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Evaluation of produced water quality by using water quality indices in Heglig area, Sudan

Mohamed Osman Zoealnoon and Adam Musa

ABSTRACT

The rate of produced water production of oilfields increases as oilfields age. This study aims to evaluate water quality of produced water from oilfields in the Heglig area using various water quality evaluation indices and study the significance of evaporation for cumulative pollutants after bioremediation in Heglig oilfield. Produced water samples were collected and analyzed for three locations in Heglig and Neem oilfields in order to determine the physicochemical, radioactivity, and heavy metal variables. The data obtained were used to determine the heavy metal pollution index, heavy metal evaluation index, weighted arithmetic water quality index, and Canadian water quality index (CCME WQI). The study revealed very poor water quality and high heavy metals at Neem oilfield. In addition, produced water quality at Heglig oilfield before the bioremediation was very poor and after the bioremediation was found to be poor, also the heavy metals were low before the bioremediation and medium after the bioremediation. Low levels of chemical oxygen demand (COD) oil in water, and total suspended solids (TSS) are mainly responsible for improvement of water quality after the bioremediation. Variation in the heavy metals before and after the bioremediation was a result of cumulative effect in the evaporation ponds.

Key words | metal contamination, produced water, water quality index

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INTRODUCTION

According to the US Department of Energy (DOE), the term ‘produced water’ has been assigned to water trapped in underground formations and brought to the surface along with oil or gas (Clark & Veil 2009; Jahan & Strezov 2017). Oilfields are responsible for more than 60% of daily generated produced water worldwide (PWTAEO 2017). Despite its significance, petroleum is produced with large volumes of waste, with wastewater accounting for more than 80% of liquid waste (Azetsu-Scott *et al.* 2007; Ahmadun *et al.* 2009). In addition to the amount generated, another important factor to be considered regarding produced water is its complex composition, once it is a mixture of a variety of organic and inorganic compounds. Produced water generally has as its main constituents: oils and greases, dissolved solids, organic and inorganic salts, dissolved gases, bacteria, chemical additives, heavy metals, and sometimes even radionuclides can be found (Lyman *et al.* 2018; Zemlick *et al.* 2018). Thus, the potential effect associated with discharging this wastewater on the environment without appropriate treatment has become an important issue and its disposal requires meeting the environmental regulations. Therefore, it has become essential to assess the water quality to identify the pollutants, categorize the water use, and strategize the remedial measures to maintain ecological health. Water quality impairment is a substantial environmental hazard which affects a wide variety of stakeholders and interests, particularly those who participate in outdoor water-based recreational activities (Barnett *et al.*

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2018). Over the last few decades, in order to assess the water quality, researchers from different parts of the world have developed a number of methodologies: heavy metal pollution index (HPI) (Mohan *et al.* 1996), heavy metal evaluation index (HEI) (Prasad *et al.* 2013), Canadian water quality index (CWQI) (CCME 2014), fuzzy comprehensive evaluation method, comprehensive pollution index method (C), and water quality index (WQI) (Boateng *et al.* 2016). This study focused on evaluating the produced water quality in the Heglig area in Sudan using weighted arithmetic water quality index method WAWQI, HEI, HPI, and CWQI by measuring minerals, radionuclides, and physiochemical parameters, and also considered the significance of evaporation in Heglig oilfield after the bioremediation.

METHODS

Study area

Heglig area is located in the Muglad basin between south Kordofan state in Sudan and the Unity state in South Sudan, and is limited by latitudes 9° 45′ and 11° 15′ N and longitudes 28° 45′ and 30° 15′ E. Heglig area extends almost from a tropical zone to semi-arid savanna. The annual rainfall rises from 600 mm in the northern part of the area to more than 800 mm in the south (Whiteman 1971). Heglig area accommodates two oilfields, Heglig and Neem. In Heglig oilfield, the produced water of around 39,747 m^3 per day is transferred from Heglig central processing facility ponds to bioremediation with a flow rate of 2,000 m^3 per hour for treatment (mainly oil in water) and then transferred to the forestry area (Figures 1 and 2). In Neem oilfield, the produced water of around 11,129 m^3 per day is stored in three ponds around the Neem processing facility.

Collection and analysis of samples

Produced water samples were collected from the inlet and outlet line of the bioremediation at Heglig oilfield. In addition, other water samples were collected from the outlet produced water line at Neem oilfield. Samples were collected in clean screw-capped polypropylene bottles. For trace metal analysis, a well-mixed 100 mL acid preserved sample was placed into a pre-cleaned, labeled beaker, 5.0 mL concentrated HNO_3 was added, the beaker was placed in a heater in a hood and temperature was adjusted to 105 °C. More concentrated nitric acid was added until digestion was completed by observation of a clear solution. The beaker was removed from the heater, cooled, and diluted back to the original 100 mL volume with metal-free water in a volumetric flask. Then, samples were analyzed using inductively coupled plasma optical emission spectroscopy (ICP-OES) Vista-MPX manufactured by VARIAN Inc, USA. On-site measurement of pH and

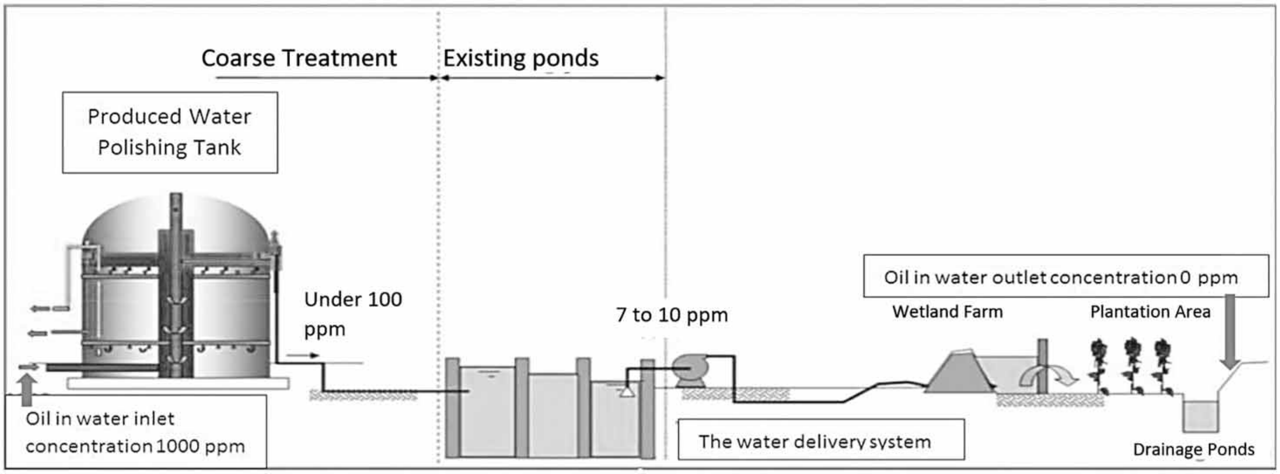

Figure 1 | Heglig produced water network.

Figure 2 | Heglig bioremediation.

dissolved oxygen was performed using a pH meter HI 98128 manufactured by HANNA Instruments, Italy, and portable dissolved oxygen meter HQ30D manufactured by HACH LANGE GMBH, Germany. Total dissolved solids (TDS) and conductivity were measured using an EC/TDS/NaCl/C° meter HI 9835 manufactured by HANNA Instruments. Total hardness, chemical oxygen demand (COD) and alkalinity were determined by titration method according to APHA (2012). Radioactivity was analyzed using gamma spectrometer LB200 Becquerel monitor manufactured by BERTHOLD, Germany. Nitrate, ammonia, phenol, and total suspended solids (TSS) were analyzed by spectroscopic method using spectrophotometer DR 6000 manufactured by HACH LANGE GMBH. Oil in water was determined by IR oil content analyzer OCMA-310 manufactured by Horiba, Japan. Grade chemicals and analytical grade reagents were used in analysis.

Water quality assessment

Four quality evaluation methods were used in this study: WAWQI for physiochemical parameters, HPI, HEI, and CCME WQI for overall pollution parameter.

Weighted arithmetic water quality index method (WAWQI)

This index indicates the total quality of water with respect to physiochemical parameters and heavy metals based on weighted arithmetic quality mean method and developed in two steps: first, by establishing a rating scale for each selected parameter giving weightage, and second, by selecting the pollution parameter on which the index is to be based. The rating system is an arbitrary value between zero and one and it can be assessed by making values inversely proportional to the recommended standard (S_i) for the corresponding parameter (Table 1). WAWQI was calculated from Equation (1) below (Satish *et al.* 2017):

$$\text{WAWQI} = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i=1}^{n} W_i} \tag{1}$$

where Q_i is quality rating for the i^{th} water quality parameters given by the expression:

$$Q_i = \frac{C_i}{S_i} \times 100 \tag{2}$$

where C_i is actual value present of the i^{th} parameter at a given sampling location. S_i is the standard allowable value for each parameter obtained from the Sudanese ministry of energy and mining standards for produced water discharge limits (RPEPIS 2005).

Table 1 | Water quality rating

WAWQI index level	Degree of pollution
0–25	Excellent
26–50	Good
51–85	Poor
85–100	Very poor

W_I is unit weight for the i^{th} parameters and was calculated from the equation below:

$$W_i = \frac{K}{S_i} \tag{3}$$

where K is relative constant and can be calculated using the following equation:

$$K = \frac{1}{\sum [1/S_i]} \tag{4}$$

Heavy metal evaluation index

HEI describes water quality condition in response to anthropogenic heavy metals (Table 2) This index was calculated according to Equation (5), as follows:

$$\text{HEI} = \sum_{i=0}^{n} \frac{H_c}{H_{mac}} \tag{5}$$

where H_c is monitored value and H_{mac} is maximum admissible concentration of the I^{th} parameter (Biswas *et al.* 2017; Ghaderpoori *et al.* 2018).

Canadian water quality index (CCME WQI)

The CCME WQI model consists of three measures of variance from selected water quality objectives (scope, frequency, amplitude). The scope (F_1) represents the extent of water quality guideline noncompliance over the time period of interest. The frequency (F_2) represents the percentage of individual tests that do not meet objectives. The amplitude (F_3) represents the amount by which failed tests do not meet their objectives. These three factors combine to produce a value between 0 and 100 that represents the overall water quality. The CCME WQI is calculated using Equation (6):

Table 2 | Heavy metal rating

HEI index level	Degree of pollution
<10	Low
10–20	Medium
>20	High

$$\text{CCME WQI} = 100 - \left[\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right] \tag{6}$$

F_1 (scope): The % of variable that exceeds the permissible value

$$F1 = \left[\frac{\textit{Number of failed variables}}{\textit{Total number of variables}}\right] \times 100 \tag{7}$$

F_2 (frequency): The % of separate tests for each variable that exceeds the permissible value:

$$F2 = \left[\frac{\textit{Number of failed tests}}{\textit{Total number of tests}}\right] \times 100 \tag{8}$$

F_3 (amplitude) represents the amount by which failed test values do not meet their guidelines and is calculated in three steps:

- The number of times by which an individual concentration is greater than (or less than, when the guideline is a minimum) the guideline is termed an 'excursion' and is expressed as follows in Equation (9):

$$\text{Excursion} = \left[\frac{\textit{Failed tests}}{\textit{Guidline value}}\right] - 1 \tag{9}$$

- The collective amount by which individual tests are out of compliance calculated by summing the excursions of individual tests from their guidelines and dividing by the total number of tests. This parameter, referred to as the normalized sum of excursions, or *NSE*, is calculated in Equation (10):

$$NSE = \left[\frac{\sum \textit{excursion}}{\textit{Total number of tests}}\right] \tag{10}$$

- F_3 is then calculated by an asymptotic function that scales the normalized sum of the excursions from guidelines

(NSE) to yield a range between 0 and 100.

$$F3 = \left[\frac{NSE}{0.01NSE + 0.01}\right] \times 100 \quad (11)$$

The guideline values are obtained from the Sudanese ministry of energy and mining standards for produced water discharge limits (RPEPIS 2005). Once the CCME WQI value has been calculated, water quality is classified into one of the following categories:

Excellent: (CCME WQI value 95–100) – water quality is protected with a virtual absence of threat or impairment; conditions are very close to natural or pristine levels.

Good: (CCME WQI value 80–94) – water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels.

Fair: (CCME WQI value 65–79) – water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels.

Marginal: (CCME WQI value 45–64) – water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels.

Poor: (CCME WQI value 0–44) – water quality is almost always threatened or impaired; conditions usually depart from natural or desirable levels (CCME 2014).

RESULTS AND DISCUSSION

A total number of 11 physicochemical parameters; total hardness, alkalinity, pH, TDS, electrical conductivity, oil and grease, COD, phenol, DO, TSS, and nitrate were measured for Heglig and Neem produced water with their observed standard deviations and used to assess the quality of produced water with the Sudanese ministry of energy and mining standard limits for produced water discharge (RPEPIS 2005). Radioactivity was measured for Neem oilfield produced water and Heglig oilfield produced water before and after the bioremediation; the result was higher than RPEPIS guidelines in Neem produced water (21 Bq/L) and zero in Heglig oilfield produced water. Radioactivity was significantly high in Neem produced water due to the high tendency of scale formation. The scale is typically a mixture of carbonate and sulfate minerals. One of these sulfate minerals is barite which is the primary host of oilfield NORM and the radioactivity is from isotopes of radium and their decay products (Lauer *et al.* 2018). The descriptive statistics of water quality and heavy metal evaluation indices generated for Heglig and Neem produced water is shown in Tables 3–5. Total hardness, pH, and phenol values of Heglig oilfield produced water were significantly affected by evaporation, showing higher values in the Heglig oilfield outlet to bioremediation compared to the inlet sample but still lower than RPEPIS guidelines. The concentration of total hardness and pH value in Neem oilfield produced water was higher than RPEPIS guidelines. The alkalinity and nitrate value for Heglig oilfield inlet to bioremediation was slightly lower than the outlet sample and both samples (inlet and outlet to bioremediation) had alkalinity and nitrate levels lower than RPEPIS guidelines. Anaerobic degradation processes, such as denitrification and sulfate reduction, have a much greater impact on increasing alkalinity for the outlet sample of the bioremediation, as denitrification and sulfate reduction occur in the bioremediation, where there is an absence of oxygen. Both of these processes consume hydrogen ions, and this consumption of H^+ increases the alkalinity (Thomas & Schiettecatte 2008). Nitrate appears in high concentrations in the water samples after the bioremediation due to dead aquatic organisms and plants and bird feces which are first decomposed to produce ammonia. Some bacteria in the water change this ammonia to produce nitrite, which is then converted by other bacteria to nitrate (Tang *et al.* 2011). Neem oilfield produced water alkalinity, TDS, electrical conductivity, and TSS has significantly standard deviations according to RPEPIS guidelines. TDS and electrical conductivity values of Heglig oilfield produced water were significantly affected by evaporation showing a higher value for the outlet to bioremediation compared to the inlet sample and exceeding RPEPIS guidelines for the outlet sample. The concentrations of COD, TSS, and conductivity in Heglig oilfield produced water before the bioremediation were higher than RPEPIS guidelines. COD is a measure of the capacity of water to consume oxygen during the decomposition of organic matter (APHA *et al.* 2012). High concentration of COD before the bioremediation is due to high concentration of

Table 3 | Weighted arithmetic water quality index (WAWQI)

	Measured value mg/L µs ppb			$K = 0.393$			$Q_i = \frac{C_i}{S_i} \times 100$			$Wi \times Qi$		
Parameters ppm, ppb Ec µs	**In BioS**	**Out BioS**	**Neem**	S_i	*1/Si*	$W_i = \frac{K}{S_i}$ W_i	**In BioS**	**Out BioS**	**Neem**	**In BioS**	**Out BioS**	**Neem**
T hardness	140	210	420	300	0.003	0.0013	46.7	70	140	0.06	0.09	0.183
Alkalinity	190	230	7,250	500	0.002	0.0008	38.0	46	1,450	0.03	0.04	1.140
pH	8.58	9.10	10.71	9	0.111	0.0437	95.3	101	119	4.16	4.42	5.196
TDS	1,138	1,502	7,650	1,200	0.001	0.0003	94.8	125	638	0.03	0.04	0.209
E conduc	2,460	3,040	13,520	2,000	0.001	0.0002	123.0	152	676	0.02	0.03	0.133
O/W	11	2	1	5	0.200	0.0786	226.0	30	14	17.76	2.36	1.069
COD	248	43	66	80	0.013	0.0049	310.0	54	83	1.52	0.26	0.405
Phenol	200	410	470	500	0.002	1.8403	40.0	82	94	73.61	151	36.988
DO	4	6.4	3	9	0.111	0.0437	41.8	71	34	1.82	3.11	1.504
TSS	268	173	346	30	0.033	0.0131	893.3	577	1,153	11.70	7.55	15.109
NH_3 as N_2	0.3	0.4	0.4	30	0.033	0.0131	0.8	1.2	1.3	0.011	0.02	0.017
Nitrate	0.3	0.3	0.12	30	0.033	0.0131	1.0	1	0.4	0.01	0.01	0.005
Sum					2.541	0.6063				52.9	50	62
WQI										**87.2**	**82.8**	**102.2**

BioS, bioremediation.

oil in water. The oil in water was significantly affected by the bioremediation where it decreased to lower than the standard target from 11.3 to 1.5 for Heglig oilfield inlet and outlet to bioremediation, respectively. According to Elbrir *et al.* (2015), the efficiency of Heglig oilfield bioremediation in hydrocarbon treatment is about 88%. The concentrations of oil in water, COD, DO, and phenol in Neem oilfield produced water were within the standard values. Heglig oilfield had standard levels of DO according to RPEPIS guidelines. According to Franklin (2014), low dissolved oxygen is most commonly encountered in unshaded areas, which explains the lack of oxygen for the location of Neem oilfield and before the bioremediation, which is an unshaded area compared to the bioremediation area. The impact of the evaporation on the physicochemical parameters before and after Heglig oilfield bioremediation was tested with the statistical t-test, where $P > 0.42$ advocates no significant difference due to evaporation.

WAWQI is created by using the measurement of some important physicochemical variables of the produced water (Table 3). The WAWQI for Heglig oilfield produced water after the bioremediation was reported as poor, while the water before the bioremediation for Heglig oilfield and Neem oilfield represented very poor water quality, as shown in Table 3. When comparing the three sites according to WAWQI, it can be seen that Heglig oilfield after the bioremediation was the site that had the best water quality due to the parameters of oil content and COD was significantly affected by bioremediation followed by Heglig oilfield before the bioremediation, while Neem oilfield was the more contaminated site. Higher levels of total hardness, alkalinity, pH, TDS, electrical conductivity, and phenol due to evaporation of the water after the bioremediation did not significantly affect water quality.

Concentration of the 17 elements: Ag, Al, As, Ba, Be, Cd, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Se, Ti, V, and Zn from Heglig and Neem oilfields produced water samples were determined (Table 4). Six out of 17 elements exceeded RPEPIS guidelines in produced water of Neem oilfield. Pb, Ti, and Ag were found in produced water of Neem with very high concentrations, which was much higher than RPEPIS guidelines, while Al, Ba, and Cd were slightly higher than RPEPIS guidelines. According to Ocean ESU (2005), the heavy metals' concentration in the background soil of the Neem produced water pond was within the standard limits, however, the presence of excessive amounts of

Table 4 | Calculated values for HEI and HPI

	Measured value μg/L				**HEI $\frac{H_c}{H_{mac}}$**			**HPI = W_iQ_i**		
Heavy metals	**In BioS**	**Out BioS**	**Neem**	**S_i & H_{mac} μg/L**	**In BioS**	**Out BioS**	**Neem**	**In BioS**	**Out BioS**	**Neem**
Ag	3.5	4	1,740	50	0.070	0.080	34.8	0.280	0.320	139.2
Al	44	2,584	1,400	1,000	0.044	2.584	1.400	0.009	0.517	0.280
As	88	65	14	50	1.760	1.300	0.280	7.040	5.200	1.120
Ba	530	321	621	625	0.848	0.714	0.994	0.271	0.164	0.318
Be	0.2	0.2	0.8	15	0.013	0.013	0.053	0.178	0.178	0.711
Cd	0.9	0.9	12.1	10	0.090	0.090	1.210	1.800	1.800	24.2
Cr	1.3	5.4	25.3	50	0.026	0.308	0.506	0.104	0.432	2.024
Cu	1.3	1.3	26.7	1,000	0.001	0.001	0.027	0.000	0.000	0.005
Fe	6.2	1,593	40	1,000	0.006	1.593	0.040	0.001	0.319	0.008
Mn	7	10	13.7	500	0.014	0.020	0.027	0.006	0.008	0.011
Mo	5	5.1	6.4	300	0.017	0.017	0.021	0.011	0.011	0.014
Ni	17.2	29	51	100	0.172	0.290	0.510	0.344	0.580	1.020
Pb	14	15	335	50	0.280	0.300	6.700	1.120	1.200	26.8
Se	56	89	44	160	0.350	0.556	0.275	0.438	0.695	0.344
Ti	0.6	147	18.2	70	0.009	2.100	0.260	0.024	6.000	0.743
V	1.6	6	31.8	70	0.023	0.086	0.454	0.065	0.245	1.298
Zn	2.2	2.2	14	1,000	0.002	0.002	0.014	0.0004	0.0004	0.003
Sum					3.7	9.7	47.6	12	18	198.1
HEI					**4**	**10.4**	**48**			
HPI								**19**	**29**	**328**

BioS, bioremediation.

Pb, Al, Cd, Ag, Ti, and Ba confirms the impacts of Neem produced water. Concentrations of elements in produced water before the Heglig bioremediation were all within the RPEPIS guidelines. Four out of 17 elements (Al, As, Fe, and Ti) exceeded RPEPIS guidelines in produced water of Heglig oilfield after the bioremediation. The impact of evaporation on the heavy metals of Heglig oilfield produced water before and after the bioremediation was tested with the statistical t-test, and the analysis showed $P > 0.09$, which statistically advocates no significant difference due to evaporation. The water quality indices based on trace metals were used to assess the quality of the produced water according to RPEPIS guidelines. The HEI shows that Heglig oilfield produced water before the bioremediation was classified as low pollution, and medium pollution after the bioremediation. The produced water in Neem oilfield was classified as high pollution according to the HEI. The HPI was very high for Neem produced water, in the category of very poor. The quality ratings of Heglig oilfield produced water before and after bioremediation were excellent and good, respectively, according to HPI. However, when comparing our results for the three locations, it must be pointed out that Heglig oilfield before the bioremediation was the site that had the best water quality, followed by Heglig oilfield after bioremediation, while Neem oilfield was the site most contaminated by heavy metals.

The above indices are designed to consider different attributes in the water quality for water assessment. Even though the WAWQI considers the wider impacts of pollution on the water quality, it neglects the toxicity of metals present in the water. Likewise, HPI and HEI do not consider the toxicological impacts of the nutrients and physicochemical parameters. To overcome this problem a separate index, CCME WQI, is used in this work (Table 5).

The descriptive statistics of 27 physicochemical and heavy metal parameters of produced water were calculated by CCME WQI, as shown in Table 5. Ten out of 27 variables exceeded RPEPIS guidelines in the produced water of Neem oilfield, which is classified as being of marginal quality. According to CCME WQI, the concentrations of Pb, Al, Cd, pH, total hardness, and TDS have increased by less than ten times the standard limits while the values of radioactivity, alkalinity, and TSS have increased between ten and 25 times the standard limits in Neem oilfield produced water. The concentration of Ag in Neem produced water has digressions in excess of 25 times RPEPIS guidelines. According to CCME WQI, Heglig oilfields produced water before and after bioremediation were classified as fair. Four variables (oil in water, COD, TSS and As) have increased by less than ten times over the RPEPIS guidelines for Heglig oilfield produced water before bioremediation. Seven variables (Al, As, Fe, pH, TDS, TSS, and Ti) appear in high concentrations for Heglig oilfield produced water after bioremediation and have increased by less than ten times the RPEPIS guidelines. In Neem oilfield produced water, the concentrations of TDS, alkalinity, Ag, Al, and Pb were in the category of severe potential irrigation problem according to FAO guidelines for evaluation of water quality for irrigation (Ayers & Westcot 1985). This confirms the scarcity of flora in the area around the evaporation ponds in Neem oilfield, unlike other areas that are not affected by the produced water. It is clear that there are differences in the values of HPI, HEI, WAWQI, and CCME WQI for samples of Heglig oilfield produced water before and after the bioremediation (Tables 3–5). This variation is due to the increase in the concentration of some sample metals after the bioremediation, which was a result of cumulative effect in the evaporation ponds. More detailed consideration of the radioactivity should be included in subsequent studies for Neem produced water. Field trials and study of heavy metal treatment by the phytoremediation technique are needed in future studies for Neem and Heglig produced water.

Table 5 | Calculated values for (CCME WQI) for Heglig produced water (before and after bioremediation) and Neem produced water

Sample	F1	F2	F3	WQI	Rank
Neem	14.8	14.8	24.2	46.2	Marginal
Heglig In BioS	25.9	25.9	30.9	74.6	Fair
Heglig Out BioS	37.0	37.0	77.1	78.5	Fair

BioS, bioremediation.

CONCLUSION

The study shows that the produced water of Neem oilfield exhibits high radioactive levels, high concentration of heavy metals like Pb, Al, Cd, Ag, Ti, and Ba, and high measurement of total hardness, pH alkalinity, TDS, electrical conductivity, and TSS. The HEI placed Neem oilfield produced water in the high contamination level, while HPI, on the other hand, considered it very poor quality. According to WAWQI and CCME WQI, the produced water quality of Neem oilfield was assessed as very poor and marginal, respectively. The trace metal concentrations in produced water before the Heglig bioremediation were within the standard limit, while concentrations of oil content, COD, TSS, and electrical conductivity were slightly high than the standard limit, which meant the produced water in Heglig oilfield before bioremediation was of fair quality and a low level of heavy metal pollution. The water quality of Heglig oilfield after the bioremediation was better than before the bioremediation due to the parameters of oil content and COD being significantly affected by the bioremediation. Higher levels of total hardness, alkalinity, pH, TDS, electrical conductivity, and phenol at Heglig oilfield after the bioremediation did not significantly affect water quality. More studies for treatment technology that can enhance the produced water quality after the bioremediation are highly required, mainly for heavy metal treatment. Furthermore, analysis for Neem produced water should be conducted to find suitable treatment technologies and avoid the nonconformance results.

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