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Assessment of Physicochemical Properties of Groundwater near Oil Well Pads in Lokichar Basin, Turkana County, Kenya

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Abstract

Oil mining wastes such as Produced water, drilling muds and cuttings may lead to contamination of groundwater. The study investigated whether Produced water from the oil well pads in south Lokichar basin, Turkana County, Kenya, leads to contamination of the neighboring groundwater resources. The specific objectives of the study were to 1) determine the physicochemical properties of Produced water and 2) determine the physicochemical properties of boreholes water near oil well pads. Produced water was found to be highly contaminated since all the selected physicochemical parameters exceeded the set drinking water quality standards. The computed Water Quality Index of 4030 found for the Produced water indicated that it was unsuitable for drinking purpose. Produced water heavy metals and salts levels that were found to be predominant exceeded acceptable water quality standards as follows: lead by 15,680%, zinc by 22%, iron by 16,567%, chlorides by 8128%, fluorides by 2500%, and nitrates by 480%. This was attributed to the usage of production chemicals to enhance oil recovery through hydraulic fracturing. Out of 11 groundwater samples analysed, eight were found contaminated with high levels of heavy metals and salts exceeding set drinking water quality standards. Nalemsekon borehole iron levels exceeded allowable standards by 250%, chloride 10.4% and fluoride 148%. RCEA borehole lead levels exceeded standards by 1500%, while fluoride 56%. Nakwakipi borehole lead levels exceeded by 5180%, nitrate levels 287%. Nakukulas 10 borehole zinc levels exceeded by 51%, nitrate 111%. Nakwakitela borehole fluoride levels exceeded by 36%, nitrate levels 428%. Nitrates levels at Irir 1, Chinese 1 and Nawoyatira boreholes exceeded standards by 604%, 463% and 322%, respectively. The high levels of heavy metals and salts observed in these boreholes was as a result of oil mining wastes contamination since these boreholes were in close proximity to the oil well pads.

Subject Areas

Water Quality

Keywords

Groundwater Quality, Produced Water, Salts, Heavy Metals

1. Introduction

Globally, the management of wastewater is mostly overlooked with water supply challenges being of utmost interest especially in water scarcity scenarios and this poses a great challenge since the wastewater ends up in the environment causing high negative impacts on human health, ecosystems and the economy [1]. Wastewater management in the oil and gas production sectors has become an important aspect due to the high volumes of water used and wastewater generated in the production process. The use of oil extraction technologies such as hydraulic fracturing and horizontal drilling aggravates the generation of wastes associated with oil production such as Produced water, drilling muds and cuttings [2] and [3]. These oil mining wastes constitute additives used within fracturing fluids such as surfactants, biocides, friction reducers, gelling agents and gel breakers as well as constituents formed within the oil reservoir such as total dissolved solids (TDS), hydrocarbons, naturally occurring radioactive material (NORM), heavy metals and other components [4]. Additionally, these wastes (especially Produced water) according to various studies are highly toxic. A study by [2], deduced that most Produced water had higher salinity levels that surpassed seawater salinity.

According to various studies [5] [6], the major oil mining waste generated from unconventional oil wells is Produced water. The American Petroleum Institute (API) had estimates of close to nine barrels (378 gallons) of Produced water being generated and recovered for one barrel of oil extracted in the oil operations at the strip zones. Additionally, this volume of Produced water generated showed a tendency to increase with the aging of the oil producing well [7]. The volume and the characteristics of Produced water also varies greatly depending on where the oilfield is located geographically, the geology of the oil bearing formation, and the methods used for oil production [8]. Produced water is the natural water found in the same formations containing oil and gas. Produced water is generated and recovered with oil during oil mining from oil bearing formations [9]. Produced water is of great importance in oil production as it acts as a supportive agent of drilling and hydraulic fracturing that increases the productivity of an oil bearing formation [3]. Produced water constitutes some of the chemical components as of the formations from which it was generated and from the hydrocarbons being explored as well as the chemical additives such as corrosion inhibitors, scale inhibitors, gelling agents, friction reducers, surfactants, acidizing agents and so on that are used to increase oil production [10]. These constituents contribute to the overall toxicity of Produced water. The prominent physical and chemical properties of Produced water are linked to the concentration of the following anions and cations Na^+, Ca^{2+}, Fe^{3+}, Zn^{2+}, Pb^{2+}, and Cl^-, NO_3^{2-}, F^-, SO_4^{2-} and so on. The salinity is dictated by the presence of Na^+ and Cl^- ions while conductivity is determined by all anions and cations present. Heavy metals such as lead, nickel, zinc, cadnium, and copper exist in most oilfield Produced water and their concentration depends on the age of the oil bearing formation [9]. Thus, this wastewater should be handled properly to protect the environmental resources.

In Africa, especially Niger delta region in Nigeria, the processes of oil extraction have had negative implications due to the wastewater generated that has greatly affected farming and fishing activities in the region which are the main socio-economic activities that local people rely on. The oil mining wastes especially the Produced water generated is contaminated according to various studies done and when it is released into the environment it causes major deleterious effects hence creating challenges on water-related activities such as farming and fishing as well as aggravating water scarcity problems by contaminating the little water sources available [11]. In Kenya, more specifically Lokichar sub-County, Turkana County, oil exploration is newly underway. Studies on implications of oil mining wastes on environment are scanty. Residents in the study area have been using oil mining wastes, especially the Produced water for their domestic needs such as farming and livestock. This is because the area depends mainly on the dwindling groundwater resources for these activities. The oil wells found in south Lokichar basin (study area) are unconventional thereby resulting in the generation of large amounts of Produced water. Produced water has been identified as one of the major sources of pollution of water resources in the study area following an Environmental Social Impact Assessment study conducted in Lokichar basin in 2019. The management of mining wastes remains a great challenge in Kenya and more so in the study area. Given the adverse environmental and health implications associated with these wastes, formulation of policies on the handling and disposal of these wastes remains a challenge due to inadequate data. This is because, oil mining is a new phenomenon in Kenya and the information on the effects of the oil mining wastes on the environment remains insufficient. Additionally, with the intensification of oil exploration activities in the area, there is a likelihood that groundwater contamination is going to scale up. Therefore, there was a need to determine the effects of Produced water on the physicochemical properties of the groundwater resources near oil production wells with the view to help the locals in the study area to access potable water and protection of the fresh groundwater resources by recommending suitable management approaches for the Produced water. The set out specific objectives of the study were to: 1) determine the physicochemical properties of Produced water and 2) determine the physicochemical properties of boreholes water near oil well pads.

2. Materials and Methods

2.1. The Study Area

The study was carried out in Turkana County covering communities living in Lokichar basin, Turkana South sub-County (**Figure 1**). Turkana County has a population of 926,976, with Lokichar Location having 12,676 people [12]. Lokichar Basin is situated 550 km Northeast of Nairobi as shown in **Figure 1**.

Turkana County experiences harsh climatic conditions with a bimodal rainfall. The County has two dry seasons, in June to September and December to March. The months of March to May and October to November are usually wet, with the rainfall known to be very unpredictable and sporadic [13]. Most meteorological data for the study area is lacking. However, long term rainfall records exist for Lodwar which is 100 Km to the North of Lokichar basin, and Turkwel Gorge which is located 60 Km Southwest of the study area [14]. The area potentially experiences high rainfall intensities of greater than 30 mm/hr which falls in short-lived storms (lasting 15 to 20 minutes) leading to occurrence of flash floods. This is attributed to the fact that the area's rainfall is sporadic and this usually takes place in the Northern parts of the study area [13]. The average temperature range in the study area is usually 24˚C to 38˚C; and this varies

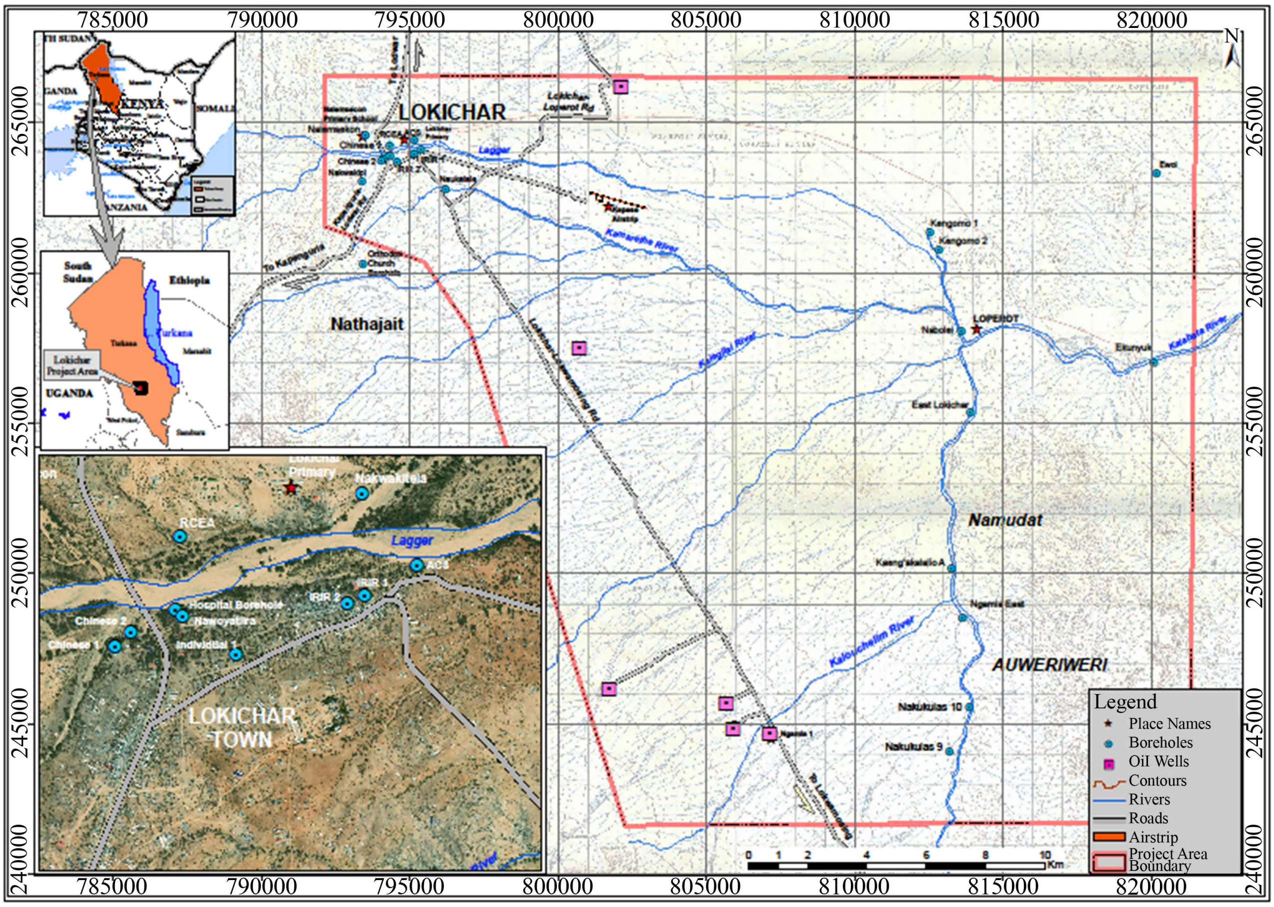

Figure 1. Location of Lokichar Basin in Turkana County, Kenya. Source (Author).

between 26˚C to 40˚C and 20˚C to 25˚C during the dry and wet season, respectively. In general, the lowest temperatures are normally experienced in November and December, while the highest temperatures are usually in January, March and August [13].

The geology of Turkana County consists of hill ranges and mountainous elongations which generally run in North-South direction. These are interspersed by superficial deposits which obscure the formations underneath [15]. The recent superficial deposits include Limestone which occur at various locations; and these mostly exist as pure Limestone but in some localities as heavy admixtures of soils and sand [16]. Soils within the study area originate from the geology of the tectonically active Rift Valley environment and/or the alluvial flood plains of major rivers and streams. The soils are moderately well drained, poor in nutrients, high pH levels, saline, highly sodic and with low organic matter and clay content. These soil properties are as a result of lack of vegetation cover as well as hot and arid climate of the area [13]. Soils in the study area fall under the Lower Midlands 5 (LM5) Agro-Ecological zone which makes the soils suitable for pastoral activities and millet farming. However, arable agriculture is not suitable in the area since the soils are poor in organic matter and the surface is mostly covered by stones and rock outcrops. This is exacerbated by soil erosion caused mostly by wind [17].

Groundwater forms the main source of water in the study area; and this occurs in three main categories, namely shallow alluvial aquifers, deep seated aquifers, and conductive fractures aquifers. Shallow alluvial aquifers are located 80 m underneath from the ground surface and usually have a high potential occurrence of 95%. These aquifers are estimated to have a thickness of 5 m and a porosity of 10% hence a storage capacity of around 1620 million cubic meters (MCM) which translates to an average of 0.5 MCM per km^2 [18]. Therefore, drilling boreholes in or adjacent to existing ephemeral rivers (Luggas) in the area potentially provide good groundwater quality. Deep seated aquifers on the other hand are those located in special rock formations between 80 m and 600 m. These have the highest groundwater potential of around 50 MCM per km^2. However, the potability of the groundwater in such aquifers is usually compromised by intense chemical weathering which in the long term leads to creation of soluble salts and minerals making the water brackish and saline [19]. Conductive fractures aquifers are the most prevalent type of aquifer in the study area. Fractures and fissures in the rock formations in the study area mostly store and conduct significant volumes of groundwater [18]. Groundwater yields of up to 5 m^3/hr. are usually realized from boreholes drilled on these types of aquifers in Lokichar basin. Therefore, most groundwater in the study area is harnessed from conductive fractures aquifers developed within the Basalts [20].

2.2. Methods

2.2.1. Primary Data Collection

Produced water samples were obtained from existing water pits within the oil well pads using grab sampling technique. Groundwater samples were collected from ten boreholes within the catchment divide, and one sample collected from outside the divide as the control of the study using snowballing technique in the month of August 2020. Standard sampling procedure for boreholes was used. In situ measurement of Physical parameters such as temperature, turbidity, pH, and electrical conductivity were determined on the field using the portable HI 98,129 Waterproof Tester. Laboratory analyses were conducted in accredited Laboratories where Laboratory protocols (that is acquisition and usage of instruments, chemicals, and reagents as well as test performance) were strictly followed to obtain reliable and accurate results. Table 1 presents a summary of the spatial data obtained using a handheld Global Positioning System (GPS) of the boreholes sampled.

2.2.2. Data Analysis

The Microsoft Excel software tools were used to prepare the physicochemical numerical data from the Laboratory analysis, to compute mean values, water quality index (WQI) and presentation of the outcomes in tables and line graphs of the Produced water and borehole's physicochemical parameters. The results from the above statistical analyses (boreholes) were displayed in box and whisker plots using PAleontological Statistics (PAST) Version 4.03 software tools. The Whisker type and Whisker length were based on the standard deviation and 95% confidence interval, respectively. The physicochemical properties of both the Produced water and boreholes water were compared to the World Health Organization (WHO) and National Environmental Management Authority (NEMA) drinking water quality standards to define their water quality status.

Table 1. Spatial data and the local names of the boreholes sampled.

Sample Name (Boreholes)	Local Names	Coordinates	Elevation (m)
BH1	Nawoyatira	35.6470377, 2.3819708	768
BH2	Irir 1	35.6543724, 2.3828575	762
BH3	Chinese 1	35.644338, 2.38075	770
BH4	RCEA	35.6469366, 2.3852019	766
BH5	Nakwakitela	35.6542841, 2.3868705	760
BH6	Nalemsekon	35.6397119, 2.3884931	774
BH7	Naukalale	35.6658418, 2.3719366	750
BH8	Nakukulas 10	35.822269, 2.21616220	683
BH9	Nakukulas 9	35.816100, 2.2030005	684
BH10	Nakwakipi	35.6385568, 2.3746816	773
BHC	Control	35.6387532, 2.3494112	794

3. Results and Discussions

3.1. Physicochemical Properties of Produced Water

The results obtained on the physicochemical properties of Produced water showed that the Produced water was highly contaminated. The selected physicochemical parameters were all above the set drinking water standards as illustrated in Table 2. The predominant parameters were total dissolved solids, fluoride, zinc, lead, iron, chlorides and nitrates. The high levels of metals and salts in the Produced water could be as a result of usage of production chemicals (such as acidizers, corrosion inhibitors, biocides, scale inhibitors, hydrate and paraffin inhibitors, friction reducers, gelling and foaming agents, cross linkers, demulsifiers, oxygen and hydrogen sulphide scavengers etc.) in oil extraction activities. The transfer of these contaminants from the chemical additives was

Table 2. Summary of the physicochemical parameters of produced water as compared to drinking water standards.

Chemical Parameters	Units	Drinking Water Standards	Produced Water Quality
Colour	Hazen	15	38
Turbidity	NTUs	5	295
pH		6.5 - 8.5 at 25˚C	5.9
Total Dissolved Solids	mg/l	1000	30352
Electrical Conductivity	µS/cm	1500	26600
Total Alkalinity	mg/l	500	653
Nitrates	mg/l	50	58
Nitrites	mg/l	3	53
Fluorides	mg/l	1.5	39
Sulphates	mg/l	250	210
Chlorides	mg/l	250	20570
Ammonia	mg/l	Taste and odour problems at concentrations above 35 & 1.5 mg/l respectively	43
Sodium	mg/l	200	4908
Magnesium	mg/l	150	185
Calcium	mg/l	200	574
Zinc	mg/l	1.5	1.83
Potassium	mg/l	200	112
Iron	mg/l	0.3	50
Lead	mg/l	0.05	7.89
Manganese	mg/l	0.4	1.9

likely exacerbated by the high temperatures in the study area as well as the low pH level of the Produced water. In addition, the computed Water Quality Index (WQI) value of the Produced water was found to be 4030; making it unfit for drinking purpose due to its high toxicity status. The results on the physico-chemical parameters of Produced water and comparison to the set drinking water standards are shown on Table 2.

3.2. Physical Parameters of Groundwater Quality

Out of the physical parameters of the boreholes water samples in Lokichar basin, temperature was found to have an overall average value of 31.3˚C, with the lowest mean value of 27.9˚C being recorded at Nawoyatira borehole. The highest mean value of 34.3˚C was recorded at Nakwakipi borehole. All the boreholes temperature values were within the set standard for drinking water of between 20˚C and 35˚C, as shown in Figure 2.

The lowest mean turbidity level recorded was 0.09 NTU at Nalemsekon borehole whereas the highest mean level was 1.83 NTU recorded at Nakwakipi borehole. The overall average turbidity value for all the boreholes water samples was determined and found to be 0.81 NTU. Generally, all the boreholes water was clear. The turbidity and color levels found for all the boreholes water sampled were within the acceptable standards for drinking water of 5 NTU and 15 Hazen respectively as shown in Figure 3.

In addition, all the boreholes water sampled had no odor or pungent smell. However, water sampled from RCEA, Nalemsekon, Naukalale, Nakukulas 10, and Nakwakipi boreholes had salty taste. This could be as a result of presence of sodium and chloride ions as well as other salts in relatively higher concentrations compared to the control borehole and the other boreholes whose water had no taste. Therefore, the study found that all the physical groundwater quality parameters examined (temperature, turbidity, color, odor and taste) in all the boreholes water were acceptable, since the parameters were within the set standards for drinking water.

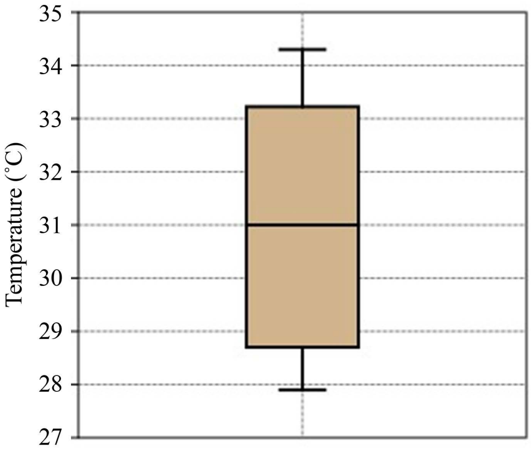

Figure 2. Mean temperatures of sampled boreholes water.

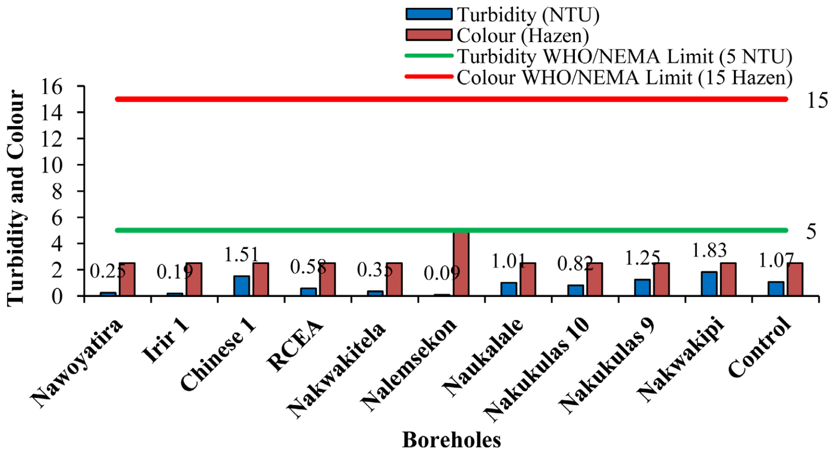

Figure 3. Mean turbidity and color values of sampled boreholes water as compared to drinking water standards for turbidity and color.

3.3. Chemical Parameters of Groundwater Quality

3.3.1. pH

The pH values of the sampled boreholes water which were determined both in-situ and through laboratory analysis, recorded the lowest mean value of pH of 7.64 at Nakwakipi borehole, and the highest mean value of 8.08 at Nakwakitela borehole (Figure 4). The overall average pH value determined in all the boreholes water sampled was found to be 7.82. Thus, the study found that the groundwater was slightly alkaline. In comparison to the set drinking water quality standards, the current study found that the pH levels of all the boreholes water sampled were acceptable.

3.3.2. Electrical Conductivity (EC)

The lowest mean value for electrical conductivity determined was 495 µS/cm for water sampled at Nawoyatira borehole. The highest mean value recorded was 3960 µS/cm for water sampled at Nalemsekon borehole. The overall average value of EC determined for all the boreholes was found to be 1192 µS/cm. In addition, 75% of the sampled boreholes had EC levels above 830.5 µS/cm indicating high salts levels in the groundwater (Figure 5). The electrical conductivity level for Nalemsekon borehole (3960 µS/cm) was above the set standard for drinking water of 1500 µS/cm as shown in Figure 5. This could be as a result of high concentration of salts from oil mining wastes pollution. This finding was supported by the relatively low level of EC recorded at the control borehole of 1066 µS/cm. Thus, the study found that the water in this borehole was unpalatable.

3.3.3. Total Dissolved Solids (TDS)

The lowest mean value of 306.9 mg/l for total dissolved solids was recorded for water sampled at Nawoyatira borehole. The highest TDS mean value of 2455.2 mg/l was observed for water sampled at Nalemsekon borehole. The average value of TDS for all boreholes was found to be 739 mg/l. The study therefore, found

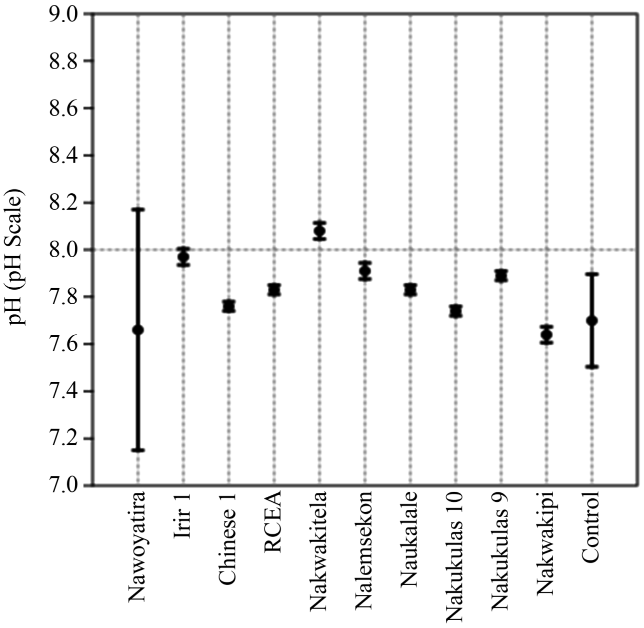

Figure 4. Mean pH levels of sampled boreholes water.

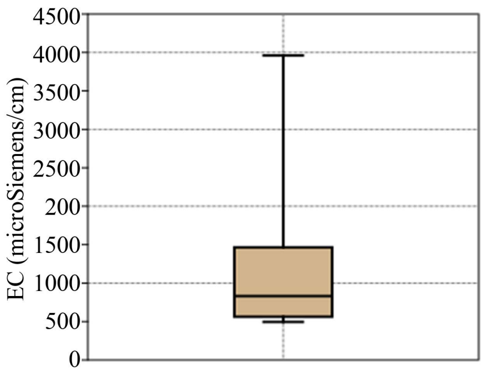

Figure 5. Mean EC levels of sampled boreholes water.

that all the boreholes water sampled had their TDS values within the acceptable standard for drinking water of 1000 mg/l except for water sampled at Nalemsekon borehole whose TDS value was 2455.2 mg/l. In addition, the current study found that 75% of all the sampled boreholes water had relatively high TDS levels above 515 mg/l (**Figure 6**). This could be as a result of presence of dissolved salts and metals ions from oil mining wastes contamination. This finding was arrived at since low level of TDS of 660.92 mg/l was recorded for the control borehole.

3.3.4. Metals

The major cations that were analysed for the boreholes water samples included calcium, magnesium, sodium and potassium while the heavy metals analysed included iron, manganese, lead and zinc. The study found that calcium levels for all the boreholes water sampled were within the acceptable standard for drinking water of 200 mg/l. The lowest mean value for calcium was recorded for water

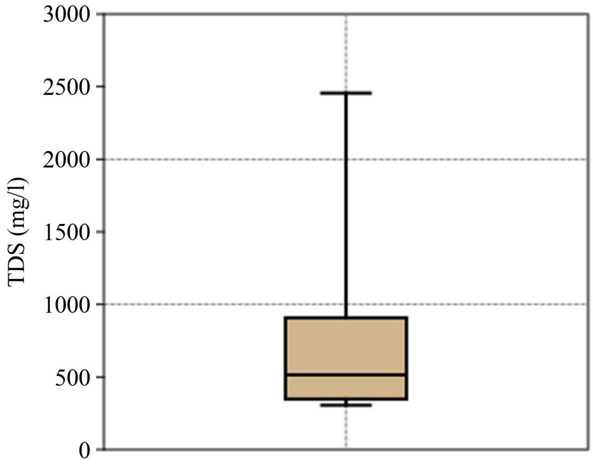

Figure 6. Mean TDS levels of sampled boreholes water.

sampled at Nakukulas 9 borehole, which had a value of 8.8 mg/l; and the highest mean value of 116 mg/l was recorded at Nalemsekon borehole (**Figure 7**).

The lowest mean value for magnesium of 27.72 mg/l was recorded at Irir 1 borehole whilst the highest mean value of 206.58 mg/l was recorded at Nalemsekon borehole. The magnesium level for water sampled at Nalemsekon borehole was above the set drinking water standard for magnesium. However, the water samples at the rest of the boreholes were within the set drinking water standards for magnesium (**Figure 7**). The high level of magnesium at Nalemsekon borehole could be as a result of contamination from the oil mining wastes generated from the oil mining activities in the study area since the magnesium level for the control borehole (31.6 mg/l) was considerably low.

It was noted from the laboratory analysis that sodium levels were significantly low for all the boreholes water sampled, with the lowest mean value of 4.77 mg/l being recorded at Nawoyatira borehole and the highest mean value of 43.85 mg/l recorded at RCEA borehole. Sodium levels for all the boreholes were within the set standard for drinking water of 200 mg/l (**Figure 7**).

The lowest mean value for potassium of 0.94 mg/l was recorded at boreholes Chinese 1, Nakwakitela, Naukalale, Nakwakipi and the Control, and the highest mean value of 2.83 mg/l recorded at Nalemsekon borehole (**Figure 7**). The potassium levels for all the boreholes water samples were within the set drinking water standard of 200 mg/l. The mean values of the major cations analysed for all the boreholes were as shown on **Figure 7**.

The results of the heavy metals analysed for all the boreholes were as follows. The study found that the manganese levels for all the boreholes water samples were within the set standard for drinking water of 0.4 mg/l. The iron levels for all the boreholes water sampled were within the set standard for drinking water of 0.3 mg/l, except for water sampled at Nalemsekon borehole which had a value of 1.05 mg/l (**Figure 8**). The high level of iron in this borehole could be as a result of oil mining wastes contamination from the oil mining activities in the study area. This was because the Control borehole had zero level of iron.

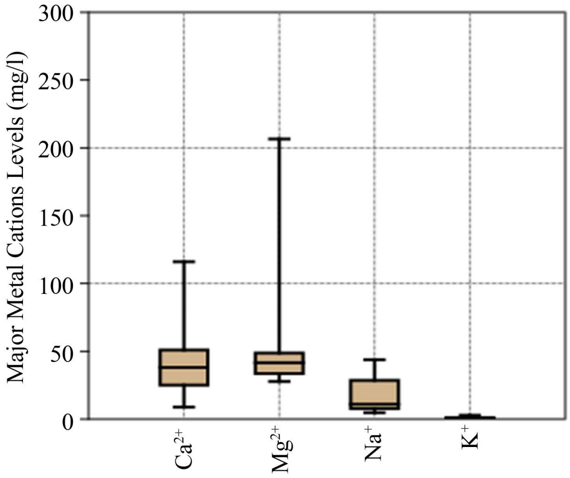

Figure 7. Mean major metal cations levels of sampled boreholes water.

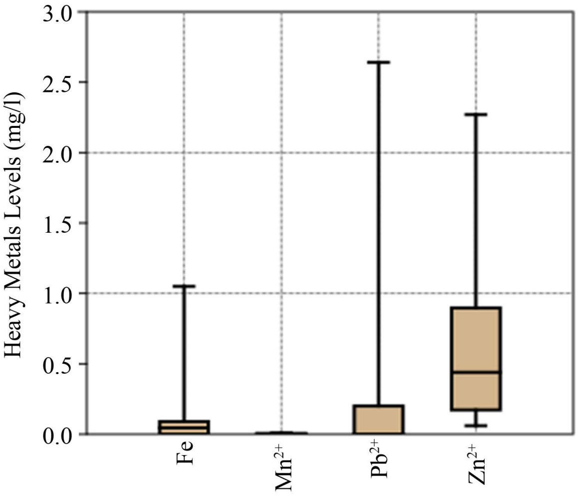

Figure 8. Mean heavy metals levels of sampled boreholes water.

Nakwakipi borehole water sample had the highest mean value for lead of 2.64 mg/l, whereas water sample at RCEA borehole had the lowest mean value of 0.8 mg/l. Water sampled at these boreholes were above the set standard for drinking water of 0.05 mg/l (**Figure 8**). This could be as a result of oil mining wastes from the oil mining activities finding its way into the aquifers which the sampled boreholes were sunk. Furthermore, this finding was supported by the fact that the Control borehole had zero level of lead.

The water sample at Nakwakitela borehole had the lowest mean value for zinc of 0.06 mg/l, whereas water sample for Nakukulas 10 borehole had the highest mean value of 2.27 mg/l. Nakukulas 10 borehole had zinc level above the set drinking water standard of 1.5 mg/l. whereas, the rest of the boreholes water samples had zinc levels that were within the set standard for drinking water (**Figure 8**). High zinc levels at Nakukulas 10 borehole could be as a result of oil mining wastes from the oil mining activities contaminating the borehole since it was in close proximity to the oil mining fields. In addition, this finding was supported by the contrast observed at the Control borehole which had zero level of zinc. The mean levels for heavy metals obtained in the boreholes water samples were as shown in **Figure 8**.

3.3.5. Salts

The result of the salts; chlorides, nitrates, nitrites, fluorides and sulphates; were as follows. The lowest mean value of 8.5 mg/l was recorded for chloride level in the water sampled at RCEA borehole, while the highest mean value of 276 mg/l was recorded at Nalemsekon borehole (**Figure 9**). Compared with the set drinking water standard for chloride of 250 mg/l, only one borehole (Nalemsekon) had a level exceeding that set limit (**Figure 9**). High chloride levels at Nalemsekon borehole could possibly be caused by contaminants from oil field Produced water (major oil mining waste). This finding was arrived at since the Control borehole had low level of chloride of 16 mg/l.

The study found that nitrate levels for the boreholes water sampled had the lowest mean value of 0.66 mg/l for Nakukulas 9 borehole, while the highest mean value obtained was 70.4 mg/l at Irir 1 borehole. It was noted that water samples at Irir 1, Chinese 1 and Nakwakitela boreholes which had nitrates levels of 70.4 mg/l, 56.32 mg/l and 52.8 mg/l respectively, exceeded the drinking water standard for nitrates levels set at 50 mg/l. In addition, Nawoyatira, Nakukulas 10 and Nakwakipi boreholes water samples which had nitrates levels of 42.24 mg/l, 21.12 mg/l and 38.72 mg/l respectively, exceeded the drinking water standard for nitrates of 10 mg/l (**Figure 9**). The presence of these elevated levels of nitrates could be as a result of pollution from oil mining wastes. This was because the Control borehole recorded a nitrate level of 2.332 mg/l which was very low as compared to boreholes with nitrates levels exceeding drinking water standards.

Nitrites levels were only obtained for boreholes water samples at Irir 1 (0.0033 mg/l), Nakwakipi (0.0033 mg/l) and the Control (0.0297 mg/l). These levels were low and posed no hazard as they were within the acceptable limits set at 3 mg/l for nitrites as shown in **Figure 9**.

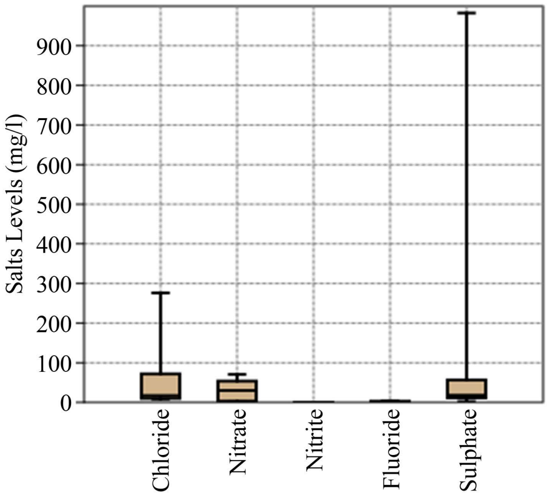

Figure 9. Mean salts levels of sampled boreholes water.

The drinking water standard for fluorides is 1.5 mg/l. However, water samples for boreholes RCEA, Nakwakitela and Nalemsekon which had levels of 2.34 mg/l, 2.04 mg/l and 3.72 mg/l respectively exceeded this limit. Thus, the study found that the water from these boreholes was unsuitable for human consumption (**Figure 9**). High fluoride levels in these boreholes could be as a result of oil mining wastes pollution since the level of fluoride in the Control borehole (0.95 mg/l) was relatively low. In addition, the study found that some of the residents in the study area suffered from the health risks associated with consumption of water with elevated levels of fluorides such as discolouration of teeth (Dental Fluorosis) and weakening and bending of bones (Skeletal Fluorosis).

The lowest mean value for sulphate of 2 mg/l was obtained for Nakwakipi borehole water sample, whereas the highest mean value of 982.86 mg/l was obtained at Nalemsekon borehole (**Figure 9**). The standard for drinking water for sulphates is set at 250 mg/l. The study found that water at Nalemsekon borehole had unacceptable sulphate levels, while the rest of the boreholes water had acceptable sulphate levels. The high level of sulphate at Nalemsekon borehole could be as a result of oil mining wastes contamination because when compared with the Control borehole sulphate level of 20 mg/l a huge contrast was realised. The mean salts levels obtained in the boreholes water samples were as shown in **Figure 9**.

3.4. Water Quality Index (WQI)

The current study adopted the Water Quality Index (WQI) approach to describe the water quality status for the sampled boreholes. This approach utilizes the obtained voluminous data on water quality parameters and reduces the same to a score that defines the water quality status of a given sample. The study found that the WQI for the sampled boreholes water ranged from 36 for the Control borehole to 506 for Nakwakipi borehole. Furthermore, the study found that Naukalale, Nakukulas 10, Nakukulas 9 and the Control borehole water samples had WQI value of less than 50. These boreholes had excellent water quality as shown on **Table 3**. It was also found that boreholes that had good water quality included Nawoyatira, Irir 1, Chinese 1, and Nakwakitela since the WQI ranged between 50 and 100 for these boreholes (**Table 3**). The boreholes that had poor water quality that is; WQI ranged between 100 and 200, were RCEA and Nalemsekon (**Table 3**). Nakwakipi borehole had water unsuitable for drinking purpose since its WQI was above 300 (**Table 3**). The water samples collected at RCEA, Nalemsekon, and Nakwakipi boreholes had high values of WQI since they had high levels of heavy metals (lead, zinc, iron and manganese). The presence of the heavy metals in the water samples indicated groundwater contamination from oil mining activities. In addition, high levels of other parameters such as total dissolved solids, nitrates, sulphates, fluorides and chlorides also contributed to the high values of WQI found in the boreholes water samples. A summary of the WQI values for all the sampled boreholes and their water quality status were as shown on **Table 3**.

Table 3. Computed Water Quality Index (WQI) values for the borehole water samples and the water quality status.

Sample Name (Boreholes)	WQI	Water Quality Status	Remarks
Nawoyatira	64	Good Water	Fit for Human Consumption
Irir 1	87	Good Water	Fit for Human Consumption
Chinese 1	75	Good Water	Fit for Human Consumption
RCEA	183	Poor Water	Water Not in Good Condition
Nakwakitela	83	Good Water	Fit for Human Consumption
Nalemsekon	148	Poor Water	Water Not in Good Condition
Naukalale	47	Excellent Water	Good for Human Health
Nakukulas 10	49	Excellent Water	Good for Human Health
Nakukulas 9	38	Excellent Water	Good for Human Health
Nakwakipi	506	Water Unsuitable for Drinking Purpose	Need Too Much Attention before use
Control	36	Excellent Water	Good for Human Health

4. Conclusion

The Produced water was found to be contaminated since all the analysed physicochemical parameters exceeded the set drinking water quality standards. The high Water Quality Index (WQI) found for the Produced water indicated that it was unsuitable for drinking purpose. The toxicity of the Produced water generated in the study area was highly attributed to the production chemicals used for hydraulic fracturing since the oil wells found in the study area are unconventional. Based on salts contamination of the boreholes water samples, the study found that the borehole water samples at Nawoyatira, Irir 1, Chinese 1, RCEA, Nakwakitela, Nalemsekon, Nakukulas 10 and Nakwakipi were unfit for drinking purpose. The water samples at RCEA, Nalemsekon, Nakukulas 10, and Nakwakipi boreholes were found to be unsafe for drinking purpose due to heavy metals contamination. The presence of heavy metals and salts in the borehole water samples indicated contamination from oil mining wastes (that is Produced water, drilling muds and cuttings). The introduction of these contaminants into the groundwater resources could probably be through leaks from the pipeline conveying the Produced water from one oil well pad to the other, leaching of the contaminants from drilling muds or drilling cuttings, transport of the chemical additives through natural conductive and induced fractures during the drilling process and hydraulic fracturing, through breached conductor or surface casing or cracked wellbore cement; transportation of contaminants with recharge water and infiltration of the Produced water from the pits storing the wastewater at the oil well pads. Wastes generated in the oil mining activities within south Lokichar basin especially the Produced water, drilling muds and cuttings were found to majorly contribute to the contamination of the groundwater resources. The contamination of the groundwater resources by oil mining wastes within the study area is expected to increase in the coming years due to the intensification of oil mining activities indicated by the increase in the development of unconventional oil well pads.

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Data Availability Statement

All relevant data are included in the paper.

Conflicts of Interest

The authors declared that they have no conflict of interests.

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