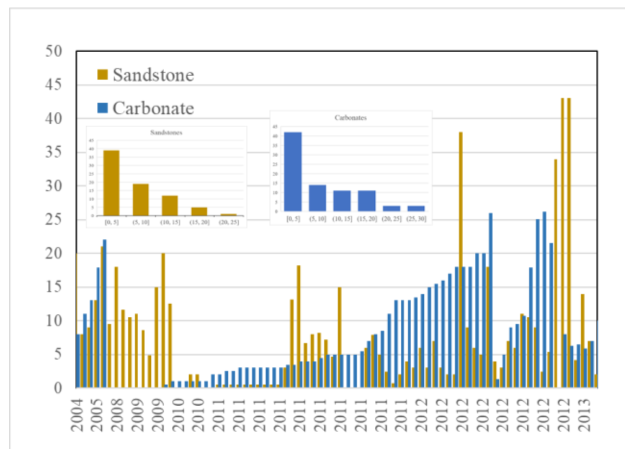


Figure 1. Reported incremental recovery as % original oil in place (OOIP) from data in table 3 by date of publication (2004 to 2013). Inset histograms of incremental recovery for sandstones and carbonates in bins of 5% OOIP. Most publications reported incremental recovery between 0 and 5%.

Another cited barrier to LSWF deployment is inconsistent results with some studies showing good response and others little to no increased. Figure 1 shows a representative distribution of incremental recovery from selected low salinity experiments and field cases. The sources are listed in Table 3 (Webb et al. 2006, Vledder et al. 2010, Austad et al. 2010, Brady et al. 2015, McGuire et al. 2005, Jerauld et al. 2008, Batias et al. 2009, Seccombe et al. 2008, Cissokho et al. 2009, RezaeiDoust et al. 2010, Shariatpanahi et al. 2011, Yousef et al 2011, Fathi et al. 2010, Thyne and Gamage 2011, Hadia et al. 2011, Gamage and Thyne 2011, Skrettlingland et al. 2010, Romanuka et al. 2012, Zhang et al. 2018, Fathi et al. 2011, Suijkerbuijk et al. 2012, Zhang and Sarma 2012, Zahid et al. 2012, Sari et al. 2017, Al-Attar et al. 2013, Abulla et al. 2012, Kulathu et al. 2013). The data show that while about one-half of the studies found between 0 and 5% incremental or additional recovery of the original oil in place (OOIP), almost as many studies had 5-15% while a few reached incremental recoveries as high as 25% OOIP in both carbonate and sandstone rocks. These levels of recovery are similar in range to CO2 EOR overall (Jarrell et al. 2008) but exceed that technique at the upper end of recovery (>15%). The differences should be expected given variations in rock, oil and water compositions, temperatures, and essential factors such as degree of dilution. Again, no enhanced recovery technique is always effective and both successes and failures are useful in formulating screening criteria.

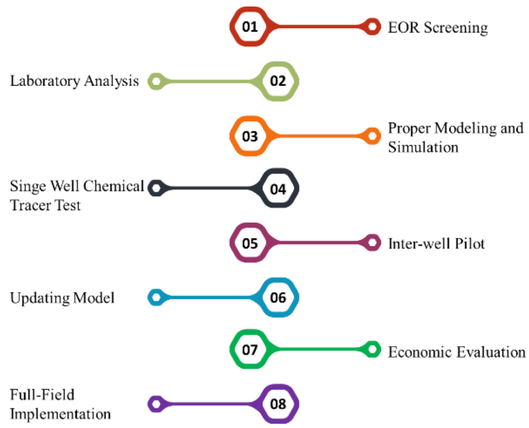


Figure 2. Modified workflow for LSWF implementation by Eni. Redraw from (Rontondi et al. 2014).

We see a lack of standard terminology and methodology as another barrier to large-scale deployment of LSWF. For example, most laboratory experiments and related papers use one of several terms for managing low-salinity fluids. We found seven common terms used including adjusting, tuning, manipulating, modifying, engineering, and controlling. All these terminologies are used to describe some process that modifies the chemistry of injected water to increase total oil production. The process is registered by various trademarks including LoSal™ (BP), Smart Water™ (Saudi Aramco), Designer Water Flooding™ (Shell), and Advanced Ion Management™ (ExxonMobil). These trademarks imply that the LSWF techniques are a specific technology, but a review of the related papers and patents show the processes described are general in nature and do not offer standardized methodology or workflows able to move LSWF from an experimental technique to a standardized production technology. Sometimes, the terms Smart Water and Low-Salinity Water are used interchangeably. However, either engineering or tuning seems the most widely applicable term to LSWF since each reservoir has its own specific characteristics of brine, rock, and oil composition. This reservoir variability can be extended to other conditions such as temperature, pressure, size of formation, and gas composition. In other words, injection water chemistry may have to be individually formulated to optimize maximum recovery for each reservoir.

Table 2
Proposed mechanisms of LSWF (column 1). Column 2 shows the number of papers that propose the mechanism, while the third column shows the references. Detailed citation for each reference can be found in the reference section.

Mechanism	# of papers	Reference
Wettability Alteration	13	Webb et al. 2006, Patil et al. 2008, Berg et al. 2009, Vledder et al. 2010, Ashraf et al. 2010, Chen et al. 2010, Wideroee et al. 2010, Emadi and Sohrabi, 2013, Mahani et al. 2013, Romero et al. 2013, Al-Shalabi et al. 2014, Aghaeifar et al. 2015, Yang et al. 2015
Surface reactions/MIE	9	Lager et al. 2006, Austad et al. 2010, Sorbie and Collins, 2010, RezaeiDoust et al. 2011, RezaeiDoust et al. 2010, Brady et al. 2012, Fjelde et al. 2013, Brady et al. 2015
Fines migration	7	Tang and Morrow 1999, Pu et al. 2010, Kumar et al. 2010, Fogden et al. 2011, Zeinijahromi et al. 2013, Hamouda and Valderhaug, 2014
Interfacial Properties	4	McGwire et al. 2005, Alotaibi and Nasr-El-Din, 2010, Alvarado et al. 2014, Moeini et al. 2014
Double layer expansion	3	Ligthelm et al. 2009, Lee et al. 2010, Suijkerbuijk et al. 2013
Mineral Dissolution	2	Hiorth et al. 2010, Pu et al. 2010b
Micro-dispersions	2	Emadi and Sohrabi, 2013, Sohrabi et al. 2016
Salt in effect	1	RezaeiDoust et al. 2009
Asperites	1	Brady et al 2015
pH change	2	McGwire et al. 2005, Pinerez et al. 2017
Osmosis	2	Fredriksen et al. 2016, Sandengen et al. 2016
Oil Rheology	2	Chavez-Miyauchi et al. 2016, Ayirala et al. 2016
Natural Acids	1	Gachuz-Muro et al. 2017

Another issue that may cause confusion is the original philosophy of using LSWF. Some authors considered LSWF as EOR, meanwhile, others considered it the IOR technique (Sheng 2014, Al-Shalabi and Sepehrnoori 2016). This conflict in the literature is based on the authors' perspectives. As discussed earlier, injection of produced water is considered a primary step in IOR activities along with operational considerations such as well pattern, well spacing, injection rate, production rate, type of well completions, water control systems, the capacity of surface facilities, distance of water sources, water disposal units, and corresponding policies of production of the field. The primary concern when injecting produced water is reservoir compatibility to avoid formation damage and to enhance oil recovery from the resulting immiscible displacement. Therefore, injection of water with altered chemistry is seen as tertiary recovery or EOR from this perspective. Injection of LSW affects CBR interaction in the reservoir which normally changes relative permeability and residual oil. We have discussed the effect of LSWF on relative permeabilities with details later. However, we suggest that it would be better to not consider LSWF as an IOR nor EOR technique. The better approach is to consider LSWF as a production technology with the application mode determining if it is a form of IOR or EOR due to the unique conditions of the candidate reservoir for injection of low salinity water.

Finally, from the industry point of view, it is important to have an identified series of steps, or workflow, for the implementation of LSWF. The standard industry methodology for deploying new recovery technology usually includes preliminary assessments (screening), economic studies (scoping), laboratory testing, reservoir modelling and simulations, and field pilots that may include single-well tracer tests and/or multi-well pilots. Researchers at Eni proposed a LSWF workflow that consists of six main stages (Rontondi et al. 2014, Callegaro et al. 2013): (1) screening; (2) 3-D preliminary modelling; (3) laboratory analysis; (4) single-well tracer testing; (5) inter-well pilot tests; and (6) full-field implementation. Figure 2 shows a modified version of this workflow. Researchers of the Shell company also reported another LSWF workflow that can be used for the matrix of deployment (Socrop et al. 2013). Table 4 shows a modified version of that matrix. Suijkerbuijk and his coworkers included surface chemistry evaluations, pore-scale physics, pore-network models, special core analysis (SCAL) experiments, and field tests before reservoir-scale deployment as shown in Figure 3 (Suijkerbuijk et al. 2013a, Suijkerbuijk et al. 2013b). This approach was implemented for the West Salym field upscaling the laboratory and field data to evaluate the potential of LSWF implementation by reservoir modelling. They concluded that project economics based on laboratory testing were promising for the offshore West Salym field, but that the reservoir modelling predicted lower recovery than the experiments (Erke et al. 2013).

Reservoir simulation is seen by many as an essential component of LSWF workflow. The key limitation of simulations is the representation of the LSWF process in the model. Currently, this is accomplished by linking the change in relative permeability to a chemical parameter such as salinity or surface charge or calculated change in wettability (Brady et al. 2012). However, the cost and time invested in reservoir modelling can be replaced by pilot projects that provide field-specific data saving time and money. Modelling and simulation are important techniques to extrapolate the experimental studies to the field scale. In another word, the creation of reliable and practical simulators is a key component to move LSWF to LSWT (low salinity water technology). But currently, there is no agreement on fundamental mechanisms of LSWF making the process of simulation and modelling to be challenging. Sanaei (2019) reported that there are two class of simulation models, (1) static and, (2) dynamic. While the first group of models emulates the incremental oil recovery through surface complexation modelling (SCM), the second group considers fluid flow in both black oil and compositional formulations (Beygi 2016, Alshakhs et al. 2020). Our evaluation is that the workflows that require multi-year laboratory testing programs with the accompanying reservoir modelling limit the deployment of LSWF and are another economic barrier to implementation by smaller producers.

3. Practical Requirements for LSWF

In each project, three main questions exist when considering implementation of LSWF: (1) how well the target reservoir will (crude oil, brine, rock (CBR) system) respond to LSWF; (2) how much oil will be produced during the LSWF; and (3) what the economics of LSWF for the target reservoir are. Answers to each question are essential in moving the current science to standard technology. Based on the data in Figure 1 we conclude that the basic technique often works and that the potential response in additional recovery is significant. So how do we determine if a reservoir is a good target for LSWF?

IOR/EOR project screening traditionally consists of applying a series of rules to evaluate the likelihood that specific techniques will work on a candidate reservoir. In contrast, current industry workflows include extensive laboratory testing and reservoir modelling. The availability of a more traditional screening tool is a critical step to transition LSWF from an academic project to a viable production technology (Bartels et al. 2019). In traditional screening, the rules can be qualitative or quantitative and are based on experience where specific criteria are related to the historic success or failure of a technique. Examples of criteria include flow response, oil-in-place, temperature, salinity, depth, oil properties (API gravity, viscosity) rock properties (porosity, permeability, mineralogy, clay content), pay thickness, and heterogeneity (Manrique and Wright 2006, Taber 1997a, 1997b). There are field and laboratory studies that can guide developing screening criteria for LSWF. For example, the temperature dependence of recovery in sandstones and carbonates can be used to help screen candidate reservoirs. In this context, we examine the conditions that apply to LSWF.

3.1. Conditions for Successful LSWF

Many authors have tried to summarize desirable conditions for LSWF (Sheng 2014, Strand et al. 2016, Austad et al. 2010, Tang et al. 1999, Alagic and Skauge 2010, Ayirala et al. 2013). Their suggested conditions focused on rock, oil, formation water composition, and the injected brine salinity. Several key parameters are widely accepted.

• Rock: Sandstone must contain some clay minerals for LSWF to work. Also, the specific type of clay (kaolinite) was initially proposed to be an essential component, but clay content rather than type is important. All types of carbonate rocks have been shown to work in some conditions.

• Oil: Polar components must be present in the oil to see a low-salinity effect. However, many papers do not report the polar content or total acid and base content of the oil (Hadia et al. 2011).

• Dilution Factor of Injected Brine: Early experiments used dilution factors of 100-fold based on the protocols from the formation damage literature, however positive results have been obtained with as little as 2.5-fold dilution. The degree of dilution to maximize recovery is an important operational consideration, but most studies do not include systematic evaluation of dilution factors. Some studies suggest that low-salinity injected water should be less than 5,000 ppm TDS for sandstones, meaning dilution factors of 20- to 50-fold, while data for a carbonate rock show that greater than 10- to 20-fold dilution produces no extra benefit (Yousef et al. 2011, Ayirala and Yousef 2013).

Table 3
Compilation of recovery factors from selected low salinity experiments and field tests between 2004 and 2016.

Authors	Rock	Lab/Field	Method	T °C	DF	RF (%OOIP)	Year
Webb et al.	SS	Lab		25	37.5	20	2004
McGuire et al.	SS	Field		76	10	8.1-21	2005
Batias et al.	SS	Lab			5	15	2009
Seccombe et al.	SS	Field		114	7	9.5-20	2010
Cissokho et al.	SS	Lab	CF	35	50	5.- 18	2009
Vledder et al.	SS	Lab			180	12.5	2010

Continued

RezaeiDoust et al 2010	SS	Lab	CF	60-130		0-2	2010
Shariatpanahi et al.	chalk/LS	Lab	IMB	110	20	13	2010
Yousef et al.	Carb	Lab	CF	100	20	17.9	2010
Fathi et al.	chalk	Lab	IMB	120	10	8.0-11	2010
Fathi et al.	chalk	Lab	CF	120	2	22	2010
Thyne and Gamage	SS	Field		60-140	0-100	0.5	2011
Tang and Morrow	SS	Lab				3	2011
Hadia et al.	SS	Lab	CF	60	100	0-18	2011
Gamage and Thyne 2011	SS	Lab	CF	25-90	100	0.7-8	2011
Skrettingland et al. 2011	SS	Lab		90	440	2	2011
Austad et al.	LS	Lab	CF	110	100	5	2011
Austad et al.	chalk	Lab	CF	110	100	0	2011
Romanuka et al.	chalk	Lab	IMB	60-120	0-219.5	0-20	2011
Zhang et al.	chalk	Lab	CF	100	20	18	2011
Fathi et al.	chalk	Lab	IMB	90	2.0-6	20-26	2011
Suijkerbuijk et al	SS	Lab	IMB	70	15-100	2.0-38	2012
Zhang and Samra 2012	Carb	Lab	CF	70-120	100	9-26.1	2012
Zahid et al.	LS	Lab	CF	25-90	20	1.38-17.9	2012
Sari et al.	LS	Lab	CF	60	10	5.0-18	2012
Al-Attar et al.	LS	Lab	CF	25	40	21.5	2013
Abdullah et al.	SS	Lab			28	4.12	2013
Kulathu et al.	SS	Lab		25	3-367	2.0-14	2013

CF = coreflood, IMB = imbibition, SS= sandstone, LS = limestone, Carb = carbonate, DF = dilution factor, RF = recovery factor

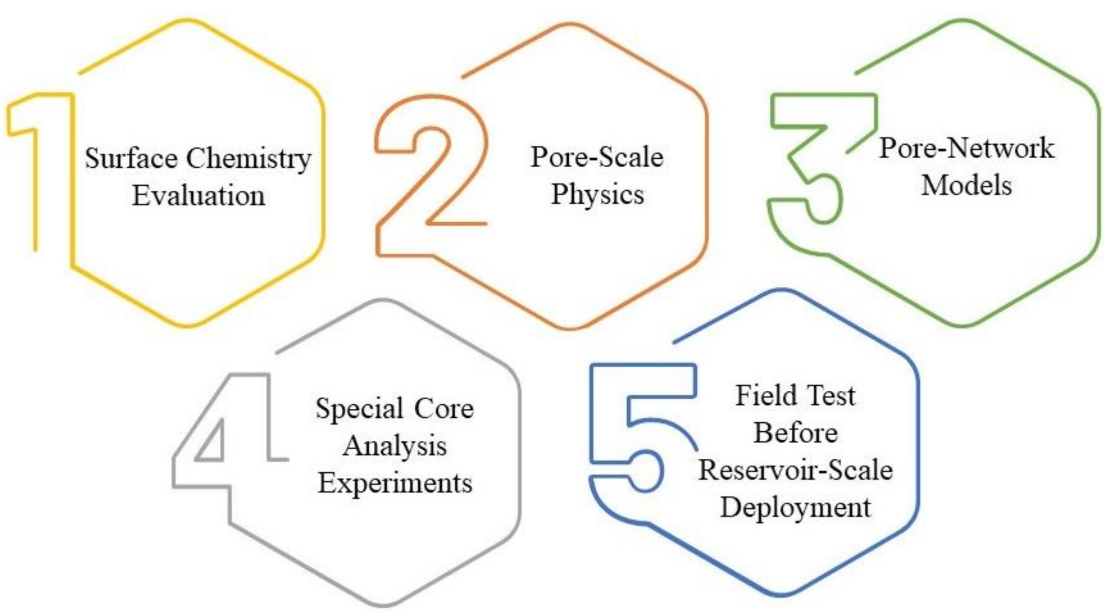


Figure 3. Shell workflow for screening LSWF. Redraw from (Suijkerbuijk et al. 2013a).

Table 4
Shell's modified workflow for LSWT (modified from (Sorop et al.2013). Field names were not listed in the original publication and the fields are represented with X, Y, Z, etc. SCAL = special core analysis, FD = facilities design.

Parallel Simulation Studies and updating Economics Evaluation							**Approved Approved**	
Field	Location	Water flooding data	Screening	SCAL	Subsurface profile evaluation	FD	Pilot Test	Full field implementation
X	Offshore	Yes	Yes	Yes	Yes	No	No	No
Y	Onshore	Yes	Yes	Yes	No	No	No	No
Z	Offshore	Yes	Yes	Yes	Yes	Yes	Yes	Yes
XX	Onshore	Yes	Yes	Yes	Yes	No	No	No
XY	Onshore	yes	yes	No	yes	Yes	Yes	No

• Temperature: Temperature has been shown to be a factor in LSWF response. In sandstones, the effect appears to be a lower recovery at higher temperatures (Vledder et al. 2010, Shariatpanahi et al. 2011, Skrettlingland et al. 2010). In contrast, in carbonate rock, the recovery is higher at higher temperatures (Zahid et al. 2012, Jiang et al. 2014, Sohal et al. 2017). An optimum temperature window of between 90–110 ◦C (Awolayo et al. 2018) was proposed, but there are many examples with positive results across the range of relevant temperatures.

• Formation Water: Type and amount of salts that are present in the formation of water have been suggested as an important factor in LSWF. For instance, Rotondi et al. (2014) state divalent cations must be present, but it is unclear why.

• Ionic Concentration: The amount and type of ions in the injected water are other key parameters that can affect the general performance of LSWF. Different icons can play a key role in the mineral surface-oil interface. Monovalent and divalent salts can have a different affinity toward the surface of the rocks changing the surface charge. Size of ions, electrical charge, and ionic strength are factors that influence surface properties due to the ionic concentration (Jackson et al. 2016 , Strand et al. 2016, Sohal et al. 2016a).

3.2. Examples of Screening for LSWF

Liu et al (2020) have reported key information for twenty field test experiences in which smart water flooding has been deployed where the injection salinity range varied from 150 up to 29,000 ppm in which 90% of field implementation (18 cases) were for sandstone reservoirs.

Table 5 shows the suggested screening criteria for LSWT from the Burgan reservoir in Kuwait (Al-Murayri et al. 2017). The authors used macro-scale parametric screening that incorporated estimated steam-oil ratio (SOR), permeability, oil properties (API, SARA, viscosity), temperature, water characteristics (TDS, divalent), and drives mechanism into the initial screening. Thyne (2016) used empirically based criteria to evaluate the suitability of low salinity waterflooding of Alaskan reservoirs (Thyne 2016). This work considered factors including dilution, temperature, porosity, permeability, and initial salinity, but found that clay content, oil composition, waterflood performance, and temperature of the reservoir were the most important factors for screening LSWF in Alaskan oil fields. Recently, Fjelde and his coworkers (2018) suggest a fast-screening methodology for LSWF in sandstone reservoirs that consists of three steps: rock and fluids studies; flotation experiments to measure wettability; and, geochemical simulations with PHREEQC. In addition to the short time scale of experiments, another advantage of the flotation used was the experimental work required only small amounts of rock samples (Sohal et al 2016b, Mwangi et al. 2018). We conclude that while there are not as many field examples for LSWF compared to other EOR techniques (chemical, thermal, and CO2), there appears to be sufficient data to formulate reasonable screening criteria and evaluate the suitability of target reservoirs for LSWF using traditional screening formulations.

Table 5
Suggested Screen Criteria for LSWF (Al-Murayri et al. 2017).

Fluid Properties	**Value**
API	NC
Oil viscosity	<2000 cp
Mobility ratio estimation	<2
Reservoir Water	Divalent Cations
Reservoir Properties	
Edge water	Acceptable
Bottom water	avoid, if large
Gas cap	better if none
Water drive	not active drive
Porosity	not critical
Wettability	oil-wet average
Clay content	kaolinite critical
Horizontal Permeability	>1md
Temperature	NC
Estimated pore volume	NC
Oil Saturation	>50%
Depth	NC
Reservoir Pressure	0% to initial
Estimated Fracture Pressure	inj P< Frac P
Net thickness	NC
Lithology	Sulfates required for Carbonates
Current Oil Cut	>9%

4. Economic Evaluations

The project economics are the ultimate determining factor for LSWF. For the useful implementation of LSWF (LSWT), economic evaluations are essential and best done in parallel with the evaluation of the technical aspects. One such methodology is shown in Figure 4. The basic considerations are the benefit of the additional recovery versus the costs that include both operational and capital expenses (OPEX and CAPEX). CAPEX usually includes the costs of a preliminary evaluation of candidate reservoirs with the accompanying laboratory work, reservoir modelling and an economic analysis. If the typical industry pattern of years of testing and modelling, this expense rapidly becomes significant. This additional expense on top of the project implementation CAPEX can form an activation barrier that is difficult to overcome.

A comprehensive evaluation should also include factors such as time value of money, the net present value (NPV), differential cash flow, internal rate of return (IRR), return on investment (ROI) and an uncertainty analysis (Layti 2017). Calculation of NPV versus an increase in additional production and increase in investment costs, delay of production peak, the effect of timing of the LSWF investment, and sensitivity of differential cash flow are all factors that may be critical in the final economic evaluation. These metrics serve as a decision assisting tools for producers. LSWF projects not only play a role of benefiting specific assets but can also diversify a company's investment portfolio and might be better than extensive drilling or exploration programs.

Explicit evaluation and design costs have not reported for current field projects. But we do know that the evaluation of the BP Clair Ridge offshore project started in 2006 with initial deployment in 2012 (Robbana et al. 2012, Reddick et al. 2012). The evaluation and field tests by BP on the North Slope lasted from 2004 to 2008 (Seccombe et al. 2010). The Eni West African project evaluation and design phase started in 2006 ending with field testing in 2013. Even without explicit costs, the current approach is time-consuming and expensive limiting this methodology to very large companies.

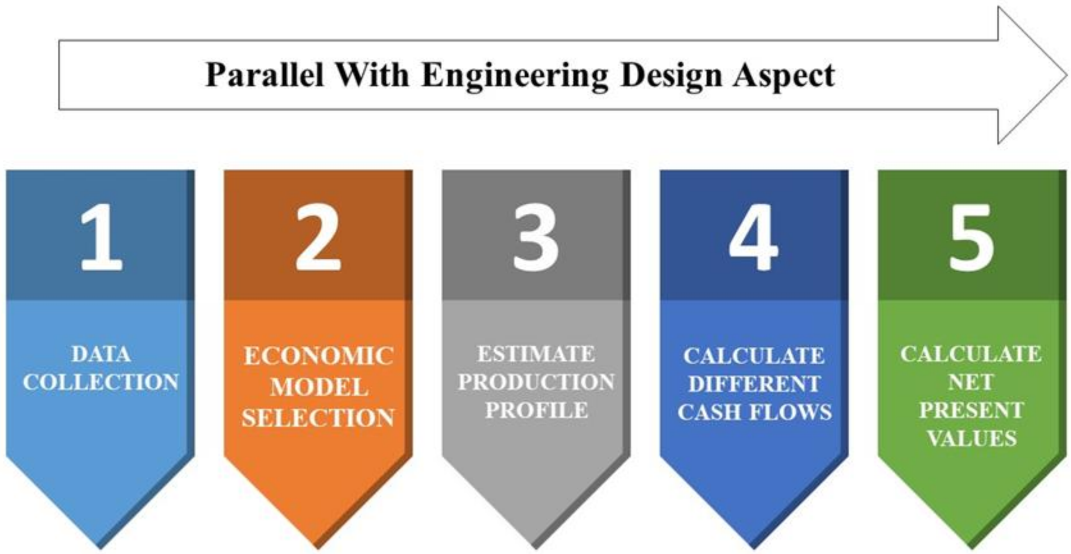


Figure 4. Modified version of different steps for profitability evaluation of LSWT. Details of this procedure can be found in Layti (2017).

A few papers address the profitability of LSWF. These papers offer economic analysis using generalized results. For instance, in a recent publication by Adityawarman1 et al. (2020), the authors evaluated the LSWF project's economy for a sandstone reservoir in Indonesia and derived two equations for CAPEX/OPEX as a function of removed salinity (RS) as follow:

$$CAPEX = 6E\text{-}06(RS) + 0.0623 \quad (1)$$

$$OPEX = 7E\text{-}06(RS) + 0.1079 \quad (2)$$

where the units of CAPEX/OPEX are USD/bbl and treated/removed salinity is ppm. The authors also noted that between the four parameters, oil production, CAPEX, OPEX, and oil price, oil price affected the NPV the most. Al-Shalabi et al. (2014) performed a sensitivity analysis for LSWF project economics (see Figure 5). The authors found that slug size was the most influential factor regarding project economics followed by reservoir heterogeneity and salinity. Fani et al. 2018 found smaller slug sizes were as effective as larger slugs in altering wettability. Sadeed et al. (2018) found the main parameters when optimizing LSWF economics in a Middle Eastern carbonate reservoir were the number and duration of slugs, degree of dilution, and injection and production rates. Based on technical, facility, and economical challenges, Muriel et al. (2020) presented a cost-benefit analysis with a focus on offshore fields. The study compared LSWF with alternative chemical EOR methods, such as surfactant flooding, alkaline-surfactant, polymer flooding, alkaline-surfactant-polymer flooding, and nanoparticle injection in two different scenarios: (1) injection from the first day of production (2) injection after secondary production. LSWF resulted in the lowest CAPEX/OPEX. Figure 6 shows projected CAPEX/OPEX for different EOR methods including LSWF. Another study (Aljuboori et al. 2020) reported a series of simulations performed for a field-scale fractured reservoir model and concluded that the sustained oil productions were up to 32,000 and 25,000 bpd due to low and high salinity water injection, respectively. That report also suggested that LSWF requires a longer time frame for sweep efficiency.

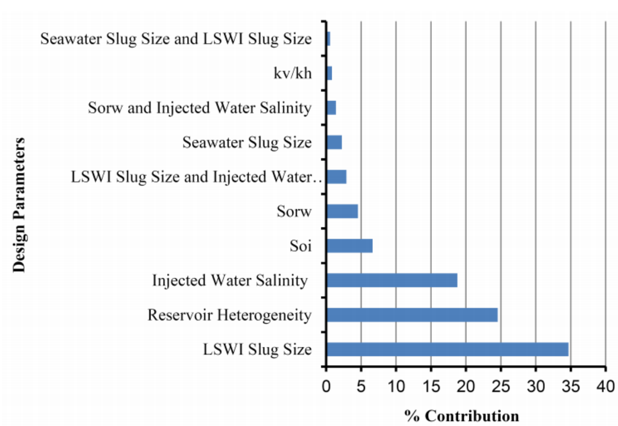


Figure 5. Sensitivity analysis of LSWF. From Al-Shalabi et al. (2014). These parameters can be used as a guide for screening and targeted investigations of LSWF. In this case the authors found slug size is the most important factor.

Our example is based on data from a LSWF project in conventional oilfields in North America that have comprehensive cost and production data. The project was aimed at a set of carbonate reservoirs in the Cedar Creek Anticline that have been waterflooded for 20+ years by re-injection of produced water (Hols and Bethel, 1957). This set of fields have significant production from the Ordovician Red River formation at 9000 feet depth, composed of 60-80% dolomite with 10-15% quartz, clay and anhydrite. The productive zone is naturally fractured, low permeability (1-10mD) reservoir with 10% porosity on average. The fields have saline formation water (75,000 to 100,000 mg/l TDS). The main variability between reservoirs is the oil composition with API gravity ranging from 27 to 38 degrees and asphaltene content from 2 to 12% due to different degrees of biodegradation. The main impetus for changing injection water salinity was operational and LSWF was implemented between 2005 and 2010 across all the fields under waterflood. A detailed economic analysis for two fields is presented and the results for the other five fields summarized.

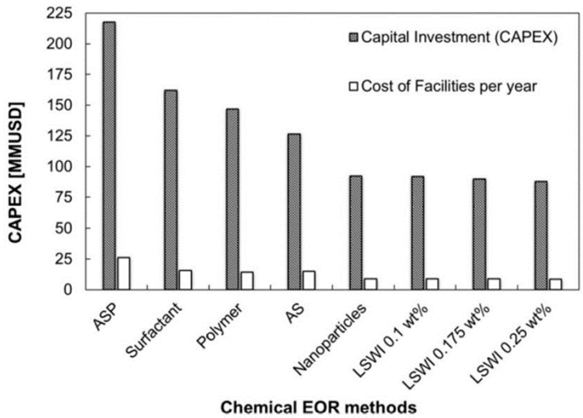
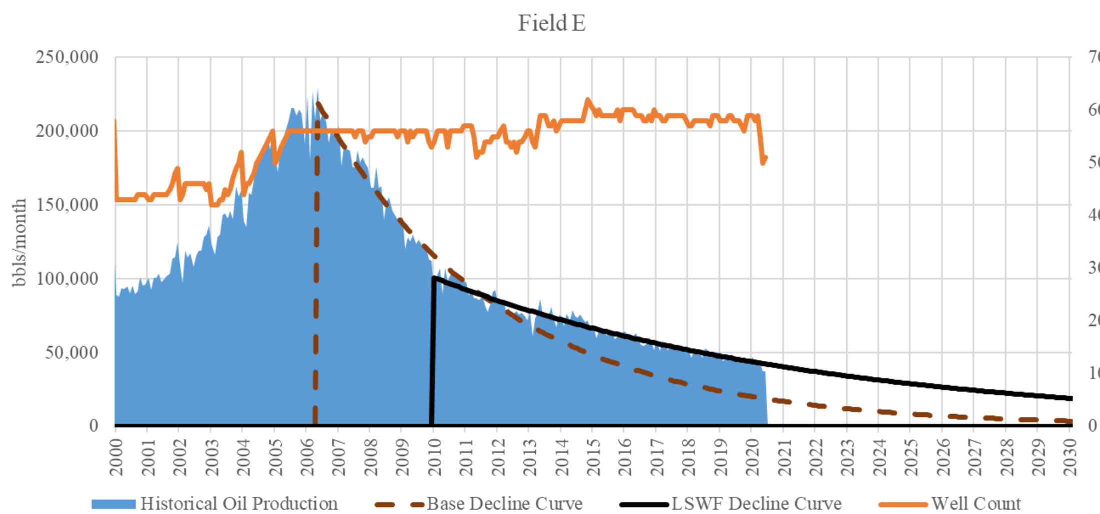


Figure 6. Comparison of CAPEX for Different Chemical EOR methods and LSWF. From Muriel et al. (Muriel et al 2020).

Table 6
Results from LSWF project on seven conventional fields in North America.

Field	OOIP	Pre-LSWF RF	LSWF	Field life
	(MMbbls)	(%OOIP)	(%OOIP)	(Years)
A	395	5.5	1.1	40
B	395	25.4	5.9	27
C	81	4.6	1.3	35
D	14	32.0	15.8	52
E	147	20.8	4.6	13
F	35	19.1	8.2	54
G	200	41.3	-19.3	-24



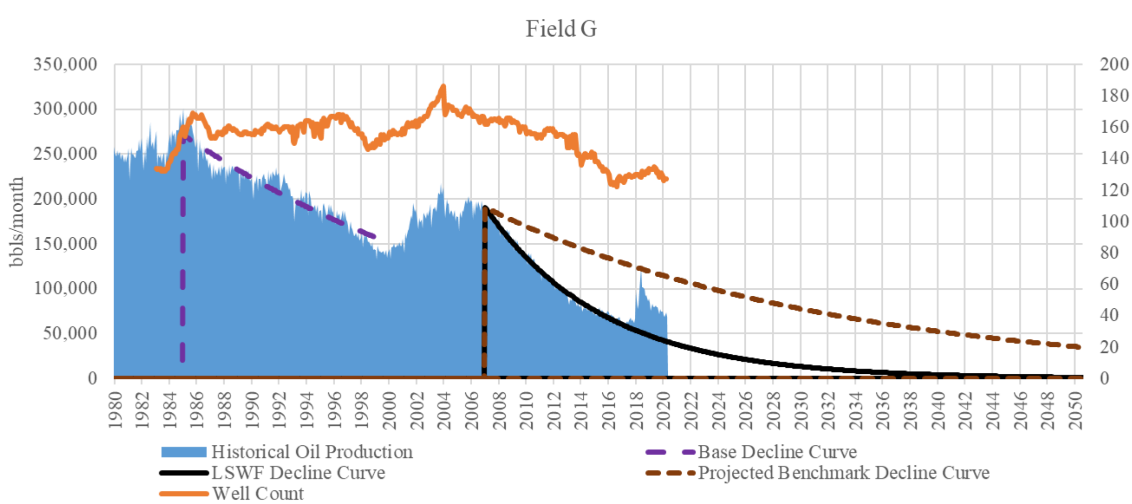


Figure 7. Plots of time versus production data in barrels per month for fields E and G (upper figure and lower figure, respectively). Production and well count data from IHS. Projected decline curves for the base case (pre-LSWF) and post-LSWF case shown by dashed and solid lines, respectively. Decline curve analysis (DCA) assumed exponential decline. Field E shows the benefit of LSWF where the post-LSWF decline projects improved recovery, while field G shows the wettability damage and reduction in recovery from LSWF.

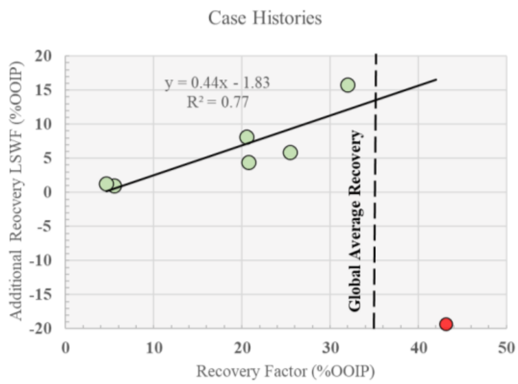


Figure 8. Plot of primary + pre-LSWF recovery factor versus estimated incremental post-LSWF recovery for 7 conventional carbonate fields. Vertical dotted line shows average global recovery of 35% for normal waterfloods. Linear regression line is for the six fields that showed positive benefit from LSWF.

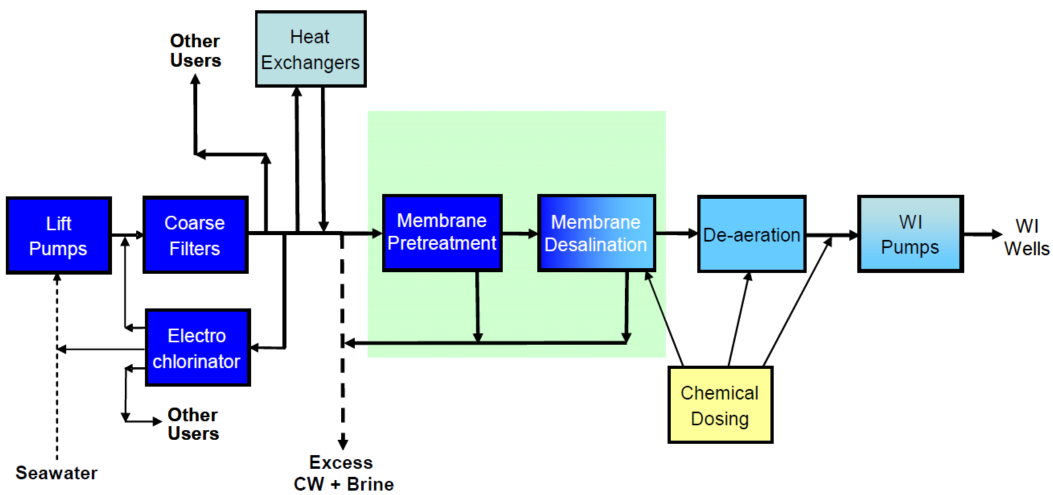


Figure 9. Schematic diagram of membrane desalination unit that could be used for LSWT implementation. This installation is more suitable for offshore reservoirs that have a good access to seawater source. From Robbanna et al. (2012).

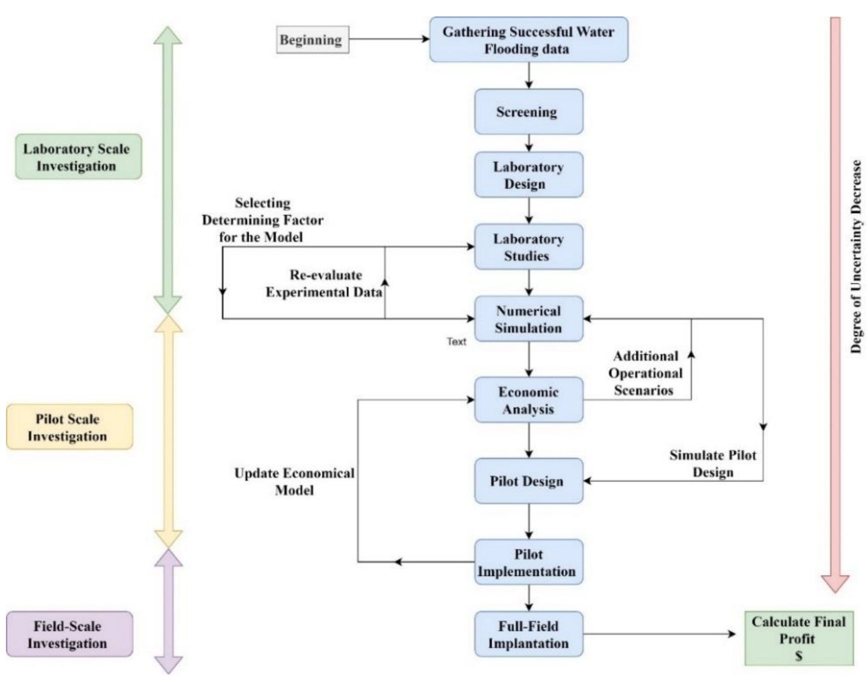


Figure 10. Proposed workflow to assess and execute low salinity water floods.

Table 7
Economic outcomes for different recovery factors. Shaded line represents field E project discussed in text.

RF	LSWF Incr Recovery, bbls	NPV Diff Cash Flow	ROI Disc	Payback Diff Cash Flow, years
0.0%	-	$(2,500,000)	-100%	#N/A
0.1%	122,500	$(859,706)	-34%	#N/A
0.2%	245,000	$780,628	31%	5.89
0.3%	367,500	$2,445,719	98%	3.68
0.4%	490,000	$4,124,506	165%	2.74
0.5%	612,500	$5,803,293	232%	2.37
1%	1,225,000	$14,393,454	576%	1.53
2%	2,450,000	$32,104,887	1284%	1.05
4%	4,900,000	$68,759,922	2750%	0.56
6%	7,350,000	$105,928,526	4237%	0.37
8%	9,800,000	$143,210,116	5728%	0.28
10%	12,250,000	$180,670,197	7227%	0.22
12%	14,700,000	$218,112,216	8724%	0.19
14%	17,150,000	$255,573,354	10223%	0.16

RF – Recovery Factor directly related to LSWF, NPV – Net Present Value of the difference between cash flows with and without LSWF, ROI Disc – return on investment considering time value of money, Diff Cash – differential cash flow, difference between expected field`s financial performance with and without LSWF technology implemented.

Local aquifers with fresher water (5000 mg/l TDS) were identified to supply the fields with sufficient volumes for the continuous injection. The higher salinity produced water was disposed by injection. No major changes in operations were made to operations except injecting low salinity water. Decline curve analysis (DCA) assuming exponential decline was used on pre- and post LSWF data to estimate the ultimate recovery (EUR) and field life. Table 6 summarizes the results of the LSWF project on seven field's OOIP, normal (primary plus secondary) recovery, LSWF recovery and change in field life. The table shows Fields A, B, C, D, E and F all showed a break in decline rate about 9-12 months after LSWF was started. LSWF in these fields produced slower decline rates with increased EUR extending field life by 13 to 54 years. The calculated benefits of the LSWF ranged between 1.1 and 15.8% OOIP, consistent with the published range of field and laboratory data (see Figure 1). In contrast, field G showed an increased decline rate and shortened field life.

The data for the more detailed analysis for field E is shown in Figure 7. The data include barrels per month and well count. Production rate is correlated with well count so calculated decline rates were based on time periods where well count was relatively constant. Field E had 21 active wells producing about 15,000 barrels of oil per month when the LSWF was executed. The pre-LSWF decline rate was 15.91% per year. The data show that about 9-12 months after changing the injection water the decline rate improved from 15.9% to 10.2% and field life extended by 12.5 years. The EUR with LSWF represents increased recovery of 4.6% OOIP. Injection of the lower salinity water has continued and produced water salinity is now about 40,000 mg/l TDS indicating that the field has not been fully swept.

The data for field G is shown in Figure 8. Field G had 162 total wells producing about 190,000 barrels of oil per month when the LSWF was executed. The pre-LSWF decline rate of 5.9% per year increased to 11.5% about 9-12 months after the injection brine was changed. The calculated EUR decreased by about 38.5 million barrels or about 19% OOIP and field life shortened by 24 years.

The projected benefits (oil production, field life and profits) are conservative because the field has not reached the injection salinity. LSWF recovery in carbonate rock tends to increase with lower salinity until reaching a plateau so there may be further improvement in recovery as the field salinity declines. Historical field data for 5 years prior to LSWF implementation and 10 years after were used to further analyse the project economics for field E with the following assumptions verified by the operator: historical WTI prices and constant $40 WTI for future production (after differential, net revenue interest (NRI), and production taxes), 21 wells, 10.2% post-LSWF decline rate, $4,800/well monthly operational cost, $5.36/barrel crude oil gathering and transportation expenses, 1.5% annual fixed OPEX reduction synergies, $2.5 million CAPEX (conversion of existing wells to water supply/disposal) to calculate pre-tax cash flows. Potential EOR tax benefits are not captured in pre-tax forecasts as such benefits are widely variable depending on location.

The economic model is applied to calculate the profitability of LSWF projects over a positive range of recovery factors for field E. Table 7 shows the incremental barrels recovered, the NPV differential cash flows, return on investment (ROI discounted) and payback period for different recovery factors. The table shows that the ROI for 4% additional recovery is 2750%, a very successful project with a payback period of 0.56 years. In fact, the results show that this project would have been profitable with recovery as low as 0.2-0.3% OOIP.

Figure 8 shows the normal recovery (primary plus secondary) plotted against the LSWF recovery for all seven fields. The data show that the amount of LSWF recovery is positively correlated with the amount of pre-LSWF recovery (primary + secondary), indicating that LSWF results are proportional to the normal waterflood response. The plot also highlights the significant negative outcome of field G. The negative case shows that LSWF projects need pre-deployment testing to avoid negative outcomes and provide the basis for calculating the economic benefits.

In terms of OPEX costs, the major expense for these fields was the supply of injection water. In this onshore case, the water source and disposal wells are in the field and long-term water cost was $0.21 per barrel. The alternative of treating produced water to lower salinity is more expensive and can become an important OPEX component in project economics. Onshore locations provide additional choices for injection water such as lakes, streams, groundwater, or greywater to mix with produced water to lower injection salinity rather than treatment. For example, typical water cost is between $0.50 and $2.0 per barrel of water for brackish water supplies in the Permian Basin of Texas. In contrast, recent evaluation of desalination costs suggests water treatment for lowering injection salinity are between $5 and $10 per barrel (Person et al, 2017). Desalination can generate water for LSWF injection but also generates high-salinity waste streams (25% of total volume) that must be disposed. For examples, Abulla et al. (2012) found costs for the Burgan field with 28-fold dilution did not go below $10 per barrel even if additional recovery was more than 4%.

Desalination is the most likely option in the offshore application using seawater as the feed water. Figure 9 shows the membrane treatment facilities for an offshore project (Robbanna et al. 2012). BP reported desalination costs generally added $3 to $6 per barrel to operations at the Clair Ridge sandstone project that included installation of a 145Mbd reverse osmosis (RO) plant on the platform to blend with produced water and achieve 2- to 3-fold dilution (Reddick et al. 2012). The saline reject water is disposed by injection. Layti (2017) calculated $5 and $8 per barrel for low- and high-salinity water injection, respectively, for the same project. The cost of water treatment may be reduced in some offshore environments by using shallow groundwater from the oceanic shelf that can be blended with produced water to reach the target injection salinity (Person et al. 2017).

Another approach to supply lower salinity injection water for offshore pilot and field-scale operations is subsea water intake and treatment (SWIT) which can produce sulphate-free (less than 20 mg/l) and low salinity waters recipes (Hegdal and Pinchin 2014, Hegdal and Pinchin 2015, Hegdal et al. 2020). SWIT can work for different capacities, water compositions, and layouts using reverse osmosis and nanofiltration. The current capacity of fully integrated SWIT for low sulphate and low salinity water is 10,000 BPD (Hegdal et al. 2020). In terms of OPEX, SWIT reduces power consumption and improves sweep due to the mobile capability of the facility which results in the optimum location of water injection and could eliminate the need of chemical injection.

5. Discussion

New technology in the oil field relies on the practical knowledge gained during operations to advance. Our review gathered the current knowledge and experiences of LSWF and highlighted the areas that have not been fully developed especially examples of field projects with economical evaluations. Although the topic of LSWF is a very attractive area of active debate, researchers have too often focused on the mechanistic studies or case-specific testing rather than offering guidance for field implementation. To move past repetitive cycles of non-definitive experiments, we propose there is sufficient knowledge to move LSWF into practice on a larger scale, that is we can move from LSWF to LSWT. Questions of how it works Our data show that LSWF projects offer an alternative methodology to acquire low-cost barrels of oil. Projects need to be driven by the financial case. As we saw for the specific full-field cases even recovery factors in the single digits can be very profitable depending on costs. We also saw that skipping the screening and lab testing steps can damage existing production (wettability damage). Finally, we see that the benefit is related to previous production, that is a good waterflood is a good candidate while applying low salinity to a poor waterflood will not generate high recovery. This is somewhat counterintuitive, as many think that good recovery prior to LSWF should leave less additional oil to be recovered. should move to “how much” and “how fast” will oil be produced in proposed LSWF projects.

The key factors to widely deploying LSWF are more rapid screening and laboratory testing in parallel with preliminary economic modelling. Figure 10 shows a workflow based on current practices with steps proceeding in a linear fashion. However, there is no reason that several steps such as laboratory testing and preliminary economic analysis cannot proceed simultaneously. Screening should provide sufficient confidence to move to preliminary economic analysis and laboratory testing. While industry currently uses reservoir modelling to evaluate projects, this is a long and expensive process. Pilot testing is rapid and provides much more robust data to refine economic modelling and verify the potential costs and benefits.

During this process, the degree of uncertainty will decrease as knowledge is gained minimizing risk and avoiding the expensive and time-consuming current practices since the current multi-year screening projects are probably not viable for most companies. Instead steamlined processes such as proposed by Fjelde and his coworkers (2018) should be considered. We estimate that following the steamlined processes will cut the current time and cost by a factor of 5-10X. This is a key step in moving LSWF to LSWT. Moving ahead to pilot projects that provide the best basis for evaluating LSWF at the larger scale short cuts the current expensive protocols. As our economic analysis showed even small projects can be very profitable. Examples of pilot studies (Windalia and Matzan fields) can be used as templates for the pilot design and pilot simulation applications (Al-Murayri et al. 2018, Haynes et al. 2013, Lüftenegger et al. 2016). Based on the information from the field pilots and economic models, deployment plans are more likely to be executed if they are driven by the economic aspects.

7. Conclusions

LSWF is a novel and powerful IOR/EOR method that is of great interest to academia and industry researchers. The numbers of papers in this area are a good indicator of that interest. Based on the review of information available, LSWF is a viable technology for many producers, but several barriers prevent more widespread deployment. The lack of standardization in experimental studies prevent integration of prior results, the time and expense of current industry workflows hinder deployment. Finally, the perception that we must have complete knowledge of the mechanisms continue to hinder the development and deployment of this technology. While additional laboratory and computational studies are valuable, field projects are essential to developing a functional understanding of the process. As our economic evaluations show LSWF projects can be profitable even at the lower end of the range of recovery. We offer the following suggestions for both academia and industry to help transform LSWF into LSWT.

1- The conditions favorable to LSWF should continue to be better defined. This information is vital to improve screening. Our knowledge of the effects of temperature, degree of dilution, brine, and oil chemistry is limited due to the lack of systematic studies that isolate and test each factor independently.

2- Standardization of testing protocols and measurements will provide an improved understanding and allow integration of results from multiple studies. This knowledge will lead to an empirical basis for predictive models rather than the current situation where many studies are only relevant to specific cases.

3- Current industry workflows for reservoir screening are a barrier to most companies trying to apply this technology. Rather than the traditional screening techniques that involve empirically based rules of use, current reservoir screening involves multiyear projects with significant expenses that only screen a single reservoir at a time. There is sufficient knowledge to allow traditional screening approaches so we can screen multiple reservoirs at the same time furthering the broader application of LSWF.

4- The development of cash flow equations that include all the important parameters to evaluate the economic performance of proposed LSWF projects is essential to deploying this technique. The example project showed that even low recovery projects can be very profitable, particularly in cases were the OPEX costs are low.

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