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Variability in Quantity and Salinity of Produced Water from an Oil Production in South Kuwait

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Abstract

Produced water (PW) is the largest waste stream in the oil and gas industry. Water remains trapped for millions of years in the reservoir with oil and gas. When a hydrocarbon reservoir is infiltrated by a production well, the produced fluids commonly contain water. The understanding of this water's constituents and volumes is vital for the sustainable continuity of production operations, as PW has a number of negative impacts on the infrastructure integrity of the operation. On the other hand, PW can be an alternative source of irrigation water as well as of industrial salt. Interestingly, both the quantity as well as the quality of PW do not remain constant but can vary, both progressively and erratically, even over short periods of time. This paper discusses such a situation of variable PW in an oil and gas operation in the State of Kuwait.

Keywords

Produced Water, Oil Wells, Water-Cut, Salinity Fluctuation, Total Dissolved Solids

1. Introduction

Produced water (PW) characteristics differ from field to field and from well to well within one specific oilfield [1]. Some factors that influence the chemical and physical characteristics of PW are the geological formation and the geographical position of an oilfield, the age of the reservoir, and the sort of hydrocarbon product being mined from the subsurface [2]. Oil well fluid flow is greatly reliant on the physical properties of the geological formation of a producing reservoir [3]. Therefore, any alteration in the operations can result in a variation in the production quantities of produced fluid to the surface. The difference in oil and produced water production and the well fluid flows present a major source of anxiety in the industry, which has caused a number of risk assessments to be conducted in order to comprehend the likely consequences of co-mingling a large network of production wells and their impact on above surface oilfield production infrastructure such as flowlines, separators and other facilities in terms of integrity and operational parameters. Hence, incessant sampling is central to monitor any changes to the process system input properly. The characterization of reservoir fluids by the implementation of a systematic approach is essential. Among other things, this makes it possible to understand the likelihood of a solid or hydrocarbon solid debris formation, which would lead to solid deposition and clogging of the production lines. Sample validity and the compatibility of the system designs are highly important to ensure seamless operations [4]. In all cases, the analysis of the quantity and quality of PW of an oilfield is important, especially since PW is usually inconsistent in terms of geochemical composition, bacterial content and varying suspended solids and oil content [5].

The fluctuating concentrations of the constituents of PW can be visible in its total dissolved solids content (TDS), where in conventional oil and gas well produced waters it ranges from 1000 to 400,000 mg/L [6]. This means that total dissolved solids can make up close to 40 percent of the PW fluid. Alkaline and earth-alkaline salts are found to be main the part of the TDS content within PW. In addition, there are other oil related organic compounds and materials such as heavy metal salts and silica [7]. High concentrations of salts in PW can cause the degradation of subsurface equipment such as production tubing, leading to blockage of the tubing and consequently limiting the extraction of hydrocarbons from the reservoirs, resulting in an overall reduction of the fluid production capacity, which jeopardizes the business' economic return.

When analyzing and discussing the quality and quantity of PW from an oilfield, it may seem as if the PW composition and quantity are stable over long periods of time and that the PW produced by different wells operating within the same oil field is the same, but neither is necessarily the case. Rather, the quality of PW can change both systematically as well as erratically over time. Also, the water-cut (WC), *i.e.*, the proportion of water in the produced fluid, can change within an over-seeable period of time. This can happen without an alteration in the production process as a whole, *i.e.* without a sudden change in material injection into the production zone and without a change in the overall extraction volume per time interval. The current contribution highlights both such erratic and continuous changes in PW in an oil production operation in Southern Kuwait.

2. Materials and Methods

Two PW samples were obtained from a sampling point in a gathering center after a three-phase separation process (oil-gas-water). The sampling point is also normally utilized by the company to assess the characteristics of the PW that is collected here from a larger array of wells servicing one oil reservoir. The samples were collected in plastic containers and transported within 5 days of collection to the chemical laboratories at the United Arab Emirates University (UAEU). Sub-samples of these 2 PW samples were sent to the CORE labs, Abu Dhabi, UAE, for compositional analysis.

Also, the PW salinity from 114 oil-producing wells were measured in a total of 222 salinity tests from 1/5/2023 to 18/7/2023 by sourcing 1 L samples of produced fluid (PF) from the wells in high-density polyethene (HDPE) plastic containers. The samples were transferred to an onsite laboratory (in Kuwait) within 5-to-30-minutes after sampling, depending on the well's location. The salinity testing was conducted at room temperature, where the exposure time to the heat and dust of the outer environment was insignificant. The oil in the produced fluid was separated according to ASTM D4007-22 [8], using a centrifuge machine Model Seta, 90000-3P, manufactured by Stanhope UK. Then the remaining PW was filtered through a filter paper to remove the remaining oil content in the separated water before PW is set for further examination. The water salinity analysis was done with an Atago, Master-S28M Salinity Refractometer. The Salinity Refractometer was calibrated by applying 3 ml of distilled water on an open daylight plate section and then allowing it to spread uniformly on the prism surface, where all air bubbles are removed. The scale was visually inspected to check, if it was clear and the blue boundary line of the salinity indicator scale was at 0. The samples of the obtained PW were added onto the prism surface of the Salinity Refractometer in the form of droplets, which were equally allotted over the surface area with no visible air bubbles. The scale was monitored visually, and the measurements of each sample were noted according to where the boundary line meets. The prism area of the salinity refractometer was cleaned by wiping the prism area, the daylight plate and the near surrounding areas with a soft moist tissue.

3. Oil Production and Produced Water in Kuwait

Kuwait has divided its oilfields into 4 directorates, as follows:

1) North Kuwait, 2) West Kuwait, 3) South Kuwait, 4) and the Burgan Area.

The main oil reservoirs in Kuwait are shown in **Figure 1**.

In 2005, Bader [10] gave as an average content of 68,959 ppm Na^+, 19014 ppm Ca^{2+}, 3198 ppm Mg^{2+}, and 2851 ppm K^+ for Kuwaiti PW. Comparative data for North American PW [11] [12] shows with 12,000 - 15,000 ppm much less Na^+ content, but a much wider range for Ca^{2+} concentrations in North American PW (1000 - 120,000), depending on the formation [11]. **Table 1** depicts representative data of Kuwaiti PW from different areas [13]. Within Kuwait, generally, PW samples originating from oilfields in West Kuwait (WK) are of highest salt content, followed by North Kuwait (NK) and then South Kuwait (SK). In our study we considered an oilfield in South Kuwait, where the site is approximately 110 km away from Kuwait City towards the border with the Kingdom of Saudi Arabia.

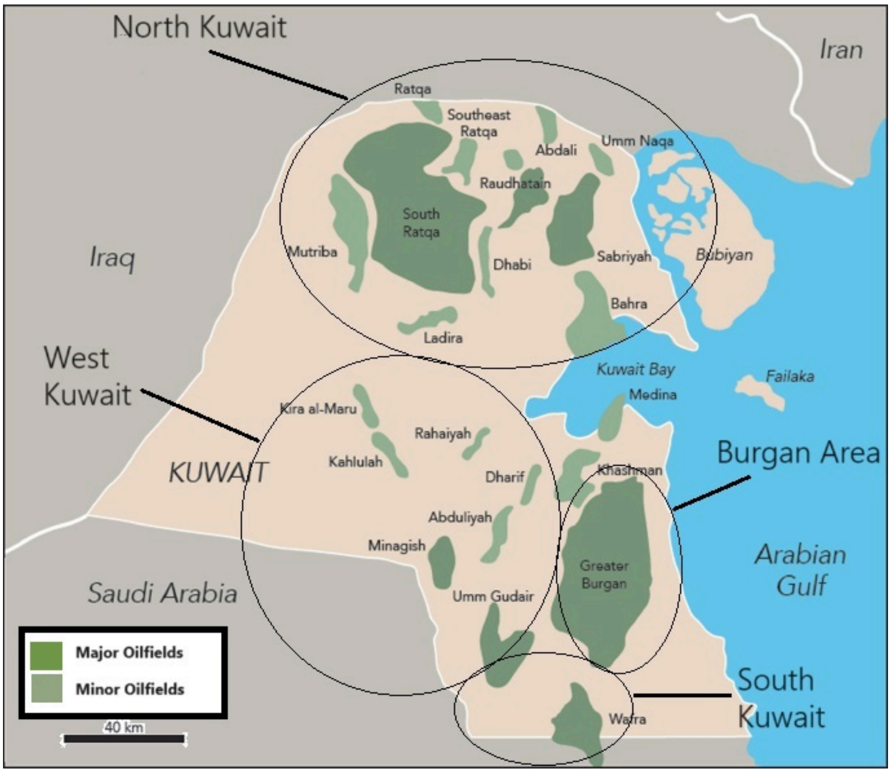

Figure 1. Map showing the location of Kuwaiti oilfields, adopted from Ref. [9].

Table 1. Characteristics of representative PW samples from different Kuwaiti oilfields [13], South Kuwait 2 being the field under investigation.

Kuwaiti Oilfield PW Samples					
Tested Properties	**West Kuwait 1**	**West Kuwait 2**	**South Kuwait 1**	**North Kuwait 1**	**South Kuwait 2**
Chloride mg/L	139,750	140,210	89,428	115,890	75,660
Sulphate mg/L	360	420	50	800	18
Density @25˚C	1.15	1.15	1.09	1.13	-
TDS (Calculated) mg/L	228,906	230,878	144,481	195,128	132,780
Conductivity ms/cm	201	201	154.7	187	ND
pH	6.81	6.27	6.8	4.73	6.88
Hardness mg/L	61,156	64,046	30,581	43,910	ND
Total Alkalinity mg/L	221.9	206.7	370.4	16.0	ND

This was chosen because it was purported that there is a dramatic increase in water cut (WC).

The oilfield under investigation (abbreviated as SK oilfield) produces heavy oil from 4 main production zones, with the first being enclosed by dolomite limestone with very porous dolomites at depths of 1000 to 1300 ft (300 to 400 m) in the Paleocene-Eocene Umm Er Radhuma Formation, The reservoir is of very high porosity (32 to 33 per cent). This can possibly be attributed to its shallow burial and early oil emplacement. It produces oils with gravities of 14˚ - 21˚ API [14]. The second oil reservoir is located in the upper Cretaceous formation where the average porosity is 24 percent with oil with an API gravity of 13˚ to 22˚. The third production zone is part of the middle Cretaceous formation with an average porosity of 26 percent and an API gravity of 24˚ for its crude oil. The fourth production zone is located in the lower Cretaceous formation with the lowest average porosity ranging from 16 to 23 percent and the highest grade of crude oil measuring 24˚ to 24.5˚ API. It must be noted that the last reservoir is the deepest of the four reservoirs in the oilfield with a difference in depth of approximately 580 m for the examined wells. The 114 different oil producing wells in the SK oilfields can be categorized into 6 groups (A-F) within the 4 main production zones mentioned above. Table 2 shows the characteristics of the reservoirs associated with the respective groups.

Table 3 shows the composition of the overall PW centrally gathered from the well groups A-F, where two samples were taken months apart. While there is a significant difference between the two samples in composition, it must be noted that this may not only be due to a variation of the PW from each well, but rather may reflect that among the multitude of connected wells, the primary producing wells may vary over time, where certain wells may also lie dormant for a time due to maintenance. Very evident is the high salinity of PW, which is up 4 times that of seawater. The order of the concentration of the main cations remains the same: $Na^+ > Ca^{2+} > Mg^{2+} > K^+ > Sr^{2+}$ and also the ratio conc. $[Ca^{2+}]$/conc. $[Na^+]$ with 0.216 - 0.217 remains similar. The sulfur content, including the H_2S content of the samples can vary significantly, which is also reflected in the sulfate concentrations in Sample and Sample 2 (Table 3).

4. Salinity of PW from Different Production Zones within One Oilfield in South Kuwait

PW characteristics from different production zones within one oilfield can be estimated, even though they may fluctuate greatly (see below), Figures 2-7 show the PW salinity for groups of wells measured within the same week, where the wells are situated at very close depths and proximity to each other.

Figure 2, shows the grouped data for 36 PW salinity analyses from 16 oil

Table 2. Characteristics of each group's reservoir.

Group	Reservoir Characteristics
A	Limestone
B	Dolomitic Limestone
C	Limestone
D	Dolostone
E	Oolitic Limestone
F	Fine to very fine-grained sands & siltstones

Table 3. Two raw PW samples taken 6 months apart from the SK oilfield under investigation. The samples are taken from a central collection point, where PW is gathered from a multitude of wells that include all well groups discussed below.

Components		Kuwait Produced Water Raw Sample 1 (mg/L)	Kuwait Produced Water Raw Sample 2 (mg/L)
Oil & Grease (Gravimetric, pH adjusted)		<5	306
TSS (0.45 μm)		11	95
Total Dissolved Solids		132,780	193,350
Dissolved Oxygen		3	N/A
pH at 25˚C		6.88	6.02
Cations	Sodium	35,600	51,500
	Potassium	1520	1800
	Calcium	7670	11,200
	Magnesium	1730	3050
	Barium	2.3	2.4
	Strontium	255	460
	Total Iron	1.36	N/D
	Dissolved Iron	0.44	<0.01
Anions	Chloride	75,660	110,090
	Sulphate	18	355
	Bicarbonate	140	300
Further Components	Silicon	12.3	N/D

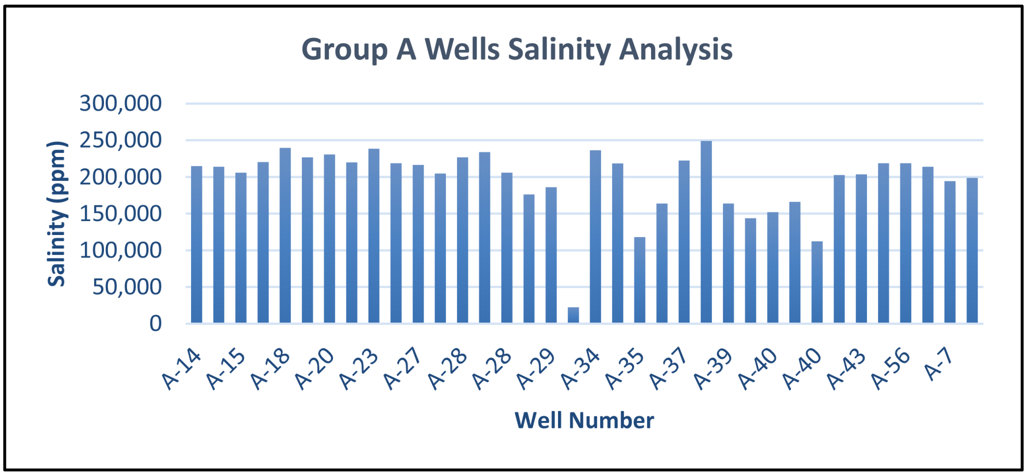

Figure 2. PW salinity of Group A wells.

producing wells in a specific field in South Kuwait. As interpreted from the data above, 9 analysis results for 5 different wells showed a salinity concentration of less than 200,000 ppm representing 25 percent of the tests performed and approximately 31 percent of the wells examined. The average salinity is 197.155 ± 44,639 ppm. When discounting the salinity value A-29 (2), the average was found to be 202,147 ± 33,571 ppm. The wells examined are drilled to the same production reservoir and are at similar depths (2083 m below the surface). All the wells are producing using the sucker-rod artificial lift method.

As part of our study, 34 tests for 16 wells have been conducted for group B wells with an average depth of 807.7 m below the surface. The average PW salinity is 73,511 ± 28,466 ppm. Discounting the "outliers" B-333 (2), and B-342 (1 and 2), the PW salinity was found to be 65,050 ± 7076 ppm. Groups B wells' salinity, however, has been seen to increase by as much as 166 percent in more than one event, as shown in Figure 3. The usual fluctuation, however, is ± 11 percent. Therefore, it must be noted that at this depth of the reservoir the salinity of PW is not constant.

Group C wells produce from the same reservoir as Group A. Therefore, they share the same depth of 2083 m below the surface. 49 tests for 23 wells were conducted to assess the salinity from the locations comprising group C wells. It was realized that these wells on average have different concentrations of salinity with a regular change of ±11 percent, but in two cases (C-156 and C-30) the produced water salinity plummeted by around 80 percent as shown in Figure 4. The average PW salinity of group C wells is 162,900 ± 33,853 ppm. When excluding the data for C-156 and C30, the average PW salinity is 168,814 ± 17,872 ppm. Significant fluctuations from the average can be to lower values as seen for C-156 and C-30 in well group C and for A-29 (2) in well group A or to high values as found in well group B.

For group D wells, which are drilled to only 609.6 m below the subsurface, making them the shallowest in our study, 55 tests were made, covering 18 different wells as shown in Figure 5. This group demonstrated two cases of changes in PW salinity from a well, where in one case the salinity decreased by more than 95 percent. This is clear evidence of the possibility of swift changes in salinity

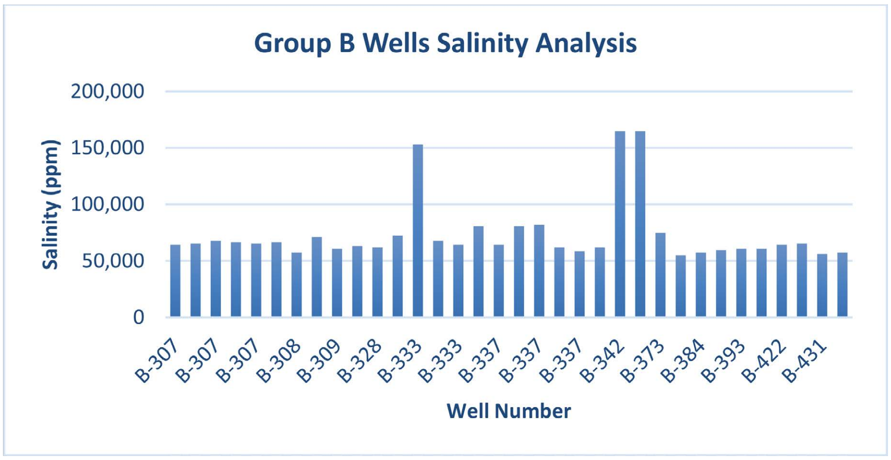

Figure 3. PW salinity of Group B wells.

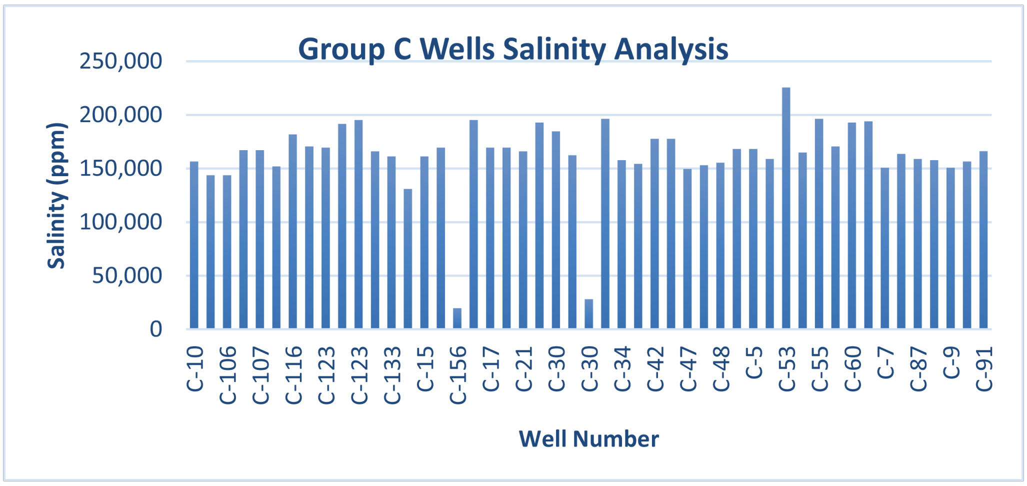

Figure 4. PW salinity of Group C wells.

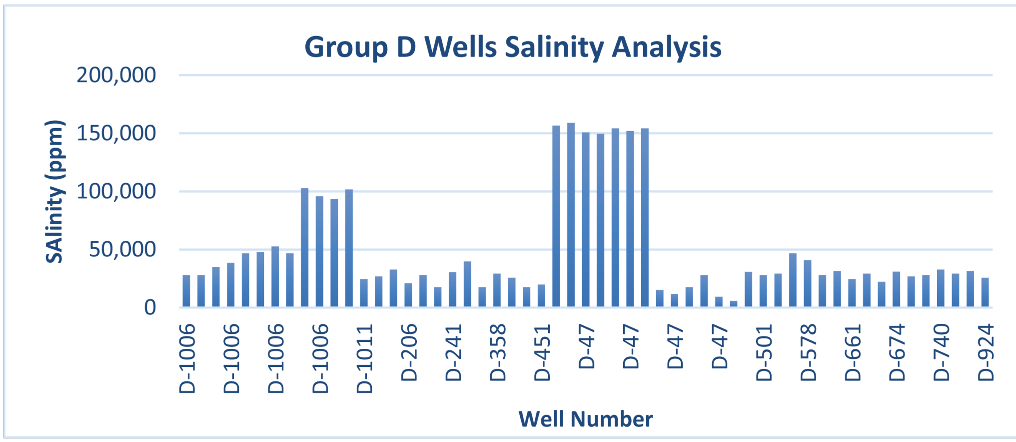

Figure 5. PW salinity of Group D wells.

in a short period of time. Overall, the average PW salinity was found to be 49,624 ± 45,049 ppm. The large standard deviation is due to the just discussed change in salinity in two wells over the study period.

Group E wells comprise of 26 wells for which 29 salinity tests were conducted (Figure 6). These are the deepest drilled wells in this study, reaching 2651 m below surface. The average salinity of the group E wells was found to be 243,268 ± 43,681 ppm. When excluding the data for E-49, the average salinity becomes 251,080 ± 11,971 ppm. The standard deviation is about ± 4.8%, when excluding the data for E-49.

Concerning Group F, which is at a depth of 1097.3 m, 12 tests for 12 unique wells were executed, as shown in Figure 7. Although the wells are producing from one single reservoir, the PW salinity ranges from 68,970 ppm to 108,640 ppm, with F-159 being treated as an outlier. Overall, the average PW salinity from the group F wells was found to be 80,110 ± 25,722 ppm. Excluding the data point from F-159, average PW salinity of the F group wells is 86,754 ± 12,042 ppm.

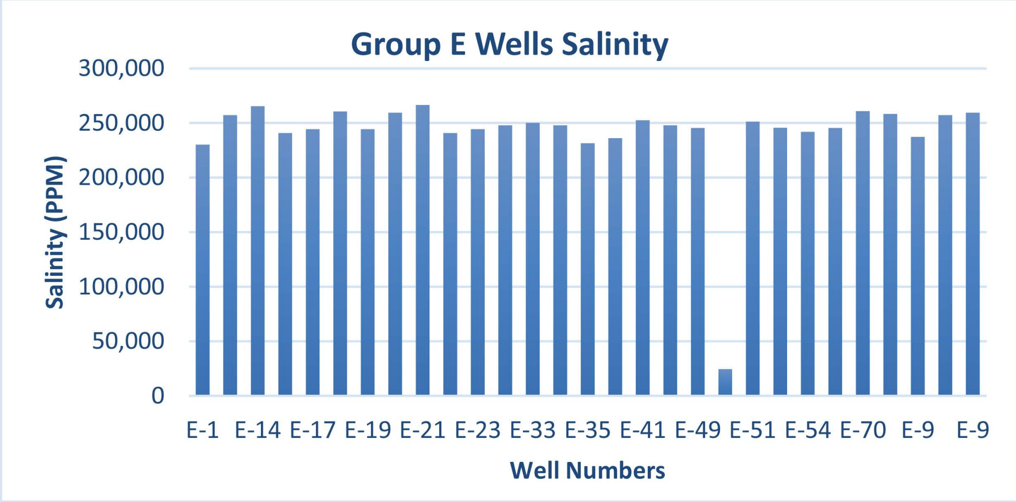

Figure 6. PW salinity of Group E wells.

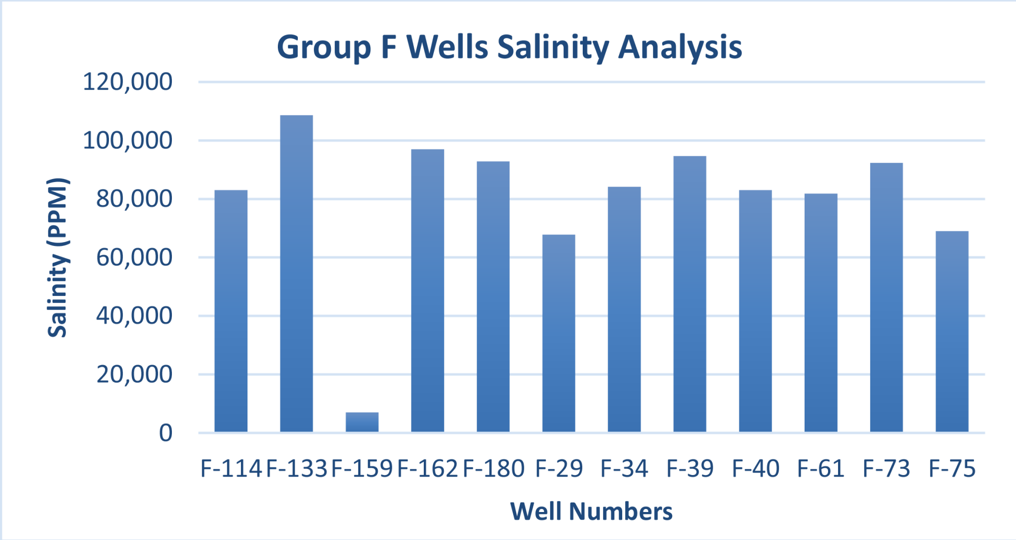

Figure 7. PW salinity of Group F wells.

Finally, also the salinity of the separated PW that is being disposed of has been monitored (Figure 8). Here, PW is pumped into injector/disposal wells, but does not directly reach the production zone. The average salinity of the disposed water is 223,112 ± 39,368 ppm. This salinity is transported back into the subsurface. There are ideas to utilize the salt composition of the disposed water, so that the salinity of the disposed water reaching the subsurface can be reduced.

5. PW Salinity Fluctuations

Figures 2-7 show a number of outliers. While these were partly disregarded, when calculating the average PW salinity, it must be noted that some of these outliers were from wells, where just a day before a PW salinity close to the average PW salinity was recorded. Fluctuations of PW salinity do not only occur for a larger production zone, but for a single oil well. This has been reflected in our results shown below, where two examples were chosen that exhibit the extraordinary variation in salinity within one single well over a relatively short period of time (Figure 9 and Figure 10). Both cases involve wells of group D, which are wells drilled at round 610 m below the surface, the shallowest placed among all groups. It had already been mentioned that the PW salinity among group D wells were the least stable. In both cases the salinity values of PW increase over relatively short periods of time to values that one could expect from PW sourced from greater depth. Although the exact reason and mechanism behind this change is still unknown, it can be imagined that turbulence in the reservoir plays a role, where PW normally residing at greater depth comes nearer to the surface.

6. Turbulence in Reservoirs

Turbulence exists in hydrocarbon reservoirs. It may lead to an enhanced upward

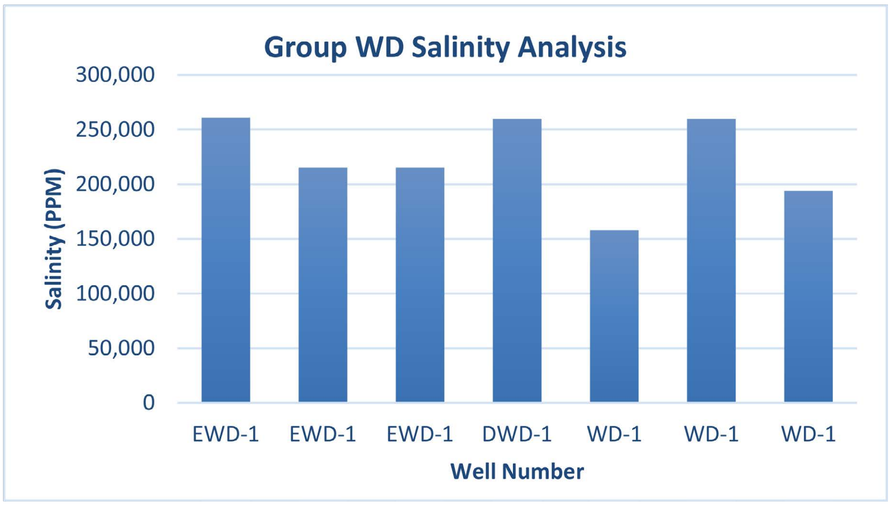

Figure 8. Salinity of PW disposed of in disposal wells (group WD).

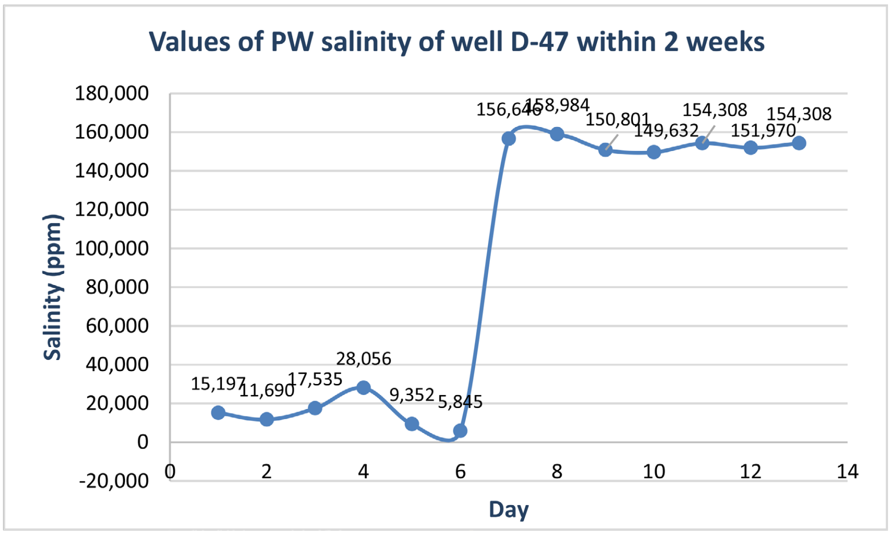

Figure 9. Fluctuations in PW salinity of well D-47 over a time period of 2 weeks.

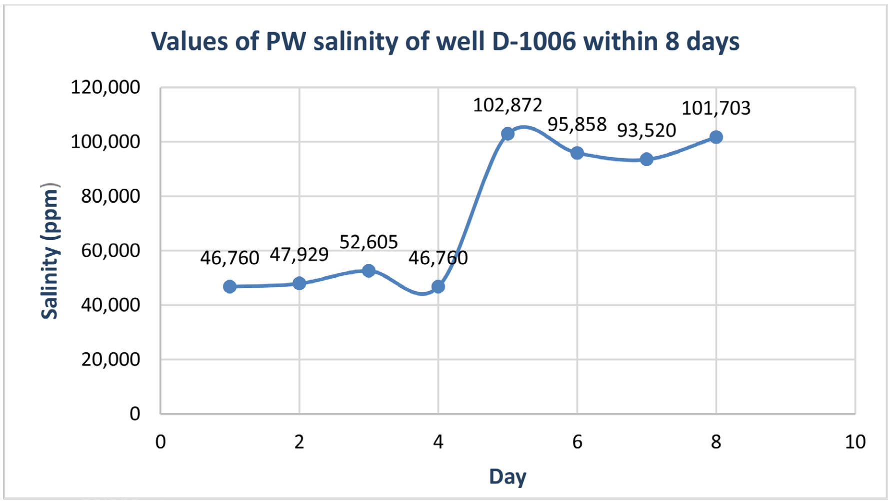

Figure 10. Fluctuations in PW salinity of well D-1006 over a time period of 8 days.

flow of fluid, but it may also cause a reduction in fluid flow to the surface, where it limits a smooth upward flow [15]. As the oil reservoirs continue to produce, their pressures drop and are compensated by pressure from water aquifers that are present, especially after a long period of production [16]. In heterogeneous carbonate reservoirs, such as the oilfield examined in this study located in South Kuwait, there can be a flow of formation/produced water in large fractures widening for tens of meters or longer that is similar to a turbulent pipe flow. This can simply result in a significant quantity of water production or even flooding and can eventually result in a production stop of the wells [17]. The degree of water invasion into the wellbore depends on a number of factors such as the aquifer volume and permeability [17]. Therefore, the greater the volume of the aquifer and the permeability are the more water is expected to enter the oil production zone in an oil well. In the SK oilfield of the current study, the situation was that as the oil production declined, elevated volumes of formation water from the water aquifers entered the oil production zone, similar to what had occurred in the Biyad oil reservoir in Yemen [18]. **Table 4** shows the difference between the initial reservoir pressures for all well groups mentioned earlier in this chapter in comparison to the current reservoir pressures. Turbulence in an oilfield can alter the natural gravity/density separation [17] and a drop in the reservoir pressure can cause significant volumes of water to intrude. This interrelationship is considered critical to historically understand in order to forecast a reservoir's output [18].

The deeper the production zone is in SK oilfield the higher are the expected PW salinity measurements from that zone (**Figure 11**). The salinity of PW in SK oilfield is fluctuating within different ranges, depending on the characteristics of each oil production zone in the reservoir. However fluctuations do in some cases surpass other production zones' salinity levels. It is difficult to control salinity levels from individual wells, let alone an entire oilfield. Therefore, the design of any facility should accommodate the maximum salinity levels over prolonged

Table 4. Average permeability, water cut and reservoir pressures of the SK reservoir under study.

Parameters	Group A	Group B	Group C	Group D	Group E	Group F
Avg Depth	6834 ft/ 2083 m	2650 ft/ 808 m	6834 ft/ 2083 m	2000 ft/ 610 m	8700 ft/ 2652 m	3600 ft/ 1097 m
Avg Permeability (md)	100 - 300	128	100 - 300	250	100 - 300	600 - 3000
Current WC %	80%	83%	80%	53%	78%	93%
Initial Pressure (psi)	3140	1125	3140	865	4050	1545
Current Reservoir Pressure (psi)	1722	998	1722	500	1700	1083
Pressure Difference (psi)	1418	127	1418	365	2350	462

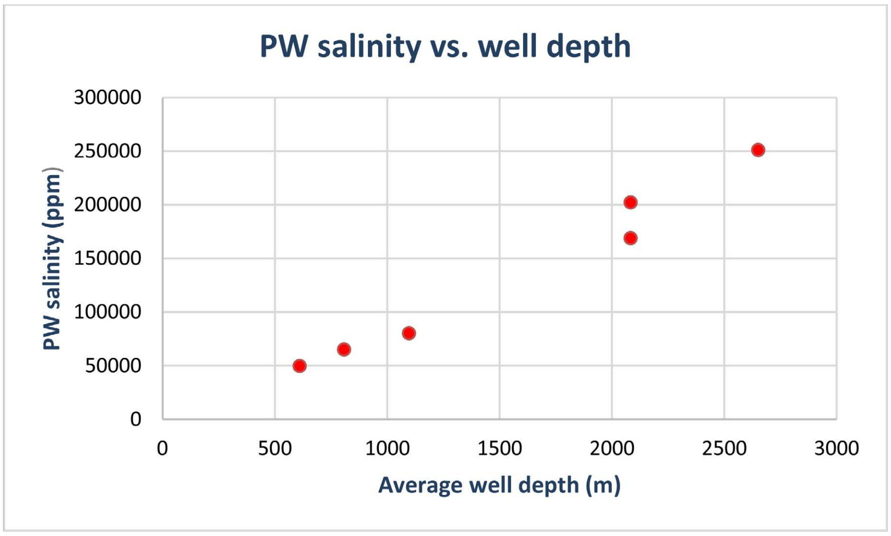

Figure 11. Average PW salinity as a function of the well depth in the SK oilfield.

periods of time. The results also highlight the need for constant monitoring of the produced water quality and infrastructure integrity to ensure the optimum design and solutions are in place for a smooth operation.

7. Maturing of Oilfields and Increase of the Water-Cut over Time

As oilfields mature, oftentimes the water-cut, *i.e.*, the proportion of PW in the produced fluid, increases [19] [20] [21] (see also above). Al-Jabri estimated that about 70% of the world's oil and gas production stems from mature fields, where these are in their secondary and tertiary production phases [22]. Renewable and other energy resources notwithstanding, production from these fields can make up more than one-half of the global energy mix for the next 2 decades [22], This is the reason why it is predicted that worldwide PW production will increase from about 250 million barrels per day in 2023 to around 605 million barrels per day in 20 years [23] [24] [25].

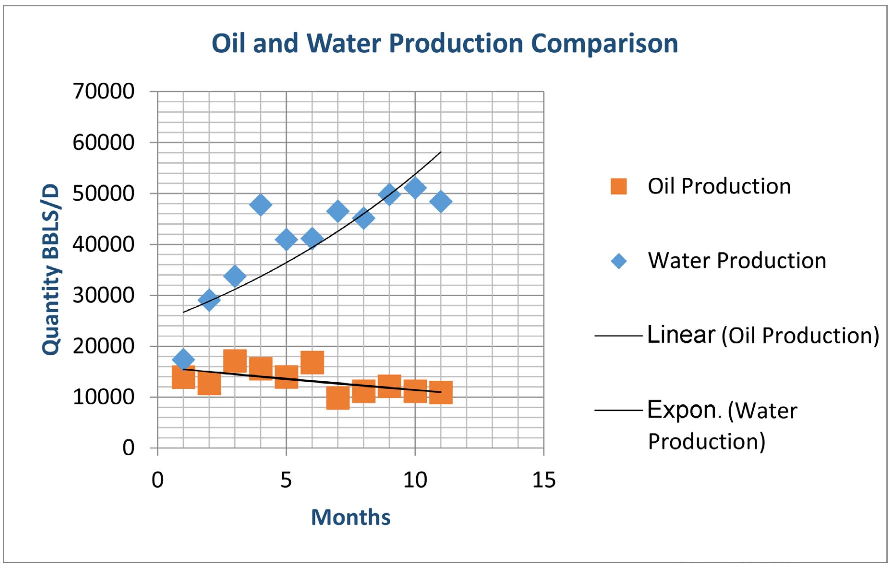

Figure 12. Water-cut of produced fluid from an oil field in South Kuwait.

Table 5. Water-cut of produced fluid from an oil field in South Kuwait.

Month	Average Water-cut (%)
January	53.81
February	68.39
March	64.81
April	72.20
May	71.39
June	69.47
July	80.94
August	79.45
September	80.33
October	81.16
November	80.27

Over 11 months of a monitoring period, the water cut of the produced fluid from the oilfield under investigation increased from 53.8% to 80.3%, having reached 81.2% at one time (Figure 12 and Table 5). Figure 12 represents a gathering center in where oil producing wells are connected of which separated PW samples have been obtained for analysis in this study, while Table 5 represents the broader results of the entire SK oilfield that demonstrates such an increase in water-cut being unusual. At the same time, there was a significant drop in pressure in the oil reservoirs of the SK oilfield, which had produced at that time for more than 50 years. A correlation coefficient calculation was made to investigate the relationship between average permeability for all groups of wells in their respective reservoirs, discussed above, and the water cut of their produced fluid, the result being a perfect correlation (−1.000). Also, an assessment of the dependence of the water cut on the reservoir pressure was made. The result showed a strong relationship with a correlation coefficient of 0.823.

Though in many Kuwaiti operations PW is still sent to disposal or re-injection wells, beneficial uses of PW are explored more and more, such as its use as injection fluid in enhanced oil recovery (EOR) [26] and in salt production [27]. Knowledge of compositional changes in PW, including knowledge about an increasing water-cut, is important, if PW is to be utilized as an alternate source for irrigation water and as a source of industrial salt, as purification processes of PW may need to be adjusted to quantity and quality of PW.

8. Conclusion

The case study presented in this contribution shows that the water-cut in production fluid from an oil and gas operation can change significantly within a few months. On top of that, within a shorter time-scale, there can be a more erratic series of changes in the quality and quantity of PW, which makes more difficult efforts of purifying PW and using it as an alternate water resource and a source of industrial salt. Given the current situation for the SK oilfield, combined with its historical data, we can expect the water cut to increase in its reservoirs as their pressure decreases over time due to the continuous extraction of hydrocarbons. A continued variation of WC is also expected due to the persistence of turbulence in the reservoirs as more quantities of formation enter the wellbore production zone to be transported to the surface in the form of produced water. The feasibility of turbulence control methods should be explored in cases of problematic and prolonged abnormal salinity from specific wells by the means of specialized subsurface equipment or chemical additives to mitigate the negative impacts of super saline PW on the oilfield's surface equipment.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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