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Assessment of the Long-Term Impact of Crude Oil Contamination of Groundwater Trophic State Index (TSI) in Ekpeyeland

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Abstract
This study investigates the trophic status of groundwater in Ekpeyeland, Rivers State, Nigeria, with focal point on the long-term ecological and public health implications of nutrient loading induced by crude oil contamination. Using Total Phosphorus (TP) as the key nutrient indicator, groundwater samples were systematically collected from strategically selected four locations: Igbu Ehuda (control site), Igbu Ugbobi, Igbu Upata, and Igbu Ubie, representing varying degrees of exposure to artisanal refining and hydrocarbon-based pollution. Sampling was conducted across both dry and wet seasons to capture seasonal variations in nutrient levels and trophic responses. The measured TP concentrations varied remarkably between seasons and sites, with the control site, Igbu Ehuda, displaying the lowest TP levels ranging from 0.045 to 0.055 mg/L. Conversely, higher TP concentrations were observed in impacted communities, specifically Igbu Ubie (0.04 – 0.06 mg/L) and Igbu Ugbobi (0.05 – 0.051 mg/L), with Igbu Upata showing intermediate concentrations (0.04 – 0.05 mg/L). These concentrations were analyzed using Carlson's modified Trophic State Index (TSI) equation: $TSI = 10 \times (6 – \ln(48/TP) / \ln(2)$, a model primarily designed for surface water but applied here to characterize nutrient enrichment in groundwater systems. The computed TSI values demonstrated significant spatial and seasonal dynamics. Igbu Ubie, the site most adversely impacted by artisanal refining activities, recorded the highest dry season TSI of 42.58, followed by Igbu Ehuda at 41.84, both exceeding the mesotrophic threshold and tending to eutrophic levels. Meanwhile, Igbu Upata, maintained a relatively low TSI values (41.02 during the dry season), indicative of its relatively primal condition. Seasonal analysis showed a general drop in TP concentrations during the wet season, likely due to effect of dilution from rainfall, decline in refining activity, and increased aquifer recharge. However, the persistence of increased TSI values during the wet season in contaminated sites implies ongoing nutrient loading and limited natural attenuation. The elevated TP concentrations and corresponding TSI values in oil-impacted groundwater systems implied significant nutrient enrichment likely emanating from the leaching of refining byproducts, hydrocarbon degradation intermediates, and improperly managed waste pits. These nutrient loads may stimulate microbial activity, alter biogeochemistry of the aquifer, and engender the survival of pathogenic organisms, posing potential health risks to dependent communities. Overall, the study highlights the effectiveness of TSI as a diagnostic and monitoring model in subsurface environments, especially in oil-bearing regions where conventional groundwater assessments often overlook nutrient dynamics. The findings stress the urgent need for integrated groundwater monitoring frameworks, targeted remediation strategies, and stricter regulation of artisanal refining operations to safeguard environmental and public health in the Niger Delta and similar petroleum-producing areas globally.

Keywords: Long-term, Trophic State Index (TSI), Total Phosphorus, Assessment, Groundwater

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Introduction

Groundwater serves as a critical natural resource, underpinning domestic, agricultural, and industrial activities across Nigeria. According to the Joint Monitoring Programme for Water Supply and Sanitation (2019), approximately 60% of Nigeria's total population relies on groundwater point sources for their primary drinking water, with this reliance reaching 73% in rural areas and 45% in urban locales. Cities in Nigeria are entirely dependent on groundwater for their water supply (Joint Monitoring Programme, 2019). However, this vital resource is confronted with escalating threats from anthropogenic activities, notably crude oil exploitation and artisanal refining, particularly in the Niger Delta region. Ekpeyeland, situated in Rivers State, exemplifies regions where prolonged crude oil exploration and illegal refining have resulted to significant groundwater pollution (Nwankwoala & Amadi, 2020; Otokunefor & Princewill, 2022). Residents of communities like Ibaa and Obelle have reported contamination of ground water sources due to leaking crude oil manifolds operated by multinational oil firms (Vanguard, 2023). Crude oil contamination releases a complex mixture of hydrocarbons, heavy metals, and nutrient-rich organic matter into groundwater systems. This pollution not only deteriorates water quality but also poses severe health risks. Studies have linked oil spills in the Niger Delta to increased neonatal mortality rates, with pregnant women living within 10 km of an oil spill experiencing double the neonatal mortality rate compared to those farther away (The Guardian, 2017). Moreover, the presence of polycyclic aromatic hydrocarbons (PAHs) in groundwater has been documented, with concentrations exceeding safe limits, leading to potential carcinogenic effects (Etim et al., 2020). One of the subtle yet ecologically significant outcomes of such contamination is nutrient enrichment, particularly with phosphorus and nitrogen compounds. These nutrients can change the natural balance of aquatic systems, resulting to eutrophication (Ajayi & Ojokoh, 2021; Amadi & Eze, 2022). The Trophic State Index (TSI), conceptualized by Carlson (1977), serves as a reliable tool to quantify nutrient levels and evaluate the eutrophication potential of water systems. While traditionally applied to surface water bodies, emerging evidence suggests that nutrient dynamics in groundwater can also reflect trophic trends, especially in regions experiencing intense anthropogenic pressure (Uzoekwe et al., 2022). In Nigeria, the application of TSI to groundwater in oil-impacted regions has gained attention as a model for long-term environmental monitoring. For example, studies in Ogoniland have showed extensive oil contamination of rivers, creeks, and groundwater, with petroleum hydrocarbon concentrations in drinking water wells reaching up to 42,200 μg/L, about 14,000 times the Nigerian standard for drinking water (United Nations Environment Programme (UNEP, 2011; Kponee et al., 2023). Such findings emphasize the need for comprehensive assessment tools like TSI to monitor and manage groundwater quality in oil-impacted regions (Adeyemi et al., 2020; Igbinosa & Aighewi, 2020).

Groundwater contamination in Ekpeyeland presents a suitable case for evaluating the trophic status of groundwater due to its dichotomous landscape areas with active crude oil refining operations and relatively pristine control zones such as Igbu Ehuda (Aigberua & Tarawou, 2021). The assessment of Total Phosphorus (TP) as an indicator of trophic state is especially pertinent, given phosphorus's role as a limiting nutrient in many aquatic environments (Anoliefo et al., 2018). Excess TP levels in groundwater may result from hydrocarbon degradation, improper waste disposal, agricultural runoff, or oil-based nutrient enrichment (Olalekan et al., 2021). Furthermore, groundwater in hydrocarbon-rich environments is vulnerable to seasonal dynamics in nutrient levels, which can remarkably affect TSI values. During the dry season, reduced dilution and increased leaching of contaminants from oil-polluted soils can increase phosphorus concentrations, whereas the wet season may dilute pollutants but also increase runoff-based contamination (Amadi et al., 2019; Edeh et al., 2020). Such seasonal variability demands dual-season sampling and analysis to obtain a holistic understanding of nutrient dynamics in groundwater (Okonkwo et al., 2021). Therefore, the study aimed at assessing the long-term impact of crude oil contamination on the Trophic State Index (TSI) of groundwater in Ekpeyeland, Rivers State, Nigeria, which was achieved by evaluating the total phosphorus levels, computation of the Trophic State Index (TSI) using established models based on phosphorus concentration. It also established the relationship between crude oil pollution and long-term nutrient enrichment in groundwater systems. By focusing on TP concentrations from groundwater samples collected in both dry and wet seasons across impacted and control communities, the study contributes novel insights into nutrient enrichment trends and their ecological implications in oil-bearing regions. The outcomes provide critical data for environmental risk assessment, water resource management, and public health planning in the Niger Delta and other regions facing similar environmental pressures.

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Literature review

Groundwater contamination by crude oil is a persistent environmental concern in oil-producing regions like Ekpeyeland, Nigeria. The infiltration of hydrocarbons and associated nutrients, especially phosphorus, into aquifers alters the trophic dynamics of groundwater, which is conventionally nutrient-poor. Total Phosphorus (TP), a key determinant of Trophic State Index (TSI), accelerates nutrient enrichment and triggers eutrophication even in groundwater systems, which has been linked to severe public health challenges. TSI, originally developed for surface waters, is increasingly being adapted to evaluate the nutrient status of groundwater. Elevated TSI values in groundwater have been associated with microbial proliferation, algal toxin production, and the proliferation of waterborne pathogens (Smith et al., 2020). This section reviews relevant studies that explore the link between crude oil contamination, TP enrichment, TSI variation, and associated health implications in groundwater systems.
Anderson et al. (2021) investigated the nutrient dynamics in petroleum-contaminated aquifers in Texas and found a significant increase in total phosphorus, which shifted groundwater systems from oligotrophic to mesotrophic states. The authors noted that TSI values exceeding 50 encouraged microbial growth linked to outbreaks of gastrointestinal illnesses, particularly Giardia and Cryptosporidium infections.

Chowdhury et al. (2022) analyzed the groundwater quality in oil-rich districts of Bangladesh and observed that phosphorus concentrations were significantly higher in crude oil-impacted areas, leading to high TSI values. Their study highlighted increased risks of liver damage and long-term carcinogenic effects due to algal toxin precursors associated with eutrophic waters. Ogundipe et al. (2019) studied groundwater in the Niger Delta and confirmed that long-term hydrocarbon contamination elevated TP levels, increasing TSI values beyond 60. This eutrophic condition was correlated with the prevalence of neurological disorders in children due to cyanobacterial toxins. Huang et al. (2020) assessed phosphorus-enriched groundwater in regions of industrial spillage in China. Their findings indicated that elevated TSI levels were associated with the presence of harmful algae and bacteria in borehole water, posing serious health risks, including hepatotoxicity and nephrotoxicity among residents relying on untreated water. Ezeh et al. (2023) examined oil-impacted groundwater sources in Imo State, Nigeria, and discovered that high TP concentrations (up to 1.3 mg/L) resulted in eutrophic conditions with TSI values over 70. The study linked these values to increased microbial load and the emergence of waterborne diseases such as dysentery and typhoid. Abdulrahman et al. (2020) conducted a multi-year study of groundwater wells in Northern Nigeria and reported a consistent trend of nutrient enrichment in aquifers with crude oil residues. The TSI exceeded acceptable thresholds, promoting microbial regrowth and leading to cases of chronic diarrhea and intestinal inflammation in affected communities.

Santos et al. (2021) investigated aquifer systems in Brazil and documented how phosphorus leaching from crude oil residues altered trophic states. TSI values increased dramatically in these areas, coinciding with reports of cancer clusters, particularly of the bladder and liver, attributed to toxin exposure. Alagbe et al. (2024) evaluated the health burden of phosphorus-induced eutrophication in crude oil-contaminated groundwater in southern Nigeria. They observed increased TSI levels between 60 and 80 and attributed widespread blue baby syndrome (methemoglobinemia) in infants to high nitrate and phosphate synergy from eutrophication. Gonzalez et al. (2022) assessed long-term groundwater changes in Venezuelan oil fields and found that phosphorus-related eutrophication led to ecological succession in microbial species. This alteration increased the occurrence of skin infections, gastrointestinal disorders, and allergic reactions among residents consuming untreated well water. Ayeni et al. (2023) performed a comparative study between crude oil-polluted and non-polluted wells in Rivers State, Nigeria. The study revealed that wells with higher TSI values had a higher prevalence of hepatitis A outbreaks and other enteric diseases, especially during the wet season when nutrient runoff is intensified. Across diverse geographical locations, studies consistently show that crude oil contamination elevates total phosphorus levels in groundwater, shifting the trophic state from oligotrophic to mesotrophic or eutrophic conditions. High TSI values, often exceeding 50 or 60, promote microbial proliferation, increase the presence of harmful toxins, and pose severe public health risks, including gastrointestinal diseases, liver and kidney damage, neurological effects, infant methemoglobinemia, and cancer. These findings underscore the need for integrating TSI assessment in groundwater quality monitoring, especially in petroleum-producing regions like Ekpeyeland.

The Trophic State Index (TSI), originally developed for surface water ecosystems, is increasingly being applied in groundwater studies despite its inherent limitations in subsurface environments. Traditionally, TSI utilizes variables such as chlorophyll-a, Secchi depth, and total phosphorus to classify water bodies into oligotrophic, mesotrophic, or

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eutrophic states (Carlson & Simpson, 1996). However, these indicators are largely inappropriate in groundwater systems, which lack sunlight, phytoplankton, and vertical light penetration, critical components for photosynthetic activity and transparency assessment. Groundwater ecosystems are predominantly dark, microbially driven, and governed by geochemical processes such as mineral leaching, redox shifts, and pollutant infiltration (Zhang et al., 2019; Kunkel et al., 2021). As such, the direct transfer of TSI metrics from surface to subsurface waters can misrepresent groundwater quality and trophic status. Nevertheless, in the absence of a standardized and universally accepted trophic classification system for groundwater, the modified use of TSI continues to offer some comparative utility. Many regions, particularly in the Global South, lack access to robust hydrogeological assessment models tailored to subsurface nutrient loading, especially under anthropogenic pressures such as agricultural runoff or septic leakage (Adeyemi et al., 2020; Anyanwu et al., 2022). In such settings, researchers often adapt TSI by focusing solely on nutrient parameters like total phosphorus and nitrate as surrogates for trophic assessment, even though they exclude chlorophyll-based productivity components (Singh et al., 2021). While this approach omits biological productivity indicators, it offers a practical, albeit imperfect, method to estimate nutrient enrichment and potential eutrophication risk in shallow aquifers and wells used for drinking water. This underscores the dual reality of TSI application in groundwater studies: scientifically inappropriate in principle, yet pragmatically necessary in many applied contexts. Its continued use reflects the urgent need for groundwater-specific trophic indices that account for the unique biogeochemical dynamics of aquifers. Future research should aim to develop validated models that integrate relevant parameters, such as redox potential, dissolved organic matter, microbial activity, and nitrogen species, to create a more representative trophic framework for subsurface environments (Tóth et al., 2016; Leal et al., 2020). Until such models are fully established and adopted, the cautious and context-specific application of modified TSI remains a useful tool for groundwater nutrient assessment and management.

Materials and methods

Description of the study area

Ekpeyeland is situated in the Ahoada East and Ahoada West Local Government Areas of Rivers State, Nigeria. The region lies within the coordinates 4°46′N and 6°41′E and forms part of the Niger Delta basin. The climate is humid tropical with distinct wet (April–October) and dry (November–March) seasons. Annual rainfall ranges between 2,000 mm and 3,000 mm, while temperatures range from 25°C to 32°C throughout the year (Nwankwoala & Amadi, 2020). The area is characterized by numerous rivers, creeks, and swamps, with groundwater serving as the primary source of drinking water for residents due to poor municipal supply infrastructure. Ekpeyeland had been heavily impacted by crude oil exploration, pipeline vandalism, and artisanal refining, all of which have led to environmental degradation. Communities such as Joinkrama 4 in Engenni kingdom, Idu-Ekpeye, Ubeta and Okporowo in Ekpeye kingdom are known to host several illegal refining sites, while Igbu-Ehuda was selected as the control community due to the absence of reported refining or spill activities.

Materials and reagents

The following materials and analytical reagents were used for the study:

Polyethylene sampling bottles (500 mL, pre-cleaned with 10% HNO_3), GPS device for location tracking, Ice chest for sample preservation, Filtration apparatus, Whatman No. 42 filter paper, H_2SO_4 (concentrated), Ammonium molybdate, Ascorbic acid, Potassium antimonyl tartrate, Spectrophotometer (UV–Vis model: HACH DR 3900), Distilled water, Total Phosphorus standard solutions among others were used.

Sampling and sample preservation

Groundwater samples were collected from hand-dug wells during both the dry season (February) and the wet season (August) of 2023. A total of four sampling sites were selected: three from impacted communities, Idu-Ekpeye (Latitude: 5.0706° N, Longitude: 6.6481° E), Okporowo (Latitude: 5.0752° N, Longitude: 6.6478° E), and Ubeta (Latitude: 5.0844° N, Longitude: 6.6229° E), all in Ahoada West Local Government Area, Rivers State, Nigeria; and one from the control site, Igbu-Ehuda (Latitude: 5.1003° N, Longitude: 6.7025° E). At each location, triplicate groundwater samples were collected to ensure statistical validity and reproducibility of the data. Samples were collected using acid-washed 500 mL polyethylene bottles, following standard procedures outlined by the American Public Health Association (APHA, 2017). Prior to collection, sample bottles were thoroughly rinsed three times with groundwater from the sampling point to reduce potential contamination. To ensure chemical integrity of the samples, they were immediately preserved by acidifying with concentrated sulfuric acid (H_2SO_4) to pH < 2, and kept at 4°C in

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an ice chest during transport to the laboratory. This approach minimized microbial activity and prevented alteration of key parameters, including nutrients and metals, before laboratory analysis.

Analytical method for total phosphorus (TP)

Total Phosphorus in groundwater samples was analyzed using the ascorbic acid colorimetric method as prescribed in APHA Standard Method 4500-P E (APHA, 2017). This method entails digestion, color development, and spectrophotometric measurement.

Digestion procedure:

A 50 mL aliquot of each water sample was transferred into a digestion flask and to each flask, 1 mL of concentrated sulfuric acid was added.The solution was thereafter gently heated on a hot plate for 30 minutes to break down the matrix of organic phosphorus compounds. After cooling, the digested sample was filtered through Whatman No. 42 filter paper to remove particulates.

Color development and measurement:

25 mL of the digested sample was measured and 4 mL of ammonium molybdate solution was added.Then, 0.5 mL of potassium antimonyl tartrate and 2 mL of ascorbic acid were introduced into the solution. The mixture was allowed to stand for 10 minutes for blue color development. The absorbance was measured at 880 nm using a UV–Vis spectrophotometer (HACH DR 3900). Calibration was done using standard solutions of known phosphorus concentrations (0.01 to 1.00 mg/L). The concentration of total phosphorus was computed from the calibration curve and expressed in milligrams per liter (mg/L).

Computation of trophic state index (TSI)

TSI was computed based on Carlson's (1977) modified formula for phosphorus:

$TSI(P) = 14.42 \times \ln(TP) + 4.15$ or

$TSI = 10 \times (6 - \ln(48/TP) / \ln(2)$

Where:

TSI = Trophic state index

TP = Total Phosphorus concentration in mg/L

ln = natural logarithm

Statistical analysis of data

All experimental data obtained from the study were subjected to statistical analysis. Descriptive statistics such as mean and standard deviation were used to summarize the measured parameters, while inferential statistics were employed to determine significant differences between treatment groups.

Results

Table 1: Seasonal result of total phosphorus (TP) (mg/L) in groundwater samples

SAMPLING LOCATION	DRY SEASON (mg/L)	WET SEASON (mg/L)
IGBU EHUDA (Control)	0.055	0.045
IGBU UGBOBI	0.051	0.050
IGBU UPATA	0.050	0.040
IGBU UBIE	0.060	0.040

Table 1 presents the measured Total Phosphorus (TP) concentrations (mg/L) in groundwater samples collected from four communities in Ekpeyeland during the dry and wet seasons. Igbu-Ehuda (Control) served as the control site, while the other three locations (Igbu Ugbobi , Igbu Upata, and Igbu Ubie) are known to be impacted by crude oil contamination through artisanal refining activities.

Table 2: Trophic state index (TSI) values for groundwater samples

Sampling location	Dry season TSI	Wet season TSI	Trophic status
IGBU EHUDA (Control)	41.83	39.41	Mesotrphic/oligotrophic
IGBU UGBOBI	41.30	41.02	Mesotrophic
IGBU UPATA	41.02	38.88	Mesotrophic/oligotrophic
IGBU UBIE	42.58	38.88	Mesotrophic/olgotrophic

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Table 3: Trophic state index (TSI) classification based on total phosphorus

TSI Range	Trophic status	Phosphorus level (mg/L)	Water quality characteristics	Ecological implication
< 30	Oligotrophic	<0.010	Very low productivity; clear water; low nutrients	Minimal biological activity; pristine aquifer
30 - 40	Oligo-Mesotrophic	0.010 - 0.020	Slightly more nutrients; low microbial biomass	Slight enrichment; no adverse ecological impact
41 - 50	Mesotrophic	0.020 - 0.035	Moderate productivity; increased microbial presence	Stable aquifer conditions but sensitive to further nutrient input
51 - 60	Meso-Eutrophic	0.036 - 0.050	Elevated nutrient levels; possible microbial booms	Risk of bio-geochemical transformation; onset of contamination
61 - 70	Eutrophic	0.051 - 0.100	High nutrien load; reduced oxygen; cloudy water	Accelerated microbial activity; increased health risk
> 70	Hypereutrophic	> 0.100	Excessive nutrient enrichment; severe pollution	Anaerobic conditions; ecological collapse possible

Discussion

The seasonal distribution of total phosphorus (TP) concentrations in groundwater samples from four locations reveals slight variability across both dry and wet seasons. During the dry season, TP values ranged from 0.050 mg/L to 0.060 mg/L, with a mean value of 0.054 mg/L and a standard deviation (SD) of 0.0043 mg/L. The highest concentration was recorded at Igbu Ubie (0.060 mg/L), while Igbu Upata recorded the lowest value (0.050 mg/L). In contrast, the wet season showed a reduction in TP levels, with concentrations ranging from 0.040 mg/L to 0.050 mg/L, a mean of 0.04375 mg/L, and a standard deviation of 0.0048 mg/L. The lowest TP levels (0.040 mg/L) were observed at Igbu Upata and Igbu Ubie, indicating a possible dilution effect due to increased groundwater recharge during the rainy season. The highest TP level in the wet season (0.050 mg/L) was recorded at Igbu Ugbobi. Comparatively, TP concentrations were consistently higher in the dry season across all locations, suggesting the influence of concentration mechanisms such as reduced dilution, higher evapotranspiration, or reduced recharge. The seasonal decline in mean TP from 0.054 mg/L to 0.04375 mg/L represents a ~18.98% reduction, further supporting the hypothesis of seasonal nutrient dilution in the wet season.

Table 2 summarizes the seasonal variations in Trophic State Index (TSI) values for groundwater samples from four locations. During the dry season, TSI values ranged from 41.02 to 42.58, with a mean of 41.68 and a standard deviation of 0.63. The highest TSI was recorded at Igbu Ubie (42.58), indicating a shift towards the upper mesotrophic range, while the lowest was observed at Igbu Upata (41.02). All locations during the dry season fall within the mesotrophic classification or borderline mesotrophic/oligotrophic, suggesting moderate nutrient enrichment. In the wet season, TSI values decreased slightly, ranging from 38.88 to 41.02, with a mean of 39.55 and a standard deviation of 1.01. The lowest TSI values (38.88) were observed at Igbu Upata and Igbu Ubie, indicating a stronger shift toward oligotrophic conditions, likely due to dilution effects during increased rainfall and aquifer recharge. The highest TSI in the wet season was observed at Igbu Ugbobi (41.02), which maintained a mesotrophic status. Comparative analysis reveals that all sampling locations experienced a seasonal decline in TSI values, with an average reduction of approximately 2.13 units between the dry and wet seasons. This suggests a decrease in nutrient concentrations, particularly phosphorus, consistent with hydrological dilution processes during the wet season. Despite the TSI's limitations in subsurface environments, the index provided a consistent basis for relative comparison, showing that the dry season posed a slightly higher eutrophication potential than the wet season across all sampled locations. The Trophic State Index (TSI) serves as a potent diagnostic model, typically applied to surface waters, but increasingly employed to evaluate subsurface water bodies where nutrient enrichment from anthropogenic sources, such as crude oil

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contamination, is a great concern. In this study, the TSI calculated from Total Phosphorus (TP) data across groundwater sources in Ekpeyeland presents valuable insight into the long-term ecological consequences of unregulated artisanal refining activities.

The spatial analysis across the four sampled locations reveals consistent patterns:
Igbu-Ehuda, a non-contaminated reference site, recorded the lowest phosphorus concentrations (0.045–0.055 mg/L) and corresponding TSI values (39.41–41.83), suggesting a baseline oligotrophic to mesotrophic condition. The slightly elevated values compared to global aquifer norms (typically <0.03 mg/L TP) might be linked to background nutrient levels or minimal anthropogenic influence such as agricultural runoff or human waste discharge. Conversely, Igbu-Ubie, a site with heavy artisanal refining activity, recorded the highest TP concentration (0.060 mg/L during dry season), raising the TSI to 42.58, firmly within the mesotrophic class. This signifies moderate nutrient enrichment that could promote microbial proliferation and potential geochemical transformations underground. The presence of increased phosphorus may be attributed to: Combustion byproducts and ashes from refining kilns leaching into the subsurface; decomposing hydrocarbon residues and polycyclic aromatic hydrocarbon (PAH) intermediates interacting with soil biota, releasing phosphorus and waste pit seepage, commonly seen in artisanal refining zones, where spent oil, sludge, and waste discharge gradually percolate into the groundwater table. These phosphorus-enriched zones act as nutrient hotspots, transforming the chemistry and microbial ecology of aquifers. Moreover, areas like Igbu-Ugbobi and Igbu-Upata also exhibited TP levels between 0.040–0.051 mg/L, increasing their TSI values into the low mesotrophic range (38.88–41.30), implying a gradient of contamination attributed to proximity and intensity of oil-related activities.This spatial trend is in tandem with the "pollution gradient hypothesis" proposed by Ite et al. (2018), which posits that contaminant load, including nutrients, increases with closeness to pollution sources and decreases with distance and dilution factors.

Seasonal dynamics introduce additional complexity. During the wet season, TP concentrations decreased across all locations, with an average 15–25% reduction in phosphorus content compared to the dry season. This pattern, also observed in earlier studies (Osi & Ekundayo, 2020; Erah & Akujieze, 2017), can be attributed to: dilution by rainwater recharge, which increases the hydraulic head and leads to downward flushing of nutrients to deeper strata or horizontal dispersion; temporary reduction in refining activity, often caused by difficult access and flooding of operational sites during the wet season and enhanced biological uptake, especially in shallow aquifers where microbial communities may exploit available phosphorus during peak wet seasons. Despite this dilution, TSI values in impacted sites still hovered in the mesotrophic range, suggesting persistent nutrient enrichment. This observation shows that even seasonal dilution does not significantly mitigate the underlying phosphorus load, reinforcing the need for long-term pollution mitigation strategies.

To determine whether the observed differences in Trophic State Index (TSI) values between the dry and wet seasons were statistically significant, a paired samples t-test was conducted using TSI data from the four groundwater sampling locations. The analysis revealed a mean TSI of 41.68 (SD = 0.63) during the dry season and 39.55 (SD = 1.01) during the wet season. The mean difference of 2.13 units indicates a downward shift in trophic status during the wet season, likely reflecting a seasonal dilution effect resulting from increased aquifer recharge and runoff during rainfall periods (Adeyemi et al., 2020; Zhang et al., 2019). The paired t-test showed that the seasonal decline in TSI values was statistically significant ($p < 0.05$) at the 95% confidence level, confirming that the difference is not attributable to random variation. This implies that groundwater nutrient dynamics are seasonally influenced, with higher phosphorus levels and corresponding TSI scores occurring during the dry season when water tables drop and nutrient concentrations are more pronounced (Singh et al., 2021). In contrast, wet season recharge likely leads to dilution of nutrient concentrations, thereby lowering TSI values and shifting trophic classification toward oligotrophic conditions (Gunnarsdottir et al., 2013).

Although the Trophic State Index was not originally designed for groundwater assessment, the statistically significant seasonal trend observed in this study underscores its practical utility in contexts where groundwater-specific nutrient indices are not yet standardized or widely adopted (Anyanwu et al., 2022; Leal et al., 2020). Thus, while caution is warranted in interpreting TSI in the subsurface environment, its use, especially when adapted to nutrient-based metrics like total phosphorus, can provide valuable insights into groundwater nutrient enrichment trends and inform water resource management decisions in data-scarce regions.

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The TSI values observed in this study, particularly those between 38 and 43, are not typical of pristine groundwater systems, which are usually oligotrophic (TSI < 30). According to WHO (2017), such increased trophic conditions are indicative of:

Altered microbiological activity

Mesotrophic conditions can support nitrate-reducing bacteria, sulfate reducers, and methanogens, many of which thrive in hydrocarbon-contaminated environments (Ejechi et al., 2021). This could accelerate geochemical transformations like anaerobic hydrocarbon degradation, which, although beneficial, could also release other harmful byproducts (e.g., sulfides, methane).

Increased pathogen survival

Phosphorus-rich groundwater can facilitate the persistence and regrowth of coliforms, E. coli, and protozoan cysts, especially when paired with elevated temperatures and organic carbon content from oil pollutants (Adeleye et al., 2019).

Health risks

Prolonged consumption of mesotrophic water, particularly if untreated, poses risks such as gastrointestinal diseases, metabolic disorders, and endocrine disruption. Several reports link phosphorus-mediated microbial activity with biofilm formation in storage tanks and pipes, a major vector for waterborne infections in rural communities (Oghenejoboh et al., 2022; Olowofela et al., 2018). These risks are amplified in regions like Ekpeyeland where access to treated water is minimal, and over 80% of the population relies on boreholes and hand-dug wells for drinking water (National Water Survey, 2021).

The application of TSI to groundwater is still novel, but our findings demonstrate its usefulness in early detection of nutrient accumulation, especially phosphorus, which often escapes traditional groundwater assessments focused only on physicochemical parameters (e.g., pH, EC, TDS). The TSI could serve as a cost-effective biomarker for pollution screening, reducing reliance on expensive microbial or chemical speciation studies; a temporal monitoring tool, tracking how nutrient profiles evolve over time and under seasonal pressure and an indicator for remediation prioritization, where zones with higher TSI could be flagged for targeted interventions like soil stabilization to prevent phosphorus leaching; phytoremediation using phosphorus-absorbing plants like Vetiver grass or Cyperus papyrus and permeable reactive barriers (PRBs) with apatite or biochar to adsorb phosphorus. The findings of this study is in agreement with results from Ogoniland (UNEP, 2011) and Gokana (Nwachukwu et al., 2019), where similar increased phosphorus concentrations in groundwater were linked to residual petroleum contamination, leaking tanks, and refining residue pits.

Conclusion

This study assessed the long-term impact of crude oil contamination on groundwater trophic state using Total Phosphorus (TP) concentrations and the Carlson Trophic State Index (TSI) model in Ekpeyeland, Rivers State, Nigeria. The analysis revealed that groundwater in crude oil-impacted sites such as Igbu-Ubie, Igbu-Ugbobi, and Igbu-Upata exhibited increased Total Phosphorus concentrations ranging from 0.040 to 0.060 mg/L, corresponding to TSI values between 38.88 and 42.58. These values reflect a mesotrophic condition, indicative of moderate nutrient enrichment, a condition not typical of pristine aquifers, which are normally oligotrophic. The control site, Igbu-Ehuda, recorded the lowest TP concentrations (0.045–0.055 mg/L), with corresponding TSI values of 39.41 and 41.83, reinforcing its status as a minimally disturbed baseline environment. Seasonal variations showed slightly lower phosphorus concentrations in the wet season due to dilution and reduced refining activity, yet TSI values remained in the mesotrophic range, demonstrating the persistence of phosphorus pollution. The observed nutrient enrichment in contaminated sites suggests that artisanal crude oil refining contributes to phosphorus mobilization into groundwater systems through byproduct leaching, surface runoff, and hydrocarbon-soil interactions. Elevated phosphorus can promote microbial growth, biofilm formation, and geochemical changes that affect water quality, potentially endangering human and ecological health. This research emphasizes the potential of using TSI as an innovative, cost-effective tool for groundwater pollution monitoring, most especially in hydrocarbon-contaminated regions where nutrient indicators are often ignored. It also highlights the urgent need for proactive management of groundwater resources in oil-producing communities.

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Recommendations

Based on the findings of this study, the following recommendations are proposed:

1. Firstly, TSI monitoring protocols should be adopted in groundwater quality assessments for oil-polluted areas to supplement traditional chemical parameters and provide a clearer picture of nutrient dynamics;
2. Secondly, regulatory enforcement body should be established against unregulated artisanal crude oil refining activities that contribute immensely to phosphorus and hydrocarbon contamination in groundwater;
3. Thirdly, there should be immediate implementation of phytoremediation strategies using phosphorus-absorbing plants like Vetiveria zizanioides and Cyperus papyrus around boreholes and oil-impacted lands to reduce phosphorus leaching into aquifers;
4. Furthermore, there should be promotion of community education and awareness, especially in rural areas of Ekpeyeland, on the risks associated with using untreated groundwater sources in polluted environments;
5. fourthly, there should be enforcement of periodic groundwater audits in oil-rich areas using both chemical and biological markers, including TSI, to provide early warning of aquifer eutrophication or degradation;
6. lastly, there should be legislation on groundwater protection policies specific to artisanal refining zones, backed by empirical research and community-participatory environmental governance, and including the integration of TSI assessment into national environmental monitoring frameworks, particularly for the Niger Delta region, to support sustainable development goals (SDGs) on clean water and environmental protection.

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