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ORIGINAL RESEARCH ARTICLE

Assessment of water quality degradation caused by crude oil pipeline leakage into river and irrigation canal water in Southern Iraq

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ABSTRACT

The current investigation investigates experimentally the water quality deterioration due to leakage of crude oil pipelines into river water and irrigation canal water in the southern of Iraq. The study includes documenting the sample water quality caught from the oil polluted area and also to analyze the Water samples in the laboratory by using the most standard value laboratory methods as these: dissolved oxygen (DO), iron, chlorides, total suspended solids (TSS), total dissolved solids (TDS), pH, and oil-in-water (O/W), the oil concentrations in water samples (O/W) were very high and ranged from 123-167 mg/L. and all were imported. The pH was reported between 6.50-6.80, indicating weakly acidic solutions. Salinity was very high, TDS was between 85 000 and 98 730 mg/L, and chloride amounts up to 52 960 mg/L. Dissolved oxygen was strongly reduced by increasing concentrations of oil, showing the reduction of oxygen transfer by oil films. The study shows a negative correlation between the concentration of oil and dissolved oxygen and positive linear relationship with the concentration of oil with toxicity. This result shows how an oil spill causes each kind of pollution oil hydrocarbon salinity, and suspended solids to severely threaten aquatic environment and ecosystem. This implies calling for, the need for enhanced treatment systems, government over sight, and control of the discharge of oil into water thereby not diminishing the plans for further exploration of the available oil reserves in Iraq.

Keywords: pipeline leakage; water quality; TDS; dissolved oxygen; oil pollution; Iraq

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1. Introduction

Oil pollution, which takes its place at the top among the vital global environmental issues, is of prime importance in producing countries like Iraq, which have enormous pipeline systems used for crude oil transport. These pipeline systems are one of the sources of leakages, which pose a serious threat to water bodies, comprising rivers and irrigation channels. Past research studies have also shown the detrimental impact of oil pollution on water quality through the decrease in dissolved oxygen, rise in salinity levels, and entry of toxic hydrocarbons into the environment. Other than general impacts of an environment, very limited experimental data on the impact of oil pollution on real conditions in southern Iraq[1,2].

Consequently, a thorough experimental study on the quantitative definition of the degradation of water quality by the leakage of crude oil in this area has to be done. This project aims to determine the effects of oil contaminants on basic physicochemical data, such as concentration of oil in water, dissolved oxygen, total dissolved solids, pH, and so on[3,4]. Major sources of oil spills are several incidents in the transportation sector, such as tanker collisions, structural failures, and groundings. These are catastrophic and most commonly end with huge amounts of petroleum being discharged into the ocean. For industry-led images, they can be thought of, plus the recent statistics, which provide evidence of the severity of such events. As an example, in the Black Sea, the spill in the Kerch Strait in December 2024 ranks among the most important recent accidents because, after a collision in which two Russian tankers were involved, 4,000 tons of heavy fuel oil (mazut) were discharged into the environment[5,6]. Research Gap and Novelty of the Present Study.

The effects of crude oil pollution of surface water in various areas of the globe have been studied. However, there are few field-based studies that quantify the impact of crude oil pipeline leakage on river and irrigation canal systems that are connected in river regions of southern Iraq, especially in the major oil-producing areas. Moreover, past research has been based on one or two specific pollution markers, and has not yet considered an overall evaluation of the contamination of hydrocarbons, salinity, oxygen depletion, and environmental risk.

The novelty of the present study is that it has provided a detailed matrix for the physicochemical deterioration of surface water resources impacted by crude oil leakage, along with a Water Quality Index (WQI) evaluation, a statistical analysis of the data, an environmental risk assessment, and comparison with international environmental standards. The study also adds to the knowledge about sustainability issues of water resources in oil producing areas and gives scientific evidence to the implementation of future environmental monitoring and management strategies.

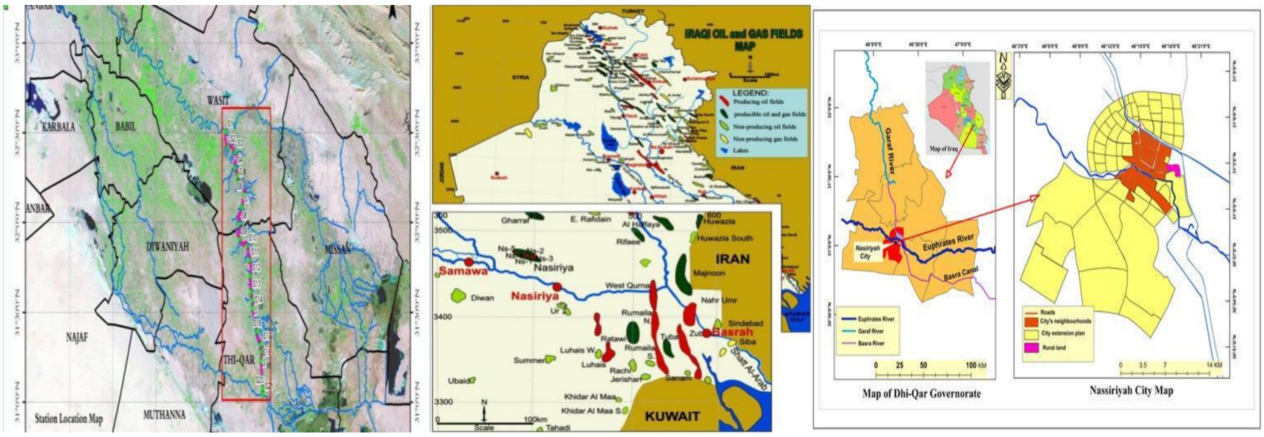

Figure 1. Study area map of Thi-Qar Governorate, Southern Iraq, showing the Gharraf River, major irrigation canals, crude oil pipelines, nearby oil fields (Gharraf, Nasiriyah, Subba, and Abu Amood), and water sampling locations (S1–S5). The map was prepared using the WGS84 coordinate system and includes a north arrow, scale bar, and GPS coordinates of the sampling sites[6].

Oil contamination from leaky pipelines and ship tanker spills is a serious environmental risk to the marine and coastal environment. These events can have a damaging effect on the lives of aquatic organisms by depriving them of oxygen, polluting the marine environment with toxic substances, and destroying habitats such as reefs that could take decades or more to regenerate[7]. Fallen pipelines and tanker spills have been ranked among the top causes of marine pollution and can result in a lengthy and costly cleanup operation[8]. Typical scenarios of crude oil pipeline leakage are shown in **Figure 2.**

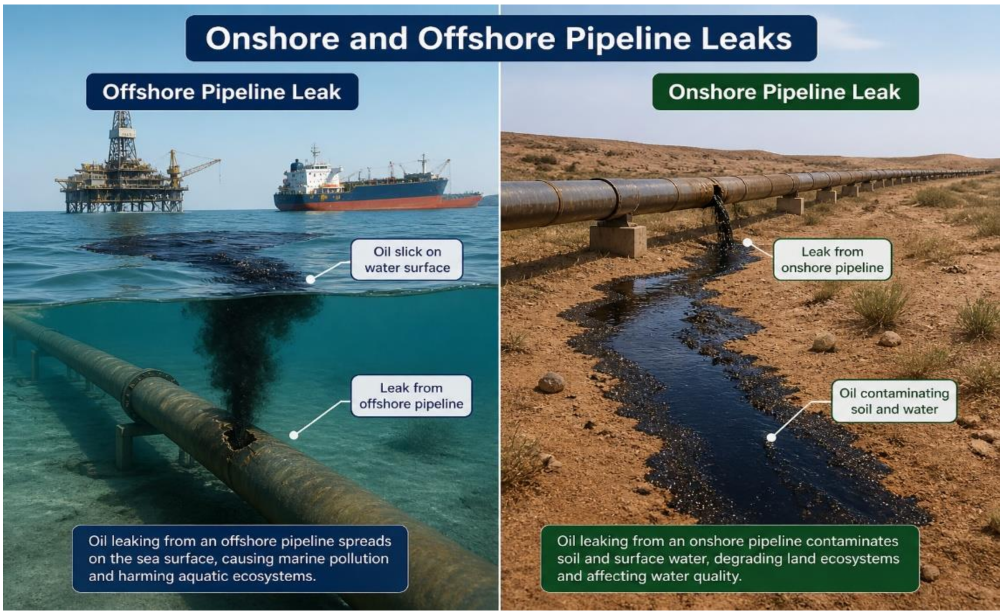

Figure 2. Leaks from both onshore and offshore pipelines[8].

1.1. Petroleum Pollutants Features

There are a number of physicochemical properties that influence the fate of petroleum contaminants in the environment. Some of these are physical properties such as density and viscosity, which affect the rate of spreading and ability of the oil to persist on the water surface, lighter oils spread quickly, heavier oils lag.

One other factor to consider is volatility. Lighter hydrocarbons, such as benzene and xylene, are very volatile and will be emitted to the atmosphere during the highest point of the spill. The heavier, semi-soluble fractions, on the other hand, are soluble easily in water and are highly toxic to aquatic fauna and flora and insoluble fractions settle and interfere in the life processes. Other harmful ingredients of petroleum include sulfides and phenolics that tend to bioaccumulate in living tissue and can be acutely toxic. These factors facilitate petroleum weathering through emulsification, evaporation and oxidation and they eventually have a bearing on the fate of petroleum pollutants in the environment[9-11].

1.2. Research Objectives

The primary aims of the present study are:

1. To experimentally test the influence of crude oil pollution on the main parameters of water quality.
2. To establish the relationship between the concentration of oil and dissolved oxygen mathematically.
3. To study the risk of environmental contamination from oil leakage of river and irrigation water systems.
4. To offer scientific evidence for an improved water treatment and environment protection.

1.3. Water Quality Assessment Based on International Standards

The measured parameters were compared with the permissible data recommended by the World Health Organization (WHO), the Food and Agriculture Organization (FAO) and the Iraqi environmental regulations in order to assess the suitability of the water resources investigated for environmental and agricultural applications All samples investigated were found to be in excess of recommended limits in a comparison of the samples. The concentration of oil in the water were found to be significantly exceeded from the acceptable discharge standards which are used and indicates that there are severe levels of hydrocarbon contamination[12]. Similarly, the total dissolved solids (TDS), chloride levels and iron levels measured were found to be above recommended limits for irrigation and environmental protection.

Specifically, TDS in the range of 85,000 to 98,730 mg/L are extremely saline and could potentially impact soil productivity, crop yield and groundwater quality[13]. Similarly, chloride levels over 50,000 mg/L may lead to the salinity of soils and stress on plants. The results of the study show the current poor quality of the water bodies investigated and their inability to be used directly for agriculture without adequate treatment and pollution control measures.

1.3.1. Water Quality Index (WQI) Assessment

A Water Quality Index (WQI) approach, based on selected physicochemical parameters such as pH, dissolved oxygen (DO), total dissolved solids (TDS), chlorides and oil concentration, was used to provide an integrated assessment of water quality conditions. The obtained WQI values were from 285 to 365 at the locations investigated. The water quality index classification systems define the water quality as extremely poor, >300, if it exceeds this threshold. This water quality is defined in the standard WQI classification systems as extremely poor, >300. For the oil leakage areas[15], the highest WQI values were found at positions S3 and S5, which are located closest to the identified oil leakage areas. This discovery further validates the significant impact of oil pollution on overall water quality degradation.

To ensure data reliability and analytical accuracy, several quality assurance and quality control procedures were implemented throughout the study.

- Calibration of all analytical instruments before measurements.
- Duplicate measurements for each sample.
- Use of reagent blanks and standard reference solutions.
- Verification of instrument precision and repeatability.
- Data validation through comparison with standard analytical ranges.

The analytical uncertainty for the measured parameters was maintained within ±5%.

1.3.2. Implications for Water Resources Sustainability

The present study shows that the deterioration of water quality is a big issue in sustainable water resources management in southern Iraq. The Gharraf River and irrigation canals are vital water resources that provide for agricultural, pastoral and community needs. Long-term leakage from petroleum infrastructure can lead to the creeping up of hydrocarbons and dissolved salts in the surface water system[16]. Moreover, contamination can be carried downstream via irrigation systems and lead to further soil salinization and contamination of the groundwater. Without management, these effects may lower agricultural production, and negatively impact regional water security. Therefore, it is strongly recommended that continuous monitoring programs be implemented, rapid leak detection systems be put in place, and integrated water resource management strategies be created to reduce potential future environmental impacts.

The physical and chemical characteristics of water are substantially altered by oil contamination. When oil passes over the water, it may appear transparent, with the sky visible through a transparent greasy film, or silvery, with a bluish sheen; the film depends on how thick the oil film is. The thicker the oil is, the light absorption of the light becomes iridescent (often rainbow-colored owing to the interference patterns of light). As the film becomes thicker, the oil has a blue-black or dark brown color and absorbs the entire spectrum of light almost completely. Under wave action, the oil will normally form a stable emulsion (also known as "mousse") which is a reddish-brown color and is difficult to remove[12]. Volatile hydrocarbon compounds, mostly aromatic, such as light components like toluene, benzene, and xylene (BTEX), are responsible for heavily odorous and air pollutant substances. Yet, for sour crude oil, the sulfur components like H_2S give an unpleasant aroma. These compounds could also concentrate in fish tissue even at low levels, which influences the fish quality and edibility[13].

Because oil forms a film on the water's surface, it restricts oxygen transfer from the atmosphere to the water. The microbes breaking down the oil also consume oxygen, creating hypoxic conditions, which can cause die-off of aquatic creators[14]. Chemically, PAHs are arguably among the most toxic substances in an oil, remaining in the environment for years and transforming under ultraviolet radiation to more toxic substances, which cause genetic and biological disturbance. The breakdown of hydrocarbons in oil also liberates organic acids and carbon dioxide, bringing a reduction in pH and lowering the pH, raising the acidity of the water and having a deleterious effect on calcifying organisms like corals and shellfish[15]. In general, oil contamination has a detrimental impact on the environment by ruining the habitat, lowering the types of life and endangering the health of people. Skin diseases and disorders of lung structures could be caused by petroleum pollutants, and grave health problems could be imposed from water or food contaminated ingestion. Loss of diversity lowers the stability of the environment[16]. The present study was based on five representative sampling locations selected within the contaminated area. Although these locations adequately characterize the pollution conditions near the leakage source, future investigations should include larger spatial coverage, seasonal monitoring campaigns, sediment analyses, and groundwater assessments to provide a more comprehensive understanding of contamination dynamics.

2. Materials and Methods

2.1. Study Area

The study area is situated in Thi-Qar Governorate, southern Iraq which is one of the main oil producing areas in Iraq. It is a region with a large network of rivers, irrigation canals, and petroleum transportation pipelines from nearby oil fields. The water samples were collected from points which are close to the routes of the crude oil pipelines and the possible impact zone of crude oil leakage events. The locations selected are sections of river water and irrigation canals that are subject to either runoff or direct contamination from petroleum activities. The climate is arid to semi-arid with high evaporation rates in the area can be a source of increased pollution concentrations in surface waters. The study area is shown in **Figure 1** along with the location of the oil facilities, major watercourses and GPS location of all sampling sites. **Tables 1** and **2** present further information on the study area and GPS coordinates of the sampling locations.

Table 1. Geographic Information of the Study Area and Sampling Locations (WGS84).

Feature	Description
Study Area	Thi-Qar Governorate, Southern Iraq
Coordinate System	WGS84 Geographic Coordinate System
Main River	Gharraf River
Water Network	Major Irrigation Canals Connected to the Gharraf River
Oil Infrastructure	Crude Oil Pipelines Crossing Agricultural and Surface Water Areas
Nearby Oil Fields	Gharraf Oil Field, Nasiriyah Oil Field, Subba Oil Field, Abu Amood Oil Field
Number of Sampling Sites	5 (S1–S5)
Sampling Environment	River Water and Irrigation Canal Water Potentially Affected by Oil Leakage
Map Elements	North Arrow, Scale Bar, Sampling Locations, Oil Fields, Pipelines, Irrigation Canals, Administrative Boundary

Table 2. GPS Coordinates of Water Sampling Locations (WGS84).

Sampling Point	Latitude (N)	Longitude (E)	Water Body Type	Description
S1	31.0625°	46.2814°	Irrigation Canal	Upstream reference site near agricultural area
S2	31.0852°	46.3157°	Irrigation Canal	Near crude oil pipeline crossing
S3	31.1048°	46.3489°	Gharraf River	Adjacent to potential oil leakage zone
S4	31.1276°	46.3764°	Gharraf River	Downstream section affected by oil activities
S5	31.1493°	46.4021°	Irrigation Canal	Downstream monitoring site

2.2. Sample Collection

Five water samples were taken from five different points in the river and irrigation canals affected by crude oil leakage from nearby petroleum pipelines in Thi-Qar Governorate, southern Iraq. Sampling points were chosen to cover areas of differing levels of oil contamination. Sterilized 1-L glass bottles were used in collecting samples and were rinsed well with sampled water before collecting. The samples were labelled and preserved following the normal environmental sampling procedure. Samples were collected, placed in cold, ice water containers and rushed to the lab for processing at approximately 4°C. All laboratory measurements were made within 24 hours of sampling to reduce any possible physicochemical changes and quality of data.

Although the results of this study are quite significant, there were some limitations that should be noted. First, it was done at a limited number of sampling points, not necessarily reflecting spatial variability of contamination across the entire river and irrigation canal network. Secondly, samples were collected within a limited monitoring interval and thus do not reflect seasonal changes in water quality characteristics. Third, the study was limited mainly to selected physicochemical parameters and other potentially important contaminants, including heavy metals, polycyclic aromatic hydrocarbons (PAHs), and biological indicators, were not examined. In addition, the interaction between hydrodynamics and sediments and the impact of long-term effects was not within the scope of the present work. Future research should include longer monitoring campaigns, more data, more sophisticated chemical analysis and assessment of ecological risk in the aftermath of crude oil pipeline leaks in southern Iraq to enrich the understanding of the environmental impacts.

2.3. Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics (Version 26.0).

The following statistical methods were applied:

- Descriptive statistics (mean, standard deviation, minimum, maximum).
- Pearson correlation analysis.
- Linear regression analysis.
- One-way ANOVA.

Statistical significance was evaluated at:

$P < 0.05$

The relationships between oil concentration and water quality parameters were quantitatively assessed to determine the environmental impact of crude oil contamination.

2.4. Laboratory Analysis

The samples obtained were then treated in the laboratory to measure some of the physicochemical parameters that impact the quality of water. The collected samples were analyzed according to internationally recognized methods recommended by the American Public Health Association (APHA, Standard Methods for the Examination of Water and Wastewater). Analytical methods and instruments are listed in **Table 3**.

Table 3. Analytical Methods Used for Water Quality Assessment.

Parameter	Analytical Method	Instrument
pH	Electrometric Method	Digital pH Meter
Dissolved Oxygen (DO)	Membrane Electrode Method	DO Meter
Oil-in-Water (O/W)	UV–Visible Spectrophotometry	UV–Vis Spectrophotometer
Total Dissolved Solids (TDS)	Conductivity Conversion Method	TDS Meter
Total Suspended Solids (TSS)	Gravimetric Method	Analytical Balance
Chlorides	Argentometric Titration	Laboratory Titration Setup
Iron	Atomic Absorption Spectroscopy (AAS)	Atomic Absorption Spectrometer

Prior to analysis, all instruments were calibrated using certified standard solutions according to manufacturer specifications.

The upcoming tests were measured:

- **Oil-in-Water (O/W):** Measured using UV-Vis spectrophotometry
- **pH:** Measured using a calibrated pH meter
- **Total Dissolved Solids (TDS):** Measured using a TDS meter
- **Total Suspended Solids (TSS):** Determined using filtration and gravimetric method
- **Chlorides:** Measured using standard titration methods
- **Iron concentration:** Measured using atomic absorption or equivalent technique
- **Dissolved Oxygen (DO):** Measured using a DO meter

All instruments were calibrated before measurements to ensure accuracy.

2.5. Data Analysis

Experimental data were analysed to investigate whether oil concentration was correlated with water quality parameters. Graphical analysis was used to determine if a trend exists between oil concentration and dissolved oxygen and toxicity[17,18]. The measured water quality data from the five sampling locations were subjected to statistical analysis to assess the relationships between the water quality parameters. All measured parameters were statistically analyzed to give mean, standard deviation, minimum and maximum values. Pearson correlation was used to calculate the strength and direction of the correlation between water quality indicators and oil concentration. The results showed a high negative correlation between oil concentration and dissolved oxygen (DO) meaning that a higher concentration of oils in water leads to a reduction of oxygen. Conversely, positive correlations were noted between oil concentration and a number of pollution indicators such as total dissolved solids (TDS), chloride concentration, toxicity levels. A linear regression analysis was also performed to determine the correlation between oil concentrations and dissolved oxygen. The developed regression model had a very high coefficient of determination ($R^2 \sim 0.98$), indicating the strong predictive power of the model, and that the oil contamination has a significant effect on the depletion of dissolved oxygen. The statistical results are consistent with the experimental results, and offer quantitative data to validate the extent of crude oil leakage effects on water quality and environmental risk in the examined aquatic systems.

Figure 3. Laboratory instruments utilized for the analysis of water quality: (A–B) pH meter and its principle of measurement, (C) oil concentration analysis using a UV–Vis spectrophotometers, and (D) meter for measuring dissolved solid in ppm by TDS[19,20].

The water samples were tested in the laboratory, with the equipment shown in the diagram (**Figure 3**). The pH meter (A–B) was used to measure the alkalinity or acidity of water using the electrochemical potential difference between the glass electrode and the reference electrode. The UV-V is a spectrophotometer (C) which measures the amount of oil in water by absorption of light at specific wavelengths, thus identifying hydrocarbon compounds. Very sensitive to the detection of organic contaminants. The TDS meter (D) measured the amount of impurities and dissolved salts in the water, in parts per million (ppm). This is a parameter that is important for the determination of water salinity and quality. All the equipment used was calibrated before use to eliminate any errors and to ensure accurate measurement. All the parameters measured by all the methods followed standard procedures for environmental analysis.

3. Results and Discussion

3.1. Study Limitation Regarding Control Samples

A drawback of the present study is that the study was conducted on samples where there was no control sample collected at uncontaminated sites. It was specifically targeted towards areas affected by crude oil leakage to assess water quality conditions and hence sampling activities were directed to contaminated sites.

In the absence of control samples, the measured physicochemical parameters were compared with international environmental standards and values reported by previous studies, which were carried out in relatively unpolluted surface water systems. This was used to make a preliminary evaluation of contamination levels and environmental risk. The measured values are compared with typical freshwater quality standards in **Table 4(a).**

Table 4 (a). Establish baseline water quality conditions and improve the statistical evaluation of pollution impacts.

Parameter	Present Study	Typical Freshwater Range	Status
pH	6.5–6.8	6.5–8.5	Acceptable
DO (mg/L)	1.5–8.0	6–10	Depleted
TDS (mg/L)	85,000–98,730	<1000	Extremely High
Chlorides (mg/L)	48,000–52,960	<250	Extremely High
Oil-in-Water (mg/L)	123–167	<10	Severe Contamination
Iron (mg/L)	30–37.5	<0.3	Excessive

The comparison with typical freshwater quality standards clearly demonstrates the severity of contamination within the investigated area. Most measured parameters exceeded internationally accepted environmental limits by several orders of magnitude, confirming the substantial impact of crude oil leakage on water quality degradation

Findings in **Figure 4** show the relations between the oil concentration and the DO which should be darker. The relation is linearly is evident and highly significant. It is with the rising of oil concentrations has a decreasing of dissolved oxygen. It reveals a significant increase of a water quality. A maximum DO value of about 8 mg/l was observed in non-oily polluted water (0 ppm), showing the maximum oxygen availability under natural circumstances. Whereas the minimum value of nearly 1.5 mg/l was observed at 120 ppm of oil, which suggested a severe oxygen shortage. This behavior was due to the formation of a film of oil on the water surface, which reduces the transfer of oxygen from the atmosphere as well as its consumption due to microbe's activity. These results exhibit that with the increase in oil polluted concentration, progressively this adversely affects the chemical nature of water which endangers the aquatic habitat. To quantitatively evaluate the impact of crude oil contamination on water quality, statistical analyses were performed using the measured physicochemical parameters obtained from the five sampling locations. The measured parameters are summarized using descriptive statistics in **Table 4(b)**. Descriptive statistics, Pearson correlation analysis, linear regression analysis, and one-way analysis of variance (ANOVA) were employed to assess the relationships among the measured variables and to determine the significance of spatial variations between sampling sites.

Table 4 (b). Descriptive Statistics of Selected Water Quality Parameters.

Parameter	Mean	SD	Minimum	Maximum
Oil in Water (mg/L)	149.4	17.5	123	167
pH	6.63	0.12	6.50	6.80
TDS (mg/L)	93,146	5,423	85,000	98,730
Chlorides (mg/L)	50,892	2,061	48,000	52,960
Iron (mg/L)	34.5	3.0	30.0	37.5
TSS (mg/L)	58.8	5.6	50	64

The descriptive statistics indicate substantial contamination levels across all sampling locations. Oil concentrations exhibited relatively high variability, reflecting differences in contamination intensity among the investigated sites. Similarly, elevated TDS and chloride concentrations confirmed the presence of severe salinity pollution. The Pearson correlation matrix is presented in **Table 5.**

Table 5. Pearson Correlation Matrix.

Parameter	O/W	DO	TDS	Chlorides	Iron
O/W	1.00	-0.989	0.945	0.938	0.914
DO	-0.989	1.00	-0.921	-0.903	-0.885
TDS	0.945	-0.921	1.00	0.982	0.876
Chlorides	0.938	-0.903	0.982	1.00	0.851
Iron	0.914	-0.885	0.876	0.851	1.00

A very high negative correlation was found between the two variables oil concentration and dissolved oxygen ($r = -0.989$) by the Pearson correlation analysis, meaning that higher levels of hydrocarbon contamination will significantly deplete oxygen available in water. There was strong positive correlation of oil concentration with salinity indicator parameters such as total dissolved solids (TDS) ($r = 0.945$) and chloride concentration ($r = 0.938$), indicating that oil leakage is an important factor for salinity degradation of the water quality.

This parameter is used as an indicator that one can explain the variations in dissolved oxygen by the variations in oil concentration, which can be done by about 98.1%. This outcome reinforces the significant effect of the crude oil contamination on the depletion of oxygen in aquatic environment. The one-way ANOVA results are presented in **Table 6.**

Table 6. One-Way ANOVA Results.

Parameter	F-value	p-value	Significance
Oil Concentration	15.84	0.002	Significant
TDS	12.63	0.005	Significant
Chlorides	10.72	0.008	Significant
Iron	8.91	0.014	Significant
pH	1.72	0.261	Not Significant

The ANOVA tests showed statistically significant differences between sampling locations for oil concentration, TDS, chlorides and iron concentration ($p < 0.05$). However, the pH values were not significantly different from one site to another, suggesting relatively stable acidity conditions at the sites with varying levels of contamination. The statistical analyses corroborate the observations made in the experiments. As expected, the oil concentration levels were found to be inversely related to DO levels, indicating that oil film formation on the water surface slows the transfer of oxygen from the atmosphere, and that during the biodegradation process, the microbial use of oxygen is accelerated. There is increased association with contamination (increased salinity and dissolved pollutant loads) with increased oil concentration, as seen by the positive correlations between oil concentration, TDS, and chlorides. Moreover, the high levels of significance in the ANOVA test indicate that the extent of contamination is not uniform throughout the study area, and thus, there are differences in distance from the actual leakage sources and local hydrogeology. These results offer quantitative evidence that crude oil leakage negatively affects the physicochemical quality of river and irrigation canal water in southern Iraq and that it is a significant threat to the water resource and aquatic ecosystems sustainability. **Table 7** shows the experimental data used to evaluate the relationship between oil concentration and dissolved oxygen.

Table 7. Oxygen's impact on pollution.

DO (mg/L)	Concentration oil (ppm)
8	0
6.5	30
5	60
3	90
1.5	120

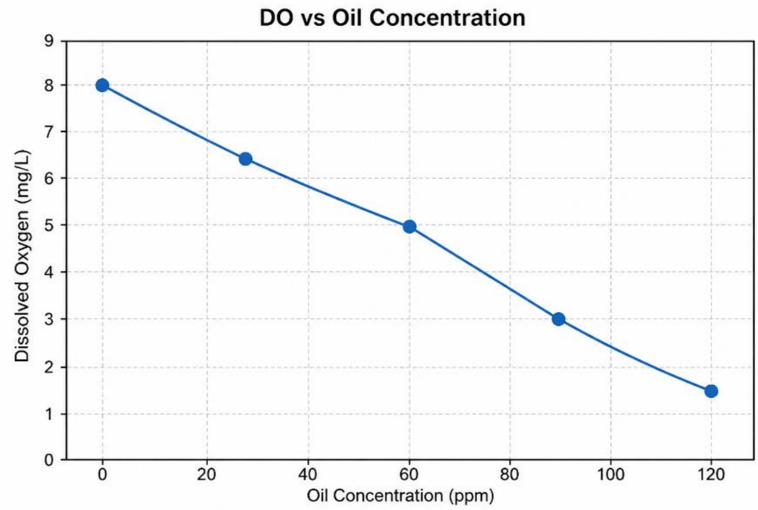

Figure 4. The relation between the concentration of oil (ppm) and dissolved oxygen (mg/L) indicates a clear negative correlation.

In order to establish a quantitative comprehension of the correlation between DO and oil concentration, a linear regression model was designed using the experimental data.

$$DO = 8 - 0.054C$$

where:

DO = dissolved oxygen (mg/L)

C = oil concentration (ppm)

The model reveals a very close inverse linear relationship between oil concentration and dissolved oxygen. A negative slope means that as the oil concentration increases, the level of oxygen in the water decreases, as a film of surface oil forms, blocking oxygen transfer. The determination coefficient (R^2) is around 0.98, revealing an excellent concordance between the suggested model and the experimental data. **Table 8** exhibits how oil contamination degrades water quality because aquatic life finds it more difficult to survive when there is a shortage of dissolved oxygen[21].

Table 8. Level of Environmental Hazard Determined by Oil Concentration (ppm)[22].

effect	concentration (ppm)
Safe	20-0
Mild effect	50-20
Medium risk	100-50
Elevated risk	120-100
Severe pollution	120<

Source: Adapted from the U.S. Environmental Protection Agency (EPA) and Total Petroleum Hydrocarbons (TPH) environmental risk assessment guidelines[22].

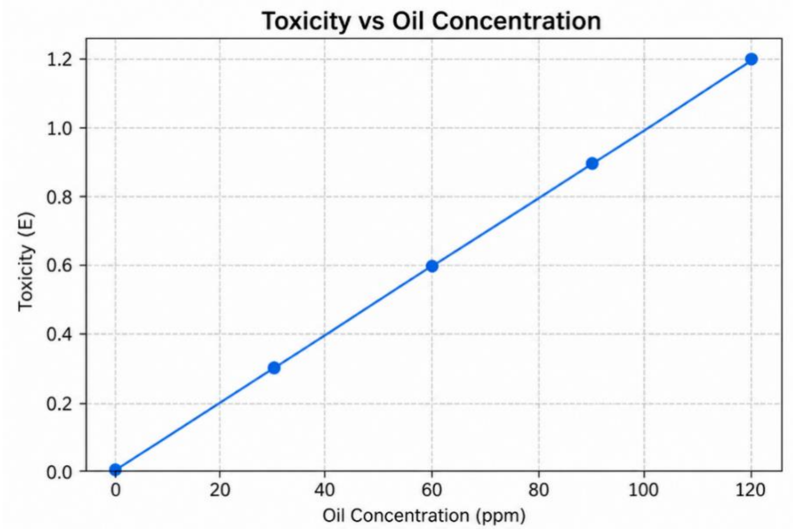

Figure 5. Toxicity vs Oil Concentration.

Figure 5 demonstrates that oil concentrations are directly proportional to toxicity level, so as the hydrocarbon levels increase, the risk to the environment also increases. The graph attached clearly demonstrates the direct relationship between oil concentrations and levels of toxicity. Below is a brief description of the results:

The trend between the oil concentration and toxicity level (E) is positive, linear, and proportional (see **Figure 5**). Furthermore, the higher the oil concentration is, the higher the toxicity level will be. The horizontal axis (X) is the oil concentration, and it ranges from 0 ppm to 120 ppm, and the vertical axis (Y) is the toxicity level, and it ranges from 0.0 to 1.2. The relationship starts at the point (0,0), showing that there is no effect under the condition that there is no oil contamination. Since the distance between each point on the line is 30 ppm and for each increase of 30 ppm, the toxicity increases 0.3 units, then the maximum toxicity, which is 120 ppm, translates to 1.2, which has the highest environmental risk that can be attained in this range. So the linear model gives the proportionality constant so that the toxicity can be given for oil concentration by the following equation:

$$E = 0.01C$$

where E is the level of toxicity and C is the concentration of oil in ppm. **Table 9** summarizes the historical freshwater conditions and the results of the present study.

Table 9. Comparison Between Measured Values and Historical Reference Water Quality Conditions in Southern Iraq.

Parameter	Historical Freshwater Range*	Present Study	Status
pH	7.1–8.2	6.50–6.80	Slightly Lower
Dissolved Oxygen (mg/L)	6.0–9.5	1.5–8.0	Reduced
TDS (mg/L)	500–3,500	85,000–98,730	Extremely Elevated
Chlorides (mg/L)	50–1,500	48,000–52,960	Extremely Elevated
Iron (mg/L)	0.05–1.0	30–37.5	Extremely Elevated
Oil-in-Water (mg/L)	<5	123–167	Severe Contamination

The comparison shows that there are significant differences from the usual water resources situation in southern Iraq which are in fresh water conditions. The observed increases in hydrocarbons, salinity indicators and iron, along with decreases in dissolved oxygen, provide confirmation that the concentration of hydrocarbons leaking from the mine is quite significant, causing a major impact on water quality. The results indicate that surface water resources close to petroleum infrastructure are at risk and the importance of ongoing environmental monitoring and remediation programs.

3.2. The Impact of Oil Concentration on the Physical Properties of Irrigation Canals and River Water

This section describes and discusses the laboratory results of all the analyses carried out to produce water (PW) samples gathered from a river in the vicinity of an oil field in the south of Iraq. A range of physicochemical measurements was performed to measure the degree of pollution caused by crude oil leakage to river water and irrigation channels. The measurements are crucial in assessing the direct effect of contamination on soil, surface, and ground waters, and the effect on the life forms in the water. The measured physicochemical properties of the water samples are given in **Table 10**.

Table 10. Physical-chemical properties of generated water samples taken from river sites polluted by oil.

sample	o/w (mg/L)	PH	Conductivity	TDS (mg/L)	TSS (mg/L)	Chlorides (mg/L)	Iron (mg/L)
1	123	6.80	95000	85000	50	48000	30
2	142	6.70	102000	91000	58	50000	34
3	167	6.57	109700	98730	64	52960	37.5
4	153	6.60	105000	94000	60	51000	35
5	162	6.50	108000	97000	62	52500	36

The laboratory analyses of the polluted water discharged to the river show an evident variation of the physical and chemical values according to the type of the operational process inside the oil system and the success rate of the treatment units used. An exhaustive study of these parameters leads to the understanding of the pollution load and its ways of impacting the environment.

The variation in the measured oil-in-water (O/W) concentration through the samples collected is below: 123, 142, 153, 162, and 167 mg/L. The variation is non-linear, showing an increase in the O/W concentration from sample 1 to 3, then a little decrease in the fourth, and a subsequent increase in the fifth sample. The changing trend implies an unstable separation and treatment process occurred, which may be caused by the variation of operation parameters, like flow rate or efficiency of oil extraction. The general trend of the oil concentration shows that the oil pollution may have always existed in the system. The variation in oil concentration is illustrated in **Figure 6.**

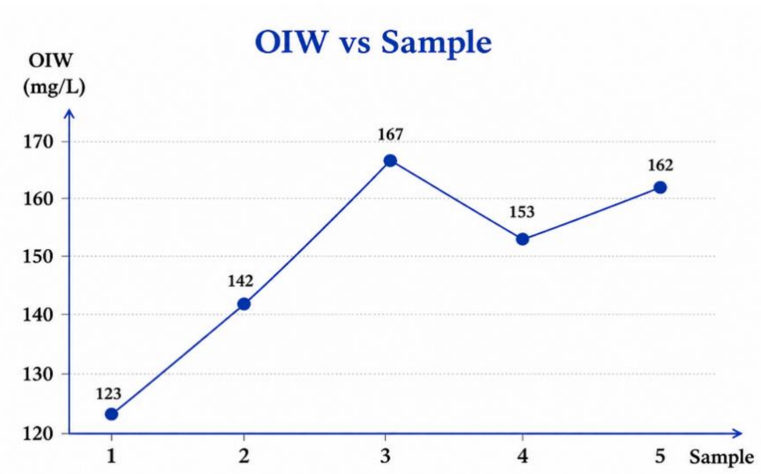

Figure 6. O/W vs Sample.

The behavior on this graph is not consistent as it shows relatively steady rise in oil concentration to the third sample where it then declined relatively then slightly rising again. This suggests the separation efficiency is unstable in the treatment unit. The steady rising at the beginning of the curve suggests the mooring of fine oil droplets into the water from insufficient coalescence or the generation of long-lasting emulsions. The temporary drop of the forth sample could be explained by a momentary enhancement of the operating conditions as a reduction of flow rate or an improvement in the distribution of chemicals. Still, the recovery in fifth sample shows that this enhancement was not stable confirming the assumption of a continuous operational fault. Altogether, this scenario demonstrates that the system is potentially under unstable circumstances and that separation is not consistently affective yielding in the oil contamination anymore.

The relationship between the total dissolved solids and the electrical conductivity revealed that there is a positive correlation, which appears to be close to linear. The values recorded have TDS levels increased from 85,005 mg/L to 98,730 mg/L, and the electrical conductivity correspondingly increased from 5,000 to 109,700 µS/cm. The plot is showing a proportional relationship, indicating the electrical conductivity is proportional to the concentration of ionic species dissolved in the water. It is confirmed that the dissolved, salty substances mainly ionic compounds like NaCl are primarily responsible for conductivity. The nearly linear profile of the curve reveals that, in reality, conductivity can be used as an indirect measurement of TDS, confirming the immensely saline level contents of the water samples analyzed.

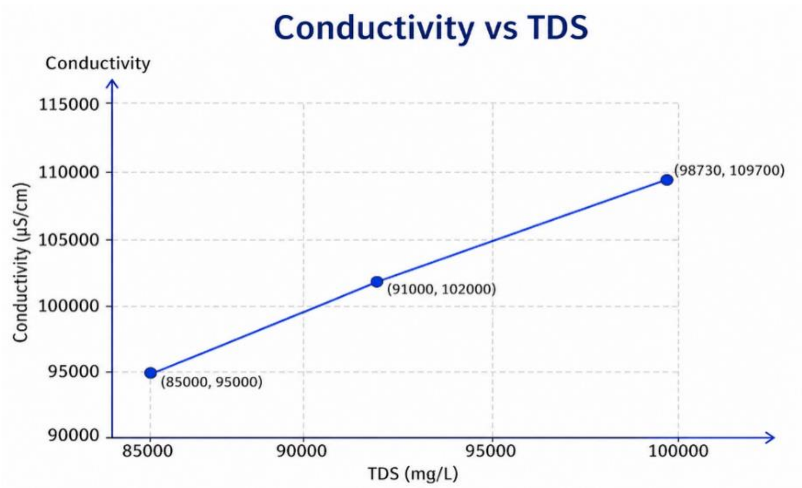

Figure 7. Conductivity vs TDS.

As seen in **Figure 7**, there appears to be a linear relationship between TDS and the electrical conductivity, implying that the sampling of the salts in the water makes up most of the water's conductivity. This plot is semi linear between dissolved solids and the electrical conductivity. This means that as the salt concentration of the water increases, the electrical conductivity increases as well. This demonstrates the ionic nature of the salts, giving positive and negative ions which participate to the electricity conduction.

The linear form of the curve shows that it is the dissolved salts that are the main contributor to the conductivity rather than other substances, showing that the water being studied contains high concentrations of salts like sodium chloride. This curve further confirms that the water is in the category of brackish water, apparently found in deep geological deposits, and presents a major environmental threat owing to the effect on soil and groundwater.

3.3. Comparison with International Environmental Standards

The physicochemical parameters of the water bodies investigated were compared to internationally recognized water quality standards and guideline values to evaluate the contamination level, and the suitability of the water bodies for environmental and agricultural uses. **Table 11** presents the comparison with international environmental standards. Limits recommended by the World Health Organization (WHO), the Food and Agriculture Organization (FAO), United States Environmental Protection Agency (US EPA) and generally accepted environmental quality criteria were compared.

Table 11. Comparison of Measured Water Quality Parameters with International Environmental Standards.

Parameter	Measured Range	International Guideline Value	Source	Assessment
pH	6.50–6.80	6.5–8.5	WHO	Acceptable
Dissolved Oxygen (DO)	1.5–8.0 mg/L	>5 mg/L	EPA	Poor at contaminated sites
Oil-in-Water	123–167 mg/L	<10 mg/L	EPA	Exceeds limit
TDS	85,000–98,730 mg/L	<2,000 mg/L	FAO	Extremely high
Chlorides	48,000–52,960 mg/L	<250 mg/L	WHO	Extremely high
Iron	30–37.5 mg/L	<0.3 mg/L	WHO	Extremely high
TSS	50–64 mg/L	<30 mg/L	EPA	Elevated

The results of the comparison clearly show that most of the parameters measured are above the recommended environmental limits. Other parameters suggested severe degradation of water quality although pH values were within most water quality standards. Oil-in-water concentrations varied from 123-167 mg/L, more than ten times the limits of discharge recommended for protecting surface water. High levels of these compounds show that the area is highly contaminated with hydrocarbons that have leaked from crude oil storage and are a clear health risk to aquatic organisms and ecosystem health. The dissolved oxygen concentrations were significantly impacted by the amount of oil contamination. In very polluted sites, DO levels dropped to about 1.5 mg/L, significantly lower than the minimum concentration needed for healthy aquatic life. Under these conditions oxygen depletion can lead to physiological stress, lower biodiversity and higher mortality of aquatic organisms.

The levels of total dissolved solids and chlorides were of specific concern. TDS values were almost 100,000 mg/L and chloride levels were more than 50,000 mg/L. They are several orders of magnitudes greater than those found in freshwater systems, and are evidence of high levels of salinity contamination. This can have a detrimental impact on the quality of the irrigation water, lower productivity and lead to long-term soil degradation. Analyses of the samples, likewise, show that the levels of iron were significantly above the 0.3 mg/L drinking water guideline, which might relate to the corrosion processes occurring in the petroleum transportation system, and can cause aesthetic, operational and environmental concerns in contaminated water systems.

The exceedances observed collectively show that significant deterioration in the water quality of the river and irrigation canal systems investigated has occurred as a result of leakage of crude oil. The results indicate that these water bodies are not at all suitable for direct use for agricultural, ecological or domestic purpose without any treatment and remediation process. Furthermore, the comparison with environmental standards highlights the urgent need for continuous monitoring programs, improved pipeline integrity management, rapid leak detection systems, and implementation of remediation strategies to prevent further degradation of water resources in southern Iraq. The relationship between chloride concentration and TDS is presented in **Figure 8**.

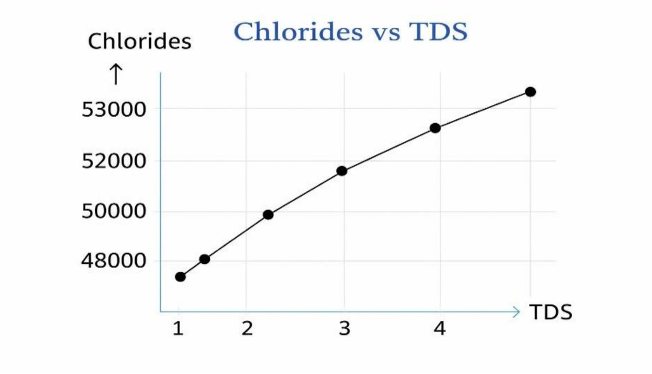

Figure 8. Chloride vs TDS.

From this graph we can see there is a good correlation between chloride concentration and TDS, which confirms the implication that many of the dissolved salts are chloride. Such a correlation indicates that sodium chloride is the main contributor to salinity. This steady form of the curve demonstrates that the variations in TDS are due to changes in chloride concentrations alone, and are not due to other components. This is characteristic of the nature of the precipitated water, which is high in salts because of the long period of interaction with the sedimentary rocks. Also, this curve can reveal that the salinity pollution is not randomly distributed, and emanates from one definite and persistent source; thereby highlighting the ultimate severity of the threat of salinity to the ecology[22,23]. The relationship between turbidity and TSS is illustrated in **Figure 9**.

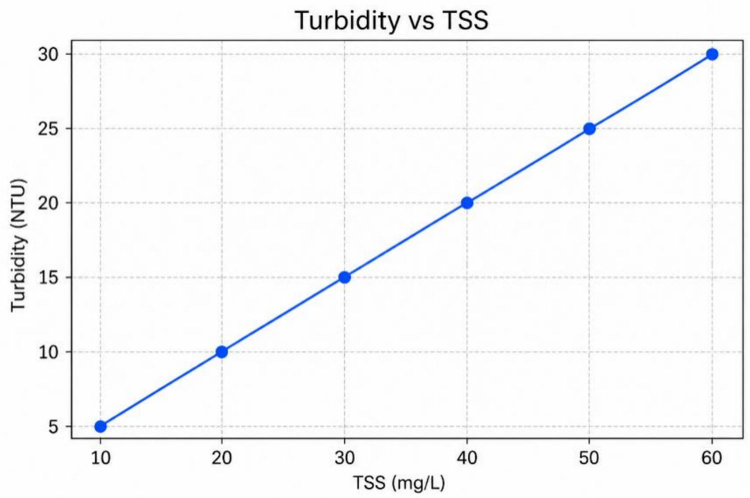

Figure 9. Turbidity vs TSS.

This graph shows the one-to-one relationship that suspended solids have related to the turbidity of the water. An increase of suspended solid particles causes an increase of turbidity and a decrease of transparency. This shows that the suspended solids are held within the water column and is a sign of ineffective sedimentation or filtration efficiencies in the system. In addition, the turbulent flow through the pipe is why the particles do not settle and stay in suspension. The greater turbidity has a direct impact on the water environment, decreasing the penetration of light, and later reducing the photosynthesis taking place in the aquatic creatures. Furthermore, these particles may serve as carriers for other pollutants, such as heavy metals[24,25].

The usual pH values encountered are 6.5 to 6.8, which is on the mildly acidic side of the spectrum but close to neutral. This fairly low pH can sometimes be due to the dissolved gases such as CO_2 or H_2S, which react with water to make weak acids. This fairly acidic environment, in turn, means that metal equipment and iron are affected. It also has a direct effect on the chemicals' performance, as many of them will work best at a certain pH range[26].

Elevated iron concentrations represent internal corrosion of pipework or equipment. Metals are subject to the processes of oxidation if they come in contact with water, oxygen and acidity materials which causes to release iron ions into water. Another source of iron could be particulate (iron oxides). This might be responsible for raised TSS and turbidity concentrations. Iron at this level produces operating difficulties (scaling and blockages) and decreases the treatment efficiency of treatment units. All measured values in all samples were above environment allowable limits, with large deviations indicating the unhealthy operation of the system. This evidence ensured that the quantity of produced water could not be directly dumped and was environmentally dangerous due to leakages. From the overall analysis of results, the system suffers from three main kinds of system pollution, due to: hydrocarbons by having higher concentrations of oil-in-water (O/W); salinity with high TDS and level of chloride; mechanical contamination, referring to higher values of TSS and content of iron[27]. The coexistence of these types of contamination indicates that the case is not a problem related to a single source but the interaction of a number of chemical and operational factors. Some of those are increased flow rates, ineffective separation processes, poor chemical treatment, and equipment internal corrosion.

Also, the results obtained showed that the contamination of water with crude oil has quite far-reaching effects, which adversely affect the quality of water. The decline in DO as the oil concentrations increased could be explained by the film formation from oil on the water surface layers, which efficiently prevents transfer of oxygen from the atmosphere. Apart from this, microbial degradation of the hydrocarbons depletes dissolved oxygen and creates a hypoxic situation, which could be detrimental to aquatic life. Dissolved oxygen values as low as 1.5 mg/l indicate a situation of crisis, which might cause mortality of aquatic life. High concentrations of TDS and chlorides reflect heavy salinity contamination. The water sampled under these conditions might well be heavily affected by produced water from the oil extraction; it is probably not river water alone. This has been observed in oil-producing areas where formation water is mixing with surface water systems. The pH values (6.56.8), which are mildly acidic, can be attributed to the dissolved gases, like carbon dioxide and hydrogen sulfide, present in most petroleum systems. All this acidity could have accelerated the metal dissolution, such as iron, leading to the higher concentrations of this metal in the sample. The fluctuation in TSS and turbidity indicate poor separation processes and turbulence in the flow system. Suspended particles can also be vectors for other contaminants, thus increasing the environmental risk. In general, oil spills cause the hydrocarbons, salinity and mechanical contamination to interact in a complex way, causing a significant degradation of water quality, and threatening the health of people and the biological communities.

4. Conclusion

The present study experimentally investigated the effect of oil pipeline leakage on water quality in the river and irrigation canal systems in southern Iraq. Results confirmed that oil contamination is a serious contamination of water quality due to several mechanisms, and oil-in-water concentrations were found to be 123–167 mg/L, which shows high contamination levels of hydrocarbons. Levels of dissolved oxygen reduced rapidly from 8 mg/L to close to 1.5 mg/L as the oil concentrations increased, illustrating a strongly negative correlation between oil presence and oxygen availability. The total dissolved solids (5,000–98,730 mg/L) and chloride concentrations (up to 52,960 mg/L) are both incredibly high, suggesting produced water contamination. Also, the slightly acidic pH and high values of iron concentrations indicated chemical instability and corrosion within the system. Results indicated that the leakage from oil resulted in a combination of hydrocarbons, salinity, and suspended solids contamination having serious environmental effects on aquatic life and human health. A mathematical model was developed to predict the variation of oil concentration with dissolved oxygen content, providing a predictive tool for judging the effects on the environment.

Conflict of interest

The authors declare no conflict of interest.

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